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An Angioplasty Intervention Simulator with a Specific Virtual Environment

G. Aloisio, L. T. De Paolis, A. De Mauro, and A. Mongelli

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. To improve the realism of the simulation, 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. 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. The searched data are downloaded from the Medical Centre to the Training Centre provided with a specific haptic device and with the software necessary both to manage the interaction in the virtual environment. After the integration of the virtual environment in the simulation system it is possible to perform training on the specific surgical procedure.

Keywords**—**Medical Simulation, Web Portal, Virtual Reality.

I. 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.

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.

Giovanni Aloisio is with the Department of Innovation Engineering - University of Lecce & SPACI Consortium (Southern Partnership for Advanced Computational Infrastructure), 73100 Lecce, Italy.

Lucio T. De Paolis is with the Department of Innovation Engineering - University of Lecce & SPACI Consortium (Southern Partnership for Advanced Computational Infrastructure), 73100 Lecce, Italy.

Alessandro De Mauro is with the Department of Innovation Engineering - University of Lecce, 73100 Lecce, Italy.

Antonio Mongelli is with the Department of Innovation Engineering - University of Lecce, 73100 Lecce, Italy.

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 some 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 [10]. In the HERMES simulator 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 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.

II. 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 that takes as input patient data acquired with standard medical imaging modalities. 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.

The Immersion Medical, Inc. has developed comprehensive simulation platforms for vascular access and phlebotomy, bronchoscopy, stenting procedures, hysteroscopy and laparoscopic abdominal procedures. The Endovascular AccuTouch® Simulator allows clinicians to practice endovascular procedures such as PTCA, Stenting, and Cardiac Pacing. The system, which simulates the look and feel of actual procedures, helps clinicians to develop skills prior to performing on patients and to maintain those skills throughout their professional practice [3], [4].

The Swedish Mentice Corporation is a supplier of several virtual reality based applications with special attention to the minimally invasive surgery and the endovascular interventions. The Procedicus VIST, a vascular intervention system trainer, reproduces the physics and physiology of the human cardiovascular system for training various procedures such as cardiac catheterization, stenting and pacemaker lead placement. The simulator combines the software simulation, the haptic interface and two monitors, one for the synthetic x-ray and one for the instructional system. Real patient's data are used to generate the simulated patient cases; modules replicating the hemodynamics, blood flow and contrast medium mixing are provided [5].

Several projects deal with developing data management architectures using the web services technologies.

The Biomedical Informatics Research Network (BIRN) creates a long term and robust infrastructure for data sharing and collaboration in biomedical science on a large scale (15 Universities and 22 Research Groups connected through Internet2). A processing pipeline has been developed to analyze and mine MR images acquired at multiple sites using processing and visualization tools developed at multiple sites [6].

At ICM (Interdisciplinary Centre for Mathematical and Computational Modelling), Warsaw University, Poland, a general framework for implementing a wide range of user applications has been developed; in order to support users with dedicated biomolecular services, a BioGRID portal that provides information on resources available, together with description of models, codes and links to most relevant related materials, has been set up and it is being further developed [7].

The European Grid of Solar Observations (EGSO) is employing the grid computing concepts to federate heterogeneous solar data archives into a single virtual archive, allowing scientists to easily locate and retrieve particular data set within the grid. The web services have been used in EGSO as a means of communicating between the various roles in the system [8].

Liu et al. have developed an unified referral information system in which patient care records can be shared among hospitals over the Internet. The XML-based medical records enable a computer to capture the meaning and structure of the document on the web [9].

III. The Angioplasty 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.

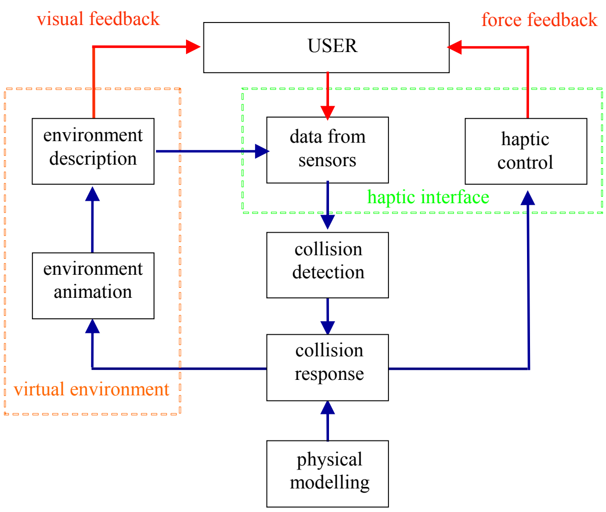

Fig. 1 Scheme of the simulator

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 shows the scheme of 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 [13].

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 S. Anna of Pisa, Italy [10], [11], [12]; this device reproduces the real shape and dimension of the surgical tools used in the stent implant procedure, and is 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.

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. 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 [14]. 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 and, 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.

IV. Virtual Environment Searching

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 [18], [19].

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.

In order to obtain the triangulated model of the organs, the Marching Cubes Algorithm has been used [20].

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 exploits a 3-tiers architecture:

- 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, shown in Fig. 2, 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.

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.

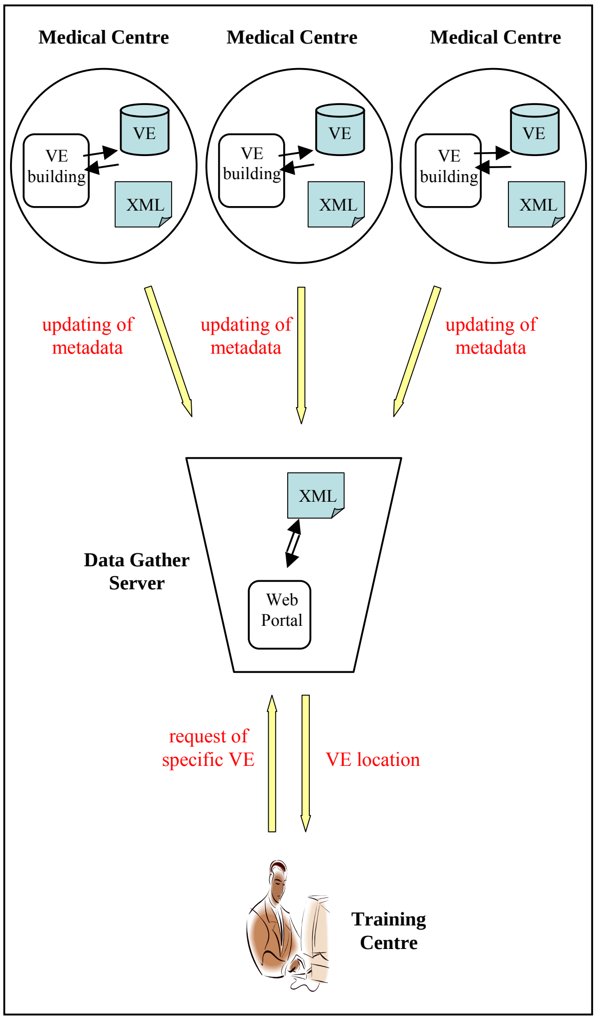

Fig. 2 The proposed 3-tier architecture

The web portal interacts with the Medical Centres using the Web Services technology, the fundamental building blocks in Internet distributed computing [15], [16], [17].

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.

V. Conclusions and Future Work

A first attempt to interact with a reconstructed artery that is the results of the HERMES Project is described. Afterwards, in order to have a more realistic simulator, a physical model that describes the artery deformations has been included.

A 3-tier architecture able to look for a virtual environment with specific features in terms of pathology or anatomy has bee designed and 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. 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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