Advanced Navigation and Augmented Visualization in Minimally Invasive Surgery

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Abstract: - Minimally invasive surgery offers advantages that make it the best choice for many diseases. The Virtual Reality technology gives a great support to this surgical procedure methods through medical image processing and visualization, 3D organ's reconstruction and intraoperative surgical guidance. In this paper is presented an advanced visualization and navigation platform that permits the surgeon to have the possibility to visualize both the traditional patient information (the CT image dataset) and a 3D model of the patient's anatomy obtained through the processing of these images. The platform permits two different visualization modalities that are available in real time and dynamically. According to the surgeon needs, it is possible to obtain the automatic reslicing of the orthogonal planes in order to have an accurate visualization exactly next to the actual position of the surgical instrument tip. In addition, it is possible to activate the clipping modality that allows cutting the 3D model in correspondence of a chosen visualization plane. The platform can be used as support for the diagnosis, for the surgical preoperative planning and also for an image-guided surgery.

Key-Words: - Medical images, 3D model, augmented reality, image-guided surgery.

1 Introduction

A new trend in surgery is the transition from open procedures to minimally invasive interventions, where visual feedback to the surgeon is only possible through a micro camera and direct palpation of organs is not possible.

Minimally Invasive Surgery (MIS), such as laparoscopy or endoscopy, offers the possibility to surgeons of reaching the patient's internal anatomy in a less invasive way and causing only a minimal trauma to patients.

As a promising technique, the practice of MIS is becoming more and more widespread and is being adopted as an alternative to classical procedures.

Shorter hospitalizations, faster bowel function return, fewer wound-related complications and a more rapid return to normal activities have contributed to accept these surgical procedures.

The advantages of this surgical method are evident on the patients, but this technique involves some limitations to the surgeon. Due to the limited field of view, the position and the orientation of the camera require frequently adjustments; in addition, a significant hand-eye coordination is necessary because the instrument movements visualized on the screen not match the surgeon's hand movements.

Taking into account that the imagery is in 2D, the surgeon can estimate the distance of anatomical structures only by moving the camera. In laparoscopic surgery, the lack of depth perception and the difficulty in estimating the distance from the anatomical structures can impose limitations on delicate dissection or suturing.

Motivated by the benefits that the MIS can bring to patients, many research groups are focusing on the development of solutions in order to assist the surgeons during the surgical procedures and to carry out their tasks in both faster and safer ways.

Even though the interpretation of the computed tomography (CT) or the magnetic resonance images (MRI) remains a difficult task, the medical imaging processing make possible the reconstruction of 3D models of the organs and provides anatomical information barely detectable by CT and MRI slices or ultrasound scan and an accurate knowledge of patient's anatomy and pathologies as well.

A suitable use of these models could lead to an improvement in patient care by guiding the instruments through the body without the direct sight of the physician; in addition, these models can be the bases to build the realistic virtual environment used in virtual reality and augmented reality applications.

The aim of this paper is to present an advanced visualization and navigation system, based on the 3D modelling of the patient's internal anatomy, that could be used as support for an image-guided surgery. The developed augmented reality system guides the surgeon in the intraoperative phase through the visualization of the anatomical structures of interest; it permits to prevent erroneous disruption of some organs during the surgical procedures.

2 3D Models of the Patient's Organs

In Minimally Invasive Surgery, the use of images registered to the patient is a prerequisite for both the planning and the guidance of this kind of operations. From the medical images of the patient (MRI or CT) it is possible to obtain a realistic 3D reconstruction of the anatomy by means of the application of some segmentation and classification algorithms. The 3D model visualization improves the standard slice view and the different grey levels are replaced by colors and associated to the different organs [1].

As modern medical imaging provides an accurate knowledge of patient's anatomy and pathologies, the medical image processing could leads to an improvement in patient care by guiding the gestures of the surgeon [2].

Currently there are many different toolkits used in medicine for the visualization and analysis of scientific images and 3D modelling of human organs [3]; some of these are open-source applications, such as 3D Slicer [4], OsiriX [5], [6] ITK-SNAP [7] and some other are commercial toolkits [8].

