Proceedings of the 5th WSEAS Int. Conf. on Signal Processing, Robotics and Automation, Madrid, Spain, February 15-17, 2006 (pp135-140)

A Training Simulator for the Angioplasty Intervention with a Web Portal for the Virtual Environment Searching

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Abstract - One of the essential requirements of a realistic surgical simulator is to reproduce haptic sensations due to the interactions in the virtual environment. However, the interaction need to be performed in real-time, since a delay between the user action and the system reaction reduces the immersion sensation. In this paper, a prototype of a coronary stent implant simulator is present; this system allows real-time interactions with an artery by means of a specific haptic device. The user can interactively navigate in a reconstructed artery and the force feedback is produced when contact occurs between the artery walls and the medical instruments. In order to obtain a realistic simulation, the Finite Element Method has been used to model the artery soft tissues, but several simplifications have been introduced to reduce the computational time and to speed up the interaction rate. The building of the virtual environment is based on real patients' images and a Web Portal is used to search in the geographically remote medical centres a virtual environment with specific features in terms of pathology or anatomy; this information are included in the metadata associated with the virtual environment.

Key-Words: - Surgical Simulator, Virtual Environment, Haptic Interface, Real-Time Interaction, Physical Modelling, Web Portal

1 Introduction

Virtual reality technology brings numerous advantages to the medical community including improved surgical training. With the continuously increasing speed of computers, surgical simulators are now being offered to hospitals as a mean of improving training and reducing the costs of education. Some simulators are based on phantoms (e.g. plastic structures) and others are virtual reality based simulators.

Although phantoms may provide realism with regard to tissue behaviour, computer based simulators will increasingly become more eligible as a training aid, especially due to their extensive range of educational features. By means of this kind of simulator it is possible to model unusual and rare cases and to practise new procedures avoiding risk for real patients; in addition it is possible to have objective measures of surgical skill. Many minimally invasive procedures need to be learned by repetition; using a real cadaver, in case of a mistake, a given procedure cannot be repeated because the body organs are altered.

Realism and real-time interactions are the essential features for surgery simulators in order to be used as training systems. The realism of the simulation strictly depends on the accuracy of the human tissue modelling and on the use of force feedback devices. Therefore, the most critical issues in designing surgical simulators are accuracy - the simulator should generate visual and haptic sensations very close to the reality - and efficiency - deformations must be rendered in real-time on the graphic display.

Accuracy and efficiency are two opposite requirements; in fact, increased accuracy implies higher computational time and vice versa. So, it is necessary to find a trade-off according to the application. For surgery training, real-time visual and haptic feedbacks are more important than deformation accuracy. However, substantial differences between the real and the virtual deformations may lead to a wrong learning of the procedure.

This work takes into account the results of the HERMES (HEmatology Research virtual MEdical System) Project managed by Consorzio CETMA, Brindisi, Italy; the aim of this project is to build the first prototype of a training system to simulate the coronary stent implant procedure. In this work, we have mainly focused on the real-time constraint and on the accuracy of the interactions in the virtual environment rather than on the visual accuracy. The developed system is provided with a haptic interface and the collision detection and response algorithm, designed exploiting the coronary stent implant features, it allows the user to interactively navigate in the artery and to produce a force feedback when a contact occurs.

In the HERMES simulator the virtual artery model is constructed using anatomical model described in the medical literature and, for this reason, it is not enough realistic.

It is very important that a Training Centre can carry out the same surgical procedure on a variety of different case studies, studies which differ in terms of the pathology, the anatomical structure and the patient's age, so that they correspond to several virtual patients, each of them exhibiting a particular difficulty. For this reason, afterwards we decided to build the virtual environment based on real patients' images. Many virtual environments can be stored in geographically remote medical centres and, using a Web Portal, it is possible to search a virtual environment with specific features in terms of pathology or anatomy.

2 Related Works

Several simulators have been developed for training on a specific procedure.

Dawson et al. [1] present an interventional cardiology training system conducted at Mitsubishi Electric Research Lab, in collaboration with CIMIT and the Massachusetts General Hospital. The system simulates the physics and physiology of the human cardiovascular system; it is interfaced with a haptic interface that measures catheter translation and rotation and independently controlled servomotors produce force and torque resistance.

