



# Modeling human behaviors and frailty for a personalized ambient assisted living framework

Joaquim Bellmunt Montoya

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# THESE POUR OBTENIR LE GRADE DE DOCTEUR DE L'UNIVERSITE DE MONTPELLIER

En Informatique

École doctorale Information Structures Systèmes

Unité de recherche Informatique

## MODELISATION DES COMPORTEMENTS HUMAINS ET DE LA FRAGILITE POUR LA CONCEPTION D'UNE PLATEFORME D'ASSISTANCE D'INTELLIGENCE AMBIANTE

Présentée par Joaquim BELLMUNT MONTOYA  
Le 21 Novembre 2017

Sous la direction de Mounir Mokhtari

Devant le jury composé de

Norbert NOURY, Professeur à l'Université Claude Bernard Lyon, France.

Rapporteur

Abdelsalam HELAL, Professeur à Lancaster University, Grande Bretagne.

Rapporteur

Philippe FRAISSE, Professeur à l'Université de Montpellier / CNRS LIRMM (UMR 5506), France.

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Associé CNRS LIRMM (UMR 5506), France.

Directeur de Thèse



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*“There’s a way to do it better - find it.”*

Thomas A. Edison



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Clear Eyes. Full Hearts. Can't Lose.

# MODELISATION DES COMPORTEMENTS HUMAINS ET DE LA FRAGILITE POUR LA CONCEPTION D'UNE PLATEFORME D'ASSISTANCE D'INTELLIGENCE AMBIANTE

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## Résumé de thèse

Les technologies d'assistance à la vie autonome sont aujourd'hui nécessaires pour soutenir les personnes ayant des besoins spécifiques dans leurs activités de vie quotidienne. Cependant, leur développement demeure limité malgré les enjeux liés à l'accompagnement des personnes âgées et dépendantes. Par ailleurs, l'élaboration de plateformes technologiques durant la dernière décennie s'est principalement concentrée sur la dimension technologique, en négligeant les dimensions humaines and sociales des personnes suivies. Les nouvelles technologies, telles que le Cloud et l'Internet des objets (IoT) pourraient apporter de nouvelles capacités dans ce domaine de recherche permettant aux systèmes de traiter les activités humaines selon des modèles orientés vers l'usage (ie. la fragilité) dans une approche non invasive.

Cette thèse se propose d'envisager un nouveau paradigme dans les technologies d'assistance et le bien-être en introduisant (i) des métriques de calcul de la fragilité humaine et (ii) une dimension urbaine dans un cadre d'assistance ambiant (extension de l'espace de vie de l'intérieur vers l'extérieur). Elle propose une plateforme basée sur l'Informatique dans le Cloud (*Cloud Computing*) pour une communication transparente avec les objets connectés, permettant au système intégré de calculer et de modéliser différents niveaux de fragilité humaine. Cette thèse propose d'utiliser des données hétérogènes en temps réel fournies par différents types de sources (capteurs intérieurs et extérieurs), ainsi que des données de référence, collectées sur un serveur de raisonnement central sur le Cloud. La plateforme stocke les données brutes et les traite à travers un moteur de raisonnement hybride combinant à la fois l'approche basée sur les données (apprentissage automatique), et l'approche basée sur la connaissance (raisonnement sémantique) pour : (i) déduire les activités de la vie quotidienne ; (ii) classifier le type de mouvement effectué par l'individu (par exemple, Walk, Cycling, MRT, Bus, Car) à l'aide de capteurs internes smartphone et un classificateur de mobilité ; et (iii) calibrer les valeurs de fragilité humaine et détecter le changement du comportement humain. Les valeurs de fragilité peuvent permettre au système de détecter automatiquement tout changement de comportement, ou toute situation anormale, qui pourrait entraîner un risque à la maison ou à l'extérieur. L'ambition à long terme est de détecter et d'intervenir pour éviter un risque avant même qu'un médecin ne le détecte lors d'une

consultation. L'objectif ultime est de promouvoir le paradigme de la prévention pour la santé et le bien-être.

Cette thèse vise à concevoir et développer une plateforme intégrée, personnalisée, basée sur le cloud, capable de communiquer avec des capteurs intérieurs non invasifs (par ex. mouvement, contact, fibre optique) et à l'extérieur (*par ex.* BLE Beacons, smartphone, bracelet..). La plateforme développée comprend également un classificateur de mobilité du comportement humain qui utilise les capteurs internes du Smart Phone pour calibrer le type de mouvement effectué par l'individu (p. ex. marche, vélo, tram, bus, et voiture). Les données recueillies dans ce contexte servent à construire un modèle multidimensionnel de fragilité basé sur plusieurs éléments standardisés de fragilité, à partir d'une littérature abondante et d'un examen approfondi d'autres plateformes. La plateforme et les modèles associés ont été évalués dans des conditions réelles de vie impliquant les utilisateurs et les aidants par le biais de différents sites pilotes à Singapour et en France. Les données obtenues ont été analysées et publiées dans de nombreuses conférences et revues internationales.

La plateforme développée est actuellement déployée en situation écologique dans 24 habitats individuels. Cela comprend cinq chambres en EHPAD, et neuf maisons en France, en collaboration avec une maison de retraite (Argentan-Normandie) et à Montpellier en collaboration avec Montpellier Métropole. D'autre part, dix appartements privés sont situés à Singapour en collaboration avec un Senior Activity Center (association à but non lucratif).

Ce travail de recherche sera utilisé dans le cadre d'un déploiement à grande échelle, impliquant une centaine d'utilisateurs, par le biais d'une nouvelle collaboration avec l'agence gouvernementale HDB à Singapour (Housing Development Board – agence qui gère les logements sociaux du pays) dans le cadre de l'initiative du maintien à domicile des personnes âgées.

## Mots-clefs

Assistance Urbaine, Plateforme *Cloud*, Intelligence Artificielle, *Plug&Play* Sémantique, Déploiement Réel, Approche Modulaire, Internet des objets, Approche centrée sur l'humain, Usabilité, Mobilité Humaine, Fragilité Humaine

# MODELING HUMAN BEHAVIORS AND FRAILTY FOR A PERSONALIZED AMBIENT ASSISTED LIVING FRAMEWORK

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## Abstract

Ambient Assisted Living is nowadays necessary to support people with special needs in performing their activities of daily living, but it remains unaltered in front of the necessity to accompany aging and dependent people in their outdoors activities. Moreover, the development of multiple frameworks during the last decade has mainly focused on the engineering dimension neglecting impact of human factors and social needs in the design process. New technologies, such as cloud computing and Internet of Things (IoT) could bring new capabilities to this field of research allowing systems to process human condition following usage oriented models (*e.g.* frailty) in a non-invasive approach. This thesis proposes to consider a new paradigm in assistive technologies for aging and wellbeing by introducing (i) human frailty metrics, and (ii) urban dimension in an ambient assistive framework (extending the living space from indoors to outdoors). It proposes a cloud-based framework for seamless communication with connected objects, allowing the integrated system to compute and to model different levels of human frailty based on several frailty standardized items, and leveraged from an extensive literature and frameworks reviews.

This thesis aims at designing and developing an integrated cloud-based framework, which would be able to communicate with heterogeneous real-time non-invasive indoor (*e.g.* motion, contact, fiber optic) and outdoors (*e.g.* BLE Beacons, smartphone) sensors. The framework stores received raw data and processes them through a designed hybrid reasoning engine combining both approaches, Data-Driven (machine learning), and Knowledge-Driven (semantic reasoning), to: (i) infer the activities of the daily living (ADL); (ii) classify the type of movement performed by the individual (*e.g.* Walk, Cycling, MRT, Bus, Car) using Smartphone inner sensors and a mobility classifier; and (iii) calibrate human frailty values to detect changes of human behavior. The frailty values might allow the system to automatically detect any change of behaviors, or abnormal situations, which might lead to a risk at home or outside.

The proposed models and framework have been developed in close collaboration with IPAL (Image and Pervasive Access Lab) and LIRMM (Laboratoire d'Informatique Robotique et Micro-électronique de Montpellier) research teams. They also have been assessed in real conditions involving end-users and caregivers through different pilots sites in Singapore and in France. Nowadays, the proposed framework, is deployed in a real world deployment in 24 individual homes. 14 spaces are located in France (5 private rooms in nursing home and 9 private houses) in



collaboration with a nursing home (Argentan-Normandie and Montpellier). 10 individual homes are located in Singapore in collaboration with a Senior Activity Center (non-profit organization).

The long-term ambition is to detect and intervene to avoid a risk even before it is detected by classical medical assessments. The ultimate goal is to promote prevention paradigm for health and wellbeing. The proposed approach and obtained results have been analyzed and published in multiple international conferences and journals.

This research is intended to be used in a large-scale deployment, involving one hundred end-users, through a new collaboration with HDB government agency in Singapore (Housing Development Board) in regards to ageing-in-place initiative.

## **Keywords**

Urban Assistive Living, Artificial Intelligence, Cloud Framework, Semantic Plug&Play, Real World Deployment, Modular Approach, Internet of Things Framework, Human Centered Approach, Usability, Human Mobility, Human Frailty

# Research Outcomes

## Research Publications

### Journals

- **Bellmunt, J.**, Mokhtari, M., Abdulrazak & B., Aloulou. Validation of an Ubiquitous Computational Frailty Model Towards an Adaptable Ambient Assisted Living Framework. In *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies & UbiCOMP. 3rd Issue Nov.* ACM, 2017. *Under Review*

### Conferences

- Kodys, M., Oliver, P., **Bellmunt, J.**, Aloulou, H., Kaddachi, F. & Mokhtari, M. Smart Mobility in Urban Assisted Living Environments. In *Information Integration and Web-based Applications & Services*, 2017. *Accepted*
  - Kodys, M., **Bellmunt, J.**, Aloulou, H. & Mokhtari, M. Oh, wait, reasoning was wrong! Let's replay. In *Semantic Web Technologies for the Internet of Things*, 2017. *Accepted*
  - Aloulou H., Endelin R., Mokhtari M., Abdulrazak B., Kaddachi F., **Bellmunt J.** Activity Recognition Enhancement Based on Ground-Truth: Introducing a New Method Including Accuracy and Granularity Metrics. In *International Conference on Smart Homes and Health Telematics*. Springer, 2017.
  - Sadek, I., **Bellmunt, J.**, Kodyš, M. & Mokhtari, M. Novel Unobtrusive Approach for Sleep Monitoring Using Fiber Optics in an Ambient Assisted Living Platform. In *Smart Homes and Health Telematics*. Springer, 2017.
  - Kadachi, F., Aloulou, H., Abdulrazak, B., **Bellmunt, J.**, Endelin, R., Mokhtari, M. & M.Fraisse, P. Technological Approach for Behavior Change Detection toward Better Adaptation of Services for Elderly People. In *Health Informatics*. 2017.
  - **Bellmunt, J.**, Mokhtari, M., Abdulrazak, B. & Aloulou, H. Agile Framework for Rapid Deployment in Ambient Assisted Living Environments. In *Information Integration and Web-based Applications and Services*. ACM, 2016.
  - Aloulou, H., Abdulrazak, B., Endelin, R., Kadachi, F. & **Bellmunt, J.** Detecting Inconsis-

tencies in Rule-Based Reasoning for Ambient Intelligence. In *Engineering of Complex Computer Systems (ICECCS)*. IEEE, 2016.

- **Bellmunt, J.**, Mokhtari, M., Abdulrazak, B., Aloulou, H. & Kodys, M. Experimental Frailty Model Towards an Adaptable Service Delivery for Aging People. In *Engineering of Complex Computer Systems (ICECCS)*. IEEE, 2016.

- Aloulou, H., Abdulrazak, B., Endelin, R., Bentes, J., Tiberghien, T. & **Bellmunt, J.** Simplifying Installation and Maintenance of Ambient Intelligent Solutions Toward Large Scale Deployment. In *Smart Homes and Health Telematics*. Springer 2015.

- **Bellmunt, J.**, Tiberghien, T., Mokhtari, M., Aloulou, H. & Endelin, R. Technical Challenges Towards an AAL Large Scale Deployment. In *Smart Homes and Health Telematics*. Springer, 2015.

## Projects

- **City4Age (HORIZON 2020)** System Architect and Technical Project Manager in 2 Pilot sites in 18 months European project focusing on the use of technologies to help frail aging to live with independence and safety. In charge of communicating with end-users to understand the needs and adjust objectives. Also in planning the technical implementation; hardware provisioning; code development; system deployment and integration; and maintenance and improvements.

- **PULSE (HORIZON 2020)** System Architect and Technical Project Manager in 2 Pilot sites in 18 months European project focusing on the use of technologies to help frail aging to live with independence and safety. In charge of communicating with end-users to understand the needs and adjust objectives. Also in planning the technical implementation; hardware provisioning; code development; system deployment and integration; and maintenance and improvements.

- **PSA Peugeot-Citroën: Urban mobility and wellbeing.** The idea is to build a hardware and software infrastructure enabling the continuity of home-based services using the car as a "Mobile Hub" for services related (among others) to health and quality of life. This would increase the living space of people, even frail ones, and contribute to prevention dimension.

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# Acronyms

**AAL** Ambient Assistive Living viii, ix, 6–10, 13, 16, 17, 32, 45–48, 51, 80, 93, 103, 138, 140, 141

**ADL** Activities of Daily Living ix, 2, 6, 8, 12, 13, 46, 47, 51, 57, 62, 69, 70, 74, 76, 84, 126, 130, 138, 139

**AI** Artificial Intelligence 6, 12, 23

**AM** Active Mobility 61

**AmI** Ambient Intelligence 6, 9, 46–48, 52, 54, 55, 90, 91, 120, 123–125

**APIs** Application Programming Interfaces 80, 81

**AT** Assistive Technology 8, 32

**BCG** Ballistocardiogram 12, 58

**BLE** Bluetooth low energy xii, 41, 50, 53, 54, 57, 59, 86, 88, 89, 95–97, 121, 135, 137, 138

**C4A** City4Age 13, 14

**CNRS** Centre National de Recherche Scientifique 34

**CW** Cognitive Walkthrough 103, 104, 138

**DB** Database 80, 82

**DDA** Data-Driven Approach ix, 60, 61

**DL** Deep Learning 30, 31

**FOS** Fiber Optic Sensor xii, xiii, xvi, 12, 53, 54, 57, 81, 89, 92–95, 118, 121, 130, 135, 137

**HA** Healthy Aging 6

**HMM** Hidden Markov Model 50

**IADL** Instrumental Activity of Daily Living 69, 70

**ICF** International Classification of Functioning, Disability and Health xii, 73–75, 77, 78, 127, 138

**ICT** Information and Communication Technology 6, 13, 14, 36, 37

**IMT** Institut Mines Télécom 34

**IoT** Internet of Things viii, 2, 6, 9, 17, 18, 23–26, 33, 36, 38, 41–44, 46–49, 139

**KB** Knowledge Base 67, 73, 85, 86, 93, 95

**KDA** Knowledge-Driven Approach 31, 60, 62

**LDA** Linear Discriminant Analysis 99, 114

**MCI** Mild Cognitive Impairment 13, 14

**MHS** Multiple House Services 53

**ML** Machine Learning 27, 28, 30, 31, 50

**MVC** Model-View-Controller 80, 82

**N3** Notation3 32, 33, 84

**NGB** Naive Gaussian Bayes 29, 99, 114

**NN** Nearest Neighbors 30, 31, 99, 114, 116, 139

**NRF** National Ressource Foundation 23

**PCA** Principle Component Analysis 99

**PIR** Passive Infra-Red 53, 54, 127

**PM** Passive Mobility 61

**PULSE** Participatory Urban Living for Sustainable Environments 14

**QDA** Quadratic Discriminant Analysis 99, 114

**QoL** Quality of Life 47, 66

**RDF** Resource Description Framework 31–33

**SAC** Senior Activity Center xiv, 125, 126, 128

**SHS** Single House Services 53

**SOA** Service Oriented Approach 47

**SVM** Support Vector Machine xiii, 29, 99, 114–117

**UAL** Ambient Assistive Living 9, 10, 15, 141

**WHO** World Health Organization 1–4, 68, 69, 73, 74, 138





# Chapter 1

## Introduction

### 1.1 Aging and Frailty

Taking care of dependent people is becoming a major societal issue. According to World Report on Aging and Health by the World Health Organization (WHO) [118], the number of people aged 60 years or older will rise from 900 million to two billion between 2015 and 2050 (moving from 12% to 22% of the total global population). Moreover the number of elderly people living alone in industrialized countries is expected to increase substantially. These numbers are explained by two main factors, the notable increase in life expectancy and the fertility rate decline.

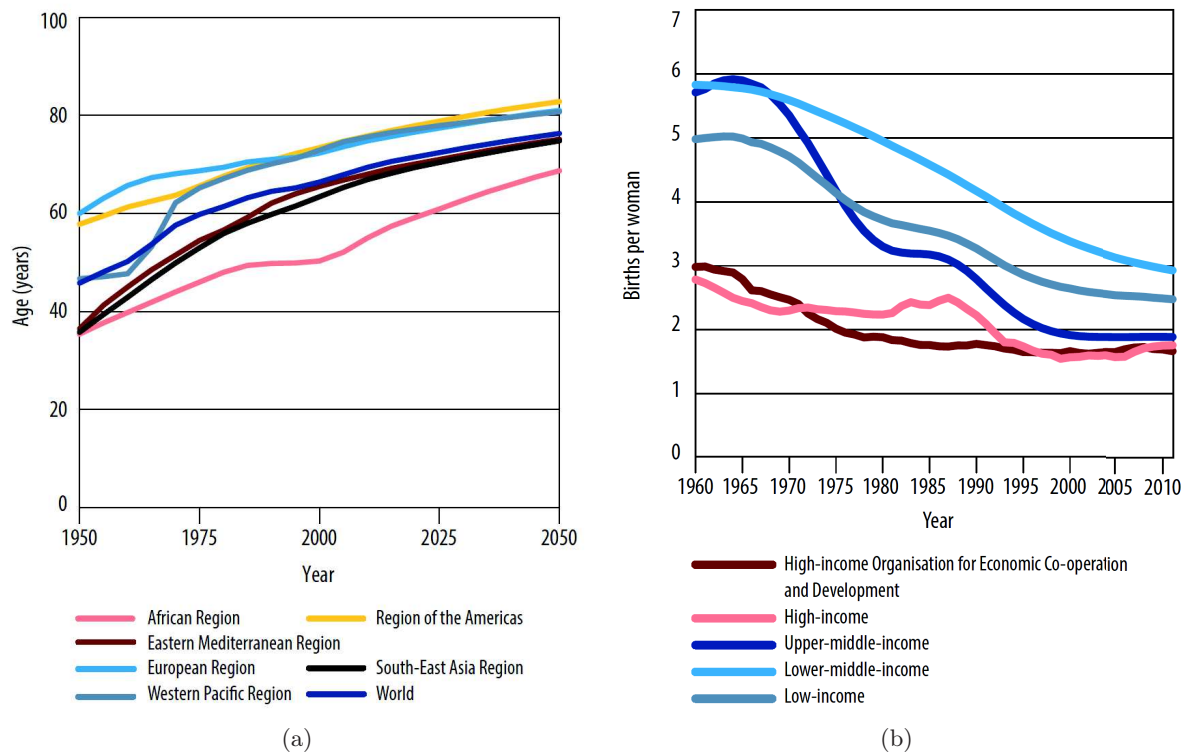


Figure 1-1: (a) Life expectancy evolution [118], (b) Fertility rate decrease [118]

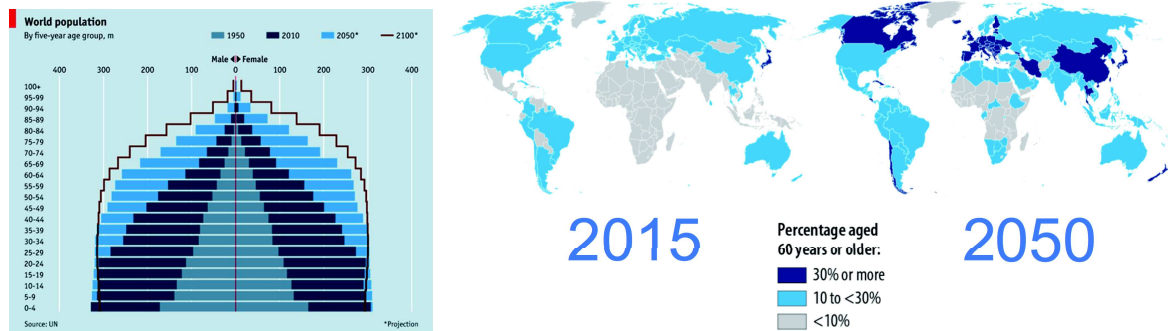
On the one hand, the increase of life expectancy increased by two decades between 1950 and 2010 as can be extracted from Figure 1-1(a), and is expected to increase even more. There are

still considerable disparities between the developed countries, at 82 years, and the developing countries, at 74 years. However, this gap has narrowed greatly in the last decades.

On the other hand, the fertility rate has declined drastically, as shown in Figure 1-1(b). The number of children born per woman fell from five children per woman in 1950 to roughly 2.5 today. It is also notable that the most of this decline has occurred in the developing world, where it is expected to divide the rate by two in 2050.

The consequence of those two factors impacts directly into the world's demography. The global society is evolving from a young population in 2015 to a society with nearly a balanced share between the young and the old population in 2050, as shown in Figure 1-2.

At the same time, and due to the recent economic downturn, health funding in most developed countries will most likely remain under pressure, and will not be able to grow significantly in the foreseeable future [164]. As a consequence, and in order to limit overall human and financial cost burden for the society, health care systems will have to find innovative ways to provide cost effective, but high quality care to an increasing number of elderly patients who are most likely to suffer from chronic disease or other disabilities. That is where smart connected homes and personal tele-health systems enter the game: they are recognized as key enablers to address the above mentioned challenges.



(a) Older people evolution over the years [119].

(b) Older people evolution over the years [118].

Figure 1-2: Reports issued by WHO in 2011 [119] and 2015 [118].

In this chapter, I will provide a definition of aging people and frailty and how technology can provide an impactful support to overcome its inherent problems. I will also present the symptoms of frailty and how it can be used to create a human model to obtain metrics based on the Activities of Daily Living (ADL) performance. Finally, I will position my work in this thesis according to the state of the art in terms of as an Internet of Things (IoT) framework to compute human frailty metrics and behavior to detect risk at early stage.

## 1.2 Aging Population and Dependency: Healthy Aging Concept

The rapid aging of humanity is perhaps the most salient and dynamic aspect of modern demography. It implies an evolving impact on the younger populations. As a result, its influence on public health and national economies is becoming critical. WHO defines the aging process as *"the gradual accumulation of a wide variety of molecular and cellular damage. Over time, this damage leads to a gradual decrease in physiological reserves, an increased risk of many diseases, and a general decline in the capacity of the individual. Ultimately, it will result in death."* [118]. This vision remains in the biological dimension and it does not take into account the real status of the individual. Therefore, in the 2015 report, WHO included a new concept in the aging process besides the biological by introducing the *Health Aging* (Figure 1-3). They state *"while some 70-year-olds may enjoy good physical and mental functioning, others may be frail or require significant support to meet their basic needs. In part, this is because many of the mechanisms of aging are random. But it is also because these changes are strongly influenced by the environment and behaviors of the individual"*.

### What makes us age differently?

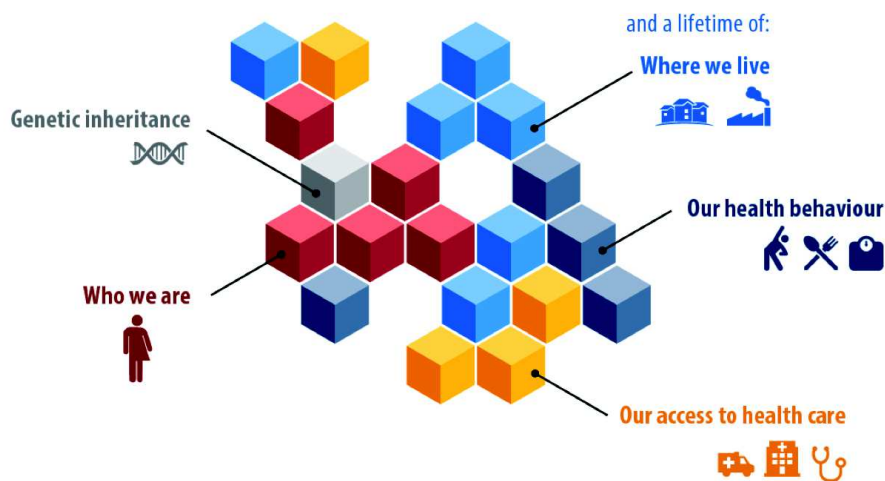


Figure 1-3: Aging well overview presented by the WHO in 2015 [118].

Aging is defined in the Literature as *"an irreversible and inevitable process which increases the vulnerability and the number of deviations compared to ideal condition. In fact, nearly all the cognitive functions, the physical strength and the different senses show age-related decline for some more than for others"* [118]. However, new studies state that aging cannot be understood as a population condition, but it has to be treated at the individual level. Genetics is only a small portion of the puzzle of Healthy Aging. The key factors to determine the quality of life of our elderlies range nowadays from personal factors (sex, ethnics, education or occupation) to environmental factors (residences, transportation, social relationships or health care access). The WHO report [118] highlights five main dimensions which impact upon the individual Quality of

Life, and that need to be taken care by the Public Health institutions:

- **Outdated and ageist stereotypes:** Society often views older people in stereotypical ways that can lead to discrimination against individuals or groups simply on the basis of their age. This has been labeled ageism, and this may now be an even more pervasive form of discrimination than sexism or racism.
- **Inadequate policies:** These stereotypes can lead to bias our policy making and see the aging as drain on economies and cost containment.
- **Lack of accessibility:** Non prepared infrastructures lead the exclusion of aging to housing, transportation and social facilities.
- **Inadequate or absent services are widespread barriers:** Lack of understanding of the individual aging process leads health systems (often designed to cure acute conditions) to be disconnected and fragmented across care providers and personal ecosystems.
- **Lack of consultation and involvement of older people:** Often the health system is build without taking into account the aging opinion when the decision taken affects their lives.

Addressing those issues, and to achieve a substantial improvement of the quality of life of our elderlies towards the healthy aging, the WHO defines four key directives: aligning health and needs of the older populations; developing long-term care health;creating age-friendly environments; improving measurement, monitoring and understanding.

### 1.2.1 Aligning Health and Needs of the Older Populations

Health systems around the world have been unchanged for the last decades while the society has evolved very quickly. New systems need to be capable of providing person-centered and integrated care to enhance and maintain the capacities of the individual. The elders has to be placed at the center of health care. This will require focusing on their unique needs and preferences, and including them as active participants in care planning and in managing their health states. Evidence suggests that focusing primarily on older people’s physical and mental capacities, and maximizing their ability to do the things that are most important to them, is more effective than prioritizing the management of specific chronic diseases. The health workforce needs to be better prepared to deliver older person-centered and integrated care. They need basic knowledge and skills in geriatrics, and they need to know how to work in integrated systems of care.

### **1.2.2 Developing Long-Term Care Health**

Health systems need to adapt to the trending of the society. Families have changed their structure, and nowadays every member has a full time job that does not allow to sustain the house on one figure. Therefore, there is a need for long term care systems that meet the needs of older people, reduce inappropriate dependence on acute health services, help families avoid catastrophic care expenditures, and free women to play broader social roles. Three points have been defined in order to achieve this goal: each country will need to take stock of its unique situation to identify the best system for its context; a crucial strategy for ensuring a sustainable workforce in the future will be to provide paid caregivers with the status and recognition that their contributions deserve; and systems and caregivers need to look at how they can optimize both the older person's capacity, and compensate for losses of capacity, in a way that maximizes dignity and choice.

### **1.2.3 Creating Age-Friendly Environments**

Another important axis is the urban adaption to this new aging paradigm. This action includes a number of actors: health and care, transport, housing, labor, social protection and IT. Ageism must lie at the core of any public health response to population aging. Although this will be challenging, experiences combating other widespread forms of discrimination, such as sexism and racism, show that attitudes and norms can be changed. One key factor is the aging autonomy. It has been shown to have a powerful influence on older people's dignity, integrity, freedom and independence, and has been repeatedly identified as a core component of their general well-being. Fundamentally, older people have a right to make choices and take control over a range of issues including where they live, the relationships they have, what they wear, how they spend their time and whether they undergo a treatment. All government sectors need to consider their contribution to and impact on Healthy Aging. National, regional, state or municipal aging strategies and action plans can help to guide this inter-sectoral response, and ensure a coordinated approach that spans multiple sectors and levels of government.

### **1.2.4 Improving Measurement, Monitoring and Understanding**

Healthy aging aims at changing the way we understand, compute and quantify the quality of life of the elderly. Older people must be included in vital statistics and general population surveys, and analyses of these information resources should be disaggregated by age and sex. Appropriate measures of Healthy Aging and its determinants and distributions will also need to be included in these studies. But research will also need to be encouraged in a range of specific fields related to aging and health, and this will require agreement on key concepts and how they can be measured: the current metrics and methods used in the field of aging are limited, preventing a

sound understanding of key aspects of Healthy Aging. Often, appropriate methods do not yet exist. Sometimes, comprehensive approaches are used in other fields but not adapted to older populations. Consensus is needed on which approaches are most appropriate: although general population-based research and surveillance may place a greater emphasis on older people, specific population-based research about older people is also required; and fostering HA will require a much better understanding of common trajectories of aging, including changes in capacity and ability over time.

Based on the new paradigm of health care for aging, I present in this thesis a technological approach to quantify the level of frailty of the individual based on the ADL performance. The detection of the activities is done through an IoT framework installed at the individual's home and neighborhood. In the next sections, I will briefly introduce the term *frailty* and the Ambient Assisted Living (AAL) technologies.

### 1.3 Relevance of Artificial Intelligence and IoT on Improving Health Condition (Frailty)

Artificial intelligence (AI) is currently considered one of the main research trends. Pervasive Health, unobtrusive sensing, Ambient Intelligence (AmI) and AAL<sup>1</sup> are the keywords that best illustrate the synergies between the technological world and the aging problematic. The main idea is to use existent state of the art technologies (hardware or software) and adapt them to help aging people in their daily life. Intelligent environment and smart spaces are the vision of including smart technologies and Information Computation and Technology (ICT) into the environment, creating a space that brings computation into the physical world. It seems clear then that creating such environments requires expertise in different enabling technology fields, essentially microelectronics (power consumption, sensors manufacturing), communication and networking technologies (broadband and wireless networks) and intelligent agents (context awareness and ontologies). Any AI needs data to be able to infer a situation in a given space. The aim of equipping any space or environments with a set of technologies is to give them the capability of collecting and sharing data. This approach is now possible because of the exponential technologies revolution.

In 1991 Mark Weiser [187] prognosticated the incorporation of sensors, actuators and wireless communications in private spaces to assess specific situations. More recently, technologies such as **Cloud Computing**, **Internet of Things** and **Semantic Web** allow us to collect, treat and reason a continuous flow of data. An aging-friendly smart space is defined as any tool, equipment, system, or service designed to help develop, maintain or improve the daily performance of a person. It helps people of all ages who may have a broad range of disabilities or limitations.

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<sup>1</sup><http://www.aal-europe.eu>

In the case of this thesis, it aims at collecting data from the elderly environments (indoor or outdoor) in order to infer the most probable activity and then build their frailty status based on specific medical items and its statistics. In this thesis, I present the design and implementation of an AAL framework, which uses the above-mentioned techniques to build a favorable micro-context reasoning to be deployed in real deployments and collect real human data with a high level abstraction. The proposed frailty model is based on the outputs of a Data-Driven Approach and a Knowledge-Driven Approach, which interact autonomously with the framework to create a new layer of service selection reasoning and visualize the data in a user-centered approach to be easily consumed.

### 1.3.1 Ambient Assisted Living (AAL)

AAL represents an emerging application area with solutions based on context aware, plastic interface, configurable human environment interaction, as well as probabilistic and rule-based reasoning, which can play an important role to solve the aging problems raised earlier. AAL can enhance aging in place by helping elderly people with their ADLs. The concept of AAL consists of a set of Assistive Technology (AT), targeting the extension of the time that elderly and disabled people live independently in their preferred environment, *e.g.* their own home, neighborhood and town. It covers personalized home care assistance, smart homes, assistive cities, etc. ATs provide personalized continuity of care and assistance, dynamically adapted to the individual needs and circumstances of the users throughout their lives [110]. They are targeted at improving the organization of health care providers; improving therapy and rehabilitation; and enhancing prevention and care.

In this sense, an AAL space is a pervasive and transparent infrastructure that is capable of observing people without interfering with their life and then react to their needs and requirements. Thus, there is an explicit focus on the individual within the environment. In AAL environments the individual does not need to adapt to what the technology can offer. It is the environment and technologies that need to be designed for the user. The AAL environment is composed of devices, applications, services and their interfaces, and the sensing systems that enable it. Using these systems, the environment becomes sensitive to the presence and the activities of the aging and reacts to their inputs. An AAL framework should be [107]:

- Non-obtrusive: the system should not interfere with the user's life style through invisible, embedded and distributed devices.
- Context aware: the system should be able to recognize and anticipate the context the user is evolving in and use this context to react to his needs and requirements.
- Personalized: users' profiles and environments are heterogeneous. The system should be



customizable in order to fit in different environments and to be used by different users.

- Adaptive: the system’s behavior can change in response to the actions and the needs of a person. New services and functionalities can be added with respect to the user needs.
- Anticipatory: it anticipates the person’s desires and environment status; it is context predictive and proactively enabler.

### 1.3.2 IoT framework for AAL

The ambition is to build an efficient large scale and deployable indoor system. Technological progress allows us to take better care of ourselves and our relatives with less effort. Furthermore, we observe an emergence of *Zero-Effort Technologies* (ZET) [103]. They represent technological solutions that provide a service without requiring any form of active participation of the user. Their main paradigm is to leverage on unobtrusive observations of daily activities and on an smart use of the available information.

Discovering the context and creating knowledge in AAL has become a key challenge when facing distant, quick and large scale deployments. Nowadays, the third generation of AAL platforms [1] focus on preventing risks, monitoring, and assisting aging in place. However, real deployments have to be addressed individually to fit its end-user’s needs, space peculiarities or even connectivity issues. Based on the experience, a deployment of the former framework needed an hour of technical preparation and about four hours of deployment time. Moreover, most of the times an expert is required to provide these details manually and often hard coded, and also maintain the system on-site. This procedure represents an even bigger obstacle when facing distant deployments at city scale. It adds complexity to any maintenance and makes the integration of these technologies and the involvement of the end-users difficult. The possibility to adapt to different environments, ease of deployment and maintenance are ongoing problems of AmI. Therefore, simplifying the deployment and maintenance of Ambient Intelligence solutions is key to enable large-scale deployment and maximize the use and benefit of these solutions.

## 1.4 From AAL to Urban Assistive Living Concept

As far as the mobility of older people within the city is concerned, the ambition is to demonstrate the effectiveness of a city-scale process, that will extend the current AAL approach to a wider Urban Assisted Living approach (UAL). The various stakeholders that care about the well-being of the aging have an interest in ensuring that the person is able to leave the house safely and with confidence [120]. This goes far beyond the simple access to timely and pertinent information in the context of the purpose of the trip. The behaviors of the person inside and outside the home (health indicators, urban indicators, mobility indicators, etc.) are key indicators of health



and wellbeing. The way that an aging moves, slows down, speeds up, avoids obstacles or avoids trips because of obstacles on the route (physical and social) all contribute to its well being (how they feel about their independence) and reveal vital information about its health (physical and psychological). The cycle of data flow and contextual knowledge to attribute meaning to the data, is a comprehensive test to validate the proposed approach through several pilot sites: 2 European projects (City4Age (C4A) and PULSE) and an industrial collaboration with PSA Peugeot-Citroen. The UAL framework is illustrated in Figure 1-4.

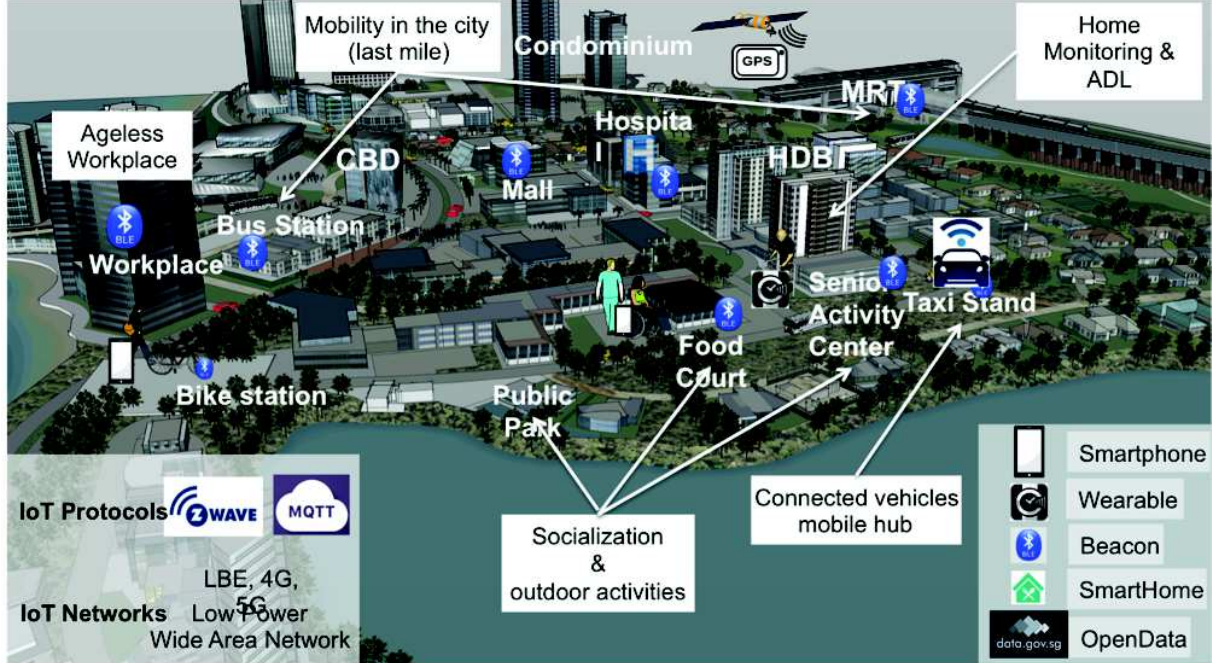


Figure 1-4: Urban Assisted Living (UAL) framework ambition.

## 1.5 Computation of Frailty within an AAL Framework

The ultimate goal of this thesis is to include human metrics will allows to compute frailty from non-invasive sensing capabilities. The chosen metrics for this work have been linked to the human frailty. The definition of frailty remains contested, but it can be considered as a progressive age-related decline in physiological systems that results in decreased reserves of intrinsic capacity, which confers extreme vulnerability to stressors and increases the risk of a range of adverse health outcomes [54]. Frailty, care dependence and comorbidity are distinct but closely related: the study conducted [57] found comorbidity in 57.7% of cases of frailty and care dependence in 27.2% of cases, with neither being present in 21.5% of frail cases.

A large European study estimated the prevalence of frailty at age 50 years to 64 years to be 4.1%, increasing to 17% in those aged 65 and over [156]. This same study found the prevalence of being pre-frail at these ages was 37.4% and 42.3%, respectively. However, the prevalence of both frailty and pre-frailty varied markedly among countries, being more higher in southern Europe.

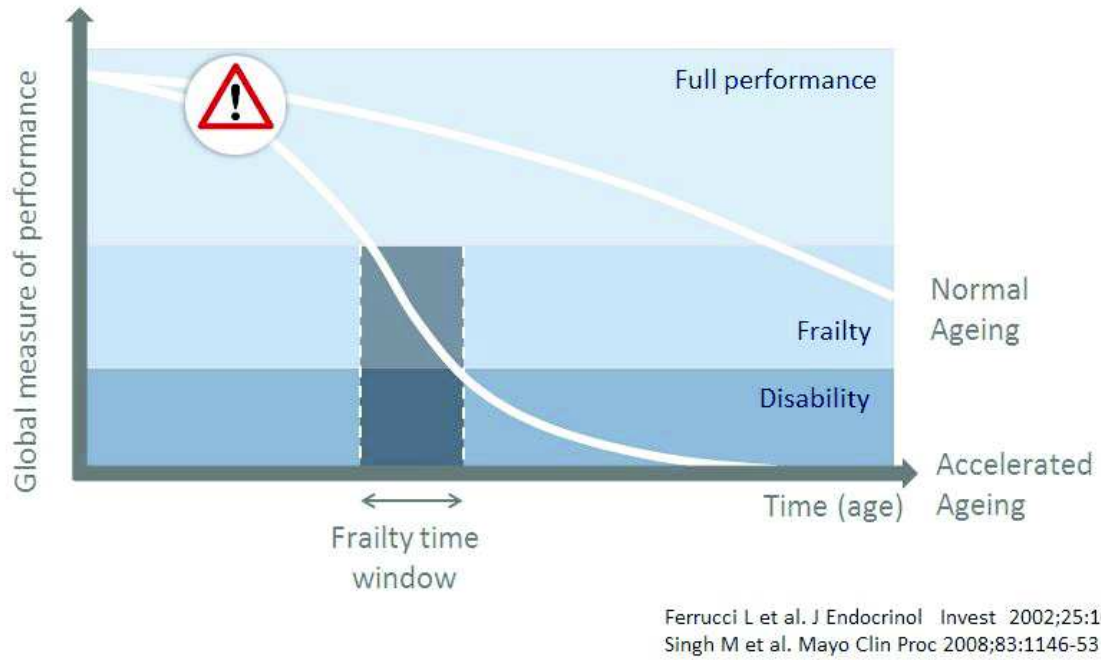


Figure 1-5: Frailty evolution according to time (age) presented by Ferruci [53].

Estimates from Japan and the Republic of Korea, put the prevalence of frailty in both countries at around 11% [160] for ages of 65 years or older. Frailty may be even more prevalent in low- and middle-income countries [11, 3], and is more common in women and in people with lower socioeconomic status [56, 144]. The course of frailty varies markedly from individual to individual and appears to be reversible, although only a small proportion of frail individuals will return spontaneously to full robustness [62]. Because frailty comprises complex decrements occurring in several systems, one key clinical approach is the use of comprehensive geriatric assessments. These assessments, and the person-tailored interventions that derive from them, have been shown to prevent many major negative health-related outcomes, including shortened survival times and care dependence [45]. Interventions aimed at increasing physical activity have also been shown to be effective, and may be most effective in more severe cases of frailty [39]. Interventions aimed at improving nutrition may also be beneficial, but evidence is limited [85]. *E.g.* Figure 1-5 presents the definition of frailty introduced by Ferruci in 2004, [53]. Ferruci describes frailty as a permanent condition that impacts on the individual performance and reduces his/her capabilities.

## 1.6 Scientific Challenges

The scientific challenges presented in this thesis are divided into two axis: first, the conception and implementation of a consistent frailty model using non intrusive sensing capabilities. Second, the design and implementation of a software solution ready to be deployed in real situations, adapted to the users needs and modular to any type of hardware.

## Frailty Model with Unobtrusive Sensors

The design of an efficient frailty model responds to the necessity of bringing the end-user in the center of the assistive technologies. In the recent years the community has improved the proposed frameworks from the engineering point of view. AI has brought new capabilities for computing and understanding situations. However, the impact of those technologies upon the user is barely assessed. To put the user at the end of the loop this thesis proposes a human model based on the frailty condition. This model allows the system to follow specific human items and draw a complete overview on his/her status with an *Small Data* approach. The model uses non invasive technologies and sensing capabilities to compute ADL, both indoor and outdoor. Specific domains such as sleep and mobility have been further investigated adding specific sensing capabilities and developing dedicated algorithms to understand the human performances deeper. Once the activities are computed, they are processed to identify frailty items and build the frailty model.

**Indoor and Outdoor ADL:** Outdoors activities are difficult to follow with non invasive technologies. However, a performing indoor activity recognition system allows to anticipate the outdoor journeys. The framework has evolved to be externalized by integrating new sensing capabilities to build the most accurate frailty model. Indoor activities such as *sleep*, *nutrition*, *hygiene* or *socialization*, have been combined with outdoors activities such: *transportation*, *outdoors nutrition* or *outdoors socialization*, to build a human model.

**Fine Grain Human Values:** Sleep and mobility performance have been detected as major indicators of the human frailty. This thesis presents dedicated non invasive sensing capabilities to better understand those domains. The system includes a fiber optic sleep (FOS) sensor that after an accurate cleaning process is capable of obtaining the Ballistocardiogram BCG of the individual to monitor his sleep. This signal contains the heart rate and the respiratory effort and it can be detected even if the sensor is placed under the mattress. The framework also uses an smartphone to receive information of devices around the city to accompany the user during his/her outdoors journeys. A dedicated mobility model has been conceived to understand the individual's displacement.

## Real Deployments - Human Centered Approach

The proposed system aims at being deployed in real situations. This ambition has been prioritized at the time of designing and implementing the framework. The system is hardware independent designed in a plug-in modular approach to be able to easily integrate new sensing capabilities. The system is build user centered and aims at modeling his condition to adapt its future interaction.

**Framework Usability Validation:** Since system is user centered, any feature at the front-end level has to be conceived from the stakeholder perspectives. In this sense, the proposed framework has been analyzed with usability tools to detect bottle necks and misconception implementations. The results show that the system responds to the users needs with some space for improvements.

**Hardware Agnostic Framework:** The AAL framework has been conceived looking for a minimal hardware invasion of the space. The objective is to remain invisible for the user while doing his ADL. Obviously, this approach needs to raise a compromise between the sensing capabilities with the number of sensors. However, as explained before, the aim of the framework is not to continuously follow the user but to understand his/her context and detect any kind of risk situation (frailty). The hardware devices all are industrial sensors, which offer robustness, and high communications and battery performances. The modular approach of the system allows to integrate any type of sensors with a minimal software development, which adapts the inner sensor behavior to the expected output. This development can be performed either at the server or the gateway level.

## 1.7 Research Valorization

This thesis has been supported within two European project HORIZON2020 (H2020), and an industrial partnership with PSA Peugeot-Citroën. It is also a key enabler to improve the proposed frameworks and investigate new dimensions of the human frailty. These projects aims at validating the research in real deployments and interact directly with the targeted stakeholders.

### 1.7.1 H2020 - City4Age

City4Age (C4A) is a European project which aims at activating urban Communities to facilitate the role of social/health services and of families in dealing with Mild Cognitive Impairment (MCI) and frailty in the elderly population. The challenge is to demonstrate that Cities play a pivotal role in the unobtrusive collection of more data on individual behaviors. This can then greatly improve the early detection of risks through the timely analysis of changes in these behaviors and, finally, the design of effective interventions for countering these risks [96, 81].

The core objective of C4A is to enable Ambient Assisted Cities or Age-friendly Cities, where the urban communities of elderly people living in Smart Cities are provided with a range of ICT tools and services that -in a completely unobtrusive manner- will improve the early detection of risks related to cognitive impairments and frailty while they are at home or on the move within the city. The second objective is to provide a range of associated tools and services which -with the appropriate interventions- will mitigate the detected risks. The final objective of C4A is

to define a model which will provide sustainability and extensibility to the offered services and tools by addressing the unmet needs of the elderly population in terms of (i) detecting risks related to other health type problems, (ii) stimulating and providing incentives to remain active, involved and engaged, (iii) creating an ecosystem for multi-sided market by matching needs and their fulfillments, (iv) contributing to the design and operation of the ultimate Age-friendly City, where the city itself provides support for detecting risks and providing interventions to those affected by MCI and frailty. To achieve these objectives C4A builds on:

- behavioral, sociological and clinical research on “frailty” and MCI in the elderly population;
- state of art ICT technology (i) for “sensing” personal data and exposing them as linked open data, (ii) for designing the algorithms and the API’s to extract relevant behavior changes and correlated risks, and (iii) for designing interventions to counter the risks,
- stakeholder engagement in order to be driven by relevant user needs to ensure end-user acceptance.

**Scientific Value - Change of Behaviors:** C4A project has allowed this thesis to be deployed in two different countries collecting data from real scenarios. In the context of Singapore the project helped at approaching residential association that linked the research team with aging and frail people willing to be part of the research. The continuous gathering of data allows the understand the individual micro context and detect change of behavior (permanent) or abnormal behavior (sporadic).

### 1.7.2 H2020 - Pulse

PULSE (Participatory Urban Living for Sustainable Environments) will leverage diverse data sources and big data analytics to transform public health from a reactive to a predictive system, and from a system focused on surveillance to an inclusive and collaborative system supporting health equity. Working within five global cities, PULSE will harvest open city data, and data from health systems, urban and remote sensors, personal devices and social media to enable evidence-driven and timely management of public health events and processes. The clinical focus of the project will be respiratory diseases (asthma) and metabolic diseases (Type 2 Diabetes) in adult populations. The project will develop risk stratification models based on modifiable and non-modifiable risk factors in each urban location, taking account of biological, behavioral, social and environmental risk factors.

**Scientific Value - Aggregated Urban Data:** This project brought the UAL framework the Open Data dimension which is needed to understand the macro context of one individual.

The Open Data had to be included and treated as one more item within the reasoning impacting at the decision level.

### 1.7.3 PSA Peugeot-Citroën

The mobility dimension, active and passive, indoor and outdoor, has a considerable contribution to the quality of life of people, particularly those with chronic disease, especially while considering the connected car as a logical extension of the connected home. This project aims to provide a number of innovative services to assist people in their daily life based on different means for mobility (pedestrians, public transport, car/taxi, MRT, etc.). The idea is to build a hardware and software infrastructure enabling the continuity of home-based services using the car as a "Mobile Hub" for services related (among others) to health and quality of life. This would increase the living space of people, even frail ones, and contribute to prevention dimension. To validate our concept, we have decided to focus on 2 different types of chronic diseases: Endocrinal disease with Type 2 Diabetes, and Respiratory with Asthma. Several key actions have been targeted:

- Intervention Planning (Exploration) Identify users, needs, motivations and means
- Create the measurement model of mobility (linked to the continuum: Between home to outside with definition of measures
- Classification of quality/level of mobility with variability of users behavior
- Personalized ways of interacting with people to increase mobility Including motivation and intervention

**Scientific Value - Holistic Mobility Program:** This project brought to the proposed framework the mobile dimension. It incorporates the data aggregation through the Data-Driven approach techniques (Machine Learning). It brought to the project the necessary industrial collaboration to expand the framework outdoors and collaborate with Urban governmental agencies. The challenge is to export as much as possible the indoor assistance while the individual is outdoors. Smart phone and transportation are the target of the first version of this project.

## 1.8 Thesis Positioning and Overview

This thesis expands the current state of the art with a novel approach to use non invasive technologies to build a human model based on the evolution of frailty human values and using a *Small Data* approach. The adopted hardware agnostic approach opens a wide range of opportunities for future improvements. The framework has been tested in diverse European projects and industrial collaboration. It has been deployed in more than 40 real environments over the



last three years in France and Singapore. This thesis brings to the community valuable lessons learned and future perspectives based on real deployments experiences.

One of the aims on this thesis is to change the paradigm of assistive health. Existent projects evolve on the infrastructure, systems, engineering, hardware side to get better sensors, performances, inferences, communications, but rarely considering the user. I propose to put the user in the loop again by making him the principal contributor and beneficiary of the system. The user is now at the beginning and at the end of the technological approach. *I.e.*, the system collects data from the user performances to compute and model human values based on his frailty and then adapt its decisions.

In this research, I also introduce an agile framework to allow non-expert users in computer science (*e.g.* local technicians) to rapidly deploy the sensing kit for the proposed AAL application. This thesis presents a solution for simplifying the monitoring and maintenance of installed systems, also targeting the accuracy, usefulness, and usability aspects of the solutions. It also discusses lessons learned from the approach for automating the deployment process in order to be performed by ordinary people. The deployment enabled us to be aware of several technical issues related to in-situ deployment (*e.g.* networking, ease of deployment, maintenance).

This document is composed by seven chapters. The introduction 1 presented the main context of this thesis, the problematic and the hypothesis in order to customize an AAL framework by inferring the frailty level of each individual. In the next Chapter 2 the main approaches to build a framework that is able to collect, clean, package and process environmental data is presented. It explains this chain from the data science perspective and rises the debate of using different techniques to treat and merge environmental and open source data. Chapter 3 positions the proposed research within the state of the art. The comparison does not only remain in the research field but also takes into account the industrial level. Once the thesis is positioned in the literature, the design and the implementation of the proposed approach is discussed. The design is presented in the Chapter 4 and the implementation in Chapter 5. Frailty is define in details in Chapter 3 to justify the design, Chapter 4, and subsequent implementation, Chapter 5. The validation of the proposed solution is presented in Chapter 6 and finally the conclusion and futures perspectives in Chapter 7.

## Chapter 2

# Introduction to Artificial intelligence and Data Science

IoT and Data Science are complementary technologies that impact on the AAL field. In this chapter, I introduce the main features of Data Science and IoT which will allow the reader to better understand the technical design and implementation.

### 2.1 Technology Evolution

Since the late 90's, both hardware and software have enormously evolved, impacting directly on the end-users. The number of connected objects per person since 2000 has exponentially increased from 0.01 devices/person in 2000 to 3.5 in 2015 and is expected to reach almost 7 devices/person in 2020, as shown in Figure 2-1.

The huge increment in the demand for connected objects impacts directly into three main fields:

1. Hardware Cost

Adapting the shape, the functionalities or the capabilities of the connected devices are major enablers to improve the existent hardware and to optimize the fabrication process to reduce the cost.

2. Entities Management

Any single new connected device (entity) must be declared and identified in the net. Thus, regulators defined standards for the entities declaration and storage. That was the origin of the Web 3.0 movement and Semantic Web with semantic concepts such as URI, Ontology and Knowledge base.

3. Data Flow



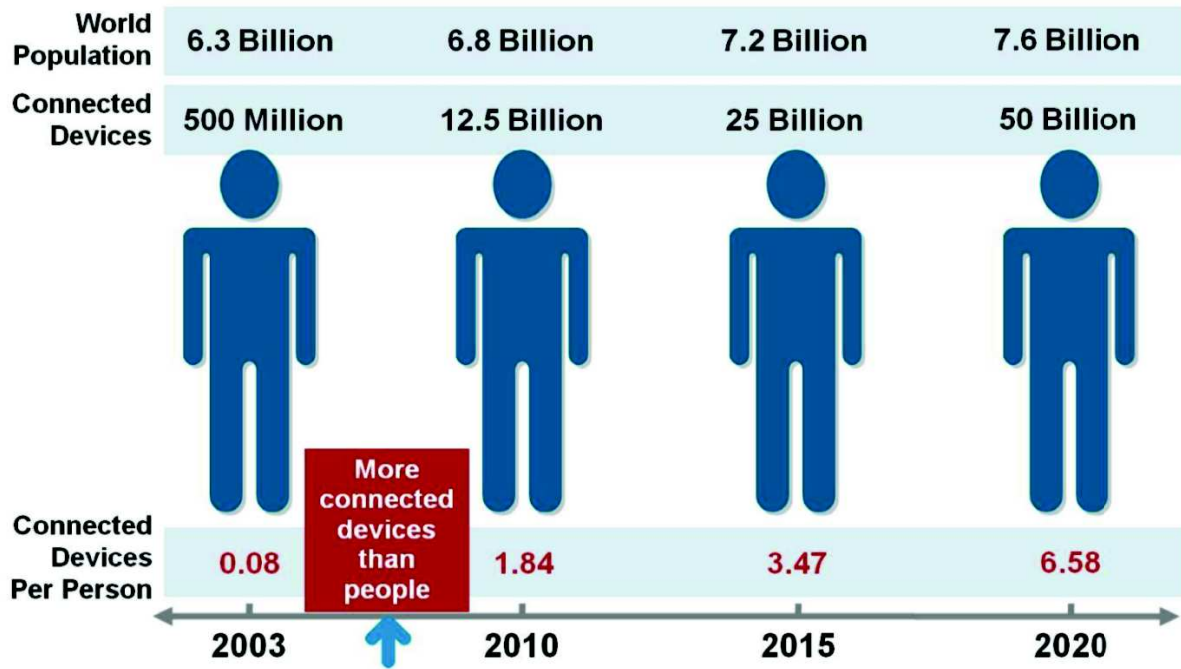


Figure 2-1: Hardware evolution focusing on connected devices per person. Source: *CISCO in 2011. IoT Future Prediction (CISCO IBSG, April 2011)*.

The main objective of connecting devices is to collect more data that may allow us to better understand the stakeholders, trends and behaviors, and leverage on it to extract insights.

The improvements of hardware and communications in the last 20 years has lead to a new era of connectivity with increased the data exchange flow. Data collection has become almost continuous and the objects are now connected not only at the device level but also at the component level. Figure 2-2 presents the most recent study, performed by *Gartner*, on trending technologies. It can be noted that IoT, Machine Learning, and connected homes are among the most trending subjects.

In the next sections, I present the new paradigm of data sourcing, also known as the IoT. With cloud solutions, the stakeholder is able to manage the collected data. Finally, I present the differences between Data- or Knowledge- Driven approaches to process and exploit the data.

## 2.2 The IoT Paradigm

A sensing device is understood as any component, module, or subsystem that has the purpose to detect events or changes in its environment and send the information to another device. The diversity and amount of sensing devices has increased with the evolution aforementioned.

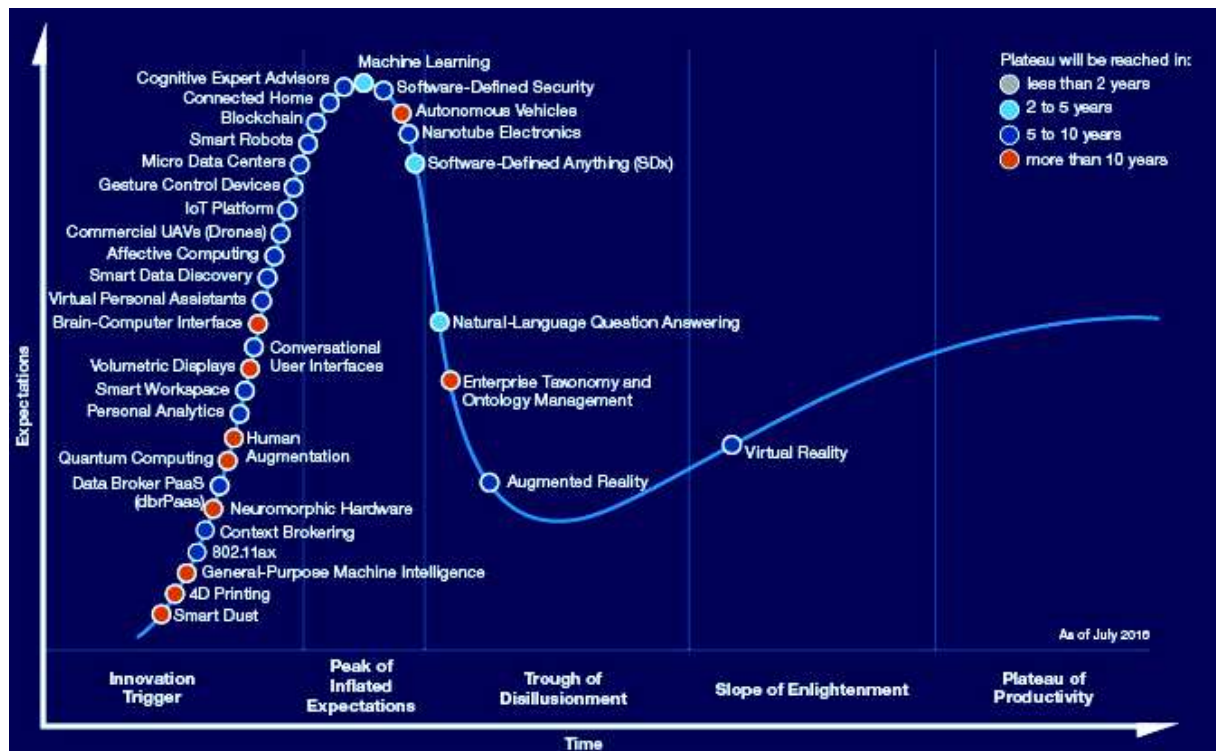


Figure 2-2: Technologies trends in 2016. Source: [www.gartner.com](http://www.gartner.com).

### 2.2.1 Wearables

An example of sensing devices are wearables, devices that are carried on the body as part or complement of the person's clothes. The most popular wearables include sport tracking wristbands, smartwatches, clothes with electronic components, health-rate chest band monitors, etc.

The popularity of smartwatches is on the rise, especially after the release of Apple Watch and the varied offer of watches with Android. This market, dominated by Apple, is predicted by the International Data Corporation to exceed the 54 million units shipped in 2020 [193]. Figure 2-3 shows the forecast and includes the ratio of smart watches and basic wearables. The distinction is done depending on the possibility to install third-party Apps. Those watches that allow to install third-party Apps are considered *smart*, and examples would be Apple Watch, Motorola's Moto 360 or Samsung Gear. Devices without this possibility, like Xiaomi MiBand or FitBit's fitness trackers, are considered *basic wearables* in Figure 2-3.

The sensing capabilities of wearables is varied and depends on each device, but accelerometer, pedometer, or heart-rate monitor are sensors commonly found in many of them. It is common that wearables work as a companion to a smartphone to which they connect through Bluetooth and interact with a dedicated application on the phone.

In the context of assisted living, wearables can track the user's activities with high accuracy thanks to being carried on-body; and the data from their activities can be used to help improve

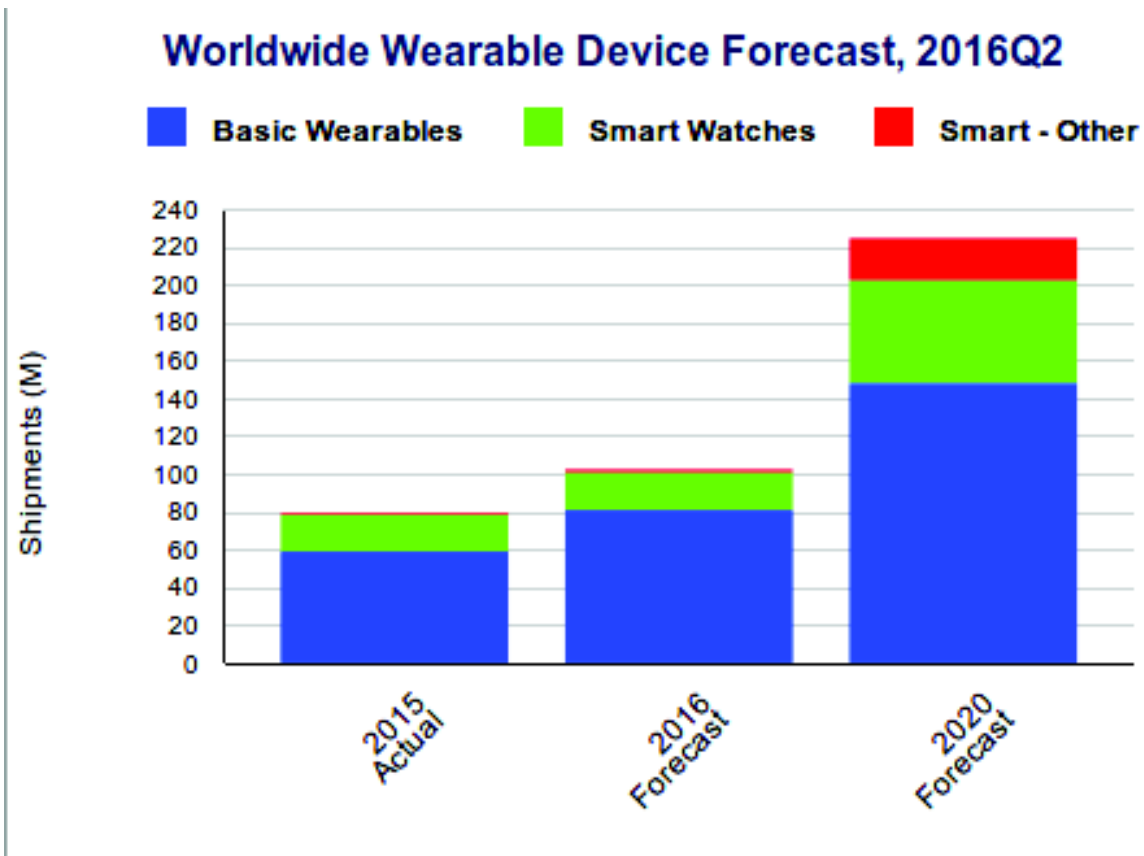


Figure 2-3: Forecast of wearable devices market. *IDC, press release 15 Sep 2016 [193]*.

their habits and life.

### 2.2.2 Connected Objects

Wearables are only one type of thing that can connect to other devices. As it becomes easier and cheaper to add sensing and connectivity capabilities to devices, many more objects are being transformed into *connected objects* such as: home appliances and objects, fridges, air conditioners, ovens, light bulbs. Some commercial examples are:

- Phillips Hue Lights: A hub connected to the Internet that controls the compatible light bulbs through Zigbee. With a smartphone App, or from any device using the Rest APIs that lives in the hub, the user can control the color, intensity and timers of their lights [131].
- Samsung's Family Hub: A smart fridge that lets you add items to the synchronized shopping list from its screen, see from your smartphone what's left in your fridge, and set up automatic reminders where you are running low of supplies [155].
- LG HomeChat: A *chatting buddy* available on the chat platform Line, which controls your connected appliances according to the instructions you write in natural language. It acts

as a remote hub between LG home devices like the refrigerator, washing machine and oven [93].

## 2.3 Data Paradigms

The high increase of data generated by numerous sources has defined a new data paradigm according to its temporality: Historical, Real-Time or Near Real-Time. It is well known that data incorporates information that is not directly visible. Each type of data needs to be treated at the right moment. Some data types need of huge amounts of samples and time-based entries to build its sense. Some other types can be treated straight from the sensor in real time flow. New trends of data processing have raised a third timing for data processing, near real time processing, in which the data is stored in real time and processed with minimum delay. Then the processed data is used as aggregated data to compute other insights.

Alternatively to the data temporality it exists a novel data paradigm based on to its structure and extraction value named *Data, Information, Knowledge, and Wisdom* (DIKW) pyramid. It is defined as "an often used method, with roots in knowledge management, to explain the ways we move from data (the D) to information (I), knowledge (K) and wisdom (W) with a component of actions and decisions" [149]. This paradigm relies on the idea that the *Data* itself does not mean anything ("*Know Nothing*") or does not add any value. It is the *Information* ("Know What"), that organizes and formats the *Data* for a purpose. *Knowledge* ("Know How") combines *Data* and *Information* with understanding and capabilities. Finally, *Wisdom* ("Know Why") adds ethics and responsibility with vision foresight.

### Real-Time Data

Real-time data is collected with a periodicity that allows us to know the status of the target at any given time, with no significant delays that would make the latest information obsolete: information that is delivered immediately after collection. There is no delay in the timeliness of the information provided. Real-time data is often used for navigation or tracking. Real-time analytics is also known as dynamic analysis, real-time analysis, real-time data integration and real-time intelligence. The basic definition of real-time data is that it is data that is not kept or stored, but is passed along to the end user as quickly as it is gathered. It is important to note that the user does not receive real-time data instantly. There may be any number of bottlenecks related to the data collection infrastructure, the bandwidth between various parties, or the speed of the end user's computer. Real-time data does not promise data within a certain number of microseconds, but that the data is not to be kept back from its eventual use after it is collected.

In computer science, real-time computing (RTC), or reactive computing describes hardware and software systems subject to a "real-time constraint". Real-time programs must guarantee

response within specified time constraints, often referred to as "deadlines". The correctness of these types of systems depends on their temporal aspects as well as their functional aspects. Real-time responses are often understood to be in the order of milliseconds, and sometimes microseconds. A system not specified as operating in real time cannot usually guarantee a response within any timeframe, although typical or expected response times may be given. A real-time system has been described as one which "controls an environment by receiving data, processing them, and returning the results sufficiently quickly to affect the environment at that time." [3] The term "real-time" is also used in simulation to mean that the simulation's clock runs at the same speed as a real clock, and in process control and enterprise systems to mean "without significant delay".

### **Near Real-Time Data**

Near real-time processing is used when speed is important, but processing time can be in the order of minutes instead of seconds. We can consider near real-time data any data with new availability ranging from every few minutes to every a few hours. Data collected with a high frequency but shared in less frequent batches is also considered near real-time.

The term "near real-time" or "nearly real-time", in telecommunications and computing, refers to the time delay introduced by automated data processing or network transmission between the occurrence of an event and the use of the processed data, such as for display or feedback and control purposes. The distinction between the terms "near real time" and "real time" is somewhat nebulous and must be defined for the situation at hand.