In our application we have used 3D Slicer, a multi-platform open-source software package for visualization and image analysis; a radiologist has validated the obtained 3D models. 3D Slider provides functionality for segmentation, registration and three-dimensional visualization of multi-modal image data. Therefore we have paid special attention to the smoothing of the reconstructed models in order to maintain a good correspondence with the real organs.

For the visualization and image processing the IGSTK library has been used [9], [10]. IGSTK (Image-Guided Surgery Toolkit) is a set of high-level components integrated with low-level open source software libraries and application programming interfaces. IGSTK includes VTK (Visualization Toolkit) [11], an open-source software system that employs leading-edge segmentation and registration algorithms in two, three, and more dimensions.

IGSTK provides the possibility to interface to common tracking systems. Among the different tracking systems based on mechanical, optical or visual technologies, we chose an optical tracker (Polaris Vicra of the NDI Inc.) in order to avoid the problems typical of the mechanical systems and associated to the use of metal devices. The Polaris Vicra tracks both active and passive markers and provides precise, real-time spatial measurements of the location and orientation of an object or tool within a defined coordinate system. The system consists of 2 IR cameras and some tools with reflective beads placed on known geometry frames; a position sensor is used to detect infrared-emitting or retro-reflective markers affixed to a tool or object. Based on the information received from the markers, the sensor is able to determine position and orientation of tools within a specific measurement volume. The system can calculate the current position of the tool in the space with an accuracy of 0.2mm and 0.1 tenth of a degree [12].

Figure 1 shows an example of the building of the 3D model of the organs from the patient's medical images.

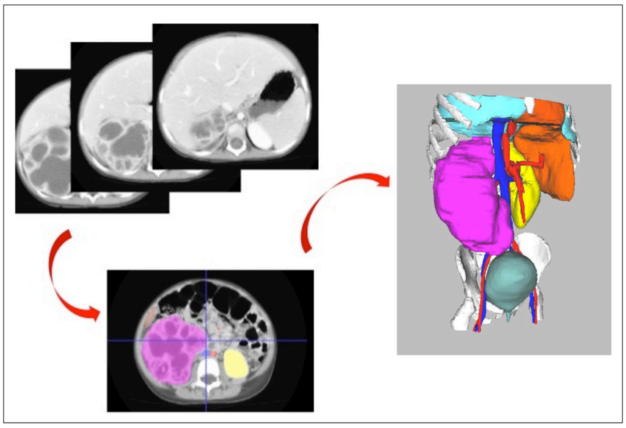

Figure 1: The building of the 3D model of the organs.

3 The Navigation Platform

The developed visualization and navigation platform is based on the idea to provide both the visualization of the 3D models of the organs and the medical image dataset.

The software interface is provided of some buttons and windows; on the left side the buttons are located in strict order taking into account the temporal step sequence necessary to obtain the different visualizations and navigation modalities starting from the loading of the medical images.

The remain part of the interface presents four windows used for the visualization of the CT slices in the axial, coronal and sagittal planes and the 3D model of the organs built from these images. A slider bar, one for each visualization plane, allows sliding the different views of the medical image set.

When the 3D models of the human organs are loaded in the main window the outlines of that organs are visualized superimposed on each slice in the others three windows, so that the surgeon can evaluate the quality and the accuracy of the segmentation and classification results.

In addition, it is possible to add on the 3D model the visualization of each plane shown in the windows located in the lower side of the software interface. Figure 2 shows the user interface with the different buttons, the visualization of a 3D model of the organs and 3 windows with the slice visualization in axial, coronal and sagittal planes.

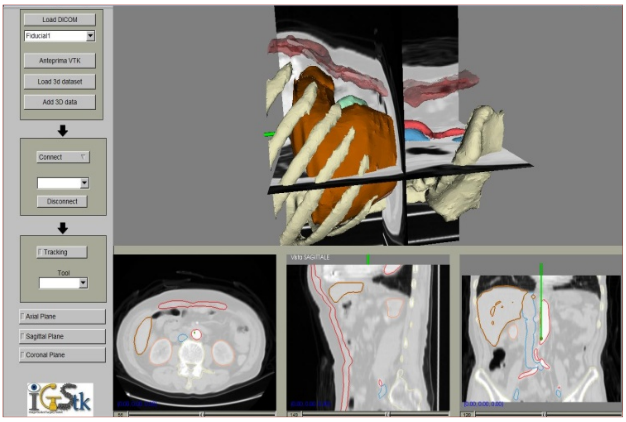

Figure 2: The user interface.

