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ENGINEERING COLLABORATIONS IN MEDICAL MODELING AND SIMULATİON

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Abstract

Fifty years ago computer science was just beginning to see common acceptance as a growing discipline and very few universities had a computer science department although other departments were utilizing computers and software to enhance their methodologies. We believe modeling and simulation (M&S) is on a similar path. Many other disciplines utilize M&S to enhance their methodologies but we also believe that M&S fundamentals can be essential in making better decisions by utilizing the appropriate model for the problem at hand, expanding the solution space through simulation, and understanding it through visualization and proper analyses. After our students learn these fundamentals, we offer the opportunity to apply them to varied application areas. One such application area is medical M&S, which is a broad area involving anatomical modeling, planning and training simulations, image-guided procedures and more. In this paper, we share several research projects involving M&S and the collaborations that make them possible.

Keywords: Medical, Modeling, Simulation, training

Introduction

Old Dominion University invested significantly in Modeling and Simulation (M&S) area by establishing the Virginia Modeling, Analysis and Simulation Center (VMASC) and integrating M&S into programs in all colleges, as well as initiating the first Modeling, Simulation, and Visualization Engineering (MSVE) department in the nation. VMASC is one of the world's leading research centers for computer modeling, simulation, and visualization. The mission of the center is to conduct collaborative M&S research and development, provide expertise to government agencies and industry, and to promote the discipline of M&S. The MSVE department offers an undergraduate four-year degree program leading to the Bachelor of Science in Modeling and Simulation Engineering. The department also offers programs of graduate study leading to masters and doctoral degrees in Modeling and Simulation. The department houses several instructional and research laboratories, a virtual reality theater, and a four-walled C.A.V.E. (Cave Automatic Virtual Environment). MSVE academic programs are coupled with a strong department research program conducted jointly with researchers from VMASC.

A significant focus of the MSVE department is in medical and healthcare M&S, and so this paper aims to describe our efforts in fostering significant collaborations with medical organizations including Eastern Virginia Medical School (EVMS) and Children's Hospital of the King's Daughters (CKHD), two of the largest medical and heathcare facilities in southeastern Virginia. EVMS has a Center for Simulation and Immersive Learning which is a nationally-respected program for human and device simulation. Its 25,000-square-foot medical simulation facility serves as a regional and national platform for simulation training, research and new product development. The center's mission is to promote and provide high quality clinical education and experiences and reliable assessment of skills and procedures, with the ultimate goals of advancing patient care, increasing patient satisfaction and promoting better health outcomes. CHKD is a multi-specialty health system offering comprehensive pediatric care. Services include inpatient and outpatient care, surgery, emergency medicine, radiology/imaging, rehabilitation, pastoral services, hospitality services, pharmacy, and respiratory care to name a few. MSVE's collaborations with CHKD primarily involve the pectus group, which specializes in the treatment of pectus excavatum, pectus carinatum, and other pediatric complications involving the pectus.

Below we describe various collaborative research projects with EVMS and CHKD with the purpose of creating opportunities that eventually result in better outcomes for patients.

Augmented Standardized Patients For Medical Student Training & Evaluation

To become clinically competent physicians, medical students must develop knowledge and skills in many areas of both the art and science of medicine. As part of the students' early clinical training, students must train and practice doctor-patient communication, information gathering and physical exam involvingauscultation, and clinical diagnostic reasoning about patient pathology.A variety of mechanical or computer-based simulators are now used in medical education, including software for testing clinical reasoning and diagnostic skills, computer simulations of physiological processes, and physical models for practicing selected procedural skills. However, the live interaction with the patient remains a key limitation. Over the past few decades, Standardized patients (SPs), individuals trained to portray real patients, have been widely used for such training, thereby overcoming the problem of waiting for suitable real patients. SPs also provide a way to reliably test students' clinical skills in a realistic setting, interacting with a person. EVMS pioneered the use of SPs and continues to be a leader in the field working closely with our MSVE department to expand the capabilities of SPs using simulation, such as augmented reality. Augmenting SPs with the ability to simulate abnormal physical findings would increase the opportunities for students to learn more clinical skills, as the range of clinical problems SPs can portray is limited since they are healthy individuals.