Gobetti et al. [2] present an experimental catheter insertion system supporting head-tracked stereoscopic viewing of volumetric reconstruction registered with direct haptic 3D interaction. The system takes as input patient data acquired with standard medical imaging modalities and regards it as a visual and haptic environment whose parameters are defined using look-up tables. By means of a mirror, the screen seems to be positioned like a surgical table giving the impression of looking down at the patient in a natural way. During the insertion procedure the system provides perception of the force of penetration and positional deviation of the inserted catheter.

Urbino et al. [3] present the CathSim intravascular catheterization simulator with a special-purpose haptic interface called AccuTouch. The CathSim system combines cognitive and motor skills training into an integrated learning experience.

The Swedish Mentice Corporation [4] is a supplier of several virtual reality based applications regarding minimally invasive surgery. An example of their products in the cardiology field is the VIST system. It allows a high realistic simulation for training in angiography and angioplasty.

3 Architecture of the Simulator

The coronary stent is a relatively new tool used to keep coronary arteries expanded. The arteries become narrow and this disease reduces blood flow to the heart muscle. The primary cause of coronary artery disease is fat deposits blocking the arteries. By forming a rigid support, the stent can prevent restenosis and reduce the need for coronary bypass surgery. The stent catheter is threaded into the artery and the stent is placed around a deflated balloon. When this is correctly positioned in the coronary artery, the balloon is inflated, expanding the stent against the walls of the coronary artery. The balloon catheter is removed, leaving the stent in place to hold the coronary artery open.

Therefore, a realistic stent implant simulator has to accurately model the anatomy of the human coronary artery and provide a real-time tissue-tools interaction and a fair force feedback by means of the haptic device.

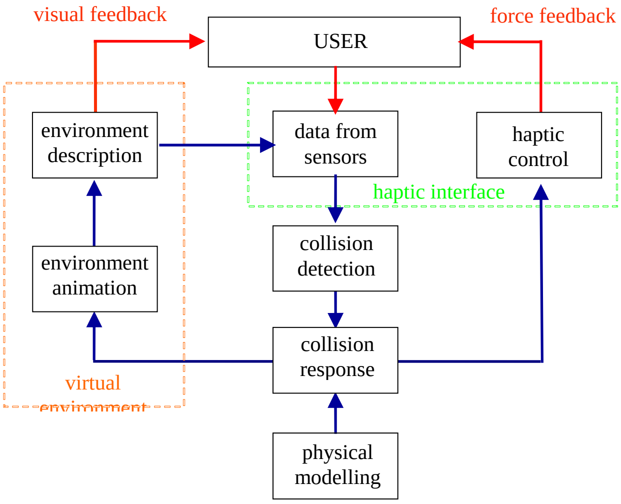

Fig. 1: Architecture for the simulator

Fig. 1 shows the proposed architecture for the simulator. The user interacts with the simulator using a haptic interface. Data acquired from the haptic device sensors are used both to graphically represent the surgical instruments and their positions in the virtual environment and to determine possible collisions between the virtual objects. Movements of the haptic device lead to changes in the virtual scene.

Collisions between virtual objects produce both forces, which have to be replicated on the user's hand by the haptic interface, and virtual organs deformations, which have to be rendered by the visual interface. In particular, the force computation and organ deformation strictly depend on the physical model which describes the mechanical properties of the virtual bodies.

In order to have a realistic simulation, a physical modelling that describes the mechanical properties of the real body and its deformations has been included.

4 Haptic Rendering Algorithms

The haptic rendering algorithm is made of two parts: collision detection and collision response. As a user manipulates the probe of the haptic device, the new position and the orientation of the haptic probe are acquired and collisions with the virtual artery wall are detected. If a collision is detects, the interaction forces are computed using pre-programmed rules for the collision response and conveyed to the user through the haptic device. The collision detection and the collision response algorithms have to guarantee a stable interaction with the force feedback device [5], [6].

In the first version of the coronary stent implant simulator we addressed the real-time constraint, which imposes a very high frequency in contact determination and force computation. To achieve this aim, the virtual objects involved in the simulation (artery and surgical instruments) were considered as rigid bodies.

