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Virtual Guides and Mechatronic Device for Interactive Surgical System

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Abstract. This paper presents an interactive surgical system dedicated to mini-invasive endovascular intervention. This system uses both the advantages of virtual reality and micro-robotics. The requirements of this system are presented with its architectural design. The interaction and the deformation modelling are the main key for surgery simulation, by ensuring both real-time computation and realism. In order to improve the precision and the security of the intra-operative gesture, an approach using virtual guide metaphors is proposed. This approach is based on the artificial potential field method for virtual guidance of the micro-robot's distal extremity. In order to show the computational efficiency of the proposed approach, simulations results are given.

Keywords: Virtual reality for medical applications, mini-invasive surgery, robotic-assisted surgery, surgery simulation, physically-based modelling, virtual guides, interactive navigation.

Introduction

During the last few decades various parts of the human body can be accurately depicted using three-dimensional medical imaging techniques, such as Computed Tomography (CT) and Magnetic Resonance (MR) imaging. The resulting images can be used as an aid in diagnosing pathology and for planning of medical treatment. Conventionally, diagnosis is performed in a visual way: clinicians compare what is seen in patient images with knowledge of anatomy and pathology. Planning of treatment is performed similarly. Prior to surgery, surgeons use the images to mentally project the three-dimensional patient's anatomy for determining the surgical plan.

Recently, advances in computer technology and a significant increase in the accuracy of imaging have made it possible to develop systems that can assist the clinician in the full path of diagnosis, planning and treatment.

The MATEO[1] project concerns image-guided treatment of Abdominal Aortic Aneurysm (AAA), an arterial wall pathology responsible for a life-threatening dilatation of the abdominal aorta. Rupture of an AAA leads to instant death in the majority of cases. The goal of interventions is therefore to repair the growth and prevent the rupture of the aneurysm.

Conventionally, these aneurysms are treated with open surgery via the abdomen. Recently, a minimally-invasive technique has been introduced for the endovascular placement of an aortic prosthesis via the femoral arteries.

[1] The MATEO project means: "Computers-aided Endovascular Arterial and Therapeutic Modelling"

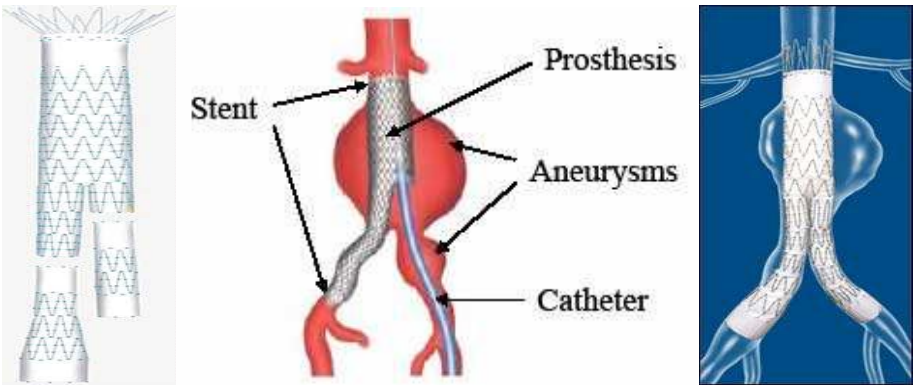
Minimally invasive endovascular interventions differ in a couple of aspects from conventional vascular surgery:

- There is no direct visual feedback during an intervention: feedback is provided by intra-operative X-Ray images;
- There is no direct manipulation of the instruments. The intervention is performed by manipulating parts of the instruments that are outside the body.

In order to assist the surgeon in the prosthesis delivering, the first step in the MATEO project has allowed realising a prototype in scale 1 (Fig. 1) of a new surgical instrument of active catheter type. The latter is a flexible device with elastic bellows deformation based on active compliance, in order to increase the dexterity of the surgeon. More details on the micro-robot control are given in [1, 2].

Fig. 1. Experimental device in scale 1.