Near real-time also refers to delayed real-time transmission of voice and video. It allows playing video images, in approximately real-time, without having to wait for an entire large video file to download. Incompatible databases can export/import to common flat files that the other database can import/export on a scheduled basis so that they can sync/share common data in "near real-time" with each other.

### **Historical Data**

Historical data is the storage and classification of any type of data that can be exploited to extract information, patterns and insights. A better organization of the collection and analysis of such data, allows to take advantage of all the available information and make informed decisions based on measurable and compelling evidence, to anticipate problems and resolve them proactively, and finally to coordinate resources and processes more effectively.

Historical Data is less time-sensitive than near real-time. In fact, batch processing jobs can take hours, or perhaps even days. Batch processing involves three separate processes: First, the data is collected, usually over a period of time. Second, the data is processed by a separate

program. Thirdly, the data is returned. Examples of data entered in for analysis can include operational data, historical and archived data, data from social media, service data, etc. Examples of uses for batch processing include cancer detection, which needs recorded labeled data from past medical records, such as X-Ray and soft tissues samples.

Following, I discuss the type of data storage to use with big or small amounts of data, and the different types of data exploitation algorithms to optimize the sensing.

## **2.4 Data Science**

Data science is an interdisciplinary field that aims at understanding and analyzing specific phenomena with data. It employs techniques and theories drawn from many fields within the broad areas of mathematics, statistics, information science, and computer science.

This thesis has been endorsed by the Singaporean AI.SG program by providing a favorable ecosystem to deploy and test the technology. AI.SG is a national program in Artificial Intelligence (AI) to catalyze, synergies and boost Singapore's AI capabilities to power the future digital economy. AI Singapore brings together all Singapore-based research institutions and the ecosystem of AI start-ups and companies developing AI products, to grow the knowledge, create the tools and develop the talent to power Singapore's AI efforts. It is driven by a government-wide partnership comprising the National Research Foundation (NRF), the Smart Nation and Digital Government Office, the Economic Development Board, the Infocomm Media Development Authority, SGInnovate, and the Integrated Health Information Systems. NRF will invest up to \$150 million over five years in AI Singapore.

Therefore, in this thesis the data science concept has been enlarged to include features that complements the IoT approach. Small data vs Big data paradigm, data standardization, data exchange, data communication protocols, data storage and data processing (both Data- and Knowledge- Driven approaches) have been detailed in this section aiming at helping the reader to understand the design and implementation, Chapters 4 and 5.

### **2.4.1 Small Data vs Big Data**

Small Data is usually understood as a set of structured values, which are accessible and exploitable with light preprocessing. It comprises of definite and specific attributes of datasets, which can be used to analyze current situations. Big Data contrasts with Small Data because in this case, the data is a combination of structured and unstructured values with large amounts entries.

Small Data needs for a mastering of the data to be able to extract the maximum conclusions. Big Data, on its side, is based on discovering patterns, behaviors, predictions based on nonvisible information. The lack of knowledge in Big Data projects represents a high computer consumption



with a high a risk of failure. Small Data, reasons faster and allow to see the results upon the problematic quicker. Figure 2-4 represents the differences between both approaches by comparing their principal features.

Category	Big Data	Small Data
Data Sources	Data generated outside the enterprise from nontraditional data sources. Include: <ul style="list-style-type: none"> <li>• Social media</li> <li>• Sensor data</li> <li>• Log data</li> <li>• Device data</li> <li>• Video, Images, etc.</li> </ul>	Traditional enterprise data. Includes: <ul style="list-style-type: none"> <li>• Enterprise Resource Planning transactional data</li> <li>• Customer Relationship Management (CRM) systems</li> <li>• Web transactions</li> <li>• Financial data e.g. general ledger data</li> </ul>
Volume	<ul style="list-style-type: none"> <li>• Terabytes (<math>10^{14}</math>)</li> <li>• Petabytes (<math>10^{15}</math>)</li> <li>• Exabytes (<math>10^{16}</math>)</li> <li>• Zettabytes (<math>10^{21}</math>)</li> </ul>	<ul style="list-style-type: none"> <li>• Gigabytes (<math>10^9</math>)</li> <li>• Terabytes (<math>10^{12}</math>)</li> </ul>
Velocity	<ul style="list-style-type: none"> <li>• Often real-time</li> <li>• Requires immediate response</li> </ul>	<ul style="list-style-type: none"> <li>• Batch or near real-time</li> <li>• Does not always require immediate response</li> </ul>
Variety	<ul style="list-style-type: none"> <li>• Structured</li> <li>• Unstructured</li> <li>• Multi-structured</li> </ul>	<ul style="list-style-type: none"> <li>• Structured</li> <li>• Unstructured</li> </ul>
Value	<ul style="list-style-type: none"> <li>• Complex, advanced, predictive business analysis and insights</li> </ul>	<ul style="list-style-type: none"> <li>• Business Intelligence, analysis and reporting</li> </ul>

Figure 2-4: Comparison of principal features of Small Data and Big Data approaches. (<http://www.b-eye-network.com/blogs/oneal>)

## 2.4.2 Data Standardization

The first feature treated in this thesis is the data standardization when sending information from a sensor to the cloud. Respecting the standardization allows the interconnectivity between applications. In this case, it helps at exchanging data between platforms within the European project. Moreover, it facilitates the data storage and it rends quicker the data cleaning phase before the exploitation. Following, Table 2.1 lists the main sensor data standards in the literature.

## 2.4.3 Data and Communication Protocols

IoT has opened a new spectrum of communications protocols for small and near devices. IoT exploits different communication protocol depending of the space to cover. However, as some of the applications remain in a smaller area new protocols have been developed. Figure 2-5 represents the main communication protocols for the IoT applications and Table 2.2 enumerates the main features for the new communications protocols.

The apparition of new protocols represents an opportunity but also a need for standardization and consensus to avoid problems of interoperability and scalability. Here we present a Table with the communications consensus in the IoT best practices.

The system follows an IoT approach and thus follows the IoT best practices. The data protocols have been affected by the increasing number of connected objects exchanging small amounts

Table 2.1: Standards for Data homogenization in IoT

Name	Description
<b>IOTDB</b>	Linked Data standards for describing the Internet of Things.
<b>SensorML</b>	provides standard models and an XML encoding for describing sensors and measurement processes.
<b>Semantic Sensor Net Ontology W3C</b>	Ontology describing sensors and observations, and related concepts. (It does not describe: domain concepts, time, locations, etc.)
<b>Wolfram Language</b>	Symbolic representation of each device. Then there are a standard set of Wolfram Language functions.
<b>SENML</b>	Simple sensor descriptor that is intended to be use with HTTP or CoAP.
<b>LsDL (Lemonbeat smart Device Language)</b>	XML-based device language for service oriented devices.

of data. Web-based protocols such as TCP do not fit with the IoT expectations where the user expects to send the information quickly, light and try to avoid heavy sessions or handshakes.

As IoT is a very vast field covering everything, the kind of protocols to be used is also very diversified. There are three main kinds of connections: D2D (Device to Device), D2S (Device to Service), and S2S (Service to Service). There are different protocols adapted for each type of communication as listed in Table 2.3.

MQTT and CoAP are the most extended in the IoT applications with a big developers community:

**MQTT:** MQTT (Message Queue Telemetry Transport) is a many-to-many communication protocol for passing messages between multiple clients through a central broker (a server). While MQTT has some support for persistence, it does best as a communications bus for live data. MQTT messages can be used for any purpose, but all clients must know the message formats up-front to allow communication. Since MQTT offers publish/subscribe semantics on the same socket and the cloud server acts as the message broker between the IoT device and other App/services, it is specially suitable for remote IoT communications.

**CoAP:** CoAP (Constrained Application Protocol) is a document transfer protocol that allows UDP broadcast and multicast to be used for addressing, following a client/server model (clients make requests to servers, and servers send back responses) with packets much smaller than HTTP TCP flows. It is a good mechanism for local network communication, particularly when there is an ecosystem of other CoAP devices.



Table 2.2: Protocols sensor-gateway communication in IoT.

Protocol	Description
<b>6LoWPAN</b>	The 6LoWPAN group has defined encapsulation and header compression mechanisms. It allow IPv6 packets to be sent and received over IEEE 802.15.4 based networks.
<b>X10</b>	X10 is a protocol for communication among electronic devices used for home automation. It primarily uses power line wiring for signaling and control, where the signals involve brief radio frequency bursts representing digital information. The wireless protocol operates at a frequency of 310 MHz in the U.S. and 433.92 MHz in European systems
<b>Zigbee</b>	Zigbee is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks (PAN) with small, low-power digital radios
<b>Zwave</b>	Z-Wave is a wireless communications protocol used primarily for home automation. It is a mesh network using low-energy radio waves to communicate from appliance to appliance. Z-Wave uses the Part 15 unlicensed industrial, scientific, and medical (ISM) band. It operates at 868.42 MHz in Europe, at 908.42 MHz in the North America.
<b>RFID</b>	Radio-frequency identification (RFID) uses electromagnetic fields to automatically identify and track tags attached to objects. The tags contain electronically stored information. Passive tags collect energy from a nearby RFID reader's interrogating radio waves. Active tags have a local power source such as a battery and may operate at hundreds of meters from the RFID reader.

Table 2.3: Protocols for gateway-server communication in IoT.

Protocol	Type	Description
<b>MQTT</b>	D2S	Protocol for collecting device data and communicating it to servers.
<b>CoAP</b>	D2S	Document transport protocol like HTTP but for constraint environment.
<b>DDS</b>	D2D	Fast bus for integrating intelligent machines.
<b>AMQP</b>	S2S	Queuing system designed to connect servers to each other.

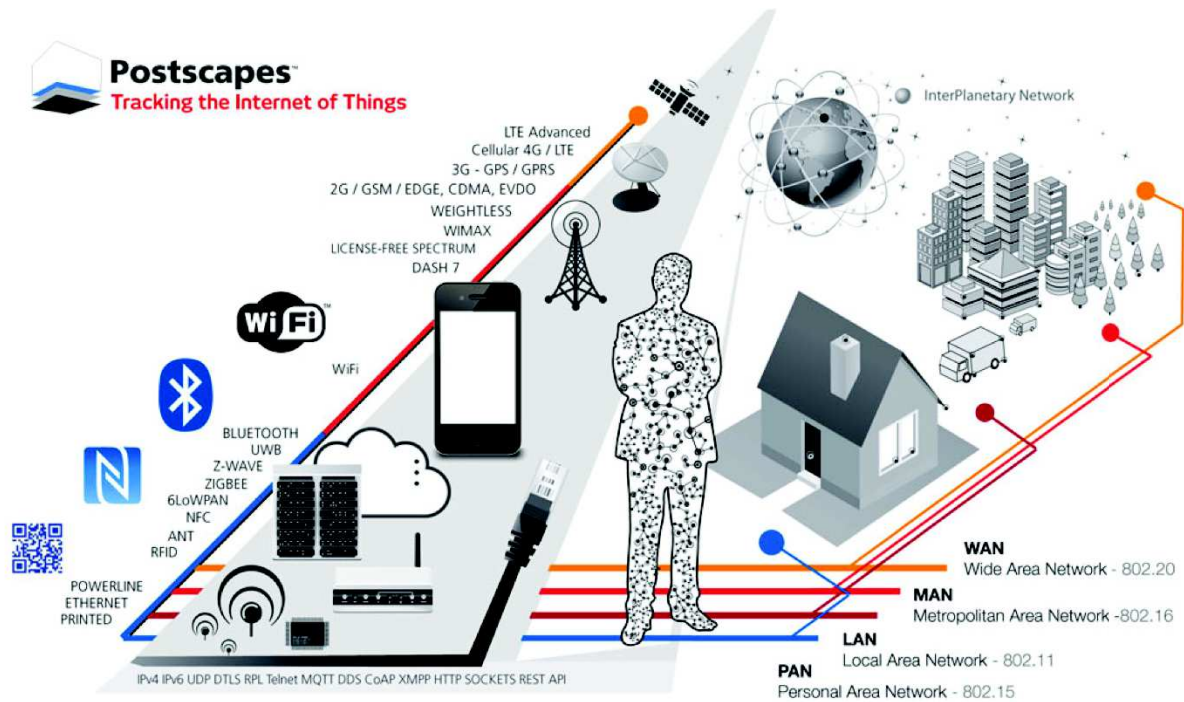


Figure 2-5: Protocols for gateway-server communications in IoT.

#### 2.4.4 Data Storage

Data storage is nowadays one of the key challenges in Data Science. The number and organization of the entries, the accessibility and the I/O read and writing speed are crucial questions that need to be answered when choosing a type of data structure. There are two main types of data storages structures: Non-Relational Databases (DB), which uses text and flexible structures and Relational DB, which uses tables and rigid structures. Next I provide more details on both types and examples of technologies for each of them.

##### Non-Relational Databases

Non-Relational DB are the preferred solution when dealing with large amount of data. A non-relational DB stores data without explicit and structured mechanisms to link data from different tables to one another. The data is stored in JSON arrays and does not need to contain the same fields or attributes on each entry. Non-relational DB can be spitted and stored in different servers avoiding hardware limitations. On the downside, Non-relational DB do not create any link between entries and need to be initialized manually. This increments the number of errors and mismatching commands.

##### Relational Databases

Relational DB use Structured Querying Language (SQL), making them a good choice when the collected data is stored on different connected tables. In other words, SQL allows to create links

between different sets of data through unique identifiers (foreign keys). If the application handles a lot of querying, DB transactions and routine analysis of data, the best choice is a relational DB. However, relational DB have a strong hardware dependency because the whole DB needs to be stored in the same exploitation system.

The proposed framework deals with a small amount of data (order of Gigabytes) collected from sensors placed at elderlies homes and outdoors locations. Therefore, a relational DB is the best choice. The most used relational DB are: SQL, LiteSQL, Postgresql.

**SQLite:** SQLite is a library that gets embedded inside the application. It is suitable for solutions that need scale for concurrency, as it is a single file and a linked C based library and embedded applications without multiuser access with limited throughput.

**MySQL:** MySQL is an open source product and the most used DB. MySQL supports a lot of the SQL functionality and has a security features, also offering better user functionalities. However, MySQL remains less reliable than other DB when performing transactions and concurrency. MySQL is suitable when high security is needed on the applications, distributed operations or if the application needs a lot of customization.

**PostgreSQL:** PostgreSQL, or Postgres, is the advanced, open-source DB management system which has main goal of being standards-compliant and extensible. It supports concurrency, is highly programmable and it is the best choice for Data integrity. The main disadvantage is that Postgres is slower than MySQL.

#### 2.4.5 Data Processing - Data-Driven Approach

Also referred as Machine Learning (ML), Data-Driven approaches are strictly based on statistics within historical data. The greater the amount of available data, the richer the analysis will be. Based on existent data a machine learns to interpret and recognize patterns in order to classify future inputs.

The Arthur Samuel defined Machine Learning in 1959 as: *“the field of study that gives computers the ability to learn without being explicitly programmed.”* More recently, in 1997, Tom Mitchell gave a “well-posed” definition that has proven more useful to engineering types: *“A computer program is said to learn from experience  $E$  with respect to some task  $T$  and some performance measure  $P$ , if its performance on  $T$ , as measured by  $P$ , improves with experience  $E$ .”*, i.e. given a data set  $E$ , the system is able to predict a certain Task  $T$  with a certain precision  $P$ .

In the era of Big Data collection, new ML techniques have been developed to deal with it, such as Deep Learning. Nowadays, where machines are able to collect huge amounts of data from different sources, Data-Driven approaches offer a transversal solution to retrieve abstract

patterns or insights, which could be very helpful to refine business objectives. In order to better understand such amount data, DL are techniques used to automate the feature construction as a part of the ML pipeline. ML techniques are more suitable when the pattern to be recognized has a high occurrence in your dataset. This kind of algorithms are not able to create new information other than from your set of data, and can only recognize pre-trained situations.

Depending whether the observation labels are available, the learning is classified between:

- **Unsupervised Learning** The program is given a dataset and must find patterns and relationships therein.
- **Supervised Learning** The program is “trained” on a predefined set of “training examples”, which then facilitate its ability to reach an accurate conclusion when given new data.

## Unsupervised ML

In order to illustrate the differences between Supervised Learning and a Unsupervised Learning let's suppose that we are running a survey among aging people that takes one hour per participant. Most of them complain about how time and effort consuming it is. To reduce the survey length we run unsupervised learning upon our reduced response dataset to detect which questions add contaminant bias or do not add any value.

An example of a popular Unsupervised learning algorithm for data clustering is K-Means. Starting from a random center initialization the data points are projected and clustered according to their distance to the cluster centers. The centers and the groups are updated iteratively until a compromise is achieved.

The frailty model proposed in this thesis and presented in Chapter 4 uses a non supervised model based on statistics to detect outliers.

## Supervised ML

In the majority of supervised learning applications, the goal is to develop a predictor function  $h(x)$ , to predict the output values from a matrix of inputs (equation 2.1). The output to be predicted,  $Y$ , can be linear (*i.e.* any integral number), know as regression systems, or discrete (*i.e.* 1 or 0, Class N, ...), know as classification systems. ML consists in modeling a function that will minimize the difference between the inputs  $\underline{X}$  and the outputs  $Y$ , also know as the *Function Cost*.

$$Y = h_{\theta}(X) \tag{2.1}$$

The minimization of the cost function may give some information on the dependencies between variables or even noisy bias. One possible estimator for a a regression problem may be a

linear regression model  $h_\theta$  with the following function cost:

$$\frac{1}{2m} \sum_{i=1}^m \left( h_\theta(X^{(i)}) - Y^{(i)} \right)^2 \quad (2.2)$$

**Model Training** To train a model, the data is spited in two sub-dataset: training and test. Training sub-dataset will be used to build model with nearly 70% of data. Test will be used to test the accuracy precision and recall of the proposed model. It is important that both, training and test subsets, contain the same proportion of items for each label to avoid bias or mismatching.

There is a large number of methods to minimize the cost function. Some of the most commonly used are listed below:

- **Linear Regression:** It is used to estimate real values (cost of houses, number of calls, total sales etc.) based on continuous variable(s). Relationship between independent and dependent variables are established by fitting the best boundary. This best fit boundary is known as regression line and can be defined by a linear equation.
- **Logistic Regression:** This classification algorithm estimates discrete values based on a given set of independent variables. It predicts the probability of occurrence of an event by fitting data to a logic function.
- **Decision Tree:** This type of supervised learning algorithm is mostly used for classification problems. The population is spited into two or more homogeneous sets, based on the most significant attributes to make as many different groups as possible.
- **SVM (Support Vector Machine):** This classification method projects each data item as a point in an  $N$ -dimensional space (where  $N$  is number of features in your dataset). SVM can find non linear hyperplanes to separate different classes, maximizing its distance to any point of any class.
- **Discriminatory Analysis:** Discriminant analysis is a a supervised learning algorithm that uses statistical technique with a linear decision boundary generated by fitting class-conditional densities to the data using Bayes' rule. The model fits a Gaussian density to each class, assuming that all classes share the same covariance matrix. The fitted model can also be used to reduce the dimensionality of the input by projecting it to the most discriminative directions.
- **Naive Bayes:** This classification technique is based on Bayes' theorem. In simple terms, a Naive Bayes classifier assumes that the presence of a particular feature in a class is unrelated to the presence of any other feature. Naive Bayesian (NGB) models are easy to

build and particularly useful for very large data sets. Along with simplicity, Naive Bayes is known to outperform even highly sophisticated classification methods. Naive Bayes often works well even with not very large amounts of data. However it assumes that the features are independent

- **K-NN:** This algorithm can be used for both classification and regression problems. However, it is more used in classification problems in the industry. KNN classifies new classes by a majority vote of its K nearest neighbors. the vote is frequently weighted by a distance function to the neighbor.
- **Artificial Neural Networks (ANN):** NN simulate the brain neuron's activation. It models the dataset in several variables (inputs) and target variables (output), with intermediated hidden neuron layers. The values to bring forward on each layer depend in the activation of the neurons to input data. The last layer applies a simple classification model obtaining the outputs (*e.g.* linear regression, logistic regression, ...).

## Deep Learning

Even if the proposed framework does not treat large amounts of data, small data processing, it is important to define the technologies that allow its processing. For very large amount of data with no prior knowledge of its structure and features (in the order of tens of thousands or millions of examples), precision of ML do converge, therefore DL is nowadays the strategy to extract insights from it.

DL can be defined as “a particular kind of machine learning that achieves great power and flexibility by learning to represent the world as nested hierarchy of concepts, with each concept defined in relation to simpler concepts, and more abstract representations computed in terms of less abstract ones.”

By definition, DL complements ML in 6 points:

**Data dependencies:** For medium to large datasets, ML and DL performs similarly. However, for higher amount of data the performances of ML may converge to a flat performance due to the lack of data structure and feature description. To obtain more data for better DL experiments, many researchers use data augmentation from the original samples, *e.g.* image cropping and rotations.

**Hardware dependencies:** DL models should be trained on a GPU processor for speed purposes. On the other hand, ML analysis can be performed in mostly any local computer, even laptops.

**Feature engineering:** ML can be improved by pre-processing the data with feature engineering [49]. Instead of that, DL treats the raw data from the very beginning without any prior process needed.

**Problem solving approach:** ML recommends to process independent problems in different steps, *e.g.* object detection and object recognition. On the contrary, DL handles at the same time different experiments.

**Execution time:** Usually, a DL algorithm takes a long time to train.

**interpretability:** Since DL is based on the NN it remains very confusing when interpreting the results, as there is no complete feedback on the inner processes within the NN. On the other hand, ML has alternatives to the NN which are much more explicit when interpreting the results.

In conclusion, I believe that DL will lead the research and the industry in the future years because it give precious insights hidden in the data. However, it is not interesting to use it when dealing with small amounts of data that can be handled with ML algorithms.

#### 2.4.6 Data Processing - Knowledge-Driven Approach

Knowledge-Driven (KDA) approaches simulate the human brain behavior and create relational graphs and ontologies that represent the knowledge understood by a certain entity (human or computer), relying on prior or relational knowledge.

To represent semantically structured knowledge, the cognitive scientist Allan M. Collins, linguist M. Ross Quillian and psychologist Elizabeth F. Loftus coined The concept of the Semantic Network Model in the early 60's. When applied in the context of the modern Internet it enables automated agents to access the Web more intelligently and perform more tasks on behalf of users. Tim Berners-Lee has described the Semantic Web as "a web of data that can be processed directly and indirectly by machines", which is a component of "Web 3.0" [21].

As defined, semantic web looks at translating human readable language (natural language) into a machine language. The web community has put at disposition several tools and languages to achieve this ambition. The mainstream language for semantic technologies is RDF. A collection of RDF statements intrinsically represents a labeled, directed multi-graph, also called ontology. Within a semantic model there exist representations that have been standardized. I present below the main standards that builds a semantic ontology.

- Individuals: Instances or objects (the basic or "ground level" objects)
- Classes: Sets, collections, concepts, classes in programming, types of objects, or kinds of things



- **Attributes:** Aspects, properties, features, characteristics, or parameters that objects (and classes) can have
- **Relations:** Ways in which classes and individuals can be related to one another
- **Function:** terms Complex structures formed from certain relations that can be used in place of an individual term in a statement
- **Restrictions:** Formally stated descriptions of what must be true in order for some assertion to be accepted as input
- **Rules:** Statements in the form of an if-then (antecedent-consequent) sentence that describe the logical inferences that can be drawn from an assertion in a particular form
- **Axioms:** Assertions (including rules) in a logical form that together comprise the overall theory that the ontology describes in its domain of application. This definition differs from that of "axioms" in generative grammar and formal logic. In those disciplines, axioms include only statements asserted as a priori knowledge. As used here, "axioms" also include the theory derived from axiomatic statements
- **Events:** The changing of attributes or relations

## Semantic Reasoning

A semantic reasoner, reasoning engine, rules engine, or simply a reasoner, is a piece of software able to infer logical consequences from a set of asserted facts or axioms. The notion of a semantic reasoner generalizes that of an inference engine, by providing a richer set of mechanisms to work with. The inference rules are commonly specified by means of an ontology language, and often a description logic language.

Knowledge can be acquired through pure reasoning alone (rationalist approach) or via experiences as perceived through the senses and stored in the memory (empiricist approach) [46]. In AAL, a mix or a compromise between these two approaches can be considered where context is first perceived via the sensors and stored into ontologies. Reasoning is then employed to transform contextual data into meaningful information and infer new, implicit context information that is relevant for the AT. Table 2.4 summarize the main the features of common semantic reasoners. The reasoners used in this thesis is EYE, which uses a semantic language Notation 3 (N3).

**Notation 3** N3 is based on Resource Description Framework RDF, which is used with a variety of data serializations. This format is often called simply RDF because it was introduced among the other W3C specifications defining RDF. However, it is important to distinguish the XML



format from the abstract RDF model itself. In addition to serializing RDF as XML, the W3C introduced N3 as a serialization of RDF models designed with human-readability in mind. N3 is much more compact and readable than XML RDF notation because it is based on a tabular notation which makes the underlying triples encoded in the documents more easily recognizable. The format, developed by Tim Berners-Lee and others from the Semantic Web community, was motivated by the frustrations resulting from their use of RDF over the years. N3 has several features that go beyond the serialization of RDF models, such as the support of RDF-based rules. It is in fact a full assertion and logic language, a superset of RDF, which extends the latest's data model by adding formulae (literals which are graphs themselves), variables, logical implication, and functional predicates. Following an example of N3 is presented.

Service selection inference rule

$$\begin{aligned} &\forall \text{ User } u; \text{ Deviance } dv; \text{ Service } s; \text{ MotionEstimation } m; \text{ Room } r \\ &(u, \text{ detectedIn}, r) \wedge (r, \text{ is}, \text{ Bedroom}) \wedge m, \text{ Math:notGreater}, 1 \\ &\Rightarrow (u, \text{ believedToDo}, \text{ Sleep}) \end{aligned}$$

Table 2.4: Comparative table of semantic reasoners.

	<b>Jena</b>	<b>Pellet</b>	<b>RacerPro</b>	<b>EYE</b>
<b>Rule format</b>	own, basic & built-ins	SWRL	own, powerful	N3 & built-ins
<b>Retractability</b>	yes	can emulate stateless	yes	stateless
<b>Ease of use</b>	average	easy	complex	easy
<b>Response time for 100 triples</b>	783ms	442ms	503ms	4ms
<b>Response time for 1,000 triples</b>	29,330ms	38,836ms	44,166ms	40ms
<b>Response time for 10,000 triples</b>	out of memory	out of memory	out of memory	436ms
<b>Scalability</b>	Very limited	Average	Limited	Good
<b>Size (download)</b>	22.3Mb	24.3Mb	60.3Mb	12.9Mb
<b>Licensing</b>	freeware, open source	freeware, open source	shareware, closed source	freeware, open source

## 2.5 Data Protection and Ethics

The scope of this thesis is to build a Proof of Concept of an IoT Urban Living framework and deploy it in real scenarios. In this case, the project has to take into account more dimensions than the engineering challenges. When dealing with real and personal data, the ethics becomes a key constraint. As presented in Chapter 1 the framework is deployed in 14 houses in France, 10 houses in Singapore and has been included in two European projects. In order to be able

to deploy the solution, the system needed to follow the French, Singaporean and European legislation in terms of data privacy and ethics. In this section, I detail the main procedures for each legislation to accomplish the ethics requisites. Appendix E contains the ethical approvals, both Singapore and France, detailed below.

### **2.5.1 France - CNIL**

The French law provides for the possibility for a private or public body to nominate a "Data Protection correspondent", commonly called "Correspondant Informatique et Liberté (English: The Computer and Freedom correspondent" (CIL)). This correspondent is responsible for ensuring compliance with the law within the organization. The formalities for reporting to the CNIL (Commission Nationale de l'Informatique et des Libertés English: National Commission on Informatics and Liberty) are then largely simplified, except for the most sensitive treatments, such as automated biometric data processing or those relating to state security. In general, the CIL advises the company on all matters relating to the respect of personal data. The CIL acts independently of the private or public body to which he is affected. He may appeal to the CNIL.

In accordance with the General Data Protection Regulation (GDPR) in France, a data protection correspondent has been designated for the Institut Mines Telecom (IMT). This implies that, as long as the IMT is responsible for the processing, the ethical process consists to forward all the specifications of the deployment to the data protection correspondent. A detailed description of the system to be deployed in Montpellier pilot site was sent to the IMT Data Protection Correspondent on May, 18th 2017.

### **2.5.2 Singapore - IRB**

For the Singapore Pilot Site, CNRS follows the procedure established by the National University of Singapore (NUS) Institutional Review Board (IRB). An Institutional Review Board (IRB) is an independent committee established within the university that conducts scientific and ethical review on research involving human research participants. The purpose of the IRB is to review all human participant research proposals before the research is conducted. IRB monitors research, by way of receiving feedback, continuing review or regular reports, as determined by the IRB. The NUS-IRB follows the Singapore Good Clinical Practice GCP, ICH Good Clinical Practice GCP guidelines, BAC guidelines and the applicable laws and regulations of Singapore.

Relevant information about personal data description and research data which have been included in the confidentiality & privacy part for the ethical approval application, are reported for completeness: personal data information sheets including name, address and phone number are kept separated from the research data and a code is used to identify the participant. The MAC address of the deployed gateway (address of the micro-computer) is also included in the personal

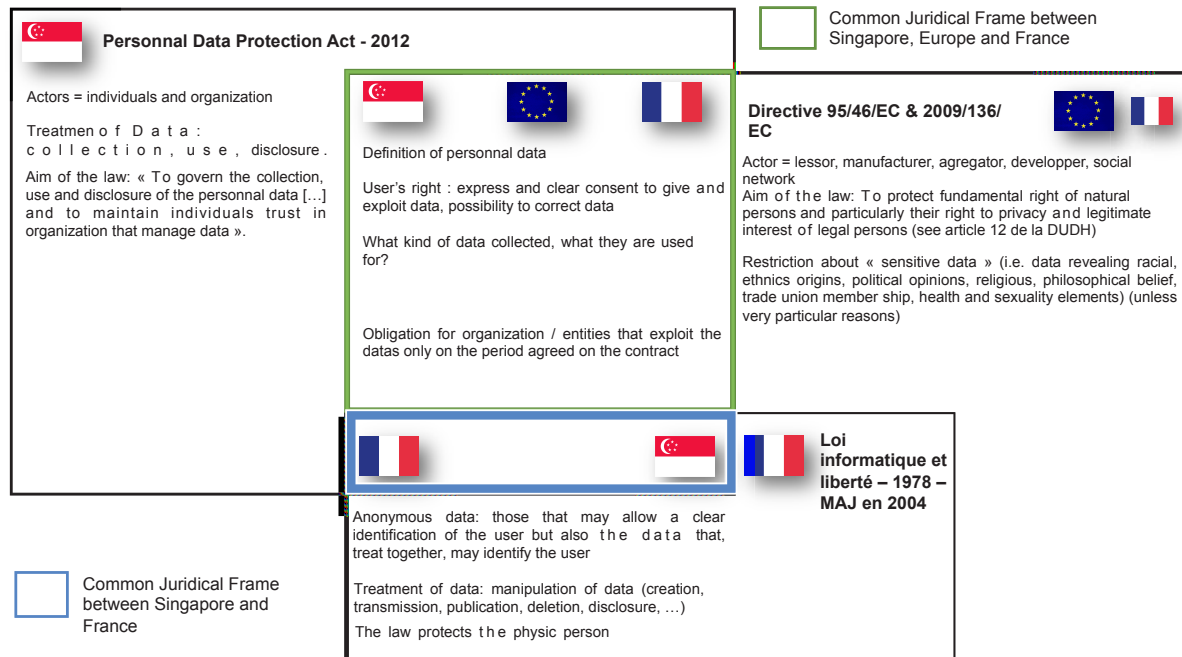


Figure 2-6: Comparing data protection legislation in France and Singapore within an European Project Framework.

data information sheet in order to make the link between the sensors and the participant's apartment. All research data is identified by the participant ID and are kept detached from the personal data information. Only the research team has access to the personal data information and is not to be released to any other person or institution. Identifiable information will never be used in a publication or presentation. Only aggregated data is to be used for publication.

### 2.5.3 Comparative with HORIZON 2020

A new data legislation has been defined in the context of the new set of European Projects HORIZON 2020. The comparison between the French and Singaporean legislations puts in value that Singapore and Europe (including France) treat differently the information regarding ethnicity, sex, health and politics of the individuals. Singapore exploits this feature contextualizing the information while in France and H2020 this information has to be avoided not to bias the study. All three contexts use anonymous data to preserve the privacy of the person. However, France and Singapore may exploit the real information if required. Horizon2020 instead demands to keep the data anonymous at all moments and only allows the exploitation during the project duration. Figure 2-6 illustrates the main features for each frame and how they intersect.

## Chapter 3

# Related Work and Urban Solution

In this chapter, I present the frailty concept based on medical and social literature to contextualize the human centered approach of this thesis. I also present the technical progress and results of other research teams and industrial partners that would add context and value to this thesis. The work presented in this manuscript looks at external outdoor technologies to help people and in particular, seniors, to prepare their journey and accompany them during their outdoors activities. The thesis presents a new approach for an adapted smart city by using IoT technologies and strong hybrid cloud reasoning. The next sections present approaches that were adapted by smart cities with a closer examination of IoT solutions to assist aging people during their indoors and outdoors activities, and reasoning engines to merge and treat the highest number of heterogeneous data.

### 3.1 Frailty Definition

The ultimate goal is to use the collected data to build a human model by computing the levels of human frailty. Frailty is a recent term that has been defined in diverse ways. The early approaches treated frailty as a synonym of disability [143], comorbidity [191], or a characteristic of advanced age [190]. Recent studies differentiate frailty from disability and treat it as a biological condition with a cumulus of deficiencies across multidisciplinary dimensions [28, 56]. There is a growing consensus that frailty markers include age-associated declines in lean body mass, strength, endurance, balance, walking performance, and low activity, [128, 56] and that these components must be clinically present to constitute frailty. Figure 3-1(a) illustrates the frailty evolution presented by Ferruci [53]. Figure 3-1(b) illustrates the evolution of *Healthy Aging* presented by WHO. It can be noted that the evolution are similar, however Ferruci does not consider that the frailty is an occasional condition which can be recovered. On the contrary, WHO does consider frailty a sporadic condition that may be temporary.

Back in 1997, Powell *et al.* [133] defined frailty as "*People with multiple problems.*" In 2004,

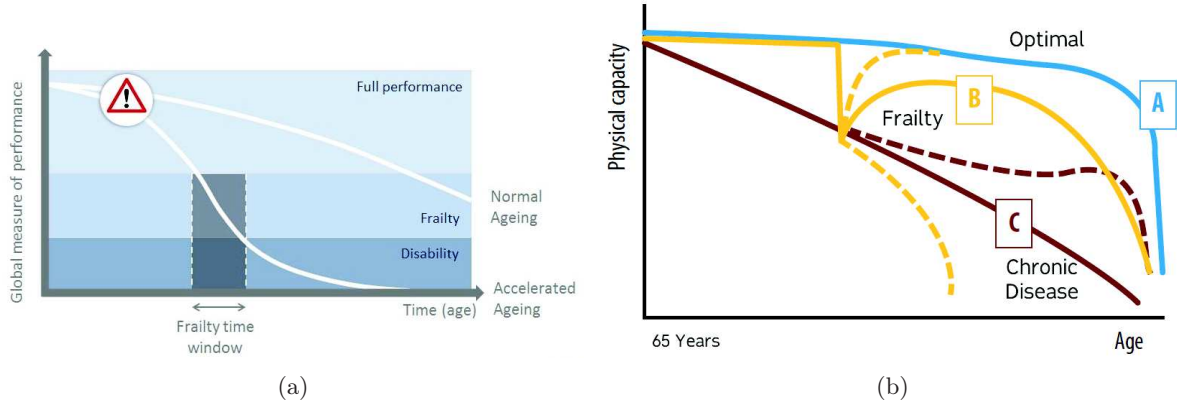


Figure 3-1: Frailty evolution presented by: (a) Ferruci [53] and (b) WHO [120].

Fried *et al.* [57] defined frailty Phenotype as "An aggregate expression of risk resulting from age- or disease-associated physiologic accumulation of subthreshold decrements" (see Figure 3-2). In 2007, Rockwood *et al.* [141] stated that a person should be declared frail if he presents 3 or more symptoms among *unintentional weight loss, feeling exhausted, weak grip strength, slow walking speed or low physical activity*. Additionally, in 2009, Kanapura *et al.* [82] treated frailty purely as a physical condition and stated that there is no clear relation with any specific disease.

In order to understand how frailty is currently detected and its main domains, I have conducted a deep survey of the literature. I reviewed the origin of the term, the main scales, models, and tests conducted in the health domain. In this survey, I note that most of the studies are based on the personal performance of ADL and Instrumental Activity of Daily Living (IADL). The IADL was introduced by Lawton *et al.* in 1988 [91] referring to the personal activities that let the individual live independently. However, I also detected a lack of consensus between the different studies in the way to define frailty domains and items.

My definition of frailty is based on Fried's principles [57]. The frailty model will be composed of domains and items which can be quantified. Quantifying the personal performance has been an interesting research topic for many years. At the beginning, studies focused on the medical point of view yet remained wide in the details. Mahonney *et al.* proposed in 1965 the Barthel Index [95], one of the first approaches to measure numerically the individual performance. They did not differentiate any special medical condition, however, further specific works were based on it. In 1987 Kieth *et al.* presented the Functional Independence Measure (FIM) [84]. Based on ADL performance, they evaluated the physical and cognitive dimension of the individual. In 1992 Ware *et al.* presented The MOS 36-item short-form health survey (SF-36) [185] (one of the most used scales in the present). This scale focuses on physical and cognitive dimensions, and, at the same time, takes into account medical and social inputs. In 1994 Suurmeijer introduced the Groningen Activity Restriction Scale (GARS) [170], which takes into account the medical, physical and cognitive dimension based on the ADL/IADL performance.

The coin of the frailty term allowed the evolution of existing studies and led to the appearance

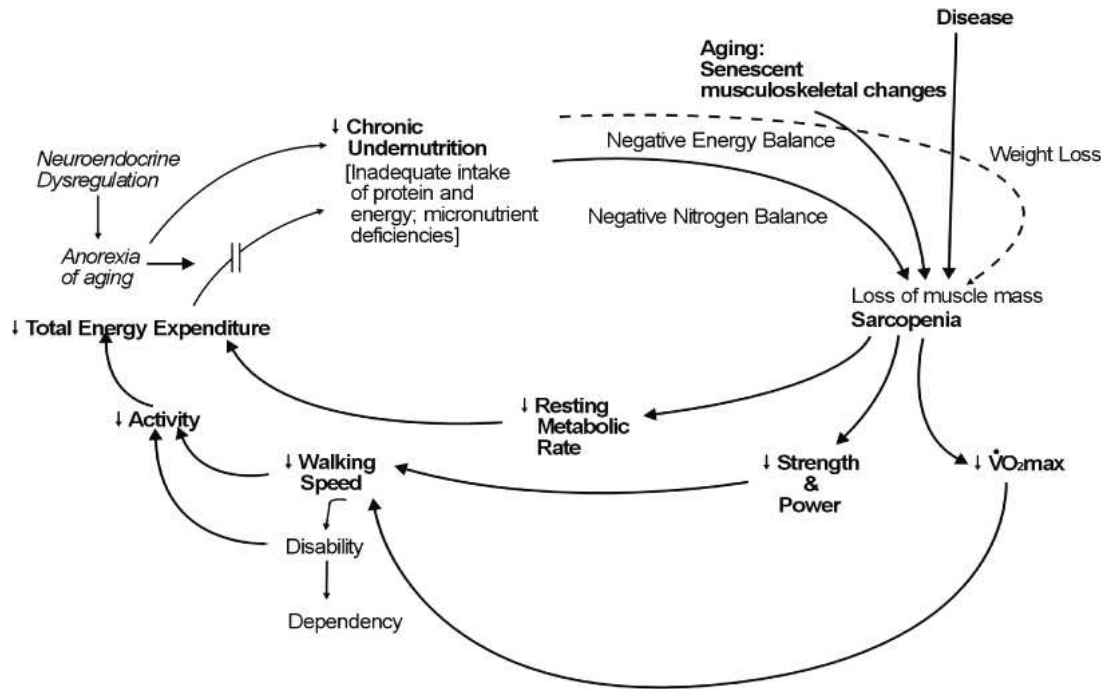


Figure 3-2: Frailty Phenotype presented by Fried [56] in 2004.

of improved and detailed works. In 1998, Strawbridge *et al.* [166] diagnosed a person as frail if the person presented a lack in at least two of these 4 parameters: *physical function, nutritional status, cognitive level and sensory functions*. In 1999 Rockwood *et al.* [143] presented the Frailty Scale based in the Geriatric Status Scale. This classifies the patients in 3 levels of frailty based on their independence in the ADL and their physical, cognitive and medical level. In 2001 Steverink *et al.* [165] enhanced the GARS and presented the Groningen Frailty Indicator (GFI) focused on the physical, cognitive, medical and social domain. Later in 2005 Jones *et al.* presented the Frailty Index (FI) [78] which evaluates frailty from a global point of view. It studies the performance of ADL/IADL and translates the result in the medical, physical, cognitive and social domain.

There are a number of scales and models either focused on a specific domain such as Vellas *et al.* [183] in the medical and Syddall *et al.* [171] in the physical, or on many domains at the same time such as Rolsfon *et al.* [146] in medical, physical, cognitive, social and ADL. Grouping these works, some surveys review have been done in this field. One of them, in 2004 by Ferrucci *et al.* [53], listed the scale according to the medical, physical and cognitive domains. Another example is De Vries *et al.* [48] in 2009, which reviewed the main items that characterize frailty: *nutritional status, physical activity, mobility, energy, strength, cognition, mood, social relationship*.

Table 3.1 lists the qualitative surveys along the years. used in the medical assessments to detect frailty. It can be concluded that among the diversity of domains and the big number of items, 5 main domains are highlighted: **Medical, Physical, Cognitive, Social and ADL**. More over, the majority of studies have based their measures on the ADL performance.

From the technological perspective, there exist initiatives studying one dimension of frailty.

Table 3.1: Survey on the existent models, studies, scales and exams, which treat, detect and qantify the frailty.\* in 1965 Mahoney *et al.* presented a functional model, which did not treat specifically the frailty but it has been a base model for most the posterior studies.

Study			Domains				
			Medical	Physical	Cognitive	Social	ADL/IADL
Mahoney <i>et al.</i> *	1965	[95]	✓	✓	✓		
Keith <i>et al.</i>	1987	[84]		✓	✓		✓
Winograd <i>et al.</i>	1991	[191]	✓	✓		✓	✓
Ware <i>et al.</i>	1992	[185]	✓	✓	✓	✓	
Ory <i>et al.</i>	1993	[121]		✓			
Pendergast <i>et al.</i>	1999	[130]	✓	✓			
Suurmeijer <i>et al.</i>	1994	[170]	✓	✓	✓		✓
Tinetti <i>et al.</i>	1994	[181]		✓			
Brown <i>et al.</i>	1995	[30]	✓	✓	✓		✓
Guralnik <i>et al.</i>	1995	[68]		✓			
Gloth FEFA <i>et al.</i>	1995	[64]	✓	✓	✓		
Gill <i>et al.</i>	1996	[61]		✓	✓		✓
Rockwood <i>et al.</i>	1996	[142]	✓	✓	✓		
Campbell <i>et al.</i>	1997	[31]	✓	✓	✓		
Dayhoff <i>et al.</i>	1998	[47]		✓			
Carlston <i>et al.</i>	1998	[36]	✓	✓			✓
Strawbridge <i>et al.</i>	1998	[166]	✓	✓	✓		
Paw <i>et al.</i>	1999	[128]	✓	✓			
Vellas <i>et al.</i>	2000	[183]	✓				
Nourhashémi <i>et al.</i>	2001	[112]	✓		✓		✓
Fried PHENOTYPE <i>et al.</i>	2001	[56]	✓	✓			
Syddall <i>et al.</i>	2003	[171]		✓			
Studenski <i>et al.</i>	2004	[167]	✓	✓	✓	✓	✓
Jones <i>et al.</i>	2004	[79]	✓	✓	✓	✓	✓
Mattheus <i>et al.</i>	2004	[100]	✓	✓	✓		
Puts <i>et al.</i>	2005	[135]		✓			
Carriere <i>et al.</i>	2005	[37]		✓	✓		✓
Rolfson <i>et al.</i>	2006	[146]	✓	✓	✓	✓	✓
Rockwood <i>et al.</i>	2007	[141]	✓	✓	✓	✓	✓
Ensrud <i>et al.</i>	2007	[51]	✓	✓	✓		
Ravaglia <i>et al.</i>	2004	[137]		✓		✓	✓
Guilley <i>et al.</i>	2008	[67]	✓	✓	✓		✓
Rothman <i>et al.</i>	2008	[148]	✓	✓	✓		
Gobbens <i>et al.</i>	2012	[65]		✓	✓	✓	✓
Murad <i>et al.</i>	2012	[109]	✓	✓	✓		✓
Jürschik <i>et al.</i>	2012	[80]	✓	✓	✓	✓	✓

In 2011 Bravo *et al.* [29] presented a mobile proposal to monitor frailty through physical daily activity. They based their score on two physical frailty models: Barthel index [95] and Tinetti



scale [180]. Through an accelerator, they detected the ADL and the IADL of the individual. They then based their contribution on preventing, rehabilitating and revising the abnormal activity behavior according to their profile. Also, Zhang *et al.* [195] investigated the correlation between the data collected from a movement pendant sensor and the ADL in 2015. They compared their approach to the Groningen Activity Restriction Scale (GARS) and proved that there is a high correlation only in the physical frailty domain. In 2013, Jaber *et al.* presented ARPEGE [77], as a set of technological tools assisting frail people at their homes using Fried’s scale [56]. Within a controlled facility, they brought up to 150 people to evaluate domains such as weight, balance, strength, walking speed, physical activity level, exhaustion, and the human computer interaction with their platform.

These works state the interest of the frailty quantification as a wellbeing indicator. Nevertheless, the approaches presented remain within controlled facilities and compute their experiences manually. I present a step forward in the frailty quantification with a complete computational solution deployed in real scenarios.

### 3.2 AAL Frameworks for Frail People

AAL has in recent times become a widespread topic with a large research community behind it. In 2012, Mokhtari *et al.* presented a review of the new trends to support people with dementia [107]. They summarized the trends through 4 main requirements: remembering simple daily living task, maintain their social links, feeling motivated to participate in everyday life, and boosting their feeling of safety. Back in 2005, Helal *et al.* presented an AAL prototype for houses [72]. They divided the system into 6 layers: physical or hardware, sensor, service, knowledge, context-aware and application.

More recently, in 2011, Marinc *et al.* [98] presented an overview of the general requirements that have to be fulfilled by an AAL platform to allow an efficient personalization by the user. They differentiate the basic requirements from the user-kind requirements. On the one hand, they highlight basic requirements such as: the hardware abstraction layer as the user should be able to interact with all devices; the interaction with framework; the rule-based system; the service based on infrastructure; the context reasoning; and, finally, the semantic description. On the other hand, they also take into account the user-kind requirements. They differentiate between the expert user, who is able to implement, see the details and receive a direct feedback; a regular user, who is interested in a simple interaction with the system (help-files, simple interfaces and an attractive system front-end); and, finally, the impaired user, who are usually skeptical with the system and his environment. Therefore, the system needs to be non-invasive, invisible and stoppable.

However, even though real AAL deployments have been very recent, their use has been



increasing rapidly. Tapia et al. [173] in 2004 did one of the first implementations where they deployed in different residential environments simple sensors detecting activities. They obtained a wide accuracy percentage depending on the activity, with the more frequent activities being more easily detectable than the less frequent ones. More recently, in 2011, Morales et al. [108] presented the architectural aspect of and the deployment of their systems. They expose the challenges of implementing a system in a medical environment, such as personal tracking in order to localize person with issues, humans' willingness, skepticism, and interaction. Though their project, they reveal that the tuning part for system implementation typically takes more time/effort than expected; basic, simple services are one of the best advantages for AAL environments; and, finally, they encourage the use of wireless communication with data flow control (Zigbee). Helal *et al.* presented in 2012 [70] a 3D framework capable of simulating ADL and human behaviors. The authors aims at developing a tool that could anticipate risk situations or indoor and outdoor obstacles. In 2014 Noury *et al.* presented the main benefits of implementing ambient intelligence to support longevity and independence for aging in place [113]. The author presented the lessons learned from two projects: Ailisa [115] to visualize the detections of presence sensors distributed around the flat. It highlights the main periods of activity, the spatial frequencies and thus the periods of higher activities; MAPA project (Orange Labs) on activities collected from the events on the electrical power line [116, 20]. Later, Falco et al. [52] in 2013 presented the MonAMI European project provisioning a deployment in Zaragoza, Spain. They ran a trial during four months with 15 patients and obtained satisfactory results. The project also lead to next steps in their solution such as: including wireless reliability, context understanding services, and sensor detection. In 2014 Palumbo et al. [125] developed a sensor network infrastructure for home care. The system has been developed for a European project, GiraffPlus, and deployed in real homes across Europe. They identify the crucial features of the system through an easy and reliable integration of all the hardware and software components. Also, in 2014 Cubo et al. [44], presented a complete AAL system hosted in the cloud. They designed a framework based on cloud computing technology. Their work proposes a platform to manage the integration and behavior-aware orchestration of heterogeneous devices. They implemented and generated a novel cloud-based IoT platform of behavior-aware devices as services for AmI system. This work inspired the work presented in this thesis in the sensor integration. However, the service orientation is tackled differently as the final user is prioritized in the implementation.

In 2015, Lyons *et al.* [94] presented a project based on pervasive computing technologies to assess Alzheimer patients' condition. The authors collected data from deployments in real scenarios. Then, they calculated the parameters from noninvasive sensor raw data and manual annotations. The aim was to investigate the patient's cognitive evolution through their performance in the following activities: sleep, computer use, medication adherence, walking, mobility and social engagement, telephone usage, and online video chat. The methodology of the in-

vestigation uses pattern recognition on all the collected data in non real time approach. The study concludes that it is possible to predict change of patterns using a quantification of these parameters.

To our knowledge, there are no other investigations on modeling a personal condition in a multidimensional way using an AAL platform. However, there are AAL platforms focusing on service delivery. Blackman *et al.* recently presented a survey on ambient assisted technologies [24]. The authors list the current projects and developments in AAL. The projects are divided into 4 domains: physical, mental, user interaction and ADL support. The survey highlights the increasing trend of (IoT) technologies in AAL platforms. Connected objects, dedicated mobile applications, and social networking are the emerging topics in the future AAL.

AAL platforms can be used to a particular situation [41], or even intervene this situation [102]. Mayer *et al.* [101] identify two stakeholders to be addressed: firstly, *patients* who should be provided with dedicated services to help them perform ADL or remember actions [174]. And secondly, *caregivers*, either professional health carers or relatives, who should be provided with services to help keep them connected with the seniors. Sevrin *et al.* presented in 2016 a holistic approach to detect ADL including social activities. In [157, 159] the authors presented a living lab, which uses Kinect depth cameras to infer the number of people in each room and the type of activity performed by the participants. In [158] the author presented the REC@MED project, a data fusion model between GPS and ECG to understand the type of activity performed by the user. They distinguish between physical, cognitive and rest activities. In 2012 Noury *et al.* presented a living lab study to use smartphone sensors to model the type of the individual indoor activities [114]. The author focused on 5 type of activities: walk, lying, sitting, standing and transfer. The transfer is considered as the sequence of movements to change from one activity to any other.

Specifically, in the service delivery field, many studies focus on the delivery of static solutions based on design decisions. Among them, Ghorbel *et al.* [60] provide an adaptable framework according to the user profile. They take into account user preferences and capabilities to deliver the services. Such services can adapt to different configurations and devices depending on the context, for example, the service can be delivered acoustically or textually depending on the activity performed by the patient. Similarly, Mitseva *et al.* [105] presented the ISISEMD's project in 2010, in which the authors evaluate the impact of their platform upon the patient, their relatives, and caregivers. The explored domains are cognition, Quality of life (QoL), ADL and user satisfaction. The study computes the user satisfaction through user interaction, feelings of safety and security, self-care and independence, memory support, and remote communication with other seniors. However, the evaluation is manually driven by the patients themselves or by care professionals. Recently, Mileo *et al.* [104] presented a dynamic service delivery based on the context. The authors work on the prediction and prevention of falls through context sensors,

personal data, and knowledge reasoning. 10 items are manually tracked in order to prevent falls: mobility, balance, gait, nutrition, BMI, vision, hearing sleep, environment, and clinical profile.

However, there are few investigations that use medical conditions as a dynamic and decisive parameter. This thesis would like to propose to computing of daily frailty values, based on a novel frailty model. Moreover, I believe that this computation will provide the essential necessary information towards new applications in AAL, such as the adaption of the service delivering. Therefore, we present a fully computational framework that it is adapted to the end users (caregivers) and calculates the personal frailty of our seniors.

### 3.2.1 AAL Framework for Sleep Monitoring

Healthcare systems worldwide are struggling with significant challenges, such as: rapid growth in aging population, increased number of people with chronic and infectious diseases, rising costs, and inefficiencies in existing health-care systems. As a response to these challenges, the healthcare community is seeking for novel non-invasive solutions that can improve the quality of healthcare for the patient while maintaining a reasonable cost of the service provided. To achieve this goal, early diagnosis, prevention, and more efficient disease management systems are in demand [87]. For example, sleep disordered breathing (SDB), also known as obstructive sleep apnea (OSA), is one of the most common clinical disorders that can affect elderly people. The patient with OSA will need to stay in a specialist sleep clinic for the whole night to be diagnosed with multiple sensors attached to his/her body to monitor different vital signs besides sleep activates. Therefore, non-intrusive and less-expensive sleep diagnostic modalities are very important for long-term monitoring.

A thin air-filled cushion is introduced by Watanabe *et al.* [186] to detect sleep staging. Sleep data from eight university students were collected over 27 overnight recordings, where the cushion is placed between the bed and the mattress. For validation purposes, the students went to bed at a specific time at night. The proposed system provided heartbeat, respiration, snoring, and body movements. Kortelainen *et al.* [89] proposed the use of an Emfit foil sensor to monitor sleep stages by placing the sensor under the bed mattress. The sleep data was then recorded from nine female subjects in a sleep laboratory. The recorded data consisted of heart rate, respiratory rate, and body movements. Matar *et al.* presented [99] an application for gesture recognition in sleep monitoring. The authors used a pressure mattress covering the whole surface of the bed. The raw data is collected from the pressure sensors. Afterward, the movement is classified through a supervised learning method. Although these systems might be consistent with gold standard methods, an intermediate training phase is required. Thus, they might not be applicable to real-life deployment. On the other hand, Paalasmaa *et al.* [123] provided a fully automated web application for home-based sleep monitoring using a piezoelectric film sensor, which can be

placed under the mattress topper. The sensor can provide heart rate, respiratory rate, and body movements. The proposed approach was validated with 40 patients in a sleep clinic.

Finally, Rosales *et al.* [147] used a hydraulic bed based sensor to monitor sleep quality of four subjects over two to four months in-home living conditions. The hydraulic sensor was placed under the bed mattress, and they estimated the sleep quality based on the heart rate using two different methods. The contribution of this work is superior to other related works in the literature since authors deployed the system in real-life conditions without any constraints of in-lab environments. As it can be seen above, there are few approaches in existing literature dedicated to unobtrusive sleep monitoring in-home living situations.

### 3.2.2 AAL Framework for Human Mobility

In outdoor assistance services, activity recognition and tracking are one of the promising fields of study, along with fall detection and user navigation. It is not surprising that an extensive amount of effort has been invested to take advantage of the most proliferated telecommunication technology – personal cellphones, commonly known as *smartphone* – due to their sensing abilities, computational power, and connection to an ecosystem facilitating application development.

A recent survey [175] studied currently marketed and future technologies, their limitations and even the potential for insurance companies. More specifically, smartphone-based detection featured in [76] uses GPS and vibration sensors to detect activities. The proposed approach relies on current technologies, such as IoT, cloud computing and data mining to understand the individual mobility. There are numerous technologies that aim at assisting aging people during their outdoor activities. ML model to classify the type of human mobility using on-body sensors or urban positioning through BLE Beacons detection using connected devices are interesting approaches that will help us to position our research.

The topic of activity classification based on on-body sensors has been previously explored with very positive results. In [97], Mannini *et al.* presented in 2010 a dataset obtained from a network of five on-body accelerometers, using different classifiers. A 98.5% accuracy was achieved with a geometric approach, Nearest Mean, while a probabilistic approach, Naive Bayes, yields a 97.4% accuracy. They demonstrate that a Markov modelling can be used to further increase the accuracy, to 99.1% using a chained hidden Markov model and after rejection of spurious data. However, those studies were performed in controlled scenarios allowing the researchers to define the position of the device and duration of the records. More recently, Su *et al.*[169] present in 2017 a complete study on a mobility classifier. In this case, the authors restricted the position of the phone at the moment of recording the activity. In the case of this thesis, I am interested in a very light real deployment model, which is able to identify the type of mobility without any device constraints.

Typical locomotion types include different pedestrian modalities (such as walking, running or moving in stairs), non-engine transportation (such as bicycling, roller skating) and engine transportation (such as bus, train or car). The accelerometer is the most widely used sensor for detecting locomotion. A number of early systems used the embedded accelerometer for detecting different pedestrian and non-engine modalities, such as walking and running [73, 184], or cycling [23]. Instead of relying on the accelerometer, Zheng et al. [196] detect transportation modalities using features extracted from GPS measurements. In addition to speed and location information, the authors also consider features that characterize changes in movement direction, velocity and acceleration. Together with information about street segments, the authors reach an average accuracy of 76% in classifying between stationarity, walking, biking, driving and traveling by bus. Recent work has focused on decreasing energy consumption by requiring only sparse GPS data [27], introducing more effective graph-based postprocessing techniques [196], and improving the detection accuracy by fusing external information on the real-time location of the transportation vehicles [163]. Finally, Reddy et al. [139] combine GPS and accelerometer to distinguish between stationary, walking, running, biking and engine transportation, achieving over 90% accuracies. Classification is performed with a hybrid classifier consisting of a decision tree and a first order discrete Hidden Markov Classifier HMM classifier.

### 3.2.3 Deployment Simplification

Early researches on adaptable deployments for AmI are those by Helal et al. [71] who proposed a programmable spaces, Elzabadani et al. [50] who proposed a Plug&Play device, and Ranganathan et al. [136] who proposed a polymorphism application similar to today's cloud computing. These three papers, all published in 2005, carry the vision of a customizable and extensible ecosystem for AmI, from hardware to software. Since 2005, a number of researches have been published about automatic sensor discovery using SOA architectures [5, 162, 90] and the integration of sensors into a knowledge-base for the reasoning [2]. SOA is a popular architecture in AmI, as it helps to create Plug&Play integration of sensors/actuators (S/A) into the system. Similarly, a large number of AmI solutions rely on ontological models using semantic web technologies, as these models can easily integrate new S/A into the knowledge-base. Pathan et al. [127] propose a complete approach ranging from sensor discovery to a semantic-based automatic configuration of the system.

The problematic of deployment simplicity in AmI was originally introduced by Abdulrazak et al. [1] in 2006, who introduced for the first time the term "*smart-home in a box*." In this paper, the authors mention their goal of minimizing engineering expertise and lowering the cost of deployments. They make use of SOA architecture, using the Java OSGi framework for automatic sensor integration. To our knowledge, only few researches have been published since

2006 on the simplicity of deployment. In the last couple of years, industrial solutions such as Resin.io<sup>1</sup> propose to automate the deployment, provisioning and maintenance of IoT solutions, using technologies like Docker. This solution is interesting, but it mainly targets IoT, and does not include dynamic integration of sensors in knowledge-bases, communication between gateway and server, nor specific aspects related to AmI. In addition, to our knowledge, the maintenance of AmI deployments has yet to be addressed in the literature. Lively<sup>2</sup> proposes an integrated industrial solution for AAL, which can easily integrate new sensors but does not offer customization: custom sensors are solely used for log and cannot harness data for AAL reasoning.

The number of the research activities that target quick easy deployment is limited. As mentioned in a previous paragraph, in 2006 Abdulzarak *et al.* presented ‘*"A Smart Home in a Box"*’ approach [1], based on a generic reference architecture for programmable pervasive spaces. This architecture makes the construction of smart spaces quick and easy and makes them more programmable and usable. In 2012, Aloulou *et al.* presented a semantic Plug&Play proof-of-concept in a real-world AAL framework leveraging web technologies [7]. The authors proposed the use of *abstract* and *instance* models achieving good results in terms of deployment velocity and scalability. Another study related to a do-it-yourself (DIY) smart home is presented by Woo and Lim in 2015 [192]. The researchers conducted a three weeks in situ observational study identifying six different stages where the users get familiar with a new system. They concluded that involving the user in a DIY procedure helps the integration of these technologies in their routine. Also, the feedback obtained during the experience helped them to improve each step of the proposed procedure. Recently, in 2016, Hu *et al.* presented their evolution of the "Smart Home in a Box", [75]. The authors provided a complete plug & play solution, which can be deployed rapidly. Yet, the solution is previously prepared and configured, and the user participation is limited to following the instructions.

### 3.3 IoT and Data Frameworks

Internet of Things is a consequence of the evolution of the Web, communications and hardware. In the recent years the communication spectrum has been awash with the apparition of the new technologies. Smart devices, connected objects and permanent connectivity have taken over the daily activities. The IoT is the inter-networking of physical devices, vehicles (also referred to as "connected devices" and "smart devices"), buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange data. This topic has been accelerated by the exponential reduction of the hardware

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<sup>1</sup><https://resin.io>

<sup>2</sup><http://www.mylively.com/>

cost and the dynamism of the connectivity between machines.

In the recent years several technological companies have launched its own IoT platforms. They put at disposition a Cloud structure to help the end-users to build their IoT applications. These services offer from cloud storage or server instantiation to data hub and analytics or security providers. There are few service providers that offer an open source solution for those who needs low level customization. In order to differentiate the proposed framework among the principle IoT providers, I list 16 specific IoT features:

1. **Open Source:** This domain is related to the open availability of the framework source code.
2. **Release Date:** Date when the IoT framework was released.
3. **IoT Devices plug-ins:** Capabilities of the framework to interact with different type of sensors.
4. **Gateway Software:** the framework provides software on the gateway to interact and communicate with the sensors independently of the hardware.
5. **Gateway Processing:** Possibility of running light preprocessing on the gateway before sending the data to the cloud to reduce bandwidth.
6. **IoT communication Protocol:** Availability of IoT communication protocols (CoAP, MQTT)
7. **Real-Time Workflow:** Data Reception on the cloud in real time.
8. **User Management:** User and account management to attribute roles and access restrictions on the cloud platform.
9. **Security:** Secured access to the cloud and the gateway to guarantee the data integrity.
10. **Data Repository:** Data structure on the cloud whether with relational or non-relational DB to be exploited.
11. **Data Ownership:** Following the European directives the data must remain anonymous and secure. Moreover, it does be collected directly from the source without using any third party server.
12. **Public Data APIs:** Framework capability to share and aggregate data from others sources through Restful applications.
13. **Data-Driven Approach:** Data analytics based on Data-Driven algorithms.
14. **Knowledge-Driven Approach:** Data analytics based on Knowledge-Driven algorithms.



15. **Embedded Data Visualization:** Out of the box visualizations of the data for a better understanding and presentation.
16. **User Micro Services:** availability of service prototype to built any custom services to exploit or present the data.

The Table 3.2 presents the IoT frameworks with the availability of the previous features.

The results show that the proposed IoT Open-Source approach, UbiSmart, was launched in mid-2014 before the main IoT platforms available today. UbiSmart includes the main IoT features: *Devices Plug-ins*, *Real-Time Workflow*, *Data Repository*, *User Management* and *Embedded Data Visualization*. UbiSmart also includes additional features, such as *Gateway Software*, *Pre-processing*, *Data Ownership* and *Knowledge-Driven Approach* reasoning, and dedicated *User Micro Services*. UbiSmart represents a real and valuable alternative to the current IoT platforms for specific approaches such as the AT and AAL systems.

### 3.4 Smart City

A smart city is an urban development vision to integrate ICT and IoT technology to manage its assets. These assets include local departments' information systems, schools, libraries, transportation systems, hospitals, power plants, water supply networks, waste management, law enforcement, and other key community services. ICT allows city to interact directly with the community and the city infrastructure, and to monitor what is happening in the city, how the city is evolving, and how to enable a better quality of life. Through the use of sensors with real-time monitoring systems, data are collected from citizens and devices, processed and then analyzed [168].

Smart city concept remains unclear to its specifics and therefore, it is open to many interpretations. Precise this ambiguity that provides a unique opportunity for such a research projects as is being proposed in this thesis. Smart city applications are developed to manage urban flows and allow for real-time responses. A smart city may therefore be more prepared to respond to challenges than one with a simple "transactional" relationship with its citizens. ICT is used to enhance quality, performance and interactivity of urban services, to reduce costs and resource consumption and to improve contact between citizens and government [4]. A smart city may therefore be more prepared to respond to challenges than one with a simple "transactional" relationship with its citizens.

Major technological, economic and environmental changes have generated interest in smart cities, including climate change, economic restructuring, the move to online retail and entertainment, aging populations, urban population growth and pressures on public finances. The European Union (EU) has devoted constant efforts to devising a strategy for achieving 'smart'





urban growth for its metropolitan city-regions [126].

The concept of the smart city has been the primary objective of policy discussions in recent years. Its main focus seems to be on the role of ICT infrastructure, although much research has also been carried out on the role of human capital/education, social and relational capital and environmental interest as important drivers of urban growth.

The availability and quality of the ICT infrastructure is not the only definition of a smart or intelligent city. Other definitions stress the role of human capital and education in urban development. Berry and Glaeser [22] and [63] show, for example, that the most rapid urban growth rates have been achieved in cities where a high proportion of educated labour force is available. In particular Berry and Glaeser [22] model the relation between human capital and urban development by assuming that innovation is driven by entrepreneurs who innovate in industries and products that require an increasingly more skilled labor force. This recognized tendency of cities to diverge in terms of human capital levels has attracted the attention of researchers and policy makers.

In this sense, this thesis is positioned at the human level of the smart city paradigm. It looks at enhance the human capital of our elders by providing sustainable and adapted environments when they move from an indoor an controlled space into an open and unsupervised zone. Two authors defined different levels of smart city. Caragliu [34] defined in 2011 the a holistic framework for conceptualizing smart innovation ecosystems in 6 main characteristics.

1. The “utilization of networked infrastructure to improve economic and political efficiency and enable social, cultural and urban development”. This point brings to the forefront the idea of a connected city as the main development model, and a connectivity as the source of its growth.
2. An “underlying emphasis on business urban development” based on the hypothesis that business-oriented cities are indeed among those with a satisfactory socio-economic performance.
3. A strong focus to achieve "social inclusion of various urban residents in public services". This prompts researchers and policy makers to give attention to the crucial issue of equitable urban growth.
4. "High-tech and creative industries in long-run urban growth". This factor is also known as soft infrastructure, which means that creative occupations are growing and attracts more creativity.
5. "Social and relational capital in urban development". A smart city will be a city whose community has learned to learn, adapt and innovate. People need to be able to use the technology in order to benefit from it.

6. "Social and environmental sustainability as a major strategic component of smart cities". Linked to the third item, relies on the wise balance of growth-enhancing measures, on the one hand, and the protection of weak links, on the other.

This thesis is strongly linked to Caragliu description. The proposed framework aims at helping the social inclusion of frail people by using soft technologies inside and outside their places. It demands of a transversal effort from major actors such as Public Institutions, communities and urban designers.

An alternative was proposed in 2013 by Zygiaris [197]. The author introduces seven layers where innovation in the smart cities can be proposed: City, Green City , Interconnection, Instrumentation, Open Integration, Application and Innovation. Figure 3.4 illustrates the seven layers and the synergies with the this thesis.