Over the last years, we have developed several training simulations for augmenting SPs, such as a Virtual pathology stethoscopes (VPS)[1], Virtual pathology Echocardiography (VPE)[2], and virtual sonography[3]. The VPS can automatically play abnormal sounds by tracking the location of the stethoscope over the SP's torso. The prototype systems utilized a tiny magnetic sensor for tracking purposes or relied on SP-triggered approach, a version is now available from Cardionics, Inc. as Simscope [4]. The Echocardiogram and sonography simulators show virtual 3D organs, such as the heart or fetus, when the sensor/transducer is placed within an appropriate location. Using virtual models, it is easy to modify the models to represent and produce different pathology images. These simulators are good examples of the potential of medical simulation to improve the training of medical and health professionals and, ultimately, to improve patient safety.

Pectus Research in Medical Modeling and Simulation

Designing surgical simulators is also an importantasset from our collaboration with EVMS and Children's Hospital of The King's Daughters (CHKD). Surgical simulators allow medical procedures and treatments to be safely administered and ensure that the patient receives the maximum benefit without costly complications. CHKD surgical advancements in the treatment of a common chest deformity, pectusexcavatum (PE), have made their hospital the top location in the world for such treatment. PE, also called sunken or funnel chest, is a congenital chest wall deformity which is characterized, in most cases, by a deep depression of the sternum, as shown in Figure 1. This condition affects primarily children and young adults and is responsible for about 90% of congenital chest wall abnormalities [5]. Among various PE treatment options, the minimally invasive technique for the repair of PE, often referred to as the Nuss procedure, has been proven to have a high success rate, satisfactory aesthetic outcome and low interference with skeletal growth [6].The Nuss procedure involves placing a metal bar(s) underneath the sternum forcibly changingthe geometry of the ribcage. After a period of at least two years, the bar is removed, resulting in a largely permanent result.

Figure 1. Patient with PE

Surgeons often reported difficulties removing the pectus bar since it has to be straightened first, Figure 2. After identifying the problems associated with the tools for bar removal, we designed,using a CAD software, an optimized surgical tool for the pectus bar extraction and performed a finite element model (FEM) to validate our approach [7]. In addition, physical models and metal prototypes of the tool were built to allow evaluation of various design variants. The metal prototypes, shown in Figure 3,are being successfully used by the surgeons from CHKD in a clinical study where preliminary resultsshow superiority to the commercial bar benders in terms of shortening the time of surgery which may limit costs and reduce the risk of infection.

Figure 2.Pectus bar straightening for bar removal

Figure 3. Metal prototype of the updated design: the hook and the foot (left), engagement with the pectus bar (right).

Pre- and post-surgical surface scans, as shown in Figure 4, were obtained from 22 consenting patients using a portable handheld 3D laser scanner. A difference map showing the extent of displacement at each location on the chest wall was created as an objective measure for improvement by comparing pre and post surgery, Figure 5. The proposed 3D surface scanning method was successful to objectively demonstrate improvement in chest shape after the surgical correction.

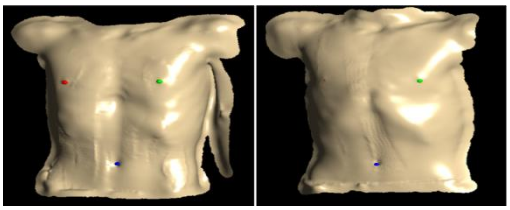


Figure 4.Pre-surgical (left) and post-surgical surface scan (right).

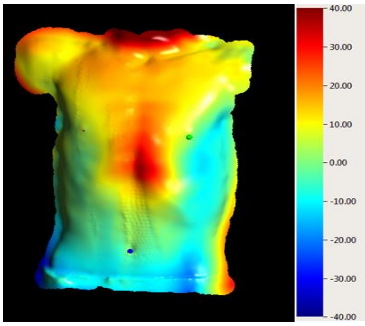


Figure 5.Pre- and post-surgical scan comparison (scale in mm).

Our research team has also developed a Nuss procedure surgical simulator (NPSS) to provide a platform for adequate training on the procedure [8]. Such simulation is an invaluable training tool mitigating the steep learning curve and improving surgical planning. The NPSS workstation was constructed integrating a Geomagic Phantom Premium 1.5 high force feedback device with the graphical image displayed on a stereo monitor, as shown in Figure 6. An important aspect of the simulation is to give surgeons the ability to interact with a surgical space resembling the actual procedure.Sophisticated 3D modeling platforms were utilized to design the surgical tool as well as the anatomical structures of the patient's body with appropriate and realistic surfaces and textures [8]. The haptic device provided the limited field motion and the constrained nature of the surgical tool's movement, similar to what occurs in the actual surgery. The NPSS can also be scaled down to the web-based teaching tool or used with a low cost haptic device.

