Simulation, Planning, and Execution of Computer-Assisted Surgery

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I. Project Summary

THIS project addresses the development of advanced simulation, planning, and execution technologies for the next generation of computer-assisted surgical systems. The project is a collaboration among researchers and clinicians in bioengineering, computational mechanics, computer science, robotics, and surgery. Total hip replacement surgery, one of the most common procedures in orthopaedic surgery, is targeted because of the anticipated benefits of high precision and accuracy.

Research is necessary in both computational biomechanics and robotics. Research in biomechanics is aimed at developing physics-based simulation tools that provide surgeons with feedback on the mechanical consequences of a given surgical plan. Robotics research seeks to develop technologies to execute these plans accurately and register the bone non-invasively.

II. Area Background

Biomechanics-based Surgical Simulation. Research in biomechanics focuses on building fast, accurate biomechanics-based surgical simulation tools to aid surgeons in optimal planning of robot-assisted procedures. The success of total hip replacement surgery depends strongly on the postoperative mechanical environment of the bone-implant system. To predict the critical postoperative stress state and load transfer mechanism, a surgical simulator must model the actual implantation of a component into the prepared cavity within the patient's bone. This model must be based on the geometry and material properties of the specific patient for whom the procedure is contemplated, a difficult task because the geometry is not directly observable. Physically-based modeling represents a new challenge for surgical simulators; historically they have simulated only the geometry and not the physics of surgical procedures. Simulation of the physics of implantation is a complex, large-scale, and highly nonlinear problem in solid mechanics. A central aspect of our work is thus the development of new algorithms that exploit advanced architecture computers to perform biomechanics-based simulation in near-real time.

One strategy for patient-specific geometric modeling is to develop solid models of bone volumes by reconstructing CT data, and then use these models to generate finite element meshes within the encompassed volumes. Physics-based modeling imposes a set of demands that traditional geometry-oriented simulation need not address. For example, we must be able to perform boolean operations that simulate femoral preparation; prescribe material models, constitutive laws, boundary conditions, and forcing functions on the bone-implant system; and generate quality volume meshes for finite element solution of the solid mechanics equations. Thus, we must extend the geometric modeling algorithms common in medical applications to support the needs of physics-based modeling. Towards this end, we are developing methods and building software to establish the sequence of transformations that will take a CT scan, a given implant, and the implant location within the bone, and produce a simulation-ready biomechanical model. Standard finite element methods can then be applied.

Because of the difficulties inherent in physics-driven geometric modeling discussed above, we have also pursued techniques for bypassing the surface reconstruction and volume meshing steps. We are developing a method that approximates the governing equations directly on a regular grid derived from the CT data. Rather than satisfy boundary conditions by conforming an unstructured mesh to an irregular boundary, we impose them weakly through Lagrange multipliers, ultimately resulting in algebraic constraints expressed in terms of the regular grid unknowns. In addition to its advantage of not requiring surface reconstruction, it is also significantly faster than standard unstructured-mesh finite element methods, as well as requiring an order of magnitude less storage. This is because computations are primarily carried out on regular grids, thus enabling compact storage schemes as well as fast multilevel solvers that exploit this structure. Finally, the structure permits easy mapping onto parallel computers. Our current implementation produces solutions to 2-D implantation problems (with about 35,000 unknowns) at near-interactive speeds on a desktop workstation, directly from CT data and implant geometry.

Surface-based Registration. As discussed above, the preoperative surgical simulations aid in seeking an optimal interventional plan. Once a plan has been decided on, the challenge in in executing it as faithfully as possible. A critical step is establishing a common reference frame between pre-surgical data and the corresponding patient anatomy. The process is referred to as intra-surgical registration. Once a common ref-

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erence frame is established, pre-surgical data can be used for a variety of tasks including: guiding robotic tool movements, superimposing graphical overlays of internal anatomy upon a surgeon's view of the patient, or guiding a surgeon's tool movements. Recent clinical approaches to intrasurgical registration assume a known correspondence between points in the two data sets being registered. This is usually achieved by attaching fiducial markers to the underlying object and extracting the locations of these markers in both data sets. Unfortunately, attachment of markers typically requires an additional surgical procedure prior to the collection of pre-surgical data. Furthermore, these markers are invasive and cause added trauma to the patient in sites far from the primary surgical field.

An alternative to fiducial-based registration is to use anatomical surface-based registration. If data from the bounding surface of an anatomical object can be extracted pre- and intra-surgically, these data sets can be matched to perform registration. Surface based methods, though advantageous in removing the need for costly and invasive external markers, do place a heavy burden on sensing and modeling technology. Accurate pre- and intra-surgical surface data is needed, which is a much more difficult task than simply acquiring 3-D fiducial locations as required by previous approaches.