The principle of the treatment is to insert a catheter containing an auto-expansible prosthesis into the body through a small incision in the femoral artery. Under radioscopic control, this catheter is directed through the arteries to the place of the aneurysm then it is placed inside it. Withdrawal of the catheter allows expanding of the prosthesis that will settle level to the superior and lower aneurysm collar, excluding therefore the aneurismal pocket from blood pressure and thus avoiding its extension [3]. Fig. 2 shows the prosthesis delivering process in AAA endovascular procedures.



(a) (b) (c)

Fig. 2. (a): Prosthesis, (b): Prosthesis delivering procedure, (c): Final disposition of the prosthesis.

In order to successfully carry out these procedures, proper training is required. Simulating minimally invasive interventions for training has a number of attractive properties. The simulation can be made patient specific. The simulation of surgical procedures has been the interest of a variety of research groups. Progress in this field has been made over the last few years, including simulation of the brain's intravascular interventions [4, 5, 6, 7]. Endovascular interventions are performed through catherization. To simulate these interventions, some steps need to be performed:

- Modelling the required patient information from 3D data. To this end tissue types, composed by various structures with different mechanical properties, need to be modelled (the vasculature, soft tissue and bone structure);
- Modelling the interaction between the patient organ and the instruments (catheter, guide wire) used during an intervention.

In this paper we focus on the interactive surgical system dedicated to mini-invasive endovascular intervention. The outline of this paper is as follows. The section two presents some issues of the deformation modelling and our adopted method to mimic the deformation of soft biological tissues in interactive haptic simulation. In section three, interactive simulation of endovascular procedures is described. The physical setup and the software support of computer- and robot-assisted endovascular system are presented. Finally, the needs of the clinical users are analyzed with respect to the various steps involved in image guided surgery (pre-operative imaging, pre-operative planning, intra-operative navigation and intra-operative prosthesis delivering). Moreover, a virtual guidance technique is proposed in order to increase the precision and the safety of the surgeon gesture. In section four, simulations and performances analysis are given. Finally, we conclude and give some perspectives in the last section.

Dynamic Simulation Environment of Patient Organ and Surgical Instruments

The advanced simulation environments design requires accurate modelling at the geometrical, physical and physiological levels. It takes into account many fields of science and engineering, including medicine, medical imaging, computer vision, numerical analysis, biomechanics, bio-rheology and robotics.

The biological tissue's mechanical deformation modelling constitutes an essential part of surgery simulation [8, 9]. It runs up against two fundamental and antagonistic constraints: realism of numerical modelling and computation speed.

The main features of an advanced surgery simulation environment can be summarised as follows:

1. High precision of 3d-data acquisition is accomplished by medical imaging and/or vision systems. A pre-treatment extracts the anatomical structures and creates geometrical models;
2. Accuracy of deformation modelling of the biological tissues and surgical tools, allowing the surgeon to modify geometry and topology of various Virtual Environment "VE" objects for incisions simulating, tissues repositioning, transplantation, cutting, perforation, etc;
3. Continuous collision detection algorithm between deformable and/or rigid VE objects and contact-friction management;
4. Realism by haptic rendering synthesis (contact efforts of medical tools and biological tissues), and real-time insuring (Parallel computing), using adequate interaction devices to feel the haptic sensations met in a conventional surgery are required;
5. Specific problems for some interventions: assistance by Virtual Fixtures during navigation of tools in hollow bodies, in order to improve the precision and the security of the operative gesture, particularly at the time of guidance and placement of the surgical tools.

Thus, the design of a surgery simulation environment requires finding a compromise between complexity of the adopted models and fast calculation of the algorithms. In this paper, we will focus on the deformation modelling stage by taking into account four main constraints:

1. accurate geometrical and mechanical models of the human body organs;
2. fast calculation algorithms able to use these models in the simulation loops running in real-time;
3. complex behaviours of biological tissues, showing nonlinear, viscoelastic, anisotropic and inhomogeneous behaviours obtained through in-vivo experimentation;
4. the possibility to allow topological changes (cutting, tearing, perforation...) which can occur during the surgical process.