- "City Layer". This layer conveys the traditional components present in every city [15]: **socio-economic** (commercial, academic, science, entertainment, logistics zones, industrial, residential) [43], **infrastructure** (utility networks, streets, transport), **citizens and communities** that have a behavioral influence to city's historical and cultural heritage.
- "Green City Layer". A city's sustainable future is attached to smart city structures. Green cities are emerging as holistic playgrounds for smart cities toward sustainability. As an example, the Smart Cities Initiative of the European Union's HORIZON2020 [124] proposes to progress towards a 40% reduction of greenhouse gas emissions through sustainable use and production of energy through smart city technologies by 2020.
- "Interconnection Layer". This layer refers explicitly to the innovation support capacity of the telecomm infrastructure to connect people, smart nodes, workstations, and other embedded devices and provide high-speed network access to a city-wide area to strengthens city economic capacity [16] and enhances social inclusion [55].
- "Instrumentation Layer". Cities are considered as urban machines of real events requiring real-time system response [138]. IoT is expected to greatly contribute to addressing today's urban challenges [194, 124].
- "Open Integration Layer". Smart city applications should be able to intercommunicate, and share among others data, content, and services [140]. Ontologies and semantic web services provide an important inter-operable data representation standard.
- "Application Layer". Smart city involves interconnected and instrumented real-time operators that process real time and historical data and provide insights. Utilizing the intelligent application of new technologies, smart cities also enhance social and environmental capital in order to transform the life and work of cities.

- "Innovation Layer". Smart city creates a conducive environment [168]. Emerging technologies push for instrumented, interconnected, and intelligent in nature cities ensuring the long-term viability of smart city projects [15].

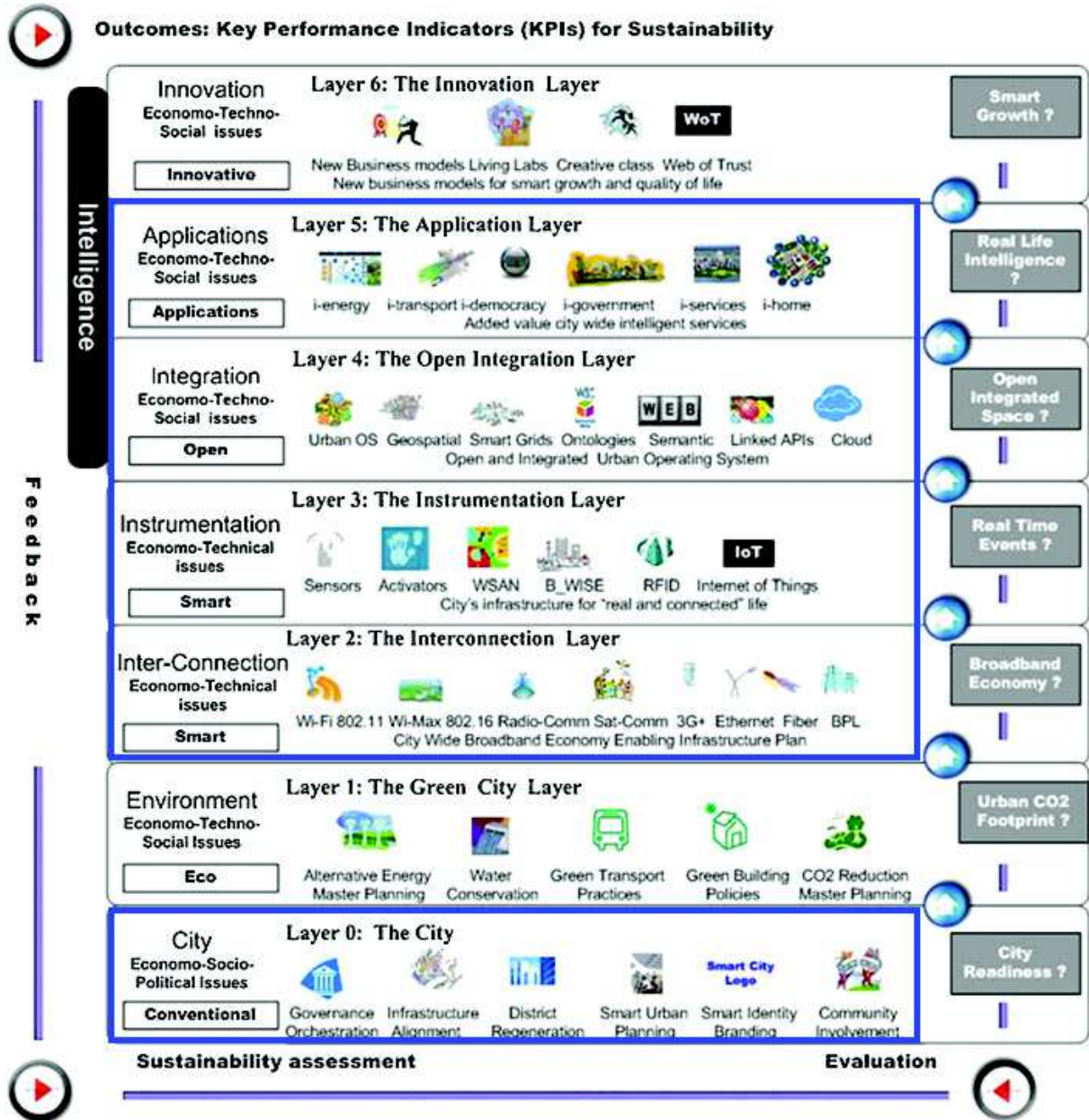


Figure 3-3: Smart Requisites proposed by Zygiaris [197].

The approach proposed by Zygiaris [197] focus more on the targeted domain. In this case, the proposed framework in this thesis responds to necessities on the *City*, *Interconnection*, *Instrumentation*, *Open Integration* and *Application* layer.

### 3.5 Smart Cities Initiatives

There are a number of Smart City incentives around the globe [12, 40, 88]. For the sake of this thesis, I will concentrate on the vision of the smart cities in Europe and Singapore [33,

35]. The EU has developed a range of programs under HORIZON2020 [124] to enhance and potentate smart city programs in several European cities. Singapore has recently launched the AI.SG initiative as presented in the previous Chapter 2.

## **Amsterdam**

The Amsterdam Smart City initiative [32] began in 2009 and currently has more than 170 projects collaboratively developed by local residents, government and businesses. These projects run on an interconnected platform through wireless devices to enhance the city's real-time decision making abilities. The city of Amsterdam claims that purpose of the projects is to reduce traffic, save energy and improve public safety. To promote efforts from local residents, the city runs the Amsterdam Smart City Challenge annually, accepting proposals for applications that fit its framework.

## **Barcelona**

Barcelona has established a number of projects that can be considered "*Smart City*" applications within its "CityOS" strategy [13, 198]. A primer example would be the use of sensor technology that has been implemented in the irrigation system at Parc del Centre de Poblenou, where real-time data is transmitted to gardening crews about the level of water required for plants. The city has also designed a new bus network based on data analysis of the most common traffic flow patterns, using primarily vertical, horizontal and diagonal routes with a number of interchanges. Integration of multiple smart city technologies can also be seen through the implementation of smart traffic lights as buses run on routes designed to optimize the number of green lights.

## **Madrid**

Madrid is a city tackling traffic congestion, pollution and public services. It takes a unique bottom-up approach to using digital data [14] by focusing less on how or how much data is collected. Madrid aims to keep solutions citizen-centric, and avoid the pitfalls of a technology disassociated from the people. In the recent years instead of starting at the technical problematic, Madrid targets first which social problems need to be addressed by new, individual technologies or networks.

## **Montpellier**

With the Smart City, Montpellier Méditerranée Métropole [132] plans to focus its priorities on three complementary objectives: supporting economic development, better coordinating and optimizing various urban services, and involving local citizens to set the stage for the sustainable city. In particular, the Big Data concept is an important part of Montpellier's project by combin-

ing data from different sources and sharing information to develop new solutions. The projects are focused on: Citizens, users and consumers, local economy, territorial attractiveness, Montpellier Métropole's international positioning and accompanying societal changes. Montpellier has also launched an initiative to connect its tram circuit with BLE Beacons.

## **Manchester**

Manchester's CityVerve project started in December 2015 [59]. It was chosen as the winner of a government-led technology competition and awarded £10m to develop an IoT smart cities demonstrator. The project is composed by a consortium of 22 public and private organizations, including the Manchester City Council, and is aligned with the city's on-going devolution commitment. The project addresses barriers when deploying smart cities, such as city governance, network security, user trust and adoption, interoperability, scalability and justifying investment.

## **Milton Keynes**

Milton Keynes has a commitment to reinvent itself a "*Smart City MK:Smart*" initiative [182, 66]. Their approach is the collaboration of local government, businesses, academia and third sector organizations. The focus of the initiative is on making energy use, water use and transport more sustainable whilst promoting economic growth in the city. Central to the project is the creation of a state-of-the-art 'MK Data Hub' which will support the acquisition and management of vast amounts of data relevant to city systems from a variety of data sources.

## **Singapore**

Singapore has recently launched a new initiative called AI.SG. This new approach is build upon the foundation of the Singapore Smart Nation project[172, 74]. Singapore strives to become a Smart Nation to support better living, stronger communities, and create more opportunities. Smart Nation enhances 5 key domains: transport; home & environment; business productivity; health and enabled aging; and public sector services. Moreover it relies on 3 main enablers: facilitating smart solutions; nurturing a culture of experimentation and sustaining innovation; and building computational capabilities. Singapore has launched the next phase of transformation towards a "*Smart Nation*", and endeavors to harness the power of networks, data and info-comm technologies to improve living, create economic opportunities and build closer communities.

## Chapter 4

# Software Design and Reasoning

The objectives of this thesis are to exploit existing technologies and to adapt them to help aging people within and around their homes. The first goal is to develop and deploy continuous and unobtrusive AAL platforms in real scenarios. The aim is to recognize aging ADL through semantic and rule-based reasoning with various level of abstraction and data processing techniques for the human mobility [179, 10]. The second goal is to move towards distant and large scale deployments of AAL platforms [19, 9]. The ultimate goal of this thesis is to build a human frailty model based on the collected data to personalize the assessment. All these goals have been integrated in a unique framework called UbiSmart. This chapter presents the evolution from a local system into a cloud solution. It also lists the main components of the system, the technical choices for the adopted technologies and new sensing capabilities. I detail the design of the frailty model and its inclusion in the framework. Finally, I explain the data reasoning techniques exploited in UbiSmart.

### 4.1 Objectives of the AAL Cloud Solution

UbiSmart is a web-enabled AAL platform intended for large-scale deployments. Key features are: *plug & play* ability; privacy protection; easy interaction for end-users; and a generic architecture. This AAL framework is able to transform any environment into a smart space in 20 minutes, enabling an unobtrusive assessment of indoor as well as outdoor activities. The purpose of UbiSmart is to detect the ADL, to provide rich services in the right context through appropriate channels, and finally treat the collected data in the background to build a human frailty model. UbiSmart targets several goals in the design phase to achieve the ambition of large scale and distant deployments: simplify the deployment and maintenance process; seamlessly extend for multiple deployments; and design for the end-users and stakeholders.



## **Simplify the Deployment Process**

In order to achieve this goal, different measures need to be adopted. First, the installation and customization process should be made simple and easy to perform. Therefore, I propose an approach including an automatic Sensors & Actuators discovery and integration into the system. The use of a configuration interface is preferred rather than manually modifying files. This enable to generate the configuration file automatically and minimize syntactic and semantic errors. Second, the maintenance should be performed remotely as much as possible. In order to reduce the technician's workload and the unnecessary move in-situ, the system should automatically detect problems and send notifications. It is also emphasized the use of industrial sensors, which are easier to maintain and replace than prototyped sensors [19].

## **Seamlessly Extend for Multiple Deployments**

Technically, it is proposed to extend the regular AmI architecture in order to facilitate the installation, deployment and maintenance process. I propose to provide technicians with a service provisioning that enables smooth install, remote maintenance and update of gateways. It is recommended to integrate dedicated user-interfaces into the framework to facilitate the deployment by non-experts (*e.g.* regular end-users). In addition, the use of a monitoring interface allows technicians to check the system status and be notified in case of problems. Remote access tools should also be provided to grant access to deployed gateways when needed. Avoiding computational problems in a distant large scale deployment is essential to handle several houses at the same time saving computer resources. In this case, the system saves resources by avoiding duplication in the code and allowing the interaction through final user interfaces which will complete the semantic model for each deployment.

## **Design for the End-Users and Stakeholders**

Facing the problematic of real deployments UbiSmart needs to be accepted among the medical community. In this sense, the system puts at disposition of the stakeholders several services that responds to their needs. The design of these user interfaces has been performed by an iterative method between the stakeholders and the development. Different types of stakeholders are proposed in the system: technical user that needs to access to the inner functionalism of the platform in case something seems to do not be not working properly (*i.e.* sensors sending too much o too few information); Consumer user, medical or relatives profiles, who aims to access the processed data in views that can be understood quickly and simply.

The consumer interaction with the web app is done through the available services. The framework provides the users with real-time activities visualization, tracking service with location maps, statistical visualization, and alert services. There are two ways of classifying the services:



by its nature, On-Demand or Context-Aware service; by their scope as Single House service SHS or Multiple Houses service MHS.

The On-demand services are triggered by the user action. The Context-Aware services stand-by waiting to be activated through the reasoning. For example, based on the statistical behavior of the patient trigger a notification if the a frail situation is detected. There are services dedicated only to one space, SHS, and other services covering several houses, MHS. This type of classification leads to the creation of user roles. The framework make available four user profiles. The *Consumer* profile is intended for patients, family or friends. A user can only have one personal account per house but may be present in different houses. This profile only provides access to SHS services. Secondly, there exists the Caregiver profile intended for health personal. They have access to the MHS in order to track several spaces at the same time. One user may have a *Caregiver* and *Consumer* profile simultaneously but never in the same houses. Furthermore, there exist two more user profiles such as *Technician* and *Admin*. They are oriented to the platform maintenance and users administration. They will be explained in the *Admin* and Tech interaction.

## 4.2 Challenges in a Distant and Large Scale Deployment

The continuous real deployment brought some precious inputs on what to improve or even change in the system in order to make a significant step forward towards a large-scale real deployment. Three main challenges and technical are key choices to achieve them. First, the platform needs to handle multiple users and multiple houses natively and efficiently. Secondly, it has to be easy to deploy, upgrade and maintain, allowing adaptability to different needs and conditions. Finally, the user interaction must be natural, intuitive, adaptable and versatile.

### 4.2.1 Cater to Multiple-User and Multiple-House

The first challenge is how to manage many houses and many users with a many-to-many correspondence network. I want to scale to a central server for many houses while maintaining a satisfying response time to events coming from each house. That includes, for instance, making sure that a faulty house flooding the framework with events would not cause a drop in performance for others houses. The proposed solution is to run a unique server instance managing all houses at the same time, and simultaneously handling the users' actions and specifications (login, roles, profiles, ...).

The last issue related to this challenge has been the reproduction of the sensing part for each house. I chose to use generic and industrial sensors as PIR, read switch, FOS and BLE Beacons because they are, nowadays, industrially available, and widely used. I choose to locate an gateway system in each house communicating with the main sensors. It provides a large range

of network adapters both for the Wireless Sensor Network and Internet and it has a low footprint in the user environment.

#### **4.2.2 Ease of deployment**

The second faced challenge is to build a solution of easy installation. That means the system needs to be simple and adaptable to the space. In the same way, it has to be easily maintained both on-site and remotely. In this sense 4 key factors are highlighted to tackle this challenges: adaptability and setup; serial provisioning; enable gateway and sensors/actuators discovery; and maintenance.

##### **Adaptability and Setup**

Simple sensors are chosen in order to build an adaptable solution, such as a passive infrared sensor (PIR), read switch, BLE Beacon, smartphone, FOS. As detailed in the previous section, the aim is to adopt the industrial sensors as much as possible to the detected needs. Nevertheless, industrial solutions do not, always, cover all the needs, *e.g.* Nonexistence of a commercial bed sensor detecting whether the patient is lying on the bed and reporting this information in real time. For this kind of custom sensors the software becomes essential.

Within the sensing part, a custom gateway has been built. In fact, the gateway receives the raw data from the sensors through communications protocols. It treats this data to extract the events and send them to the cloud through the Internet. The Internet connection can be established through most available networks. Specifically, it uses LAN or WiFi in the spaces where these connections are available, otherwise the connection was provided through a 3G key.

These previous choices have been made with the aim of building a simple and quick installable sensing part. The objective is to be able to assume a serial provisioning that needs few installation steps and where including sensors is practically automatic.

##### **Serial Provisioning**

The gateway is a hub connecting deployed sensors of an AmI solution to a remote server. It is in charge of collecting raw data from sensors, making some preliminary processing, and transferring result outputs to the remote server. Therefore, different modules need to be installed on the gateway to collect raw data from sensors using specific communication protocols, make basic processing, guarantee the communication between the gateway and the server, and perform configurations to adapt the gateway to the AmI solution's use case.

Preparing a gateway for a deployment is very tedious and time-consuming task. It requires installing the appropriate operating system, configuring the network in order to enable remote connection with the server, installing the different modules needed for the communication be-

tween sensors/actuators and server, and make sure that software dependencies are fulfilled. This installation is also a repetitive task as the same gateway installation process will be performed for each new deployment.

## Enable Gateway and Sensors/Actuators Discovery

Deployed gateways and sensors need to be recognized and integrated into the server framework in order to receive events, perform context understanding and provide appropriate services to end-users. Usually, gateways and sensors are manually integrated into the framework and linked to specific spaces and objects. This manipulation requires an expert of the framework details to make the required changes and configurations. In this case I propose a communication protocol between the gateway and the framework in order to automatize this process and ease the deployment of AmI solutions.

## Maintenance

The maintenance is a key point for a real deployment and becomes crucial for a large-scale deployment. From the moment that it is not possible to do it in-situ when the system is located away, the maintenance becomes another strong argument for using industrial sensors since they are easy to connect and, overall, replace. Furthermore, these sensors usually have an efficient battery lifetime. For example, X10 battery holds one year. Moreover, the gateway software needs to be failure-proof and capable of restoring the different modules on the gateway. I, therefore, have leveraged Linux services systemD ensuring that the programs are running in any situation.

UbiGate contains a daemon service that open a permanent ssh connection with a dedicated server, see Figure 4-1. This connections allows us to detect if the device is connected to Internet and can be used as a enter point to fix different potential errors. There are four maintenance scenarios: Software upgrade; automatic error recovery; distant error recovery; in-situ error fixing.

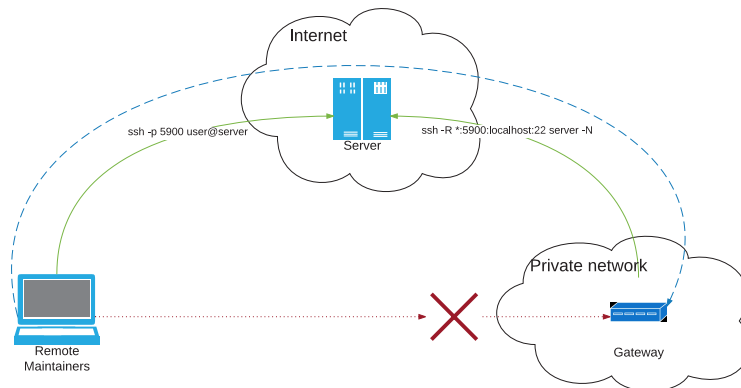


Figure 4-1: Reverse Proxy architecture.

## 4.3 Hybrid System Reasoning

The software represents the strength of the proposed approach. The ambition is to be able to interact with the largest number of service providers: sensors, local and cloud data providers, messaging capabilities, ... to tackle the proposed challenges with the highest guarantees. UbiSmart reasons upon the collected data and store them to make them accessible anytime. Regarding the reasoning part UbiSmart adopt both the two data processing approaches: the Knowledge-Driven Approach (KDA) and the Data-Driven Approach (DDA). The KDA reasons upon contextual and behavioral situations. On the other hand, the DDA techniques classify the collected raw data, extract human features and feed the knowledge approach to improve its decisions. For the frame of this thesis the Data-Driven approach has been applied to understand and classify the human outdoors mobility based on the inner smartphone sensors values. Following, both approaches are detailed in terms of design and technologies.

### 4.3.1 UbiSmart Data-Driven Approach - Mobility Paradigm

Human mobility is a key enabler to understand the impact of the cities of tomorrow upon the elderlies. The increase of the connectivity, the transportation choices and instantaneously availability of the services may impact differently upon different range of persons. Being a part of smartcities (or cities of tomorrow), UbiSmart follows the same approach by adapting the new technologies to keep assisting seniors, even in their outdoor activities. The interest is to understand how individuals move around the city and what their places of interest are. The framework aims at detecting whether the changes of their habits can indicate a risk for them. UbiSmart leverages on existent sensing technologies to extend the presence with the individuals and to improve the data. Then, it analyses smartphone's inner sensors to model and classify the type of movement performed by the elderly outside their homes.

The objective is to distinguish which kind of mobility is performed by the elders while they are outdoor. Then, I want to classify in two main branches: *Active* and *Passive* mobility. To do so, it was needed to use a device with different sensing capabilities already installed, smartphone. Most of these devices include an accelerometer, which has been proved to be very capable of determining the activity of a person wearing one [97]. Positive results have been obtained too if the accelerometer is from a smartphone and the user is wearing the device on their hip [161]. Therefore, the work here is based on those results and follows a similar work of line.

To be more specific on the mobility paradigm. I define AM [134] as a form of transport of people, that only uses the physical activity of the human being for the locomotion. The most known forms of AM are walking or cycling. On the other hand, we understand PM as form of transport that uses door to door engine locomotion transport (Taxi, Private Car). In this scenario, there are still some common transportation, Public Bus and MRT, that are not

included in any category. For those cases, they are included into the AM because even if the main transport is done by an engine locomotion, they still imply human movement.

It is well known the importance of the data collection when training a DDA. The first option to collect data was to use available inner smartphones dataset to train the model. However, accordingly to the literature review there are not available dataset that fits the requirements in terms of types of transportation, number of sensors taken into account and non restrictions on the device position when recording data.

Then, in order to fit the specific requirements the data was collected by the team members. To achieve that, first Activitrack was developed, an Android application, see Figure 4-2. In a simple interface, it allows users to select an activity and start recording. While the recording lasts, the application listens to the available sensors in the phone, accelerometer, gyroscope, magnetic field, rotation vector, geomagnetic rotation vector, linear acceleration, and their uncalibrated versions where applicable. The geolocation coordinates are also recorded, speed, accuracy of the location values, bearing and altitude.

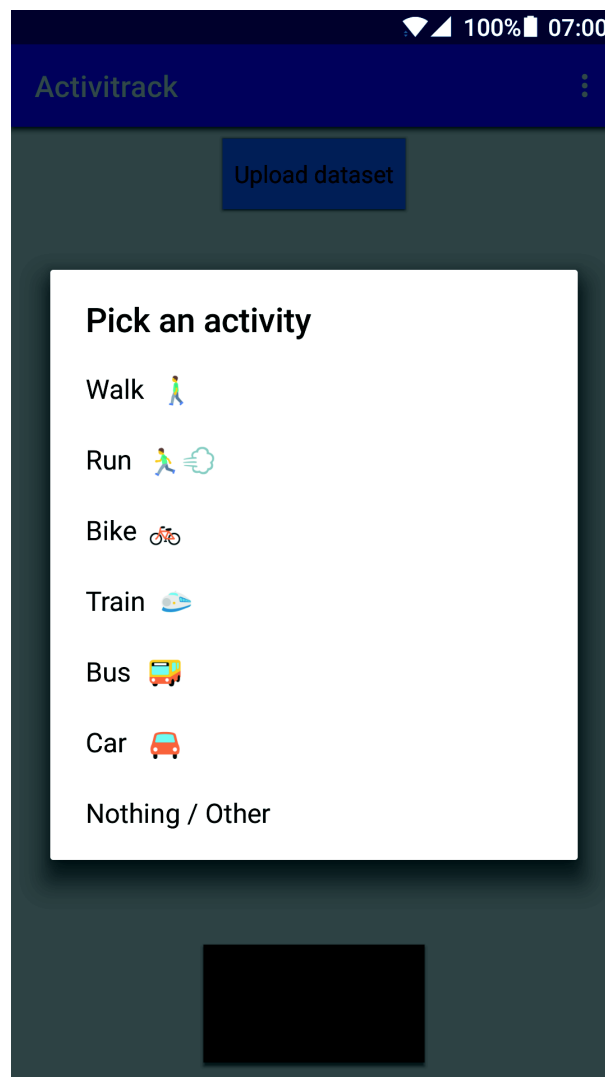


Figure 4-2: ActiviTrack activity selection screen.

### 4.3.2 UbiSmart Knowledge-Driven Approach

KDA is based on building an ontology that represents the system context. UbiSmart uses the web technology and the user interaction to convert any environment into a smart space in 20 minutes. It minimizes the impact upon the end-users by reducing the number of sensors, however, the quality of the assessment is not affected. The end-user is allowed to enter specific context information, which confers versatility and adaptability. Moreover, the hardware installation and the maintenance are automated, to reduce the human effort, and allow the user to be an active part of the system. The framework disposes of dedicated end-user services which build the *instance* model without requiring prior or expert knowledge. UbiSmart is able to use the same semantic engine for many spaces by combining the *abstract* and the *instance* model. Thus, it infers decisions independently and accordingly to peculiarities of each deployment. The final purpose of UbiSmart is to detect the ADL and provide services at the right time and through appropriate device.

**Abstract Model:** model shared by all the deployments at the same time and contains the initialization of the model, basic declarations (abstract classes, objects, relations, ...).

**Instance model:** Unique model for each deployment containing specific declarations, relative relations between two entities.

The system is composed of several sensors deployed in the environment to perform some monitoring of the residents' behavior, and a set of interaction devices used to render the assistive services. A reasoning process is integrated in order to perform the context understanding based on previous team work presented by [178, 6]. It is based on sensors' events and select the adequate assistive services for the residents when needed. This reasoning process also selects the suitable devices of interaction for the provision of the selected services. The selection of suitable assistive services and interaction modalities is performed by a rule-based semantic reasoner realizing a semantic matching between the knowledge about users' context derived from sensors' events, and respectively services' and devices' semantic profiles acquired from a global semantic model (ontology). The semantic model represents the knowledge about entities in the environment (including users and their activities, locations, assistive services, sensors and devices) and the relations between them. Figure 4-3(a) represents different classes in this model while Figure 4-3(b) shows the possible properties between them.

The ontology has been extended to tackle the urban challenges, however, the inner functionalism has been respected. When the system starts receiving events from sensors, UbiSmart recognizes the house  $N$  and uploads the specific instance model house  $N$  which complements the abstract mode. The ontology is automatically updated and a set of inference rules is applied to infer the context of the user, select the adequate assistive service depending on this context, and

select the appropriate device of interaction. Used inference rules are presented below:

The system takes into account the frequency of sensor events received to build a motion estimator. This technique allows the reasoner to infer different type of activities with a same kind of sensors [178, 6]. I.e if the user generates a high flow of sensor event in the bedroom, he/she is most likely doing activities in the room. If he/she generates a low flow of sensors events, it likely means that he/she is lying on the bed but still awake. Finally if he/she does not move at all it means the he/she is likely sleeping. This activity recognition has been improved by the use of the Fiber Optic Sensor, however, sometimes it is not possible to deploy this kind of sensor.

Service selection inference rule

$$\begin{aligned} &\forall \text{ User } u; \text{ Deviance } dv; \text{ Service } s; \text{ MotionEstimation } m; \text{ Room } r \\ &(u, \text{detectedIn}, r) \wedge (r, \text{is}, \text{Bedroom}) \wedge m, \text{Math:} \text{notGreater}, 1 \\ &\Rightarrow (u, \text{believedToDo}, \text{Sleep}) \end{aligned}$$

User location detection

$$\begin{aligned} &\forall \text{ Sensor } se; \text{ SensorState } st; \text{ Room } r; \text{ User } u \\ &(se, \text{hasCurrentState}, st) \wedge (se, \text{hasType}, \text{PIR}) \wedge (st, \text{indicateLocation}, \text{true}) \\ &\wedge (se, \text{deployedIn}, r) \wedge (u, \text{liveIn}, r) \Rightarrow (u, \text{detectedIn}, r) \end{aligned}$$

User activity recognition

$$\begin{aligned} &\forall \text{ User } u; \text{ Deviance } dv; \text{ Service } s; \text{ MotionEstimation } m; \text{ Room } r \\ &(u, \text{detectedIn}, r) \wedge (r, \text{is}, \text{Bedroom}) \wedge m, \text{Math:} \text{Greater}, 6 \\ &\Rightarrow (u, \text{believedToDo}, \text{bedroomActivity}) \end{aligned}$$

In Figure 4-3(a), the class **Environment** represents the different scenes of the patient's environment, such as bedroom, shower-room or toilet for the indoor assessment or food court, mall or tram station as outdoors **Points of Interest** at the **City Level**. **Furniture** represents the different objects of the environment. **Device** and **Sensor** classes contain all the sensors and interaction devices detected and connected to the framework. The **SensorType** class represents the different possible types of sensors while **SensorState** class represents the different status that sensors might have. The **Resident** and **Caregiver** are represented under the class **Person**. The provided assistive services are under the **Service** class.

In Figure 4-3(b), the **hasPossibleState** relation represents the possible states that a sensor might have while **hasCurrentState** relation indicates the current status of a sensor. **hasId**, **hasType** are intrinsic properties of devices and sensors. The relation **liveIn** specifies the environment in which a resident is living. The **detectedIn** relation marks the location of a patient while the **deployedIn** relation represents the location in which a sensor or a device is deployed. The relation **attachedTo** indicates the furniture to which a sensor or a device is attached. If a resident is performing a new activity, the relation **believedToDo** is created between him and

this activity. If an assistive service is to be rendered on a specific device for the patient, the `useDevice` relation is created between them.

Appendix B contains the ontology model and the semantic rules developed for this thesis.

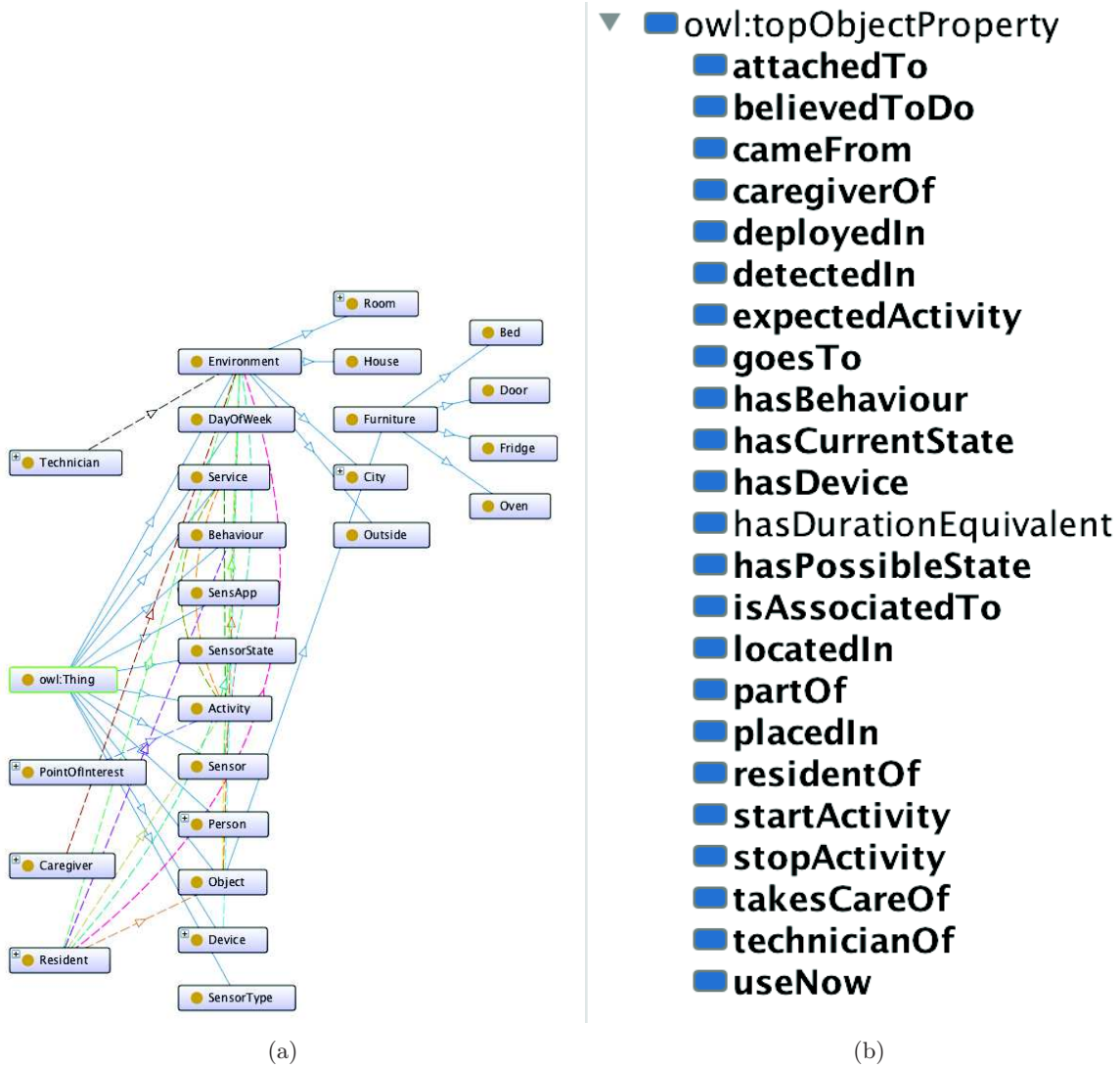


Figure 4-3: (a), (b), classes and objects properties of the ontological model.

## 4.4 UbiSmart Architecture - Overview

To summarize, the UbiSmart architecture is presented in Figure 4-4. The purpose of the framework is to collect *quality of life* QoL indicators and use them to detect risky situations [18, 154], long-term evolution [81] and to enhance the quality of life by an intervention. The main monitored target group is aging and frail population, although caregivers benefit as well [106]. Figure 4-4 includes concepts and terms that will be detailed in next Chapter 5.

To achieve its goals, the platform UbiSmart makes use of standard commercialized sensors producing events, a gateway **UbiGate** or **UbiTracks** that relays the structured event data to the main component – the **Server** written in *Node.js*. Eventually, notifications are sent to other



devices as part of **Service Provisioning**. The reasoning is situated in the server: incoming events are stored in a database, translated in triples using Notation3 format and queued to be processed within the reasoning cycle.

The ontology in the system has been created manually as well as the rules. They represent a common sense about observations (presence detection in a space, object manipulation) and implied conclusions based on past *Knowledge* (the person is in the kitchen, preparing some food, receiving a visitor).

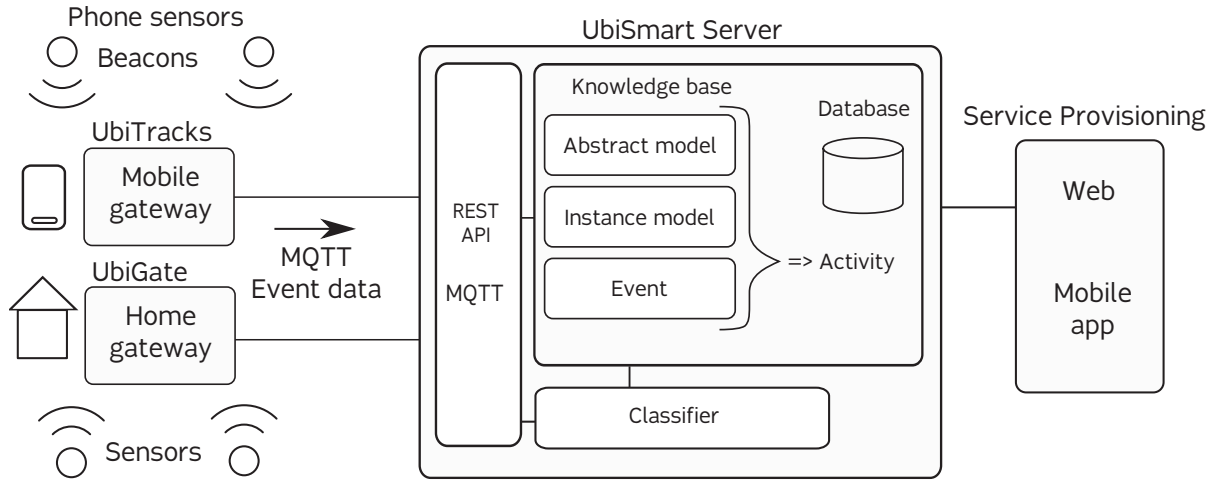


Figure 4-4: UbiSmart framework in three blocks. The UbiGate or UbiTracks, the Server and the Service Provisioning.

Whenever the server is ready to process a queued event, reasoner (EYE<sup>1</sup>) is executed with knowledge originating from three ontological layers (as illustrated in Figure 4-4 as content of knowledge base:

- *Abstract model*: **Static ontology** describing the world that does not change (sensor type associated to its abilities and characteristics, type and description of detectable activities);
- *Instance model*: **Instantiated ontology** comprising persisted information that was instantiated and has current information (*e.g.* sensor-room associations, durations of previously detected activity, ...);
- *Action*: **Injected knowledge** produced by the sensors or a user interaction.

Using the described Knowledge Base (KB), the framework applies rules that conclude about what the current user's activity is, computes new durations, updates the persisted information about this instance, and decides about notifications to be sent. The conclusions are passed to software components performing decided actions. The reasoning cycle ends and waits till next event triggering a new cycle.

The sensors in the space  $N$  communicate with **UbiGate** or **UbiTacks** exchanging raw data values. The gateways process the information and generate sensors events that are sent to

<sup>1</sup>Euler Yet another proof Engine, <https://github.com/josd/eye>

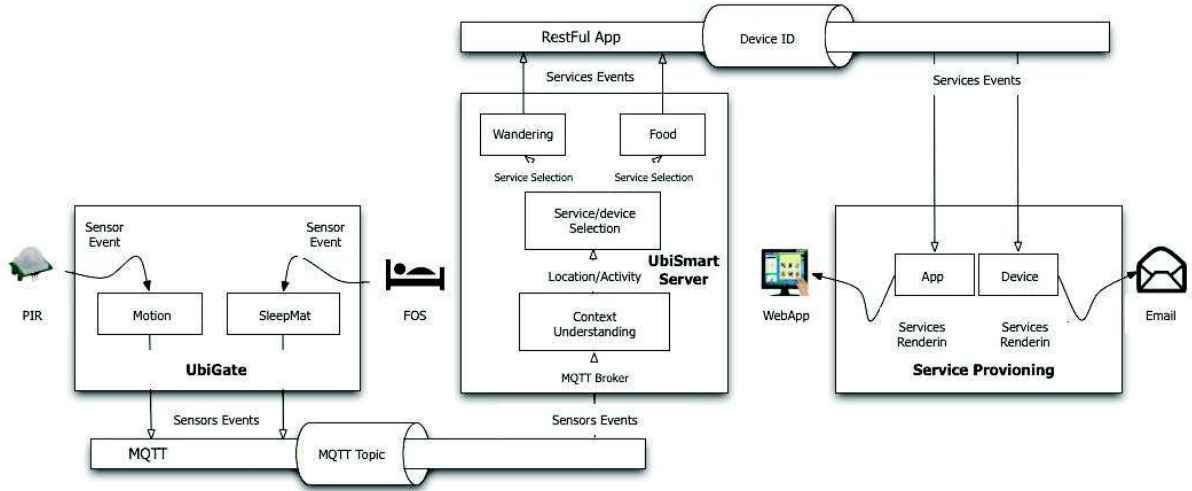


Figure 4-5: UbiSmart Data flow from the sensor event message to the human-centered interaction.

UbiSmart Server. The events reach the server through the IoT protocol MQTT using a publish and subscribe exchange. The information is then classified following the specific topic and sent to a dedicated *Controller*. The server stores the sensor event in specific DB also known as *Models*. The *Instance* model for the Space  $N$  is updated and the server loads the *Abstract* and the *Semantic Rules* and runs the reasoning. The output range from *Activity* recognition, user *Location* or *Service* allocation. The server then stores the semantic output in other dedicated *Models* and disseminate the information to: WebApp interface (also know as *View*); device notification; and frailty model computation. Figure 4-5 represents the data flow from the sensor to the UbiSmart **Server** and the **Service Provisioning**.

Figure 4-6 lists the main classes and objects that compose UbiSmart. First, the gateways, UbiGate and UbiTracks, consists of different sensor plug-ins that convert raw sensor data into MQTT events. In the case of the indoor gateway, UbiGate, there is a plug-in for each type of sensor (X10 and Zwave) and an external module, Domoticz Open-Source Framework, which helps with the interaction of new sensing capabilities. Each gateway also contains a routine that communicates with the MQTT Broker in the UbiSmart Server. The Broker is a routine that continuously listens to the MQTT messages on port 1883. It is subscribed to specific topics and redirects the messages if there is a match between message topic and topic subscription.

In addition to the above-mentioned sensor event data flow, UbiSmart *Service Provisioning* includes diverse routines that facilitate the interaction between the user and the KB. The framework provides to the end-users simple and friendly interfaces, (*Views*), to exchange information with the inner routines. It allows the external interaction through several *Public APIs*, that connect to the *Server* but restrict the access. Also, the public APIs module interacts with others Restful Apps or requests data from third-party servers.

UbiSmart *Server* is composed by the MQTT Broker, the DB and five modules: the *Models*

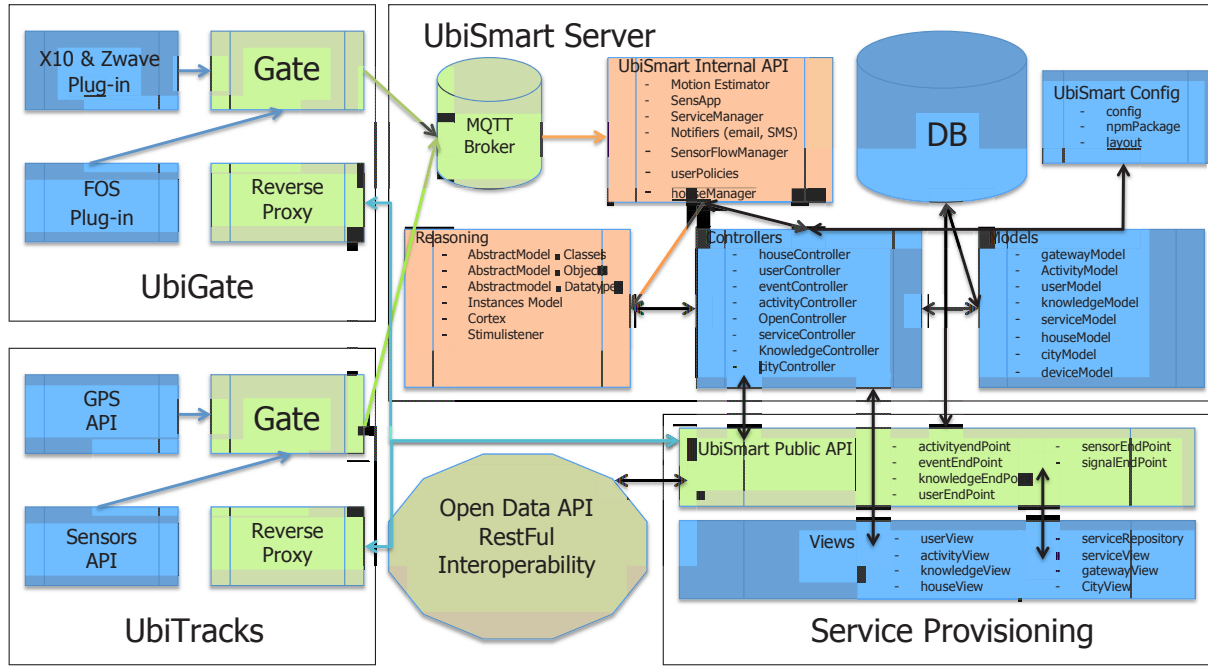


Figure 4-6: UbiSmart modules diagram. Blocks in blue represent internal routines, blocks in green illustrates Input/Output channels. Orange blocks are dedicated to internal server routines (e.g. reasoning), and brown block represents the communication with external and third-party collaborators (e.g. Open Data repositories).

are the bridge between the DB and the server routines. They contains the methods to extract, modify, delete any entry in the DB tables; the *Controllers* are in charge of consolidating the data, either to be stored in the DB through the *Models*, visualized in the *Views*, or send to external servers through the *Public APIs*; *UbiSmart Configurations* are the needed files to lift the server. They contain the engineering packages and configurations to put the server online and accessible. The *UbiSmart Internal APIs* contains specific routines to improve the reasoning (*motionEstimator*), define user policies, create device notifiers or manage the functionalism of the services. In fact, this block complements the *Controllers* to make the code more accessible and readable; finally, the *Reasoning* cycle is based on Aloulou et Tiberghien research, [6, 178], and it has been improved during this thesis. It includes the *Abstract* and *Instance* models, the routines in charge of detecting new sensor events to launch the semantic engine (*Stimulistener*), and the routine that handles the reasoning cycle and the inference extraction (*Cortex*). Following, I present several examples for each module within the *Server*.

*gatewayController* is a user interface that allows to distantly manage, update and maintain the gateways. The associated *View* is named *gatewayView*. From this interface the user can access to any gateway status and change their specifications, as well as update or removed it. *userController* is a routine that handles the users in the framework. It allows assigning roles and permissions to the users. *userModel* defines the dedicated user table in the DB, it also allows to state links between tables, e.g. *houseModel* contains a house *ID*, which is included

in the *userModel* to link a given user  $A$  and a given environment  $N$ . *sensApps* defines the type of sensors included in the KB. From this routine, the technician can enable or disable any type of sensor for a given space  $N$ . *Notifiers* is in charge of generating a message (mail, SMS, etc) to a specific user with certain information. Regarding the inner functionalism of the semantic reasoning, specific routines are included. The *motionEstimator* computes the quantity of movement generated by the user in his/her environment. This computation provides valuable information to the reasoning to infer more or less active activities. Finally, *Cortex* uploads the correct *Instance* model for a given space  $N$ , runs the reasoning, the inference rules, and extract the results, if any, to be exploited in other modules.

## 4.5 Targeted Cohort - Frailty Reasoning Design

The frailty model has been designed to be part of the UbiSmart framework. It has been conceived as an ontological extension of the existent KB in the system. Figure 4-7 illustrates the inter connexions between the framework, the user, the environments and the frailty model.

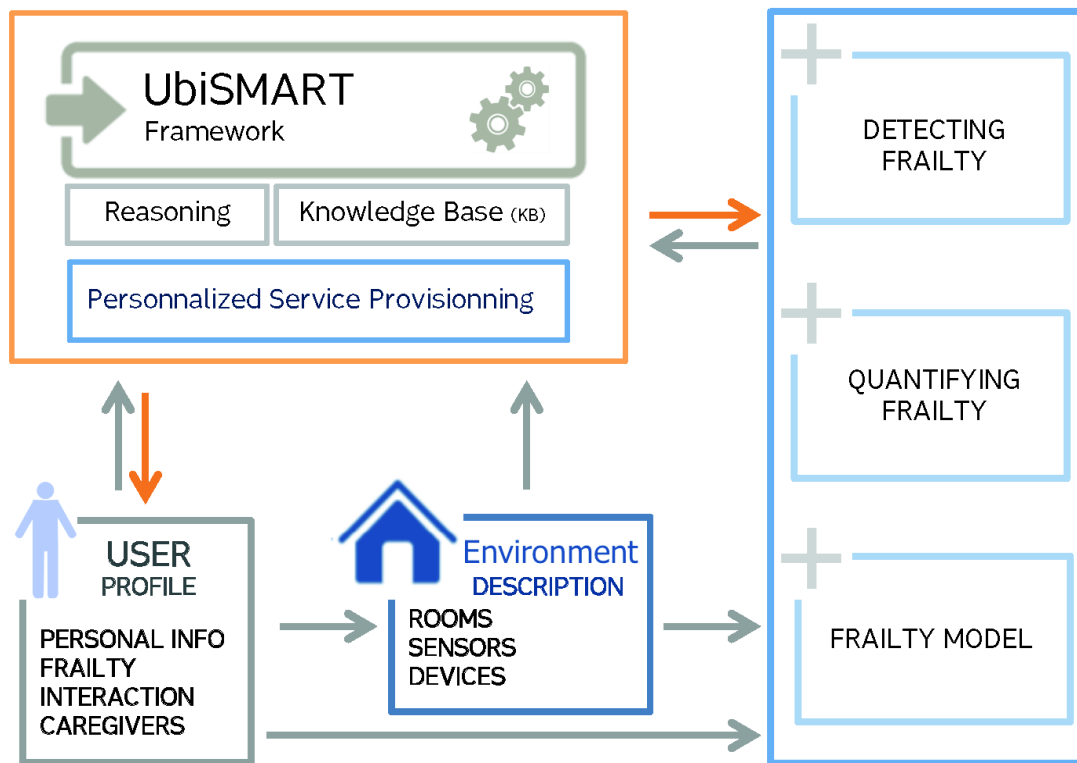


Figure 4-7: Frailty inclusion in UbiSmart Framework.

The model has been adapted into an ontological structure to be easily include in the *Abstract* model of UbiSmart. Each item is then instantiated and included in the *Instance* model for each user. Figure 4-8 represent both, *instance* and *abstract*, models with the entity relationships and an example of frailty value. It also represents the numerical computation for the frailty values detailed in the next lines.

### 4.5.1 Frailty Model Conception

The literature is still debating about a common definition of frailty. There have been studies that have tried to converge into a functional and complete definition of frailty following the *Delphi* method. *Delphi* method consists of responding several rounds of questions. Each round begins with an answer report of the previous round, relying on the hypothesis that preconceived ideas may lead to an agreement. In 2012 Rodriguez *et al.* [145], performed a three rounds *Delphi* study towards a frailty definition. The cohort of the study was composed of five focus groups with five/seven people per group (geriatricians, nongeriatrician physicians, other health professionals, basic scientists, and social and nongovernmental workers). Each group was provided with 27 publications about frailty. The study highlighted that the response between rounds remained similar on 75% of the cases. Only 44% of the statements regarding the concept of frailty and 18% of the statements regarding diagnostic criteria were accepted. There was a consensus regarding the term multidimensionality (six dimensions), however the clinical and laboratory biomarkers remained unclear.

The definition highlighted by the *Delphi* method contrasts with the World Health Organization WHO notion, that considers frailty as a contextual factor and may be indicated by some degree of disability [117]. In this direction, I believe that frailty can be modeled through the activity performance, which is also the central part of the International Classification of Functioning, Disability and Health ICF model by WHO. This study was presented in 2001 by the World Health Organization (WHO) aiming to provide a tool to identify and measure the effectiveness of the physical and social environment on people with impairment or disability. As defined by WHO: ICF extends the medical paradigm integrating biological, physiological, physical and social dimensions into the person model to evaluate his functioning and disability.

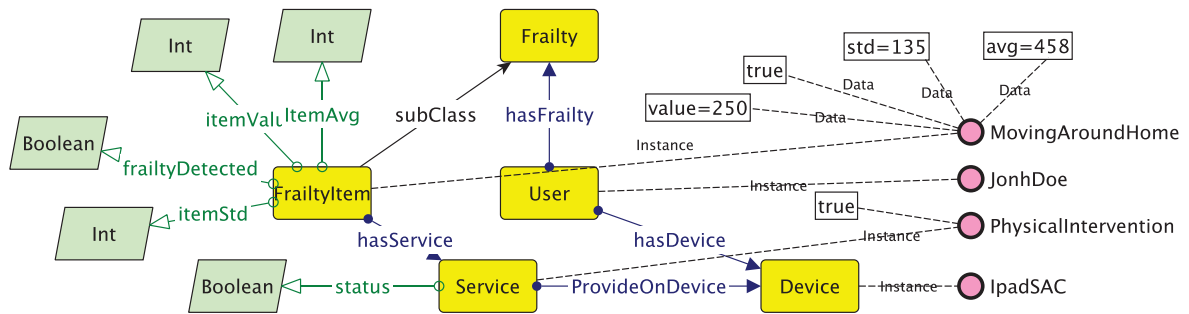


Figure 4-8: Abstract and Instance model of the ontology representing the frailty of the user. This model is replicated for each indicator. Each frailty item contains its main values to be able to track the evolution of the frailty.

From my perspective, frailty is to the proposed model as activity is to the ICF model. Therefore, I took advantage of relations and matched the domains to those featured in the ICF model. Figure 4-9 illustrates the model overlaid on the ICF model. The proposed domains for

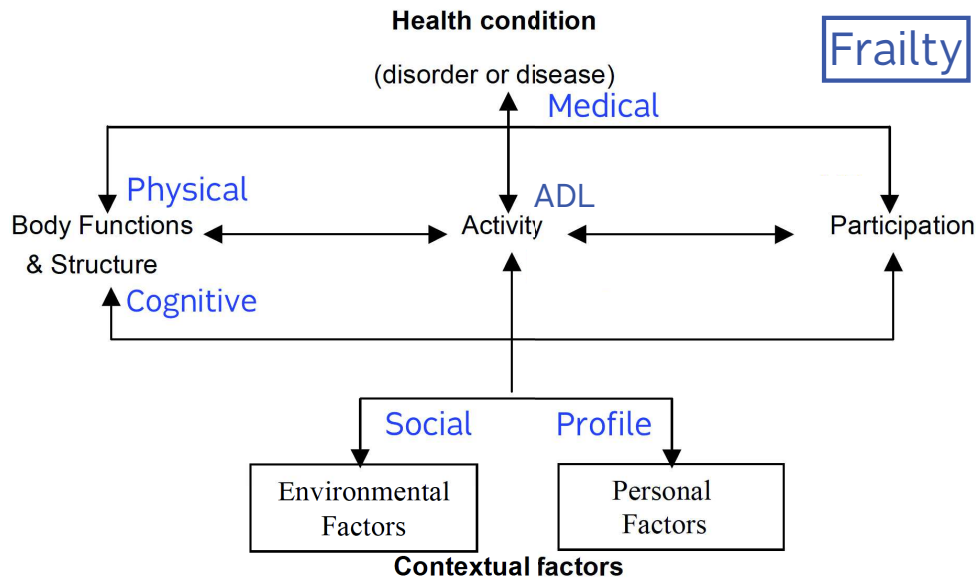


Figure 4-9: Proposed frailty model harmonized with International Classification of Functioning, Disability and Health (ICF) model presented in 2001 by the World Health Organization.

the frailty model are mapped as follows: the **ADL** with the participation as the capability for executing tasks; the **Social** with the contextual factors as the influence that these factors affect the person; the **Physical** domain with body functions & structure as the personal performance in terms of mobility and effort; the **Cognition** with another part of body functions & structure as the mental capabilities; and, finally, the **Medical** domain with the health condition. Following, I present each domain and the choice of its items relied on the availability of data and the possibility to quantify them.

## Health Condition

By its definition, this ICF branch comprises all medical items. This domain has been excluded from this study because its evaluation remains a professional duty that can not be performed automatically by UbiSmart.

## Personal Factors

The profile has been included in the system but it has remained static during the study. It takes into account intrinsic and personal information such as: name, address, contact number, relatives information, etc.

## Body Functions and Structure

This ICF branch takes into account the physiological functions of body systems (including psychological functions). In the model, I include the **Physical** and the **Cognitive** domains. The **Physical** dimension includes the physical performance in terms of mobility, movement, effort and recovery activities. As explained in the introduction, the system does not seek to compute

how many meters the person walks during the day but to infer if the amount of movement remains within the normality borders. The items in the **Physical** domain are:

- **Consciousness** as the amount of time invested by the individual doing non-static activities.
- **Time Out of Home** is considered a valuable quality of life indicator in aging people [58]. The system computes this item, which also can be considered under the **Social** domain. Therefore, even if it cannot be guaranteed the interaction with other people at present, going out avoids social exclusion and reinforces social value.
- **Sleep Quality** is computed as the amount of sensor events inferred during the night time. **Sleep** is considered as a **ADL**, so this item can also be matched in that domain.
- **Night Cycles** represents the bed time performed by the aging. I compute two items: first, the **Bed Time** when the senior goes to bed, and second, the **Wake Up Time**. This item is also considered under the **Social** domain [69].
- **Respiratory Functions** and **Heart Rate** are computed through the fiber Optic sensor [152, 151].
- **Mobility Outdoor** is computed as the amount of movement performed by the individual outdoors. The computation is performed by the classification of his displacement with the inner sensors of the smart phone. This item implies the computation of **Active** and **Passive** mobility as presented in Chapter 4. These items are also considered in the **Social** dimension.

On the other hand, the **Cognitive** dimension covers all items related to the mental abilities of the individual, such as memory, perception, language, etc. Several studies [150, 38, 86] support the fact that there is a dependency between the cognitive domain and the other three domains. Ruthirakuha *et al.* [150] state that a reduction of the physical activity or socialization can be either the effect or the cause of a reduction of the individual cognitive rate. Therefore, the cognition has not been addressed in this study.

## Environmental Factors

In this branch, I include the **Social** dimension, that covers the integration and the interaction between the individual and his/her environment. There have been studies demonstrating that social engagement can improve the quality of life of the individual [42]. Including some items in the above **Physical** domain, the **Social** domain is also characterized by the following item :



- **Relations** represents the amount of time spent with visitors at place. The approach can not assure the interaction with other persons, yet it is supposed that a visit implies interaction. This item is also considered as a **ADL** item.

## Participation

Finally, participation is matched to the **ADL** domain, which studies specific activities performed by the individual and his limitations during its execution. The **ADL** dimension is characterized by these items:

- **Daily Routine** studies the execution of specific activities and detects if some of them are missing. The main routine contains four essential activities in the morning followed by four more in the afternoon. As an example: Wake Up, Toileting, Kitchen activity and a Leisure activity such as Go Out, Watching TV or Visit in the morning, and then Toileting, Kitchen activity, Bedroom activity and Sleep in the afternoon. It is computed as the ratio of different detected activities to the number of expected activities according to his profile, reporting a final value between 0 and 1.
- **Moving Around House** is computed as the number of room transitions performed by the user when he is alone at home [176]. This item is also considered in the **Physical** domain.
- **Walking Short Distances** studies the energy of the person by counting the number of sensor events when he is alone at home [83]. This item is also considered in the **Physical** domain.
- **Toileting** is the daily number of visits to the bathroom. The system also takes into account **Night Toileting**, which counts the number of visits to the bathroom when the senior is supposed to be sleeping.

As presented, some of the items fit into multiple domains. Yet, in this first approach, the classification of the items does not affect the final computation because they are treated independently. In Table 4.1, I present each dimension with its items and its corresponding item in the ICF model.

### 4.5.2 Frailty Dataset and Quantification

The numerical computation of frailty values deals with the heterogeneity of data collected the items. Most of the items are based on the activity reasoning inference. Yet, UbiSmart is not intended to track the movements of the senior with precision or infer exactly what the person is doing. On the contrary, it aims at inferring certain activities or scenarios that allow the system to predict the level of risk or detect abnormal behaviors.



Table 4.1: Frailty model with a human survey. Frailty items computed during our deployments. Each item is represented by its code in the ICF model, the source of raw data used for its computation, and its counterpart in the reasoning output. (Note that PIR acronym refers to Passive Infrared Sensor).

ID	Frailty Item / ICF Item	Proposed Domain	ICF Code	Data Source	Daily Computation
1	Consciousness	Physical	b110	PIR Sensor	Inferred <b>Active Time</b> during the day
2	Time out of Home	Physical & Social & ADL	b1260 & e3 & d7	PIR & Contact Sensor	Inferred <b>Go out</b> activity
3	Relations	Social & ADL	e3 & d7	PIR & Contact Sensor	Inferred <b>visit</b> activity
4	Perform Daily Routine	ADL	d230	PIR & Contact Sensor	Inferred <b>Daily Routine</b>
5	Moving Around Home	ADL & Physical	d460 & b7	PIR Sensor	Inferred <b>Changing Rooms</b>
6	Walking Short Distances	ADL & Physical	d450 & b7	PIR Sensor	Inferred <b>Energy Rate</b>
7	Toileting	ADL	d530	PIR Sensor	Inferred <b>Toilet</b> activity
8	Active Mobility	Physical & Social	b7 & e3	smartphone & PIR Sensors & BLE Beacons	Amount of <b>active time</b>
9	Passive Mobility	Physical & Social	b7 & e3	smartphone & PIR Sensor & BLE Beacons	Amount of <b>passive time</b>
10	Mobility outdoor	Physical & Social	b7 & e3	smartphone & PIR Sensor & BLE Beacons	<b>Mobile time</b> spent outside performing
11	Sleep time	Physical	b1340	FOS & PIR Sensor	Amount of <b>sleep time</b>
12	Sleep Quality	Physical & ADL	b134 & d230	FOS & PIR Sensor	Inferred <b>troubles in sleep</b>
13	Wake Up time	Physical	b1343	FOS Sensor & PIR	Time when the <b>user wakes up</b>
14	Bed time	Physical & ADL	b1343 & d4	FOS & PIR Sensor	Time when the <b>user goes the bed</b>
15	Respiration functions	Physical & ADL	b440 & d4	FOS	<b>Respiratory effort</b>
16	Heart rate	Physical & ADL	b4100 & d4	FOS	<b>Heart rate</b>

The generated dataset per user results to be very heterogeneous. While items as **Bed Time** or **Wake Up Time** are computed in time scale, others as **Heart rate** are expressed as a natural number. Moreover, some items are represented on a much smaller scale than the sleep time. Therefore, the system processes these values to reduce its range and homogenizes them into the same scale. Consequently, the collected datasets have been normalized using the zero normalization ( $Z_{\text{Norm}}$ ), or standardization, to reduce the large trend of the data, see Equation 4.1.

$$\widehat{x}_{id} = Z_{\text{Norm}} = \frac{x_{id} - \mu_{id}}{\sigma_{id}}$$

$$-1 \leq \widehat{x}_{id} \leq 1 \quad (4.1)$$

where:  $\mu_{id} = \text{mean}(\mathbf{x}_i)$ ,  $\sigma_{id} = \text{SD}(\mathbf{x}_i)$

and  $\mathbf{x}_i = \{x_{ij} \mid 0 \leq j \leq d\}$

Let  $x_{id}$  be the observation for an item  $i$  in a day  $d$ . This value  $x_{id}$  is then standardized using a  $Z_{\text{Norm}}$  with the previous days' observations. The values will be in the range of  $-1$  to  $1$ ,

The standardization highlights the outliers within a dataset. On daily basis, the system produces reference items' values for each user. The proposed solution aims to detect spontaneous and unexpected abnormalities. For this purpose, the system applies the Bland-Altman analysis [26], which is employed to find unpredictable or aberrant values. As a person might change his behavior in a long-term deployment, the system computes the average value  $\mu$ , and the standard deviation  $\sigma$ , for a given day  $d$  based on all previous observations. This procedure helps to evolve the boundaries of normality for each parameter adding dynamism to the Bland-Altman analysis. The system generates day by day its own item's reference values for each user. The proposed solution aims to detect spontaneous and unexpected abnormalities.

Let  $x_{id}$  be the observation for item  $i$  in day  $d$ . This value  $x_{id}$  is then standardized using a  $Z_{\text{Norm}}$  with the previous days' observations. The frailty level for item  $i$  at a given day  $d$ ,  $F_{id}$ , is defined following the Equation 4.2.

$$F_{id} = \begin{cases} F_s & \text{if } x_{id} > \mu_{id} + 1.96 * \sigma_{id} \\ N & \text{if } \mu_{id} - 1.96 * \sigma_{id} \leq x_{id} \leq \mu_{id} + 1.96 * \sigma_{id} \\ F_i & \text{if } x_{id} < \mu_{id} - 1.96 * \sigma_{id} \end{cases} \quad (4.2)$$

where  $\mu_{id} = \text{mean}(\mathbf{x}_i)$ ,  $\sigma_{id} = \text{std}(\mathbf{x}_i)$ , and  $\mathbf{x}_i = \{x_{ij} \mid 0 \leq j \leq d\}$ ;  $N$  represents the range of normal values;  $F_{s/i}$  represents the superior ( $F_s$ ) and inferior ( $F_i$ ) borders of frailty.

Finally, the third block of the frailty model, *Detecting Frailty*, details the development and integration within the UbiSmart framework. This section has been included in Chapter 5 for the coherence of the manuscript.

## 4.6 Discussion

The expertise acquired during previous deployments raised two main challenges to tackle when deploying the new version of UbiSmart: the deployment effort and the personalization of the service. As presented in this chapter, an AAL cloud framework that performs satisfactorily in real deployments needs to be easily deployed to be replicated in multiple sites, and designed by and for end-users. A satisfactory implementation simplifies the deployment and minimizes the disturbance upon them.

The adaptability and ease of deployment are improved by using as much as possible existent commercial sensors and available communications protocols. An automatic procedure is set in place to replicate the gateway when discovering and placing the sensors in a new location. To facilitate the maintenance, and to avoid disturbing the stakeholders' daily activities, the system provides a constant open channel accessible by a simple Internet connection that allows the technician to access to the gateway OS.

To cater for multiple users and multiple houses, the design phase of UbiSmart involves an iterative loop with the end-user to refine and align the services to their expectations. This technique, considered as an Agile method, involves the stakeholders from the very beginning and accelerates the implementation phase and their learning curve during the deployment.

The proposed framework presented in this chapter is divided in three blocks. First, the Ubi-Gate and UbiTracks, which are the gateways placed at the user environment or their smartphone and are easy to install and replicate. The second block, the UbiSmart Server, includes the inner functionalism of the framework, the database and the reasoning engine, and allows for remote maintenance. The third block is the Service Provisioning, which provides user experience and interaction with the stakeholders and is thus personalized.

In terms of reasoning, UbiSmart has an hybrid intelligence composed by a DDA for mobility data aggregation and KDA for activity and human status inference. The DDA is based on ML techniques that build a mobility model to understand the outdoors displacements of the individual. The KDA is based on a ontology rule-based reasoning. It is composed by an *Abstract* and *Instance* model. The *Abstract* model contains the definition of semantic classes, objects and properties, and it is shared by all the deployments. The *Instance* model is specific for each deployment and contains the precise description of the environment (*e.g.* number and type of rooms), the description of the user (*e.g.* health status) and the description and localization of the sensors and devices (*e.g.* sensor *A1* placed in *Bedroom*).

The ultimate objective of UbiSmart is to monitor the user by minimum personal invasion. In this thesis, I include the detection of anomalies by putting the end-user at the beginning and at the end of the system. The proposed frailty model has been conceived subject to the available non-invasive sensor data provided by UbiSmart. It has been harmonized with the

existent ICF model presented by the WHO, highlighting six dimensions (and 16 frailty items): Medical, Profile, Social, ADL, Physical, Cognitive. Frail situations are detected based on the outliers (detected through the bland-Altman methodology) on the user's daily values.

In the next chapter I present the implementation of each block, the integration of the reasoning within the UbiSmart and the inclusion of the frailty model. Finally, Chapter 6 presents the validation of UbiSmart performed in 4 blocks: framework usability, mobility model, real deployment, and frailty detection.

## Chapter 5

# Framework Development and Implementation

In this chapter, I present the software implementation to tackle the design phase detailed in Chapter 4. The structure of this chapter responds to the development of each of the UbiSmart blocks. I detail the integration of each type of sensor or data source, the reasoning inference engine and the creation of context knowledge. Then, I detail the deployment procedure and the architectural implementations to tackle the objective of a cloud AAL for distant and large-scale deployments. And finally how the frailty is implemented within UbiSmart. Figure 5-1 represents the UbiSmart overview with its implementation for each block.

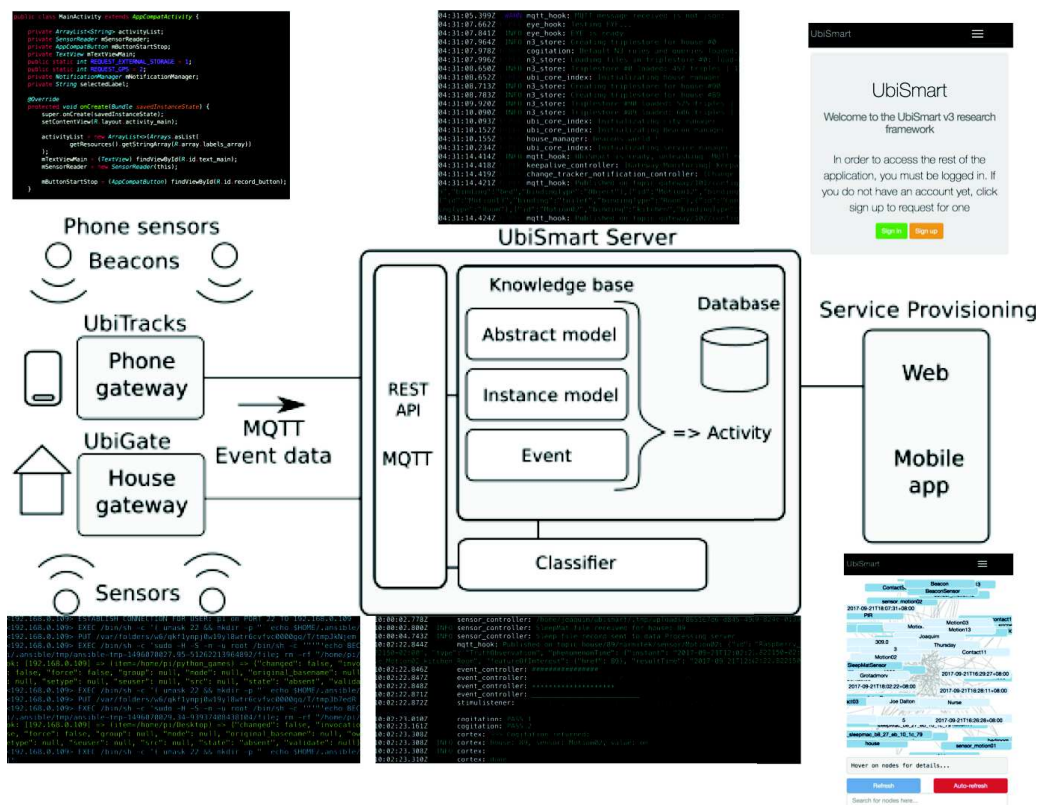


Figure 5-1: UbiSmart framework implementation in three blocks: The UbiGate (UbiTracks), the Server and the Service Provisioning. the image contains code samples for each block.