The system provides the user with a haptic interface which realistically reproduces the real surgical tools, in order to feel the forces generated during the interaction. In fact, force feedback is the main requirement for the cardiologist who executes this surgical procedure. The computation of the force replicated by the haptic interface is based on the penetration distance [7].

Fig. 2 shows the steps followed by the simulator to provide the force sensations generated during a real-time interaction with an artery.

Furthermore, the artery is a soft tissue with visco-elastic behaviour; this means that they elastically change their shape because of the contact with the catheter. In order to have a realistic simulation, a physical modelling that describes the mechanical properties of the real body and its deformations has been included. Information about the tissue responses are used to graphically model the artery wall deformations in consequence of the contacts with the catheter.

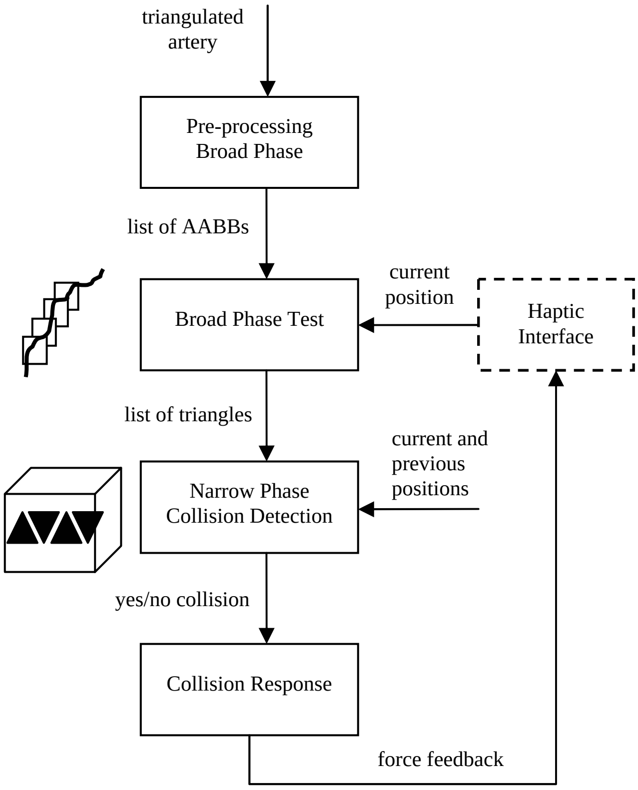

Fig. 2: The force feedback in a real-time interaction

The Finite Element Method (FEM) has been used, but several simplifications have been introduced to reduce the computational time and to speed up the interaction rate [8]. This method is based on the linearity theory and on the superposition principle. Interactive rates of deformation can be obtained in a two-steps process:

- a pre-processing stage performed off-line and used to compute a set of elementary deformations of the model;
- a real-time stage where each deformation is computed as a linear combination of previous pre-computed ones.

The pre-processing stage can take from a few minutes to several hours; this depends on the model size and the desired accuracy level. The pre-processing stage needs to be performed only once for a given model and the result can be saved for further simulations.

Some tests have been performed in order to verify the time that is necessary to carry out the off-line and the real-time elaboration in relation to the complexity of the model and the desired accuracy level. As the model complexity increases, the FEM requires longer computation times for the pre-processing stage, but the time required for the real-time elaboration remains sufficiently low and it allows to obtain interactions without perceptible delay.

5 HERMES Haptic Device

An interactive environment should be able to get the result of the manipulation like a visual-kinaesthetic interaction, very similar to the eye-hand coordination required in the real situation. Moreover, the haptic device has to be able to reproduce, without distortion, the sensations associated with the interaction in the virtual environment; in addition the workspace has not be reduced by mechanical constraints.

In order to achieve a realistic simulation, no commercially available haptic device has been used, but the interface has been planed ad hoc for the coronary stent implant simulation.

The HERMES haptic interface has been designed and built at the PERCRO Laboratory of Scuola Superiore S. Anna of Pisa, Italy; this device reproduces the real shape and dimension of the surgical tools used in the stent implant procedure, allowing the user to interact in a more natural way [9]. This device, provided with two degrees of freedom controlled by means of motors that produce force and torque resistance, responds to the following user applied forces:

- the longitudinal forces in the form of push and pull movements;
- the torque forces in the form of twisting around the longitudinal axis.