Currently, we are investigating "frameless" registration methods for computer-assisted interventions in orthopaedics. Our technique is initially aimed at our model problem, the total hip replacement surgery with the use of cementless acetabular components; it is nevertheless our goal to extend this approach to other procedures. Initially we are concentrating on acquiring intra-operative surface data using a digitizing probe to touch exposed surfaces of the bone; however, there is potential to expand this approach to many other data acquisition methods. The accuracy resulting from surface-based registration depends highly on the underlying data. In our studies these data include the geometric surface models from pre-operative CT scans, as well as data collected intra-surgically using digitizing probes, ultrasound, fluoroscopes or CT. We are currently developing methods for planning the acquisition of potentially costly intra-surgical registration data using pre-operative geometric models as input.

Intra-surgical Navigational Guidance. Finding a common reference between pre-surgical and intra-surgical data is only a first step in the successful execution of a pre-operative plan. Providing real-time navigational guidance to a surgeon during surgery is a way for ensuring that the surgery will be more accurate and more dependable. Within the context of our prototype surgical procedure, the application of our navigational guidance work is to allow for the accurate placement of the acetabular implant during hip replacement surgery.

We have developed a testbed to demonstrate registration and navigational guidance for implant placement. The current testbed is not designed for clinical use, so issues of sterility, and clinical safety have not yet been addressed. However, we are in the process of validating this system on human cadavers and intend to initiate a limited clinical trial on human patients shortly. Our system consists of an optical position sensor capable of tracking conventional surgical tools at very high speeds, and a video display monitor for providing navigational feedback to the surgeon. Navigational feedback is derived by computing the difference between desired tool location (as specified in the pre-operative plan) and current tool location (as determined from the optical tracking sensor). The surgeon uses this feedback to decide what direction the tool must be moved in order to align the acetabular implant with its desired location.

III. Related Research Areas

Biomechanics-based Surgical Simulation. Patient-specific simulation of biomechanical phenomena is of course not limited to planning hip replacement surgery. Modeling the biomechanics of the human body is a subject of considerable interest, and includes the modeling of the mechanics of bone, soft tissue, and biofluid flows. Of course, at the heart of biomechanical modeling is numerical solution of PDEs, which has a rich history. However, biomechanics problems possess several features that magnify the difficulties associated with solution of generic PDE problems: (i) complex, patient specific geometries that must be derived from CT/MR data; (ii) highly nonlinear equations, as a result of either nonlinear constitutive laws or large, and (iii) the need for interactive speed simulation in planning applications.

Surface-based Registration. Registration is a common problem in many areas of engineering and science, and a fair amount of research can be found on the general 3-D registration problem. Example applications include surface inspection of arbitrarily-shaped manufactured parts, and computer vision-based object recognition. While there is crossover between earlier research and the intra-surgical registration problem, the current work has two requirements that have not been considered in earlier work. First, due to the high costs of acquiring registration data during surgery, it is necessary to minimize the number of intra-surgical measurements required for accurate localization of the patient. This goal is met via the "intelligent" selection of registration data. Second, it is imperative that intra-surgical registration be sufficiently accurate. Therefore, our work focusses on algorithm validation/testing and on-line identification of registration errors during surgery.

Intra-surgical Navigational Guidance. Providing navigational guidance to a surgeon requires the communication of complex three-dimensional spatial relationships between multiple moving objects. This information may be presented on a television monitor, head-mounted display or other visual display device. Research in areas such as augmented reality, aircraft cockpit design and human-computer interaction may have relevance to the current work. Related research questions include: (i) How should display hardware be designed to communicate the required information while integrating seamlessly into the operating room? (ii) How should visual information be presented in a manner which maximizes clarity, spatial discriminability and task accuracy?

IV. Potential Related Projects

Biomechanics-based Surgical Simulation. The practice of medicine has been revolutionized by medical imaging, i.e. simulation of the *geometry* of the human body. As computers become faster, algorithms advance, more realistic constitutive models become available, and imaging methods improve, we expect to see increasing use of biomechanics simulation in medical applications. These applications include diagnosis, training, surgical planning, and device design. Special difficulties include the need to solve inverse problems (diagnosis and device design), and the need for real-time simulation (training and surgical planning). Nevertheless, we expect that simulating the *physics* of the human body will further revolutionize medical practice, much as it has done in structural, aerospace, automotive, and electromagnetic design.

Intra-surgical Navigational Guidance. The general goal of the navigational guidance problem addressed in this work is to provide information to a human operator in a manner that allows him or her to accurately perform a spatial hand-eye positioning task. The technology being investigated in the context of guidance for hip replacement surgery will likely have broad application to both surgical and non-surgical tasks. Related surgical tasks include: guidance of drills, saws, reamers and other tools in a variety of orthopaedic procedures; guidance of biopsy needles toward suspected tumor sites. Non-medical guidance tasks may include: manual assembly and maintenance of complex mechanisms.

V. Further Information

The award for this project was made in support of NSF's National Challenges initiative, ENG-CISE-IITA94. The NSF program area is Robotics and Machine Intelligence (IRI/CISE), with Dr. Howard Moraff as program manager. Principal investigator is Takeo Kanade. Further information may be obtained from http://www.cs.cmu.edu/afs/cs/project/mrcas/www/hippocrates.html.

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