TOWARDS A FLEXIBLE GENERAL TRAINING SIMULATOR PLATFORM BASED ON MODELICA

Anders Sandholm *,**,[1] **Peter Fritzson** *,[2]
Gunilla Nilson **,[3] **Göran Petersson** **,[4]

* *PELAB - Programming Environment Lab*
Dept. Computer & Information Science
Linköping University, Sweden
http://www.ida.liu.se/~pelab

** *eHealth Institute*
Dept. Health and Behavioural Sciences
University of Kalmar, Sweden
http://www.hik.se/ehalsa/

Abstract: Today we demand highly experienced surgeons who are capable of performing any surgical procedure. Unfortunately many patients deny medical students and physicians to perform surgery even under experienced supervision, since they are afraid of mistakes.

This paper gives an overview of four different medical training simulators which can replace the initial training sessions in an operation room. These simulators are using complex computer algorithms for simulating the human anatomy and deliver the correct physical force through a force feedback interface. Our work aims at replacing the hand written software with models in a modern, strongly typed, declarative and object-oriented language for modeling and simulation of complex systems, and methods for combining such models to develop complex medical simulation software.

1. INTRODUCTION

During the last 15 years surgical procedures have become more and more complex, which has lead to a higher demand on the education of new surgeons. The most common way has been for a student to learn the procedure from a more experienced surgeon. For less difficult procedures plastic rubber models have been used. Unfortunally these lack realism and provide no useful feedback. Another possibility, giving more realism, is to use for surgical training, but this raises a number of ethical and moral questions. The use of animals in surgical training is also costly.

Therefore there is a growing interest in using medical simulators with haptic feedback to provide realistic and cost efficient training. In a medical simulator the surgeon can practice and learn a new procedure without risking patient safety. Medical simulators can also offer a numbers of advantages such as learning from mistakes and failures, the ability to practice with a mentor, using different scenarios ranging from standard procedures to complications that are extremely rare. However,

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[1] andsa@ida.liu.se
[2] petfr@ida.liu.se
[3] gunilla.nillson@hik.se
[4] goran.petersson@nshu.se

medical simulators have more potential than just to be used as training tools. If the simulation model is using patient-specific data the surgeon will be able to detect difficulties and plan remedies before the surgery is carried out.

Medical simulators can be classified into three different generations, se figure 1 (Satava, 1991).

Fig. 1. Medical Simulation classification according to Satava

The first generation focused on the concepts of navigation and immersion. Ideas and technology from Virtual Reality were applied to create a geometric representation of the organs to create a visual effect where the user only could navigate within the virtual representation. Today there exist several commercial simulators of this generation focused mainly on virtual endoscopes.

The second generation aimed at modeling the physical interaction of the anatomical structure. The simulators now allowed realistic interaction between soft tissue and the surgical instrument for which cutting and deformation were possible. Bone simulation could be done with the correct kinematics constraints and muscle deformation (Delp and Loan, 1970). Examples of the second generation simulators are the Melerit PelvicVision, PacoVision, TraumaVision (AB, n.d.). There are also second generation simulators for gall bladder resection (Mark *et al.*, 1996) and gynecological surgery (Kuhnapfel *et al.*, 2000).

The third generation medical simulators include anatomical, physical and physiological modeling of the organ (Delp and Loan, 1970) The simulation model now includes the functions of the organ system, for example, cardiovascular system is simulated when cutting a vessel that is a physical phenomenon, which has influence on the blood pressure and therefore affects other organs. Only some models have been developed for cardiopulmonary system (Szekely *et al.*, 1991), vascular system (Kaye *et al.*, 1997) and the cardiac system (Quarteroni *et al.*, 2000) but no complete simulators have been produced due to the complexity of the coupled nature of physiological and physical properties.

2. MEDICAL TRAINING SIMULATORS

The Melerit Medical AB training simulators are all based on standard PC technology. Techniques such as Virtual Reality, coordinated pictures, force feedback and sound are used to create a realistic environment where the surgeon can see, feel, and hear exactly the same things that he/she would do in real surgery (Ayache *et al.*, 2001).

The Melerit PelvicVision, se figure 2, is a simulator to train and assess prostate resection where the surgeon can view the complete pelvic anatomy, including the prostate, urethra and the bladder. The Melerit PacoVision,se figure 1, simulates catharact surgery that has become a standard procedure in hospitals. However, the physical procedure is still a difficult and risky surgery for the patient. The simulator replaces the need for wet labs and has a more realistic lens behavior than a cadaver or pig eye.