## 5.1 Sensors for ADL

The strength of the system is on its software and this should remain agnostic to any type of hardware. The large availability of any type of sensing hardware and the competitive prices lead the team to use out of the shell material, avoiding prototyping sensors. Therefore, the main goal is to build software than can adapt industrial and markets devices to specific aims.

### 5.1.1 Gateway

There are a number of gateway devices. In this case, I compared, in Table 5.1, the two options with the biggest community in 2014: BeagleBone and RaspberryPi.

RaspberryPi is the choice for the experiments based on the connectivity, the possibility of adding more storage through a SD card, the increasing community and the lower price.

Table 5.1: Gateway models comparison.

Gateway	BeagleBone	RaspberryPi
Developer	Texas Instruments	Raspberry Pi Foundation
Operating System	Linux	Linux
Power	Mini USB 5V	Micro-B USB 5V
Processor	1GHz ARM® Cortex-A8	1.2 GHZ quad-core ARM Cortex A53
Memory	1 Gb	1 Gb
Storage	4GB on-board	SD Card
Connectivity	4 USB, Ethernet, HDMI, DVI-D, PC audio, optional: Wifi & Bluetooth	4 USB, Ethernet, HDMI, RAC, WiFi & Bluetooth, Jack 3.5 mm
Dimensions	8.8cm	8.5cm
	5.4cm	5.3cm
	1.5cm	1.7cm
Price	94.83 SGD	56.71 SGD

The sensors & actuators used are out of the shell devices that communicate with the gateway without any prior change. In this research UbiSmart uses four kinds of sensors: motion, contact, FOS, BLE Beacons and the inner smartphone sensors. Figures 5-2, 5-3, 5-4, 5-5 and 5-6 present the devices used in the real deployments.

### 5.1.2 Motion and Contact

For home indoor activity recognition UbiSmart uses motion and contact sensors. In the first deployments the technology was based on X10 Radio Frequency. It is a protocol for communication among electronic devices used for home automation. It primarily uses power line wiring for signaling and control, where the signals involve brief radio frequency bursts representing digital information.

The motion sensors were Marmitek X10 Motion Detector MS13E, which sends wireless radio frequency (RF) signals to a Transceiver Module when motion is detected. The MS13E sends off signals after a designated time, as long as no motion has been detected. For the contact sensors, Marmitek DS90 were chosen. Finally, both devices communicated to an RF transceiver plugged, Marmitek CM19E, into the raspberry Pi.



Figure 5-2: Motion sensor.



Figure 5-3: Door sensor.



Figure 5-4: Bed sensor.

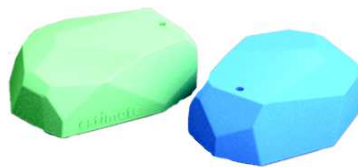


Figure 5-5: BLE Beacon position sensor.



Figure 5-6: Raspberry Pi.

Marmitek sensors stopped the production of its motion and contact sensors at the end of 2016. The system then moved to Z-wave technology, which is a wireless communication and mesh network using low-energy radio waves to communicate from appliance to appliance allowing for wireless control.

Z-wave has advantages and disadvantages compared to X10 sensors. On one hand, X10 sensors resulted simpler to deploy as they had very few options to be configured by the user. The name is automatically and randomly generated. The receiver does not need to establish any prior communication with the sensors and acts like a broadcast node. On the other side, Z-wave offers a high customization of the sensors. The users can choose the identifier but need to link the receiver with the devices with a prior manipulation. The Z-wave sensors put at disposition a user interface to manipulate and change options and disposition of the sensors. In the case of this deployment, the system includes Aeotec sensors: motion multisensor 6 (motion, humidity, Temperature, Light, shake, UV), contact Door/Window Sensor Generation 5 and the receiver Z-Stick Generation 5. For the purpose of this project the system includes Domoticz, an open source framework to handle the Z-wave technologies.



### 5.1.3 Fiber Optic Sensor - Sleep Sensor

Sleep plays a vital role in a person's health and well-being. Unfortunately, most people suffering from sleep disorders remain without diagnosis and treatment since the current sleep assessment systems are cumbersome and expensive. As a result, there is an increasing demand for cheaper and more affordable sleep monitoring systems in real-life environments. In this thesis, a novel non-intrusive system is proposed for sleep quality monitoring using a micro-bend fiber optic mat placed under the bed mattress.

The fundamental principle is based on the light intensity modulation induced by micro-bending in multi-mode fibers, which is used as a transduction mechanism for detecting pressure obtaining the Ballistocardiogram signal (BCG). A 10-meter loop of graded-index multi-mode fiber is sandwiched between two layers of tuned grating structures that subject the fiber to mechanical perturbation when there is a pressure applied as shown in Figure 5-7. The pressure causes the transmission modes in the multi-mode fiber to be coupled into the loss mode, reducing the amount of light received by the photo-detector. Hence, the detected light is converted to current by the photo-detector, which is, in turn, converted into a voltage using a trans-impedance amplifier. The signal is filtered via a 20Hz low-pass filter and then digitized by a 16-bit analog-to-digital converter with a sampling frequency of 50Hz. (The signal processing part is the research subject of Sadek, [151, 153]).

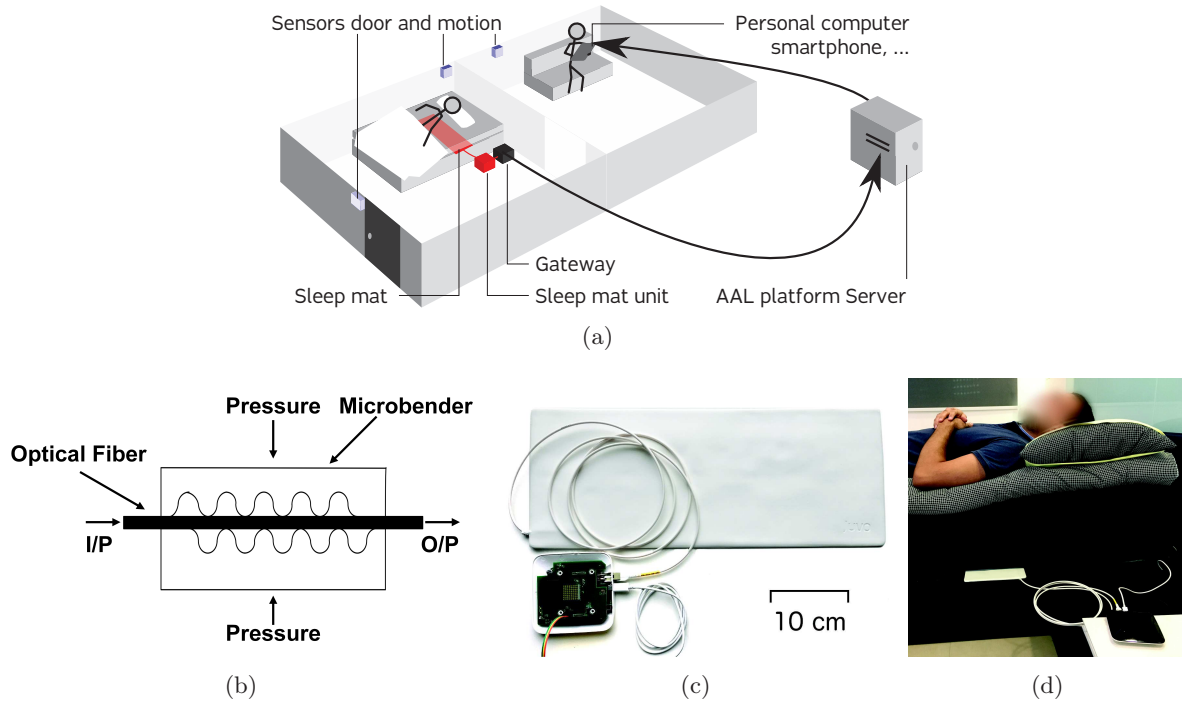


Figure 5-7: (a) Overview of the unobtrusive monitoring in a living space (b) Longitudinal section of the micro-bend fiber optic sensor, (c) Sleep mat and processing box. (Mat dimensions: 20 cm × 50 cm × 0.5 cm) (d) Sleep mat positioned under the mattress.



### 5.1.4 Outdoor

The outdoors sensors are divided into two branches. On the one hand, UbiSmart uses static BLE Beacons <sup>1</sup> and on the other hand, inner smartphone sensors.

BLE Beacons are Bluetooth low energy transmitters that broadcast an unique identifier to nearby compatible devices. The identifier and several bytes sent with it can be used to determine the device's physical location, track movement, or trigger a location-based action on the device such as a check-in on social media or a push notification. Beacons differ from some other location-based technologies as the broadcasting device (beacon) is only a 1-way transmitter. The interaction needs a dedicated App that listens the incoming signals and reads the BLE Beacons identifier.

UbiSmart is interested in understanding the mobility activity performed by users based on the sensor readings on their phones while wearing them in their pocket. In the case of this thesis, the problem is treated as a supervised machine learning model with a labeled dataset. The mobility model is a classifier that distinguishes between activities, depending on the temporal evolution of the smartphone sensors. Code sample 5.1 lists the type of smartphone sensors included in the study. Also, Code sample 5.12 list the type of data collected from the device sensors. For the sake of the study, "Nothing" activity has also been recorded. The aim is to discriminate static activities that could add bias and noise to the classifier.

```
Vector of outputs %\underline{Y}% =['Walking','Cycling','MRT','Bus','Car','Nothing']
Matrix of Sensors %\underline{\underline{X}}% = [
'gyroscope_x', 'gyroscope_y', 'gyroscope_z',
'gyroscope_uncalibrated_x', 'gyroscope_uncalibrated_y',
'gyroscope_uncalibrated_z', 'gyroscope_uncalibrated_x2',
'gyroscope_uncalibrated_y2', 'gyroscope_uncalibrated_z2',
'gravity_x','gravity_y', 'gravity_z', 'accelerometer_x',
'accelerometer_y', 'accelerometer_z', 'linear_acceleration_x',
'linear_acceleration_y', 'linear_acceleration_z',
'magnetic_field_x', 'magnetic_field_y',
'magnetic_field_z', 'magnetic_field_uncalibrated_x',
'magnetic_field_uncalibrated_y', 'magnetic_field_uncalibrated_z',
'magnetic_field_uncalibrated_x2', 'magnetic_field_uncalibrated_y2',
'magnetic_field_uncalibrated_z2', 'rotation_vector_x',
'rotation_vector_y', 'rotation_vector_z',
'rotation_vector_x2', 'rotation_vector_y2',
'geomagnetic_rotation_vector_x', 'geomagnetic_rotation_vector_y',
'geomagnetic_rotation_vector_z', 'geomagnetic_rotation_vector_x2',
'geomagnetic_rotation_vector_y2']
```

Code 5.1: Collected data on smartphone device for mobility classification.

---

<sup>1</sup>[https://en.wikipedia.org/wiki/Bluetooth\\_low\\_energy\\_beacon](https://en.wikipedia.org/wiki/Bluetooth_low_energy_beacon)

## 5.2 Cloud Hosting - Server

Hosting the server raised up a problematic to host the machine. Hosting it locally in the laboratory or acquiring a third-party service to host it and take charge of the physical maintenance. Taking into account the available human resources and the time consuming of maintaining a cloud server locally, it is located into a cloud hosting service. In this case, UbiSmart needs to be deployed in a plain operating system. In this case, a Digital Ocean server is chosen based on the location of the servers, the monthly prices and the ease of usage. The hardware is a Linux/Ubuntu 14.04, 1Gb of RAM and 30Gb storage. The system is protected by a Private/Public RSA key and uses SSL certification for accessing the web browser.

The server is in charge of collecting the data from any source and store it within a relational DB. It also contains the reasoning engine, both the semantic and machine learning models (refer to sections 4.3.2 and 4.3.1). It is coded in JavaScript using NodeJS. It also uses MQTT Publish and Subscribe communication protocol as a simple and scalable way to deal with data coming from different spaces at the same time. UbiSmart uses Mosquitto as MQTT broker because of its compatibility with JavaScript [19]. UbiSmart Server is also built upon Sailsjs as an auto generated Model-View-Controller framework for the basic web App infrastructure. The packages are installed through the Node packages manager (NPM) including every javascript package in the configuration file package.json and the config file. In order to add more flexibility and security to the system, UbiSmart counts with internal and external API which interacts with the Data and Knowledge Base. An internal DB is part of the MVC framework with full access to the DB. These routines are intended for software development and technician operations. An external APIs or EndPoint has limited access to the DB. It can only access specific methods and queries on the data and knowledge. They are intended for specific services.

Since information for each deployment has to be independent from the others, each deployment is hosted in a different cloud instance. It relies on a version control software (Git) for a quick and agile replication of the last version of UbiSmart in any machine.

Each UbiSmart Server contains a configuration file that is customized for each deployment. This file contains the main passwords to access the DB, the SSL certification with the specific name of the server (<NAME>.ubismart.org), the repository to access the reasoning, and the dedicated URL APIs to process specific data (*e.g.* FOS raw data) (Code 5.2).

```

var fs = require('fs');
module.exports = {
  appName: 'UbiSmart',
  port: process.env.PORT || 443,
  environment: process.env.NODE_ENV || 'development',
  connections: {
    postgresql: {
      user      : 'sails',
      password  : '<PASSWORD>',
      database  : 'ubidb'
    },
  },
  ssl: {
    key      : fs.readFileSync('ssl/selfsigned.key'),
    cert    : fs.readFileSync('ssl/selfsigned.cert')
  },
  mosca: {
    enabled: false,
    accounts: [{
      login: 'osgi',
      password: '<PASSWORD>'
    }, {
      login: 'ubisimu',
      password: '<PASSWORD>'
    }]
  },
  unixEnvironment: {
    username: '<USER>',
    serverName: '<SERVERNAME>'
  },
  bedServer: {
    bedServer: '<SERVER>.ubismart.org',
    bedUser: '<USER_BEDSERVER>',
    key: '<PATH_TO_KEY>'
  },
  ubi: {
    servicesRepository: '/home/<USER>/ubismart/ubi/services/repository/',
    n3: {
      n3filepath: '/home/<USER>/ubismart/ubi/core/kb/n3/',
    },
    debugFolder: '/home/<USER>/ubismart/debug/'
  },
  github: {
    sshKey: '/home/<USER>/.ssh/id_rsa'
  }
};

```

Code 5.2: Ubismart configuration File. The sensible informations have been hided for the sake of this manuscript

The server is not only a reasoning engine. It is also a web framework that responds to the stakeholder's needs. Therefore it is built as a friendly website where the user can interact with the backend and create a user profile, assign roles, create a space and assign a resident, etc. Later in this chapter, the procedure to use UbiSmart to discover and create knowledge is detailed. To show an example of the of the user interaction, Code 5.3 and 5.4 present the internal flow of information to create a user. Specifically, Code 5.3 represents the creation of a user role in UbiSmart. First, the method recovers the information arriving from the Service Provisioning (1). Second, the user is created in the UbiSmart DB (2), and finally, (3) if the user is an *Admin* a MQTT user is created for testing reason. Alternatively, Code 5.4 illustrates the flow sensor event that reaches the framework. First, the system listens on port 1883 the arrival on any MQTT message (1). When a message reaches UbiSmart, it goes through a JSON format checker (2). If the format is correct the event is stored in a queue *q* that handles every event chronologically. Third, the system recovers the sensors events and matches the MQTT topics in order to point the message to the correct endpoint (3). Appendix A includes UbiSmart code samples for a better understanding of the MVC implementation.

```
var uu = require('underscore');
var ubi = require('ubiutils');
var log = ubi.log('user_controller');
module.exports = {
  _config: {},
  create: function(req, res, next){
    1) var params = req.params.all();
    params.roles = {};
    2) User.create(params).exec(function(err, user) {
      if(!err) {
        var withAdmin = ((user.admin) ? " (admin)" : "");
        log.info("User created: "+user.username+withAdmin);
        // add Mosquito account for admin
        if(sails.config.mosca.enabled && user.admin)
          3) sails.mosca.addUser(user.username, req.param('password'), function(err){})
      }
      res.redirect("/user/edit/"+user.id);
    } else {
      res.serverError(err);
    }
  }); },
```

Code 5.3: Background routine creating a new user profile.

```
1)client.on('message', function (topic, message) {
// wait for ubi to be ready
2) if(ubi.json.isJSON(message)) {
  q.push({
    topic: topic,
    payload: message
  }, function(err) {});
} else {
```

```

        log.warn('MQTT message received is not json: ' + message);
        log.warn('MQTT message received is not json: ');
    }
});
3) var q = async.queue(function (packet, cb) {
    if(packet.topic === 'bedSensor') {
        var message = JSON.parse(packet.payload);
        var arr = /[^\]]+(?=)]/.exec(message);
        var messageBed = JSON.parse(arr[0]);
        messageBed.id = messageBed.id.replace(/:/g, "_");
        sails.controllers.sensor.sleepMatManager(packet.topic, messageBed);
    } else if(packet.topic === 'sgtest') {
        var messageBeacon = JSON.parse(packet.payload);
        sails.controllers.sensor.beaconManager(packet.topic, messageBeacon);
    } else if(packet.topic.search('owntracks') !== -1) {
        var messageBeacon = JSON.parse(packet.payload);
        sails.controllers.sensor.cityBeaconManager(packet.topic, messageBeacon);
    } else {
        log.debug('Published on topic ' + packet.topic + ': ' + packet.payload);
        route(packet.topic, packet.payload);
    }
    cb();
}, 1);

```

Code 5.4: Sensor event flow within UbiSmart. The MQTT message reaches the MQTT Broker and it is redirected to the specific Controller based on its topic.

### 5.3 Service Provisioning

Service provisioning of UbiSmart focuses on the inner human-machine interaction of the platform. Since the framework is service provisioning for the stakeholders, it is built the system as a participative and collaborative WebApp. This service structure is conceived as prototype extension that allows the access to the data through a limited APIs.

There are two main profiles charged to interact with the framework. Firstly, the Technician profile, who is allowed to access the framework status service (Fig.5-8(a)) which determining if any maintenance action is required. Secondly, the Consumer profile, who can access informative ADL and inference data services called On-Demand services. For administration and development purposes there is a third Admin role.

**Interaction with the Admin and Technician:** The services for the Consumer user are available on the cloud on a Git repository and can be installed on a deployment server by the Technician. The platform verifies the structure submitted and if it meets the requirements the service is instantaneously available to the user. Complementary, the service deletion must be done by an Admin profile.

**Interaction with the Consumer User:** The On-Demand services, which are typically a 24h service, show charts of all the house activities in real time. As an example *Life Service* shows the user activity within the home, Fig.5-8(b).

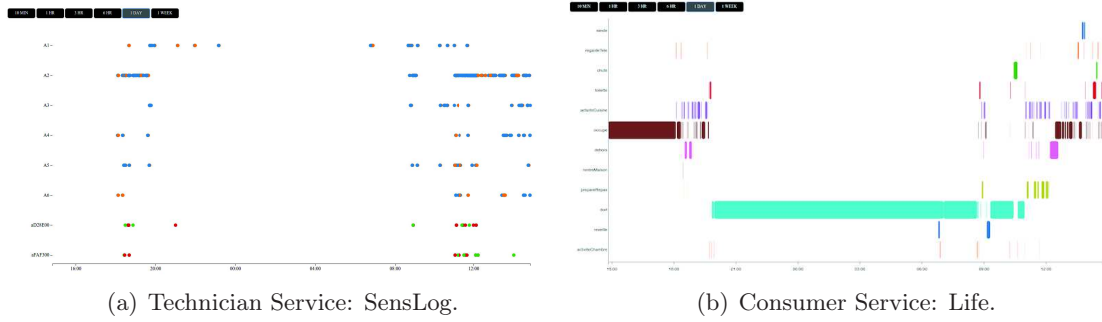


Figure 5-8: (a) Technician service showing the status of the sensors and (b) consumer service showing activity grant chart in real-time.

## 5.4 Discovering and Creating Semantic Knowledge

A key point in UbiSmart framework is its capability of discovering and creating semantic knowledge in a fast and simple manner. UbiSmart includes two semantic models in which the reality is expressed in machine language (N3). On the one hand, the *Abstract* model is common to all the deployments and is replicated to any UbiSmart instance deployed around any server. This model is built a priori and defines the relations between semantic classes, objects or instances which are used on the reasoning.

On the other hand, the *Instance* model define the singularities of each deployment. This model describes the resident for a given space. It also contains the number and disposition of the rooms in a given space, and the disposition and type of the sensors.

### 5.4.1 Building the Instance Model

The *Instance* model is built following four steps.

**First: Creation of the User Profile and his Environment** For this task, the user profile and the environment information are created by submitting the information through a simple form view. This action triggers the generation of a new *instance* model, and the inclusion of this information in the Knowledge Base (KB) is automatically done in the background.

**Second: UbiGate Discovery** The software embedded in the gateway is customized and optimized gathering and processing sensor data. Thus, when the gateway is plugged for the first time to the electricity and the Internet, it tries to connect to a specific public API of the UbiSmart Server through HTTPS protocol. This service listens to these requests and shows the information

in real time as shown in Figure 5-9. The end-user is then required to accept the connection and to pair the gateway with a specific environment. Once the gateway is included in the reasoning, UbiSmart creates the MQTT credentials for further communications automatically.



Figure 5-9: Registration request interface on UbiSmart website.

**Third: Context Discovery** It requires the minimal necessary information on the *Instance* model to run the inference engine, as shown in Figure 5-10. It gathers personal information and environment distribution: resident, caregiver, the number of pieces, connected objects. The proposed pieces and objects are loaded from the *abstract* model to keep a consistency in the declaration of variables. Second, the sensors discovery is automatic. Once a sensor is within the range of detection of UbiGate, it can be eligible for this space. The end-user can approve the sensors to use one by one and place them in the environment. *E.g.* sensor *A2* is a *motionSensor* placed in the *Toilet* or tablet *D1* placed in the *Bedroom*. Figure 5-10 illustrates this dedicated service to populate the *instance model* for each environment. The code sample 5.5 represents the automatic generation of the triples which will be integrated into the *Instance model*. The main objective of the Code is translating from the *Natural Language* provided in the form into a *Semantic Language* readable and exploited by the KB. The first action (1) creates a semantic triple for each room created in the web page and push it into a triples vector. In the same direction, the second action (2) translates each sensor information and push it in the same triple vector. Finally, the third action (3) updates the triple vector into the semantic *instance model* for the house *houseId* of the KB.

Figure 5-10: Space description interface.

```

// generate triples for rooms
1)_.each(pN3.rooms, function(room) {
    triples.push(['hom:'+room.name, 'rdf:type', 'qol:'+room.type]);
    triples.push(['hom:'+room.name, 'qol:partOf', 'hom:house']);
});
// generate triples for sensors
2) _.each(pN3.sensors, function(sensor) {
    var sensorUri = 'hom:'+sensor.id.toLowerCase();
    triples.push([sensorUri, 'rdf:type', 'hom:'+sensor.sensapp]);
    triples.push([sensorUri, 'qol:id', '"' + sensor.id + '"^^xsd:string']);
    var bindingPredicate = (sensor.bindingType === 'Room') ? 'deployedIn' : 'attachedTo';
    triples.push([sensorUri, 'qol:'+bindingPredicate, 'hom:'+sensor.binding]);
});
//Load triples into the KB
3)kb.store.addTriples(houseId, triples);

```

Code 5.5: Contextual Knowledge generation and inclusion in the KB through the HomeDesc service.

**Fourth: Urban Context Discovery** Called CityDesc, this services collects the localization of the BLE Beacons placed around the city and it labels each BLE beacon with a specific activity. CityDesc is a common DB containing the information of each BLE beacon that is related to the elderlies. The inclusion of the devices is done through a web page in UbiSmart. The view is a simple form that allows to declare a new City and opens a new view with three fields to be filled: the Beacon ID, which has to be the same than in the application; the place of interest where this device is located; the related activity that the system will detect when a person is located near by (see Figure 5-11 and Code 5.6). The Code illustrates the data flow when a BLE Beacon reaches UbiSmart. The message contains the *beaconId*, the *beaconValue*, and the *beaconHouse*. First the *beaconID* need to be matched on the *Beacon* DB (1). If there is a match it means that the beacon has been included in the DB (2), however, it can link to several environment and user at the same time. Therefore the *beaconHouse* is retrieved and matched on the *House* DB. Once the matching is done (3), the system links the *Beacon* message with an *Environment* and *User*. The method then formats a MQTT event and sends it to the UbiSmart *Event* Controller (4).

```

cityBeaconManager: function(topic, payload) {
if (payload._type == "transition" && payload.event == "enter") {
1)Citybeacon.findOne({beaconName: payload.desc}).exec(function(errorBeacon, beacon) {
if (errorBeacon) return log.error(errorBeacon);
2)if (beacon) {
var result = {}; result.date = new Date();
result.sensor = payload.desc; result.beaconId = payload.desc; result.value = 'on'; result
    .procedure = beacon.id;
result.type = 'beacon'; result.house = topic.split("/")[2];
3)if (result.house[0] == 'h') {

```



```

result.house = result.house.split("h")[1];
result.house = parseInt(result.house);
House.findOne({id: result.house}).exec(function(errorHouse, house) {
if (errorHouse) return log.error(errorHouse);
if(house) {
4)sails.controllers.event.create_mqtt(JSON.stringify(result));
} else {
log.debug("House #" + result.house + " is not found!");
} }); }
} else {
log.debug("Beacon " + payload.desc + " is not found!");
} }); } },

```

Code 5.6: Outdoors location definition at the server level

UbiSmart
Joaquim
Admin
My Spaces
My Services
Sign-out

### Configuration of the city : Singapore

#### Add Beacons

Add

#### Beacons

Beacon Name	Point of interest	Activity	
lbeacon-846382-0752-6182	62_Geylang_Barhu_HDB_Court	HDB_court	Delete
Handbag	ipalstaff	working_staffroom	Delete
Fridge	ipalpantry	resting	Delete
Bicycle	Bicycle	BicycleAvailable	Delete
Car	Car	CarAvailable	Delete
Scooter	Scooter	ScooterAvailable	Delete
BusStation	BusStation	BusStationAvailable	Delete

Figure 5-11: CityDesc service declaring outside locations

Once the device is declared, the system checks the incoming MQTT messages and checks if the ID of the BLE Beacon in the messages matches with declared BLE Beacons. If the device is unknown the system will discard the connection. Otherwise, the system retrieves the information from the Database and builds a sensor event according to UbiSmart structure. Code 5.7 presents the semantic inclusion of *Point of interest* and BLE Beacons. The Code shows the translation between *Natural Language* obtained from a web page into a semantic language to be sent to the KB. The first action performed in the method *resultOntology* (1) is the matching between the

*houses* from the view and the house in UbiSmartDB. If there exist a concordance the method *updateBeaconConfiguration* (2) is called. It manages the translation between the information entered on the web page and the creation of the entities with their objects and data links. Sub-methods *beaconConfiguration2triples* (2.1) and *cityConfiguration2triples* (2.2) are in charge of creating the triples for both, beacons and cities, and return that new data structure to the main thread.

```

resultOntology: function(cb) {
//Add beacon to ontology of all houses
1)House.find().exec(function(errorHouse, houses) {
    if(errorHouse) return log.error(errorHouse);
    async.eachSeries(_.each(houses), function(house, cb) {
        services.updateBeaconConfiguration(house.id, newBeacon, cb);
    }, cb); });
2)var updateBeaconConfiguration = function(house.id, newBeacon, cb) {
    2.1)beaconConfiguration2triples = function(newBeacon, cb) {
        var triples = [];
        var sensorUri = 'hom:sensor_'+newBeacon.beaconName.toLowerCase();
        triples.push([sensorUri, 'rdf:type', 'hom:BeaconSensor']);
        triples.push([sensorUri, 'qol:id', ''+newBeacon.beaconName+'^^xsd:string']);
        triples.push(['hom:'+newBeacon.pointOfInterest, 'rdf:type', 'qol:PointOfInterest
    ']);
        triples.push(['hom:'+newBeacon.inferredActivity, 'rdf:type', 'qol:Activity']);
        triples.push(['hom:'+newBeacon.inferredActivity, 'rdfs:label', ''+newBeacon.
inferredActivity+'@en']);
        triples.push(['hom:'+newBeacon.inferredActivity, 'rdfs:label', ''+newBeacon.
inferredActivity+'@fr']);
        triples.push([sensorUri, 'qol:deployedIn', 'hom:'+newBeacon.pointOfInterest]);
        triples.push(['hom: johndoe', 'qol:goesTo', 'hom:'+newBeacon.pointOfInterest]);
        triples.push(['hom:'+newBeacon.pointOfInterest, 'qol:isAssociatedTo', 'hom:'+
newBeacon.inferredActivity]);
        cb(null, _.map(triples, function(triple) {
            return {
                subject: triple[0], predicate: triple[1], object: triple[2]
            }; })); };
    2.2)cityConfiguration2triples= function(cityName, cb) {
        var triples = [];
        triples.push(['hom:'+cityName.toLowerCase(), 'rdf:type', 'qol:City']);
        cb(null, _.map(triples, function(triple) {
            return {
                subject: triple[0],
                predicate: triple[1],
                object: triple[2]
            }; })); };
    ...
}

```

Code 5.7: Outdoors Location Semantic Integration. BLE Beacons and points of interest semantic integration.

## 5.5 UbiGate and UbiTracks

UbiGate and UbiTracks are the gateways used to received and forward the sensor events to the cloud. UbiGate is the indoor gateway which collects data from motion, contact (X10 & Zwave) and the fiber optic sensors FOS. On the other hand, UbiTracks is the outdoor gateway. It is built as a mobile App. It interacts with the BLE Beacons and collects the raw data coming from the inner mobile sensors.

### 5.5.1 UbiGate

UbiGate is a gateway, which has been continuously evolved from the beginning of the project to support interaction with different sensors. The sensor-gateway communication is done by an adapted code plug-in. Following, I detail the four steps to be performed at the UbiGate level to tackle large-scale and distant deployments.

#### Install UbiGate

The gateway runs on default operating system is installed on the gateway (for the deployment: Raspbian, the most widespread Linux distribution for Raspberry Pi). A serial provisioning code is run through SSH connection. As a final step to be performed off-site, Sensors & Actuators have to be prepared (*e.g.* placing batteries, setting up unique code). Sensor & Actuators receiver modules also have to be plugged into the gateway.

A guided installation along with a script automatize the setup of the operating system on gateways. It uses a provisioning tool automatize the installation of the gateway modules on the operating system, *Ansible*<sup>2</sup>. It is a free provisioning and application deployment platform. There are a number of alternatives to *Ansible* for software management such as *Nomad* or *Kubernetes*. Comparing *Ansible* to *Nomad* results that *Ansible* reports a higher number of companies adopting the solution, a bigger community and bigger integrations with others software. Comparing to *Kubernetes* results more difficult to choose one solution among the other. However, *Ansible* has an out of the shell integration with *Digital Ocean*, so the deployment and the interaction between Gateway and Server are easily integrated.

*Ansible* includes playbooks<sup>3</sup> that allow to configure and automatize the installation of the different modules. It also handles parallel installation and deployment process on multiple gateways. With the same methodology *Ansible* is linked to a Github account that handles the software updates. A daily software job (*Cronjob*) is setup to automatically check the version of the code and update it.

Once a gateway is deployed, it only has the IP address of the framework's server, while the

---

<sup>2</sup><http://www.ansible.com>

<sup>3</sup><http://docs.ansible.com/ansible/playbooks.html>

framework doesn't have any information about the gateway. Since the gateway configuration file doesn't have the information needed to exchange with the framework on switch-on, the gateway uses a secured communication protocol (HTTPS) to send basic information (*e.g.* mac address and local IP address) to the server and ask for registration in the framework.

The registration request is sent repetitively until approval by an installer (e.g., end-user, technician) through a dedicated user interface. Once approved, a virtual AmI space is generated in the framework and linked to the newly approved gateway. The framework therefore generates and sends credentials to the gateway. The configuration file contains the ID and the name associated with the gateway. It also has a blank list of sensors which will be updated progressively upon detection, approval, and integration of new sensors into the framework.

## Deploy UbiGate

To deploy is as to be plugged-in the gateway to an electric source and the sensors placed in the environment. Then, it is necessary to set up the final configurations with the deployment server URL. To do so, the technician edits the UbiGate.service by changing <SERVERNAME> by the name of the server for the given deployment (Code 5.8).

```
#ubigate service
[Unit]
Description=Run ubigate as a Daemon
After=syslog.target network.target
[Service]
ExecStart=/bin/bash -c 'ubigate -s https://<SERVERNAME>.ubismart.org -L debug -l info --
    no-verify-ssl'
Restart=on-failure
RestartSec=5
[Install]
WantedBy=multi-user.target
```

Code 5.8: UbiGate server subscription.

## Configure UbiGate

At the gateway discovery service, the server generates a unique and random identifier that is sent through HTTPS to UbiGate: *credentials.json*. At the home description level the server generates a configuration file which contains the identifier, location and type for each sensor: *config.json* (see Code 5.9). The user is able to acknowledge the existence and location of any sensor. Also, any sensor can be blacklisted to prevent the gateway from listening to it. Figure 5-12 summarizes the automated discovery and recognition protocol between the gateway and the server.

The registration request is sent repetitively until approval by an installer (e.g., end-user, technician) through a dedicated user interface. Once approved, a virtual AmI space is generated in

the framework and linked to the newly approved gateway. The framework therefore generates and sends credentials to the gateway. The configuration file contains the ID and the name associated with the gateway. It also has a blank list of sensors which will be updated progressively upon detection, approval, and integration of new sensors into the framework.

Part of the configuration concerns the sensors plugged and registered for that gateway. Gateway keeps list of sensors it received messages from. Sensors can either be registered, new or blacklisted. Registered sensor events are sent to the server for processing (activity recognition and service provisioning). Blacklisted sensor events are ignored. New sensors events are sent for registration to the server on a dedicated handler which records and broadcasts the event for the space linked to the gateway. A configuration interface (for technicians now, and users in the long term) allows the description of a given space and the approval or blacklisting of sensor registrations received previously (record) or in real time (broadcast). This interface also serves to describe the bindings between the sensors and the space.

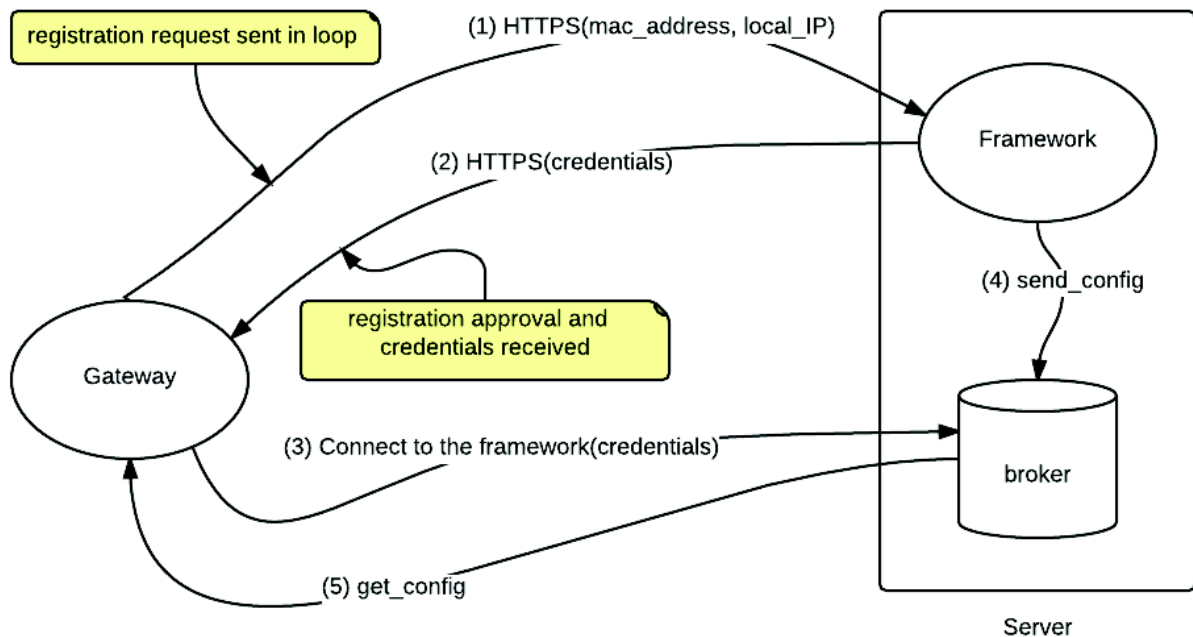


Figure 5-12: Gateway-Server discovery protocol.

```

Credentials.json
{"username": "gateway_<GATEWAY_ID>", "password": <PASSWORD>, "id": 101, "server": "<
  SERVER>.ubismart.org", "port": 1883}
config.json
{"houses": [{"id": "<ID>", "name": "<NAME>", "sensors": [{"id": "<sensorCode>", "binding
  ": "<locationOfTheSensor>"}]}], "blacklist": ["<ID1>", "<ID2>", ..., "<IDn>"]}

```

Code 5.9: Ubigate config and credential file recieved from te ubismart server.

## Maintain UbiGate

Some maintenance activities that have been automatized at UbiGate level. First, the system allows the access to its inner source code with a permanent SSH session. This also allows to check the availability and status of UbiGate at anytime. This service is also coded as a daemon that permanently sends SSH request to a dedicated server.

The second strategy to maintain the gateway is to use a daemon that checks the status of the Git server with the last version of the code. UbiGate checks daily if the unique identifier of his code version matches with the last version of the Git repository. In case there has been an update the service updates and reboots the device. A list of actions to fix possible errors are listed below:

### **Software upgrade:**

Every 24 hours, the gateways make a request on the UbiGate Git remote repository, looking for updates. If the developer has indeed edited the repository, the gateways will download the new file, and upgrade itself automatically, with no need for human intervention.

### **An error occurs that can be fixed automatically:**

If the error can be fixed automatically (*e.g.* by restarting a service), it will be done. The solution may either come locally from the gateway's own procedures or use remote procedures from the monitoring system.

### **An error occurs that can be fixed remotely by a human:**

If the error cannot be fixed automatically, the technician will remotely log-in to the gateway using the remote access procedure, and solve the problem manually.

### **An error occurs that requires a physical human intervention:**

In case the technician cannot fix the problem remotely (*e.g.* connection lost, hardware problem), he/she will duplicate the faulty system, move on-site, and replace the faulty system by the new one.

## **5.5.2 Sensors Plug-ins**

The system is agnostic to any type of hardware, and new devices can be integrated with minor software developments. UbiGate deals with different type of motion and contact sensors, X10 (Mochad) and Zwave, and FOS sensor. The first version of UbiGate only interacted with X10 and later Zwave and FOS were included, new plug-ins were needed.

### **X10 - Mochad**

UbiGate includes a plug-in which converts the information from the X10 sensors into a sensor event. The plug-in converts the raw data from X10 sensors into a sensors events. These are

pushed into an output vector that sends the events to the server through MQTT protocol. This plug-in is exclusive for X10 sensors.

## Zwave - Domoticz

To have maximum interoperability with different hardware the Domoticz Open-Source framework is included in the UbiGate. Domoticz<sup>4</sup> is a Home Automation system designed to control various devices and receive input from various sensors. It is a multi-platform open source framework that offers a friendly user interface to handle numerous types of sensors. It also disposes of communication layers to use any web services to send the data to the cloud. Figure 5-13 illustrates the user interface provided by Domoticz framework. Figure 5-13(a) list the Zwave sensors included in the receiver, and Figure 5-13(b) define the type of sensors included in the receiver.

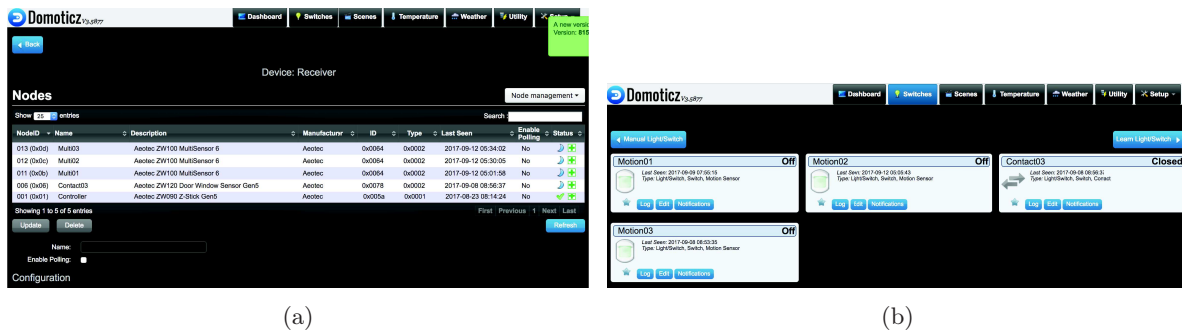


Figure 5-13: Domoticz Framework inclusion and adaption.

Z-wave sensors need an initial configuration to be included in the receiver and the platform. Domoticz allows to do it through its interface. The sensors send the information to the receiver plugged into Domoticz. The framework converts the information into a sensor event and sends the information to the UbiGate main process, which puts the event in the same queue than any other hardware. This approach allows to handle X10 and Zwave technologies in the same deployment and increases the flexibility of the system.

## Fiber Optic Sensor

The FOS equipment is considered as another sensor that contributes to the KB of the AAL platform. The FOS processing unit is wired to the *Gateway* (Raspberry Pi). Voluminous raw data is read and stored on a micro SD-card for a deeper off-line analysis. Simultaneously, the data is preprocessed to generate high level events, such as *bed empty*, *bed motion*, *sleep*. It currently operates on a time window of 10 seconds. For each time window an event is produced. The events are then sent to the *Server* as a structured sensor data using MQTT protocol over an Internet connection [17].

<sup>4</sup><http://www.domoticz.com/DomoticzManual.pdf>

**Fiber Optic Data Processing:** The sleep data is stored in 5-minutes chunks on a Micro SD-Card embedded in the processing unit. Then it is sent to a cloud-based server for data processing. Subsequently, the resident bed state is determined using a sliding window  $w$  with a size of 1500 samples, *i.e.* 30 seconds. Thereafter, three bed-states are recognized, as illustrated in Figure 5-14: if the standard deviation (SD) of the window is greater than 0.7 of the mean SD of all windows, the status is considered as *bed motion*: if the SD of the window is smaller than a predetermined threshold, the status is regarded as *bed empty*: and finally, in other cases, the state is identified as a *sleep*. Code 5.10 summarizes the bed state data processing. The code computes the mean and the standard deviation of the optical signal and it is able to determine if the user is on the bed with or without sleeping. The heart rate is computed in beats per minute and the respiratory rate is computed in breaths per minute using a sliding time window of a size 20 seconds, as introduced in [151, 153].

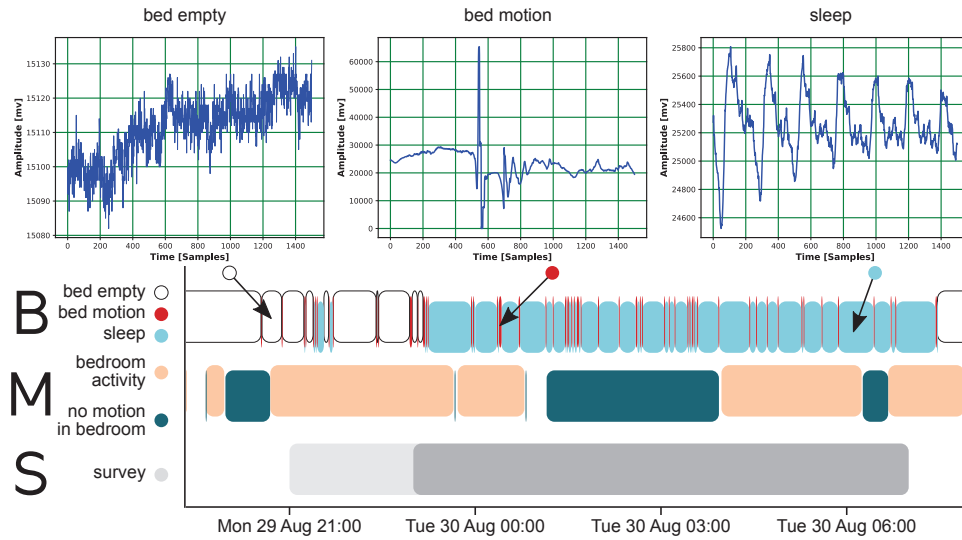


Figure 5-14: FOS data processing implementation. Representation of a participant's night from our real life deployment. Three typical signal shapes are labeled according to recognized conditions: *bed empty*, *bed motion*, *sleep*. Gantt diagram: *B* is the result of the signal processing from the bed sensor. *M* shows a very inaccurate detection using motion sensors (blank space indicates activity detection in other rooms out of scope). *S* indicates the participant's answer in the survey table 6.8 about their waking and sleeping habits.

```

Require W = {w_{1}, w_{2}, ... , w_{N}}, T = 10$
For() i = 1, ... , N$
    Compute S(i) = SD(w_{i})
EndFor
For() j = 1, ... , N
    If{SD(w_{j})} > 0.7*M
        State = bed_motion
    ElseIf(SD(w_{j}) < T)
        State = bed_empty
    Else
        State = sleep
    EndIf
EndFor

```



**Sleep Monitoring - Knowledge Base Inclusion:** The server handles the received structured information (event) and creates a new bed sensor entity that will appear in the *home description* interface as available for association to a house. If confirmed, this association is stored in the KB. Any subsequent events are then inserted into the KB of the associated house, allowing the reasoning engine to be aware of the bed occupancy with respect to the ontology (Code 5.15). Coupled with the information from other sensors and sources, it provides an accurate contextual information. In parallel, the raw data is processed every 5 minutes to extract information about the occupant's respiratory effort and heart rate. This information is also inserted into the KB. The Code 5.15 list the semantic description of the sleep monitoring. First the *Abstract* model defined by classes (*rdf:type*), the objects properties (*qol:locatedIn*, *qol:hasPossibleState*), and the datatypes properties (*qol:hasValue*, *qol:indicateSleep*). It presents the *instance* model completed by the Service Provisioning. It contains the *qol:id*, the type of sensor (*qol:Sensor*, *hom:SleepMatSensor*). It presents the real-time processing of the activity inference rule and the activity output (*qol:believedToDo*).

```
## Workspace definition ##
@prefix rdf:      <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
@prefix qol:      <http://www.ubismart.org/n3/qol-model#>.
@prefix hom:      <http://www.ubismart.org/n3/home#>.

## ABSTRACT MODEL##
hom:bed rdf:type qol:Object.
hom:sleep rdf:type qol:Activity.
hom:bed qol:locatedIn hom:house.
_:b1 qol:hasValue "bed_empty".
_:b2 qol:hasValue "bed_motion".
_:b2 qol:hasValue "sleep";
_:b2 qol:indicateSleep "true"^^xsd:boolean.
hom:SleepMatSensor qol:hasPossibleState _:b1.
hom:SleepMatSensor qol:hasPossibleState _:b2.

## INSTANCE MODEL##
hom:sensor_sleepmac_b8_27_eb_10_1c_79 qol:id "sleepMac_b8_27_eb_10_1c_79".
hom:sensor_sleepmac_b8_27_eb_10_1c_79 rdf:type qol:Sensor.
hom:sensor_sleepmac_b8_27_eb_10_1c_79 rdf:type hom:SleepMatSensor.
hom:sensor_sleepmac_b8_27_eb_10_1c_79 qol:attachedTo hom:bed.
hom:sensor_sleepmac_b8_27_eb_10_1c_79 qol:locatedIn hom:house.

## INFERENCE RULE ##
{?se qol:hasLastUpdate true. ?se qol:indicateSleep true. ?se qol:attachedTo ?b. ?b a qol:
  Bed.}
=> {hom:user qol:believedToDo hom:sleepOnBed}.

## ACTIVITY ##
hom:sensor_sleepmac_b8_27_eb_10_1c_79 qol:hasValue "sleep".
hom:user qol:believedToDo hom:sleepOnBed.
```

---

Code 5.11: Simplified sample of the knowledge base in *Notation3* – sleep monitoring model featuring basic ontology, rule, instantiation and conclusions. (Note that not all the objects have been declared in the code sample).

### 5.5.3 UbiTracks

The user location is obtained from BLE Beacons, as small low-powered devices that emit a specific signal repeatedly, which are quickly expanding. BLE Beacons have a very high potential in activity tracking. The other technology that could be used for this task is GPS. It gives a good overview of all-day itinerary, although some segments are usually very inaccurate (zigzag pattern), therefore a path filtering is needed. Moreover, this feature rises concerns about the privacy of the tracked person. Additionally, GPS is very battery-intensive. Cellular network localization (*e.g.* GSM) is an alternative option. However, even if the energy footprint is lower and its availability is broader, resolution is very poor and depends on fixed stations positions.

Beacons must be physically placed in the environment and provide information about presence or absence of the receiver within a certain radius. They are easy to deploy (size, device simplicity, market availability) and they operate well with current smartphones equipped with Bluetooth technology. As a downside, the signal detection on the receiver side may have an important energetic impact and smart strategies for resource management might be needed.

For this use-case of activity tracking, a set of points of interest are defined. These are public places where people usually attend: supermarket, food centers, daily activity centers, parks, etc. Furthermore, smart cities projects (*e. g.* Montpellier) tend to deploy this technology so in these cases, Beacons are already available in the environment. Having Beacons in places of interest provides a general overview of the tracked people’s activity and mobility on the urban level, while keeping the privacy intrusion on a very low level as only selected well-known places are detected. In addition, the integration in UbiSmart is flexible to allow the personalization of the interpretation of the Beacon’s proximity, or even completely disable the detection of any subset.

The implementation section is divided into two parts. First the implementation in UbiSmart platform of the dedicated service to position and recognize outdoor Beacons. Second the implementation and deployment of the App to collect mobility data, and the training of the proposed mobility classifier.

### Location Detection

The location detection with BLE Beacons is a client-server communication. UbiSmart acts a server with a dedicated service that allows to declare the Beacons. On the other side, the client

side is a dedicated mobile App, which recognizes the declared Beacons and sends the information through the MQTT protocol.

The first version of the Beacon App was developed completely by the team. The application uses the smartphone Bluetooth sensors to detect and broadcast any Beacon detected around the phone. The device acts as a broadcast proxy and the server was in charge of recognizing and interpreting the interaction.

However, this first version was not prepared for the smartcities paradigm. As it is expected in the coming years, cities will use this sensing technologies all around the city for multiple objectives. This fact may exponentially increment the information flow and it will certainly impact on the server performance (handling too many unrelated messages) and on the phone battery.

For this reason, the second version of the App relies on the Open Source project OwnTracks [122]. This is an Android and IOs App that allows to declare interest Beacons and to limit the interaction to known devices. This App reduces the number of messages and allows for the customization of each Beacon device. Moreover, as an open source project other features and usability, User Experience (UX) and the optimization of the battery are ensured by the community contributions.

The main feature of this App is the automatic detection of near BLE devices and the custom labels for each accepted device. It also communicates through MQTT protocol to UbiSmart. The activity and location inference is then, handled by the server instance. The Beacons discovery can be done a priori, so that the sequence remains transparent for the end user with no direct impact upon him.

## Mobility Classification

To detect the user motion pattern, an activity classifier from the smartphone inner sensors was trained. The mobility model is a classifier that distinguishes between activities, depending on the temporal evolution of the smartphone sensors. Code sample 5.12 list the type of data collected from the device sensors. Activity 'Nothing' has been also recorded to be able to detect moments of inactivity. The aim is to discriminate static activities that could add bias and noise to our classifier.

To obtains the training data, 4 volunteers recorded their motion activity through an App developed by the team. To start a tracking the user labels the type of motion. then, the App stores the sensors data into a local DB when there's a new reading for all of them, or every second at most. If one second passes before receiving new values for some of the sensors. The missing values are replaced with nulls. Example of such records is shown in Code 5.12.

```
_id, timestamp, label, latitude, longitude, speed, location_provider,  
location_elapsed_time, android.sensor.gyroscope, android.sensor.
```

```

gyroscope_uncalibrated, android.sensor.gravity, android.sensor.accelerometer, android
.sensor.linear_acceleration, android.sensor.magnetic_field, android.sensor.
magnetic_field_uncalibrated, android.sensor.rotation_vector, android.sensor.
geomagnetic_rotation_vector
14, 372995164198180, Walk, 1.3122463, 103.7950039, 1.34, fused, 770019186069222,
-2.7261353;-0.59477234;0.4584198,
-2.749237;-0.5873108;0.43417358;-0.023101807;0.007461548;-0.024246216,
-1.8542471;-8.485359;-4.553113, -1.4540558;-6.732193;0.7741089,
-0.11951113;-1.0813999;4.9288964, 13.171387;-62.776184;29.301453,
-31.332397;-92.47742;-38.606262;-44.503784;-29.701233;-67.907715,
-0.740267;-0.42912582;0.34916484;0.38202062;3.1415927,
-0.69039387;-0.18713912;0.24806073;0.65330017;3.1415927
15, 372999009673543, Walk, 1.3122264, 103.7950505, 1.35, fused, 770022973585523,
1.836731;0.586853;-0.010864258,
1.8136292;0.5943146;-0.035110474;-0.023101807;0.007461548;-0.024246216,
-1.2714756;-8.654573;4.4330683, -0.80267334;-12.904404;-3.22435,
1.198271;-2.0042658;-6.566405, 22.247314;-55.249023;33.506775,
-22.25647;-84.95026;-34.40094;-44.503784;-29.701233;-67.907715,
-0.46306577;-0.24402152;0.5025845;0.6880642;3.1415927,
-0.7181905;-0.1767835;0.197897;0.6432626;3.1415927
16, 373003064980260, Walk, 1.3121916, 103.7950886, 1.37, fused, 770026989610052,
1.4004364;0.49421692;0.22825623,
1.3773346;0.50167847;0.20401001;-0.023101807;0.007461548;-0.024246216,
-0.59025073;-9.482084;2.4314744, -1.4987335;-12.964371;-4.549118,
-0.49818528;0.73143387;-3.6257346, 25.239563;-51.812744;32.266235,
-19.264221;-81.51398;-35.64148;-44.503784;-29.701233;-67.907715,
-0.5064052;-0.34580794;0.48512554;0.62339705;3.1415927,
-0.70392084;-0.21917605;0.26190892;0.6227849;3.1415927

```

Code 5.12: Sample of data collected into the DB in comma-separated format. Note that some fields contain multiple components separated by a semicolon. The data is a part of the activity *Walk*.

Table 5.2: Data points collection generated per user and activity for mobility classification.

Activity	User 1	User 2	User 3	User 4
<b>Walk</b>	7393	986	10484	0
<b>Bike</b>	3919	513	0	6500
<b>MRT</b>	1933	2401	1801	0
<b>Bus</b>	365	1992	636	0
<b>Car</b>	727	479	8836	8177
<b>Nothing</b>	1860	869	0	0
<b>Total</b>	16197	7240	21757	8177

After a tracking session is finished, the generated DB is exported as a comma separated value (CSV) file to the phone's storage. A button on the main screen was added to upload the exported files to one of our servers. This allowed the users to collect their daily activities, in real conditions, and send them to us easily.

To clean and process the data a Python environment with Pandas (0.17.1), Numpy (1.8.0rc1)

and matplotlib (1.3.1) is used. Specifically for the model training the scikit-learn library is used. It is a Python module for machine learning built on top of SciPy and distributed under the 3-Clause BSD license [129]. In code 5.13 the data cleaning in order to remove null values and the noise added at the beginning and the end of each recording is illustrated. As the data collection is not performed with the personal smartphone, some inconsistencies were found for the sensors availability. If any of the requested sensors are not available the code modify this entry by adding a *NaN* value. The obtained dataset was splitted in columns by a CSV method (*splitfun*) and every number is converted to integers (*getIthNumber*).

```
def splitfun(x):
    if (type(x) == str):
        return x.split(";")
    elif (pd.isnull(x)):
        return [""]
    else:
        raise Exception("Cannot split this value")
def getIthNumber(x, i):
    if len(x) > i:
        return pd.to_numeric(x[i])
    return None
def add_multidimensional_columns(df):
    try:multidimensional_columns = [c for c in df.columns if df[c].dtype == 'object' and
    'android.sensor' in c and (len(df[c].iloc[df[c].first_valid_index()].split(';')) > 1)
    ]
    for multicol in multidimensional_columns:
        try:
            list_col = df[multicol].apply(splitfun)
            num_axis = len(list_col.iloc[0])
            axis_names = ['x', 'y', 'z', 'x2', 'y2', 'z2']
            for i in range(num_axis):
                df[multicol + '_' + axis_names[i]] = list_col.apply(lambda x:
get_ith_number(x, i))
            except Exception as e: raise(e)
        except Exception as e: raise(e)
```

Code 5.13: Data cleaning sample to remove null values, homogenize types of values and add one column for each dimension of the multidimensional sensors.

Using the ActiTrack around 56 500 data points provided by 4 participants were collected (see Table 5.2). Due to the variety of devices used, null values were accepted if sensor not recorded 5.13.

Since ground-truth labels are available, a supervised machine learning model is used to train the activity classifier. Five classifiers has been tested: Gaussian Naive Bayes (NGB), Discriminant Analysis, both linear LDA and quadratic (QDA), *K*-Nearest Neighbors (KNN), and Support Vector Machines (SVM).

A features correlation study and a Principal Component Analysis (PCA) were performed.

The correlation matrix highlights that calibrated and calibrated sensors are highly correlated, Figure 5-15(a). The PCA illustrates that 20% of the variance is related to the first component, Figure 5-15(b). However, the variance curve converges slowly. Thus, even if the NGB should perform well, a priori, for small, it can be expected to report low results due to the results of the correlation and PCA. Chapter 6 presents detailed results and performances for each classifier.

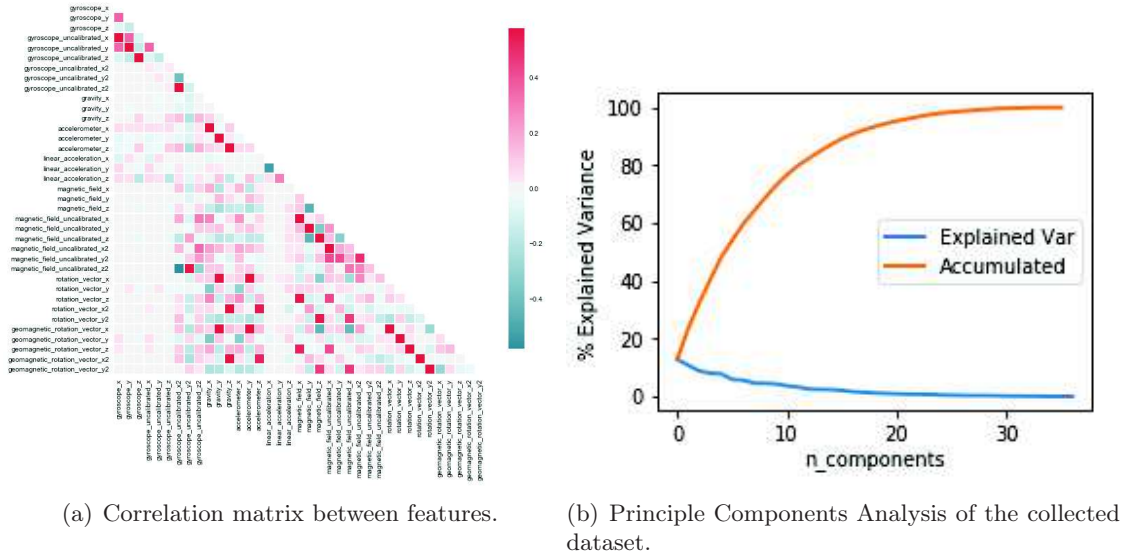


Figure 5-15: Figure (a) shows that calibrated and uncalibrated features are highly correlated. Figure (b) shows that the learning curve converges slowly. The first ten components hold 80% of the data variance.

### 5.5.4 OpenData Integration

Taking advantage of the connectivity of the server and the exponential increase of available data on the net, UbiSmart interacts with an open data APIs. The principle aim is to collect new types of data that the system is not intended to collect but which could impact in the reasoning, such as weather, contamination, air quality, disease spread... UbiSmart interacts with the national environmental agency of Singapore following an Open APIs as presented in the Code 5.14. The Code represents a snippet of the code included in a UbiSmart Controller collecting information from a public APIs. The connection is performed by an NPM package that provides an authentication token. The request uses an HTTPS GET method native in the REST framework. The responds contains real-time values in JSON format that are included in the KB *Instance* model for a given user *N*.

```
var ubi= require('ubiutils'); var mail= require('.././ubi/services/notifiers/mail');
var log= ubi.log('openDataController'); var xml2js= require('xml2js');var parser= new xml2js.Parser();
var sms= require('.././ubi/services/notifiers/sms'); var request= require('request');
var API= require('sg-gov-nea/'); var lib= require('sg-gov-nea/sg-gov-nea.js');
var api= new API(new lib.sg.gov.nea.APIConfig({key: <KEY_TOKEN>}));

module.exports = {
  airPollution2: function(req, res, next){
    request('http://api.nea.gov.sg/api/WebAPI/?dataset=pm2.5_update&keyref=<KEY_TOKEN>',
```

```

function (error, response, body) {
  if (!error && response.statusCode == 200) {
    parser.parseString(body, function (err, result) {
      cb(error, result);
    });
  } else cb();
};
\\ SERVER RESPONSE
"air": {"channel": {"title": ["PM2.5 Update"],"source": ["Airviro"],"item": [{"region": [{"id": ["rNO"],"
latitude": ["1.41803"],"longitude": ["103.82000"],"record": [{"$: {"timestamp": "20170921120000"},"
reading": [{"$: {"type": "PM25_RGN_1HR","value": "6"}}]}]}],

```

Code 5.14: OpenData data request API.

## 5.6 Frailty Implementation within UbiSmart

The frailty model is included in the framework under an ontology implementation, which allows the interaction with the rest of UbiSmart functionalities. This exchange of information allows the model to quantify the level of each frailty item and compare it to its time evolution.

### 5.6.1 Frailty Model Technical Implementation

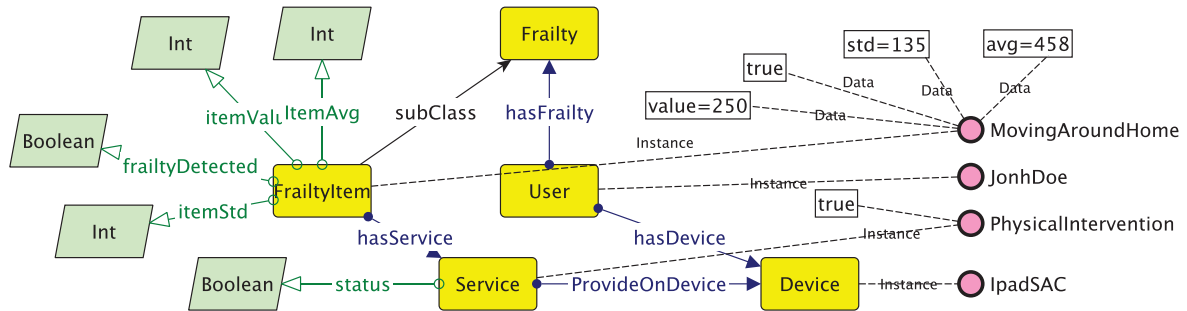


Figure 5-16: Abstract and Instance model of the ontology representing the frailty of the user. This model is replicated for each indicator. Each frailty item contains its main values to be able to track the evolution of the frailty.

The model adopts an ontological model based on Aloulou *et al.* [8]. Specifically, the frailty ontology is composed of a *Frailty* class having *FrailtyItem* class as a subclass. Each item is characterized by several data properties, representing value, mean, standard deviation and status indicating the presence of the frailty. Moreover, each item is linked to a dedicated service. The ontology implementation is presented Code sample 5.15 in N3 language. The code represents a part of the KB focused on the semantic definition of the frailty *Abstract* model. There are several classes representing the *User*, framework *Service*, output *Device*, and *Frailty* model and a sub-class of frailty for the *frailtyItems*. Each entity is link to another one through the objects *hasFrailty*, *hasService*, *ProvidedOnDevice* and *hasDevice*. Those links are represented in the picture figure

5-16. Finally, the instantiation for each *frailtyItem* is represented in the *Datatype Properties*. the entities *itemValue*, *itemAvg*, *itemStd* model the frailty status, the entity *frailtyDetected* is a boolean representing the existence of abnormal values for this item, and *status* represent the activation value for the associated service of this item.

```
## FRAILTY MODEL IMPLEMENTATION ##
## Workspace definition ##
@prefix rdfs:<http://www.w3.org/2000/01/rdf-schema#>.
@prefix qol:<http://www.ubismart.org/n3/qol-model#>.

## CLASSES ##
qol:User a rdfs:Class.
qol:Service a rdfs:Class.
qol:Frailty a rdfs:Class.
qol:frailtyItem a rdfs:Class;
rdfs:subClassOf qol:Frailty.
qol:Device a rdfs:Class.

## OBJECT PROPERTIES ##
# Link between an User and his frailty profile #
qol:hasFrailty a rdf:ObjectProperty;
rdfs:domain qol:User;
rdfs:range qol:Frailty.
# Link between frailty items and frailty services #
qol:hasService a rdf:ObjectProperty;
rdfs:domain qol:frailtyItem;
rdfs:range qol:Service.
# Link between frailty service and available devices #
qol:ProvidedOnDevice a rdf:ObjectProperty;
rdfs:domain qol:Service;
rdfs:range qol:Device.
# Link between user and his/her available devices #
qol:hasDevice a rdf:ObjectProperty;
rdfs:domain qol:User;
rdfs:range qol:Device.

## DATATYPE PROPERTIES ##
# Daily value for this frailty item #
qol:itemValue a rdf:DatatypeProperty;
rdfs:domain qol:frailtyItem;
rdfs:range xsd:integer.
# Flag activating frailty service #
qol:frailtyDetected a rdf:DatatypeProperty;
rdfs:domain qol:frailtyItem;
rdfs:range xsd:boolean.
# Average value for this frailty item #
qol:itemAvg a rdf:DatatypeProperty;
rdfs:domain qol:frailtyItem;
rdfs:range xsd:integer.
# Standard deviation for this frailty item #
```



```

qol:itemStd a rdf:DatatypeProperty;
rdfs:domain qol:frailtyItem;
rdfs:range xsd:integer.
# Status of frailty service #
qol:status a rdf:DatatypeProperty;
rdfs:domain qol:Service;
rdfs:range xsd:boolean.

```

Code 5.15: Implementation of the frailty model in notation3. (Note that not all the UbiSmart objects have been declared in the code sample).

The daily computation of the frailty items is performed as an UbiSmart micro-service. The computation is based on the sensors events raw data and the ADL inference. Some items are based on occurrences (*Toileting*, *Moving Around Home*, etc) and others are based on temporal evolution (*Sleep Time*, *Consciousness*, etc). Appendix C presents the codes samples for the items. As an example, Code 5.16 presents some item computation. It is a python snippet that includes several methods. It samples the data per day starting from 10 am and computes the amount of events generated in the environment when the user is alone (*getMovingAroundHome*), it also infers the time outside spend by the user based on the inactivity within the environment (*OutsideTimeEstimator*). The last two methods compute the amount of occurrences and accumulated time per day of toilet activity (*toiletDurationEstimator* & *toiletCountEstimator*).

```

##getMovingAroundHome Item##
def getMovingAroundHome(events, user=None):
    if user is not None:
        return events.loc[user].resample('24h', base=10)['id'].count()
    else:
        return events.resample('24h', base=10)['id'].count()

##OutsideTimeEstimator##
def OutsideTimeEstimator(activities, user=None):
    outside = my_day[my_day.activity == "Go Out"]
    time_spend_outside = outside.reset_index().apply(lambda x: x.date - x.since, axis=1)
    if time_spend_outside.empty:
        return timedelta(seconds=0)
    return time_spend_outside.sum()

##toiletDurationEstimator##
def toiletDurationEstimator(activities, user=None):
    outside = my_day[my_day.activity == "Go Toilet"]
    time_spend_outside = outside.reset_index().apply(lambda x: x.date - x.since, axis=1)
    if time_spend_outside.empty:
        return timedelta(seconds=0)
    return time_spend_outside.sum()

##toiletCountEstimator##
def toiletCountEstimator(activities, user=None):
    outside = my_day[my_day.activity == "Go Toilet"]

```

```
return outside.count()
```

Code 5.16: Examples of frailty items computation for human modeling.