Deformation Modelling Problems. Surgical simulator design requires precise geometric and physical models of the human body organs and fast computation algorithms to implement these models under real-time constraints. The earlier simulators had been developed for navigation within 3d-anatomical data bases and found many applications in education and training. These simulators used only geometrical models for the anatomical structures, without taking into account their physical reality. Therefore, new simulators have been proposed in order to overcome the drawbacks cited above, by using more realistic physical modelling of the various anatomical structures and their interactions [10, 11]. Taking into account the physical phenomena should not only allow to improve quality of the medical simulators, but also to widen considerably their field of application.

The real-time constraint is essential for surgery simulation systems. It has been shown that the immersion of the operator and thus its capacity of training are directly related to the simulator update frequency [8]. For graphic rendering, the acceptable frequencies are about 25-60 Hz, while for the haptic rendering they go up to 300-1000 Hz. It is significant to keep a short latency time, as well as minimizing computation time. The first constraint depends primarily on the communications speed between the various elements of the acquisition system, while the second depends on the complexity of the geometrical and physical models and the calculation algorithms.

Real-time computation of nonlinear elastic mechanical deformations is an active research area. We can distinguish two great communities. On the one hand the biomechanics community is interested into the precise characterization of the behaviour laws of biological tissues, but without being concerned about computation time. On the other hand, the computer graphics expert's community is committed to the development of deformable objects simulators for biomedical applications, but adopts very simple mechanical models, in generally linear elastic ones, and without being concerned about matching these mechanical models to the experimental behaviour of biological tissues.

Recently, some groups [12, 13, 14, 15] tried to join together these two fields and proposed approaches aiming towards simulation of more complex behaviours, and closer to real biological tissues. Our work joints the same point of view by proposing an approach which is sufficiently simple and quick to be compatible with real-time applications and try to reproduce, as exact as possible, the real biological tissue behaviour obtained by biomechanical experimentation.

Real-time Interactive Navigation. The conception of surgery simulation requires finding a compromise between the complexity of the adopted models (realism) and the computation time (real-time).

The surgeon's assistance for pre-operative, as well as for intra-operative gestures, requires both a real-time realistic visualization (soft tissue deformation modelling) and force feeling (haptic rendering interface).

The goal of a medical simulator is to allow real-time interactions with realistic modelling. It is well known that during a simulation, given any physical model, the most difficult aspects, in terms of computational time or updating data structures, are collision detection, the different rates for haptic interaction between graphical updates and physical simulation and topology modification during specific surgical procedures.

Haptic systems gives people the sensation of touching objects in virtual environments or teleoperation applications. Including haptic technology improves the perception of a surgeon leading to a deeper sense of immersion [16]. Many problems arise in haptic applications especially in the case of deformable objects manipulation, for instance computational time, numerical instability in the integration of the body dynamics, time delays, etc. Lengthy computations are forbidden in haptic systems which need high simulation rates (about 300 Hz to 1 KHz) to obtain realistic force feedback. The update rates of the physical objects being simulated is normally of the order of 25 to 60 Hz. This difference in simulation rates can cause an oscillatory behaviour in the haptic device that can become highly unstable [17]. Several numerical approaches [18] have been proposed to solve the difference rate problem.

For our purpose, the objective is to develop robust and rapid algorithms which allow haptics feedback for deformable objects. The reaction calculation is ensured by a compliance method (interaction between a flexible or rigid body, the surgical tool for instance, and deformable body as soft biological tissues).

The reaction force ($\vec{F}_c$) is calculated using the minimal distance dist between the local model (soft biological tissue) and the haptic tool.

Thus, the force vector $\vec{F}_c$ is given by:

$$\vec{F}_c = \begin{cases} -k \cdot dist \cdot \vec{n} - b \cdot (\vec{v} \cdot \vec{n}) \cdot \vec{n} & if\ dist < 0 \\ \vec{0} & otherwise. \end{cases} \quad (1)$$

Where k is the rigidity coefficient, b is a damping coefficient, *dist* is the penetration depth between the two bodies, $\vec{v}$ is the relative linear velocity of these two objects at collision. $\vec{n}$ is the normal direction of contact.