In the 3D model of the organs, the surgeon has the possibility to add or remove the visualization of some organs in order to have a better vision of the area of interest; some organs (for instance the muscles) are visualized in transparency or completely hidden in order to permit the vision of the behind located organs.

In the developed application it is possible to have a real-time interaction between the virtual organs and the real patient's body; the surgeon have the possibility to dynamically visualize the medical slices (CT or MRI) corresponding with the actual position of the tip of the surgical instrument. In other words, the exact localization of the instrument tip is detected by means of the optical tracker and this information is used to choose and to visualize the patient's medical image corresponding with the specific point of the body where the tip of the surgical instrument is located.

In order to have a perfect correspondence between virtual and real organs it is necessary to carry out an accurate registration phase that provides as result the overlapping of the virtual 3D model of the organs on the real patient [13].

The method of the registration phase is based on the placement of some fiducial points on the patient's body before the CT scanning and the following detection of these in the 3D model built from the acquired medical images. Before the surgical procedure, the optical tracker permits the correct overlapping among virtual points in the 3D models and the real fiducial points localized on the real patient's body. The developed registration algorithm is based on the Horn method [14].

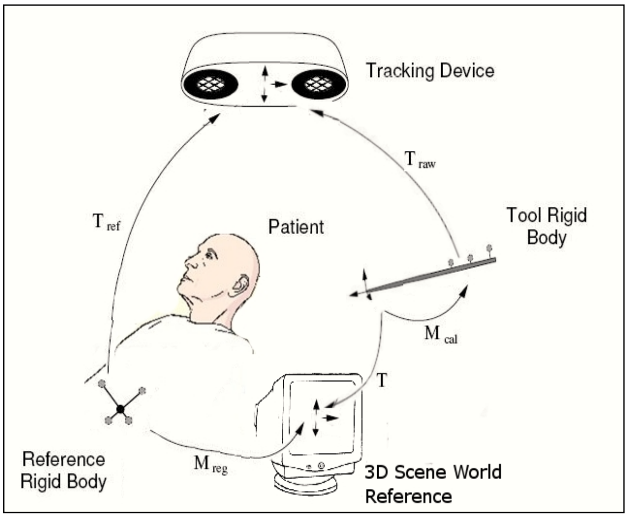

Figure 3: The relations among the reference systems.

In this application it is very important to have a correct detection and overlapping of the fiducial points; a very small error can have very serious consequences for the patient. The registration phase is carried out just once at the beginning of the surgical procedure; in order to maintain the correct overlapping among virtual and real organs also in case of movements of the patient's body during the surgical procedure, a reference tool, detected by the optical tracker, is positioned on the patient skin.

Figure 3 shows the transformation chain that takes into account the different reference systems of each device used in the application. The T_{comp} transformation, shown in (1), is used to find the position of the surgical instruments compared to the reference rigid body.

$$T_{comp} = T_{ref}^{-1} T_{raw} M_{cal} \qquad (1)$$

This transformation is calculated by means of the T_{raw} (the transformation that specifies the surgical tool pose with respect to the tracker coordinate system), $T^{-1}{}_{ref}$ (the relation between the reference rigid body coordinate system and the tracker coordinate system) e M_{cal} (the relation between the surgical tool pose and position of its tip).

The T transformation, shown in (2), describes the position of the probe tip inside the 3D virtual scene:

$$T = M_{reg} T_{ref}^{-1} T_{raw} M_{cal} \qquad (2)$$

In (2) the M_{reg} transformation is the result of the registration phase and is used to define the reference rigid body position in the global 3D scene reference system.

In the application is possible to have the automatic reslicing of the orthogonal planes in order to associate the tip of the surgical instrument to the intersection point of the coronal, sagittal axial planes. This situation is shown in Figure 4.

In this way the surgeon, during a minimally invasive surgical procedure, can have an accurate visualization of the 3D model and of the CT slices exactly next to the actual position of the surgical instrument.