## 5.7 Discussion

There are four main technical contributions in this thesis, whose implementation has been described in detail in this chapter: first, the inclusion of further sensors (FOS, BLE Beacons); second, the automation of the processes to speed up the deployments; third, the simplification of the interaction between the end-user and the KB; and fourth, the inclusion of the mobility and frailty models in the framework.

For a more robust and compatible framework, industrial and commercial sensor devices are chosen over prototyping. Such sensors include the gateway with motion and contact sensors for the indoor recognition, the FOS for sleep monitoring, and BLE Beacons and smartphone for outdoors tracking. For major compatibility between devices, the indoor gateway, UbiGate, has been coded in Python language over a Linux layer. Each type of sensor has its specific Python plug-in which handles the conversion of raw data (signal) into a sensor event. To allow the system to keep tracking the chronology of the events and recover the information if the connexion is momentarily unavailable, the main UbiGate code thread includes every sensor event into a single vector queue and sends them one by one in chronological order when the Internet connection is available. The outdoor gateway, UbiTracks, is based on an existent open source mobile App, *OwnTracks*. To be compatible with UbiSmart requirements, the App has been modified to use MQTT and offer satisfactory performance in terms of battery life.

The server is coded in NodeJs (JavaScript) using a MVC web App framework. The MVC structure allows UbiSmart to deploy new features, both Backend and Frontend, very fast and easily, with a big developer community behind. The Service Provisioning represents the interaction between the end-users and UbiSmart enhancing the KB population through web interfaces. The system is conceived to simplify this interaction and most of the actions are coded as web pages where the users can interact. To reinforce the idea of human-centered framework UbiSmart provides different types of roles with different levels of accessibility. It also automatizes the deployment with its interface and guides the user through the procedure. The semantic inclusion of every action is handled automatically by UbiSmart backend reducing the complexity for non-expert users.

# Chapter 6

## Validation

The validation of UbiSmart has been divided into four main axis evaluating the contributions of this thesis. First, the validation of the framework design and implementation with social and cognitive tools. Second, the validation of the proposed mobility classifier. Third, the validation of the development installation and maintenance in controlled scenarios. Fourth, the validation of the AAL framework in real deployments in more than 30 environments. And finally, the validation of the proposed frailty model with the data collected during the deployments.

### 6.1 Design Validation

As part of the UbiSmart project, an analysis of the Consumer user interface has been carried out. The main objective is to improve the user experience (UX) and usability. This section presents the methodologies implemented and the results obtained with possible improvements.

There are a number of methods which can help to evaluate a human interface. User Experience (UX), Human enhancement (HX) and Knowledge Conceptualization(KX) represent the three axis to implement improvements. This thesis concentrates the efforts at the UX axis with two specific methods: Cognitive Walkthrough CW for the usability and Heuristic analysis for the ergonomics. Studies in the other axis will be performed in the next months within the deployment phase of the Singapore pilot site. Figure 6-1 illustrates the context of the UbiSmart analysis.

In this evaluation with CW and Heuristic analysis are focused on five interfaces that represent the most usual actions of the end-users. Figure 6-2 represents the first page encountered by the user which demands connexion credentials. Figure 6-3 is the main menu offered to the user where he/she can access their personal information or navigate to specific services. Figure 6-4 is a dashboard service for a quick access to aggregated data specially dedicated for non-professional caregivers. Figure 6-5 is a Gantt chart service that shows time-line activity evolution for a given user. Figure 6-6 is a frailty item visualization that allows the caregivers to follow the item

evolution in terms of time and occurrences for a specific matter, in this case, *Sleep* and *Toileting*.

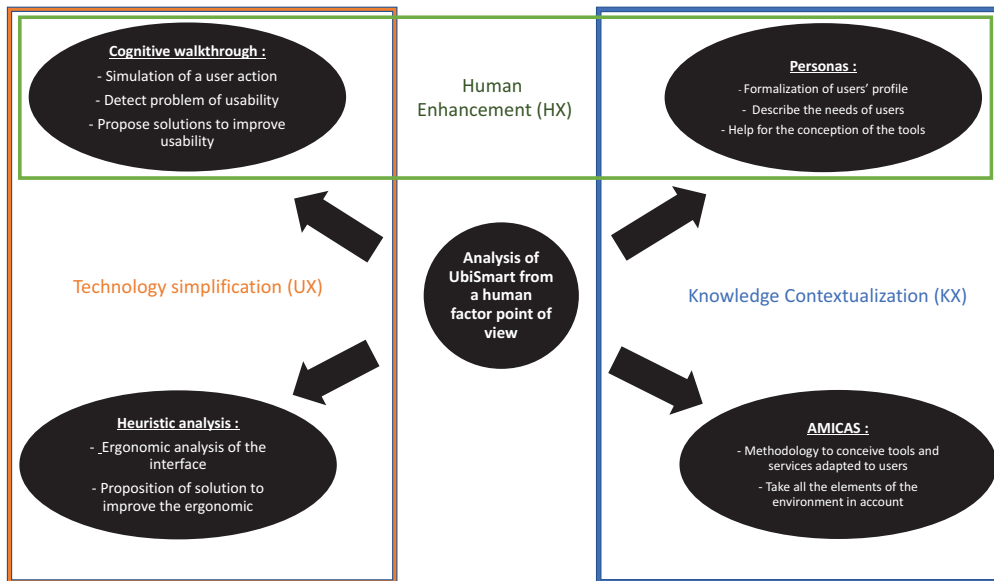


Figure 6-1: User Interface Analysis Overview. Three axis are represented: Technology simplification (UX), Human enhancement (HX) or Knowledge Conceptualization(KX).

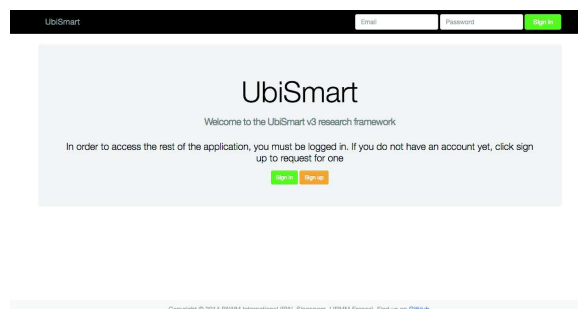


Figure 6-2: *Login* interface evaluation. This Interface is representative for Cognitive Walkthrough Analysis Task 1-1 and Heuristic analysis Interface 1.

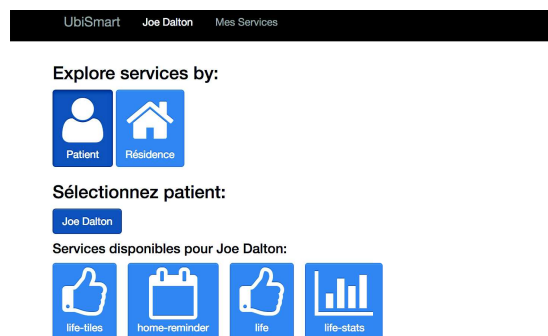


Figure 6-3: *Resident* interface evaluation when accessing the UbiSmart. This Interface is representative for Cognitive Walkthrough Analysis Task 1-2, 2-1, 2-3 and Heuristic analysis Interface 2.

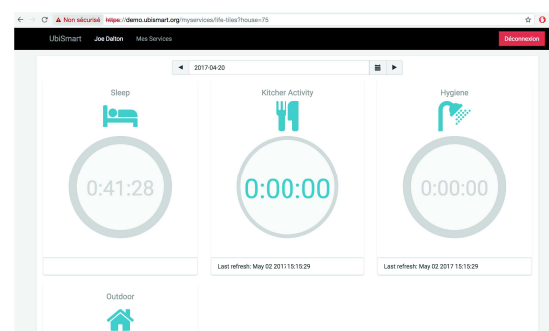


Figure 6-4: *Life-Tiles* service interface evaluation. This Interface is representative for Cognitive Walkthrough Analysis Task 2-2 and Heuristic analysis Interface 3.

Nielsen theory accords that three participants will observe 60% of the ergonomics issues, five

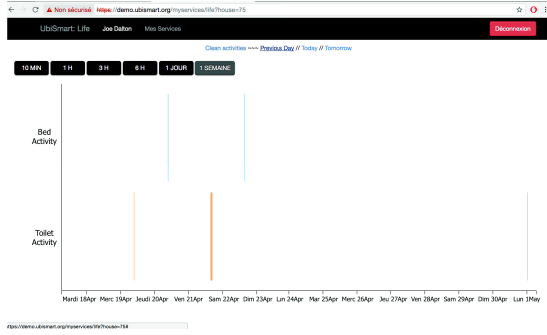


Figure 6-5: *Life* service interface evaluation. This Interface is representative for Cognitive Walktrough Analysis Task 2-4 and Heuristic analysis Interface 4.

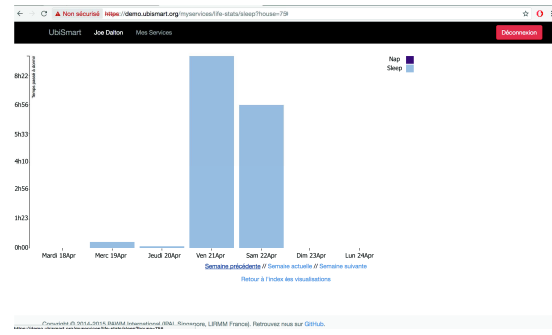


Figure 6-6: *Life-Stats* service interface evaluation. This interface is representative for Cognitive Walktrough Analysis Task 2-5 and Heuristic analysis Interface 5.

participants will detect 75% of the issues, and more than five stabilize the detection curve at around 80%. In this case, the experiments required of four users for both, CW and Heuristic, studies. The cohort was composed of two consumer end-users and two computer domain experts. The participants reported ages between 24 and 35 years old, all living in Singapore but originally from France. The study was performed in the laboratory facility taking one hour per user.

### 6.1.1 Cognitive Walkthrough

The CW is a Human Centered Design (HCD) approach. It is a usability inspection method for web interfaces (Blackmon & al, 2002 [25]) that originally focuses on evaluating a design for an ease of learning (Lewis & al, 1990 [92, 188, 189]). The aim is to evaluate the behavior of the user during his/her interaction with the interface through a usability criteria. This methodology can be used at any time during the conception of the interface. There are two measures associated with the methodology of the CW: list of usability problems and Ergonomics recommendation.

## Experiments and Results

For UbiSmart CW, two scenarios are created with following a sequence of tasks illustrated in Figures 6-2, 6-3, 6-4, 6-5, 6-6.

### Scenario 1 - Login

*Task 1- Case 1: there was a mistake in identification*

*Task 1- Case 2: there was no mistake in identification*

### Scenario 2 - Resident Data

*Task 2- Case 1: the user selects a resident*

*Task 2- Case 2: the user consults the life-tile service*

*Task 2- Case 3: the user returns to the resident page*

*Task 2- Case 4: the user consults the life service*

*Task 2- Case 5: the user consults the life-stat service*

Each scenario and task is evaluated by four questions with three possible answers. And, finally the failure rate is calculated following Equation 6.1.

Importance Questions

*Q1. Is the effect of the current action a user's goal?*

*Q2. Is the action visible?*

*Q3. Does the user recognize the action as correct?*

*Q4. Does the user understand the feedback?*

Frequency Answers

Yes = 3

I don't know = 2

No = 1

$$ScoreCW = \frac{1}{N} \sum_{k=0}^{k=N} ValueQuestion(k) \quad (6.1)$$

Where N is the number of participants

The results are reported as *Failure rate*. It means that the study aims at understanding the interface bottlenecks. The global results are presented in figure 6-7.

The evaluation of the first scenario (Figure 6-2) highlights that there is a need for improvements at the directives and feedback level. The user complaints about the fact, that there is not advice and help and the feedback is poor in case of failure. The rest of the features are satisfactorily documented. In the case of successful login, Figure 6-3, the failure rate decrease because the user is grated for access.

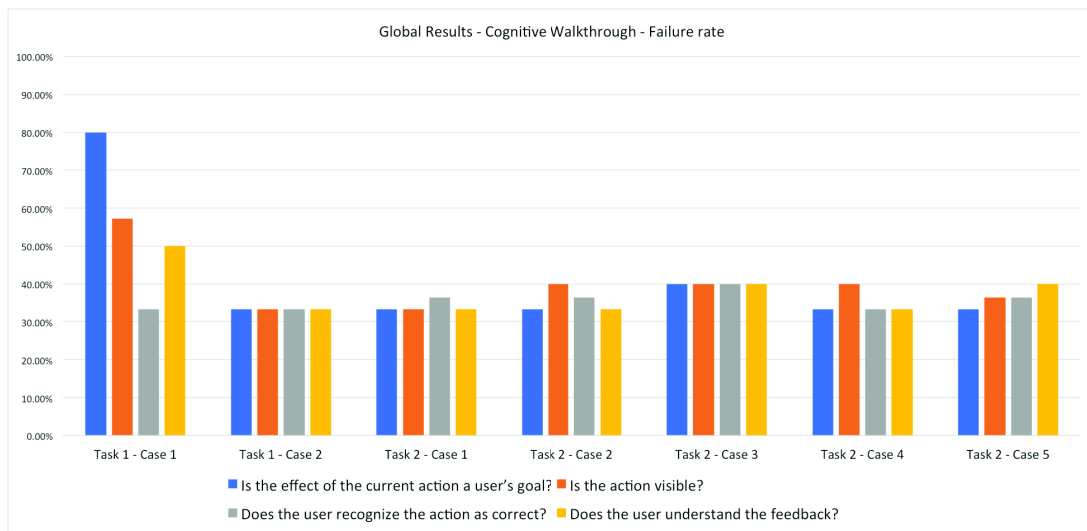


Figure 6-7: Global Results for Cognitive Walkthrough Analysis.

The second scenario shows better ratios. However, the participants reported that the service logos are repeated and they feel confuse (Figure 6-3). Figures 6-5, 6-4 and 6-6 show that the in-

formation is not clear enough for the end-user with lack of legends and data interactivity. Finally, going back to the resident page from a service page reports problems and unclear directives. At the end of this section, I present and discuss the improvements and adjustments to mitigate the design issues highlighted by the CW study.

### **6.1.2 Heuristic Analysis**

The Heuristic analysis is a Human Centered Design (HCD) approach, which projects the interface upon a list of heuristics criteria. By definition "A heuristic refers to simple task-specific decision strategies that are part of a decision maker's repertoire of cognitive strategies for solving judgment and decision tasks" (Gigerenzer 1999 [177]). In other words, heuristic is a criteria that facilitates the task to achieve an action. The heuristic analysis can be done at any time during the conception of a product or a service. The main objective of a heuristic analysis is to detect positive and negative elements from an ergonomic point of view. It categorizes ergonomics defaults to judge their importance and propose solutions and adaptations. There are different types of heuristics that can be used: Nielsen Heuristics, Bastien & Scapin Criteria, Schneiderman Golden Rules, ISO 9241-10 Norm and Tognazzini Criteria.

## **Experiments and Results**

The aim of this study is to evaluate the proposed interface in order to make propositions to improve the user experience at the Consumer level. Consequently, for the evaluation of UbiSmart, Nielsen Heuristics have been chosen [111]. There are two measures associated this method: list of usability problems and Ergonomics recommendation.

Moreover, ten criteria are proposed by Nielsen to analyze the usability and ergonomics:

1. Visibility of System Status: the system should always keep users informed about the status through appropriate feedback within reasonable time.
2. Relation between System and Reality: the system should "speak" the users' language, with words, phrases, and concepts familiar to the user, rather than system-oriented terms.
3. User Control: the user often chooses system functions by mistake and will need a clear "Go Back" action.
4. Consistency and Standards: the user should not have to wonder whether similar words, situations, or actions.
5. Error Prevention: The design should prevent a problem.
6. Recognition vs Recall: minimize the user's memory load by making objects, actions, and options visible. Usability instructions should be visible or easily retrievable.

7. Flexibility and Efficiency: the system should allow users to tailor frequent actions.
8. Esthetic's and Minimalist Design: dialogs should not contain information which is irrelevant or rarely needed.
9. Recognize, Diagnose and Recover Errors: error messages should be expressed in plain and precise language.
10. Help and Documentation: even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation.

Each user participating in the study was requested to assign an importance score for the aforementioned criteria and the frequency of use for each task in UbiSmart. The possible results were:

<u>Importance</u>
<i>Blocking criteria</i> = 1
<i>Major criteria</i> = 2
<i>Minor criteria</i> = 3
<i>Not a Priority</i> = 4
<i>Not a problem</i> = 5
<u>Frequency Answer</u>
<i>Always</i> = 1
<i>Often</i> = 2
<i>Sometimes</i> = 3
<i>Never</i> = 4

And the associated normalization formula to Nielsen methodology is presented in Equation 6.2.

$$ScoreNielsen = (\frac{1}{N})^2 \sum_{k=0}^{k=N} Criteria(k) \cdot \sum_{k=N}^{k=0} Frequency(k) \quad (6.2)$$

Where N is the number of participants

Finally, the five interfaces included in this study were:

<u>Interfaces Evaluation</u>
<i>Interface 1: Login, (Figure 6-2)</i>
<i>Interface 2: Resident, (Figure 6-3)</i>
<i>Interface 3: Life-Tile, (Figure 6-4)</i>
<i>Interface 4: Life service, (Figure 6-5)</i>
<i>Interface 5: Life-Stat service, (Figure 6-6)</i>



Results, presented in Figure 6-8, highlight that there are improvements to do for error prevention, user control, errors recovery and help, and documentation. In general terms the *Resident* interface is the best considered. UbiSmart shows an average ratio between system and reality with the *Resident* interface with the 80% of satisfaction and *Life-Tiles* and *Login* around the 50%. This issue may represent an entry barrier for non-expert users to interact naturally. In terms of services, *Life-Tiles* is considered the best interface, so it can be inferred that users prefer reduced and summarized data presentations rather than verbose interfaces.

Only the *Resident* interface obtains a satisfactory score for the visibility of the items. This means that the user may feel lost or frustrated by using UbiSmart. The user control, standards, and consistency need to be improved at the services level. The error prevention does not perform satisfactorily for any of the interfaces. This issue may create confusion and frustration at the user level. The recognition vs recall criteria only performs satisfactorily for the *Resident* interface. The customization is not yet treated by UbiSmart and that explains the poor performance at flexibility and efficiency level. The participants reported that the presented interfaces are not shown with a minimalist approach. The *Login* interface performs well in terms error recognition, however, the rest of interfaces need for improvement. And, finally, the participants claim the need for documentation and help during their navigation.

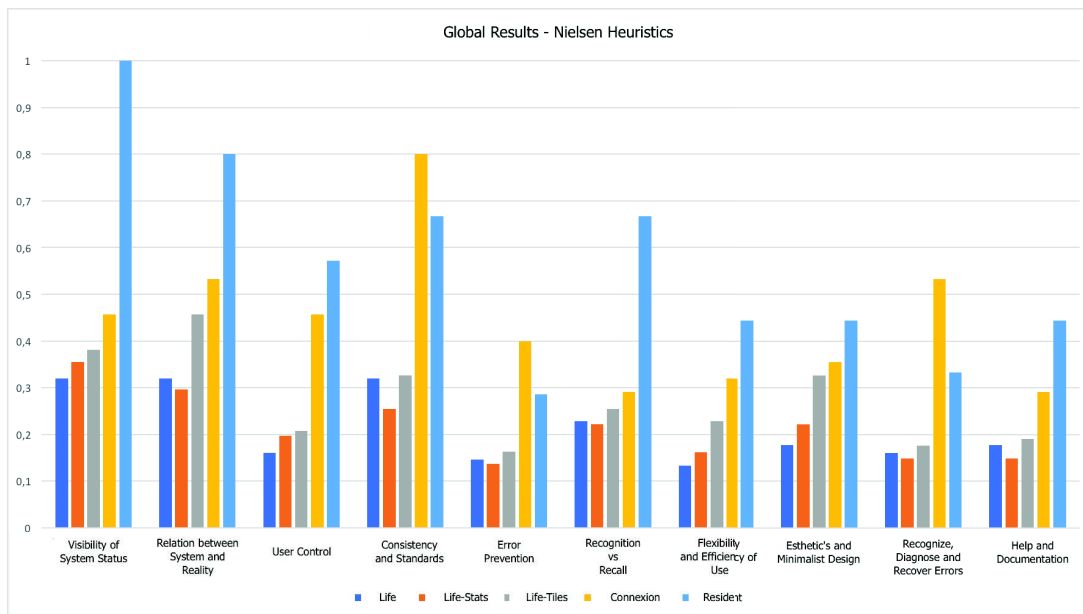


Figure 6-8: Nielsen results overview for each criteria and interfaces.

### 6.1.3 Discussion and Improvements

According to the results some improvements have been proposed for the next version of UbiSmart. One of the main issues encountered is the lack of a *Design for Zero Data* for initial or empty pages. This is a key point for the proposed framework because it aims to be used by non-technical profiles and this issue could create confusion in the usage.

Linowski & Malik <sup>(1)</sup> reported in 2016 that "it is often forgotten to design for zero data, for initial cases [...] A zero data world is a cold place. When first time users look at the App/website and this one shows a blank slate without any guidance, then, there we are probably missing out on an opportunity [...] The most common of [the zero data] scenario is probably the transition from the first time use with zero data toward future use with a lot more data". The literature states that in any case the user should not feel alone in the system. According to that adapted instructions must be proposed to guide and facilitate the usage.

Moreover, The participants highlighted valuable comments in order to illustrate their impressions. User 1 (expert) reported: "it will be great to have an image which clearly states the connexion error" and "There exists a user plasticity and error if two logos are too similar". User 2 (expert) reported the largest number of comments. He/She agreed with user 1 and added: "the navigation needs of standardization to help the user" regarding the consistency; "The system needs more minimalism to guide the user" when analyzing the aesthetic; in the case of error recovery "The interfaces lack of guidance in case of error"; regarding the freedom and user control "It is really annoying a control panel that does not control anything"; he/she stated "The navigation y recognition is very important"; and finally "a guided tutorial in the first visit may help the user to avoid problems on navigation, legends, interactivity". User 3 and 4 (consumer end-users) did not report a large number of comments, however they highlighted: "Language is not consistent in the system"; about the user flexibility "More details when clicking a button is necessary"; about the system status visibility "The button navigation is necessary"; the aesthetics and minimalism reported "lack of help and legend explanation"; finally they reported "the system should show a message if there is no data to be shown because I feel that I did something wrong".

Combining the literature, best practices methodologies and the user feedback, following some improvements are enumerated and proposed for each interface:

**Connection Page:** The vocabulary needs to be standardized and explicit. *E.g.* the "Adresse Email" should be changed for "Identifiant Utilisateur" (Figure 6-9(a)). In case of an error, the message should be displayed with explicit information and it should contain possible solutions (Figure 6-9(b) and 6-9(c)). Also, the state of connection should be indicated. If the connection is successful, a message should be displayed on the top of the screen, Figure 6-9(d).

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<sup>1</sup><https://www.goodui.org/>

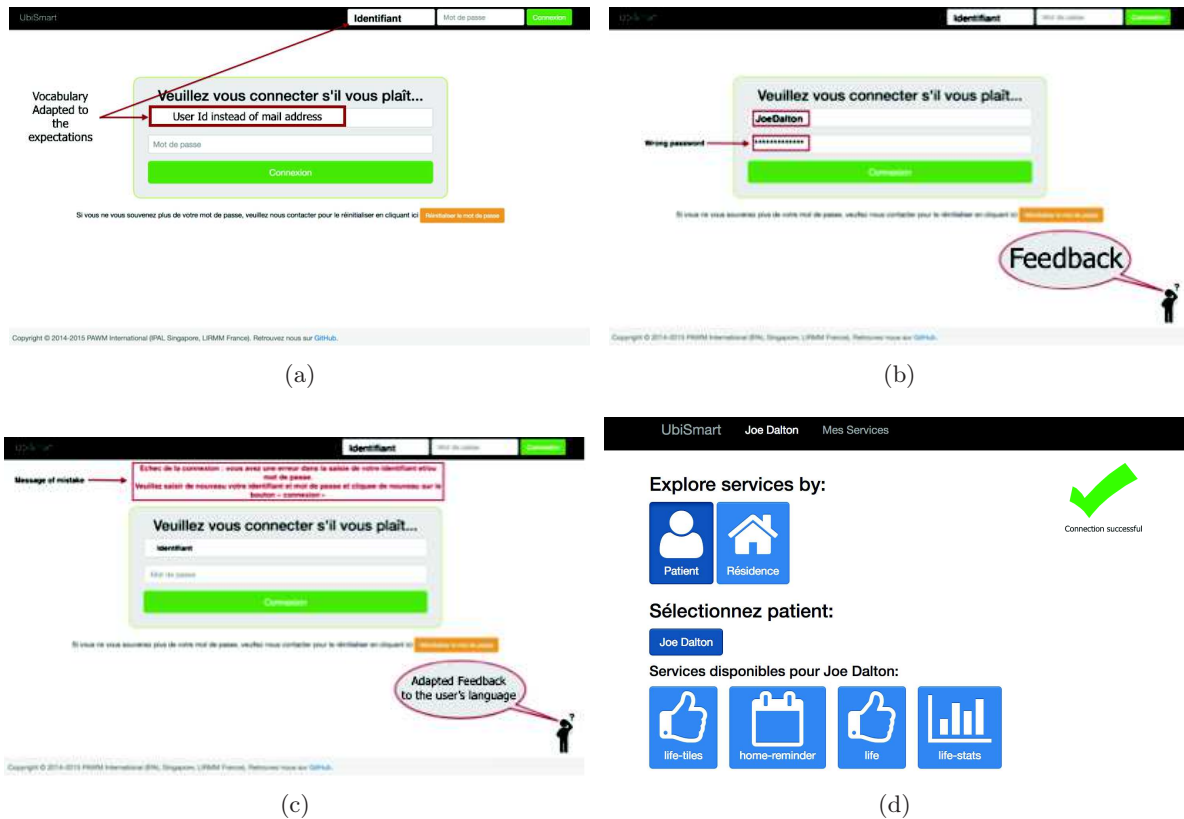


Figure 6-9: Improvements proposed for the *Login* page.

**Resident Page:** In this page the language should also be harmonized according to the user and his native language. The logo and menu titles should be unique and the user should have information about his/her connection (Figure 6-10(a)).

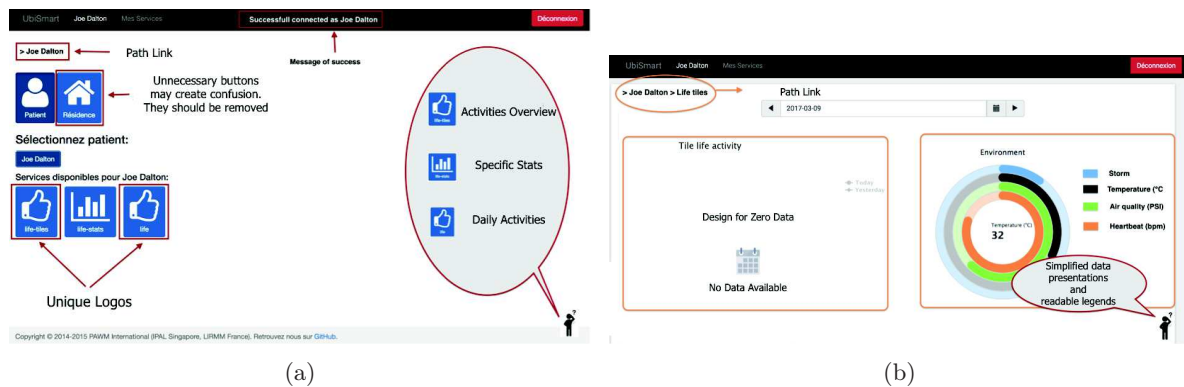


Figure 6-10: Improvements proposed for *Resident* and *Life-Tiles* Services.

**Life-Tiles:** This interface should be simplified as suggested in see Figure 6-10(b). The data is clustered and the navigation made easier. The inclusion of *Design for Zero Data* when there is no data to be shown is also included.

**Life-Stats** Figure 6-11(a) proposes to add a path link and a data legend to orient the user. Moreover, data should be interactive, the user should have the choice to add or remove items

(Figure 6-11(b)). Finally, *Design for Zero Data* should be implemented if there is no data to be displayed. An informative message should appear in the data place (Figure 6-11(c))

**Life** Finally, the *Life* service reports globally the same issues than *Life-Stats* service. The data should be clarified with legends (Figure 6-11(d)), and an informative message should appear if no data is available (refer to Figure 6-11(c)).

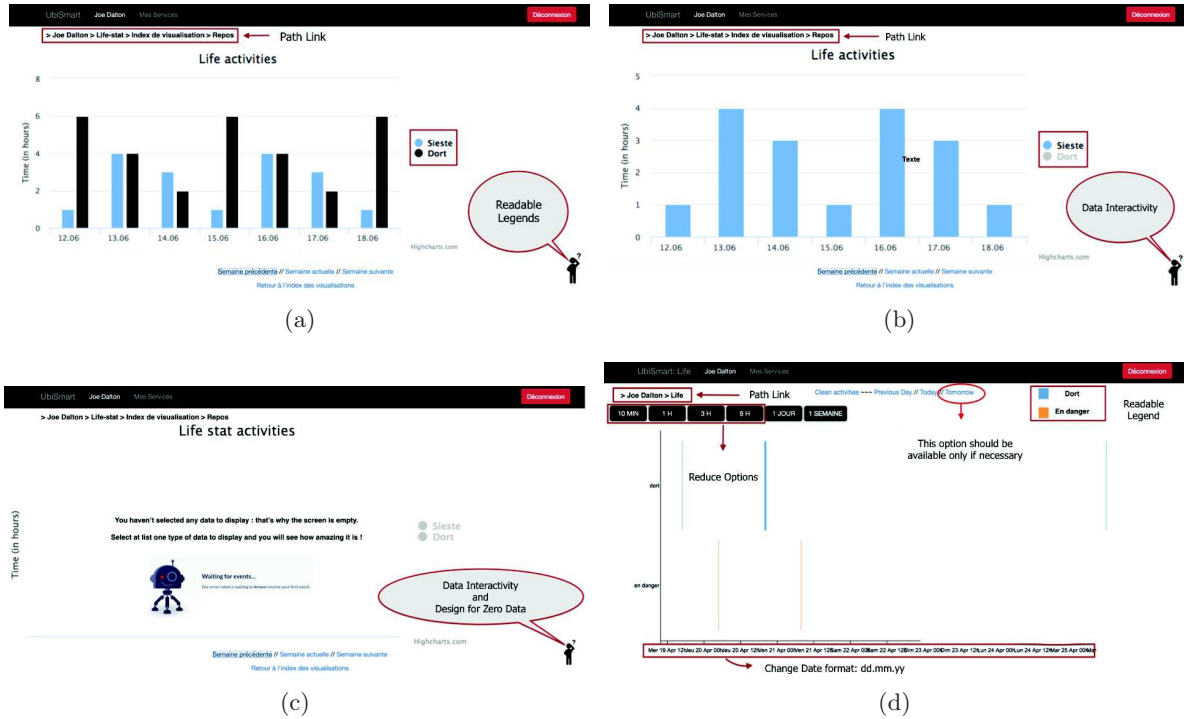


Figure 6-11: Improvements for *Life-Stats* (a, b, c) and *Life* (d) Service.

## 6.2 Mobility Classification Validation

To validate the mobility classifier five classifiers were trained using different configurations: Gaussian Naive Bayes (NGB), Linear Discriminant Analysis (LDA), Quadratic Discriminant Analysis (QDA),  $K$ -Nearest Neighbors (KNN) and finally Support Vector Machines (SVM). The computation times for NGB, LDA, QDA and KNN classifiers are presented in Table 6.1. The training and test experiments are performed following a cross-validation approach with four splits. The performances of each classifier have been characterized according to its *Precision*, *Recall* and *F1Score* (see Equation 6.3).

$$\begin{aligned} Precision &= \frac{TP}{(TP + FP)} \\ Recall &= \frac{TP}{(TP + FN)} \\ F1Score &= 2 * \frac{P * R}{P + R} \end{aligned} \tag{6.3}$$

### 6.2.1 Classifiers

The Gaussian Naive Bayes (NGB) classifier works by applying the Bayes' theorem with a strong assumption of independence between the features. This assumption is far from being fulfilled, given that we include both the calibrated and uncalibrated versions of some sensors. In this case the data is standardized by subtracting its mean,  $\mu$ , and dividing by their standard deviation,  $\theta$ . Alternatively, an essential assumption of the *Discriminant Analysis* classifiers is that the independent variables are normally distributed. Additionally, the LDA assumes homoscedasticity, which implies that the class covariances are identical and they have full rank.

The NGB training performance with the original cleaned dataset remains far from our expectations in terms of accuracy, 65%, even though the training and testing time are very low. QDA gives a much higher (10 points) accuracy than LDA or NGB (the results are presented in Table 6.1). KNN classifier obtains very promising results with standardized values. The experiments are performed using different values of  $K$ : three, four and five. SVM uses two configurations for the kernel, *radial* basis function (RBF) and *polynomial*. The best results are obtained with *radial* configuration with 91% of accuracy. For the polynomial configuration, the *Accuracy* peaks at degree 3 and decreases with higher degrees. However it remains 4% lower than *radial* kernel. The best results are obtained with K-NN with  $K = 3$  with the high accuracy and acceptable training time.

The classifiers were trained and tested for 6 different splits of the data, using cross-validation. The accuracy values presented here are the average of the obtained in the different splits, unless otherwise stated. The plots in Figure 6-12 show the class labels for four different splits. The data points are shown in a projection on the first two principal components. Observing the differences

Table 6.1: Classifiers performances.

Classifier	Degree	Time	Accuracy
GNB	NA	0.509s	0.65
LDA	NA	1.526s	0.5899
QDA	NA	1.221s	0.7147
KNN	<b>3</b>	<b>12.128s</b>	<b>0.9625</b>
KNN	4	14.257s	0.9583
KNN	5	17.374s	0.9592
Polynomial SVM	2	124.363s	0.8481
Polynomial SVM	3	123.749s	0.8646
Polynomial SVM	4	121.176s	0.8492
Polynomial SVM	5	148.284s	0.8202
Radial SVM	NA	210.434s	0.9007

Table 6.2: Confusion Matrix for K-Nearest Neighbors with  $k = 3$  with raw data (values presented in percentages).

Data Points		Walk	Bike	Train	Bus	Car	Nothing
<b>18863</b>	<b>Walk</b>	96.29	0.9	1.19	0.64	0.98	0
<b>6594</b>	<b>Bike</b>	1.9	96.21	0.91	0.68	0.3	0
<b>6135</b>	<b>Train</b>	4.07	0.73	90.95	3.02	1.22	0
<b>2993</b>	<b>Bus</b>	2.84	0.33	2.84	89.97	3.85	0.17
<b>18219</b>	<b>Car</b>	0.52	0	0.38	0.14	98.96	0
<b>2734</b>	<b>Nothing</b>	0.18	0	0	0.18	0.91	98.72

between the real classes and the predicted classes, it can be seen the good performance of the classifier. Wrong classifications are located in areas where different activities are concentrated, *e.g.* *Nothing* events (red dots) located inside the *Car* space events (green) are mistakenly classified. The global numbers are also referred in the confusion matrix, Table 6.2.

### 6.2.2 Windowing

The previous models use the raw data (after a preprocessing and standardization process). The results are encouraging and the *Accuracy* achieved allows to deploy the model in real life. However, these models do not take into consideration the *temporal dimension* of the data. In an outdoor activity, it matters not only the state of the phone at a certain point but also its state in previous and future moments. For example, walking can have moments where the legs (and phone) are in a very similar way as certain parts of the process of riding a bike. Therefore, the progression and position of the phone over a small window of time has been studied (Windowing). This approach allows to draw a complete cycle of movement specially indicated for activities such as *Walk* or *Biking*.

Based on that hypothesis, the data was grouped in 2 seconds windows events. Each row has statistical measures of the events within the window, for the accelerometer and rotation vector (mean, median, min and max).

The results using a two seconds window are presented in Table 6.3. Note that only the most



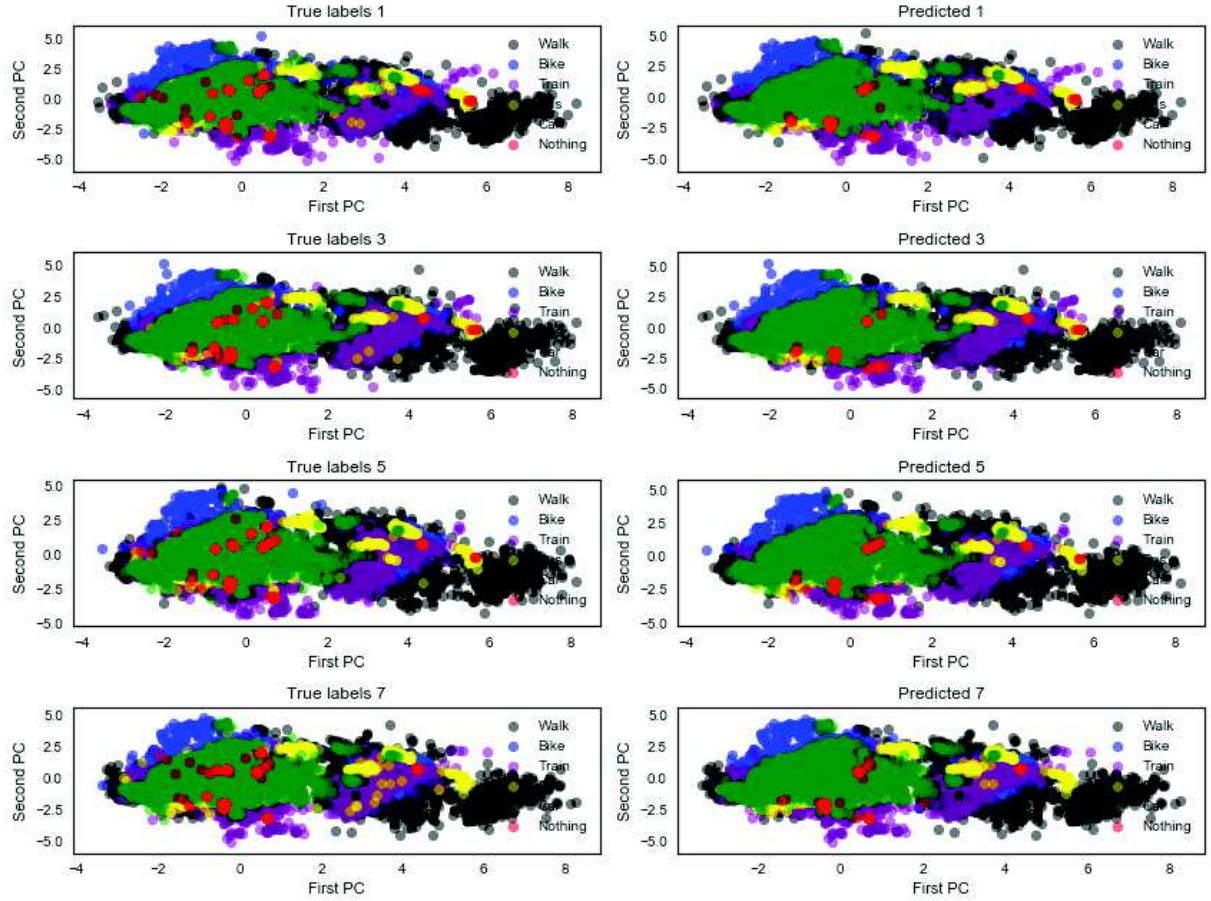


Figure 6-12: Real classes vs. Predicted for the four splits of cross-validation for SVM with RBF.

Table 6.3: Classifiers performances using windowing processing of two seconds.

Classifier	Degree	Time	Accuracy
KNN	3	7.965s	0.9886
Polynomial SVM	2	124.363s	0.9883
Polynomial SVM	4	115.176s	0.9883
Polynomial SVM	5	148.284s	0.9852

accurate classifiers has been reported in Table 6.3. SVM is the best classifier for temporal data. The best results are obtained with the fourth degree. However the compromise *Accuracy/Time* highlights that the best classifier is K-NN with  $K = 3$  with similar *Accuracy* and 110 seconds faster.

Facing real deployments, both raw data or windowed data, could be easily implemented. This classifier has been only tested in controlled facilities, however it is expected to be deployed in real scenarios in the next months. Current UbiSmart development has an specific feature to provide a public APIs that receives sensor data from the smartphone and returns the classifier output. At the same time, the data is stored on the server for further analysis (frailty model).

### 6.3 Real Deployment

UbiSmart has been deployed for more than three years. The platform was deployed in France in 2015. Five private houses and three nursing home rooms. The system performed indoor analysis with motion and contact X10 sensors. Later, in November 2016, the FOS was deployed in three houses in Singapore in a technical Pre-Test of 30 days. More recently, the C4A pilot site was launched with the inclusion of 10 houses and it is currently on-going. This deployment includes the motion, contact and FOS. Also, the French deployment increased by 9 the number of houses deployed. Summarizing, a total of 31 houses have been already deployed and 24 of them are currently on going. Finally, Pulse Singapore and C4A Montpellier Pilot Site will be launched soon including five houses each with indoor and outdoor technologies. Table 6.4 references the past, present and future deployments from September 2014 until today. The table also includes the technologies deployed for each environment. Table 6.5 resumes the number of sensor events collected by UbiSmart along the time.

Table 6.4: Pilot sites history and technology inclusion.

ID	Location	Starting Date	Ending Date	X10	Zwave	FOS	BLE Beacon
1	France	23/09/2014	ongoing	✓			
2	France	23/09/2014	31/12/2016	✓			
3	France	04/05/2015	ongoing	✓			
4	France	07/08/2015	31/12/2016	✓			
5	France	28/08/2015	ongoing	✓			
6	France	23/09/2014	31/12/2016	✓			
7	France	23/09/2014	ongoing	✓			
8	France	04/05/2015	12/01/2017	✓			
9	France	07/08/2015	ongoing	✓			
10	France	07/08/2015	31/12/2016	✓			
11	Singapore	19/08/2016	19/09/2016	✓		✓	
12	Singapore	19/08/2016	19/09/2016	✓		✓	
13	Singapore	19/08/2016	19/09/2016	✓		✓	
14	Singapore	05/06/2017	ongoing	✓		✓	
15	Singapore	05/06/2017	ongoing	✓		✓	
16	Singapore	05/06/2017	ongoing	✓		✓	
17	Singapore	05/06/2017	ongoing	✓		✓	
18	Singapore	05/06/2017	ongoing	✓		✓	
19	Singapore	05/06/2017	ongoing		✓	✓	
20	Singapore	05/06/2017	ongoing		✓	✓	
21	Singapore	05/06/2017	ongoing		✓	✓	
22	Singapore	05/06/2017	ongoing		✓	✓	
23	Singapore	05/06/2017	ongoing		✓	✓	
24	France	07/08/2015	ongoing	✓			
25	France	07/08/2015	ongoing	✓			
26	France	07/08/2015	ongoing	✓			
27	France	07/08/2015	ongoing	✓			
28	France	07/08/2015	ongoing	✓			
29	France	07/08/2015	ongoing	✓			
30	France	07/08/2015	ongoing	✓			
31	France	07/08/2015	ongoing	✓		✓	✓



Table 6.5: Collected event data over more than 3 years deployment.

Deployment	Duration	Events
France	40 months	1,518,136
Singapore	5 months	234,980

Figure 6-16 illustrates the deployment sessions performed in 2017 for the C4A pilot site. This deployment was performed in two days, dedicating 1hour per house. Figures 6-13, 6-14 and 6-15 show the installation of the sensors in the user houses. Singaporean houses have usually two main doors, so the door sensor was placed in the metal door because it is usually closed and illustrates better the door action. The FOS is placed under the mattress. However, the real deployment reported some curiosities, as one of the participants placed the sensor under a wood carpet because he preferred to sleep there.



Figure 6-13: Deployment design overview.

Figure 6-14: Door sensor installation.

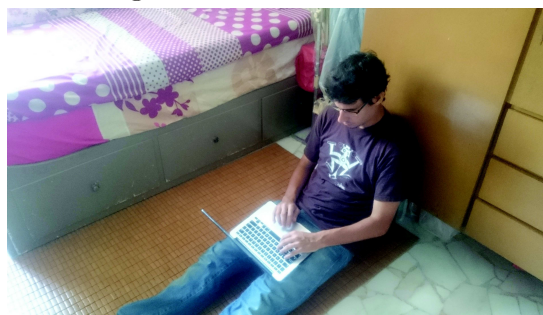


Figure 6-15: Bed sensor installation.

Figure 6-16: Real deployment execution in Singapore pilot site.

Finally, Figures 6-17 and 6-18 illustrate the inner functionalism of the reasoning, the system receives raw sensor events and converts them to ADL. This transformation is done by the semantic reasoning presented in [179, 6] and improved and extended in during thesis. As presented in previous chapters, the system receives raw sensor data from several sensors sources and infers

the type of activity performed by the user. The output of these interaction can be visualized by using the UbiSmart Service Provisioning as presented in Figures 6-17 and 6-18. Moreover, the continuous flow of data and inference allows UbiSmart to draw several trending curves for specific activities (Figure 6-19 and 6-20). This data represents a valuable input for computation of the frailty model (section 6.4).

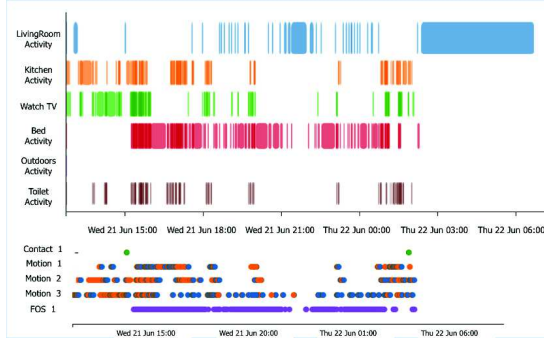


Figure 6-17: Sensor and activity charts collected at the Singapore pilot site (1).

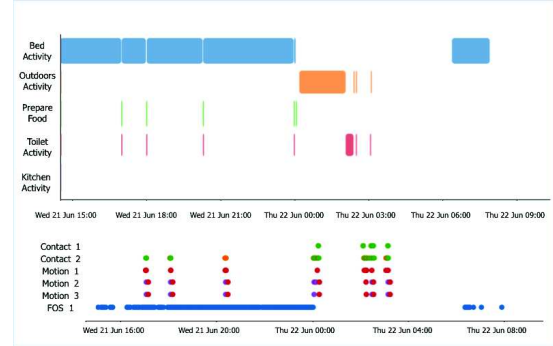


Figure 6-18: Sensor and activity charts collected at the Singapore pilot site (2).



Figure 6-19: *Kitchen* activity timeline collected at the Singapore pilot site.

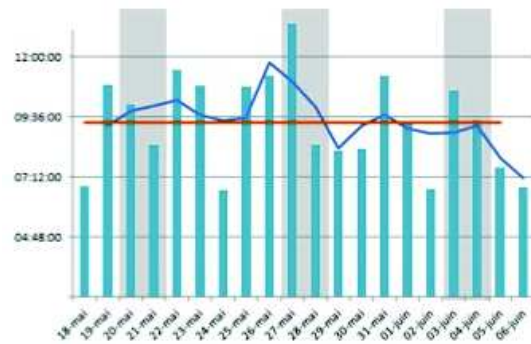


Figure 6-20: *Sleep* activity timeline collected at the Singapore pilot site.

### 6.3.1 UbiSmart Deployment and Maintenance Validation

The maintenance is another key point for a real deployment. It is hard to perform, time consuming and economically expensive if essential procedures have not been adopted. In fact, in-situ maintenance should be minimized and limited to critical situations hard to solve remotely. Also the time of detection and intervention is very crucial, and can have a strong impact in specific AmI solutions (*e.g.* failure in dependent people assistive AmI solutions).

Based on the real world deployment feedback, the three key issues that need to be addressed for any future large scale deployment are: failure handling and remote monitoring.

#### Automatic Failure Handling

Numerous cases of failure issues have been detected in the gateway during the real deployments. An example is the gateway shutdown, whether accidentally by the user or due to power cut. Another issue is related to possible software bugs that break the gateway modules operation. In addition, the network is one major problem that affect the normal behavior of the system. Internet disconnection causes loss of sensor events. A human intervention should not be required to re-operate the system in any of the following situations: the gateway was shut down; the software was stopped on the gateway (possibly due to a bug); the Internet connection is lost on the gateway; and the gateway is connected to the Internet, but not reachable from the server.

Different techniques are proposed to handle the discussed failures:

First, every module in the gateway should be running as a background process (*i.e.* daemon). The gateway ensures that the required processes are running.

Second, a script should permanently check the gateway Internet connection (through LAN or 3G) to detect disconnections and reconnect consequently.

Third, a process should be integrated on the server side to notify the gateway to restart its faulty services when one or more of its services are unreachable. From our experience, the most straightforward solution to this problem is to restart the gateway. Therefore, an script which detects these disconnections has been developed, and restarts the gateway when necessary.

Finally, a process should be integrated on the server side so that when the gateway is reachable over the Internet, but one or more of its services are unreachable, the server sends an alert to the gateway to restart its faulty services.

#### Gateway Remote Access

A large scale deployment of AmI solutions raises the problem of remote accessing, maintaining and updating of these systems. In fact, thousands of copies of an AmI solution might be installed on a large area in a city, country or even all over the world. Moving in-situ to solve problems or update these systems at this scale becomes virtually unfordable.

Different technical problems could arise unexpectedly after the installation of an AmI solution. In addition, new versions of modules installed on the gateway could appear and therefore these modules need to be updated. Several technical solutions can be adapted to overcome this issue, without the need for specific hacking tricks such as port forwarding, static IP addresses or dynamic DNS. UbiGate provides a SSH Reverse Proxy constantly connected to a dedicated server. The code runs as a Linux daemon that is automatically relaunched if it stops. The connection reaches a dedicated APIs and exchanges critical data such as temperature, physical space or swap memory. Figure 6-21 reports the status of the deployments in real-time in a dedicated interface on UbiSmart.

```

11: 59.1°C 1.30V RAM419M SD25% CPU 6.6 04:28:36 up 16:14, 1 user, load average: 0.66,
0.64, 0.38 Swp.00% Domo Marm
12: 51.5°C 1.20V RAM706M SD25% CPU 5.0 04:28:36 up 53 days, 22:35, 1 user, load average:
0.00, 0.02, 0.13 Swp11.87% Domo Marm
13: failed
14: failed
15: 56.9°C 1.20V RAM722M SD26% CPU 5.3 04:28:36 up 60 days, 23:06, 1 user, load average:
0.02, 0.21, 0.23 Swp8.17% Domo Marm
16: 71.4°C 1.30V RAM535M SD25% CPU 8.9 04:28:36 up 5 days, 15:35, 1 user, load average:
1.01, 1.18, 1.17 Swp.00% Domo
17: 54.8°C 1.20V RAM689M SD25% CPU 6.0 04:28:36 up 42 days, 20:25, 1 user, load average:
1.22, 1.04, 0.96 Swp1.86% Domo
18: 58.0°C 1.28V RAM674M SD25% CPU 6.0 04:28:37 up 48 days, 22:38, 1 user, load average:
0.04, 0.23, 0.24 Swp3.63% Domo
19: 60.7°C 1.25V RAM710M SD54% CPU 6.3 04:28:37 up 17:28, 1 user, load average: 0.04,
0.19, 0.23 Swp2.01% Domo Marm
20: 76.8°C 1.28V RAM703M SD25% CPU 6.5 04:28:36 up 42 days, 18:33, 1 user, load average:
1.00, 1.00, 1.05 Swp1.86% Domo

```

Figure 6-21: Gateway monitoring system implemented. The information is frequently updated in a public dashboard and the system triggers alerts when unexpected values are detected.

## UbiGate Update

The installation and maintenance procedure presented in this paper has the potential to boost a large scale deployment of AmI solutions. The benefits of the approach are highlighted through the validations of following three main features:

**Validation of the Installation Process:** Theoretically, without the proposed approach, an expert technician needs an average of 45 minutes of active work to install and configure the system, diluted in a total of 1 hour and 45 minutes (including 1 hour of background process). However, when using the UbiGate approach, the technician only needs less than 5 minutes of active work to run the process. The process will execute in background for approximately 1 hour. Furthermore, installing the system with the proposed approach requires only few technical skills.

( 5min+ 1h+non expert installer compared to 45min+ 1h+expert installer)

Empirically, the recent deployments have required to 20 minutes in-situ, using the configuration interface provided by UbiSmart, whereas earlier deployments required up to 4 hours. The

in-situ deployment consists of placing the sensors, plugging the gateway, configuring and testing the system.

( 20min+non expert installer compared to 4h+expert installer)

**Validation of Improvements on the Upgrade Process:** A manual upgrade of the gateway, assuming it is performed remotely, requires between five minutes and to 20 minutes per gateway. The total duration of the upgrade scales poorly as the number of gateways increases, and would be as high as several hours if considering 50 gateways. Using UbiGate, the upgrade process is now fully automated, and requires no involvement from a technician.

(0 min compared to 5 to 20min required from a technician)

**Validating the Maintenance Process:** Equations 6.4 and 6.5 are introduced in order to measure the impact of the approach during the maintenance stage. It estimates respectively the daily maintenance duration of Aml systems, and the expected downtime in case of failure.

$$\text{Daily Maintenance Duration} = N \times (C + R \times (1 - A) \times T) \quad (6.4)$$

$$\text{Expected Downtime} = D + (1 - A) \times T \quad (6.5)$$

Where:  $N$  is the number of houses deployed;  $C$  is the time required to check one house manually;  $R$  is the daily probability of having a failure in a house;  $A$  is the probability that a house can be fixed automatically after a failure,  $T$  is the time required to manually fix a house; and  $D$  is the expected duration until a faulty house is noticed.

When using UbiSmart, it is reasonable to assign  $C = 0$  (*i.e.* no need to check houses manually),  $A = 0.8$  (*i.e.* 80% of the failures can be fixed automatically) and  $T = 30min$  (*i.e.* solving a failure manually needs in average 30 min). Without UbiGate, it can be assumed  $C = 1min$ ,  $A = 0$  and  $T = 30min$ . On a deployment of five houses, and given  $R = 0.05$  (*i.e.* there will be a failure every 20 days in average for a given house),  $D = 10sec$  if using UbiSmart (*i.e.* the monitoring system checking frequency), and  $D = 12h$  without UbiSmart, the daily maintenance duration of the deployment is 1 : 30 minutes with UbiGate approach, and 12:30 minutes without. On a deployment of 50 houses, the Daily Maintenance Duration of the deployment becomes 15 minutes with this approach, and more than 2 hours without. With these assumptions, the expected downtime of a house would be six minutes with UbiGate, and 12 hours without.

### 6.3.2 Deployment Performance and Lessons Learned

The expertise acquired during those deployments highlighted some valuable lessons to learn that diverge from the expected result projected in controlled facilities. Following, I detail some of the difficulties encountered and the lessons learned acquired from the real deployments:

First, new **technologies and the elders**. The participants did not have an Internet connection at their homes. To mitigate this issue, one 3G USB Modem is provided in the installation kit. However, this connexion reported several interruptions of up to 5 minutes. Moreover, the continuous use of the USB routers collapsed the device, which needed to be rebooted on-site. In the same direction, elderly people do not report any interest in new technologies (smartphones, tablets, wearables) and even a slight rejection. *E.g.* one of the participants felt anxious because we installed a *Happy button* App on her phone. She reported to feel stressful and watched in her daily routine.

Second, **gateway OS failures**. The inclusion of new sensing capabilities, such as the FOS increased the number of events sent to the server. Some gateways reported errors when the FOS had an erroneous connection in the RaspberryPi GPIO. This created a repetitive error sequence (1000errors/second) higher to the error-handling frequency of the RaspberryPi corrupting the system. This overflow corrupted the RaspberryPi OS, which needed to be reinstalled or replaced.

Third, **Server performances and resources allocation**. UbiSmart Server performed a linear response time when increasing the number of houses. The experiments performed at the implementation level did not offer any server disruption. However, UbiSmart Server reported low functionalities and performances in the middle of the deployment. This is due to the interface's high resource demand. It has been detected that the implemented services allocate high CPU performances and RAM Memory. Therefore, the system was increased to 2GB RAM and 2 CPU. Then, the sensors flow improved but there is an important development work in reducing the resources allocation from the interaction services.

Fourth, **real deployment on-site maintenance**. A total of 80 devices were installed at the Singaporean pilot site (30 motion, 20 contact, 10 FOS, 10 RaspberryPi, 10 routers). During the deployment time, three main interventions were performed. The most current problems affect the sensors replacements due to detachments. A total of 18 motion and contact sensors needed to be replaced with new adhesive. Two sensors needed to be changed because of the damage when detached. Three RaspberryPi had to be changed due to functionalities. The main reason detected is the accumulated dust, however, the reparation strategy relies on changing the device fast reducing the intervention time at the elder's place. In terms of batteries, four motion sensors needed batteries replacement. The rest of the sensors are performing well and batteries report from 20% to 66% of remaining energy. This wide range remains in the normal expectations and may be due to the activity rate performed in the environment. Further investigation is planned



at the end of the deployment to model the relation between *battery consumption* and *sensor activity*.

Finally, the **participant inclusion** is a tedious but necessary task. Singapore presents the language as an additional barrier. Therefore, the inclusion was supported by a local institution close to the local society and focused on elderly people. However, one of the participants refused to take part of the experiment the day of the deployment. This participant was obviously respected and replaced with a new one. Another participant reported his unconformity in the middle of the study, and the system was removed from his place.

## 6.4 Frailty Model Validation

In collaboration with TOUCH, a Senior Activity Center (SAC) in Singapore, a survey among 28 aging people was conducted to validate the choice of frailty items. The SAC are neighborhood social providers that take care of aging members of their community. Their responsibilities are to maintain the social link between the aging members of the neighborhood by proposing activities, meetings and a meeting point. They are also aware of the daily health status of their community members. They alert their relatives if they detect a problem or someone does not appear in the center within few days. The context of these institutions are illustrated in Figure 6-22.

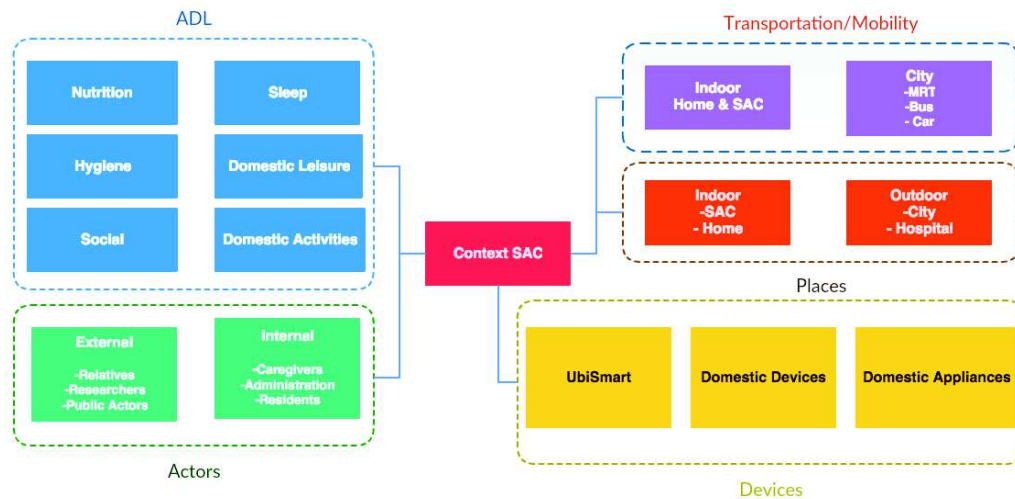
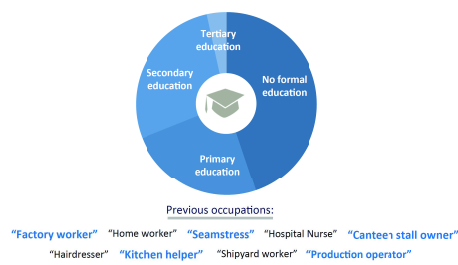


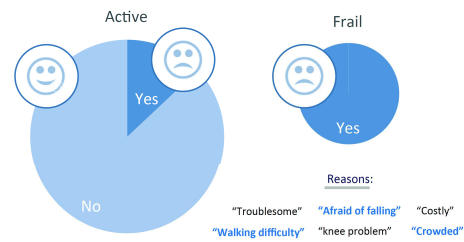
Figure 6-22: Context overview of TOUCH SAC in Singapore.

The survey conducted in collaboration with the SAC distinguishes *Active Aging* people, considered as *non frail*, and home bound aging people, considered as *frail*. The outcomes of the survey point out the key factors which may indicate the transition from one situation to another. The first observations show that *non frail* people enjoy active social life. They are able to perform outdoor activities independently, and they are involved in TOUCH daily activities. On the contrary, *frail* people suffers from mobility limitations, are most of the time at home without visits, and they rarely participate in social activities. While *non frail* people are not afraid of outdoors activities, *frail* people report difficulties, such as being afraid of falling, limited mobility or lack of social links. Finally, *frail* people report difficulties performing ADL such as cooking, toileting, and housekeeping. These conclusions confirm that the dimensions chosen by the frailty model respond to a real necessity and the items taken into account cover the spectrum of issues reported by the *frail* people. Figure 6-23 show the feedback from the survey for the physical and social dimension. Table 6.6 completes the frailty model with the issues extracted from the survey.

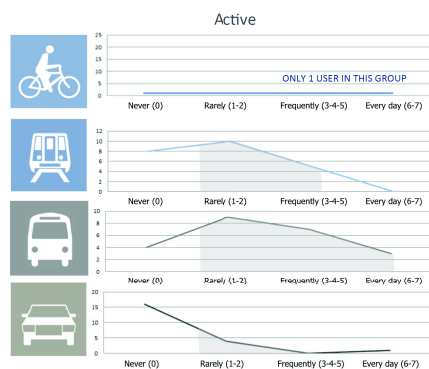




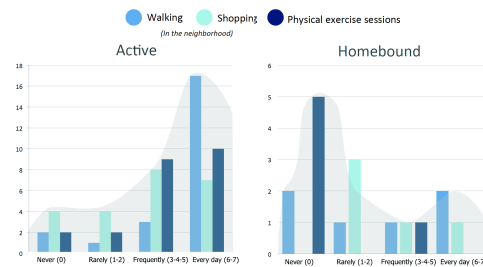
(a) Education Level



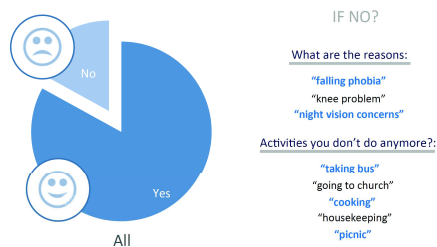
(b) Outdoors Activities



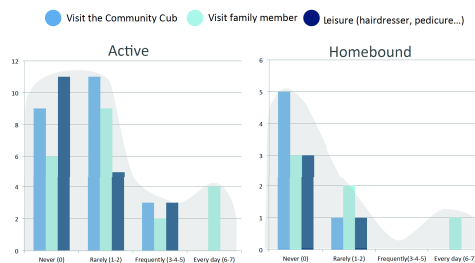
(c) Mobility Transportation



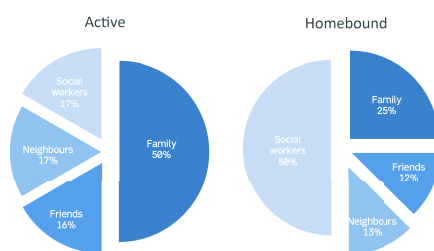
(d) Physical Activity



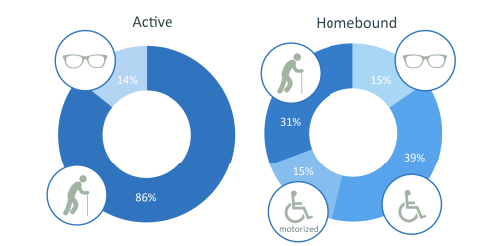
(e) Outdoors Safety Issues



(f) Social Activity



(g) Type of Social Link



(h) Type of medical Support

Figure 6-23: Physical and Social Exclusion Survey performed in collaboration with TOUCH SAC.

Table 6.6: Frailty items computed during the deployments. Each item is represented by its code in the ICF model, the source of raw data used for its computation, and its counterpart in the reasoning output. (Note that PIR acronym refers to Passive Infrared Sensor).

ID	Frailty Item / ICF Item	Proposed Domain	ICF Code	Data Source	Daily Computation	Survey Indications
1	Consciousness	Physical	b110	PIR Sensor	Inferred <b>Active Time</b> during the day	Detect indoor activities
2	Time out of Home	Physical & Social & ADL	b1260 & e3 & d7	PIR & Contact Sensor	Inferred <b>Go out</b> activity	Detect lack of outdoor activities
3	Relations	Social & ADL	e3 & d7	PIR & Contact Sensor	Inferred <b>visit</b> activity	Detect social exclusion
4	Perform Daily Routine	ADL	d230	PIR & Contact Sensor	Inferred <b>Daily Routine</b>	Detect indoor activities
5	Moving Around Home	ADL & Physical	d460 & b7	PIR Sensor	Inferred <b>Changing Rooms</b>	Detect lack of mobility
6	Walking Short Distances	ADL & Physical	d450 & b7	PIR Sensor	Inferred <b>Energy Rate</b>	Detect sedentary
7	Toileting	ADL	d530	PIR Sensor	Inferred <b>Toilet</b> activity	Detect hygiene troubles
8	Active Mobility	Physical & Social	b7 & e3	smartphone & PIR Sensors & BLE	Amount of <b>active time</b>	Detect Social exclusion
9	Passive Mobility	Physical & Social	b7 & e3	smartphone & PIR Sensor & BLE	Amount of <b>passive time</b>	Detect Social exclusion
10	Mobility outdoor	Physical & Social	b7 & e3	smartphone & PIR Sensor & BLE	<b>Mobile time</b> spent outside performing	Detect Social exclusion
11	Sleep time	Physical	b1340	FOS & PIR Sensor	Amount of <b>sleep time</b>	Detect Sleep troubles
12	Sleep Quality	Physical & ADL	b134 & d230	FOS & PIR Sensor	Inferred <b>troubles in sleep</b>	Detect Sleep troubles
13	Wake Up time	Physical	b1343	FOS Sensor & PIR	Time when the <b>user wakes up</b>	Detect sleep troubles
14	Bed time	Physical & ADL	b1343 & d4	FOS & PIR Sensor	Time when the <b>user goes the bed</b>	Detect Sleep troubles
15	Respiration functions	Physical & ADL	b440 & d4	FOS	<b>Respiratory effort</b>	Detect Sleep troubles
16	Heart rate	Physical & ADL	b4100 & d4	FOS	<b>Heart rate</b>	Detect sleep troubles

## 6.5 Frailty Model Technical Validation

The frailty model presented in this work has been integrated as a part of the reasoning and it infers frailty values in combination with the already existing model of activity recognition. Each item has been calculated separately and treated independently. It means that the result is able to build a daily multidimensional representation. Figure 6-24 characterizes the frailty items for a given user  $N$  at a given day  $d$ . The standardization allows representing all the items on the same scale facilitating the comprehension.

