Development of a Patient-Specific Surgical Simulator for Pediatric Laparoscopic Procedures

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Abstract. The goal of this study is to develop an open-ended pediatric patient-specific surgical simulator for the planning, practice, and validation of laparoscopic surgical procedures prior to intervention, initially focusing on the choledochal cyst resection and reconstruction scenario. The simulator is comprised of software elements including a deformable body physics engine, virtual surgical tools, and abdominal organs. Hardware components such as haptics-enabled hand controllers and a representative endoscopic tool have also been integrated. The prototype is able to perform a number of surgical tasks and further development work is under way to simulate the complete procedure with acceptable fidelity and accuracy.

Introduction

With the advent of computer technology and its increasing capabilities in recent years, surgical simulation has garnered special interest as a means to enhance the training of surgeons and a tool to practice procedures in advance of any intervention. Current surgical education involves mostly cadavers or laboratory animals, whereas state-of-the-art simulators offer the potential to decrease operating costs, reduce training times, and provide easier training access to students and staff. Surgical simulation can also provide additional feedback to operators via numerical analysis of tracked inputs and procedure-based results. While first-generation simulation systems utilized box trainers and physical objects to teach the basic psychomotor coordination actions necessary for laparoscopic surgery, more recent computer-based devices benefit from graphical representation of tissues and organs with realistic physical behavior in the simulator's virtual environment [1]. Such devices could be haptically-enabled and incorporate patient-specific 3D models of human anatomy, allowing for the practice of both basic instrument-tissue manipulation skills and more complicated tasks as part of a complete surgical procedure [2].

We aim to develop an open-ended Patient-Specific Surgical Simulator (P3S) intended to provide a virtual environment where surgical procedures can be planned, practiced, and validated prior to actual surgical intervention. The first scenario to be simulated is choledochal cyst resection and reconstruction with Type 1 pathology of the common bile duct. This procedure is complicated and requires the operator to isolate and extract the gallbladder and the common bile duct. A Roux-en-Y step is then performed to suture the duodenum to the remaining bile duct from the liver in order to maintain proper flow of bile into the digestive track. The procedure also involves several basic surgical elements such as cutting, stapling, application of clips, and extraction of organic matter which makes it an excellent candidate for a full-scope open-ended simulation.

Methods & Materials

The initial P3S prototype is intended to be a proof-of-concept for how the different technologies can be integrated and/or developed to meet a core subset of overall requirements. It will be used for actual training, planning, and validation support.

The key features of the P3S are summarized as follows:

- Multi-Purpose: The simulator provides a simplified procedural training method of 'practicing by repetition' and improving certain skills. The training can occur under automated supervision (with metrics) or can be performed without any constraints (free play mode). In addition, the simulator is capable of planning a specific procedure and verifying any surgical assumptions, with actual patient specific imaging data. The planning can be performed by the operating surgeon alone or with a surgical team. Finally, the simulator is capable of exploring existing or new procedures, providing support and validating different scenarios and approaches.
- Mix of Real (Physical) and Virtual: The simulator is able to integrate real and simulated laparoscopic components and camera views. It also incorporates high speed haptics connected to real and/or simulated bodies. For this purpose, the simulator employs the three haptic devices: two for the left and right operator-selected laparoscopic tools, and one to control the operator's virtual endoscope. Visualization of the endoscopic view is performed through a relay

to a LCD monitor for display to the operator.
- Metrics: For automated evaluation purposes, data from the simulations are collected, stored, and processed. These are then evaluated against specific pre-defined performance criteria and provided in graphical form to the operator in order to visualize and analyze specific performance parameters once a simulation session has been completed. Additionally, session results are stored and used to score and track trending improvements in skills.
- High-Fidelity: The final version of the simulator will incorporate patient-specific anatomy and pathology; state of the art visual graphics; real-time simulation of laparoscopic and robotic devices; real-time physiological and deformable soft body models; and real-time cutting and suturing of soft bodies as part of the overall procedure.