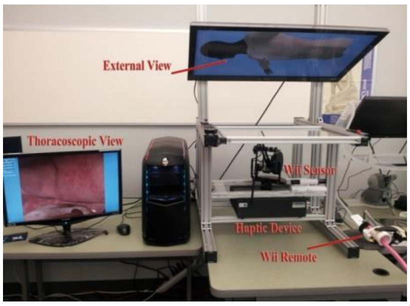


Figure 6. Hardware setup of the Nuss procedure trainer

Even relatively simple procedures can have steps which, if incorrectly performed, may lead to serious complications or fatalities. Surgical simulation has become a valuable tool in the training process of medical students and surgeons on specific types of procedures, improving skills such as eye-hand coordination and the ability to perform three dimensional actions using a two-dimensional monitor.

Computer-Assisted Neurosurgery

With the neurosurgery residency workweek now limited to 80 hours, and with the neurosurgical armamentarium ever increasing in complexity, the need for simulation-based training has never been greater. The MSVE department is devoted to development of a broadly usable neurosurgery simulator for training purposes. A characteristic of our research approach is the emphasis on providing undergraduate and graduate researchers with the most advanced software toolbox achievable, based on both open-source as well as contributed software code. Some of our commonly used toolkits are Insight Segmentation and Registration Toolkit (ITK) [9] for medical image analysis, Visualization Toolkit (VTK) [10] for 2D and 3D scene visualization, Simulation Open Framework Architecture (SOFA) [11] for interactive medical simulation, Computational Geometry Algorithms Library (CGAL) [12] for meshing and computational geometry, and Connectome Mapping Toolkit (CMTK)[13] for automatic pipeline for tractographic and connectomic analysis of brain images.

Convergence of research and education

This emphasis on open-source software is also true of our approach to education, with the result that there is convergence between education and research: our approach to graduate and even undergraduate education in particular subsumes the use of open-source and public-domain software as a teaching tool. In particular, we endorse the use of Matlab for an introductory medical image analysis class, and ITK for the more advanced graduate class; the senior author is also collaborating with INRIA, to develop a textbook on SOFA.
By encouraging students to access and manipulate source code that implements state-of-the-art algorithms and models, we accomplish two things at the very least: i) we make the learning experience much more vivid, as students visualize the effect of these algorithms and models taught in class as well as obtain an intuitive feel for their sensitivity to various parameters, and ii) we form experts in the practical usage of these toolkits, many of which are becoming industry standards, thereby enhancing career prospects of students in industry. For example, Siemens is developing state-of-the-art cardiac simulation built on SOFA, while GE is a both a user of and contributor to ITK. Some of our ongoing neurosurgery simulation projects are described below.

Simplex-based minimally supervised tissue segmentation

Our research in anatomical modeling emphasizes segmentation methods that build on digital atlases as well as physically based active surface models, in particular, the Simplex active surface model. An n-Simplex mesh is defined in terms of vertex connectivity, where each vertex has (n+1) vertex neighbors linked to it by an edge. As depicted in figure 7, A 1-simplex is typically contour in 3D, 2-simplex is a surface, and a 3-simplex is a 3D mesh that is the dual of a tetrahedral mesh. The 2-simplex is an active surface model based on a mesh of vertices, whose motion is governed by a Newtonian law:

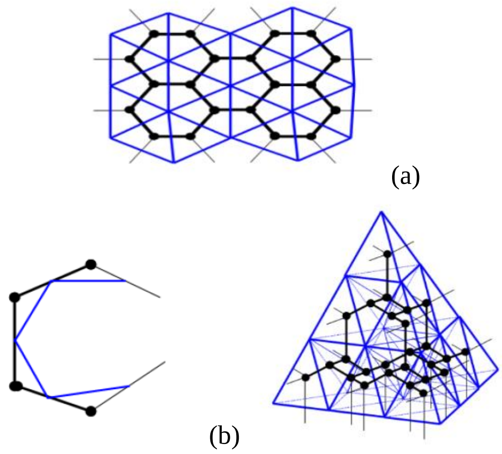


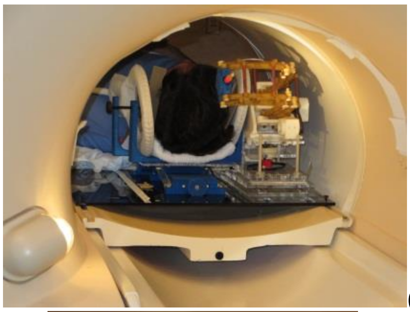
Figure 7. Simplex topology. (a) Top: 2-Simplex showing each vertex with 3 neighbors (black), dual of triangulation (blue); bottom, left: 1-simplex contour (black), right: 3-simplex topology (black), with dual tetrahedral mesh (blue).(b)
Reproduced with permission from Gilles [14].

$$m \frac{d^2 P_i}{dt^2} = -\gamma \frac{dP_i}{dt} + \alpha \mathbf{F}_{int} + \beta \mathbf{F}_{ext} \qquad (1)$$

Image forces attract the mesh surface to the tissue boundary. Variable m denotes the vertex mass and γ the damping factor. $\mathbf{F}_{int}$ is the sum of internal forces, while $\mathbf{F}_{ext}$ represents summed external forces.

