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Surgery Simulation – A Challenge for Graphics and Vision[1]

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1 MOTIVATION

Medicine is an extremely challenging field of research, which has been - more than any other discipline - of fundamental importance for human existence. The variety and inherent complexity of unsolved problems has made it a major driving force for many natural and engineering sciences. Hence, from the early days of Computer Graphics and Computer Vision the medical field has been one of most important application areas with an enduring provision of fascinating research challenges. Conversely, individual Graphics and Computer Vision tools and methods have become increasingly irreplaceable in modern medicine. In this article I will present my personal view of the interdisciplinary field of surgery simulation which encompasses many different disciplines including Medicine, Computer Graphics, Computer Vision, Mechanics, Material Sciences, Robotics and Numeric Analysis. I will discuss the individual tasks, challenges and problems arising during the design and implementation of advanced surgery simulation environments, where my emphasis is directed towards the roles of graphics and vision.

In modern computer-aided medicine visionaries foresee fully immersive real-time simulation environments in which surgeons can learn, plan, and rehearse complex operations using individual patient models and being supported by sophisticated input devices, such as virtual scalpels. The design of such types of simulation environments is a highly interdisciplinary endeavor which requires input from a variety of disciplines. The conceptual components of an advanced surgery simulation environment can be summarized of as follows: In a first step, raw data sets have to be acquired by highly accurate 3D medical imaging or vision systems. Subsequent preprocessing steps extract anatomic substructures and create geometric models of the patient attributed with respective material parameters. A sophisticated modeler will allow the surgeon to modify the geometry and the topology of individual parts of the derived model while simulating cuts, bone and tissue repositioning, transplants, inlays, etc. Force feedback as a function of the underlying material has to be computed and interpolated to meet the high update rates, being necessary to beat the temporal resolution of the human tactile channel. Tissue forces and deformation fields as well as collision detection must be computed in real-time, since they convey the parameters for visual and force feedback. In essence, fast

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[1] This article is a revised and extended version of [3]

approximations of the underlying differential equations have to be found. Though for some applications, such as for facial surgery simulation, more expensive and accurate solution strategies would have to compute the deformation fields in batch mode, yet, the design of appropriate real-time engines remains the most challenging part of the simulation.

2 DATA ACQUISITION AND ANALYSIS

Since CT and MR scanners have still their limits in spatial resolution highly accurate 3D surface data acquisition is of crucial importance for many application scenarios. In this context, fast and robust 3D active vision methods are necessary to satisfy the resolution constraints needed to build accurate 3D models. Furthermore, color and texture samples must be recorded to feed subsequent rendering algorithms. Especially when using both volume and surface data various registration and alignment problems come up including surface-surface, surface-volume and volume-volume registration. Robust (semi)automatic methods are desirable, an example of which is depicted in figure 1.

Since the early days of medial imaging segmentation and feature extraction have lost none of their importance and though decades of research there is no robust and fully automatic method in sight. Likewise, semiautomatic strategies might be an appropriate alternative and collaborative effort of researchers from *Computer Graphics* and from *Computer Vision* is necessary to optimize interactive 3D segmentation strategies.

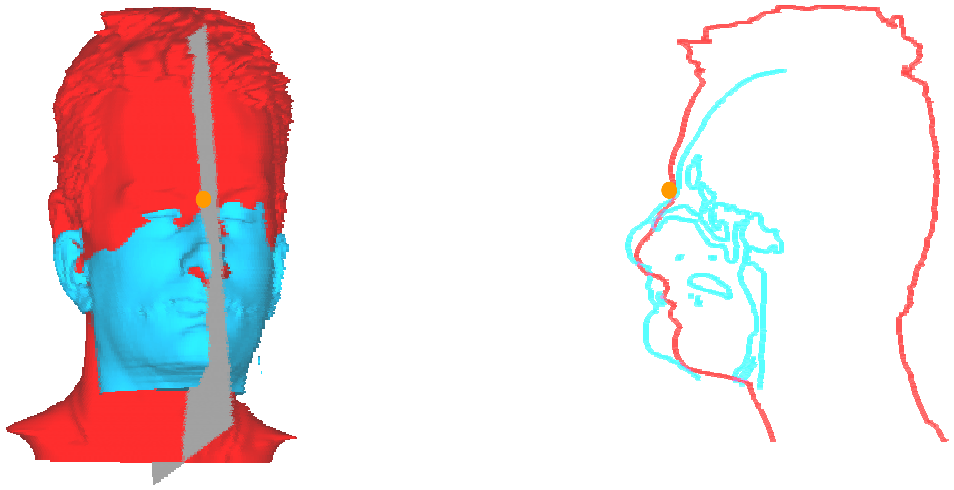

Figure 1: Example for semi-automatic registration of CT and laser range data. We solve a Procrustes problem using interactively selected landmarks (from [1]).