Simulation of Endovascular Procedures

The execution of endovascular procedures requires good eye-hand coordination, appreciation of fluoroscopic imaging in three dimensions and through knowledge of vasculature and pathological conditions. Pre-treatment planning and training of endovascular intervention can be facilitated by using simulators. These procedures are particularly well suited for simulation because they already place the physician at a distance from the operative site while manipulating instruments and viewing procedures on video monitors. The development of a computer simulator for endovascular intervention is a challenging task. This kind of simulator should have standard generic features such as realism, interactivity, user friendliness. Such simulator requires also various advanced methods for the following functionalities: filtration and enhancement of angiographic data, vasculature segmentation and feature extraction, quantification of normal and pathological vasculature, geometric modelling and meshing of vasculature, physical modelling of vasculature and interventional devices, hemodynamic analysis, device-vessel interaction analysis, visualization, and haptic feedback. In addition, for the specific clinical procedure (endovascular), considered in this paper, angioplasty and stent placement must be addressed.

EVARSim Description. We have developed a real-time, interactive, simulation based planning and training system for endovascular repair of abdominal aortic aneurysm called EVARSim (EndoVascular abdominal aortic Aneurysm Repair Simulator) [2, 19]. The EVARSim supports:

1. Extraction of vasculature from various imaging modalities and construction of a vascular model that represents the anatomy of patient in a computationally efficient manner;
2. Physics-based deformable models describing biomechanics behaviour of the aorta aneurysm (vessel with pathology) and the active-catheter (intervention device);
3. Collision detection and contact-friction management between the device and the aorta aneurysm;
4. Haptic rendering, achieved through a mechanical interface with force-feedback [20] respecting the ergonomics of the intervention instruments (compliant micro-robot, active-catheter) and allowing the surgeon sensing during intervention planning and training.

In a computer- and robot-aided surgery system, two approaches adopting different points of view may be considered. While the first one [21] is centred on medical data, the second one [22] takes into account the use of the system by the surgeon. The complementary of these approaches constitutes a "Perception-Reasoning-Action" loop.

In [2], we describe our proposed computer- and robot aided endovascular system. This architecture describes all the steps which are necessary for real-time practice operative gesture of the endovascular procedure.

The software support of the EVARSim contains a visual user interface with three synchronized windows (global viewer, local viewer and control panel as shown in Fig. 3).

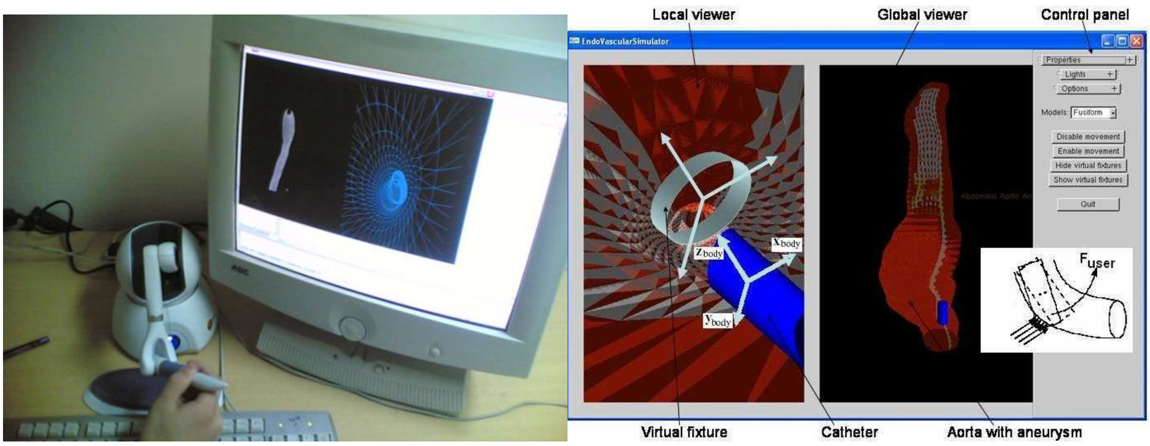
The global viewer provides an exocentric viewpoint of the training environment. It gives an overall view of the whole vessel and the position of the surgical tool. In this viewer, distance measurement on the 3D model of the aorta can be performed. The local viewer provides an egocentric view of the training environment. In this viewer, the viewpoint is placed in the current position of the tip of the surgical tool with the current orientation, providing an endoscopic view of the vessel. Finally, the control panel allows distance tool manipulation and AAA shapes (fusiform, cylindroid or saccular) selection.