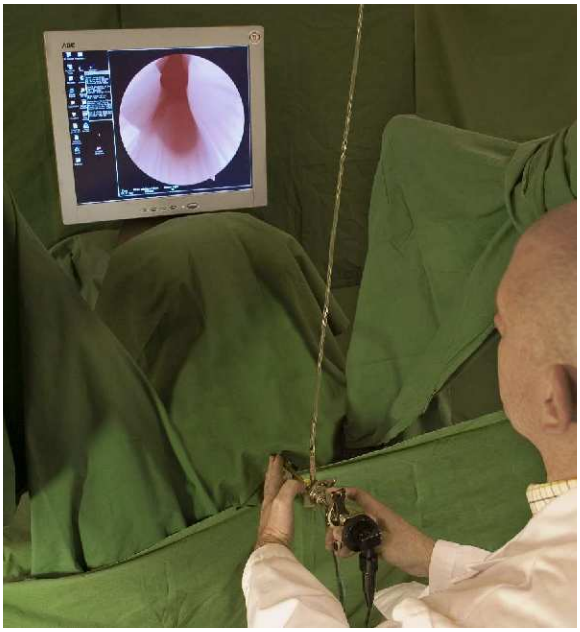

Fig. 2. Melerit PelvicVision

The Melerit TraumaVision, se figure 3, simulates several orthopedic procedures, such as hand-eye coordination, procedure training and instrument handling. The use of the simulator has proved to reduce the risk for secondary fraction caused by too many drill holes. The Melerit UreCat simulator (figure 4) is a new simulator under development. It is aimed to be used both by physicians and nurses during the period of learning

Fig. 3. Melerit TraumaVision

male catheterization. Today most of the training is performed using primitive simulators which do not give a realistic force feedback or information on how the procedure has been carried out. The simulator is being developed to create a realistic environment within which physicians and nurses can develop the skills that they need.

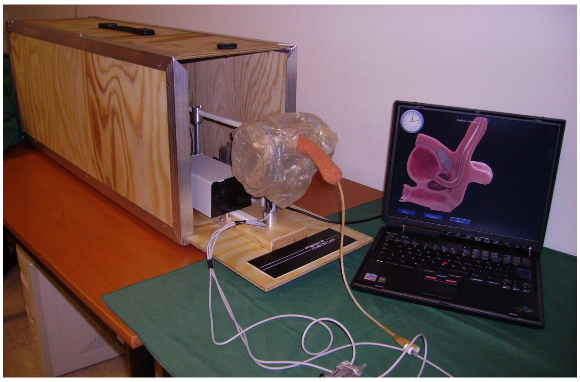

Fig. 4. Melerit UreCat

3. THE BENEFITS OF MEDICAL TRAINING SIMULATORS

In many hospitals the common surgical teaching method is based on the old master-apprenticeship model where the medical students learn in the operating room under the supervision of a skilled surgeon. This method is time consuming, costly and might even lead to higher patient mortality (Bridges and Diamond, 1999). In the operation room the student is also exposed to a stressful environment that is not ideal for learning. Using a training simulator the environment can be controlled so that an ideal learning environment is created. The simulator also removes the demand for a smooth patient flow through the operation room. Instead the student can learn the basics in the procedure and as the students or physicians progress, the level of difficulty can be increased. It is also possible to introduce complications during the procedure, complications that might be rare and therefore are impossible for the student to study in an operation room.
It has been shown in independent studies that simulator training increases the operation skills but that a high degree of realism and the possibility to perform the whole procedure is required (Scott *et al.*, 2000).

4. COMMON SIMULATION METHODS FOR MEDICAL TRAINING SIMULATORS

One of the most important features in the second generation medical simulators is the ability to model and manipulate virtual deformable objects in real time. Today there exist many different simulation methods developed both for the use in computer graphics and in engineering applications, but only a few are fast enough to handle real-time simulators with a haptic interface with a update frequency of 1000 Hz. In some medical simulators this has been solved by using one haptic interface thread and one simulation thread. Using this it may be possible to run the physical simulation at 300-500 Hz. For the first generation of medical simulators the focus was mainly on creating fast collision detection algorithms (Ayache *et al.*, 2001). In the second generation simulators these algorithms could not be used for accurate tissue simulation, since they were not accurate enough for soft tissue, which has led to the development of more advanced methods. Three of the most common methods will be presented here.