3 THE HUMAN COMPUTER INTERFACE

The design of a sophisticated natural human computer interface is certainly one of the keys to successful simulation. The illusion of an immersive medical working environment can only be created with the help of advanced virtual reality hardware. Contemporary output devices, such as head-mounted displays, Caves, Visdomes and

Workbenches are promising tools to study the behavior and acceptance of medical users, however, we foresee smart, small, light-weight and very high resolution eyeglass displays as the ultimate devices for mediating visual information to the surgeon. We believe that future display technology will provide a new generation of sophisticated solutions.

Much more than the display itself is the provision of tactile and force feedback information of critical importance for any surgeon. Therefore, we require highly accurate haptic interfaces capturing the responses of human tissue to mechanical stimuli. One of the major problems, however, is that the haptic device must be thoroughly tailored to the underlying application. In facial surgery simulation, for instance, a completely different setup is required than in laparoscopy. Moreover, complex surgical procedures usually employ extensive sets of individual mechanical tools. Although various haptic interfaces are available in research labs or on the market and form experimental steps into the right direction we are still far from sophisticated solutions. All in all, the design of individual force feedback devices is strongly influenced by the application context and by the underlying physics. Optimization to the users demands requires thoroughly engineered systems.

4 MECHANICS AND NUMERICAL ANALYSIS

The differential equations governing any volumetric tissue deformation have their roots in *Mechanics*. In the past, linear volumetric strain and deformation models have been extensively investigated and are widely available for various kinds of material simulation. In surgery simulation, however, mostly large stains and deformations occur and the material tensors change as functions of the strain. The resulting phenomena are highly nonlinear and extremely difficult to model. Other effects relate to compressibility of human soft tissue. The high percentage of liquid makes it almost incompressible, however, local tissue forces generated during surgery force liquid to stream out and influence the mechanical behavior of the material.

Besides mathematical models appropriate material parameter databases are of great importance in surgery simulation. Moduli of elasticity or non-linearities are usually functions of age, sex, ethnic group, and others. Unfortunately, it is extremely difficult to obtain the desired parameters and extensive experimental research has to be pursued. In fact, we need the help of *Material Scientists* to provide us with appropriate sets of parameters and interpolation models for individual patients and tissue types.

The strategies for optimal solutions of partial differential equations are critically dependent on the complexity of the underlying mechanical model. In order to achieve real-time response we have to balance mathematical accuracy versus computational effort. *Numerical Analysts* have developed various classes of solution strategies, where FEM is only one prominent example. Hence, appropriate solution strategies have to be designed in close cooperation with numerical analysts. Here, *hierarchy, progression* and *localization* might be some of the key words to success.

5 GRAPHICS ALGORITHMS

The particular attractiveness of highly complex surgery simulation environments lies in the versatility and depth of individual research problems touching or covering almost every important subfield of *Computer Graphics*. This encompasses especially the following topics:

- *Modeling of geometry and topology:* Any sophisticated surgery simulation system is based on the efficient mathematical description of the underlying geometry and topology. Here, most of the physics is embedded into a full volumetric setting. Sophisticated discretizations and approximation models are essential preprocessing steps for advanced numerical procedures. An example is given in figure 2. Conformity and polynomial degree of individual elements strongly affect the complexity and accuracy of numerical solutions. Therefore we have to adapt our models to subsequent numerical strategies where piecewise linear approximations are mostly insufficient. Our challenge is to create new generations of higher order volumetric approximations which do not impose unnecessary topological restrictions on our model.