Fig. 3 shows the basic visual-haptic platform. It has been implemented using OpenGL/OpenHaptics library and it provides force feedback through means of a haptic interface of type 6 dof PHANToM Omni.

Surgeon's Needs in Endovascular Intervention. The needs of the clinical users were analyzed with respect to the various step involved in image-guided surgery (pre-operative imaging, pre-operative planning, intra-operative navigation and intra-operative prosthesis delivering).

For patients satisfying some selection criteria [3], the minimally-invasive endovascular procedure can replace the rather invasive conventional procedure in which the abdomen is completely opened to replace the aorta by prosthesis. A careful pre-operative planning is necessary to see whether the patient satisfies the selection criteria, to evaluate the suitability of the access trajectory and to determine the dimensions of the required endoprosthesis. We have also evaluated whether intra-operative surgical guidance could improve the accuracy of positioning the prosthesis as planned.

For pre-operative planning, patient-specific models have to be reconstructed. After loading the patient-specific data and extracting the vascular model, the surgeon sets the size and shape of catheter and/or guide-wire to be used for intervention.



(a) (b)

Fig. 3. (a): Haptic interaction device, (b): The software support of the EVARSim system.

A devices library, including catheters, guide-wires and stents from various manufacturers, can be used into the EVARSim. Next, the surgeon sets the insertion/entry point. In order to improve the precision and the security of the intra-operative gesture, particularly at the time of the prosthesis delivering, we propose an approach using virtual reality-based techniques associated with virtual guide metaphors concept i.e. "Virtual Fixtures". Thus, graphical aid tools are proposed, beside the robotics aid tools (compliant micro-robot), in order to improve the intra-operative gesture.

Two kinds of virtual guide are used:

- The navigation guide to take into account the displacement of the active-catheter in the blood vessels. A force feedback is computed from a virtual force field in order to feel contacts with the aorta wall. In addition, such a guide generates, for the surgeon, a nominal trajectory under some constraints (manoeuvrability and reachable workspace of the active-catheter). This feature is particularly useful in the case of the presence of highly sinuous arteries;
- The delivering guide to increase the surgeon's performances at the time of the prosthesis delivering.

More details on tasks analysis and requirements of endovascular technique are provided in [2].

Simulations Results

The real-time graphic environment is implemented in C++ using the OpenGL library. Our simulator is also based on the GLUT library and basic GLUI features for building useful applications and providing joystick support. For the D-FEM, mesh is done using the GiD software. The EVARSim simulator is running on a 2.8 Ghz Pentium IV station with a graphic card equipped with the GeForce 6600 GT processor.

The dynamic simulator and the haptic interface are designed as independent processes and connected via a local model.

Fig. 4 describes the main functionalities of the EVARSim simulator namely (modelling, interaction and navigation) as well as the methodological and algorithmic tools necessary to its implementation (finite element method, cartography and potential field).

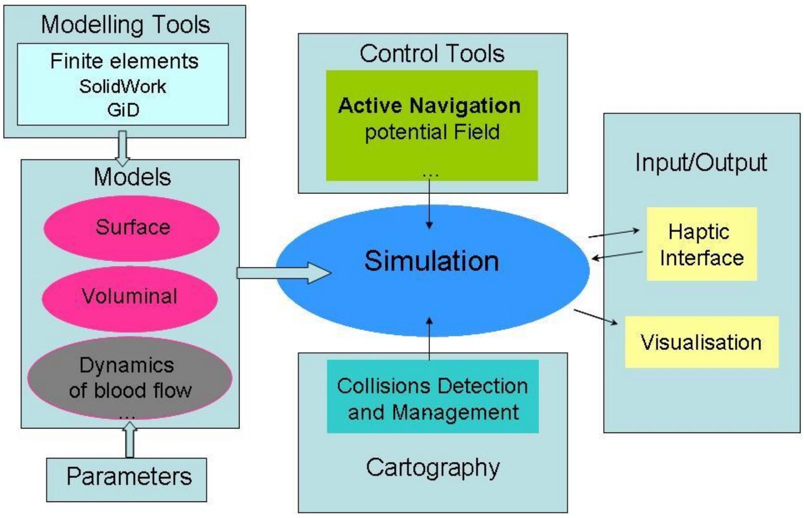


Fig. 4. Global architecture of the EVARSim system.