The prototype simulator hardware setup consists of:

- Left and right force-feedback haptic devices with functional laparoscope handles
- Instrument port for inserting the simulated endoscope
- Monitor showing the simulated endoscope camera view
- Touch screen for Graphical User Interface (GUI) to set up and control the simulator Optional head-mounted display for viewing simulated camera views
- Height-adjustable support structure for the above equipment
- Computer that runs the simulation models

The prototype simulator software setup consists of:

- A Graphical User Interface (GUI)
- A software model of the simulated patient abdominal cavity and various organs (liver, gallbladder, cystic duct, common bile duct, colon, stomach, small intestine, transverse colon and connective tissue). The prototype currently supports the scenario of choledochal cyst removal and reconstruction for a 5 year old child and an adult patient model.
- A software model of various simulated laparoscopic instruments
- Data analysis and metrics evaluation tools

The software architecture of the simulator is built based on a distributed and modular architecture. Its design consists of five main components that communicate data via TCP/IP or UDP connections (Fig. 1):

- GUI: used to control the simulator and access the virtual surgical environment (Figs. 2 and 3)
- Haptics Device Process: used to read and return simulation data to the hardware haptics devices
- Physics Core Process: runs the core of the physics computations, including all soft body mechanics; some elements are parallelized via threads.
- Visual Core Process: runs the core of the rendering task for realistic visualization of various graphics components within the virtual environment
- Metrics Process: Data collection and metrics algorithm computations to analyze and evaluate operator performance

In order to provide a working prototype in a relatively short time, the P3S simulator framework was built using extensive open-source software available, as follows:

- GUI: Based on CEGUI [3] and OGRE [4]
- Physics Engine: Based on SOFA [5]
- Visual Renderer Engine: Based on CEGUI and OGRE
- Data Gathering (Metrics) Engine: Based on BOOST [6]

Results

Choledochal Cystectomy Procedure

The initial part of the choledochal cystectomy procedure is now simulated: the common bile duct and cystic duct can be stapled on both sides; the ducts can be cut; and the gallbladder and cystic duct can be removed. What remains to be implemented is the Roux-en-Y, where the bile duct is reconnected via an incision and suturing to the small intestine.

Fidelity vs. Performance

It was decided that the main large organs involved in the chosen surgical scenario, i.e. the gallbladder, liver, and pancreas, would remain true finite element models in the P3S, whereas the smaller tubular components, i.e. the cystic and common bile ducts, would be represented by flexible chains of rigid-body beads linked by springs. The chain is mapped to a tubular visual model which can then deform as the chain is moved, elongated, or cut.

Whenever real-time simulations of physical systems are attempted, the question of trade-offs between the fidelity of the model and the constraints of available computing power is always in the forefront. Real-time finite element models are notorious for requiring exponentially greater computing resources as the number of elements increases. In the case where the number of interacting components of a simulation is high (such as in a laparoscopic procedure in the abdomen, where many organs are present), it is inevitable that some level of simplification and optimization must be performed in order to achieve real-time performance.

Some level of parallelization was achieved with the SOFA engine in order to optimize the solving of the finite element components; in initial trials, this process decreased solution times from 33 ms to 17 ms. Delegating solver functions to the graphic card via GPU CUDA cores led to issues, such as minimizing data transfers between CPU and GPU, managing topology changes, etc.

Haptic Force Feedback

The simulated laparoscopic instruments are coupled with force feedback-enabled equipment, in order to provide a sense of the contacts between the surgical tools and the simulated organs. The realism of the sensed force essentially depends on the accuracy of the calculated forces inside the dynamic solver. This, in turn, depends on the speed at which the solver can be run and the thresholds applied to the solver iterations. At the time of writing this abstract, a tenfold improvement in speed is required in order to achieve an acceptable level of realism. Further optimizations are being investigated in order to achieve this performance improvement.

Patient-Specific Pathology

The creation of finite-element meshes and graphical models usually involves considerable manual intervention. Meshes have to be manually optimized to provide the most details where accuracy is most important, and the graphical models have to be mapped with texture images with manual editing tools. Some automation can be achieved by scaling existing models instead of creating new ones for new patients. This is the approach that will be followed for the P3S. The existing models will be scaled using information from patient data or from interpreted scans, and the models then entered in the new patient-specific scenario. The scaling method was initially verified to work manually by creating a generic 5-year old patient and a generic 6-month old patient when starting from an adult patient. However, some adjustments needed to be made for the general build of the thoracic and abdominal cavities which have somewhat different shapes in adults and children.