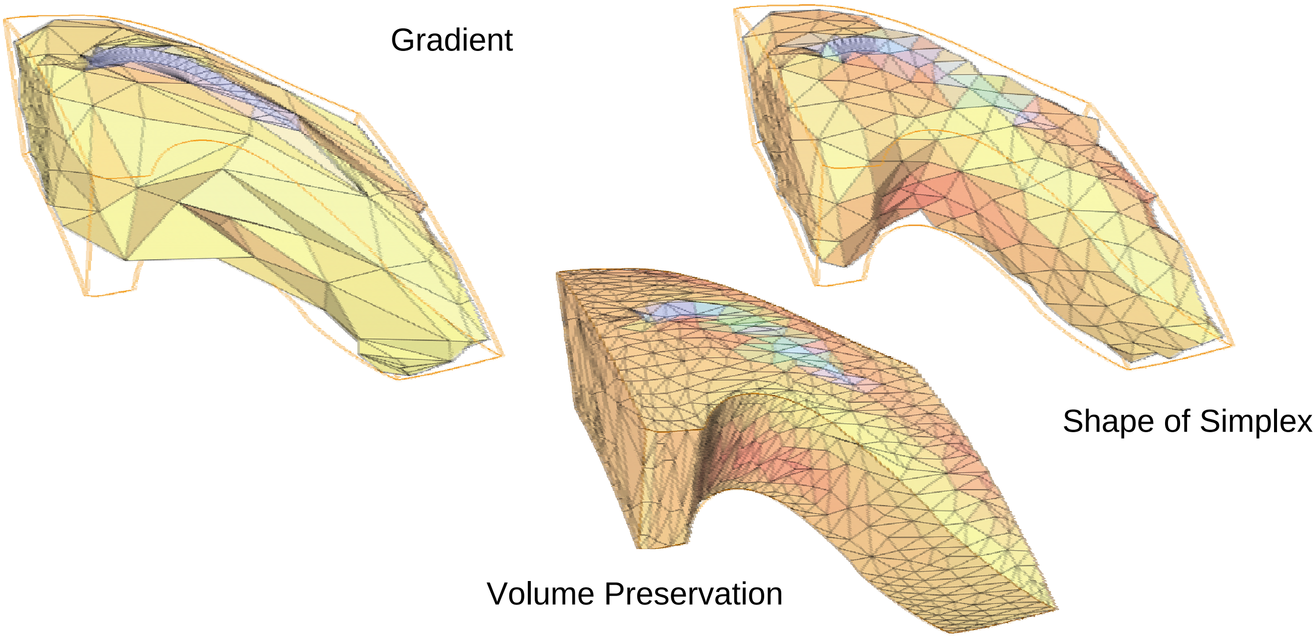

Figure 2: Progressive tetrahedral domain decomposition of volume data. The pictures illustrate the influence of different cost functions (from [6]).

- *Editing of complex structures:* With appropriate approximation methods in place we can move to the design of powerful editors allowing the user to modify the geometry and topology of anatomic structures. Again, mere surface editing is certainly not sufficient for cutting and repositioning of individual pieces of soft tissue. Figure 3, for instance, illustrates different topological cases arising when cutting tetrahedral tesselations. Functions like a zoom into substructures are highly desirable enabling a surgeon to operate on different scales of the volumetric representation. Therefore, elaborate data structures have to be devised giving efficient access to and maintaining individual primitives of the underlying approximation. Furthermore, these data types will have to accomodate all essential parameters of the physically based models.

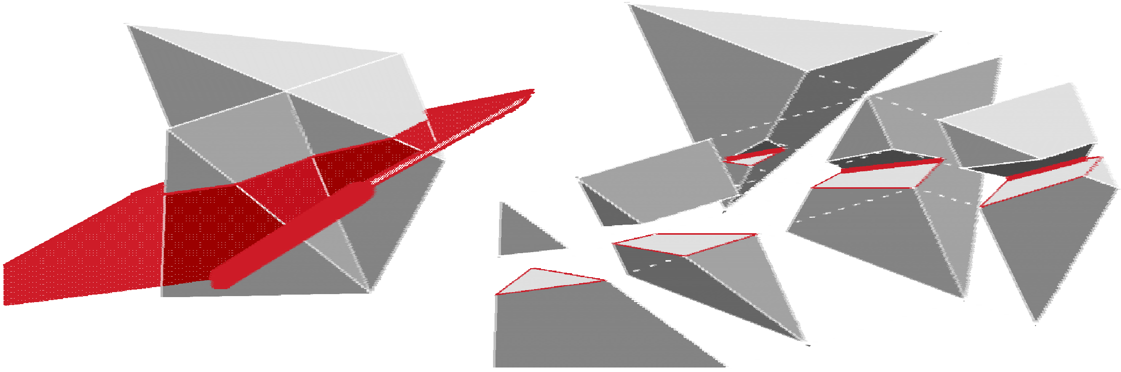

Figure 3: Interactive cut through a tetrahedral representation of volumetric soft tissue. The different cases that can occur are shown on the right (from [2]).