Within sight of their properties, the modelling of soft tissues is primarily based on the theory of continuum mechanics from the experimentation laws. There are two types of representation of deformable structures under real-time constraint: surface and volumetric. Their use depends on the type of tool-tissue interaction to simulate [24]. In the surface representation, objects are described by only information of surface. It is about the most current form in computer graphics where dedicated processors allow rendering, handling and updating of surfaces in real-time [24].

For training simulators, for example, where one of the main criteria of performance is the computing time, the surface representation proves much more effective and was largely used [25]. The surface representation is limited when it is a question of modelling more complex non-homogeneous structures in their internal configuration. As example, the modelling of fluids or tissue cutting cannot be considered [26].

We chose the surface model to represent the hollow bodies (aorta and arteries), because in our case, this situation does not require a volumetric deformable model because of the tools of navigation control, i.e. virtual guides. On the other hand, the surgical tools (catheter, guide wire, micro-robot) are modelled by a volumetric model.

For the soft biological tissues modelling, we must deal with mechanical deformation of the aortic aneurysm tissues under contact with the catheter. These tissues present complex behaviours, showing viscoelasticity and anisotropy among other things. In [23], the authors provide rare experimental data on the aneurysm behaviour.

The interaction includes the detection/management of the collisions and the haptic rendering in the virtual environment. Active navigation is considered as a tool for assistance to the realization of the intra-operative gestures during the endovascular interventions. This assistance solution is ensured by the metaphors of virtual guides (Virtual Fixture). The latter does not relate only to the visual aspects but are extended to the haptic aspects by the installation of haptic guides by potential field technique or by calculation of deformation force in the contact case.

The main results, given here, concern the performances and the computational efficiency of our approach. Several simulations were conducted with several meshes (different number of surfaces elements). The results show that the constraint of restitution time of the interaction effort (haptic rendering) remains respected until an aorta mesh with 6000 surfaces elements.

The dynamic simulator carries out the physical simulation, collision detection and the graphical rendering of different deformable objects in the virtual environment. It receives the haptic position from the PHANToM (and eventually, the distance between the haptic point and the local model) and sends to the haptic process the different parameters (i.e. set of colliding facets between the deformable virtual object and the tool) to update the local model. This update process is repeated at a rate of 30 Hz.

We plan to integrate the dynamics of blood flow in the simulator in order to study its influence on the distal end of active catheter which progresses in the light of the arteries. We consider blood flow as disturbances on the active catheter which it is necessary to take them into account when designing robust control for the catheter trajectory.

Conclusion

In this paper, EVARSim, a virtual reality endovascular procedures system used to treat AAA, has been presented. This system aimed at educating the novice specialist, by using the system as a simulator or guiding the expert surgeon, by using the system as a 3D navigation system.

We have addressed some important issues in the conception of a realistic virtual medical simulator. Some important aspects have been presented, in order to ensure real-time computation with realistic biomechanical modelling and haptic interaction modelling. For surgeon assistance, two kinds of virtual guides are proposed: the navigation guide for the displacement of the active-catheter in the blood vessels and the prosthesis delivering guide for the precise orientation guidance of the active-catheter.

The development of the EVARSim is in progress. Realistic modelling of pathology will be enhanced in visual and haptic senses. In addition, a hemodynamic model will be developed for blood flow simulation and its interaction with the devices.

Our next step is to present clinical meaning of EVARSim experiments tests with novice and expert physicians to evaluate the practical added value of EVARSim. We plan to compare the accuracy, efficiency and required time for a variety of endovascular tasks by a various surgeons with and without EVARSim.

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