Robotic Deep Brain Stimulation (DBS) surgery planning

The first application is the development of a 2-Simplex mesh with shared boundaries, which coincide with anatomical boundaries of deep-brain structures. This will lead to a sparse multi-surface-based representation of the atlas, which will be registered to preoperative patient images based on multi-contrast MR imaging [15] that enables direct targeting of subcortical structures such as the subthalamic nucleus (targeted by DBS for Parkinson's disease). In turn, this light-weight representation of patient neuroanatomy will be compatible with fast non-rigid registration for tracking brain shift in real-time, in conjunction with the DBS robot depicted in Figure 8. Some surgical robots entail a process which exploits characteristic fiducial patterns that are visible in medical images and can be probed in the OR. Our research focuses on the soft tissue shift, which can be characterized as the basis of intraoperative MR imaging that is anatomical based.


(a)

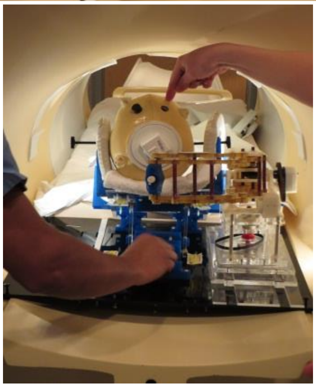

(b)

Figure 8. MRI-compatible deep-brain stimulation robot: (a) anthropomorphic phantom study, and (b) simulated patient study; courtesy of Greg Fischer of Worcester Polytechnic Institute.

Spine surgery simulation

A second research project emphasizes patient-specific anatomical modeling of the spine for discectomy simulation, which can also be applied to spine surgery planning and navigation. This work involves the multi-surface Simplex model of Gilles [16], which will be refined to incorporate population statistics of shape, which have been demonstrated for single-surface Simplex by Tejos and Schmid [17, 18], but never for multi-surface models. It is also essential for the Simplex model to be able to cope with local areas where the shape statistics term is turned off, namely the herniated disc, since there is no meaningful average shape for a population of pathologies. Preliminary results for an intervertebral disc are shown in Figure 9.

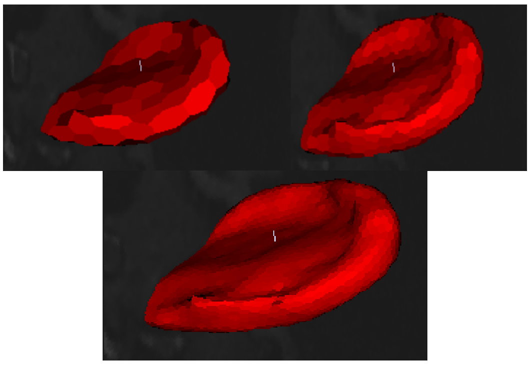


Figure 9. Simplex mesh-based, coarse-to-fine segmentation of intra-vertebral disc for discectomy simulation; top: coarse and medium levels, and bottom: fine-level segmentation.

Modeling the brainstem and cranial nerves

Another ongoing anatomical modeling project is the development of a model of the brainstem and cranial nerves, which we will then be able to register to patient image datasets in a minimally supervised manner to segment these structures. In contrast with the work done in the previous two anatomical modeling projects, this one will emphasize 1-Simplex 3D active contour model, which is needed for curvilinear structures like nerves, rather than a surface. Some of the nerves may be barely visible; therefore our approach will build on a combination of 1-Simplex and shape statistics, as well as probabilistic localization of both ends of the nerve.

Conclusion

Synergistic relationships between medical / healthcare practitioners and engineering developers must exist to advance technology and procedures for improving the experience and outcome of the patient. Although such relationships are likely to arise out of even the most difficult and resource starved environments, progress and expediency for the patient is best served with healthy support from government, society, and institutions involved. We presented several projects that are a result of spirit cooperation and support from both sides of the coin -medical and engineering institutions. Not every project results in success but these collaborations ensure focused approaches with realistic constraints. Such collaborations are not only to be encouraged but should be sought out and sustainable.

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