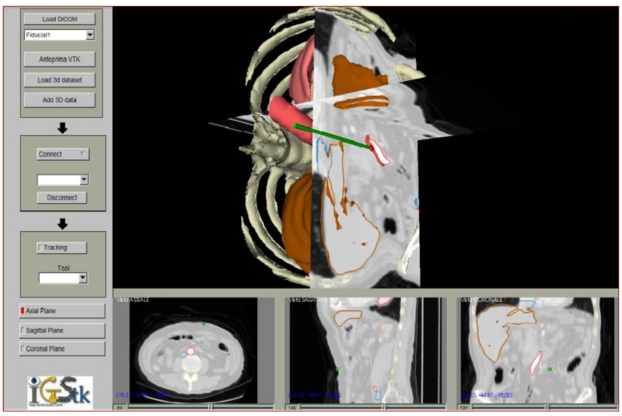

Figure 4: The visualization of the clipping modality.

In order to have a more clear visualization of the interest area, it is possible to activate the clipping modality visualization where the 3D model is cut in correspondence of a chosen plane pointed by the surgical instrument. Figure 4 shows a visualization using the clipping modality; in this case the cuts are applied for the sagittal and coronal planes and the axial plane is not visualized. The clipping visualization, as well as the reslicing modality, is dynamically obtained.

4 Augmented Visualization

The use of the augmented reality technology shows a way forward in bringing the direct advantage of the visualization of the open surgery back to minimally invasive surgery and can increase for the physician the view of the organs with information obtained from the image processing of the patient.

Augmented Reality can avoid some drawbacks of the minimally invasive surgery and can lead to new medical treatments [15], [16].

The research in augmented reality aims to allow the real-time fusion between the computer-generated digital content and the real world. Thanks to augmented reality, it is possible to see hidden objects and therefore to enhance the users' perception and to improve the interaction with the real world. The virtual objects, displaying what the users cannot detect directly with their own senses, help them to perform real-world tasks better.

In contrast with virtual reality technology where the user is completely immersed in a synthetic environment and cannot see the real world around him, the augmented reality technology, that consists of the addition of extra information to the real scene, allows the user to see virtual objects overlapped in the real world.

The augmented visualization supplements reality rather than completely replace it. The user has a feeling that the virtual and real objects coexist in the same space [15], [16].

In order to have a true AR application, the computer-generated organs must be accurately positioned on the real ones. For this reason it is necessary to carry out an accurate registration phase, which provides, as result, the correct overlapping of the 3D model of the virtual organs on the real patient.

In medicine, the augmented reality technology has the potential to bring the direct visualization advantage of open surgery back to minimally invasive surgery and can increase the physician's view of his surroundings with information gathered from a patient's medical images [17].

It is possible to overlay virtual medical images onto the patient, allowing surgeons to have a sort of “X-Ray" vision of the body and providing a view of the patient’s anatomy. Several research groups are exploring the use of the AR in surgery.

The process of registration can be obtained using the optical tracking systems that are the best choice at the moment; these devices are already in use in the modern operating rooms. For the registration of patient data with the AR system it is possible to have a point-based registration approach where specific fiducials can be used and fixed on the of the patient. These points are touched with a tracked pointer and their positions have to match the correspondent positions of fiducials placed during the patient scanning and segmented in the 3D model. The point-based registration is known to be a reliable solution if the set of fiducials is carefully chosen. The accuracy depends on the number of fiducials, the quality of measurement and the spatial arrangement.

Navab et al. [18] introduce the concept of a laparoscopic virtual mirror: a virtual reflection plane within the live laparoscopic video that is able to visualize a reflected side view of the organ and its interior.

Nicolau et al. [19] present the results of their research into the application of AR technology in laparoscopic procedures. They have developed an AR application that takes into account a predictive deformation of organs and tissues during the breathing cycle of the patient.

To allow a proper integration of the virtual scene (consisting of a 3D model of the organs of a patient obtained by its CT images) in the real scene, in the application an appropriate chain of rigid transformations has been implemented.

The system designed is monitor-based; the augmented scene appears on a monitor and uses a point-based (or fiducial-based) method to register or to identify some points on the virtual scene and to overlay these on the corresponding points on the real ones.