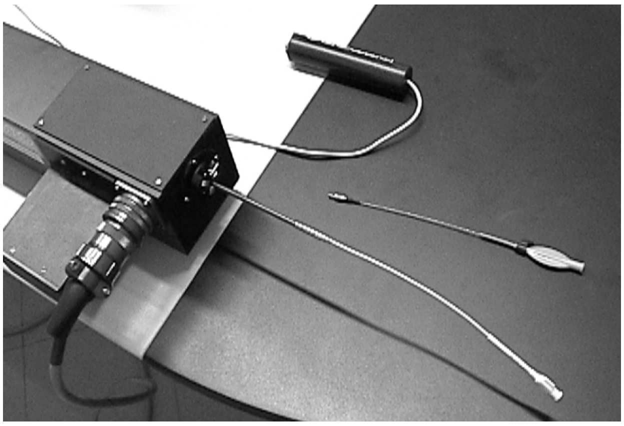

Fig. 3: The HERMES haptic device

The device can generate any combination of the two following components of force:

- an axial force directed along the cylinder axis;
- a torsional moment directed along the cylinder axis.

Data acquired from haptic device sensors are used to represent the surgical instrument position in the virtual environment and to determine possible collisions between the virtual objects.

Fig. 3 shows the HERMES haptic device.

6 HERMES Virtual Environment

In the HERMES project the virtual arteries model is built using anatomical models described in medical literature and refined in collaboration with cardiologist.

The system allows students to practice the stent implant using different case studies, corresponding to virtual patients, each of them exhibits a particular difficulty depending on the different artery geometry and the number and type of stenosis.

The rendering software, developed at the CETMA Consorzio, has been realized on a LINUX platform, using MOTIF for the building of the graphic user interface and OpenGL Performer as a rendering engine for the virtual reconstruction of the 3D scene. The software architecture is based on a classic multi-process application. In particular, it consists of three processes: the first one is dedicated to the management of the events generated from the interaction of the user with the GUI, the second one concerns the management and the data exchange between the haptic device and the virtual environment and the third process concerns the rendering of the virtual scene.

All the phases of the coronary stent implant are simulated.

7 Virtual Environment Built from Real Patient's Images

Recently, the use of digital images for medical diagnosis has increased considerably. New and better applications are therefore needed in order to effectively manage such information.

To build a virtual environment from real patients' images, the geometric models of the human organs have been reconstructed using data acquired by a CT scanner; data are processed to distinguish the anatomical structures and to associate different chromatic scales to the organs. In order to carry out a high quality recognition of the tissues it is necessary to use the correlative information obtained in the three acquisition phases. Due to the distortion produced by the movement of the organs, the three images have to be aligned, using a morphing algorithm, and then recognized, using a clustering algorithm.

Multi-spectral classification uses registered 3D image volumes from more than one imaging modality or from different sequences within a modality to classify tissues within those volumes.

The complementary information contained within the different image volumes may allow for the separation of tissue class types.

The segmentation and classification phases are carried out in order to obtain information about the size and the shape of the human organs

A Region Growing Algorithm has been used in the segmentation phase; whereas the classification phase is a user-driven process [10]. In order to obtain the triangulated model of the organs, the Marching Cubes Algorithm has been used [11].

The data processing procedure is performed in an off-line phase before starting the real-time simulation.

8 Virtual Environment Searching

We are developing a service-oriented architecture that wraps virtual medical environments and data applications as Web services. These services are capable of satisfying multiple client requests at the same time.

Our idea is to obtain a virtual environment based on real patients' images and to use a Web Portal to search a virtual environment with specific features in terms of pathology or anatomy.

The virtual environment is located in geographically remote medical centres and is downloaded on the training centre in order to be integrated in the local simulator; this happens independently of the medical centre where the data has been generated.

The proposed system, shown in Fig. 4, exploits a 3-tiers architecture [12]:

- the **trainee tier** where the search starts using a browser and the decompression of the virtual environment happens;
- the **middle tier** where the web portal is located with the list of metadata;
- the **back-end** where the building of the virtual environment is carried out and the data repository is located.