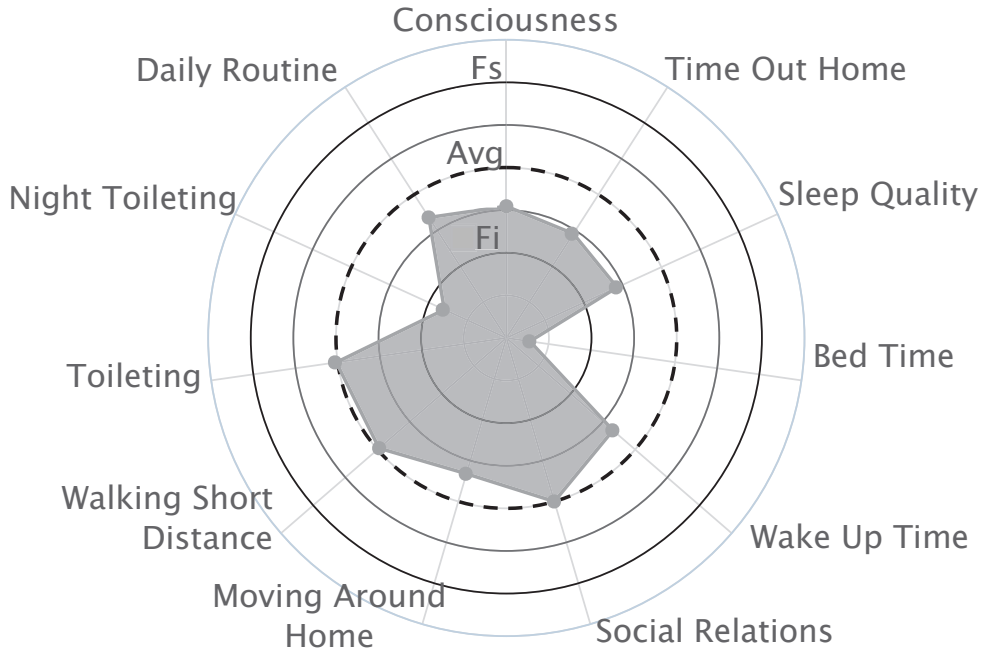


Figure 6-24: Frailty representation for patient  $M$  on day  $d$ . The vortexes represent the status of the person relative to the average values (dashed line) and to the boundaries of *Low* (Fi) and *High* (Fs) frailty.

To validate the frailty model, medical feedback is required from social or medical partners. The objective is to confirm if the frailty model is able to detect substantial human behavior changes. The objective is to correlate these occurrences with real health issues. Additionally, the experiments aim at discovering the relation between the number of frail items detected and the patient's health problem. 13 deployments out of 24 reported a ground-truth for the validation of the frailty model. Table 6.7 presents the time line for the ground-truth.

The French nursing home shared internal daily reports. Those reports included valuable information such as sickness, risk situations, accidents, hospitalizations or absences. Appendix F presents an anonymous example of those reports.

Singapore ground-truth was challenging and it was collected during the Pre-Technical deployment for sleep feedback. Table 6.8 presents the *Sleep* collected ground-truth.

Since the deployments in France and Singapore have not included the same type of sensing technologies, they have been validated separately. France ground-truth has validated the ADL frailty model, with *Sleep* activity inferred from motion sensors. On the Singapore pilot site, the

Table 6.7: Ground-truth Collected in collaboration with France and Singapore partners.

ID	User	Location	Feedback Starting Date	Feedback Ending Date
1	A	France	23/09/2014	31/12/2016
2	B	France	23/09/2014	31/12/2016
3	C	France	04/05/2015	12/01/2017
4	D	France	07/08/2015	31/12/2016
5	E	France	28/08/2015	31/12/2016
6	F	France	23/09/2014	31/12/2016
7	G	France	23/09/2014	31/12/2016
8	H	France	04/05/2015	12/01/2017
9	I	France	07/08/2015	31/12/2016
10	J	France	07/08/2015	31/12/2016
11	K	Singapore	19/08/2016	19/09/2016
12	L	Singapore	19/08/2016	19/09/2016
13	M	Singapore	19/08/2016	19/09/2016

Table 6.8: Age and sleep profile of each independent resident in Singapore (no chronic diseases or disabilities are reported).

Resident	Age	Living Situation	Sleep Time (approx)	Wake up Time (approx)	Nap
1	68	Family	18:30 –19:30 Sometimes 22:00	02:30	2–3 times 14:00–15:00 pm 30 minutes
2	69	Alone	23:00–00:00	07:00 Weekends 05:30	1–2 times 14:00–15:00 30–60 minutes
3	65	Family	21:00 – 23:00	07:00 Wednesday 04:00	Not reported

use of the FOS with motion and contact sensors is evaluated. The use of the FOS adds a high sensitivity on the *Sleep* activities. It allows to improve semantic rule to add robustness.

Motion Wake Up semantic rule

$\forall$  Sensor *se*; SensorState *st*; Room *r*; User *u*

$$\begin{aligned}
& (se1, hasCurrentState, st1) \wedge (se, hasType, PIR) \wedge (st1, indicateLocation, true) \\
& \wedge (se, deployedIn, r) \wedge (u, liveIn, r) \wedge (u, believedToDo, Sleep) \\
& \Rightarrow (u, believedToDo, WakeUp)
\end{aligned}$$

Motion and FOS Wake Up semantic rule

$$\begin{aligned}
& (se1, hasCurrentState, st1) \wedge (se, hasType, PIR) \wedge (st1, indicateLocation, true) \\
& \wedge (se, deployedIn, r) \wedge (u, liveIn, r) \wedge (se2, hasCurrentstate, st2) \\
& \wedge (se2, attachedTo, o) \wedge (o, a, Bed) \wedge (u, believedToDo, Sleep) \\
& \wedge (st2, indicateSleep, false) \\
& \Rightarrow (u, believedToDo, WakeUp)
\end{aligned}$$

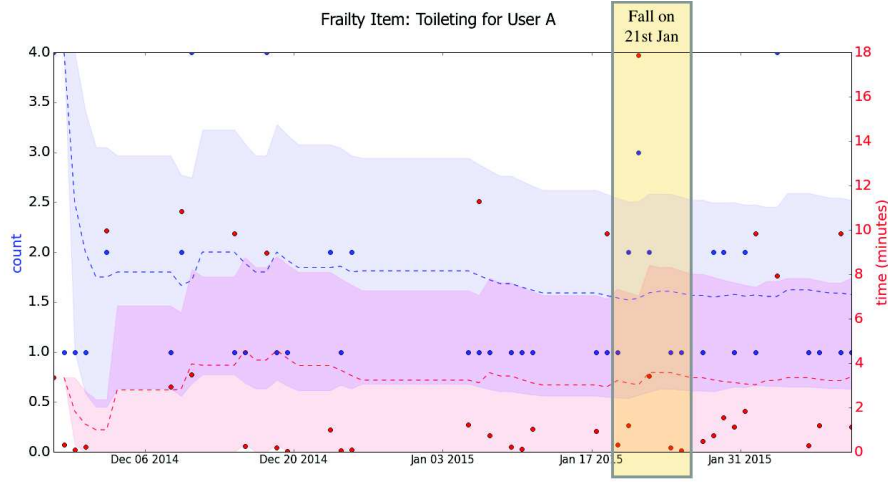
The system aims at detecting outliers in the individual trending according to a specific action. Figure 6-25(a) shows the evolution of the *Toileting* activity for user *A*. Figure 6-25(b) focuses

on the *Night Toileting* activity, and Figure 6-25(c) presents the amount of *Sleep* activity in the same dates. It can be noted that this figure also includes aggregated information that it is used in the performance validation of the frailty model.

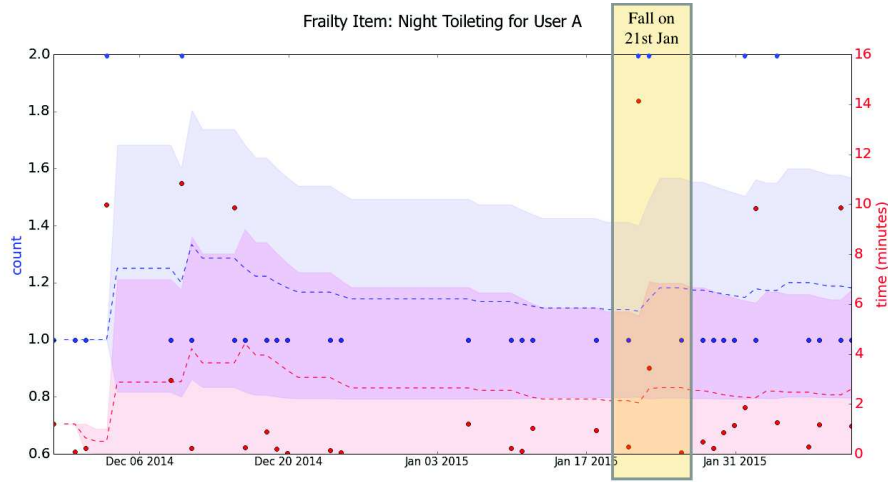
The deployments performed in France did not include the FOS because this sensor was integrated at the end of 2016 in the Singapore Pilot Site. Therefore, an additional validation was performed independently of the others sensors, and the study was completely centered on FOS combined with motion sensors.

The sleep data is continuously acquired from the pilot site. Figure 6-26(c) represents the evolution of the *Wake Up Time* item with its boundaries computed day by day. It can be observed that at the end of the deployment this senior woke up several days later than usual. Figure 6-26(b) shows the evolution of the amount of time spent by the same senior during the deployment. It can be also noted that at the end of the deployment the senior slept fewer hours regarding his average and he overpassed the normality boundaries.

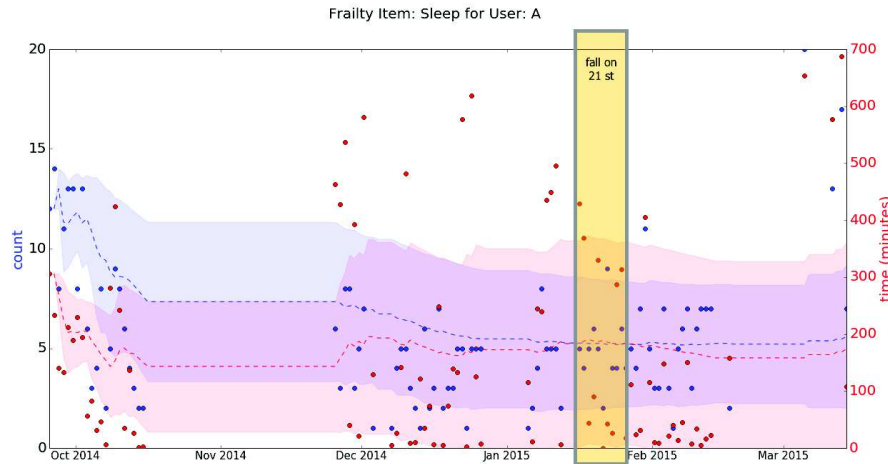
It can also be observed a notable improvement in terms of detection of bed activity compared to the previous approach using motion sensors. In Figure 6-26(a) the user is characterized in a multidimensional spider graph. The heart rate and the respiratory rate are computed and updated each hour. Figure 6-26 represents the result of the evolution of the *bed activity* along the deployment. For instance, it is detected that resident *M* started the bed activity very soon in the evening, and he/she woke up around 2.30 am. At first, it seemed to be an aberration in the measurement. However, in the survey, the resident confirmed that the sleeping time matched the results.



(a) *Toileting* frailty item for user *A*. the user reports high abnormal *Toileting* behaviors in time and occurrences around the 21st September, when a fall was detected.

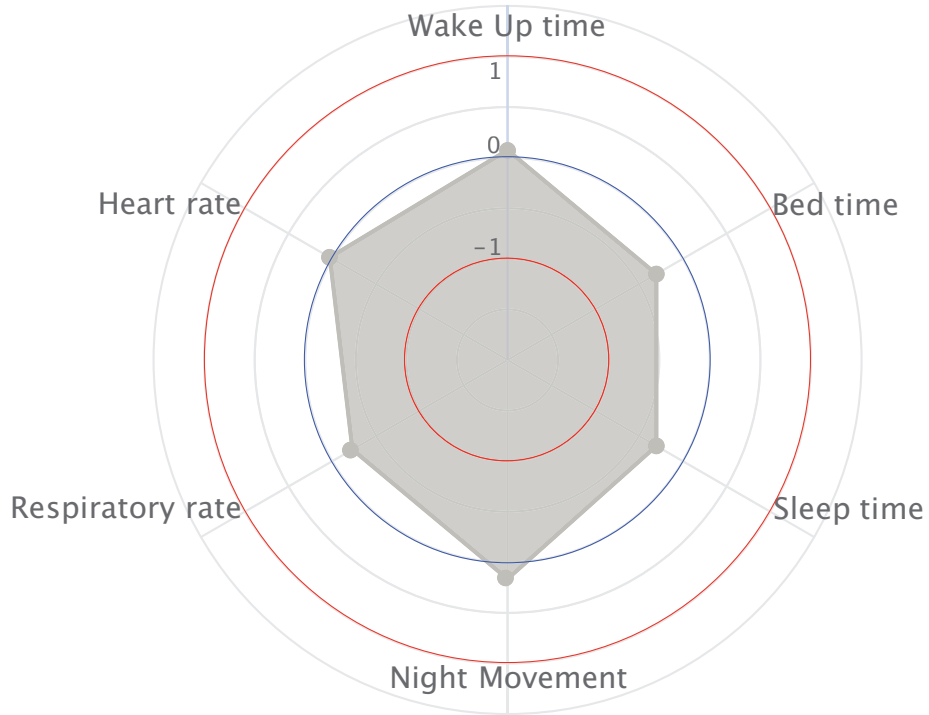


(b) *Night Toileting* frailty item for user *A*. The user reported high abnormal behavior in *Night Toileting* around the 21st September.

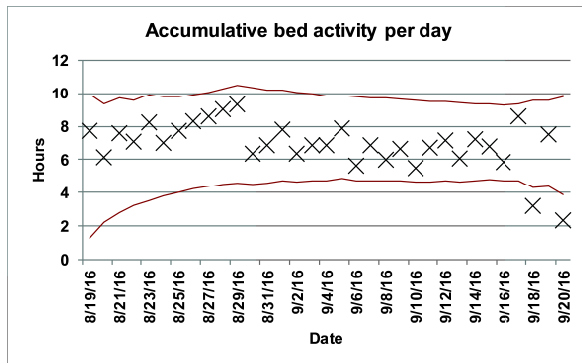


(c) *Sleep* frailty item for user *A*. The user has a very variable behavior in *Sleep* time, however, an abnormal behavior in *Sleep* occurrences is reported around the 21st September.

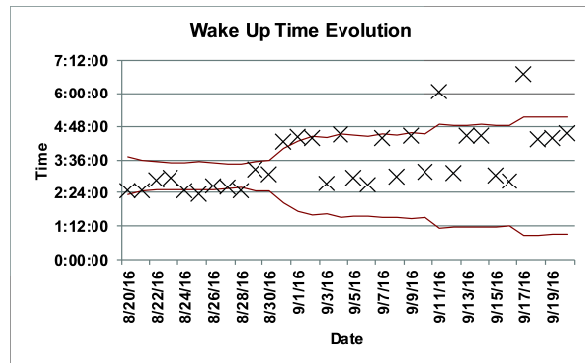
Figure 6-25: Frailty values for User *A*. The presented items reported troubles on sleep and toileting before the user has a fall accident. The data in red corresponds to the daily time-based computation and the data in blue to the occurrences. Each day is represented by a colored dot. The dotted line represents the mean for each frailty item and the colored surfaces are the bland-Altman boundaries, *High* and *Low* frailty. The yellow surface represents a time-window around a risk situation reported by the medical collaborators.



(a)



(b)



(c)

Figure 6-26: Validation on *Sleep* frailty model for resident *M*; (a) Sleep frailty model (b) Bed activity, (c) Wake up time.

Future deployments are planned in the next months, six in France and five in Singapore. Moreover, Singapore pilot site will include a neighborhood equipped with BLE Beacons. Next deployments will allow to improve the proposed frailty model with all sensing capabilities simultaneously. Table 6.9 lists the expected new deployments and its implemented technologies.

Table 6.9: Future Deployments and technology inclusion.

ID	Location	X10	Zwave	FOS	BLE	Mobility
32	Singapore		✓	✓	✓	✓
33	Singapore		✓	✓	✓	✓
34	Singapore		✓	✓	✓	✓
35	Singapore		✓	✓	✓	✓
36	Singapore		✓	✓	✓	✓
37	France	✓		✓	✓	✓
38	France	✓		✓	✓	✓
39	France	✓		✓	✓	✓
40	France	✓		✓	✓	✓
41	France	✓		✓	✓	✓

### 6.5.1 Frailty Model Performance and Discussion

In order to validate the performance of the frailty model, the feedback data is treated and included in the dataset. This validation has been performed by comparing the frailty values inferred by UbiSmart to the ground-truth reports provided by the medical collaborators. The nature of the reports are based on nursing home feedback, therefore some of the ADL have not been calculated, such as *Nutrition*. Using the feedback from the collaborators, the frailty model has been characterized in terms of *Precision* and *Recall*, see Equation 6.3.

The medical reports were manually annotated for each user detecting *sickness*, *falls*, and *hospitalizations*. Any risk situation reported by the ground-truth is highlighted within a two days windows, before and after, in order to allocate an action time for each risk situation (see Figure 6-27 as an example).

The ultimate goal is to discover the compromise between the number of items triggered and the type of event detected. The experiment counts how many items are triggered when a risk situation is detected. The study also includes false positive occurrences when the system detects a frail situation but does not match with the medical reports. The results of this experiment are reported in Table 6.10. Needless to say, if three items are detected. two and one item are also detected. However, for the ease of the study, the number of items have been treated independently.

In order to illustrate the study, Figure 6-26 exposes one of the possible frailty scenarios with several frailty items are out of their normal values when a frail situation is detected. It can be noted that in September the user experienced frail situations during his/her visits to the bathroom and the amount of *Sleep*. This information is correlated to risk situation from this



Table 6.10: UbiSmart Precision and Recall detecting a frail situations depending on the number of frailty items triggered.

	Frailty Items	Precision	Recall	F1-Score
Any Risk	1	<b>49.5%</b>	<b>68.6%</b>	<b>57.5%</b>
	2	33.8%	24%	28.1%
	3	50%	19.2%	27.7%
	4	25%	3.6%	6.3%
Sickness	1	<b>46.9%</b>	<b>75%</b>	<b>57.7%</b>
	2	22%	18 %	19.8 %
	3	13%	11.1%	12 %
	4	3%	4.1%	3.5 %
Fall	1	1.7%	66.6%	3.3%
	2	5.08%	66.6%	9.4%
	3	<b>12%</b>	<b>50%</b>	<b>19.3%</b>
	4	0	0	0
Hospitalization	1	0.86%	80%	1.70%
	2	6.77%	80%	12.5%
	3	<b>12.5%</b>	<b>57%</b>	<b>20.5 %</b>
	4	0	0	0

user and it can be concluded that these frailties were detected days before the user suffered a fall. In the same direction Figure 6-27 represents another scenario where a single frail item is triggered. In this case User *E* incremented his/her movement around the home before falling.

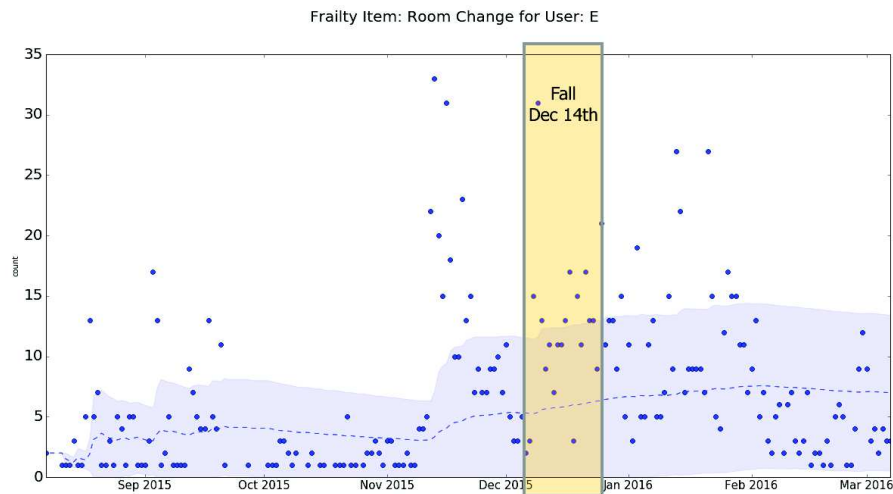


Figure 6-27: Frailty detection for user *E* based on a single item. The user *E* increased the movement in his/her place before a fall. It can be also noted that the user reports an increase of movement during several days before the fall. The data in blue corresponds to the daily computation. The dotted line represents the mean for the frailty item and the colored surface limits the bland-Altman boundaries, *High* and *Low* frailty.

Others users did not experience falls but they had physical impairments such as leg or foot pain. User *B* reduce drastically his/her mobility inside the home when suffering from left foot pain, as presented Figure 6-28.

User *I* experienced two different types of trouble in a short period of time. At the beginning

of September the user had leg pain and he/she reduces the amount of *Sleep* time (Figure 6-29(c)) and the movement inside the home (Figures 6-29(b) and 6-29(a)). Weeks later, the nursing home reported anxiety episodes with sleep troubles and wandering during nights.

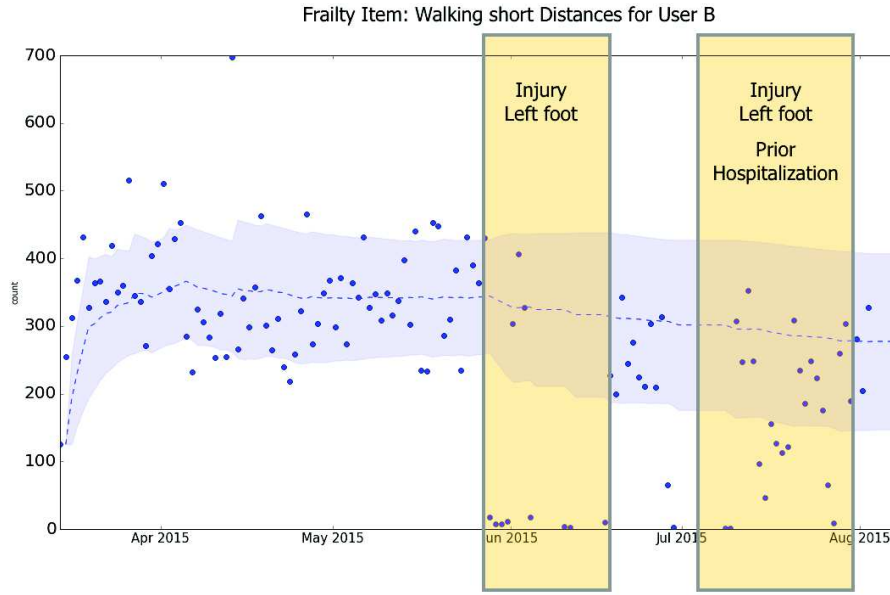
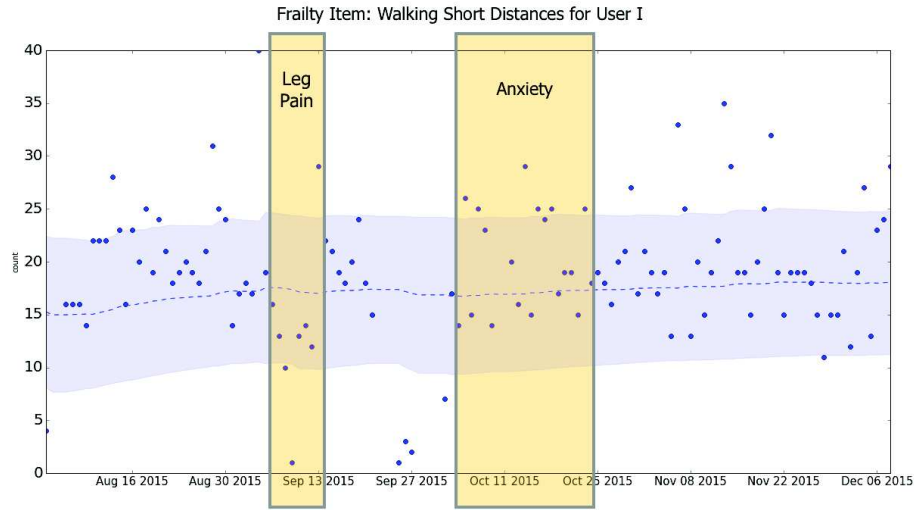


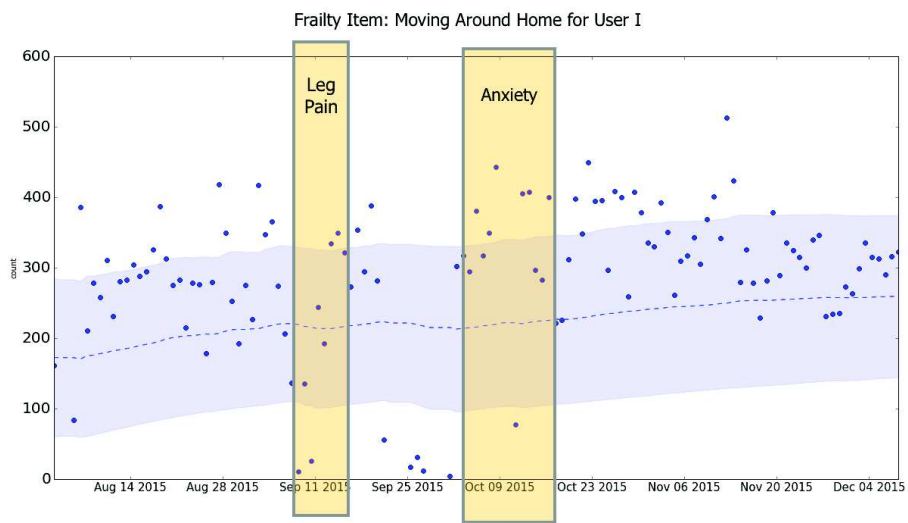
Figure 6-28: Frail situation reported by an independent frailty item for user *B*. It can be clearly stated that the user drastically reduced his/her indoor movement during the foot injury. The data in blue corresponds to the daily computation. The dotted line represents the mean for the frailty item and the colored surface limits the bland-Altman boundaries, *High* and *Low* frailty.

Results show acceptable performances at the *Sensitivity* level. In general terms, the system is too sensitive when using a single frailty item. For any risk situation it reaches 68.6% of *Sensitivity* and 50% of *Precision* with one frailty item. Fall and Hospitalization results are also satisfactory when combining three frailty items reaching 66.6% and 80% of *Sensitivity*. However, the system performs with low *Precision* when detecting a specific risk situation. Using independent frailty items the system detected a large number of frail situations with a high number of *False Positives*. I understand that the system needs to prioritize the low ratio of false Negative *FN* even if it increases the False Positive ratio *FP*.

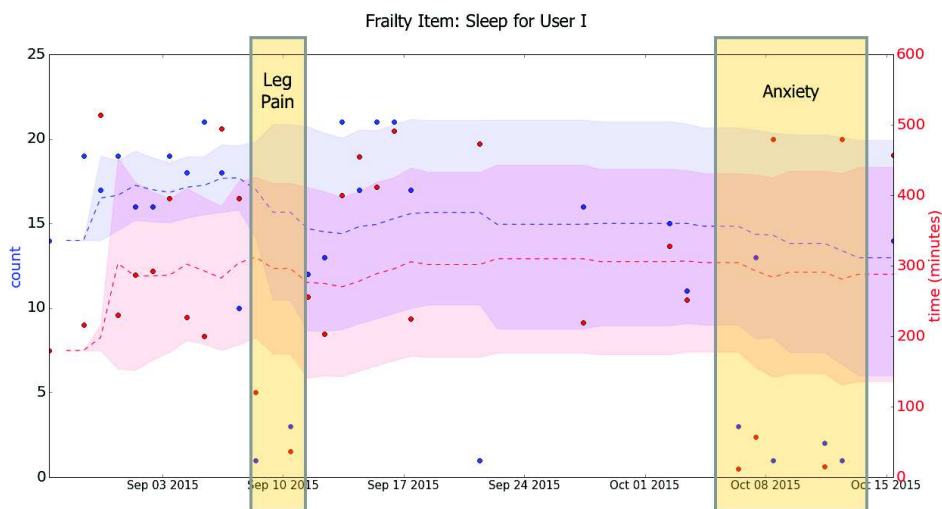
Results also highlight that to detect *Any Problem* or *Sickness* the best choice is to use single independent frailty items. To detect high risk situations (*Fall* and *Hospitalizations*) the best choice is to require three positive frailty items to trigger a frail situation, or two if increasing false positives is not a concern. The most sensible frailty items in this thesis resulted to be the *Sleep Performance*, *Time Out of Home*, *Toileting*, *Moving Around Home* and *Walking Short Distance*. The results are encouraging to future research and report promising results by only using unobtrusive technologies. Future deployments combining multiple sensing capabilities will bring new insights expected to improve the frailty assessment.



(a) *Moving Around Home* frailty item for user A. The user reported and variable behavior around a leg pain. Days later the user increased his/her movement during an anxiety process.



(b) *Walking Short Distances* frailty item for user A. The user reported and variable behavior around a leg pain. Days later the user increased his/her movement during an anxiety process.



(c) *Sleep* frailty item for user A. The user reported a decrease of *Sleep* time and occurrences during the leg pain. During the anxiety process, the user reported a drastically decrease of *Sleep* time and occurrences.

Figure 6-29: Frailty values for User A. The presented items highlighted troubles on sleep and toileting before the user has a fall accident. The data visualization follows the same legend than Figure 6-25.

## Chapter 7

# Conclusion

In this thesis, I have presented the design, the software development and implementation, and the validation in real conditions of life of a holistic AAL framework, which aims at understanding the individual activities of daily living (ADL), both indoors and outdoors. The integrated system was developed by using human-centered approach, and associated human metrics, to detect and prevent risk situations based on user frailty values. The proposed system uses a *Small Data* approach to infer the maximum information from non-invasive data. The system has been deployed in more than 30 living environments for the last three years, in both France and Singapore. The deployments raised awareness of limitations and precious lessons learned that allowed us to improve the framework and validate it with the involvement of end-users and caregivers.

The framework, UbiSmart, uses a minimal invasive hardware approach with non-invasive sensors to track the user constantly. The hardware is based on industrial devices offering robustness and ease of maintenance. The sensing relies on motion, contact, and Fiber Optic sensors for the indoor event and BLE Beacons and the smartphone inner sensors for the outdoors. UbiSmart uses a hybrid reasoning of Data-Driven and Knowledge-Driven approach keeping a compromise between a minimum amount of hardware and maximum sensing capabilities. The system refers to specific ADL (such as *Sleep*, *Mobility* (indoor and outdoor), *Socialization*, and *Hygiene*) to infer the human performance.

A model of six dimensions of the human frailty (with 16 frailty items) is used to understand the human behavior from a novel perspective. The computation is based on the ADL and is homogenized with the WHO definition of human International Classification of Functioning, Disability and Health, ICF. The definition of each dimension and value is based on an extensive medical literature review on frailty. The model has been validated using real ground truth collected from medical collaborators. The validation is divided into four parts: framework design, mobility classification, real deployment, and frailty model.

First, the design and implementation of UbiSmart is evaluated with cognitive and usability

tools, CW and Heuristic Analysis. The results show that UbiSmart reaches the expectations in terms of usability with average values with space for improvements in terms of User Experience (UX). The validation is centered in five interfaces and it has included four participants (technical and non-technical profile). The study highlights that the main user interface performs above the rest of interfaces. The connection page lacks guidance and does not help in recovering from potential errors. The services interfaces are in general low rated. There are improvements to be performed at the interaction level with clear and explicit legends. Also, the framework needs to be simplified to help the navigation and avoid the confusion of the user.

Second, the mobility classifier is validated using ground-truth collected with a mobile App. It aims at detecting the type of displacement done by the user (*walk, Cycling, MRT, Bus, Private Car*) using the inner smartphone sensors and without postural or position restrictions. This classifier defines a novel mobility paradigm with an *Active* and *Passive* approach. *Active* is understood as a type of mobility that demands of physical effort and *Passive* is a door to door movement with no physical effort involved. Different learning algorithms using raw data from the sensors and preprocessed data (time windowing) have been studied. The best results scale up to 96% accuracy when using fourth polynomial SVM with a two-second window. However, this classifier reported a lower compromise *Accuracy/Time* comparing to the K-NN with  $K = 3$  with a similar *Accuracy* and 110 seconds faster. This model has not been deployed in real scenarios yet. It is expected to be deployed in the immediate months.

Third, UbiSmart has been validated in real scenarios subject to diverse technical issues, and user feedback has been collected. The validation details the impact of the improvements in the deployment procedure to succeed with a real and distant deployment. Different versions of UbiSmart have been deployed for the last three years in France and Singapore using multiple types of sensors and combining their feedback. The IoT approach recently adopted reduced the human effort, and the deployment time and maintenance time from two hours to one hour and from one hour to 20 minutes, respectively.

Fourth, the proposed frailty model is validated with medical ground-truth. The system computes 16 frailty items within six frailty dimensions. This thesis details the steps followed to understand the concept of frailty, the computational model and its implementation in UbiSmart. This validation has been performed by comparing the frailty values inferred by UbiSmart to the ground-truth reports provided by the medical collaborators. The nature of the reports are based on nursing home feedback, therefore some of the ADL have not been calculated, such as *Nutrition*. The results confirm the feasibility of computing personal condition from non-invasive sensor data through a non-supervised model. These values are analyzed in relation to their respective long-term average. To facilitate their interpretation, the boundaries *Low* and *High* frailty are introduced.

Using independent frailty items the system detected a large number of frail situations with a

high number of *False Positives*. Therefore, an exhaustive study was performed to find the right compromise between *Precision* and *Recall* when detecting a frail situation. The medical ground-truth was classified as *Sickness*, *Fall*, *Hospitalizations* and *Any Problem*. Results shown that to detect *Any Problem* or *Sickness* the best choice is to use single independent frailty items. To detect high risk situations (*Fall* and *Hospitalizations*) the best choice is to require three positive frailty items to trigger a frail situation, or two if increasing false positives is not a concern. The most sensible frailty items in this thesis resulted to be the *Sleep Performance*, *Time Out of Home*, *Toileting*, *Moving Around Home* and *Walking Short Distance*. Future deployments combining multiple sensing capabilities will bring new insights expected to improve the frailty assessment.

## 7.1 Lessons Learned

This thesis highlights some lessons learned which add value and bring precious feedback for future experimentations. Deploying in real situations requires a high involvement from the technical side and the end users. Recruiting participants is a hard task that needs to be performed in collaboration with social and medical partners. In the case of this thesis, a nursing home in France and a Senior Activity Center in Singapore helped our team to approach seniors willing to participate in the study. Moreover, the partners helped to define the real needs associated with each frailty item in the proposed model. One of the conclusions is that aging people fears technology due to lack of familiarity. Aging people in Singapore are reluctant to add technology in their daily life. An exhaustive task of explanation and introduction to technology was performed to reassure the participants about the aims of the study and its boundaries. It can be also highlighted that despite the technical issues the stakeholders reported a high system adoption with a positive feedback. the caregivers reported the vision of the elderlies: "From the perspective of the seniors, especially the 10 participants, they are very receptive to this and they are also very thankful to your team for coming down to install this, because they believe that this can help to track their well-being." And their own opinion: "We are also very supportive of this because we feel that this approach is non-intrusive. It respects the seniors' privacy...able to ensure that they are okay at home."

Globally, the system needed a minimum of one on-site visit. The principle interruptions were due to electrical shutdowns or user manipulation. At the hardware level, UbiSmart experienced major changes during the three years deployment. This fact highlighted difficulties to stabilize the system. As an example, Singapore aging do not have an Internet connection at their places neither a smartphone. A small WiFi router was placed in their homes attached to the gateway with a prepaid data plan. After three weeks of continuous working, the router reported problems and it needed to be rebooted on-site. The inclusion of the Fiber Optic sensor increased the need for better computational capabilities of the framework, as the gateway was overflowed with a

very large number of messages. The gateway reported a performances failures over a long period deployment and it needed a rebooting.

At the software level, the change of motion and contact sensors from X10 to Z-wave technology required to add new software layers to adapt the Z-wave behavior to fit UbiSmart needs. Moreover, Z-wave sensors needed a supplementary action to include each sensor to the receiver instead of X10 sensors. An extensive report from the Singapore deployment is included in Appendix D.

Finally, at the reasoning level, time-based frailty items such as *Time Sleeping*, *Wake Up time*, *Time out of home*, etc, were very faulty along time. To deal with this issues, mitigating rules were added on the reasoning. With the inclusion of the Fiber Optic sensor and the mobility classifier I believe the system will increase notably on the time-based computational performance.

From my point of view, AAL for aging and frail people needs to be deployed in real situations. From this assumption, the research in assistive technology becomes a transversal topic between engineering, social and medical. Even though this thesis focuses on the engineering point of view, many interactions were required to define the strategy of design and implementation. Moreover, simulated data is not aligned with the daily life of people. It is necessary to prepare the system in controlled environments and export the solution to real problematics. The user inclusion and recruitment is a key challenge and highly valuable in this field. Real deployments are often exhausting and frustrating because it takes a long time to stabilize at the hardware (such as device failures, battery problems, disconnections, etc) or software level (rules faulty, uncertainty handling, etc). However, I believe that real deployments are highly rewarding as they impact on the daily problematics of our seniors.

## 7.2 Perspectives

I believe that the inclusion of the Fiber Optic sensor and the mobility classifier in further research will increase the accuracy and precision of the system when detecting frailty situations. New algorithms to understand frailty will be able to build strong correlations between frailty items. However, there is a need to build new methodologies to collect reliable ground-truth. Related to the human performances, there is a complementary field that can be studied in parallel such as the human change behavior as a permanent evolution of the human.

The hardware agnostic approach in UbiSmart opens a wide range of possibilities in terms of sensing capabilities, even though it demands a special effort at the software and reasoning level. Using industrial sensors reduces the maintenance cost and physical failures. Industrial sensors are becoming smarter, and thus powerful to the AAL field from the reasoning point of view.

Including new technologies will be easier in the near future since the aging of the future will be more familiar with them (open data, wearables, etc). New sensing capabilities will be highly



valuable for the outdoor and vital signs record.

Research on real problematics with real deployments have raised high expectations on the industrial field. Exporting research to the real scenario will approach the industry and research fields. The research experimentation will interest the industry on how novel methods could impact on their business. Therefore, I believe that AAL and UAL will build strong research and transversal projects between, research laboratories, industry, and Public organizations.

This thesis raised new research topics and challenges to tackle in the near future:

- Refinement of the frailty model by including new sensing capabilities, new pilot sites and improving the ground-truth collection.
- Hybrid reasoning (Data-Driven and Knowledge-Driven) with data pattern recognition with long period and uninterrupted deployments.
- Human modeling using data fusion from the UbiSmart approach and aggregated data from water and electricity consumption.
- Inclusion of supportive and adaptive technology for dependent people during their transportation upon his/her situation.



# Bibliography

- [1] B. Abdulrazak and A. Helal. “Enabling a Plug-and-play integration of smart environments”. In: *2006 2nd International Conference on Information & Communication Technologies*. Vol. 1. IEEE. 2006, pp. 820–825.
- [2] B. Abdulrazak et al. “A standard ontology for smart spaces”. In: *International Journal of Web and Grid Services* 6.3 (2010), pp. 244–268.
- [3] S. Aguilar-Navarro et al. “The Phenotype of Frailty Predicts Disability and Mortality among Mexican Community-Dwelling Elderly.” In: *The Journal of frailty & aging* 1.3 (2012), pp. 111–117.
- [4] E. Al Nuaimi et al. “Applications of big data to smart cities”. In: *Journal of Internet Services and Applications* 6.1 (2015), p. 25.
- [5] R. S. Alonso et al. “Implementing a hardware-embedded reactive agents platform based on a service-oriented architecture over heterogeneous wireless sensor networks”. In: *Ad Hoc Networks* 11.1 (2013), pp. 151–166.
- [6] H. Aloulou. “Framework for Ambient Assistive Living: Handling Dynamism and Uncertainty in Real Time Semantic Services Provisioning”. PhD thesis. Institut Mines-Télécom, EDITE, 2013.
- [7] H. Aloulou et al. “A semantic plug&play based framework for ambient assisted living”. In: *Impact Analysis of Solutions for Chronic Disease Prevention and Management*. Springer, 2012, pp. 165–172.
- [8] H. Aloulou et al. “A Semantic Plug&Play Based Framework for Ambient Assisted Living”. In: *Impact Analysis of solutions for chronic disease Prevention and Management*. Lecture Notes in Computer Science. Springer, 2012.
- [9] H. Aloulou et al. “Simplifying Installation and Maintenance of Ambient Intelligent Solutions Toward Large Scale Deployment”. In: *Inclusive Smart Cities and Digital Health: 14th International Conference on Smart Homes and Health Telematics, ICOST 2016, Wuhan, China, May 25-27, 2016. Proceedings*. Cham: Springer International Publishing, 2016, pp. 121–132. ISBN: 978-3-319-39601-9.
- [10] H. Aloulou et al. “Uncertainty Handling in Semantic Reasoning for Accurate Context Understanding”. In: *Knowledge-Based Systems* (2015).
- [11] B. E. Alvarado et al. “Life course social and health conditions linked to frailty in Latin American older men and women”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 63.12 (2008), pp. 1399–1406.
- [12] A.-V. Anttiroiko. “Science cities: their characteristics and future challenges”. In: *International Journal of Technology Management* 28.3-6 (2004), pp. 395–418.
- [13] T. Bakıcı, E. Almirall, and J. Wareham. “A smart city initiative: the case of Barcelona”. In: *Journal of the Knowledge Economy* 4.2 (2013), pp. 135–148.
- [14] N. Baucells, C. Moreno, and R. M. Arce. “Mapping Smart Cities Situation+ CITIES: The Spanish Case”. In: *International Conference on Smart Cities*. Springer. 2016, pp. 95–105.
- [15] J. Bélistent et al. “Getting clever about smart cities: new opportunities require new business models”. In: *Cambridge, Massachusetts, USA* (2010).

- [16] R. Bell, J. Jung, and L. Zacharilla. “Broadband economies”. In: *Creating the community of the 21st century. New York: Intelligent Community Forum*. 2008, pp. 22–32.
- [17] J. Bellmunt et al. “Agile Framework for Rapid Deployment in Ambient Assisted Living Environments”. In: *Proceedings of the 18th International Conference on Information Integration and Web-based Applications and Services. iiWAS '16*. Singapore, Singapore: ACM, 2016, pp. 410–413. ISBN: 978-1-4503-4807-2. DOI: 10.1145/3011141.3011196. URL: <http://doi.acm.org/10.1145/3011141.3011196>.
- [18] J. Bellmunt et al. “Experimental Frailty Model towards an Adaptable Service Delivery for Aging People”. In: *Engineering of Complex Computer Systems (ICECCS), 2016 21st International Conference on*. IEEE. 2016, pp. 227–230.
- [19] J. Bellmunt et al. “Technical Challenges Towards an AAL Large Scale Deployment”. In: *Inclusive Smart Cities and e-Health*. Springer, 2015, pp. 3–14.
- [20] M. Berenguer et al. “Automatic detection of activities of daily living from detecting and classifying electrical events on the residential power line”. In: *e-health Networking, Applications and Services, 2008. HealthCom 2008. 10th International Conference on*. IEEE. 2008, pp. 29–32.
- [21] T. Berners-Lee. *Closed World Machine (cwm)*. <http://www.w3.org/2000/10/swap/doc/cwm.html>. 2000-2009.
- [22] C. R. Berry and E. L. Glaeser. “The divergence of human capital levels across cities”. In: *Papers in regional science* 84.3 (2005), pp. 407–444.
- [23] G. Bieber, J. Voskamp, and B. Urban. “Activity recognition for everyday life on mobile phones”. In: *International Conference on Universal Access in Human-Computer Interaction*. Springer. 2009, pp. 289–296.
- [24] S. Blackman et al. “Ambient assisted living technologies for aging well: a scoping review”. In: *Journal of Intelligent Systems* 25.1 (2016), pp. 55–69.
- [25] M. H. Blackmon et al. “Cognitive walkthrough for the web”. In: *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM. 2002, pp. 463–470.
- [26] J. M. Bland and D. G. Altman. “Comparing methods of measurement: why plotting difference against standard method is misleading”. In: *The lancet* 346.8982 (1995), pp. 1085–1087.
- [27] A. Bolbol et al. “Inferring hybrid transportation modes from sparse GPS data using a moving window SVM classification”. In: *Computers, Environment and Urban Systems* 36.6 (2012), pp. 526–537.
- [28] W. M. Bortz. “A Conceptual Framework of Frailty A Review”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 57.5 (2002), pp. M283–M288.
- [29] J. Bravo et al. “A mobile proposal for frailty monitoring by rehabilitation and physical daily activity”. In: *Consumer Electronics-Berlin (ICCE-Berlin), 2011 IEEE International Conference on*. IEEE. 2011, pp. 176–180.
- [30] I. Brown, R. Renwick, and D. Raphael. “Frailty: constructing a common meaning, definition, and conceptual framework.” In: *International Journal of Rehabilitation Research* 18.2 (1995), pp. 93–102.
- [31] A. J. Campbell and D. M. Buchner. “Unstable disability and the fluctuations of frailty”. In: *Age and ageing* 26.4 (1997), pp. 315–318.
- [32] C. F. Capra. “The Smart City and its Citizens: Governance and Citizen Participation in Amsterdam Smart City”. In: *International Journal of E-Planning Research (IJEPR)* 5.1 (2016), pp. 20–38.
- [33] A. Caragliu, C. Del Bo, and P. Nijkamp. “10 Smart cities in Europe”. In: *Smart cities: governing, modelling and analysing the transition* (2013), p. 173.

- [34] A. Caragliu, C. Del Bo, and P. Nijkamp. “Smart cities in Europe”. In: *Journal of urban technology* 18.2 (2011), pp. 65–82.
- [35] A. Caragliu, C. Del Bo, and P. Nijkamp. “Smart cities in Europe”. In: *Journal of urban technology* 18.2 (2011), pp. 65–82.
- [36] J. E. Carlson et al. “MEASURING FRAILTY IN THE HOSPITALIZED ELDERLY: Concept of Functional Homeostasis<sup>1</sup>”. In: *American journal of physical medicine & rehabilitation* 77.3 (1998), pp. 252–257.
- [37] I. Carrière et al. “Hierarchical components of physical frailty predicted incidence of dependency in a cohort of elderly women”. In: *Journal of clinical epidemiology* 58.11 (2005), pp. 1180–1187.
- [38] A. Carvalho et al. “Physical activity and cognitive function in individuals over 60 years of age: a systematic review.” In: *Clinical interventions in aging* 9 (2013), pp. 661–682.
- [39] M. Cesari et al. “A physical activity intervention to treat the frailty syndrome in older persons—results from the LIFE-P study”. In: *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 70.2 (2014), pp. 216–222.
- [40] A. Cocchia. “Smart and digital city: A systematic literature review”. In: *Smart city*. Springer, 2014, pp. 13–43.
- [41] D. J. Cook et al. “CASAS: A Smart Home in a Box”. In: *Computer* 46.7 (2013), pp. 62–69. ISSN: 0018-9162.
- [42] E. Y. Cornwell and L. J. Waite. “Social disconnectedness, perceived isolation, and health among older adults”. In: *Journal of health and social behavior* 50.1 (2009), pp. 31–48.
- [43] P. M. Cozens. “New urbanism, crime and the suburbs: A review of the evidence”. In: *Urban Policy and Research* 26.4 (2008), pp. 429–444.
- [44] J. Cubo, A. Nieto, and E. Pimentel. “A Cloud-Based Internet of Things Platform for Ambient Assisted Living”. In: *Sensors* 14.8 (2014), pp. 14070–14105.
- [45] R. Daniels et al. “Interventions to prevent disability in frail community-dwelling older persons: an overview”. In: *European Journal of Ageing* 7.1 (2010), pp. 37–55.
- [46] W. Dargie. *Context-aware computing and Self-Managing systems*. Vol. 3. Chapman & Hall/CRC, 2009.
- [47] N. E. Dayhoff et al. “Balance and muscle strength as predictors of frailty among older adults”. In: *Journal of gerontological nursing* 24.7 (1998), pp. 18–27.
- [48] J. De Lepeleire et al. “Frailty: an emerging concept for general practice”. In: *Br J Gen Pract* 59.562 (2009), e177–e182.
- [49] P. Domingos. “A few useful things to know about machine learning”. In: *Communications of the ACM* 55.10 (2012), pp. 78–87.
- [50] H. Elzabadani et al. “Self-sensing spaces: smart plugs for smart environments”. In: *Proceedings of the 3rd International Conference on Smart Nomes and Health Telematics*. 2005, pp. 91–98.
- [51] K. E. Ensrud et al. “Frailty and risk of falls, fracture, and mortality in older women: the study of osteoporotic fractures”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 62.7 (2007), pp. 744–751.
- [52] J. L. Falcó et al. “AmI and deployment considerations in AAL services provision for elderly independent living: The MonAMI project”. In: *Sensors* 13.7 (2013), pp. 8950–8976.
- [53] L. Ferrucci et al. “Designing randomized, controlled trials aimed at preventing or delaying functional decline and disability in frail, older persons: a consensus report”. In: *Journal of the American Geriatrics Society* 52.4 (2004), pp. 625–634.
- [54] M. A. Fiatarone et al. “Exercise training and nutritional supplementation for physical frailty in very elderly people”. In: *New England Journal of Medicine* 330.25 (1994), pp. 1769–1775.

- [55] G. S. Ford and T. M. Koutsy. “Broadband and economic development: A municipal case study from Florida”. In: *Review of urban & regional development studies* 17.3 (2005), pp. 216–229.
- [56] L. P. Fried et al. “Frailty in older adults evidence for a phenotype”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 56.3 (2001), pp. M146–M157.
- [57] L. P. Fried et al. “Untangling the concepts of disability, frailty, and comorbidity: implications for improved targeting and care”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 59.3 (2004), pp. M255–M263.
- [58] C. Gagliardi et al. “Associations of personal and mobility resources with subjective well-being among older adults in Italy and Germany”. In: *Archives of Gerontology and Geriatrics* 50.1 (2010), pp. 42–47.
- [59] L. Georghiou. “Integrating Health and Social Care to Cope With an Aging Population: Innovation Challenges”. In: *2017 AAAS Annual Meeting (February 16-20, 2017)*. aaas. 2017.
- [60] M. Ghorbel, M. Mokhtari, and S. Renouard. “A distributed approach for assistive service provision in pervasive environment”. In: *Proceedings of the 4th international workshop on Wireless mobile applications and services on WLAN hotspots*. ACM. 2006, pp. 91–100.
- [61] T. M. Gill et al. “Impairments in physical performance and cognitive status as predisposing factors for functional dependence among nondisabled older persons”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 51.6 (1996), pp. M283–M288.
- [62] T. M. Gill et al. “Transitions between frailty states among community-living older persons”. In: *Archives of internal medicine* 166.4 (2006), pp. 418–423.
- [63] E. L. Glaeser and C. R. Berry. “Why are smart places getting smarter”. In: *Taubman Center Policy Brief 2* (2006).
- [64] F. M. Gloth III et al. “Reliability and validity of the Frail Elderly Functional Assessment questionnaire.” In: *American journal of physical medicine & rehabilitation* 74.1 (1995), pp. 45–53.
- [65] R. Gobbens et al. “Towards an integral conceptual model of frailty”. In: *The journal of nutrition, health & aging* 14.3 (2010), pp. 175–181.
- [66] D. Gooch et al. “Reimagining the role of citizens in smart city projects”. In: *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers*. ACM. 2015, pp. 1587–1594.
- [67] E. Guillely et al. “Dynamics of frailty and ADL dependence in a five-year longitudinal study of octogenarians”. In: *Research on Aging* 30.3 (2008), pp. 299–317.
- [68] J. M. Guralnik et al. “Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability”. In: *New England Journal of Medicine* 332.9 (1995), pp. 556–562.
- [69] T. L. Hayes et al. “Estimation of rest-activity patterns using motion sensors”. In: *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology*. IEEE. 2010, pp. 2147–2150.
- [70] A. Helal et al. “3D modeling and simulation of human activities in smart spaces”. In: *Ubiquitous Intelligence & Computing and 9th International Conference on Autonomic & Trusted Computing (UIC/ATC), 2012 9th International Conference on*. IEEE. 2012, pp. 112–119.
- [71] S. Helal. “Programming pervasive spaces”. In: *Pervasive Computing, IEEE* 4.1 (2005), pp. 84–87.

- [72] S. Helal et al. “The gator tech smart house: A programmable pervasive space”. In: *Computer* 38.3 (2005), pp. 50–60.
- [73] S. Hemminki, P. Nurmi, and S. Tarkoma. “Accelerometer-based transportation mode detection on smartphones”. In: *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*. ACM. 2013, p. 13.
- [74] S. L. Hoe and S. L. Hoe. “Defining a smart nation: the case of Singapore”. In: *Journal of Information, Communication and Ethics in Society* 14.4 (2016), pp. 323–333.
- [75] Y. Hu et al. “Smart home in a box: usability study for a large scale self-installation of smart home technologies”. In: *Journal of Reliable Intelligent Environments* 2.2 (2016), pp. 93–106.
- [76] T. Hur et al. “Smartphone Location-Independent Physical Activity Recognition Based on Transportation Natural Vibration Analysis”. In: *Sensors* 17.4 (2017), p. 931. ISSN: 1424-8220. DOI: 10.3390/s17040931. URL: <http://dx.doi.org/10.3390/s17040931>.
- [77] R. Jaber et al. “ARPEGE: Assessment of frailty at home”. In: *e-Health Networking, Applications & Services (Healthcom), 2013 IEEE 15th International Conference on*. IEEE. 2013, pp. 434–438.
- [78] D. Jones et al. “Evaluation of a frailty index based on a comprehensive geriatric assessment in a population based study of elderly Canadians”. In: *Aging clinical and experimental research* 17.6 (2005), pp. 465–471.
- [79] D. M. Jones, X. Song, and K. Rockwood. “Operationalizing a frailty index from a standardized comprehensive geriatric assessment”. In: *Journal of the American Geriatrics Society* 52.11 (2004), pp. 1929–1933.
- [80] P. Jürschik et al. “Prevalence of frailty and factors associated with frailty in the elderly population of Lleida, Spain: the FRALLE survey”. In: *Archives of gerontology and geriatrics* 55.3 (2012), pp. 625–631.
- [81] F. Kaddachi et al. “Technological Approach for Behavior Change Detection toward Better Adaptation of Services for Elderly People.” In: *HEALTHINF*. 2017, pp. 96–105.
- [82] B. Kanapuru and W. B. Ershler. “Inflammation, coagulation, and the pathway to frailty”. In: *The American journal of medicine* 122.7 (2009), pp. 605–613.
- [83] J. Kaye et al. “One walk a year to 1000 within a year: Continuous in-home unobtrusive gait assessment of older adults”. In: *Gait & posture* 35.2 (2012), pp. 197–202.
- [84] R. Keith et al. “The functional independence measure”. In: *Adv Clin Rehabil* 1 (1987), pp. 6–18.
- [85] E. Kelaiditi, G. A. van Kan, and M. Cesari. “Frailty: role of nutrition and exercise”. In: *Current Opinion in Clinical Nutrition & Metabolic Care* 17.1 (2014), pp. 32–39.
- [86] N. J. Kirk-Sanchez and E. L. McGough. “Physical exercise and cognitive performance in the elderly: current perspectives”. In: *Clin Interv Aging* 9 (2014), pp. 51–62.
- [87] S. M. Koenig, D. Mack, and M. Alwan. “Sleep and Sleep Assessment Technologies”. In: *Eldercare Technology for Clinical Practitioners*. Totowa, NJ: Humana Press, 2008, pp. 77–120. ISBN: 978-1-59745-233-5. DOI: 10.1007/978-1-59745-233-5\_5. URL: [http://dx.doi.org/10.1007/978-1-59745-233-5\\_5](http://dx.doi.org/10.1007/978-1-59745-233-5_5).
- [88] N. Komninos and E. Sefertzi. “Intelligent cities: R&D offshoring, Web 2.0 product development and globalization of innovation systems”. In: *Second Knowledge Cities Summit 2009* (2009).
- [89] J. M. Kortelainen et al. “Sleep Staging Based on Signals Acquired Through Bed Sensor”. In: *IEEE Transactions on Information Technology in Biomedicine* 14.3 (2010), pp. 776–785. ISSN: 1089-7771. DOI: 10.1109/TITB.2010.2044797.
- [90] D. G. Korzun, S. I. Balandin, and A. V. Gurtov. “Deployment of Smart Spaces in Internet of Things: Overview of the design challenges”. In: *Internet of Things, Smart Spaces, and Next Generation Networking*. Springer, 2013, pp. 48–59.



- [91] M. P. Lawton and E. M. Brody. *Instrumental Activities of Daily Living Scale (IADL)*. 1988.
- [92] C. Lewis et al. “Testing a walkthrough methodology for theory-based design of walk-up-and-use interfaces”. In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM. 1990, pp. 235–242.
- [93] LG. 2017. URL: <http://www.lghomechat.com/>.
- [94] B. E. Lyons et al. “Pervasive computing technologies to continuously assess Alzheimer’s disease progression and intervention efficacy”. In: *Frontiers in aging neuroscience* 7 (2015).
- [95] F. I. Mahoney. “Functional evaluation: the Barthel index”. In: *Maryland state medical journal* 14 (1965), pp. 61–65.
- [96] L. Mainetti et al. “An IoT-aware AAL System to Capture Behavioral Changes of Elderly People”. In: (2017).
- [97] A. Mannini and A. M. Sabatini. “Machine learning methods for classifying human physical activity from on-body accelerometers”. In: *Sensors* 10.2 (2010), pp. 1154–1175. ISSN: 14248220. DOI: 10.3390/s100201154.
- [98] A. Marinc et al. “Interactive personalization of ambient assisted living environments”. In: *Human Interface and the Management of Information. Interacting with Information*. Springer, 2011, pp. 567–576.
- [99] G. Matar et al. “Internet of Things in sleep monitoring: An application for posture recognition using supervised learning”. In: *2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom)*. 2016, pp. 1–6. DOI: 10.1109/HealthCom.2016.7749469.
- [100] M. Matthews et al. “Use of a questionnaire to screen for frailty in the elderly: an exploratory study”. In: *Aging clinical and experimental research* 16.1 (2004), pp. 34–40.
- [101] C. Mayer et al. *AALuis, a user interface layer that brings device independence to users of AAL systems*. Springer, 2012.
- [102] A. Mihailidis et al. “The COACH prompting system to assist older adults with dementia through handwashing: An efficacy study”. In: *BMC Geriatr* 8.1 (2008), p. 1.
- [103] A. Mihailidis et al. “Zero effort technologies: Considerations, challenges, and use in health, wellness, and rehabilitation”. In: *Synthesis Lectures on Assistive, Rehabilitative, and Health-Preserving Technologies* 1.2 (2011), pp. 1–94.
- [104] N. Millor et al. “Kinematic parameters to evaluate functional performance of sit-to-stand and stand-to-sit transitions using motion sensor devices: a systematic review”. In: *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* 22.5 (2014), pp. 926–936.
- [105] A. Mitseva et al. “ISISEMD: Intelligent System for Independent living and self-care of SE-niors with mild cognitive impairment or Mild Dementia”. In: *The Journal on Information Technology in Healthcare* 7.6 (2009), pp. 383–399.
- [106] M. Mokhtari et al. “Measuring the Impact of ICTs on the Quality of Life of Ageing People with Mild Dementia”. In: *Smart Homes and Health Telematics*. Springer, 2015, pp. 103–109.
- [107] M. Mokhtari et al. “New trends to support independence in persons with mild dementia—a mini-review”. In: *Gerontology* 58.6 (2012), pp. 554–563.
- [108] A. Morales et al. “Communication architecture for tracking and interoperable services at hospitals: A real deployment experience”. In: *Ambient Assisted Living*. Springer, 2011, pp. 84–91.
- [109] K. Murad and D. W. Kitzman. “Frailty and multiple comorbidities in the elderly patient with heart failure: implications for management”. In: *Heart failure reviews* 17.4-5 (2012), pp. 581–588.

- [110] H. Nakashima, H. Aghajan, and J. Augusto. *Handbook of ambient intelligence and smart environments*. Springer, 2009.
- [111] J. Nielsen. “Enhancing the explanatory power of usability heuristics”. In: *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM. 1994, pp. 152–158.
- [112] F. Nourhashémi et al. “Instrumental activities of daily living as a potential marker of frailty a study of 7364 community-dwelling elderly women (the EPIDOS study)”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 56.7 (2001), pp. M448–M453.
- [113] N. Noury. “Ambient intelligence might support increased longevity”. In: *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*. IEEE. 2014, pp. 1760–1764.
- [114] N. Noury et al. “A feasibility study of using a smartphone to monitor mobility in elderly”. In: *e-Health Networking, Applications and Services (Healthcom), 2012 IEEE 14th International Conference on*. IEEE. 2012, pp. 423–426.
- [115] N. Noury et al. “Ailisa plateformes d’évaluations pour des technologies de télésurveillance médicale et d’assistance en gériatrie”. In: *Gérontologie et société* 28.2 (2005), pp. 97–119.
- [116] N. Noury et al. “Building an index of activity of inhabitants from their activity on the residential electrical power line”. In: *IEEE Transactions on Information Technology in Biomedicine* 15.5 (2011), pp. 758–766.
- [117] W. H. Organization. *International Classification of Functioning, Disability and Health: ICF*. World Health Organization, 2001.
- [118] W. H. Organization. *World report on ageing and health*. World Health Organization, 2015.
- [119] W. H. Organization et al. “Global health and aging”. In: *Geneva: World Health Organization* (2011).
- [120] W. H. Organization et al. “Urban Green Spaces and Health—A Review of Evidence”. In: *Geneva, Switzerland: WHO* (2016).
- [121] M. G. Ory et al. “Frailty and injuries in later life: the FICSIT trials”. In: *Journal of the American Geriatrics Society* 41.3 (1993), pp. 283–296.
- [122] *OwnTracks - Your location companion*. URL: <http://owntracks.org/> (visited on 08/03/2017).
- [123] J. Paalasmaa et al. “Unobtrusive online monitoring of sleep at home”. In: *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2012, pp. 3784–3788. DOI: 10.1109/EMBC.2012.6346791.
- [124] F. Pacheco-Torgal. “Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020”. In: *Construction and building materials* 51 (2014), pp. 151–162.
- [125] F. Palumbo et al. “Sensor network infrastructure for a home care monitoring system”. In: *Sensors* 14.3 (2014), pp. 3833–3860.
- [126] K. A. Paskaleva. “Enabling the smart city: The progress of city e-governance in Europe”. In: *International Journal of Innovation and Regional Development* 1.4 (2009), pp. 405–422.
- [127] M. Pathan, K. Taylor, and M. Compton. “Semantics-based Plug-and-Play Configuration of Sensor Network Services”. In: *Proc. 3rd International Workshop on Semantic Sensor Networks (SSN’10)*. 2010.
- [128] M. J.C. A. Paw et al. “How to select a frail elderly population? A comparison of three working definitions”. In: *Journal of clinical epidemiology* 52.11 (1999), pp. 1015–1021.
- [129] F. Pedregosa et al. “Scikit-learn: Machine Learning in Python”. In: *Journal of Machine Learning Research* 12 (2011), pp. 2825–2830.

- [130] D. R. Pendergast, N. M. Fisher, and E. Calkins. “9 Cardiovascular, Neuromuscular, and Metabolic Alterations With Age Leading to Frailty”. In: *Journal of Gerontology* 48.Special Issue (1993), pp. 61–67.
- [131] Philips. 2017. URL: <https://www.philips.co.uk/c-m-li/hue>.
- [132] P. Pierce and B. Andersson. “Challenges with smart cities initiatives—A municipal decision makers’ perspective”. In: (2017).
- [133] C Powell. “Frailty: help or hindrance?” In: *Journal of the Royal Society of Medicine* 90.Suppl 32 (1997), p. 23.
- [134] J. Pucher et al. “Walking and Cycling to Health: A Comparative Analysis of City, State, and International Data”. In: *American Journal of Public Health* 100.10 (2010). PMID: 20724675, pp. 1986–1992. DOI: 10.2105/AJPH.2009.189324. eprint: <http://dx.doi.org/10.2105/AJPH.2009.189324>. URL: <http://dx.doi.org/10.2105/AJPH.2009.189324>.
- [135] M. Puts, P. Lips, and D. Deeg. “Static and dynamic measures of frailty predicted decline in performance-based and self-reported physical functioning”. In: *Journal of clinical epidemiology* 58.11 (2005), pp. 1188–1198.
- [136] A. Ranganathan, C. Shankar, and R. Campbell. “Application polymorphism for autonomic ubiquitous computing”. In: *Multiagent and Grid Systems* 1.2 (2005), pp. 109–129.
- [137] G. Ravaglia et al. “Development of an easy prognostic score for frailty outcomes in the aged”. In: *Age and Ageing* 37.2 (2008), pp. 161–166.
- [138] P. Rawat et al. “Wireless sensor networks: a survey on recent developments and potential synergies”. In: *The Journal of supercomputing* 68.1 (2014), pp. 1–48.
- [139] S. Reddy et al. “Using mobile phones to determine transportation modes”. In: *ACM Transactions on Sensor Networks (TOSN)* 6.2 (2010), p. 13.
- [140] T. Robles et al. “An IoT based reference architecture for smart water management processes.” In: *JoWUA* 6.1 (2015), pp. 4–23.
- [141] K. Rockwood and A. Mitnitski. “Frailty in relation to the accumulation of deficits”. In: *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 62.7 (2007), pp. 722–727.
- [142] K. Rockwood, P. Stolee, and I. McDowell. “Factors associated with institutionalization of older people in Canada: testing a multifactorial definition of frailty”. In: *Journal of the American Geriatrics Society* 44.5 (1996), pp. 578–582.
- [143] K. Rockwood et al. “A brief clinical instrument to classify frailty in elderly people”. In: *The Lancet* 353.9148 (1999), pp. 205–206.
- [144] K. Rockwood et al. “Frailty in elderly people: an evolving concept.” In: *CMAJ: Canadian Medical Association Journal* 150.4 (1994), p. 489.
- [145] L. Rodríguez-Mañas et al. “Searching for an operational definition of frailty: a Delphi method based consensus statement. The frailty operative definition-consensus conference project”. In: *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 68.1 (2012), pp. 62–67.
- [146] D. B. Rolfson et al. “Validity and reliability of the Edmonton Frail Scale”. In: *Age and ageing* 35.5 (2006), pp. 526–529.
- [147] L. Rosales et al. “Heart rate monitoring using hydraulic bed sensor ballistocardiogram1”. In: *Journal of Ambient Intelligence and Smart Environments* 9.2 (2017), pp. 193–207.
- [148] M. D. Rothman, L. Leo-Summers, and T. M. Gill. “Prognostic significance of potential frailty criteria”. In: *Journal of the American Geriatrics Society* 56.12 (2008), pp. 2211–2216.
- [149] J. Rowley. “The wisdom hierarchy: representations of the DIKW hierarchy”. In: *Journal of information science* 33.2 (2007), pp. 163–180.



- [150] M. Ruthirakuhan et al. "Use of physical and intellectual activities and socialization in the management of cognitive decline of aging and in dementia: a review". In: *Journal of aging research* 2012 (2012).
- [151] I. Sadek et al. "Sensor data quality processing for vital signs with opportunistic ambient sensing". In: *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 2016, pp. 2484–2487. DOI: 10.1109/EMBC.2016.7591234.
- [152] I. Sadek et al. "Automatic heart rate detection from FBG sensors using sensor fusion and enhanced empirical mode decomposition". In: *Signal Processing and Information Technology (ISSPIT), 2015 IEEE International Symposium on*. IEEE. 2015, pp. 349–353.
- [153] I. Sadek et al. "Continuous and Unconstrained Vital Signs Monitoring with Ballistocardiogram Sensors in Headrest Position". In: *IEEE-EMBS International Conferences on Biomedical and Health Informatics*. 2017, pp. 289–292.
- [154] I. Sadek et al. "Novel Unobtrusive Approach for Sleep Monitoring Using Fiber Optics in an Ambient Assisted Living Platform". In: *Inclusive Smart Cities and Digital Health: 15th International Conference on Smart Homes and Health Telematics, ICOST 2017, Paris, France, August 29-31, 2017. Proceedings*. Springer International Publishing, 2017.
- [155] Samsung. 2017. URL: <http://www.samsung.com/us/explore/family-hub-refrigerator/overview/>.
- [156] B. Santos-Eggimann et al. "Prevalence of frailty in middle-aged and older community-dwelling Europeans living in 10 countries". In: *The Journals of Gerontology: Series A* 64.6 (2009), pp. 675–681.
- [157] L. Sevrin. "Mesure et suivi d'activité de plusieurs personnes dans un Living Lab en vue de l'extraction d'indicateurs de santé et de bien-être". PhD thesis. Université de Lyon, 2016.
- [158] L. Sevrin et al. "A data fusion system to study synchronization in social activities". In: *e-Health Networking, Applications and Services (Healthcom), 2016 IEEE 18th International Conference on*. IEEE. 2016, pp. 1–4.
- [159] L. Sevrin et al. "Detection of collaborative activity with Kinect depth cameras". In: *Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of the*. IEEE. 2016, pp. 5973–5976.
- [160] H. Shimada et al. "Combined prevalence of frailty and mild cognitive impairment in a population of elderly Japanese people". In: *Journal of the American Medical Directors Association* 14.7 (2013), pp. 518–524.
- [161] M. Shoaib et al. "Fusion of Smartphone Motion Sensors for Physical Activity Recognition". In: *Sensors* 14.6 (2014), pp. 10146–10176. ISSN: 1424-8220. DOI: 10.3390/s140610146. URL: <http://www.mdpi.com/1424-8220/14/6/10146/>.
- [162] T. G. Stavropoulos et al. "aWESoME: A web service middleware for ambient intelligence". In: *Expert Systems with Applications* 40.11 (2013), pp. 4380–4392.
- [163] L. Stenneth et al. "Transportation mode detection using mobile phones and GIS information". In: *Proceedings of the 19th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. ACM. 2011, pp. 54–63.
- [164] D Steven and B Patrice. "Doing More with Less: The Aging Population Challenge". In: *ARM Medical Special* ().
- [165] N Steverink et al. "Measuring frailty: development and testing of the Groningen Frailty Indicator (GFI)". In: *Gerontologist* 41.1 (2001), p. 236.
- [166] W. J. Strawbridge et al. "Antecedents of frailty over three decades in an older cohort". In: *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 53.1 (1998), S9–S16.