Conclusions & Discussion

The P3S demonstrates that it is possible to simulate complex procedures in a virtual environment, where one is able perform both simple tasks and more complicated processes as part of a complete laparoscopic surgery. However, challenges in real-time performance remain to be addressed, both in finite element modeling of the underlying soft body physics and in realistic haptic force feedback.

In the next phase, the functionality limitations of the initial prototype will be analyzed and existing or proposed technological advances will be examined for feasibility. These include inclusion of the Roux-en-Y, import of patient-specific pathology to generate 3D models of internal organs, and validation of the metrics algorithms. The later model is intended to be a mature product, with the potential for more general usage and distribution.

Future iterations of the P3S will be made available to the hospital's surgical staff, in order to verify the assumptions and to refine the requirements.

References

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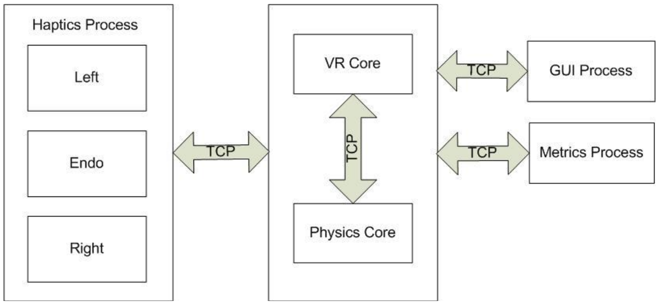
[2] Heinrichs, WL. Simulators for laparoscopic surgical skills training. *Prevention Management of Laparoendoscopic Surgical Complications*. chapter 14. ed. Paul Alan Wetter, MD., 2005.
[3] http://www.cegui.org.uk
[4] http://www.ogre3d.org
[5] http://www.sofa-framework.org
[6] http://www.boost.org

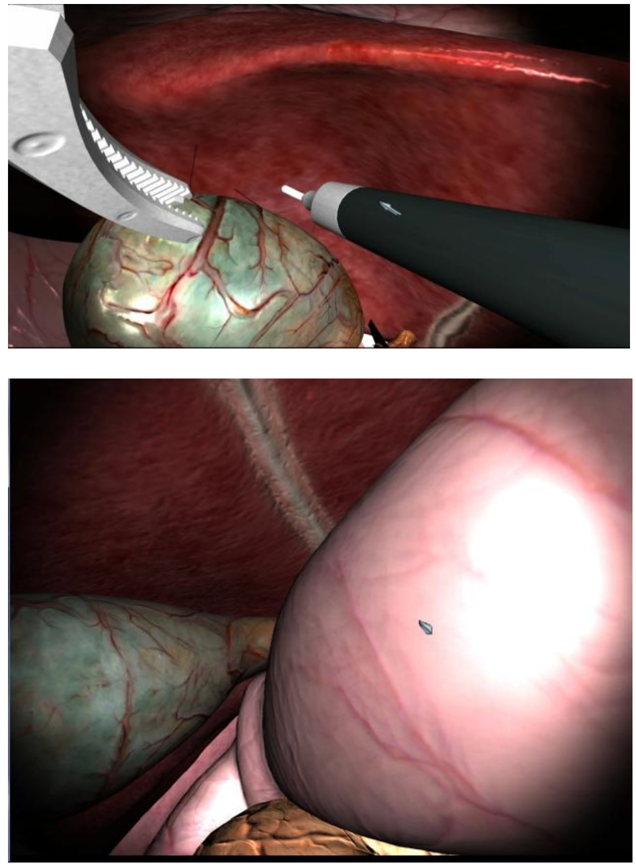
Illustrations



#1. Flowchart diagram of simulator design

#2. Virtual operating room of the P3S

#3. Snapshot of simulator GUI, illustrating the external surface of the abdomen; surgical tools placed in the virtual tray; and the selected endoscope and laparoscopic hand controllers



#4. Sample views of virtual laparoscopic tools and abdominal organs: liver and gallbladder (top); stomach and pancreas (bottom)

#5. P3S hardware setup and integration