- *Simplification and adaptation of physical models:* One of our core challenges in surgery simulation is to understand and to simplify the physics of the simulation process. The quest for real-time update rates in visual and haptic feedback forces us to develop sophisticated solutions that find a balance between computational complexity and accuracy. To this end, we have to thoroughly investigate and analyze the governing equations and to study their error bounds. Based on a profound knowledge and observation of the physical phenomena efficient approximate solutions must be designed. Different strategies and paradigms have to be investigated and evaluated, such as finite elements versus finite differences, flat versus hierarchy, local versus global or polynomial degree versus spatial resolution. Required update rates for visual and force feedback rendering might be decoupled from the numerics engine and appropriate temporal interpolation will compute the desired dense output. In addition, we will have to consider next generations graphics hardware to accelerate the envisioned algorithms.
- *Image generation:* Generally, fast rendering algorithms are irreplaceable in surgery simulation. However, with the design of advanced volumetric approximations new types of possibly unstructured graphics primitives will enter the scene and appropriate hardware support will be highly desirable. Thus, both surface and volume rendering of higher order primitives will be of great interest. The required visual quality, however, depends critically on the application context. The mostly lubricant surfaces of the interior of human bodies, for instance, are mostly specular and will ask for hardware support of more sophisticated shading models. Furthermore, bump, displacement and texture databases or procedural models for human skin and soft tissue have to be created. Here, multipass methods might be a promising approach. Apart from real-time constraints some applications deserve extremely sophisticated illumination models. In facial surgery simulation, for instance, the rendering of photorealistically looking images might be computed off-line by raytracing of the

higher order primitives described earlier. Here we need advanced reflection and scattering models for facial skin, which, of course, will be functions of age, sex and other parameters. In addition, high quality rendering of human hair is still widely open.

- *Systems Design and Layout:* Besides the mere development, tuning and tailoring of individual vision and graphics algorithms we will have to consider overall systems layout and optimization. Especially global design issues, such as communication and object brokering between editor, rendering, simulation engine and force feedback are of importance. Some recently developed standards, such as CORBA, might be employed.

6 EXAMPLES

The sequence of images presented in Fig. 10 shows four frames of a cut through a grid of initially 576 tetrahedra. To enhance the visual realism of the tissue, we applied texture mapping both for the exterior and for the interior faces generated during the cut. Displacement boundary conditions were set along the left- and right-hand sides of the volume.

Figure 4: Sequence of four frames of an interactive 3D cut through a piece of soft tissue decomposed by tetrahedra (from [2]).

The second example depicts some results of the simulated correction of a short face syndrome (figure 5). The patient suffers from a retrodisplacement of the maxilla and mandible (upper and lower jaw) in combination with a deep bite because of a predominantly horizontal growth pattern of the bases of the jaws in relation to the skull base. The correspondence of simulation and real surgery is exceptional. The profile lines are given in figure 4d, where blue, green and red represent the pre-surgical, simulated and post-surgical situations respectively. Minor deviations can only be observed in the region of the mouth. In addition, the frontal error visualization reveals artifacts due to swelling.