4.1 Mass-Spring-Damper Method

The mass-spring simulation method is a non-physical based model where the object is constructed by a network of point masses connected with massless springs (de Casson and Laugier, 1999),(Delingette *et al.*, 1994). In this mass-spring setup the equation of motion can easily be discretized and simulated.

When a mass in the mass-spring grid is exposed to a force, the mass is displaced, which result in an internal force that affects the springs connected to the node. This spring is then affecting the other mass connected to it. The model can then be described by inertial and damping forces, and the forces that a node is subject to can be described as equation (1).

$$m\ddot{\mathrm{p}} + b\dot{\mathrm{p}} + \sum_i F_i = \sum F_{ext} \tag{1}$$

Here p is the position, $\dot{p}$ the velocity, $\ddot{p}$ the acceleration and m is the mass of a node. Viscosity is modeled as dampers and is described as$b$. F_i

represent the internal forces in the model and F_{ext} is the external forces acting on the model.

The mass-spring model is a fast simulation method that meets the requirements for a real-time simulation, even for quite large objects. The major drawback is that no object in real life consist of point masses that re connected with springs and dampers. To create a realistic soft tissue simulation an infinitely number of masses has to be connected with an infinitely numbers of springs/dampers.

4.2 Finite Element Method

One of the most common continuum simulation methods is the finite element method, FEM. The idea with FEM is that when an object is subject to an external force the total potential energy is minimized to find the shape of the deformed body.

A FEM simulation starts by dividing the object into volumetric elements where the continuous equilibrium equation is approximated over each of the elements. These elements are commonly created as either tetrahedrons or cube shapes. If tetrahedron elements are used the deformation of the object can be described using the Green-Lagrange tensor which is both rotational and translational invariant. The deformation tensor for a point ,x, on the non-deformed volume can be described as equation (2) with condition (3)

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial x}{\partial \alpha_i} \cdot \frac{\partial x}{\partial \alpha_j}\right) - \delta_{ij} \tag{2}$$

$$\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases} \tag{3}$$

To calculate the deformation of the object for a given force we only need to know the stress-strain relationship since the deformation is proportional to the internal stress of the volume. When the stress-strain relationship is know the force acting on the particles can be calculated and equation (4) can be solved.

$$M\ddot{U} + C\dot{U} + KU = \sum F^{ext} \tag{4}$$

Where M, C and K are the mass, damping and stiffness matrices for the object. F^{ext} are the force matrix acting on the object and the displacement vector, respectively.
The benefit of using FEM simulation is that an accurate deformation of the object can be achieved and therefore will create a more accurate soft tissue simulation than the mass-spring method. The disadvantage is that FEM is computationally more intensive and currently can't be used in real-time haptic simulators for large objects.

4.3 Long Element Method

The Long Element Method, LEM, was developed for real-time physically based dynamic simulation of deformable objects, and therefore highly suitable for soft tissue simulation (Costa and Balaniuk, 2001). The different compared to standard FEM is that a LEM calculation is performed on a grid of long element instead of cubes or tetrahedrons as in FEM. LEM also uses common variables such as pressure, density and volume along with two principles, Pascal's Principle and the conservation of volume.
The force acting on an element can be described by equations (5)

$$\begin{aligned} P &= \frac{F}{A} \\ \varepsilon &= \frac{E\Delta L}{L} \\ F &= \frac{AE}{L}\Delta L \end{aligned} \tag{5}$$

Here ε is the material stress coefficient, the elastic coefficient of the element.
The calculation of a deformed object is based on using the internal pressure P_{int} in an element and the external pressure P_{ext} that is acting on the long element.

The external pressure working on the long element is created from atmospheric pressure, P_{atm} and from surface tension. The internal pressure, at a distance δ, is determined by the objects density ρ, the fluid pressure P_{fluid} and gravity g acting on the object. The external and internal pressure can be described as equations (6)

$$\begin{aligned} P_{ext} &= P_{atm} + \frac{E\Delta L}{L} \\ P_{int} &= P_{fluid} + \rho g \delta \end{aligned} \tag{6}$$

Applying this equation to a group, n, of long elements and using Pascal's Principle will give us a continuous equation (7).

$$\Delta P = P_{fluid} - P_{atm} \tag{7}$$

Fluid is incompressible and therefore a volume conservation constraint is needed (8).

