THE UNIVERSITY OF NORTH CAROLINA
AT CHAPEL HILL

Ming C. Lin
John R. & Louise S. Parker Distinguished Professor
Phone: (9l9) 962-l974
Internet: lin@cs.unc.edu
http://www.cs.unc.edu/~lin

Department of Computer Science
College of Arts and Sciences
Campus Box 3175, Sitterson Hall
Chapel Hill, NC 27599
FAX: (919) 962-1799

January 4, 2013

To: The University of Lille 1 - Science and Technology

Subject: Report on Christian Duriez's Habilitation Thesis

This report summarizes my review of Dr. Christian Duriez's Habilitation Thesis on "***Real-time haptic simulation of medical procedures involving deformations and device-tissue interactions***".

Recent technological advances have made it possible to consider using computer simulation of soft tissues for training, education, and planning of various medical and surgical procedures. However, there are many outstanding scientific challenges in realizing such a vision. One of the foremost issues is the trade-off between computational efficiency and simulation fidelity. Similar to many man-in-the-loop systems, a computer simulator for training must run at interactive rates, while accurate, stable and robust numerical simulations often require higher-order numerical methods that usually cannot be executed in real time. Achieving real-time performance while increasing the level of realism and accuracy of the simulation so that the simulation is sufficiently predictive for medical procedures is the central scientific challenge addressed in this thesis. A significant assumption is to use the finite element methods (FEM), known for proven accuracy over simpler spring-mass systems and other alternatives, for interactive contexts. To validate the techniques, concepts, algorithms, and implementation, Dr. Duriez has chosen liver simulation to be the benchmark used throughout his research described in this thesis. This thesis documents important results on four key topic areas from his recent research with collaborators and students, as presented in each of the four chapters in this thesis.

Chapter 1 examines many techniques for modeling of tissue deformation and presents a rather in-depth and broad survey of the state of the art research in this area. Different from typical surveys, the objective of this chapter is to focus on discussing the scientific issues among the existing models and algorithms to justify the technical choices made and their applicability to the target organ, liver, simulation. The sub-areas examined include numerical integration techniques, beam theory for wires and tubes (used in the medical procedures for livers), surface-based models using shell theory, and volume deformation techniques. He and collaborators (including his Ph.D. students) introduced a novel "quasi-dynamic splines" method. They also developed the first model based on beam theory in the context of interventional radiology for catheters and guide-wires – common procedures for liver cancer treatments. Most recently, he and collaborators further proposed to couple the beam elements with volume model to simulate the effects of the vascularization on the liver deformation mechanics. For volumetric deformation, multi-resolution deformation, a new numerical method based on asynchronous preconditioning associated with inhomogeneity of soft tissues, and a new coupling strategy for vascularized organs (e.g. liver) were introduced.

Chapter 2 addresses modeling of interaction and the boundary conditions. The chapter starts again by surveying related work on modeling various types of mechanical interactions, including collision detection and response, non-smooth mechanics, and constraint-based simulation, with focuses on some target medical procedures for livers. First, a real-time time-stepping method combined with a low-order integrator and a constraint-based method were introduced to compute non-smooth mechanic in real time. Then, a catheter navigation algorithm, an approximate compliance technique, and an asynchronous update of compliance matrix were described. Next, two constraint-based contact response methods, one based on contact mapping and one based on GPU algorithm, were introduced. Finally, the use of complementary constraints (for contact and friction) mixed with bilateral constraints to model interaction of slender and thin medical devices (e.g. needles) was presented. Such approaches are also applicable for real-time motion planning and interactive guidance of medical procedures using needle-like devices.

Chapter 3 is dedicated to realistic haptic rendering of 3D volumetric deformable objects. As described in the previous two chapters, deformations are modeled with Finite Element Method and the contacts are simulated based on several efficient numerical methods and contact handling algorithms. He has proposed different strategies to accelerate the solvers in order to be compatible with haptic refresh rates in this thesis. Part of this chapter was based on extension of his earlier work in ***IEEE Transactions on Visualization and Computer Graphics*** (***TVCG***), for which I was the Associate Editor-in-Chief handling this paper (and now the presiding Editor-in-Chief), and a contributed book chapter, for which I was the co-editor. Dr. Duriez and collaborators proposed a new and more generic model, called "multirate compliant mechanism", combined with methods introduced earlier to handle various types of interactions. Furthermore, asynchronous simulation of deformable models with varying stiffness for real-time haptic rendering was also introduced here – limited to mostly quasi-static behaviors.

Chapter 4 illustrates the application of these works on efficient simulation of interactive medical procedures, including interventional neuroradiology (minimally invasive treatment of brain vascular disease), catheter-based procedures, biomechanical simulations of brain shift, and ossicular (middle-ear) surgery simulation. These simulation systems take advantage of all the algorithms and techniques described in the previous 3 chapters, such as static and dynamic beam theory, the interaction between the medical devices and soft tissues/blood vessels, etc. Equally importantly, the research described in this thesis has made several important contributions to the open-source SOFA framework including a generic formulation and mechanisms for constraints process, haptic rendering algorithms, FEM models, and some new applications such as ophtalmology procedure simulation, virtual grasping of deformable objects. With the open-framework SOFA, the INRIA team aims at proposing an efficient prototyping tool and a way of helping the development of new algorithms in medical simulation. The research as described in this habilitation thesis has helped to improve the haptic rendering and the models used for boundary conditions. SOFA is already very popular and the number of download is quite impressive!

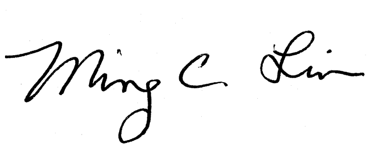
For intervenional radiology and ophtalmology, he has proposed new and realistic training approaches that could improve patient safety. A start-up company (http://didhaptic.com/) is currently using some of the haptic rendering algorithms he developed in their dental simulation. He has been co-supervising Ph.D. students with Dr. Stephane Cotin, teaching at summer schools, local universities, etc. He has been involved in several national and European projects related to medical simulation. He is already an integral part of a consortium of French and European researchers led by Dr. Stephane Cotin. Their research direction is to work on more realistic biomedical models that are patient specific and can enable pre-operative and per-operative simulation of complex procedures, i.e. "simulation guided therapy".

From many different aspects, I believe this habilitation thesis has documented an excellent collection of coherent, focused, and well-motivated research projects, as well as suggesting new directions for continuing research in physics-based simulation, haptic rendering, to simulation guided therapy. There remain many challenging research issues in these areas. For example, some of the questions emerging from this thesis include better choices of simulation parameters, more incorporation of patient-specific data, further evaluation of simulated-guided procedures, etc.

Overall, this habilitation thesis documents several important scientific results. The proposed techniques are innovative, effective, and clever. I have worked in these areas for over two decades. There is a huge collection of literature. I am impressed that the thesis has done an excellent job in surveying prior research, analyzing previous work and synthesizing together techniques to improve the overall performance of the deformable body simulation. The technical writing of the dissertation is clear, carefully thought out, and well organized. The diagrams and captured images clearly illustrate the basic concepts and further enhance the overall presentation of the dissertation. The works have been published in the best venues in the field, including ***ACM Transactions on Graphics, IEEE/ASME Transactions, MICCAI***, ***Computer Aided Surgery***, etc. This thesis successfully presents a very impressive body of research projects conducted by Dr. Christian Duriez over the last few years.

I accept and approve this habilitation thesis.

Sincerely,



Ming C. Lin
John R. and Louise S. Parker Distinguished Professor
Department of Computer Science
University of North Carolina at Chapel Hill