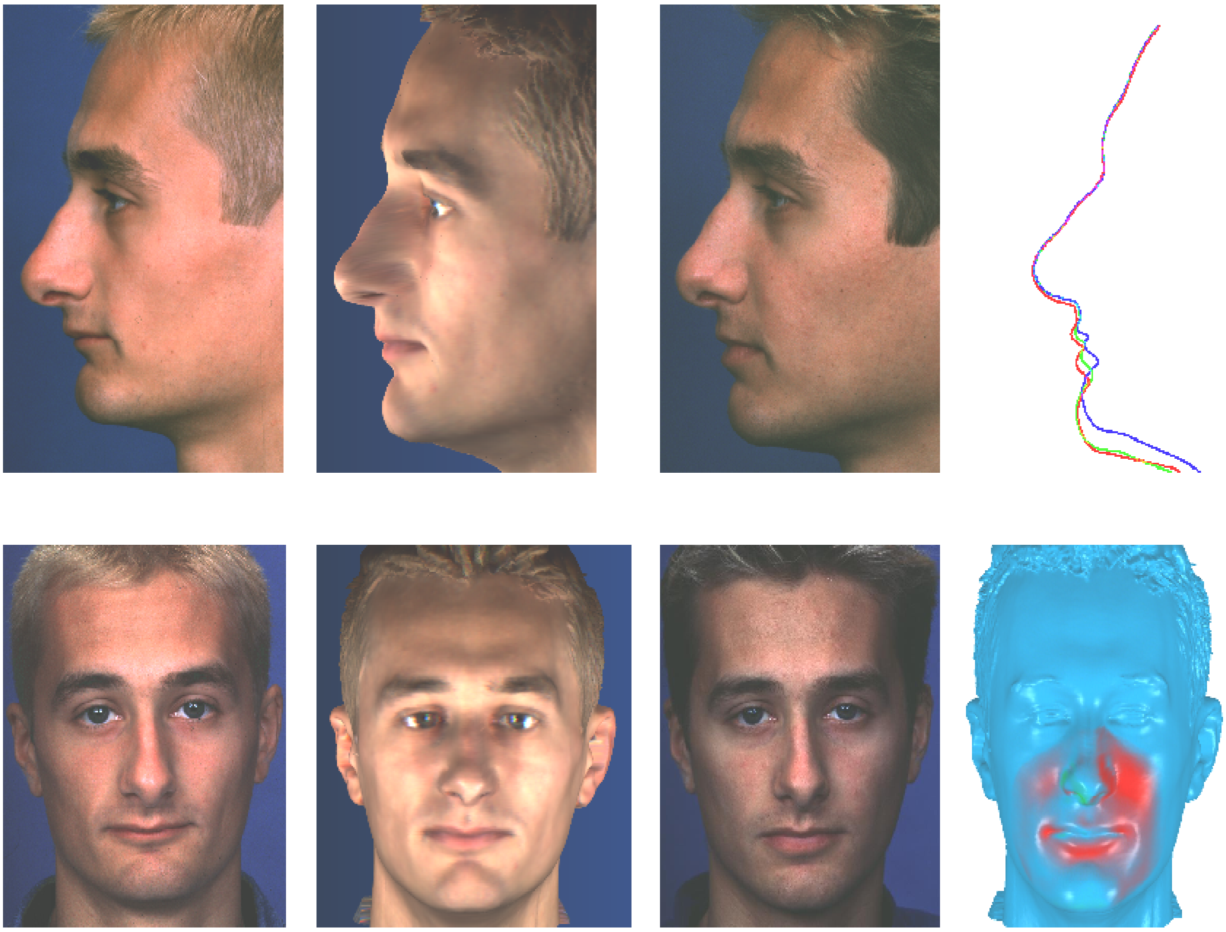

Figure 5: Pre- and postsurgical images of a patient with a short face syndrome. Profiles: (a) pre-surgical, (b) predicted, (c) post-surgical, (d) profile lines. Portraits: (e) pre-surgical, (f) predicted, (g) post-surgical, (h) error visualization (from [1])

Finally, figure 6 illustrates the reference points and jaw bone repositionings on the patient's skull.

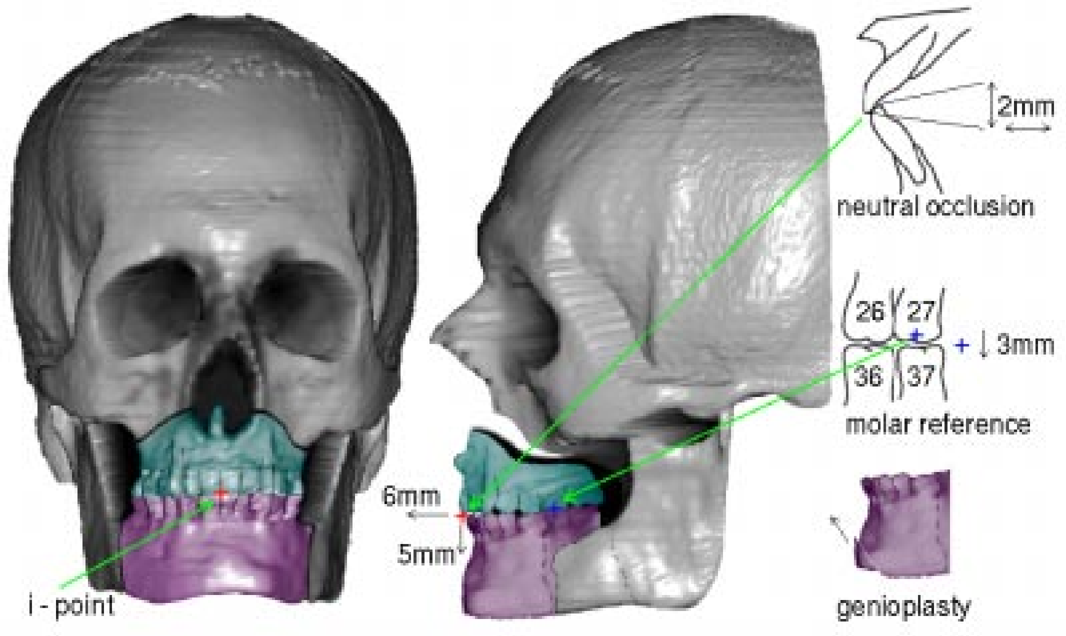

Figure 6: Reference points used to model craniofacial surgery using the Alias™ modeling system (from [1]).

7 RELATED READINGS

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