- [167] S. Studenski et al. “Clinical Global Impression of Change in Physical Frailty: development of a measure based on clinical judgment”. In: *Journal of the American Geriatrics Society* 52.9 (2004), pp. 1560–1566.
- [168] K. Su, J. Li, and H. Fu. “Smart city and the applications”. In: *Electronics, Communications and Control (ICECC), 2011 International Conference on*. IEEE. 2011, pp. 1028–1031.
- [169] X. Su. “Travel Mode Identification with Smartphone Sensors”. PhD thesis. City University of New York, 2017.
- [170] T. Suurmeijer et al. “The Groningen Activity Restriction Scale for measuring disability: its utility in international comparisons.” In: *American Journal of Public Health* 84.8 (1994), pp. 1270–1273.
- [171] H. Syddall et al. “Is grip strength a useful single marker of frailty?” In: *Age and ageing* 32.6 (2003), pp. 650–656.
- [172] T. B. Tan. “Smart nation & its implications: the state in a hyper-connected Singapore”. In: (2015).
- [173] E. M. Tapia, S. S. Intille, and K. Larson. *Activity recognition in the home using simple and ubiquitous sensors*. Springer, 2004.
- [174] M.-R. Tazari et al. “The PERSONA service platform for AAL spaces”. In: *Handbook of Ambient Intelligence and Smart Environments*. Springer, 2010, pp. 1171–1199.
- [175] S. Tedesco, J. Barton, and B. O’Flynn. “A Review of Activity Trackers for Senior Citizens: Research Perspectives, Commercial Landscape and the Role of the Insurance Industry”. In: *Sensors (Basel, Switzerland)* 17.6 (June 2017). ISSN: 1424-8220. DOI: 10.3390/s17061277. URL: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC5492436/> (visited on 08/09/2017).
- [176] S. M. Thielke et al. “Associations Between Observed In-Home Behaviors and Self-Reported Low Mood in Community-Dwelling Older Adults”. In: *Journal of the American Geriatrics Society* 62.4 (2014), pp. 685–689.
- [177] R. P. Thomas and J. Shanteau. “Simple heuristics that make us smart. Oxford University Press, London, 1999. No. of pages 432. ISBN 5-12156-2. Price US 35.00/28.00”. In: *Applied Cognitive Psychology* 16.3 (2002), pp. 359–360.
- [178] T. Tiberghien. “Strategies for context reasoning in assistive livings for the elderly”. PhD thesis. Institut National des Télécommunications, 2013.
- [179] T. Tiberghien et al. “Semantic Reasoning in Context-Aware Assistive Environments to Support Ageing with Dementia”. In: *Proceedings of the 11th International Semantic Web Conference (ISWC)*. Springer, 2012, pp. 212–227.
- [180] M. E. Tinetti. “Performance-oriented assessment of mobility problems in elderly patients”. In: *Journal of the American Geriatrics Society* 34.2 (1986), pp. 119–126.
- [181] M. E. Tinetti et al. “A multifactorial intervention to reduce the risk of falling among elderly people living in the community”. In: *New England Journal of Medicine* 331.13 (1994), pp. 821–827.
- [182] A.-M. Valdez. “Urban sensing systems for behaviour change: emerging issues in a smart transport project in Milton Keynes”. In: *Proceedings of the ISM-Open Conference 2014 ‘Broadening the Scope’*. ISM-Open Institute for Social Marketing. 2014, pp. 71–72.
- [183] B Vellas et al. “[Falls, frailty and osteoporosis in the elderly: a public health problem].” In: *La Revue de medecine interne/fondee... par la Societe nationale francaise de medecine interne* 21.7 (2000), pp. 608–613.
- [184] S. Wang, C. Chen, and J. Ma. “Accelerometer based transportation mode recognition on mobile phones”. In: *Wearable Computing Systems (APWCS), 2010 Asia-Pacific Conference on*. IEEE. 2010, pp. 44–46.

- [185] J. E. Ware Jr and C. D. Sherbourne. “The MOS 36-item short-form health survey (SF-36): I. Conceptual framework and item selection”. In: *Medical care* (1992), pp. 473–483.
- [186] T. Watanabe and K. Watanabe. “Noncontact method for sleep stage estimation”. In: *IEEE Transactions on Biomedical Engineering* 51.10 (2004), pp. 1735–1748. ISSN: 0018-9294. DOI: 10.1109/TBME.2004.828037.
- [187] M. Weiser. “The computer for the twenty-first century (pp. 94-100)”. In: *Scientific American, September Issue* (1991).
- [188] C. Wharton et al. “Applying cognitive walkthroughs to more complex user interfaces: experiences, issues, and recommendations”. In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM. 1992, pp. 381–388.
- [189] C. Wharton et al. “The cognitive walkthrough method: A practitioner’s guide”. In: *Usability inspection methods*. John Wiley & Sons, Inc. 1994, pp. 105–140.
- [190] C. H. Winograd. “Targeting strategies: an overview of criteria and outcomes”. In: *Journal of the American Geriatrics Society* 39.S1 (1991), 25S–35S.
- [191] C. H. Winograd et al. “Screening for frailty: criteria and predictors of outcomes”. In: *Journal of the American Geriatrics Society* 39.8 (1991), pp. 778–784.
- [192] J.-b. Woo and Y.-k. Lim. “User experience in do-it-yourself-style smart homes”. In: *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM. 2015, pp. 779–790.
- [193] *Worldwide Smartwatch Market Will See Modest Growth in 2016 Before Swelling to 50 Million Units in 2020, According to IDC*. 2016. URL: <https://www.idc.com/getdoc.jsp?containerId=prUS41736916> (visited on 08/31/2017).
- [194] A. Zanella et al. “Internet of things for smart cities”. In: *IEEE Internet of Things journal* 1.1 (2014), pp. 22–32.
- [195] W. Zhang et al. “Chair Rise Peak Power in Daily Life Measured with a Pendant Sensor Associates with Mobility, Limitation in Activities and Frailty in Old People”. In: (2015).
- [196] Y. Zheng et al. “Understanding transportation modes based on GPS data for web applications”. In: *ACM Transactions on the Web (TWEB)* 4.1 (2010), p. 1.
- [197] S. Zygiaris. “Smart city reference model: Assisting planners to conceptualize the building of smart city innovation ecosystems”. In: *Journal of the Knowledge Economy* 4.2 (2013), pp. 217–231.
- [198] S. Zygiaris. “Smart city reference model: Assisting planners to conceptualize the building of smart city innovation ecosystems”. In: *Journal of the Knowledge Economy* 4.2 (2013), pp. 217–231.

# Appendices

# Appendix A

## UbiSmart Framework Code Samples

### A.1 UbiSmart Server Configuration

```
{
  "name": "ubismart",
  "private": true,
  "version": "3.2.2",
  "description": "A modern framework for Ambient Assisted Living (AAL)",
  "dependencies": {
    "async": "0.9.0",
    "bcrypt": "0.7.8",
    "bunyan": "0.22.3",
    "connect-mongo": "^0.8.0",
    "ejs": "~0.8.4",
    "eyeserver": "0.1.1",
    "glob": "4.2.1",
    "grunt": "0.4.2",
    "grunt-contrib-clean": "~0.5.0",
    "grunt-contrib-coffee": "~0.10.1",
    "grunt-contrib-concat": "~0.3.0",
    "grunt-contrib-copy": "~0.5.0",
    "grunt-contrib-cssmin": "~0.9.0",
    "grunt-contrib-jst": "~0.6.0",
    "grunt-contrib-less": "0.11.1",
    "grunt-contrib-uglify": "~0.4.0",
    "grunt-contrib-watch": "~0.5.3",
    "grunt-sails-linker": "~0.9.5",
    "grunt-sync": "~0.0.4",
    "i18n": "0.5.0",
    "include-all": "~0.1.3",
    "leveldown": "^0.10.2",
    "lodash": "^3.0.0",
    "minimatch": "0.3.0",
    "moment": "2.7.0",
    "moment-timezone": "0.1.0",
    "mosca": "0.24.0",
    "mv": "2.0.3",
    "n3": "0.3.0",
```

```

"node-gcm": "0.9.12",
"optimist": "0.3.4",
"password-generator": "^1.0.0",
"path": "0.4.9",
"rc": "~0.5.0",
"rimraf": "2.2.8",
"sails": "~0.11.0",
"sails-disk": "^0.10.4",
"sails-migrations": "^2.0.7",
"sails-postgresql": "^0.10.9",
"touch": "0.0.3",
"underscore": "1.6.0",
"zmq": "2.7.0"
},
"files": {},
"scripts": {
"start": "sudo forever start --uid 'ubi' -l ~/forever.log -a app.js",
"info": "sudo nodemon app.js | .bin/bunyan -o short -l info",
"debug": "sudo nodemon app.js | .bin/bunyan -o short -l debug",
"trace": "sudo nodemon app.js | .bin/bunyan -o short -l trace"
},
"main": "app.js",
"os": [
"linux"
],
"cpu": [],
"repository": {
"type": "git",
"url": "https://github.com/pawmint/ubismart.git"
},
"bugs": "https://github.com/pawmint/ubismart/issues",
"author": "PAWM International (https://github.com/pawmint)",
"license": "All rights reserved."
}

```

Code A.1: UbiSmart webApp Packages

## A.2 UbiSmart Server CityDesc Controller

MODEL

```
module.exports = {

  attributes: {

    beaconName: {
      type: 'string'
    },

    pointOfInterest: {
      type: 'string'
    },

    inferredActivity: {
      type: 'string'
    },

    cityId: {
      type: 'integer'
    }
  }
};
```

VIEW

```
<!DOCTYPE html>

<form action="/citydesc/editCity" method="POST" class="form-signin">

  <h2 class="form-signin-heading">{{_("Add New city")}} </h2>
  <input type="text" name="newCityName" placeholder="New City" >
  <input type="hidden" name="_csrf" value="{{_csrf}}" />
  <input type="submit" class="btn btn-lg btn-primary btn-block" value="{{_('Add')}}"/>

</form>

<form class="form-signin" >

  <h3>{{_("Cities")}} </h3>
  <table class='table'>
    <tr>
      <th>{{_("City Name")}} </th>
      <th></th>
      <th></th>
      <th></th>
    </tr>
```

```

<% _.each(cities , function( city) { %>
<tr>
  <td> <%=city.cityName%> </td>
  <td><a href="/citydesc/selectCity/<%=city.id %>" class="btn btn-sm btn-primary"><%=
__("Select ") %></a></td>
  <td><a href="/citydesc/deleteCity/<%=city.id %>" class="btn btn-sm btn-warning"><%=
__("Delete ") %></a></td>
</tr>
<% }) %>
</table>
</form>

```

## CONTROLLER

```

selectCity: function(req, res, next){

  if (req.param('newBeaconName')&& (req.param('newPointOfInterest'))&&(req.param('
    newInferredActivity')) )
  {
    var cityId = req.param('cityId');
    var beaconName = req.param('newBeaconName');
    var pointOfInterest = req.param('newPointOfInterest');
    var inferredActivity = req.param('newInferredActivity');

    var newBeacon = {};
    newBeacon.beaconName = beaconName;
    newBeacon.pointOfInterest = pointOfInterest;
    newBeacon.inferredActivity = inferredActivity;
    newBeacon.cityId = cityId;
    var temp ={};
    var msg="";

    async.series({
newBeacon: function(cb) {
      var varBeaconFound, varPointOfInterest, varInferredActivity;
      Citybeacon.findOne({ beaconName:newBeacon.beaconName }).exec( function(
errorBeacon, beaconFound){
        if(errorBeacon) return log.error(errorBeacon);
        if(beaconFound) msg=msg+"the beacon "+beaconFound.beaconName;
        // search if point of interest exist !!
        Citybeacon.findOne({ pointOfInterest:newBeacon.pointOfInterest }).exec( function(
errorPoi, poi){
          if(errorPoi) return log.error(errorPoi);
          if(poi) msg=msg+" the Point of interest "+poi.pointOfInterest;
          // search if inferred activity exist!!
          Citybeacon.findOne({ inferredActivity:newBeacon.inferredActivity }).exec(
function(errorIa, ia){
            if(errorIa) return log.error(errorIa);
            if(ia) msg=msg+" the inferred Activity "+ia.inferredActivity;

            if(!beaconFound && !poi && !ia){

```



```

        Citybeacon.create(newBeacon).exec(cb);

        // temp={"newBeacon":newBeacon};
    }else{
        log.debug(msg+" exist already in the db");
        res.redirect('/citydesc/beaconExist');
    }

    });
});
});

},
resultOntlogy: function(cb) {
    //Add beacon to ontology of all houses
    House.find().exec(function(errorHouse, houses) {
        if(errorHouse) return log.error(errorHouse);

        async.eachSeries(_.each(houses), function(house, cb) {
            sails.services.persistedn3synchronizer.updateBeaconConfiguration(house.id,
newBeacon, cb);
        }, cb);
    });
}

},function(errorAll, resultAll) {
    if (errorAll) return log.error(errorAll);
    log.debug(resultAll);

var idCity = req.param('id');
    Citybeacon.find({cityId : idCity}).exec(function (err, cityBeaconFound){
        City.findOne({ id : idCity }).exec(function(err, cityFound){
            if(err) return log.error(err);
            if(cityBeaconFound) {
                index0=0;
                indexCityBeacon=1;
                //select={"id":idCity,"cityBeaconFound":cityBeaconFound};
                select={"id":idCity,"cityBeaconFound":cityBeaconFound,"cityName":cityFound.
cityName};
            }else {
                log.debug("cityBeacon Not ");
                indexCityBeacon=2;
                select={"id":idCity,"cityName":cityFound.cityName};
                log.debug("the city doesn't have any beacon yet ");
            }
            res.view({ select :select});

        });
    });
});
});
}
else{
var iddCity = req.param('id');

```

```

var select;

log.debug(iddCity);

Citybeacon.find({cityId : iddCity}).exec(function (err , cityBeaconFound){
City.findOne({ id : iddCity}).exec(function(err , cityFound){
    if(err) return log.error(err);
    if(cityBeaconFound) {
index0=0;
        indexCityBeacon=1;
        select={"id ":iddCity,"cityBeaconFound ":cityBeaconFound};
        select={"id ":iddCity,"cityBeaconFound ":cityBeaconFound,"cityName ":cityFound.
cityName};
    }else {

        indexCityBeacon=2;
        select={"id ":idCity,"cityName ":cityFound.cityName};
        log.debug("the city doesn't have any beacon yet ");
    }
    res.view({ select :select});
});
});
},

```

Code A.2: CityDesc Model-View-Controller (The Controller has been reduced).

## A.3 Service Prototype








 <b>assets</b>	Add basic service prototype.
 <b>lib</b>	Add service libs and life cycle methods extension to basic service code.
 <b>locales</b>	Add locales to default service.
 <b>views</b>	Fixing the code changes in master branch.
 <b>.gitignore</b>	Add basic service prototype.
 <b>README.md</b>	Update link in README.
 <b>serviceProto.js</b>	Update serviceProto.js

Figure A-1: Service prototype structure.

```
var servicePrototype = require ( '../service ' );
var ubi = require ( 'ubiutils ' );

var service = servicePrototype.create ( "Your Service Name" );
service.version = '0.1.0';

// below are optional service parameters overrides
service.autostart = true; // default false
service.webAccess = false; // default true
service.singleton = false; // default true
service.scope = "neighborhood"; // default "house"
service.logo = 'fa-thumbs-o-up';

// override policies at will
service.policies = {
  'test': 'admin',
  '*': 'authenticated'
};

/* LOAD LOCAL LIBS BELOW */
service.libname = require ( '../lib/' + service.name + '/libname ' ) ( service );

/* DEFINE YOUR OWN ACTIONS BELOW */
service.index = function ( params, res ) {
  res.view ( 'servicesRepository/' + service.name + '/index ' );
};

service.test = function ( params, res ) {
  var message = 'hello ' + params.name;
  res.json ( { 'ack': message } );
};

/* EXTEND LIFECYCLE METHODS BELOW */
/* AVAILABLE EVENTS: activated, deactivated, started, stopped, houseAdded, houseRemoved
*/
```

```
service.on('started', function() {  
  //TODO: custom start code  
});  
  
module.exports = service;
```

Code A.3: UbiSmart Service Prototype

## A.4 UbiGate Setup Code

```
from setuptools import setup, find_packages
readme = open('README.md').read()
history = open('HISTORY.md').read()
setup(
    name='UbiGate',
    version='0.2.3',
    description=('A gateway utility between sensors and the ubismart server'),
    long_description=readme + '\n\n' + history,
    author='Clement Palliere, Romain Endelin, Joaquim Bellmunt',
    author_email='joaquim.bellmunt@ipal.cnrs.fr',
    url='https://github.com/pawmint/ubiGATE.git',
    packages=find_packages(),
    include_package_data=True,
    install_requires=[
        'mosquitto>=1.2.3',
        'paho-mqtt>=1.0',
        'argparse>=1.2.1',
        'tzlocal>=1.1.1',
        'appdirs>=1.4.0'
    ],
    license='Copyright',
    zip_safe=True, # To be verified
    classifiers=[
        'Development Status :: 4 - Beta',
        'Intended Audience :: Developers',
        'Intended Audience :: Science/Research',
        'Natural Language :: English',
        'Programming Language :: Python :: 3',
        'Programming Language :: Python :: 3.4',
        'Environment :: Console',
        'License :: Other/Proprietary License',
        'Topic :: Scientific/Engineering'
    ],
)
```

Code A.4: UbiGate Installation Code

## A.5 Ubigate Code

```
# -*- coding: utf-8 -*-
from ubigate.utils.log import logger
from ubigate.utils import config, log
import paho.mqtt.client as paho
from appdirs import AppDirs
from tzlocal import get_localzone
import atexit
import threading
import logging
import os
import time
from threading import Lock

try:
    import simplejson as json
except ImportError:
    import json

QOS = 1 # Quality of service
KEEPALIVE = 20 # The client stay connected during until 20s without handshake
SYNC_FREQUENCY = 0.1 # s^-1 - frequency of synchronization with the broker
RETAIN = False

def subscribe_method(method):
    def inner(client, userdata, message):
        return method(message.topic, message.payload)
    return inner

class Ubigate(object):
    def __init__(self, name, author='pawmint',
                 default_file='resources/conf.json.default'):
        """Initializes the gate:
        Runs the MQTT clients,
        Routes functions to topics
        Setup the log
        """
        self.dirs = AppDirs(name, author)
        self.config = config.init(name, author, default_file)
        self.timezone = get_localzone()
        self.locks = {}
        self.persistent_buffer = {}
        log.setup(name, author, self.config.get('logging', {}))
        self._display_config()
        self.clients = self._init_clients()
        atexit.register(self._quit)
    def _init_clients(self):
        """Creates the mosquitto clients
        """
        clients = []

        for gateway in self.config['gateways']:
```

```

        client = self._make_client(gateway)
        clients.append(client)
    return clients

    @staticmethod
    def _connect(client, server, port, keepalive):
        while True:
            try:
                client.connect(server, port, keepalive)
            except Exception:
                logger.warning("Unable to connect to MQTT")
                time.sleep(2)
            else:
                break
        client.loop_start()

    def _make_client(self, gateway):
        """Create a client for a given server
        Connect to the server
        Subscribe to the topics
        Send pending messages in the buffer
        """
        client = paho.Client(gateway['name'], clean_session=False)
        self.locks[client] = Lock()
        self._init_buffer(client)
        client.on_connect = Ubigate._connect_callback
        client.on_disconnect = Ubigate._disconnect_callback
        client.on_publish = self._publish_callback
        client.on_subscribe = Ubigate._subscription_callback
        client.on_message = self._on_message_callback
        client.max_inflight_messages_set(0)
        client.username_pw_set(gateway['username'],
                               gateway['password'])
        thread = threading.Thread(target=Ubigate._connect,
                                  args=(client,
                                         gateway['server'],
                                         int(gateway['port']),
                                         KEEPALIVE)
                                  )

        thread.daemon = True
        thread.start()
        self._push_buffer(client)
        return client

    @staticmethod
    def _disconnect_callback(client, obj, rc):
        """ Log a disconnection with the broker
        This is a callback method
        """
        logger.debug("%s: Disconnected successfully." % client._client_id)

    @staticmethod
    def _connect_callback(client, obj, state):
        """ Log the status of the connection
        This is a callback method
        """

```

```

states = {
    0: ["MQTT Connected sucessfully.", "DEBUG"],
    1: ["MQTT Connection Refused: unacceptable protocol version",
        "ERROR"],
    2: ["MQTT Connection Refused: identifier rejected", "ERROR"],
    3: ["MQTT Connection Refused: server unavailable", "ERROR"],
    4: ["MQTT Connection Refused: bad user name or password", "ERROR"],
    5: ["MQTT Connection Refused: not authorized", "ERROR"]
}

message, level = states[state]
logger.log(logging.getLevelName(level), "%s: %s" % (client._client_id,
                                                    message))

def _quit(self):
    """ Disconnect every MQTT clients on exit
    This is a callback method called on program's exit
    """
    for client in self.clients:
        client.disconnect()
        client.loop_stop(force=True)
        self._save_buffer(client)

def push(self, house, topic, data):
    """ Publish the given data through MQTT, given a topic and a house
    The MQTT message is saved to a persistent buffer until the publishing
    has been acknowledged.
    """
    for client in self.clients:
        complete_topic = "house/%s/%s" % (house, topic.strip('/'))
        logger.debug('%s: Preparing to post message: %s, to topic: "%s"'
                     % (client._client_id, data, complete_topic))
        self.locks[client].acquire()
        _, mid = client.publish(complete_topic, json.dumps(data),
                                QOS, retain=RETAIN)
        self._add_to_buffer(client, mid, complete_topic, data)
        self.locks[client].release()

def _publish_callback(self, client, obj, msg_id):
    """ Acknowledge that a message has been published.
    This is a callback method.
    It will clear the message from the persistent buffer
    """
    logger.debug("Message %d published to %s." % (msg_id,
                                                  client._client_id))

    self.locks[client].acquire()
    self._remove_from_buffer(client, msg_id)
    self.locks[client].release()

def _add_to_buffer(self, client, msg_id, topic, payload):
    """ Add a MQTT message to the persistent buffer for a given client
    """
    buf = self.persistent_buffer[client]
    buf[msg_id] = {'topic': topic, 'payload': payload}

```



```

        self._save_buffer(client)

def _remove_from_buffer(self, client, msg_id):
    """ Remove a MQTT message from the persistent buffer for a given client
    """
    buf = self.persistent_buffer[client]
    del buf[msg_id]
    self._save_buffer(client)

def _push_buffer(self, client):
    """ Publish every message that are currently in the buffer for a client
    To make sure these message aren't lost, we save them back to the buffer
    until the publish is acknowledged
    """
    self.locks[client].acquire()
    buf = self.persistent_buffer[client]
    for mid, data in buf.items():
        _, new_mid = client.publish(data['topic'],
                                     json.dumps(data['payload']),
                                     QOS, retain=RETAIN)
        self._remove_from_buffer(client, mid)
        self._add_to_buffer(client, new_mid,
                             data['topic'], data['payload'])
    self._save_buffer(client)
    self.locks[client].release()

def _init_buffer(self, client):
    """ Load buffer from the file, for a client
    If the file doesn't exist, load an empty buffer
    """
    filename = self._get_buffer_filename(client)
    if not os.path.isfile(filename):
        buf = {}
    else:
        try:
            with open(filename, 'r') as f:
                buf = json.load(f)
        except ValueError:
            buf = {}
            logger.error("Existing data could not be loaded (broken data)")
    self.persistent_buffer[client] = buf

def _save_buffer(self, client):
    """ Save the current buffer to a file, for a client
    The file is overwritten every time
    """
    buf = self.persistent_buffer[client]
    with open(self._get_buffer_filename(client), 'w+') as f:
        json.dump(buf, f)

def _get_buffer_filename(self, client):
    """ Return the buffer filename for a client

```

```

"""
return os.path.join(self.dirs.user_cache_dir,
                    "%s.json" % client._client_id)

def _on_message_callback(self, client, userdata, message):
    """ Callback catching the server messages.
    """
    logger.info("message received: %s' on topic '%s' with QoS %s"
                % (message.payload, message.topic, message.qos))

def associate(self, topic, function, house):
    full_topic = "house/%d/%s" % (house, topic)
    for client in self.clients:
        client.subscribe(full_topic, qos=1)
        client.message_callback_add(full_topic, function)
    logger.info("associate topic %s to function %s" % (topic, function))

@staticmethod
def _subscription_callback(mosq, obj, mid, qos_list):
    """
    Log the status of the subscription. This is a callback method
    """
    logger.debug("Subscribe with mid %d received." % mid)

def find_house(self, sensor):
    """Returns the house id given a sensor.
    """
    return self.config['sensors'][sensor]

def _display_config(self):
    """Shows an overview of the gate through the info canal.
    """
    logger.info("Gateways:")
    for gateway in self.config['gateways']:
        logger.info('\tGateway: %s' % gateway['name'])
        logger.info('\t\tServer: %s' % gateway['server'])
        logger.info('\t\tPort: %s' % gateway['port'])

    logger.info("Houses:")
    for house in self.config['houses']:
        logger.info('\tName: %s' % house['name'])
        logger.info('\t\tId: %s' % house['id'])
        logger.info('\t\tSensors: %s' % ', '.join(house['sensors']))
        logger.info('\t\tPrefix: %s' % house['prefix'])

```

Code A.5: UbiGate Main Threat Module

## A.6 Zwave Plug-in

```
# -*- coding: utf-8 -*-
#from ubigate import credentials , gateway_config
#from ubigate.buffer import MessagesBuffer
#from ubigate.keepaliveNotifier import KeepaliveNotifier

# MQTT broker
import paho.mqtt.client as mqtt
import paho.mqtt.publish as publish
import time

from datetime import datetime
try:
    import simplejson as json
except ImportError:
    import json
from ubigate.buffer import MessagesBuffer
from ubigate.log import logger

# Get time
import pytz
from tzlocal import get_localzone

def run(plugin):
    # TODO Move config in the config file
    DOMOTICZHOST = "127.0.0.1"
    DOMOTICZPORT = 1883
    QOS = 1 # Quality of service
    KEEPALIVE = 60 # The client stays connected for []s without handshake
    RETAIN = False

    while True:
        try:
            client = mqtt.Client()
            client.connect(DOMOTICZHOST, DOMOTICZPORT, KEEPALIVE)
            client.plugin = plugin # refer to UbiGate object

            client.on_connect = on_connect
            client.on_message = on_message

            client.loop_forever()
            logger.info("MQTT client for Domoticz sucessfully initialised")
        except Exception as e:
            logger.error('MQTT client for Domoticz Error: ' + str(e))
            # Wait some time before re-trying
            time.sleep(5)
        else:
            print('Gateway not linked to UbiSmart')

def on_connect(client , userdata , flags , rc):
    logger.info("Connected with result code " + str(rc))
```

```

client.subscribe("domoticz/out")

def on_message(client, userdata, msg):
    value = None
    data=msg.payload.decode()
    data= json.loads(data)
    tz = pytz.timezone(str(get_localzone()))
    date = tz.localize(datetime.now()).isoformat()
    try:
        if any(['Contact' in data['name'], 'Motion' in data['name']]):
            logger.info("Z-wave received some data:" + str(data))
            sensor = data['name']
            details = client.plugin.get_details_deprecated(sensor)
            if 'Contact' in data['name']:
                if data['nvalue'] == 1:
                    value = "alert"
                else:
                    value = "normal"
            if 'Motion' in data['name']:
                if data['nvalue'] == 1:
                    value = "on"
                else:
                    value = "off"
            myMAC = open('/sys/class/net/eth0/address').read().rstrip()
            result = {}
            result['type']= "TruthObservation"
            result['observedProperty']= data['switchType'] # Contact or Motion
            result['procedure']= "Zwave_%s_%s_%s" % (sensor, details['binding'], details
['bindingType'])
            result['featureOfInterest']= details['house']
            result['uom'] = '' # unit of measurement
            #result['id']= "Raspberry_Pi/%s/Zwave_%s_Room" % (client.ubigate.credentials
['id'], sensor)
            result['id'] = '/'.join(['Raspberry_Pi', myMAC, result['procedure'], date])

            client.plugin.push_event(sensor, value, date, result['id'], result['type'],
result['observedProperty'], result['procedure'], result['featureOfInterest'], result
['uom'])
        except KeyError:
            pass
        except Exception as e:
            logger.info("D2M: Exception: " + str(e) + " " + str(details) + " " + sensor)

def push_event(client, msg, sensor, value):
    """Push a sensor event to Ubismart through MQTT.
    If the sensor is known, we send it to house/<ID>/<plugin>/sensor/<ID>.
    If the sensor is unknown, we send it to gateway/<ID>/sensor/register.
    If the sensor known and blacklisted, we skip it.
    """
    tz = pytz.timezone(str(get_localzone()))
    date = tz.localize(datetime.now()).isoformat()
    logger.debug("BROKER: pushing an event at ", date)

```

```

try:
    house = [house['id']]
    for house in client.ubigate.config['houses']
        #for house in config['houses'] # if not in use, remove the global
variable
        for s in house['sensors']
            if s['id'] == sensor][0]
except IndexError:
    logger.debug("Sensor %s not found in the config %s" % (sensor, client.ubigate.
config['houses']))
    if('blacklist' not in config or
        sensor not in config['blacklist']):
        logger.info("Unknown sensor, notifying to Ubismart")
        topic = ("gateway/%s/sensor/register"
            % credentials['id'])
        data = {"id": sensor,
            "state": value,
            "date": date}
        client.ubigate.push(topic, json.dumps(data))
    else:
        logger.info('This sensor is blacklisted, message skipped')
except KeyError:
    logger.error("Can't send sensor event, missing config")
else:
    measurement['id']= "Raspberry_Pi/%s/Zwave_%s_Room" % (client.ubigate.credentials
['id'], sensor)
    measurement['type']= "TruthObservation"
    measurement['phenomenonTime']= {'instant': date}
    measurement['procedure']= "Zwave_%s_%s" % (sensor, house)
    measurement['featureOfInterest']= {'href': house}
    measurement['resultTime']= date
    measurement['result']= {'value': value}#, 'uom': uom}
    topic = "house/%s/marmitek/sensor/%s" % (house, sensor)
    client.ubigate.push(topic, measurement)

def main(plugin):
    run(plugin)

if __name__ == '__main__':
    main()

```

Code A.6: UbiGate Zwave Plug-in

## A.7 X10 Plug-in

```
# -*- coding: utf-8 -*-
from xml.dom import minidom
import glob
import socket
import time
from tzlocal import get_localzone
import pytz

from sensors import motion_signal, door_signal
from ubigate.log import logger

def _init():
    # TODO Put the config in the config file
    MOCHADHOST = "127.0.0.1"
    MOCHADPORT = 1099
    while True:
        try:
            Sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
            Sock.connect((MOCHADHOST, MOCHADPORT))
            Sock.settimeout(10)
            logger.debug("Successfully connected to Mochad")
            return Sock
        except socket.error as e:
            Sock.close()
            logger.error("Unable to listen from Mochad : %s" % e)
            time.sleep(5)

def read_from_mochad():
    Sock = _init()
    while True:
        lines = None
        try:
            data = Sock.recv(1024)
            line = repr(data).strip("b'")
            lines = line.split('\n')
        except socket.timeout:
            logger.debug("Disconnected from mochad")
        finally:
            Sock.shutdown(2)
            Sock.close()
            Sock = _init()
            if lines is not None:
                yield lines

def gather_data(signal):
    signal_types = [motion_signal, door_signal]

    for checker in signal_types:
        data = checker.matches(signal)
        if data is not None:
```

```

        return data
    return None

def run():
    myMAC = open('/sys/class/net/eth0/address').read()
    tz = pytz.timezone(str(get_localzone()))
    lastDoorEvents = {}
    for lines in read_from_mochad():
        for signal in lines[:-1]:
            logger.debug('Signal received: %s' % signal)
            data = gather_data(signal)

            if data is None:
                continue

            file = ''.join(glob.glob('/home/pi/*_' + data['sensor'] + '_*_*.xml'))
            if file is '':
                data['id'] = 'ID'
            data['observedProperty'] = "http"
                data['procedure'] = "http"
                data['featureOfInterest'] = "http"
                data['type'] = 'TYPE'
                data['uom'] = "http"
            logger.debug('unregistered sensor')
        else:
            xmldoc = minidom.parse(file)
            itemlist = xmldoc.getElementsByTagName('gml:identifier')
            data['procedure'] = itemlist[0].firstChild.nodeValue
            itemlist = xmldoc.getElementsByTagName('sml:feature')
            data['featureOfInterest'] = itemlist[0].attributes['xlink:title'].value
            itemlist = xmldoc.getElementsByTagName('sml:ObservableProperty')
            data['observedProperty'] = itemlist[0].attributes['definition'].value
            itemlist = xmldoc.getElementsByTagName('sml:ObservationType')
            data['type'] = itemlist[0].attributes['name'].value
            itemlist = xmldoc.getElementsByTagName('swe:uom')
            data['uom'] = itemlist[0].firstChild.nodeValue
            data['id'] = ''.join(['Raspberry_Pi', '/', myMAC.rstrip(), '/', data['procedure'], '/', data['date']].isoformat())
            logger.debug("data format is: %r" % data)
            data['date'] = tz.localize(data['date']).isoformat()
            sensor = data['sensor']
            if not (data['sensorKind'] == 'door'
                    and lastDoorEvents.get(sensor, "") == data['value']):
                if data['sensorKind'] == 'door':
                    lastDoorEvents[sensor] = data['value']
            yield data

```

Code A.7: UbiGate X10 Plug-in

## Appendix B

# UbiSmart Semantic Ontology

### B.1 Abstract Model

```
@prefix rdf:    <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
@prefix rdfs:   <http://www.w3.org/2000/01/rdf-schema#>.
@prefix owl:  <http://www.w3.org/2002/07/owl#>.
@prefix xsd:    <http://www.w3.org/2001/XMLSchema#>.

@prefix qol:    <http://www.ubismart.org/n3/qol-model#>.
@prefix unc:    <http://www.ubismart.org/n3/uncertainty-model#>.

## CLASSES ##
## ———— ##
qol:Person a rdfs:Class.

qol:Resident a rdfs:Class;
rdfs:subClassOf qol:Person.

qol:Caregiver a rdfs:Class;
rdfs:subClassOf qol:Person.

qol:Technician a rdfs:Class;
rdfs:subClassOf qol:Person.

qol:Environment a rdfs:Class.

qol:House a rdfs:Class;
rdfs:subClassOf qol:Environment.

qol:Outside a rdfs:Class;
rdfs:subClassOf qol:Environment.

qol:Room a rdfs:Class;
rdfs:subClassOf qol:Environment.

qol:Bedroom a rdfs:Class;
rdfs:subClassOf qol:Room;
```



```

rdfs:label "Bedroom"@en.

qol:Livingroom a rdfs:Class;
rdfs:subClassOf qol:Room;
rdfs:label "Living room"@en;
rdfs:label "Salon"@fr.

qol:Diningroom a rdfs:Class;
rdfs:subClassOf qol:Room;
rdfs:label "Dining room"@en.

qol:Kitchen a rdfs:Class;
rdfs:subClassOf qol:Room;
rdfs:label "Kitchen"@en;
rdfs:label "Cuisine"@fr.

qol:Bathroom a rdfs:Class;
rdfs:subClassOf qol:Room;
rdfs:label "Bathroom"@en;
rdfs:label "Salle de bain"@fr.

qol:Toilet a rdfs:Class;
rdfs:subClassOf qol:Room;
rdfs:label "Toilet"@en;
rdfs:label "Toilettes"@fr.

qol:Lift a rdfs:Class;
rdfs:subClassOf qol:Room;
rdfs:label "Lift"@en;
rdfs:label "Ascenseur"@fr.

qol:Object a rdfs:Class.

qol:Furniture a rdfs:Class;
rdfs:subClassOf qol:Object;
rdfs:label "Furniture"@en;
rdfs:label "Meuble"@fr.

qol:Door a rdfs:Class;
rdfs:subClassOf qol:Furniture;
rdfs:label "Door"@en;
rdfs:label "Porte"@fr.

qol:Bed a rdfs:Class;
rdfs:subClassOf qol:Furniture;
rdfs:label "Bed"@en;
rdfs:label "Lit"@fr.

qol:Fridge a rdfs:Class;
rdfs:subClassOf qol:Furniture;
rdfs:label "Fridge"@en.

```

```

qol:Oven a rdfs:Class;
rdfs:subClassOf qol:Furniture;
rdfs:label "Oven"@en.

qol:Sensor a rdfs:Class.

qol:SensorType a rdfs:Class.

qol:SensApp a rdfs:Class.

qol:SensorState a rdfs:Class.

qol:Activity a rdfs:Class.

qol:DayOfWeek a rdfs:Class;
rdfs:comment "we did not find any equivalent"@en;
rdfs:comment "values: Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday"@en.

qol:Behaviour a rdfs:Class.

qol:Service a rdfs:Class.

qol:Device a rdfs:Class.

qol:City a rdfs:Class;
rdfs:subClassOf qol:Environment.

qol:PointOfInterest a rdfs:Class;
rdfs:subClassOf qol:City.

qol:goesTo a rdf:ObjectProperty;
rdfs:comment "Resident goes to point of interest."@en;
rdfs:domain qol:Resident;
rdfs:range qol:PointOfInterest.
qol:isAssociatedTo a rdf:ObjectProperty;
rdfs:comment "Point of interest is associated to activity."@en;
rdfs:domain qol:PointOfInterest;
rdfs:range qol:Activity.
### OBJECT PROPERTIES ###
### ————— ###
qol:residentOf a rdf:ObjectProperty;
rdfs:comment "House where a resident live."@en;
rdfs:domain qol:Resident;
rdfs:range qol:Environment.

qol:caregiverOf a rdf:ObjectProperty;
rdfs:comment "House where a caregiver operates."@en;
rdfs:domain qol:Caregiver;
rdfs:range qol:Environment.

qol:technicianOf a rdf:ObjectProperty;

```

```

rdfs:comment "House where a technician operates."@en;
rdfs:domain qol:Technician;
rdfs:range qol:Environment.

qol:takesCareOf a rdf:ObjectProperty;
rdfs:comment "A caregiver takes care of a resident."@en;
rdfs:domain qol:Caregiver;
rdfs:range qol:Resident.

qol:detectedIn a rdf:ObjectProperty;
rdfs:comment "Room where the resident is detected."@en;
rdfs:domain qol:Resident;
rdfs:range qol:Environment.

qol:useNow a rdf:ObjectProperty;
rdfs:comment "Object a person is currently using."@en;
rdfs:domain qol:Resident;
rdfs:range qol:Object.

qol:believedToDo a rdf:ObjectProperty;
rdfs:comment "Activity a resident is believed to be doing."@en;
rdfs:domain qol:Resident;
rdfs:range qol:Activity.

qol:cameFrom a rdf:ObjectProperty;
rdfs:comment "Room the resident was in before the current one."@en;
rdfs:domain qol:Resident;
rdfs:range qol:Environment.

qol:partOf a rdf:ObjectProperty;
a owl:TransitiveProperty;
rdfs:comment "Describe inclusion of environments."@en;
rdfs:domain qol:Environment;
rdfs:range qol:Environment.

qol:locatedIn a rdf:ObjectProperty;
rdfs:comment "Location of a door in the environment."@en;
rdfs:domain qol:Object;
rdfs:range qol:Environment.

qol:deployedIn a rdf:ObjectProperty;
rdfs:comment "Deployment location of a sensor."@en;
rdfs:domain qol:Sensor;
rdfs:range qol:Environment.

qol:attachedTo a rdf:ObjectProperty;
rdfs:comment "Describe the binding of sensor to a furniture."@en;
rdfs:domain qol:Sensor;
rdfs:range qol:Object.

qol:hasPossibleState a rdf:ObjectProperty;
rdfs:comment "Possible state of a sensor."@en;

```

```

rdfs:range qol:SensorState.

qol:hasCurrentState a rdf:ObjectProperty;
rdfs:comment "Current state of a sensor."@en;
rdfs:domain qol:Sensor;
rdfs:range qol:SensorState.

qol:hasDurationEquivalent a rdf:ObjectProperty;
rdfs:comment "Links a date predicate with its equivalent duration predicate."@en;
rdfs:domain rdf:DatatypeProperty;
rdfs:range rdf:DatatypeProperty.

qol:hasBehaviour a rdf:ObjectProperty;
rdfs:comment "Behaviours of a Resident"@en;
rdfs:domain qol:Resident;
rdfs:range qol:Behaviour.

qol:startActivity a rdf:ObjectProperty;
rdfs:comment "Activity which turns on the listening state of the service";
rdfs:domain qol:Service;
rdfs:range qol:Activity.

qol:stopActivity a rdf:ObjectProperty;
rdfs:comment "Activity which turns off the listening state of the service";
rdfs:domain qol:Service;
rdfs:range qol:Activity.

qol:expectedActivity a rdf:ObjectProperty;
rdfs:comment "Activity which turns on the listening state of the service";
rdfs:domain qol:Service;
rdfs:range qol:Activity.

qol:hasDevice a rdf:ObjectProperty;
rdfs:comment "Behaviours of a Resident"@en;
rdfs:domain qol:Resident;
rdfs:range qol:Device.

qol:placedIn a rdf:ObjectProperty;
rdfs:comment "Behaviours of a Resident"@en;
rdfs:domain qol:Device;
rdfs:range qol:Environment.

## DATATYPE PROPERTIES ##
## ----- ##

qol:isAlone a rdf:DatatypeProperty;
rdfs:comment "Is the resident alone in the environment?"@en;
rdfs:domain qol:Resident;
rdfs:range xsd:boolean.

qol:inRoomSince a rdf:DatatypeProperty;
rdfs:comment "The time when the resident entered his current location"@en;
rdfs:domain qol:Resident;

```

```

rdfs:range xsd:dateTime;
qol:hasDurationEquivalent qol:inRoomFor.

qol:inRoomFor a rdf:DatatypeProperty;
rdfs:comment "The duration since the resident entered his current location, in seconds"
    @en;
rdfs:domain qol:Resident;
rdfs:range xsd:duration.

qol:doesActivitySince a rdf:DatatypeProperty;
rdfs:comment "The time when the resident supposedly started an activity"@en;
rdfs:domain qol:Resident;
rdfs:range xsd:dateTime;
qol:hasDurationEquivalent qol:doesActivityFor.

qol:doesActivityFor a rdf:DatatypeProperty;
rdfs:comment "The duration since the resident supposedly started an activity, in seconds"
    @en;
rdfs:domain qol:Resident;
rdfs:range xsd:duration.

qol:motionMeasured a rdf:DatatypeProperty;
rdfs:comment "Measurement of the number of sensor activations in a given space during a
    given time window."@en;
rdfs:domain qol:Environment;
rdfs:range xsd:int.

qol:id a rdf:DatatypeProperty;
rdfs:comment "Identification number of a resource."@en;
rdfs:range xsd:string.

qol:name a rdf:DatatypeProperty;
rdfs:comment "Common name of a resource."@en;
rdfs:range xsd:string.

qol:hasValue a rdf:DatatypeProperty;
rdfs:comment "value provided by the sensors which dont have fixed state."@en.

# deprecated: remove once email notif is handled in ubi-v3
qol:hasEmail a rdf:DatatypeProperty;
rdfs:comment "The email address of the caregiver."@en;
rdfs:domain qol:Person.

qol:lastUpdate a rdf:DatatypeProperty;
rdfs:comment "Date and time of the last update of a sensor state."@en;
rdfs:domain qol:Sensor;
rdfs:range xsd:dateTime.

qol:lastUsed a rdf:DatatypeProperty;
rdfs:comment "Date and time of the last time an object was used."@en;
rdfs:domain qol:Object;
rdfs:range xsd:dateTime;

```

```

qol:hasDurationEquivalent qol:notUsedFor.

qol:notUsedFor a rdf:DatatypeProperty;
rdfs:comment "Duration since an object was last used."@en;
rdfs:domain qol:Object;
rdfs:range xsd:duration.

qol:hasLastUpdate a rdf:DatatypeProperty;
rdfs:comment "Indicate whether the sensor is the last one updated."@en;
rdfs:domain qol:Sensor;
rdfs:range xsd:boolean.

qol:indicateLocation a rdf:DatatypeProperty;
rdfs:comment "Whether SensorState indicate the resident location."@en;
rdfs:domain qol:SensorState;
rdfs:range xsd:boolean.

qol:indicateMotion a rdf:DatatypeProperty;
rdfs:comment "Whether SensorState indicate the resident's motion."@en;
rdfs:domain qol:SensorState;
rdfs:range xsd:boolean.

qol:indicatePosition a rdf:DatatypeProperty;
rdfs:comment "Whether SensorState indicate the resident's position."@en;
rdfs:domain qol:SensorState;
rdfs:range xsd:boolean.

qol:indicateUse a rdf:DatatypeProperty;
rdfs:comment "Whether SensorState indicate the use of an object."@en;
rdfs:domain qol:SensorState;
rdfs:range xsd:boolean.

qol:getRBConfidenceScore a rdf:DatatypeProperty;
rdfs:comment "Rule-Based confidence score obtained by an activity, given between 0 and
100."@en;
rdfs:domain qol:Activity;
rdfs:range xsd:decimal.

qol:started a rdf:DatatypeProperty;
rdfs:comment "service status"@en;
rdfs:domain qol:Service;
rdfs:range xsd:boolean.

qol:serviceName a rdf:DatatypeProperty;
rdfs:comment "name of service"@en;
rdfs:domain qol:Service;
rdfs:range xsd:string.

#Activity model

@prefix hom: <http://www.ubismart.org/n3/home#>.

```

```

# House #
hom:notAtHome a qol:Outside.
hom:house a qol:House.
hom:johnndoe a qol:Resident;
qol:residentIn hom:house.

# Virtual sensors #
hom:Time rdfs:subClassOf qol:Sensor;
rdf:type qol:SensorType;
rdfs:label "Time"@en;
rdfs:label "Temps"@fr.
hom:clock a hom:Time;
qol:id "clock"^^xsd:string.

hom:DayOfWeek rdfs:subClassOf qol:Sensor;
rdf:type qol:SensorType;
rdfs:label "Day of week"@en;
rdfs:label "Jour de la semaine"@fr.
hom:calendar a hom:DayOfWeek;
qol:id "calendar"^^xsd:string.

# Activities #

hom:goToilet a qol:Activity;
rdfs:label "go toilet"@en;
rdfs:label "va aux toilettes"@fr.

hom:hygiene a qol:Activity;
rdfs:label "hygiene"@en.

hom:watchtv a qol:Activity;
rdfs:label "watch TV"@en.

hom:livingRoomActivity a qol:Activity;
rdfs:label "watch TV"@en.

hom:kitchenActivity a qol:Activity;
rdfs:label "kitchen activity"@en;
rdfs:label "actif dans la cuisine"@fr.

hom:prepareFood a qol:Activity;
rdfs:label "prepare food"@en.

hom:eatMeal a qol:Activity;
rdfs:label "eat meal"@en;
rdfs:label "mange"@fr.

hom:washDishes a qol:Activity;

```

```

rdfs:label "wash dishes"@en;
rdfs:label "lave la vaisselle"@fr.

hom:occupied a qol:Activity;
rdfs:label "occupied"@en.

hom:bedroomActivity a qol:Activity;
rdfs:label "bedroom activity"@en;
rdfs:label "actif dans la chambre"@fr.

hom:sleep a qol:Activity;
rdfs:label "sleep"@en;
rdfs:label "dort"@fr.

hom:nap a qol:Activity;
rdfs:label "nap"@en;
rdfs:label "fait la sieste"@fr.

hom:goOut a qol:Activity;
rdfs:label "go out"@en;
rdfs:label "va dehors"@fr.

hom:bedActivity a qol:Deviance;
rdfs:label "bed activity"@en.

hom:comeHome a qol:Activity;
rdfs:label "come home"@en.

hom:isOut a qol:Activity;
rdfs:label "outdoor activity"@en.

hom:socialize a qol:Activity;
rdfs:label "socialize"@en;
rdfs:label "rencontre des gens"@fr.

hom:atRisk a qol:Deviance;
rdfs:label "at risk"@en;
rdfs:label "en danger"@fr.

hom:sleepMonitoring a qol:Deviance;
rdfs:label "on bed"@en;
rdfs:label "sur le lit"@fr.

```

Code B.1: UbiSmart Abstract model included in the KDA.

## B.2 Semantic Rules

```

@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
@prefix owl: <http://www.w3.org/2002/07/owl#>.
@prefix xsd: <http://www.w3.org/2001/XMLSchema#>.

```



```

@prefix log: <http://www.w3.org/2000/10/swap/log#>.
@prefix math: <http://www.w3.org/2000/10/swap/math#>.
@prefix dt: <http://buzzword.org.uk/2011/functions/datetime#>.
@prefix func: <http://www.w3.org/2007/rif-builtin-function#>.
@prefix e: <http://eulersharp.sourceforge.net/2003/03swap/log-rules#>.

@prefix qol: <http://www.ubismart.org/n3/qol-model#>.
@prefix hom: <http://www.ubismart.org/n3/home#>.
@prefix unc: <http://www.ubismart.org/n3/uncertainty-model#>.
@prefix ubi: <http://www.ubismart.org/n3/ubismart#>.
@prefix : <http://www.ubismart.org/n3/qol-rules#>.

:getScore a rdf:DatatypeProperty;
rdfs:comment "Indicates that a rule is in favor of recognizing an activity with a score."
    @en;
rdfs:comment "the score should be from -10 to 10."@en;
rdfs:domain qol:Activity;
rdfs:range xsd:int.

:getFinalScore a rdf:DatatypeProperty;
rdfs:comment "Computed total score over all single-rule scores."@en;
rdfs:domain qol:Activity;
rdfs:range xsd:int.

## RULES ##
## —— ##

# update resident location [live + persistent]
{?se qol:hasCurrentState ?st. ?se qol:hasLastUpdate true. ?st qol:indicateLocation true.
    ?se qol:deployedIn ?r. ?r qol:partOf ?h. ?u qol:residentOf ?h} => {ubi:n3store ubi:
    updateObject {?u qol:detectedIn ?r}. ?u qol:detectedIn ?r}.

{?se qol:hasCurrentState ?st. ?se qol:hasLastUpdate true. ?se qol:deployedIn ?r. ?r qol:
    partOf ?h. ?u qol:residentOf ?h.} => {ubi:n3store ubi:updateObject {?u qol:detectedIn
    ?r }. ?u qol:detectedIn ?r}.

# generic rule for city desc
{?se qol:hasCurrentState ?st. ?se qol:hasLastUpdate true. ?st qol:indicatePosition true.
    ?se qol:deployedIn ?poi. ?u qol:goesTo ?poi.} => {ubi:n3store ubi:updateObject {?u
    qol:detectedIn ?poi }. ?u qol:detectedIn ?poi}.

# update duration spent in room when room changes [live + persistent]
{?se qol:hasCurrentState ?st. ?se qol:hasLastUpdate true. ?st qol:indicateLocation true.
    ?se qol:deployedIn ?r. ?r qol:partOf ?h. ?u qol:residentOf ?h. ?u qol:detectedIn ?r2.
    ?r log:notEqualTo ?r2. ?se qol:lastUpdate ?t} => {ubi:n3store ubi:updateObject {?u
    qol:cameFrom ?r2. ?u qol:inRoomSince ?t}. ?u qol:cameFrom ?r2. ?u qol:inRoomSince ?t
    }.

# infer durations [live + persistent]

```

```

{?since qol:hasDurationEquivalent ?for. ?x ?since ?start. hom:clock qol:hasValue ?now. (?
  now ?start) math:difference ?duration} => {ubi:n3store ubi:updateObject {?x ?for ?
  duration}. ?x ?for ?duration}.

# detects if resident goes outside [live + persistent]

{?se qol:hasLastUpdate true. ?se qol:attachedTo ?d. ?d a qol:Door. ?u qol:residentOf ?h.
  ?h qol:motionMeasured ?m. ?m math:lessThan 2. ?u qol:detectedIn ?r. ?o a qol:Outside.
  ?r log:notEqualTo ?o. ?d qol:lastUsed ?t} => {ubi:n3store ubi:updateObject {?u qol:
  detectedIn ?o. ?u qol:cameFrom ?r. ?u qol:inRoomSince ?t}. ?u qol:detectedIn ?o. ?u
  qol:cameFrom ?r. ?u qol:inRoomSince ?t}.

{?se qol:hasLastUpdate true. ?se qol:attachedTo ?d. ?d a qol:Lift. ?u qol:residentOf ?h.
  ?st qol:indicatePosition true} => {ubi:n3store ubi:updateObject {?u qol:detectedIn
  hom:notAtHome }. ?u qol:detectedIn hom:notAtHome }.

# this covers case where door send off after the user exited the house
{?u qol:residentOf ?h. ?h qol:motionMeasured ?m. ?m math:lessThan 2. ?se qol:
  hasLastUpdate true. ?se rdf:type hom:PIR. ?se qol:hasCurrentState ?st. ?st qol:
  indicateLocation false. ?d a qol:Door. ?d qol:notUsedFor ?du. ?du math:lessThan 120.
  ?u qol:detectedIn ?r. ?o a qol:Outside. ?r log:notEqualTo ?o. ?d qol:lastUsed ?t} =>
  {ubi:n3store ubi:updateObject {?u qol:detectedIn ?o. ?u qol:cameFrom ?r. ?u qol:
  inRoomSince ?t}. ?u qol:detectedIn ?o. ?u qol:cameFrom ?r. ?u qol:inRoomSince ?t}.

# tracks usage of objects [live + persistent]
{?se qol:hasCurrentState ?st. ?st qol:indicateUse true. ?se qol:attachedTo ?o. ?o qol:
  locatedIn ?h. ?u qol:residentOf ?h. ?se qol:lastUpdate ?t} => {?u qol:useNow ?o}.
{?se qol:hasCurrentState ?st. ?st qol:indicateUse true. ?se qol:hasLastUpdate true. ?se
  qol:attachedTo ?o. ?se qol:lastUpdate ?t} => {ubi:n3store ubi:updateObject{?o qol:
  lastUsed ?t}. ?o qol:lastUsed ?t}.

# infer takesCareOf relation [live]
{?c qol:caregiverOf ?h. ?u qol:residentOf ?h} => {?c qol:takesCareOf ?u}.

## INDEPENDENT FOS SENSOR ##
## ----- ##

# if bed is occupied, infer activity bed_activity
{?se qol:hasLastUpdate true. ?se qol:hasCurrentState ?st. ?st qol:indicateUse true. ?se
  qol:attachedTo ?b. ?b a qol:Bed} => {hom:bedActivity :getScore 9}.

## Raw alternative in case of need.
{?se qol:hasLastUpdate true. ?st qol:hasValue "bed_occupied". ?se qol:attachedTo ?b. ?b
  a qol:Bed} => {hom:bedActivity :getScore 90}.

## ACTIVITY RECOGNITION (SCORE SYSTEM) ##
## ----- ##

# go to the toilet (limited to 30 secondes)

```

```

# Generic rule for city desc
{?u qol:detectedIn ?poi. ?poi qol:isAssociatedTo ?ia} => {?ia :getScore 9}.

{?u qol:detectedIn ?r. ?r a qol:Toilet. ?u qol:inRoomFor ?d. ?d math:lessThan 40} => {hom
:goToilet :getScore 8}.

# hygiene activities (limited to 30 minutes)
{?u qol:detectedIn ?r. ?r a qol:Bathroom. ?u qol:inRoomFor ?d. ?d math:lessThan 1800} =>
{hom:hygiene :getScore 8}.

# watch TV
{?u qol:detectedIn ?r. ?r a qol:Livingroom. ?r qol:motionMeasured ?m. ?m math:notLessThan
2} => {hom:livingRoomActivity :getScore 7}.

# cook (used fridge, limited to 30 secondes) (to be tested)

{?u qol:detectedIn ?r. ?r a qol:Kitchen. ?r. ?f a qol:Fridge. ?se qol:hasCurrentState ?st
. ?st qol:indicateUse true. ?se qol:hasLastUpdate true. ?se qol:attachedTo ?f} => {
hom:prepareFood :getScore 9}.

{?u qol:detectedIn ?r. ?r a qol:Kitchen. ?r. ?o a qol:Oven. ?se qol:hasCurrentState ?st.
?st qol:indicateUse true. ?se qol:hasLastUpdate true. ?se qol:attachedTo ?o} => {hom:
prepareFood :getScore 9}.

# kitchen activity
{?u qol:detectedIn ?r. ?r a qol:Kitchen. ?r qol:motionMeasured ?m. ?m math:notLessThan 2}
=> {hom:kitchenActivity :getScore 6}.

{?u qol:detectedIn ?r. ?r a qol:Bedroom. ?u qol:doesActivityFor ?d. ?d math:LessThan 30}
=> {hom:bedroomActivity :getScore 4}.

# bedroom activity
{?u qol:detectedIn ?r. ?r a qol:Bedroom. ?r qol:motionMeasured ?m. ?m math:notLessThan 2}
=> {hom:bedroomActivity :getScore 4}.

# take a nap (max 3h)
{?u qol:detectedIn ?r. ?r a qol:Livingroom. ?u qol:inRoomFor ?d. ?d math:notLessThan 600.
?r qol:motionMeasured ?m. ?m math:lessThan 2} => {hom:occupied :getScore 4}.
{?u qol:believedToDo hom:occupied. ?u qol:doesActivityFor ?d. ?d math:notLessThan 10800}
=> {hom:occupied :getScore -2}.

# go out of home (max 5h, see run away rule)
{?u qol:detectedIn ?o. ?o a qol:Outside} => {hom:goOut :getScore 3}.
{?u qol:believedToDo ?a. ?a log:notEqualTo hom:goOut. ?u qol:useNow ?o. ?o a qol:Door}
=> {hom:goOut :getScore 5}.

# meet people at home
{?u qol:isAlone false} => {hom:socialize :getScore 8}.

```

```

# must add scores and give confidence, if nothing up a given threshold then believe in
hom:nothing!
{?a :getScore ?x. ?SCOPE e:findall (?sc {?a :getScore ?sc} ?list). ?list math:sum ?total}
  => {?a :getFinalScore ?total}.
#{?SCOPE e:findall (?sc {?a :getScore ?sc} ?list). ?list math:sum ?grandtotal. ?
  grandtotal math:lessThan 1} => {hom:nothing :getScore 10}.
{?SCOPE e:findall (?sc {?a :getFinalScore ?sc} ?list). ?list math:sum ?grandtotal. ?
  grandtotal math:notLessThan 0.1. ?a0 :getFinalScore ?fs. (?fs ?grandtotal) math:
  quotient ?cs} => {?a0 qol:getRBConfidenceScore ?cs}.

# infer most probable activity
{?SCOPE e:findall (?rbc {?a qol:getRBConfidenceScore ?rbc} ?list). ?list e:max ?maxrbc. ?
  a qol:getRBConfidenceScore ?maxrbc. ?u qol:residentOf ?h. hom:clock qol:hasValue ?now
  . ?u qol:believedToDo ?a0. ?a log:notEqualTo ?a0} => {ubi:n3store ubi:updateObject {?
  u qol:believedToDo ?a. ?u qol:doesActivitySince ?now}. ubi:cortex ubi:concludes {?u
  qol:believedToDo ?a. ?u qol:doesActivitySince ?now. hom:clock qol:hasValue ?now}}}.
{?SCOPE e:findall (?rbc {?a qol:getRBConfidenceScore ?rbc} ?list). ?list e:max ?maxrbc. ?
  a qol:getRBConfidenceScore ?maxrbc. ?u qol:residentOf ?h. hom:clock qol:hasValue ?now
  . ?u qol:believedToDo ?a0. ?a log:equalTo ?a0. ?u qol:doesActivitySince ?since} => {
  ubi:cortex ubi:concludes {?u qol:believedToDo ?a. ?u qol:doesActivitySince ?since.
  hom:clock qol:hasValue ?now}}}.

# trigger a context-aware service
{?s qol:serviceName ?n. ?s qol:started false. ?s qol:expectedActivity ?a. ?u qol:
  believedToDo hom:fail} => {ubi:n3store ubi:updateObject {?s qol:serviceName ?n. ?s
  qol:expectedActivity ?a. ?s qol:started true}. ubi:cortex ubi:concludes {?s qol:
  serviceName ?n. ?s qol:expectedActivity ?a. ?s qol:started true}}}.

```

Code B.2: Semantic Rules included in the KDA

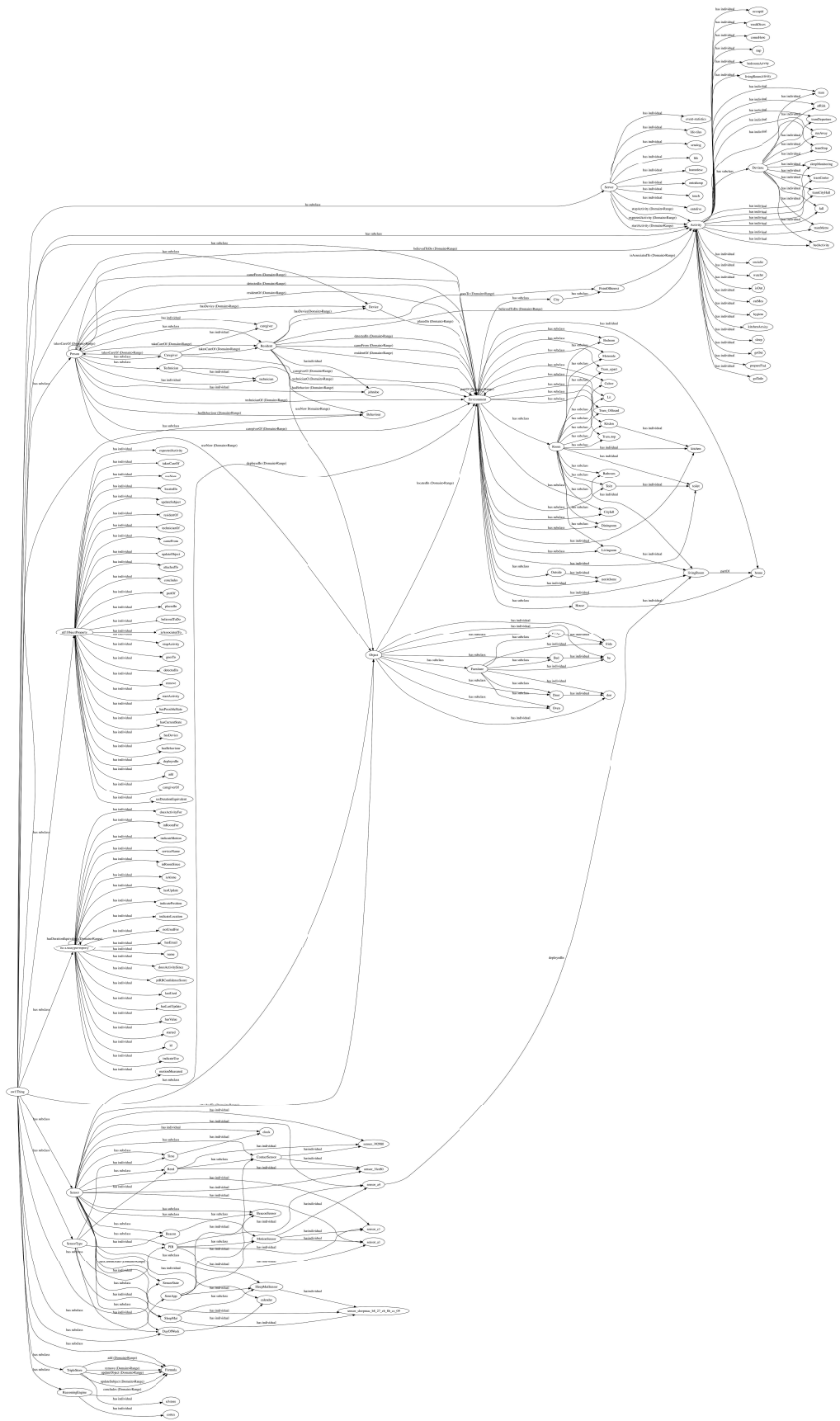


Figure B-1: UbiSmart ontology containing classes and relations between entities.