Due to the complexity of the data stored in the medical centre databases, the searching of the desired virtual environment is based on the descriptive information stored with the data (metadata). Virtual environments are saved on a database with the relevant metadata.

The main components of the system are:

- the **Training Centre** where the user can perform training on the different surgical procedures and where the specific haptic device is available;
- the **Data Gather Server** where metadata of the virtual environments present in the different medical centres are collected;
- the **Medical Centre** which provides the access to the local Data Repository where the different virtual environments are physically contained with the relevant metadata.

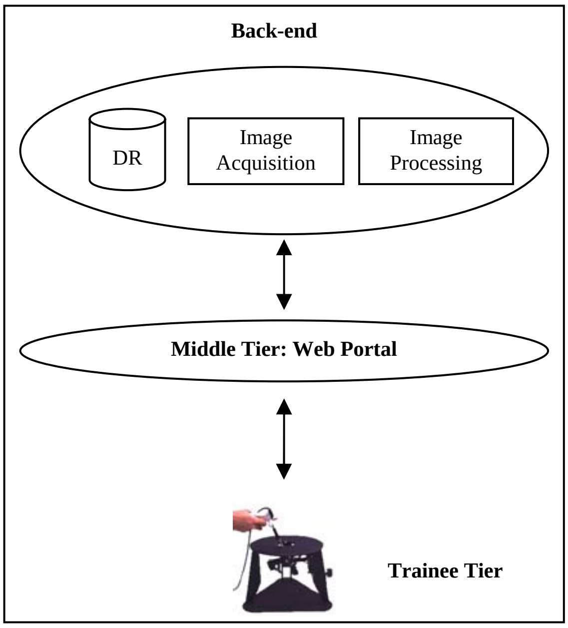

Fig. 4: The proposed 3-tier architecture

The functional architecture of the system defines several Medical Centres in which virtual environments built from the real patients' images and related metadata with specific features in terms of pathology or anatomy are stored. An updated list of the metadata is present on the web portal and indicates the Medical Centre where the virtual environment is stored.

The searched data are downloaded from the Medical Centre to the Training Centre using a compression technique based on Edgebreaker algorithm, which is a method for compressing 3D data sets and specifically triangle meshes.

Each Training Centre is provided with a specific haptic device and with the software necessary both to manage the interaction in the virtual environment (collision detection and response algorithms) and to obtain realistic deformations of the organs (physical modelling algorithm).

After the integration of the virtual environment in the simulation system it is possible to perform training on the specific surgical procedure.

The web portal interacts with the Medical Centres using the Web Services technology, the fundamental building blocks in Internet distributed computing [13]. In this way the data exchange between Medical Centres and web portal occurs automatically when new data are generated in a Medical Centre; these data are collected in a centralized database examined from the web portal.

The implementation details of the service are hidden, so the services can be used on a platform-independent basis. A descriptive information of the virtual environment (metadata) is defined using the XML technology and it is stored with the data.

9 Conclusions and Future Work

The results of the HERMES Project are presented and a first attempt to interact with a reconstructed artery is described. In order to perform a realistic training on the coronary stent implant procedure an ad hoc haptic interface has been designed and built for this kind of surgical operation. The HERMES haptic interface is provided with two degrees of freedom and the simulation guarantees real-time interactions. In this project we mainly focused on the real-time constraint and on the accuracy of the interactions in the virtual environment rather than on visual accuracy.

Afterwards, in order to have a more realistic simulator, a physical model that describes the artery deformations has been included and a 3-tier architecture able to look for a virtual environment with specific features in terms of pathology or anatomy has bee designed.

The virtual environment, built from real patients' images, and the relevant metadata are stored in the medical centres and it can be searched using a Web Portal. After downloading from the medical centre, the virtual environment can be integrated in the surgical simulator to perform training on the cathetering procedure.

The building of the web portal and a more accurate definition of the specific metadata are in progress.

Future work concerns the adopt a correct security policy to exchange data between the training and the medical centres.

At the end the platform must be validated in collaboration with physicians.

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