$$\begin{aligned} \frac{E_i \Delta L_i}{L_i} - \Delta P &= \rho_i g \delta_i \\ \sum A_i \Delta Li &= 0 \end{aligned} \tag{8}$$

To reach a final set of equations describing LEMs the surface tension, equation (9), has to be included.

$$P = \frac{kx}{A} \tag{9}$$

Here k is a local spring constant for each neighbor element and x is the distance from the deformed element to each neighbor. The LEM equations can be written as equation (10)

$$\begin{aligned} P_{st}^{i} &= \sum \frac{k_i^j(\Delta L_i - \Delta L_j}{A_i} \\ \rho_i g \delta_i &= \frac{E_i \Delta L_i}{L_i} + P_{st}^{i} - \Delta P \end{aligned} \tag{10}$$

By defining the object as a set of fluid elements the system will result in fewer variables and then also in fewer equations than FEM. The object can also be described with different materials in the elements and then also have the capacity to simulate non-homogenous materials.

5. THE MODELICA LANGUAGE AND TECHNOLOGY

Modelica is a rather new language for hierarchical object oriented physical modeling, which is being developed through an international effort (Association, 2005). The language unifies and generalizes previous object oriented modeling languages. It allows defining simulation models in a declarative manner, modularly and hierarchically and combining various formalisms expressible in the more general Modelica formalism. The multidomain capability of Modelica gives the user the possibility to combine electrical, mechanical, hydraulic, etc., model components within the same application model (Association, 2005),(Fritzson, 2004),(Fritzson *et al.*, 2006).

In the context of Modelica class libraries software components are Modelica classes. However, when building particular models, components are instances of those Modelica classes. Classes should have well defined communication interfaces, sometimes called ports, in Modelica called connectors, for communication between a component and the outside world. A component class should be defined independently of the environment where it is used, which is essential for its reusability.
Modelica technology can be summarized as:

- Declarative, mathematical, equation based, higher level of abstraction.
- Object oriented and component based. A high level of reusability of classes, better than conventional object oriented software approaches.
- Architectural language for complex systems.
- Efficient execution, comparable to C/C++ and Fortran. Industrial strength implementations handling models of over 300 000 equations on standard PC hardware.
- Strong typing, enabling safe engineering practices for mission critical system development

6. ADVANTAGES OF USING MODELICA IN MEDICAL SIMULATORS

Increasingly complex computer algorithms are being introduced that are capable of simulating the human anatomy and respond with the correct physical force using force feedback interfaces. This increase in complexity has introduced new problems in modeling and development of the simulation software.

- Higher level model based behavior specification: Today the main part of the simulator software consists of highly specialized software that is hard to maintain and develop. By using a general equation based object oriented modeling language such as Modelica, having the ability to express and simulate both continuous time behavior and discrete events, the developer can focus on physical modeling instead of low level simulation software development.
- Flexible model components: When using a standard simulation software, new models can be introduced into the simulator without the need to rewrite large parts of the software. Today Modelica has become a factory standard when it comes to general equation based object oriented languages, and has been developed to solve many different type of simulation problems, from electronics to physics simulation. It seems therefore suitable for use in a medical simulator where stability and reliability is required.
- High performance real time approximate simulation: Real time training simulators often need to prioritize real time behavior over numeric precision. The generation of fast real time code from high level Modelica models for approximate (but stable) numerical solvers should be studied in the context of training simulators.
- Improvements in medical training simulators: All the above topics need to be addressed in the context of the Melerit medical training simulators.

The following Modelica technologies are important for the development and simulation of medical models:

- Efficient execution, comparable to C/C++ and Fortran.
- Strong typing, enabling safe engineering practices for mission critical system development.
- Architectural language for complex systems.
- Declarative, mathematical, equation based, higher level of abstraction.
- Object oriented and component based

7. CURRENT STATUS

Approximate two to three years ago we developed prototypes of simple simulators based on Modelica models, which interacted with a human in real-time. One was a simple car simulator, and the other one was simulation of part of a wheel loader. Regarding using object-oriented modeling and simulation technology for medical training simulators, which is the main focus described in this paper, the work is still in an early stage. We have however indentified a suitable medical simulation, and what part of the medical simulator that is appropriate to be modeled in Modelica. We are currently working on more detailed design and implementation of a prototype based on Modelica models, as well as improving the performance of the generated code from the OpenModelica compiler, which is needed for the fast responses required by haptic interfaces.

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