## Appendix C

# Frailty Items Algorithms

```
get_ipython().magic('matplotlib inline')
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

filename = <FILE_PATH>
events, activities = pd.read_pickle(filename)

users = np.unique(np.hstack((np.unique(events.index.get_level_values('patient')),
                               np.unique(activities.index.get_level_values('patient')))))

u=<USER>
def get_count_daily_events_user(events, user=None):
    if user is not None:
        return events.loc[user].resample('24h', base=10)['id'].count()
    else:
        return events.resample('24h', base=10)['id'].count()

def group_by_day(df):
    return df.resample('24h', base=10)[['createdAt', 'duration']].agg({"createdAt": 'size',
        "duration": 'sum'})

def group_by_night(df):
    data = df.resample('12h', base=10)[['createdAt', 'duration']].agg({"createdAt": 'size',
        "duration": 'sum'})
    i = 1 if data[:1].index.hour == 10 else 0
    return data[i::2]

def get_activity_names(df, u = None):
    if u is None:
        return np.unique([a for u in np.unique(df.index.get_level_values('patient')) for
            a in np.unique(df.loc[u]['activity'])])
    else:
        return np.unique([a for a in np.unique(df.loc[u]['activity'])])

def get_event_names(df, u = None):
    if u is None:
```

```

        return np.unique([a for u in np.unique(df.index.get_level_values('patient')) for
a in np.unique(df.loc[u]['sensor'])])
    else:
        return np.unique([a for a in np.unique(df.loc[u]['sensor'])])

def change_rooms_estimator(my_day):
    e = my_day[my_day.value == "On"].copy()
    e.loc[:, 'previous_location'] = e.sensor.shift()
    e = e[(e.sensor != e.previous_location)]
    return e.count()

def get_amount_activities(df, activity, dif=5, u=u):
    data = df.loc[u]
    if 'createdAt' not in data.keys():
        data['createdAt'] = data['since'].astype(str)
        data['updatedAt'] = data.index.astype(str)

    data = data.loc[(data['activity'] == activity)]

    if len(data) > 0:
        a = np.array(data['since'][1:])
        b = np.array(data['since'][:-1])
        idx = np.hstack((True, ((a-b).astype('timedelta64[m]').astype(int) >= dif)))

        d = np.array(data['updatedAt'].astype('datetime64[ns]') -
                      data['createdAt'].astype('datetime64[ns]')) / np.timedelta64(1, 's')
        data['single_duration'] = d / 60
        data = data.loc[idx]
        dtot = d[idx] + np.cumsum(d)[np.hstack((idx[1:], True))] - np.cumsum(d)[idx]
        dtot[-1] = d[idx][-1]
        data['duration'] = np.maximum(dtot, np.maximum(d[idx], 0)) / 60

    return data

def get_amount_events(df, sensor, dif=5, u=u):
    d = df.loc[u]
    if 'createdAt' not in d.keys():
        d['createdAt'] = d.index.astype(str)
        d['updatedAt'] = d['createdAt']
    duration = (np.array(d['createdAt'][1:].astype('datetime64[ns]')) -
                np.array(d['createdAt'][:-1].astype('datetime64[ns]'))) / np.timedelta64
(1, 's')
    d['single_duration'] = np.hstack((duration / 60, 0))
    data = d.loc[(d['sensor'] == sensor) & (d['value'] == 'On')]

    if len(data) > 0:
        a = np.array(data['createdAt'][1:].astype('datetime64[ns]'))
        b = np.array(data['createdAt'][:-1].astype('datetime64[ns]'))
        t = (a-b) / np.timedelta64(1, 'm')
        idx = np.hstack((True, (t.astype(int) >= dif)))

        d = np.array(data['single_duration'])

```

```

        data = data.loc[idx]
        dtot = d[idx] + np.cumsum(d)[np.hstack((idx[1:], True))] - np.cumsum(d)[idx]
        dtot[-1] = d[idx][-1]
        data['duration'] = np.maximum(dtot, np.maximum(d[idx], 0))
    return data

activity_count = {}
for act in get_activity_names(activities):
    activity_count[act] = get_amount_activities(activities, act, u=u)
activity_count['Night Toileting'] = activity_count['Go Toilet']

event_count = {}
for event in get_event_names(events):
    event_count[event] = get_amount_events(events, event, u=u)

room_change = events.loc[u].resample("D", how=change_rooms_estimator).sensor
event_count['Room Change'] = pd.DataFrame({'createdAt': room_change})

e = events.loc[u].resample('24h', base=10)['createdAt'].count()
event_count['Sensor Triggers'] = pd.DataFrame({'createdAt': e})

a = [k for k in activity_count.keys() if len(activity_count[k])]
print 'activities:', a
e = [k for k in event_count.keys() if len(event_count[k])]
print 'events:', e

#df.index.get_level_values('date')
if 'risk' in locals():
    del risk
legend = []
N = 0
init = 0 #0-120
upper_limit = 12*60

for k, df in activity_count.items():
    if len(df):
        if k == 'Night Toileting':
            data = group_by_night(df)[init:]
        else:
            data = group_by_day(df)[init:]
        data.loc[data['duration'] > upper_limit, ['duration', 'createdAt']] = np.nan
        data.loc[data['createdAt'] == 0, ['duration', 'createdAt']] = np.nan
        data = data[90:]

        data['mean_c'] = [np.nanmean(data[max(0, a-N)*(N>0):a]['createdAt']) for a in
range(len(data))]
        data['std_c'] = [np.nanstd(data[max(0, a-N)*(N>0):a]['createdAt']) for a in range(
len(data))]
        data['lf'] = np.maximum(0.0, data['mean_c'] - 1.96*data['std_c'])
        data['hf'] = data['mean_c'] + 1.96*data['std_c']
        data['mean_t'] = [np.nanmean(data[max(0, a-N)*(N>0):a]['duration']) for a in range
(len(data))]

```



```

        data['std_t'] = [np.nanstd(data[max(0,a-N)*(N>0):a]['duration']) for a in range(
len(data))]
        data.fillna(value=0).astype(int)

    fig = plt.figure(figsize=(20,10))
    ax1 = fig.add_subplot(111)
    ax1.plot(data['createdAt'], 'b o')
    ax1.plot(data['mean_c'], 'b--')
    for tl in ax1.get_yticklabels():
        tl.set_fontsize(20)
    for tl in ax1.get_xticklabels():
        tl.set_fontsize(15)
    ax1.fill_between(data.index, np.maximum(0,data['mean_c']-1.96*data['std_c']),
data['mean_c']+1.96*data['std_c'], color='b', alpha=0.1)

    ax1.set_ylabel('count', color='b', fontsize=20)

    ax2 = ax1.twinx()
    ax2.plot(data['duration'], 'r o')
    ax2.plot(data['mean_t'], 'r--')
    ax2.fill_between(data.index, data['createdAt'] > data['hf'], data['createdAt'] <
data['lf'], color='r', alpha=0.1)

    ax2.set_ylabel('time (minutes)', color='r', fontsize=20)
    for tl in ax2.get_yticklabels():
        tl.set_color('r')
        tl.set_fontsize(20)
    fig.suptitle('Frailty Item: '+k+' for User: '+u, fontsize=20)
    if 'risk' not in locals():
        risk = pd.DataFrame({k: (data['createdAt'] > data['hf']) | (data['createdAt']
< data['lf']) })
    else:
        risk[k] = (data['createdAt'] > data['hf']) | (data['createdAt'] < data['lf
'])

for k, df in event_count.items():
    if len(df):
        if k == 'Room Change' or k == 'Sensor Triggers':
            data = df
        else:
            data = (group_by_day(df)).fillna(value=0).astype(int)

    #data.loc[data['duration'] > upper_limit, ['duration', 'createdAt']] = np.nan
    data.loc[data['createdAt'] == 0, ['createdAt']] = np.nan
    data['mean_c'] = [np.nanmean(data[max(0,a-N)*(N>0):a]['createdAt']) for a in
range(len(data))]
    data['std_c'] = [np.nanstd(data[max(0,a-N)*(N>0):a]['createdAt']) for a in range(
len(data))]
    data['lf'] = np.maximum(0.0, data['mean_c']-1.96*data['std_c'])
    data['hf'] = data['mean_c']+1.96*data['std_c']
    data = data[90:]

```

```

fig = plt.figure(figsize=(20,10))
ax1 = fig.add_subplot(111)
for tl in ax1.get_xticklabels():
    tl.set_fontsize(15)
ax1.plot(data['createdAt'], 'b o')
for tl in ax1.get_yticklabels():
    tl.set_fontsize(20)
ax1.plot(data['mean_c'], 'b--')
ax1.fill_between(data.index, data['lf'], data['hf'], color='b', alpha=0.1)

ax1.set_ylabel('count')
fig.suptitle('Frailty Item: '+k+' for User: '+u, fontsize=20)
if 'risk' not in locals():
    risk = pd.DataFrame({k: (data['createdAt'] > data['hf']) | (data['createdAt']
< data['lf'])})
else:
    risk[k] = (data['createdAt'] > data['hf']) | (data['createdAt'] < data['lf'
'])

risk['sum']=risk[item].sum(axis =1)
risk

fig = plt.figure(figsize=(20,10))
ax1 = fig.add_subplot(111)
ax1.bar(risk.index, risk['sum'])
c = [sum(risk['sum'] == a) for a in range(6)]
P = np.cumsum(c[-1:0:-1])[-1:0:-1]
N = np.cumsum(c)

TP=np.array([[54, 13, 8, 3],
[2,3,4,0],
[1,4,4,0]])
TP = np.vstack((TP,np.sum(TP,axis=0)))
GT = [72, 6, 5, 83]
FN = (GT - TP.T).T

FP = np.array([[P[i] - TP[l,i] for i in range(4)] for l in range(4)])
TN = np.array([[N[i] - FN[l,i] for i in range(4)] for l in range(4)])

Re=np.array([TP[i]/(TP[i] + FN[i]).astype(float) for i in range(4)])
Pr=np.array([TP[i]/(TP[i] + FP[i]).astype(float) for i in range(4)])

l=['Sick', 'Fall', 'Hospital', 'Any']
for i in range(4):
    x = (TP[i]/(TP[i] + FN[i]).astype(float))# false_positive_rate
    y = TP[i]/(TP[i] + FP[i]).astype(float)# true_positive_rate

    # This is the ROC curve
    plt.plot(x,y,label=l[i])
plt.legend()

```

```

    auc = np.trapz(y,x)
    print(-auc)
plt.xlabel('1-Sensitivity ')
plt.ylabel(' Specificity ')
plt.show()

get_ipython().magic('matplotlib inline ')

l=['Sick', 'Fall', 'Hospital', 'Any']
for i in range(4):
    #x = (TP[i]/(TP[i] + FN[i])).astype(float)# false_positive_rate
    #y = TP[i]/(TP[i] + FP[i]).astype(float)# true_positive_rate

    # This is the ROC curve
    plt.plot(a,b,label=l[i])
    plt.legend()
    auc = np.trapz(a,b)
    print(-auc)
plt.xlabel(' Recall ', 'Specifity ')
plt.show()

l=['Sick', 'Fall', 'Hospital', 'Any']
for i in range(4):
    x = (FP[i]/(FP[i] + TN[i])).astype(float)# false_positive_rate
    y = TP[i]/(TP[i] + FN[i]).astype(float)# true_positive_rate

    # This is the ROC curve
    plt.plot(x,y,label=l[i])
    plt.legend()
    auc = np.trapz(y,x)
    print(-auc)
plt.show()

```

Code C.1: Frailty Items Algorithms (1)

```

def aggregate_events(events):
    aggregated_events = events.reset_index(level=0, drop=True).value.resample('D', how='count')
    aggregated_events = aggregated_events[aggregated_events != 0]
    min_events, max_events = min(aggregated_events), max(aggregated_events)
    aggregated_events = aggregated_events * 100 / max_events
    return aggregated_events

events.groupby(level=0).apply(aggregate_events)
aggregated_events = events.loc['J'].value.resample('D', how='count')
min_events, max_events = min(aggregated_events), max(aggregated_events)
aggregated_events = aggregated_events * 100 / max_events
aggregated_events

def custom(my_day):
    a = my_day.copy()

```

```

a.loc[:, 'duration'] = a.index - a.since
falls = a[(a.activity == "Fall") & (a.duration >= timedelta(minutes=5))]
return not falls.empty

def outside_time_estimator(my_day):
    outside = my_day[my_day.activity == "Go Out"]
    time_spend_outside = outside.reset_index().apply(lambda x: x.date - x.since, axis=1)
    if time_spend_outside.empty:
        return timedelta(seconds=0)
    return time_spend_outside.sum()

a = activities.loc['J']
time_spend_outside = a.resample("D", how=outside_time_estimator).activity
time_spend_outside

max_bound = time_spend_outside[time_spend_outside != 0].quantile(.9)
time_spend_outside.loc[time_spend_outside > max_bound] = max_bound

def toilet_duration_estimator(my_day):
    outside = my_day[my_day.activity == "Go Toilet"]
    time_spend_outside = outside.reset_index().apply(lambda x: x.date - x.since, axis=1)
    if time_spend_outside.empty:
        return timedelta(seconds=0)
    return time_spend_outside.sum()

def toilet_count_estimator(my_day):
    outside = my_day[my_day.activity == "Go Toilet"]
    return outside.count()

duration_spend_in_toilet = a.resample("D", how=toilet_duration_estimator).activity
duration_spend_in_toilet

max_bound = duration_spend_in_toilet[duration_spend_in_toilet != 0].quantile(.9)
duration_spend_in_toilet.loc[duration_spend_in_toilet > max_bound] = max_bound

toilet_occurences = a.resample("D", how=toilet_count_estimator).activity
toilet_occurences

max_bound = toilet_occurences[toilet_occurences != 0].quantile(.9)
toilet_occurences.loc[toilet_occurences > max_bound] = max_bound

def kitchen_duration_estimator(my_day):
    in_kitchen = my_day[my_day.activity.isin(['Eat Meal', 'Cook Meal'])]
    time_spend_in_kitchen = in_kitchen.reset_index().apply(lambda x: x.date - x.since,
axis=1)
    if time_spend_in_kitchen.empty:
        return timedelta(seconds=0)
    return time_spend_in_kitchen.sum()

def kitchen_count_estimator(my_day):
    in_kitchen = my_day[my_day.activity.isin(['Eat Meal', 'Cook Meal'])]
    return in_kitchen.count()

```

```

duration_spend_in_kitchen = a.resample("D", how=kitchen_duration_estimator).activity
duration_spend_in_kitchen

max_bound = duration_spend_in_kitchen[duration_spend_in_kitchen != 0].quantile(.9)
duration_spend_in_kitchen.loc[duration_spend_in_kitchen > max_bound] = max_bound

kitchen_occurences = a.resample("D", how=kitchen_count_estimator).activity
kitchen_occurences

max_bound = kitchen_occurences[kitchen_occurences != 0].quantile(.9)
kitchen_occurences.loc[kitchen_occurences > max_bound] = max_bound

def sleeping_duration_estimator(my_day):
    sleeping = my_day[my_day.activity == 'Sleep']
    time_spend_sleeping = sleeping.reset_index().apply(lambda x: x.date - x.since, axis
=1)
    if time_spend_sleeping.empty:
        return timedelta(seconds=0)
    return time_spend_sleeping.sum()

def sleeping_count_estimator(my_day):
    sleeping = my_day[my_day.activity == 'Sleep']
    return sleeping.count()

def nap_duration_estimator(my_day):
    sleeping = my_day[my_day.activity == 'Nap']
    time_spend_sleeping = sleeping.reset_index().apply(lambda x: x.date - x.since, axis
=1)
    if time_spend_sleeping.empty:
        return timedelta(seconds=0)
    return time_spend_sleeping.sum()

def nap_count_estimator(my_day):
    sleeping = my_day[my_day.activity == 'Nap']
    return sleeping.count()

duration_spend_sleeping = a.resample("D", how=sleeping_duration_estimator).activity
duration_spend_sleeping

sleeping_occurences = a.resample("D", how=sleeping_count_estimator).activity
sleeping_occurences

duration_spend_nap = a.resample("D", how=nap_duration_estimator).activity
duration_spend_nap

nap_occurences = a.resample("D", how=nap_count_estimator).activity
nap_occurences

def stacked(df, categories):
    areas = dict()

```

```

last = np.zeros(len(df[categories[0]]))
for cat in categories:
    next = last + df[cat] / np.timedelta64(1, 's')
    areas[cat] = np.hstack((last[:-1], next))
    last = next
return areas

def active_duration_estimator(my_day):
    active = my_day[~my_day.activity.isin(['Go Out', 'Sleep', 'Nap', 'Inactive'])]
    time_spend_active = active.reset_index().apply(lambda x: x.date - x.since, axis=1)
    if time_spend_active.empty:
        return timedelta(seconds=0)
    return time_spend_active.sum()

duration_active = a.resample("D", how=active_duration_estimator).activity
duration_active

max_bound = duration_active[duration_active != 0].quantile(.9)
duration_active.loc[duration_active > max_bound] = max_bound

def change_rooms_estimator(my_day):
    e = my_day[my_day.value == "On"].copy()
    e.loc[:, 'previous_location'] = e.sensor.shift()
    e = e[(e.sensor != e.previous_location)]
    return e.count()

change_rooms = e.resample("D", how=change_rooms_estimator).sensor
change_rooms

```

Code C.2: Frailty Items Algorithms (2)

## Appendix D

# Deployment Report

# Deployment City4Age May 2017 Technical Guidelines

---

## *Wifi Router*

### **Wifi Setup**

- 1) Switch on the Wifi Router
  - 2) Access the Gateway 192.168.8.1 (in case of conflict use 192.168.9.1)
  - 3) Access to AP configuration
  - 4) Setup te SSID: IPAL PWD: GeylangBarhu\_2017
- In case is needed username: admin pwd:admin

### **TopUp SIMCard**

- 1) Open the SIMCard file on BOX
  - 2) Prepare the CreditCard
  - 3) Accesses to this WebSite: <http://www.starhub.com/personal/mobile/mobile-phones-plans/prepaid-cards/top-up-options/online-top-up.html>
  - 4) Insert the phone number
  - 5) Chose the option 20SGD 3.6GB
  - 6) Insert the Credit Card details
- If it is the first time deployment
- 7) Insert the SIMCard in the Wifi Router

## **RapsberryPi**

- 0) Z-Wave motion sensor does not include batteries. Please insert 2 CR123 batteries

### **Z- Wave inclusion**

- 1) Insert the Z-Wave receiver in the RPI
- 2) Open the RPi Domoticz page: <IP>:8080
- 3) Go to Hardware tab and access to the receiver Setup
- 4) On the TopRight tap NodeManagement
- 5) Press Include Node
- 6) Press the Wave Button in any Z-Wave sensor.
- 7) Press on the new sensor and Change the name (Motion or Contact)+Number
- 8) On the top page access Switches
- 9) Press Learnt Light/Switch
- 10) Generate an sensor event in the Z-Wave sensor.
- 11) Replicate the previous name (Motion or Contact)+Number
- 12) Repeat the process 3-11 for each sensor.



### **SleepMat configuration**

- 1) Refer to <https://github.com/pawmint/vital-signs-monitoring>
- 2) Set the wifi configuration on the previous Wifi Router

### **RPI configuration**

- 1) Verify on `/lib/systemd/system/ubigate.service` the UbiSmart server
- 2) Remove `/root/.config/ubigate/config.json` and `/root/.config/ubigate/credentials.json` (<https://github.com/pawmint/ansibleSetup>)
- 3) Remove XML files from `/home/pi` (<https://github.com/pawmint/ansibleSetup>)
- 4) Restart ubigate (`sudo systemctl restart ubigate`)

### **In case we use old Marmitek sensors**

- 1) Activate mochad service by removing the `#` on `/lib/systemd/system/mochad.service`
- 2) Insert the Mochad receiver
- 3) Restart Mochad (`sudo systemctl restart mochad`)

### **HomeDesc on Ubismart**

- 1) Use usual procedure on UbiSmart server

## Deployment Budget 2017

Hardware	Type	Qty	Price (SGD)	Total
<b>Gateway</b>	ELEMENT14 KIT-PI3-STARTER SBC, RASPBERRY PI 3 KIT	1	SGD 72.00	<b>SGD 72.00</b>
<b>Motion</b>	Aeotec MultiSensor 6	5	SGD 95.00	<b>SGD 475.00</b>
<b>Batteries Motion Sensor</b>	Energizer 123 Lithium Battery, 12-Count	1	SGD 51.00	<b>SGD 51.00</b>
<b>Contact</b>	Everspring Door / Window Sensor	3	SGD 60.00	<b>SGD 180.00</b>
<b>Receiver</b>	Aeotec Z-Stick Gen 5	1	SGD 90.00	<b>SGD 90.00</b>
<b>Bed</b>	Juvo	1	SGD 150.00	<b>SGD 150.00</b>
<b>Ethernet cable</b>	3M RJ45 CAT6 Ethernet Flat LAN Cable UTP Patch Router Cables 1000M - intl	1	SGD 3.50	<b>SGD 3.50</b>
<b>Tape</b>	NA			<b>SGD -</b>
<b>Mobile Wifi</b>	3G USB HSDPA USB Dongle	1	SGD 75.00	<b>SGD 75.00</b>
<b>SIMcard</b>	Starhub	1	SGD 8.00	<b>SGD 8.00</b>
<b>Data Plan</b>	StarHub	12 months	SGD 20.00	<b>SGD 240.00</b>
<b>USB cable</b>	Element14	2	SGD 3.17	<b>SGD 6.34</b>
<b>USB Adaptor</b>	Element14	2	SGD 8.00	<b>SGD 16.00</b>
<b>MultiPlug</b>	<a href="http://sg.element14.com/masterplug/srgt6-2/surge-protector-6gang/dp/5079822">http://sg.element14.com/masterplug/srgt6-2/surge-protector-6gang/dp/5079822</a>	1	SGD 48.00	<b>SGD 48.00</b>
<b>Beacon</b>	Estimote Location Beacons (Pack of 3)	1	SGD 195.00	<b>SGD 195.00</b>
<b>Mobile Phone</b>	TBC			
<b>TOTAL Single house</b>				<b>SGD 1,652.98</b>
<b>TOTAL Deployment</b>				<b>SGD 16,529.80</b>

# Lessons learned Deployment

## PreDeployment

- SD Card duplication did not work. Some files were missing or corrupted. We did recheck each SD card
- Sleep mat start failing few hours before the deployment.

Picture of the Execution

SerialException('device reports readiness to read but returned no data (device disconnected?)')

- Wifi prepaid Sim Cards needed to be top up one by one.
- Raspberry Pi case and Juvo case are not suitable for GPIO connexion and we almost destroy both cases.
- Mochad receiver hardware failed for the first time few hours before the deployment
- Each house has the number of the raspberry pi used in the deployment.

4	Salamèche	Mdm Loo	61 #09-3251 x10 (R1)	Show	Edit	Delete
5	Reptincel	Mr Cheng	62 #06-3397 (8)	Show	Edit	Delete
6	Dracaufeu	Mdm Aminah	61 #06-3291 x10 (R2)	Show	Edit	Delete
7	Carapuce	Mr Ronald	61 #12-3251 (R4)	Show	Edit	Delete
8	Carabaffe	Mr Tan	61 #03-3271 (Drop)	Show	Edit	Delete
9	Tortank	Mdm Heng	62 #09-3413 (R7)	Show	Edit	Delete
10	Chenipan	Mdm Lum	62 #09-3391 x10 (R3)	Show	Edit	Delete
11	Chrysacier	Mr Vincent	62 #13-3361 (R9)	Show	Edit	Delete
12	Papilusion	Mdm Lim	61 #12-3269 (R5)	Show	Edit	Delete
13	Aspicot	Mdm Wee	62 #08-3379	Show	Edit	Delete
14	Coconfort	Helen Wan	61 #04-3285	Show	Edit	Delete

## Deployment

### Overall

- No enough plug in the houses -> multiplug was completely necessary and we anticipated this problem
- Houses too busy

### House 1) Foo

- Sleep mat does not work
- Two fridges and not clear which ne to use or if she used

- Mochad Contact sensor send wrong event, Mochad receive information from the sensor that is not able to understand.
- Regular sensors System ok

### ***House 2) Aminah***

- Sleep Sensor script failed
- Regular sensors System ok
- The system stopped completely after one hour. It seems that the system is down, we might check with the elderly. She might unplugged the system.

### ***House 3) Lum***

- Sleep Sensor script failed
- Door sensor felt because of the painture
- Regular sensors System ok
- It seems that the system is down, we might check with the elderly. She might unplugged the system.

### ***House 4) Ronald***

- Houmebounding
- Regular sensors System ok
- Mat failed

### ***House5)***

- He change his mind, not anymore in the program

### ***House 6) Lim (Domoticz)***

- It seems that the mat works sometimes and sometimes not.
- Regular sensors System ok

### ***House 7) Heng (Domoticz)***

- Contact sensors does not send good event,
- Sleep Mat failed

### ***House 8) Cheng (Domoticz)***

- Sensor Contcat81 not recognized
- Regular sensors System ok
- Sleep mat failed

### House9) Vincent (Domoticz)

- Rpi does not receive the config file, we placed the sensor manually but we need to fix the issue to be able to receive the events.
  - Motion91 Bed, Motion92 Kitchen, Motion93 toilet, Contact91 Door, Contact92 fridge
- Sleep mat failed

### House10) Helen (Domoticz)

- Regular sensors System ok
- Mat failed

### House 11) Wee (Domoticz)

- Regular sensors System ok
- Mat failed

## Common Issues During the Deployment

- Logs are fill up the memory in 20 minuts. We need to erase them with a cronjob.
- Too mny log messages in domoticz to marmitek and sleep mat scripts.

```
2017-05-04 08:23:46,007 - ubigate.log - INFO - DZM: Nothing To Show
2017-05-04 08:23:46,044 - ubigate.log - DEBUG - Message 159 published.
2017-05-04 08:23:46,013 - ubigate.log - DEBUG - Z-wave received some data:(u'name': u'Sensor', u'idx': 3, u'nvalue': 1, u'Battery': 255, u'dtype': u'Light/Switch', u'svalue': u'255', u'unit': 1, u'switchType': u'On/Off', u'RSSI': 12, u'id': u'00000600', u'stype': u'Switch')
2017-05-04 08:23:46,014 - ubigate.log - INFO - DZM: Nothing To Show
2017-05-04 08:23:46,319 - ubigate.log - DEBUG - Z-wave received some data:(u'name': u'Alarm Type', u'idx': 1, u'nvalue': 0, u'Battery': 255, u'dtype': u'Light/Switch', u'svalue': u'0', u'unit': 1, u'switchType': u'On/Off', u'RSSI': 12, u'id': u'00000633', u'stype': u'Switch')
2017-05-04 08:23:46,320 - ubigate.log - INFO - DZM: Nothing To Show
2017-05-04 08:23:46,326 - ubigate.log - DEBUG - Z-wave received some data:(u'name': u'Unknown', u'idx': 36, u'nvalue': 0, u'Battery': 255, u'dtype': u'Light/Switch', u'svalue': u'0', u'unit': 1, u'switchType': u'On/Off', u'RSSI': 12, u'id': u'00000632', u'stype': u'Switch')
2017-05-04 08:23:46,327 - ubigate.log - INFO - DZM: Nothing To Show
2017-05-04 08:23:46,334 - ubigate.log - DEBUG - Z-wave received some data:(u'name': u'Motion62', u'idx': 4, u'nvalue': 1, u'Battery': 255, u'dtype': u'Light/Switch', u'svalue': u'255', u'unit': 1, u'switchType': u'Motion Sensor', u'RSSI': 12, u'id': u'00000635', u'stype': u'Switch')
2017-05-04 08:23:46,335 - ubigate.log - INFO - details: {'bindingType': 'Room', 'binding': 'kitchen', 'id': 'Motion62'} house: 14
2017-05-04 08:23:46,336 - ubigate.log - INFO - never shown
2017-05-04 08:23:46,337 - ubigate.log - INFO - Sending event 'on' at time '2017-05-04T08:23:46.334491+02:00' for sensor 'Motion62'
2017-05-04 08:23:46,339 - ubigate.log - DEBUG - Posted message 161: {'id': 'Raspberry Pi/08:27:eb14d16:d8/Zwave_Motion62_kitchen_Room/2017-05-04T08:23:46.334491+02:00', 'type': 'TruthObservation', 'phenomenonTime': {'instant': '2017-05-04T08:23:46.334491+02:00'}, 'observedProperty': {'href': 'Motion Sensor'}, 'procedure': 'Zwave_Motion62_kitchen_Room', 'featureOfInterest': {'href': '14'}, 'resultTime': '2017-05-04T08:23:46.334491+02:00', 'result': {'dom': '', 'value': 'on'}}, to topic: 'house/14/marmitek/sensor/Motion62'
2017-05-04 08:23:46,351 - ubigate.log - INFO - DZM: Nothing To Show
2017-05-04 08:23:46,373 - ubigate.log - DEBUG - Message 161 published.
```

- When one mat is assign to a house no need to broadcast... It is having a beacon behaviour.

# City of All Ages: Elderly-Friendly City Services for Active and Healthy Ageing

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## Introduction

Like many developed countries, Singapore faces the challenges of an ageing population. The number of Singaporeans aged 65 and above is increasing rapidly as population growth slows. The number of seniors has doubled from 220,000 in 2000 to 440,000 in 2015, and is expected to increase to 900,000 by 2030. Amongst the elderly people, close to 10% are living alone (from 35,000 in 2012 to 83,000 by 2030). The changing demographic not only increases healthcare costs but also the demand on healthcare services and care provision.

Preventing frailty and MCI is key for the elderly to maintain their day-to-day activities and remain healthy and independent at home. Prior research (Gill et al 2006) has shown that frailty, like disability, is a dynamic process with older individuals moving back and forth between different frailty states. Transition to frailty is a gradual progression that occurs over the course of several months or years, and there are surprisingly high rates of recovery. However, it is important to intervene within the right time window before a person goes into full blown frailty (see figure below). Hence it is important to detect the onset and progression of frailty and to identify the factors that may facilitate transitions to less frail states. This can inform the development of interventions to manage elderly at risk for frailty.

City for All Ages project seeks to demonstrate that smart cities can play a pivotal role in “prevention” (i.e. the early detection and consequent intervention) of MCI and frailty-related risks. The core idea is that “smart cities”, enabled by the deployment of sensor technologies and analytics can collect data about individuals: a) to identify segments of population potentially at risk, in order to start more stringent monitoring; b) to closely monitor selected individuals, in order to start a proactive intervention. In both cases, adverse changes of behaviours that are identified through a set of indicators can prompt preventive actions. The aim is to advance the research on healthcare towards a proactive rather than reactive system.

## Part 1: Elderly Interviews

We (in cooperation with the SAC Volunteers and Caregivers) conduct a personal interview in order to get to know more about the user such as living habits, daily activities and preferences. This survey is performed with several research team members and SAC staff who can speak English or Chinese (dialects) depending on the case (or any other language).

A total number of 10 elderly are currently recruited in the Geylang Bahru district (Age Dimensions, Kee-Lee and Chi 2002): 4 are “young old” (60-69), 4 are “old old” (70 - 79) and 2 are “oldest old” (80 +).

### I.1 Activities of Daily Living and Outdoor Activities

Because health problems can interfere with even the most basic aspects of daily living (for example, quality of sleep, feeding oneself, dressing, mobility...), the health care professions have codified the concepts of activities of daily living (ADLs) and instrumental activities of daily living (IADLs). Such analysis and classification helps to at least partially objectify Quality of Life (QoL). In the conducted interviews we try to get as many information as possible on the user’s habits and daily routine.

Participant ID	Sleep Time	Wakeup Time	Afternoon Naps?	Eating	Showering	Exercising
1	1030 pm – 1130 pm	700 am – 800 am	No	3 meals, Cooks lunch	2 times	Daily
2	220 am	600 am – 700 am	No	3 meals, Cooks	1 time	No exercise
3	1000 pm	800 am	No	3 meals, Cooks breakfast	1 time	Daily
4	200am – 300am	600 am	Yes (2-3 hours)	3 meals, Cooks	Irregularly	No exercise
5	1000 pm	300 am	Yes (1 hour)	3 meals, Don't cook	2 times	No exercise
6	1000 pm – 1030 pm	500 am	No	2 meals, Cooks	2 times	No exercise
7	1100 pm	600 am	Yes (0.25 hour)	3 meals, Cooks dinner	3 times	Daily
8	300 am – 400 am	500 am – 600 am	Yes (1-2 hours)	2 meals, Cooks	5 times	Daily
9	1100 pm	600 am – 700 am	Yes (Seldom)	2 meals, Cooks	2 times	Daily
10	700 pm	500 am (Also wakes up at 200 am or 300 am)	No	3 meals, Cooks	2 times	Daily



Many adults aged 65 and over spend, on average, 10 hours or more each day sitting or lying down, making them the most sedentary age group. Physical activity and exercise can help stay healthy, energetic, and independent. Mobility inside the neighbourhood is also important to this study as Singapore is building communities and planning carefully every HDB neighbourhoods (including facilities to exercises, green spaces if possible, wet-market and hawker centers). We look at participant's mobility and places of interest within the neighbourhood.

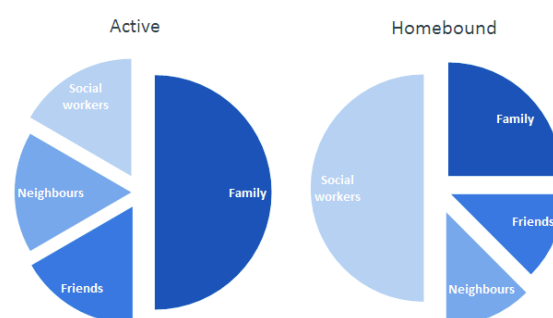
Participant ID	Walking	Physical Activities	Shopping	Marketing	Visiting Family	Meeting Friends	Religious Activities
1	Often	Often	Rarely	Rarely	Never	When free	Rarely
2	Sometimes	Often	Sometimes	Sometimes	Never	Rarely	Never
3	Sometimes	Often	Rarely	Sometimes	Often	Often	Sometimes
4	Rarely	Never	Rarely	Never	Never	Sometimes	Rarely
5	Rarely	Never	Never	Never	Never	Rarely	Sometimes
6	Rarely	Never	Rarely	Sometimes	Sometimes	Never	Rarely
7	Sometimes	Often	Rarely	Sometimes	Rarely	Sometimes	Sometimes
8	Often	Often	Sometimes	Sometimes	Sometimes	Rarely	Often
9	Often	Often	Rarely	Often	Never	Often	Never
10	Rarely	Rarely	Rarely	Sometimes	Never	Often	Sometimes

## I.2 Social Contact

For all participants, we asked and the main stakeholders they are interacting with (family, SAC volunteers, other volunteers, Friends, Neighbours).

During the technical pre-test session (surveys run to 28 elderly) we found out:

In the case of the frail elderly who stay at home (homebound), we observed that the SAC volunteers become the main point of any social interaction on a daily basis (visits, assistance, and event organizer)



Participant ID	Marital status	Interactions with family	Interactions with friends	Interactions with neighbors	Interactions with SAC volunteers
1	Widowed	Never	Never	Often	Often
2	Widowed	Never	Never	Never	Sometimes
3	Married but separated	Often	Often	Often	Often
4	Married	Sometimes	Sometimes	Often	Sometimes
5	Single	Rarely	Often	Often	Often
6	Widowed	Sometimes	Never	Often	Rarely
7	Widowed	Often	Often	Sometimes	Often
8	Married	Sometimes	Rarely	Often	Often
9	Divorced	Never	Sometimes	Rarely	Often
10	Widowed	Never	Often	Often	Often

### I.3 Quality of Life

Quality of life (QOL) is a broad multidimensional concept that usually includes subjective evaluations of both positive and negative aspects of life. Aspects of culture, values, and spirituality are also key domains of overall quality of life that add to the complexity of its measurement. We ask simple questions and collected general impressions from the participants.

Participant ID	Overall QOL	Health	Social Relationship	Independence	Home	Emotions	Leisure
1	Good	Alright	Alright	Good	Alright	Alright	Alright
2	Alright	Alright	Very Good	Alright	Very Good	Alright	Very Good
3	Very Good	Very Good	Very Good	Good	Very Good	Very Good	Very Good
4	Good	Very Bad	Alright	Good	Alright	Alright	Alright
5	Alright	Good	Very Good	Very Good	Very Good	Very Good	Very Good
6	Good	Alright	Very Good	Very Good	Good	Alright	Good
7	Very Good	Very Good	Very Good	Very Good	Good	Very Good	Very good
8	Very Good	Very good	Alright	Very Good	Good	Very Good	Very Good
9	Very Good	Very Good	Good	Very Good	Alright	Good	Good
10	Good	Bad	Very Good	Very Good	Very Good	Good	Very Good

Findings are: The elderly have a general tendency to proclaim themselves satisfied with their QOL. Exception observed for 'Social Relationships' - Most elderly are estranged from their families and have grown to rely on the SAC staff.

## Part 2: Deploying Smart Home Systems

We deploy industrial and unobtrusive sensors inside the house. Those sensors are able to set a full smart home solution in order to monitor the elderly.

The sensors, all together with the reasoning engine, are able to recognize Daily Activity patterns and observe a decline (drop-out) of ADLs. The system will use its intervention module to induce the elderly to perform a positive activity (going out for lunch, walk or exercises, join friends, visit the SAC...).



*Unobtrusive sensors are deployed inside the house for Activity of Daily Living*

### II.1 Timeline

Phase 1 Indoor Monitoring	Time	Status	Description
Recruitment	May 2017	<b>Done</b>	10 users managed by the research team and recruited with the help of TOUCH Senior Activity Centre
Surveys and Technical deployment	May - June 2017	<b>Done</b>	<p>Duration: 1 month</p> <p>1- Consent forms (approval)</p> <p>2- User surveys After collecting the consent forms, we conduct a one-to-one survey in order to get to know more about the user such as living habits, daily activities and preferences. This step is crucial as it help the platform to establish the ground truth and gives more details on the user's activities of daily living (ADL) once the data collection is started.</p> <p>3- Initial trial setup (hardware deployment) Complete set up of the deployed system composed of low cost and non-intrusive sensors (e.g. motion sensors, contact sensors, sleep mat). This step is different for each house as the configuration may vary (number of rooms, objects, flat configuration).</p>

Data Collection	July - Sept 2017	<b>Start</b>	<p>Duration: 3 months</p> <p>Systems up and running with few maintenance actions depending on any hardware issues (sensing issues, hardware off). Data collection is set for 3 months to be able to get a satisfying time frame to conduct the study.</p> <p>The SAC app will be updated to meet the needs of the SAC. We implemented a new version but any feedback from the SAC is welcome.</p> <p>A written report is sent and updated at the end of every month to give insights on the data collected within the 10 units. First report will be shared at the end of July presenting ongoing deployment results.</p>
Data Analysis	August - Sep 2017	<b>Pending</b>	<p>Duration: 2 months</p> <p>After the first month of data collection, the team will be working on giving insights on the collected data to the SAC and will send monthly reports on the deployment and data collection status.</p>

## II.2 1-Room HDB Flat to Smart Home

All provided houses are located in the same Buildings and have the same topology. We thus deployed the exact same technology to every house. An example with sensors overall positions:



**10 Units Deployed w/  
Unobtrusive Technology / Same topology:**

- M 3 Motion
- C 2 Contact Sensors
- S 1 Sleep Mat





## II.3 Photos of deployment



## II.4 Data Transmission



The figure above shows three months of data collections (each block represent one month with on the Y-axis dates and on X-axis houses number). The cells filled in green correspond to a validated data collection and the one in red means data transmission error. The first two months (blocks on the left) are trial months to validate the system and to improve the reasoning engine. The block on the right represents the first month of data collection. We can see that all houses transmit good signals except two that are disconnected.

One thing that we can also notice is that some days are highlighted in orange colour. This means that we went on site to do maintenance. All those actions have successfully set back many houses up and running.

## Part 3: Ground Truth and Data Collection

### III.1 Data Validation

“In order to improve the quality of automated monitoring to an acceptable level it is advocated that the sensor data produced be analysed through pattern recognition and machine learning, so that we can move beyond simply presenting the sensor data in a visual manner. One of the major challenges in this regard is the collection of accurate ground truth. With properly labelled and accurate ground truth, machine learning algorithms developed will have higher detection rates, while at the same time producing very few false alarms, so as to be acceptable to the end users.” Activity Recognition in Assisted Living Facilities with Incremental, Approximate Ground Truth, Authors: Jit Biswas, Romain Endelin, Clifton Phua, Aung Aung Phyo Wai, Andrei Tolstikov, Zhu Jiaqi, Thibaut Tiberghien, Hamdi Aloulou, Philip Yap Lin Kiat, Mounir Mokhtari.

Survey Data

Bed Time	Waking up time	Avg Sleep Duration (hrs)
10 07:00 PM	05:00 AM (Also wakes up at 02:00 or 03:00 AM)	7:10

Sensor's data

Date	Get Up Time
14-Jun-17	0:54
15-Jun-17	0:23
16-Jun-17	1:56
17-Jun-17	5:15
18-Jun-17	5:15
19-Jun-17	4:56
20-Jun-17	2:05
21-Jun-17	4:42
22-Jun-17	5:54
25-Jun-17	5:23
26-Jun-17	1:43
27-Jun-17	5:25
28-Jun-17	4:44
29-Jun-17	3:45
30-Jun-17	3:00
Mean	3:41:50

On the above figure, we crossed the data from the user's survey to the actual collected data from the sensors. At first we were surprised that our sleep sensor detected “waking up time” from around 1AM to 6AM, with a mean of less than 4AM. We crossed those computed data with the survey results, and they matched. See orange highlights.

## III.2 Data Collection

### Activities of Daily Living:

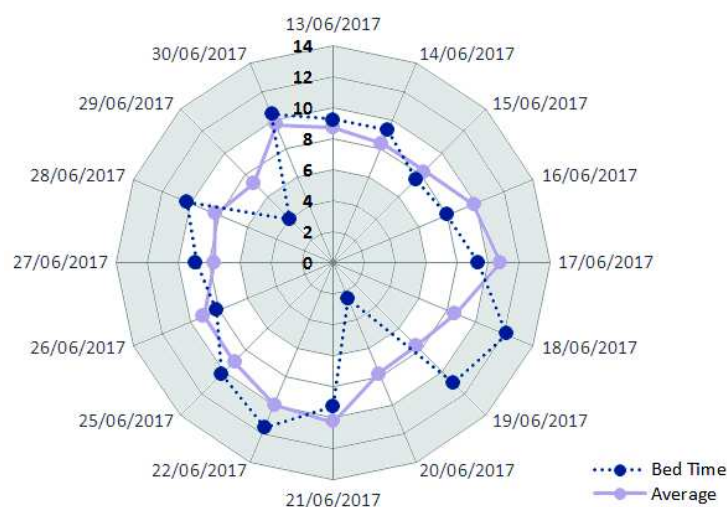
The platform is able to collect various ADL's data: bed occupancy, time sleep, kitchen activity and toilet activity for example. The figure below shows the time sleep for two different participants:



On the left: Observations made during 2 weeks - Daily Average time spent in bed: 5h06

On the right: Observations made during 3 weeks - Daily Average time spent in bed: 9h23

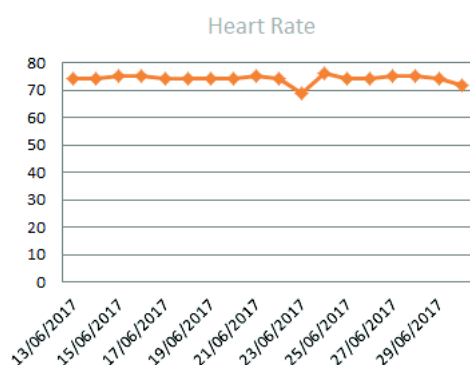
Another representation of time sleep:



### Vital Signs:

Vital signs are measurements of the body's most basic functions. The four main vital signs routinely monitored by medical professionals and health care providers include the following: Body temperature, Pulse rate, Respiration rate (rate of breathing), Blood pressure (Blood pressure is not considered a vital sign, but is often measured along with the vital signs.) Vital signs are useful in detecting or monitoring medical problems. Vital signs can be measured in a medical setting, at home, at the site of a medical emergency, or elsewhere.

### Heart Rate:

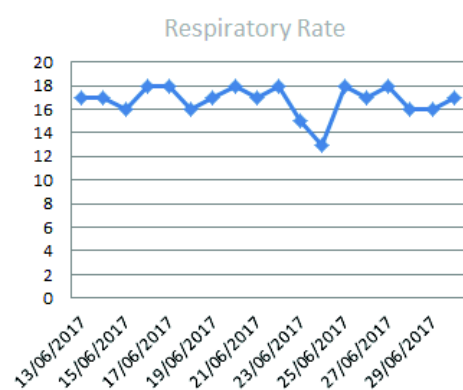


The pulse rate is a measurement of the heart rate, or the number of times the heart beats per minute. As the heart pushes blood through the arteries, the arteries expand and contract with the flow of the blood. Taking a pulse not only measures the heart rate, but also can indicate the following: Heart rhythm, Strength of the pulse.

The normal pulse for healthy adults ranges from **60 to 100** beats per minute. The pulse rate may fluctuate and increase with exercise, illness, injury, and emotions. Females ages 12 and older, in general, tend to have faster heart rates than do males.

Athletes, such as runners, who do a lot of cardiovascular conditioning, may have heart rates near 40 beats per minute and experience no problems.

### Respiratory Rate:



The respiration rate is the number of breaths a person takes per minute. The rate is usually measured when a person is at rest and simply involves counting the number of breaths for one minute by counting how many times the chest rises. Respiration rates may increase with fever, illness, and with other medical conditions. When checking respiration, it is important to also note whether a person has any difficulty breathing.

Normal respiration rates for an adult person at rest range from 12 to 16 breaths per minute.



## Annex

### A.1 Activities at the SAC

Participant ID	Frequency	Meet Friends	Morning Exercises	Having Breakfasts	Reading Newspapers	Watching TV	Playing Games
1	Sometimes	Attend (Like a lot)	Attend (Like a lot)	Attend (Like a lot)	Never Attend	Attend (Like a lot)	Never Attend
2	Sometimes	Attend (Like)	Attend (Like a little)	Never Attend	Attend (Like a little)	Never Attend	Attend (Like a lot)
3	Sometimes	Attend (Like a lot)	Attend (Like a lot)	Attend (Like a lot)	Never Attend	Never Attend	Attend (Like a lot)
4	Sometimes	Attend (Like)	Never Attend	Never Attend	Never Attend	Never Attend	Never Attend
5	Sometimes	Attend (Like a lot)	Never Attend	Never Attend	Never Attend	Never Attend	Never Attend
6	Sometimes	Never Attend	Never Attend	Never Attend	Never Attend	Never Attend	Never Attend
7	Sometimes	Attend (Like)	Attend (Like a lot)	Attend (Like a lot)	Attend (Like a lot)	Attend (Like)	Attend (Like)
8	Sometimes	Attend (Like)	Never Attend	Never Attend	Attend (Like)	Attend (Like a little)	Never Attend
9	Sometimes	Attend (Like)	Never Attend	Never Attend	Attend (Like a little)	Never Attend	Never Attend
10	Sometimes	Attend (Like a lot)	Attend (Like)	Attend (Like a lot)	Attend (Like)	Attend (Like a lot)	Attend (Like a lot)

Participant ID	Computer Classes	Befriending Sessions	Outings	Karaoke	Volunteer Works	Other Activities at SAC
1	Never Attend	Never Attend	Attend (Like a lot)	Attend (Like a lot)	Attend (Like a lot)	SAC Afternoon Activities
2	Never Attend	Never Attend	Attend (Like a lot)	Never Attend	Never Attend	-
3	Never Attend	Attend (Like a lot)	Attend (Like a lot)	Never Attend	Attend (Like a lot)	SAC Afternoon Activities
4	Never Attend	Attend (Like a little)	Never Attend	Never Attend	Never Attend	Blackjack, Trips to Tekka Market
5	Never Attend	Never Attend	Never Attend	Attend (Like a lot)	Never Attend	-
6	Never Attend	Never Attend	Never Attend	Never Attend	Never Attend	-
7	Never Attend	Attend (Like)	Attend (Like a lot)	Never Attend	Attend (Like a lot)	-
8	Never Attend	Never Attend	Never Attend	Never Attend	Attend (Like)	-
9	Never Attend	Attend (Like a little)	Attend (Like)	Never Attend	Attend (Like a little)	-
10	Never Attend	Never Attend	Attend (Like a lot)	Attend (Don't Like)	Attend (Like a lot)	-

### A.2 Technology Use

Participant ID	Age	Gender	TV	EZ-Link	Line-Phone	Cell-Phone	Tablet	Mobile Device Use
1	Young-old	F	Y	Y	-	-	-	-
2		F	Y	Y	-	Y	Y	<ul style="list-style-type: none"> <li>• Phones calls (Appointments)</li> <li>• SMS reading</li> <li>• Tablet gaming</li> </ul>
3	Old-old	F	Y	Y	-	Y	-	<ul style="list-style-type: none"> <li>• Phone Calls</li> </ul>
4		M	Y	Y	-	Y	-	<ul style="list-style-type: none"> <li>• Phones calls (To wife) → Important to subject</li> <li>• 995 emergency calls</li> </ul>
5	Oldest-old	F	Y	-	-	Y	-	<ul style="list-style-type: none"> <li>• Phone Calls</li> </ul>
6	Oldest-old	F	Y	Y	-	Y	Y	<ul style="list-style-type: none"> <li>• Phone Calls</li> <li>• SMS reading &amp; messaging</li> </ul>
7	Young-old	F	Y	Y	-	Y	-	<ul style="list-style-type: none"> <li>• Phone calls</li> <li>• Mobile apps (occasional)</li> <li>• Mobile games (occasional)</li> </ul>
8	Old-old	M	Y	Y	-	Y	-	<ul style="list-style-type: none"> <li>• Phone calls</li> <li>• Music mobile apps</li> </ul>
9	Young-old	M	Y	Y	-	Y	-	<ul style="list-style-type: none"> <li>• Phone Calls</li> <li>• SMS reading &amp; messaging</li> </ul>
10	Old-old	F	Y	Y	Y	Y	-	<ul style="list-style-type: none"> <li>• Phone calls</li> <li>• Mobile gaming</li> </ul>

# Deployment check

16 May 2017, Geylang Bahru, Participants: Martin Kodyš, Pau Oliver

Order of visits: 03, 10, 07, 08 (break) 10, 09, 01, 06, 04, 05, 02  
30 minutes slots, from 09:15 to 15:30

Each unit was checked and modifications were carried out.

DN	T <sub>st</sub>	Intervention
01	x10 XX	Door, kitchen s. repositioned (3M)
02	x10 XX	OK, no fall
03	x10 X#	RΠ with 3G modem and transceiver removed for SD-card malfunction
04	x10 XO	OK, no fall
05	x10 OO	Fridge s. installed (not deployed previously), replugin the mat cables; bedroom s. battery is discharged → <b>to be replaced on next intervention</b>
06	zw XO	Fridge s. repositioned (3M)
07	zw OX	Fixed JUVU box connection to mat (wrong pins), no change on RΠ Toilet and door s. repositioned
08	zw XO	Toilet, kitchen, door s. repositioned
09	zw XX	Bedroom s. repositioned; door s. <b>missing</b> replaced
10	zw XO	3 motion s. fallen: 2 repositioned, 1 damaged replaced, bought new batteries; fridge contact s. fallen (larger part) repositioned

T = deployed technology

st = status before and after, where X = down, O = all right, # = taken back without replacement

## Enhancements

- **ssh connection:** used default password → using a RSA key authentication only
- **screen:** → terminal is using screen profile that shows: deployment number, house number, gateway number

## Complaints

- Contact card with phone number to be provided

## Curiosities

- Painted gate with our contact sensor included deployment 6.
- One JUVU box was wrongly connected to GPIO of the Raspberry Pi.

- Mat fell down on the floor through the bed frame, we placed it slightly diagonally.

## Future recommendations

- Photo documentation of deployed equipment – to see what tape is used, where it is positioned, whether the cables are plugged in correctly
- Make a checklist for things to bring, include batteries (and spare **tested** sensors), screwdrivers, [to be completed]

## Deployment check

12 June 2017, Geylang Bahru, Participants: Joaquim Bellmont, Antoine de Marassé

Order of visits: 02, 10, 07, (break), 05, 09, 03, 06, 08.

01 was not at home. 04 system was up and running.

~25 minutes slots, from 11:15 to 4:50 pm.

	Name	R#	Tech	Blk	Unit	Language	Time	Status
1	Loo Beng Choo	R1	X10	61	#09-3251	Mandarin	Not here	✗
2	Lim Kwee Khai	R5	X10	61	#12-3269	Mandarin	11 :15 am	✓
3	Aminah	R2	X10	61	#06- 3291	English	3 :18 pm	✓
4	Ronald Riasibuea	R4	X10	61	#12- 3251	English	ok	✓
5	Cheng Heng	R8	X10	62	#06- 3397	Mandarin	1 :56 pm	✓
6	Wee Ah Bee	R10	ZW	62	#08- 3379	Mandarin	3 :48 pm	✓
7	Lum Fong Sin	R3	ZW	62	#09-3391	Mandarin	12 :10 pm	✓
8	Heng Siew Tiang	R7	ZW	62	#09- 3413	Mandarin	4 :20 pm	✓
9	Vincent Ng Kim San	R9	ZW	62	#13-3361	Mandarin	2 :22 pm	✓
10	Helen Wan	R6	ZW	61	#04-3285	English	11 :35 am	✓

Remarks:

	Name	R#	Remarks
1	Loo Beng Choo	R1	Not at home on the morning but has been looking for us, still not at home after the lunch break, can't find at the SAC (no cellphone).
2	Lim Kwee Khai	R5	Run a complete check, replaced with 3M. Noted presence of Nextan motion sensors (at least 2) for other experiments? User is very happy about our presence and we get positive feedback of our deployment.
3	Aminah	R2	Change the system and fixed sensors with 3M. User is having lunch very late because of her insulin shots.
4	Ronald Riasibuea	R4	System up and running, no check required.
5	Cheng Heng	R8	Replaced a motion sensor in the toilets, unsanitary flat.
6	Wee Ah Bee	R10	Replaced the RasPi, to confirm?
7	Lum Fong Sin	R3	All devices have been unplugged, user is going to Penang for few days and might switch the system off.
8	Heng Siew Tiang	R7	
9	Vincent Ng Kim San	R9	Taped all sensors with 3M, user fixed the contact sensor on the door.
10	Helen Wan	R6	User told us that if the sensors are too visible (contact on the fridge), her visitor will touch and play with the devices. Change on activities' pattern to be made around 22 <sup>nd</sup> of June as the user will leave her position as a receptionist and stay at home.

## Appendix

Meeting conducted on the morning, improvements to be made:

- work on the login screen (make it more user friendly and improve the experience: delete "residences", create a specific cluster for the more frail users to monitor, add details on the user's thumbnails such as the house number)

- *work on a sleep widget (aggregate more data on the sleep monitoring, such as the number of interruptions during the night)*
- *clean the timeline "life" view*
- *add an "alert" widget for the volunteers to detect unusual activities*

## Appendix E

# Data Protection Form

### E.1 IRB

# IRB APPLICATION FORM FOR SOCIAL, BEHAVIOURAL & EDUCATIONAL RESEARCH (SBER)



Please refer to the guidelines for IRB Application Form (SBER studies) before completing this. (You can download the relevant guidelines and forms from the [NUS-IRB website](#).)

## I. BASIC INFORMATION

**Protocol Title:**

**Simplified Title (if Protocol Title is too long and/or technical):**

(for use in recruitment documents, e.g. Participant Information Sheet & Consent Form, advertisements)

**Principal Investigator (Applicant):**

Title	Name	Position	Dept./Institution

(please complete section III for all co-investigators)

### Financial Declaration:

☒ Grants, Source of funding: \_\_\_\_\_

☐ Department Funding ☐ Others, please specify: \_\_\_\_\_

☐ No Funding

The financial benefits or other benefits derived from this study to the PI/Co-I(s)/Department/Institution are as follows (if any): \_\_\_\_\_

Amount of Sponsorship/Grant: \$ \_\_\_\_\_

Status of grant: ☐ Approved ☐ Pending ☐ Not applicable

### Type of Study:

☐ Archived/ Existing Database ☐ Questionnaire/ Survey / Interview / Focus Group

☐ Experiments ☐ Others, please specify: \_\_\_\_\_

### Research May Involve:

**Human Participants:** (Target Number: \_\_\_\_\_)

☐ Healthy Adults ☐ Children (under 21 yrs old) ☐ Pregnant Women ☐ Outpatients

☐ Prisoners ☐ Elderly ☐ Cognitively Impaired Persons

### Research Participants Will Be:

☐ Reimbursed \$ \_\_\_\_\_ ☐ Not reimbursed ☐ Others – please specify: \_\_\_\_\_

### Has this research been rejected by any IRB / REC / DERCs?

☐ No ☐ Yes If yes, please provide details.

### Study Site(s):

Site(s) of research (including PI's Dept. & Institution): \_\_\_\_\_

☐ Single-centre study

☐ Multi-centre study - No. of local sites: \_\_\_\_\_ No. of overseas sites: \_\_\_\_\_

### This research is also submitted to or has been approved by:

☐ NHG Domain-Specific Review Board (DSRB) A / B / C / D / E / F

☐ SingHealth Centralized IRB (CIRB) A / B / C / D / E / F

☐ Not Applicable

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NUS-IRB Application Form for SBER  
(IRB-FORM-S01)

Version 5.1, 26 Jan 2017

(please fill in)  
Version No. \_\_\_\_\_, dated \_\_\_\_\_

## II. DECLARATION OF THE PRINCIPAL INVESTIGATOR

The information provided in this form is correct.

- a. I will not initiate this research until I receive written notification of NUS-IRB approval and any other approval from relevant authorities (local/overseas) (if applicable).
- b. I will not initiate any change in protocol without prior written approval from NUS-IRB except when it is necessary to reduce or eliminate risk to the subject.
- c. I will promptly report any unexpected or serious adverse events, unanticipated problems or incidents that may occur in the course of this research.
- d. I will maintain all relevant documents and recognize that the NUS-IRB staff and regulatory authorities may inspect these records.
- e. I understand that failure to comply with all applicable regulations, institutional and NUS-IRB policies and requirements may result in the suspension or termination of this research, and other actions as stated in the NUS Code & Procedures on Research Integrity.
- f. I declare that there is no existing or potential conflict of interest for any of the investigators participating in this research.

Remarks (if any):

Principal Investigator's signature \_\_\_\_\_

Date \_\_\_\_\_

Phone: \_\_\_\_\_

Fax \_\_\_\_\_

Mailing Address: \_\_\_\_\_

Email: \_\_\_\_\_

**\*Please state the name and email address of the person(s) to copy to in the IRB's acknowledgement email. If no name(s) is listed, the IRB Secretariat will only correspond with the PI.**

1. \_\_\_\_\_

2. \_\_\_\_\_



### III. CO-INVESTIGATORS

*All co-investigators who have a responsibility for the consent process or direct data collection for this research should be listed below. Multiple copies of this form may be submitted as necessary. All co-investigators need not sign on the same form.*

Name: Position: Department: Institution:	Email: Phone: Fax:
_____	_____
Signature of Co-investigator	Date

Name: Position: Department: Institution:	Email: Phone: Fax:
_____	_____
Signature of Co-investigator	Date

Name: Position: Department: Institution:	Email: Phone: Fax:
_____	_____
Signature of Co-investigator	Date

Name: Position: Department: Institution:	Email: Phone: Fax:
_____	_____
Signature of Co-investigator	Date

### IV. DECLARATION OF THE HEAD OF DEPARTMENT\*

I declare that this research is approved by the department and is in keeping with the department's standards.

\_\_\_\_\_  
Signature of Head of Department

\_\_\_\_\_  
Date

Name of Head of Department:  
Title:

\* If the PI or co-investigator is the Head of PI's Department, this section should be completed by the Vice-Dean (Research) or Dean of the Faculty.

## V. ABSTRACT OF RESEARCH PROTOCOL

*In no more than 300 words, describe concisely the specific aims, hypotheses, methodology and approach of the application, indicating where appropriate its importance to science, existing knowledge and relevant applications. The abstract must be self-explanatory so that it can serve as a succinct and accurate description of the research study. Please use layman terms. If this is not possible, the technical terms should be explained in simple language.*

## VI. RESEARCH PROTOCOL

Organise details of the research protocol under the following headings (in no more than 7 pages).

### 1. Specific Aims and Objectives:

1.1 State concisely and realistically what the research described in this application is intended to accomplish and/or what hypothesis is to be tested.

### 2. Introduction:

2.1 Briefly describe the background and the importance of the research.

2.2 Relevant references

### 3. Preliminary Studies:

3.1 Provide a brief account of the Principal Investigator's preliminary/pilot studies (if any) pertinent to the application.

### 4. Methodology:

4.1 Describe in detail the (i) experimental design and research procedures, (ii) subject research visits (frequency and duration of procedures involved) and (iii) period of recruitment to accomplish the aims of this research.

4.2 Include details on sample size calculation and the means by which data will be analysed and interpreted.

4.3 What are the anticipated benefits and risks to human participants participating in this research?

4.4 Discuss the potential difficulties and limitations of the proposed procedures and alternative approaches to achieve the aims.

4.5 Will any part of the procedures be audio-recorded, video-recorded, or placed on other electronic media? ☐ Yes ☐ No  
If Yes, explain how the recorded information will be used? Will information collected be published with or without identifying research participants? How long will the recordings be retained and how will they be disposed of?

Will participants who decline recording be excluded from the study? ☐ Yes ☐ No

Please specify alternative: \_\_\_\_\_

### 5. Data Storage:

5.1 Please complete the following questions on measures you will take to protect research data and personal data collected. In addition, if your research involves making use of archived/ existing databases, please furnish the necessary documentation, e.g. permissions to use those databases, if applicable.

5.1.1 Where will the research data be stored?

5.1.2 Who will have access to the data, and what are the data protection measures put in place for this study? What will happen to the research data after research completion?

5.1.3 Please state the personal data that will be collected (e.g. names and contact information, etc), and how research participants' privacy and the confidentiality of their personal data will be protected. What will happen to the personal data collected after completion of the research study?

5.1.4 Any other remarks?

## 6. Characteristics of Target Research Participants/ Target Research Participants Data:

6.1 What is the number of participants to be enrolled? Give a breakdown by site of recruitment for multi-centred studies.

Institution(s)/Site(s) of Recruitment	Total	Adults (at least 21 years old)	Children

6.2 Lower Age Limit: Upper Age Limit (if any):

6.3 Are there any recruitment restrictions based on race or gender of the participant? If yes, please elaborate. If no, please state "Not Applicable".

6.4 Inclusion criteria

6.5 Exclusion criteria

6.6 Are the participants vulnerable or in a dependent relationship with the researchers?

☐ Yes ☐ No

If Yes, please provide details. Please note that research participants who are in a dependent relationship with the researchers should not be approached directly during recruitment, so as to prevent situations where participants consent under duress.

## 7. Participant Information Sheet and Informed Consent Form:

7.1 The PI is responsible for ensuring that all research participants give informed consent before enrolling into the research. Please submit a copy of the Participant Information Sheet and Consent Form.

(A sample of Participant Information Sheet and Consent Form is available on the IRB website at <http://nus.edu.sg/irb/guidelines.html>)

**Note: A Consent Form is NOT required where data collected is anonymous, e.g. anonymous surveys.**

7.2 Summarise the consent procedure. Please specify how informed consent will be obtained and who will obtain consent.

7.3 I require a waiver of:

- ☐ **Informed Consent as my research involves deception**  
☐ **Parental Consent** ☐ **Not applicable**  
☐ **Documentation of Informed Consent (i.e. no documented consent)**  
☐ **Documentation of Parental Consent (i.e. no documented parental consent)**

If applying for waiver, please justify how your research meets each of the following criteria:

7.3.1 The research involves no more than minimal risk to the participants.

7.3.2 The waiver or alteration will not adversely affect the rights and welfare of the participants.

7.3.3 Whenever appropriate, the participants will be provided with additional pertinent information after participation.

7.3.4 The research could not practicably be carried out without the waiver or alteration.

## 8. Recruitment Process:

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 NUS-IRB Application Form for SBIR  
 (IRB-FORM-S01)  
 Version 5.1, 26 Jan 2017

(please fill in)  
 Version No. \_\_\_\_, dated \_\_\_\_

8.1	<i>Explain the process of recruitment in detail, for example, state where and how potential research participants will be recruited/contacted. Please submit a copy of any advertisements/posters that will be used.</i>
<b>9. Timelines:</b>	
9.1	<i>What are the estimated start and end dates of the research? Please note that you should <u>not</u> commence your research prior to IRB approval.</i> Start Date:                      End Date:
<b>10. Financial Aspects/Reimbursement:</b>	
10.1	<i>Who will be responsible for research related costs? For sponsored research, list the costs that will be borne by the sponsor.</i>
10.2	<i>Will research participants receive payment/ student course credits for participation? If yes, please elaborate. If no, please state "No reimbursement".</i>

\* Please go to the [NUS-IRB website](#) to download the relevant guidelines and forms.



# DÉCLARATION SIMPLIFIÉE

## ENGAGEMENT DE CONFORMITÉ

(Articles 24-I, 25-II, 26-IV et 27-III de la loi n° 78-17 du 6 janvier 1978 modifiée en 2004)

### 1 Déclarant

Nom et prénom ou raison sociale :	Sigle (facultatif) :
Service :	N° SIRET :
Adresse :	Code APE :
Code postal : Ville :	Téléphone :
Adresse électronique :	Fax :

### 2 Texte de référence

Vous déclarez par la présente que votre traitement est strictement conforme aux règles énoncées dans le texte de référence.

N° de référence

AU-47 Accompagnement et suivi social et médico-social des personnes handicapées et des personnes âgées

### 3 Transferts de données hors de l'Union européenne

Vous transférez tout ou partie des données enregistrées dans votre traitement vers organisme (filiale, maison mère, prestataire de service, etc.) qui se trouve dans un pays situé hors de l'Union européenne

☒ Non ☐ Oui

### 4 Personne à contacter

Veuillez indiquer ici les coordonnées de la personne qui a complété ce questionnaire au sein de votre organisme et qui répondra aux éventuelles demandes de compléments que la CNIL pourrait être amenée à formuler

Votre nom (prénom) :	
Service :	
Adresse :	
Code postal : - Ville :	Téléphone :
Adresse électronique :	Fax :

Raison sociale :	N° SIRET :
Sigle (facultatif) :	Code NAF :
Adresse :	
Code postal : Ville :	Téléphone :
Adresse électronique :	Fax :

Exemplaire à conserver - ne pas envoyer



**5 Signature**

Je m'engage à ce que le traitement décrit par cette déclaration respecte les exigences de la loi du 6 janvier 1978 modifiée.

Personne responsable de l'organisme déclarant.

Nom et prénom :

Date le :

Fonction :

Signature :

Adresse électronique :

Les informations recueillies font l'objet d'un traitement informatique destiné à permettre à la CNIL l'instruction des déclarations qu'elle reçoit. Elles sont destinées aux membres et services de la CNIL. Certaines données figurant dans ce formulaire sont mises à disposition du public en application de l'article 31 de la loi du 6 janvier 1978 modifiée. Vous pouvez exercer votre droit d'accès et de rectification aux informations qui vous concernent en vous adressant à la CNIL: 3 Place de Fontenoy - TSA 80715 - 75334 Paris cedex 07.

Exemplaire à conserver - ne pas envoyer

## Appendix F

### Medical Reports

# TRANSMISSIONS CHRONOLOGIQUES

Du vendredi 28 août 2015 - 00:01  
Au samedi 31 décembre 2016 - 23:59

Identification	Transmissions	Agent et fonction
09/09/2015	<b>ENTREE (DOMICILE PRIVE OU D'UN PROCHE)</b> ENTRE CET AM PERSONNE AGREABLE MANGERA POUR L INSTANT A LA TABLE DE MR BELLOIS N A PAS VOULU DESCENDRE CE SOIR	
10/09/2015	AIDE A LA TOILETTE ET AU RASAGE CE MATIN, C EST TRES BIEN PASSER, ENTRECUISSE TRES ROUGE MIS BEPANTHEN POMMADE N'A PAS MANGE CE MIDI ET N'A PAS VOULU SORTIR DE SA CHAMBRE	
12/09/2015	N A PAS VOULU DESCENDRE MANGER - ET N A PAS TOUCHE A SON PLATEAU REPAS DE CE MIDI - A PRIS SON GOUTER	
13/09/2015	HABILLE DEUX FOIS CETTE NUIT <b>CHUTE DANS LA SALLE DE BAINS DE SA HAUTEUR - CAUSE : - CIRCONSTANCE : LORS D'UN AUTRE DÉPLACEMENT - CONSÉQUENCE : - DESCRIPTION : - RESPONSABILITÉ : SANS OBJET - FAMILLE PRÉVENUE : NON</b> <b>DELEU CLAIRE PRÉVENU(E)</b> N EST PAS DESCENDU MANGER CE MIDI <b>IL Y A UNE FEUILLE DE SURVEILLANCE ALIMENTAIRE AU RELAIS SOINS CAR NE MANGE PRESQUE RIEN</b>	
14/09/2015	LIT SOUILLER VETEMENTS SOUILLER . DIFFICILE DE LUI TROUVER UN CHANGE. JE LUI ET MI UN SLIP ACTIF CAR SES SLIP SON SOUILLER ENTRETIEN AVEC MR QUELLIER CE MATIN, J'AI RECUEILLI QUELQUES ÉLÉMENTS DE SON HISTOIRE DE VIE QUE J'AI NOTÉ SOUS L'ONGLET PAP. EN CE QUI CONCERNE SON ALIMENTATION, MR QUELLIER ÉVOQUE LE FAIT QU'IL A TOUJOURS EU UN PETIT APPÉTIT ET QU'IL Y AVAIT DES JOURS OÙ IL NE MANGEAIT PAS ET QU'IL PRENAIT À LA PLACE DU VIN ET DE L'ALCOOL MAIS IL DIT QU'IL A ARRÊTÉ D'EN CONSOMMER DEPUIS ENVIRON 20 MOIS. DIT QUE CELA NE LUI MANQUE PAS. COMPREND LE FAIT QU'IL SOIT ICI CAR DIT QU'IL NE POUVAIT PAS ALLER AILLEURS CAR IL TOMBAIT TROP SOUVENT À DOMICILE. LUI METTRE UN SLIP ACTIF CAR SE SOUILLE ENTRETIEN CET APRÈS MIDI AVEC LA SOEUR DE MR QUELLIER QUI M'A DONNÉ DES ÉLÉMENTS NOUVEAUX SUR SON HISTOIRE DE VIE (NOTÉ DANS L'ONGLET PAP). ELLE M'A CONFIRMÉ QUE MR QUELLIER NE MANGEAIT PAS BEAUCOUP À DOMICILE ET QU'IL NE MANGEAIT QUE DU JAMBON MÊME LE MATIN. IL NE PRENAIT JAMAIS DE CAFÉ ET N'EN FAISAIT PAS CHEZ LUI DONC À VOIR POUR LA BOISSON DU MATIN. SERAIT-IL POSSIBLE LORSQU'IL NE MANGE PAS SON PLATEAU DE LUI PROPOSER DU JAMBON AVEC DE LA SALADE? MERCI IL Y A UNE FEUILLE DE SURVEILLANCE ALIMENTAIRE AU RELAIS SOINS CAR NE MANGE RIEN (RÉPÉTITION D'UNE TRANSMISSION DU 13/09/2015)	
15/09/2015	IL S'EST LEVE PLUSIEURS FOIS ET ETAIT PERTURBE, IL S'EST DESHABILLE ET COUCHE EN TRAVERS DU LIT	