Although the organs are properly positioned within the dummy, the simple augmentation of the real scene cannot provide information on the depth of the scene, because they appear to be positioned on surface of the dummy. This augmented visualization is shown in figure 5.

Depth perception is still a major problem in many augmented reality systems when virtual objects have to be superimposed on real images. Although virtual objects have been correctly positioned in the scene, visually they are visualized in the foreground creating a situation that is not sufficiently realistic. In particular, this effect is not acceptable for surgical AR applications and it is necessary, in addition to a proper positioning of the organs in the virtual scene, to ensure correct visualization and to get an intuitive view on the anatomy of the patient [20].

The solution proposed is based on the “dark matter” method and consists in a virtual window overlaid onto the real skin of the patient, in order to create the feeling of getting a view on the inside of the patient.

The designed sliding window allows the occlusion of some part of the scene in order to obtain a more realistic impression that the virtual organs are inside the patient’s body.

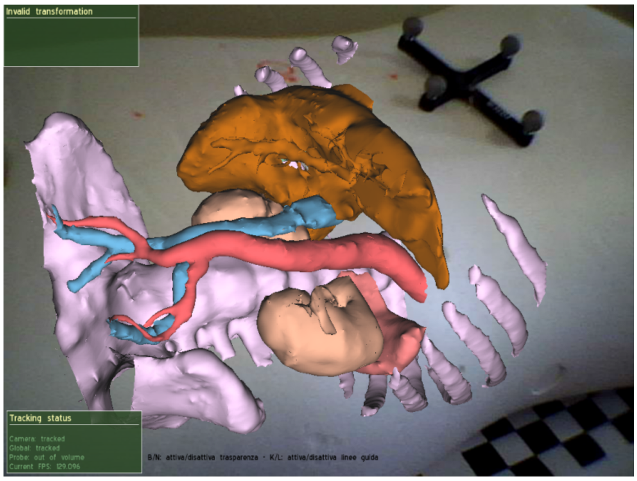

Figure 5: The augmented scene without depth perception**.**

The window enhances perceptive information permitting a partial view of the 3D model of the patient’s organs and giving the real impression that the virtual organs are placed inside the abdominal area and not on the body surface. Only through this virtual window can the internal organs be seen.

In order to occlude part of the organ’s model, a 3D model of the external surface of the body has been built; this model should be rendered only in the z-buffer (or depth-buffer), but not in the color-buffer, while virtual organs are rendered in the classical way.

In addition, the surgeon can slide the visualization window onto the surface of the patient’s body and to locate it in a precise position that can provide a view of the organs of interest. The sliding window is shown in figure 6.

Some accuracy and usability tests have been executed on the developed system.

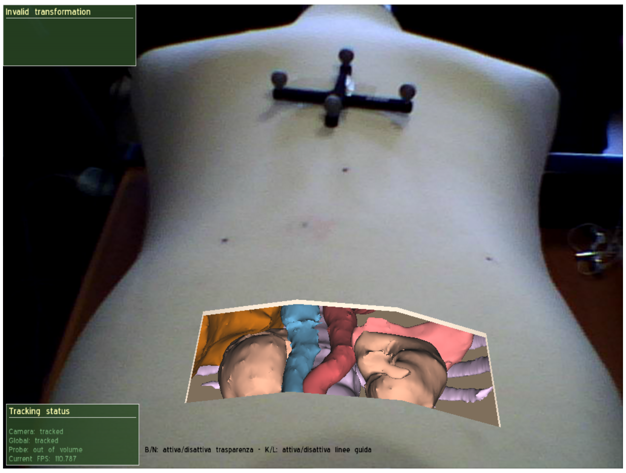

Figure 6: The sliding virtual window.

4 Conclusion

In this paper is presented an advanced navigation and visualization platform based on the 3D modelling of the patient's internal anatomy.

Using the developed system the surgeon can visualize both the traditional patient information, as the CT image dataset, and the 3D model built from this. Two different visualization modalities are available in real time and dynamically. According to the surgeon needs, it is possible to obtain the automatic reslicing of the orthogonal planes in order to have an accurate visualization of the 3D model and slices exactly next to the actual position of the surgical instrument tip. In addition, it is possible to activate the clipping visualization modality that allows cutting the 3D model in correspondence of a chosen visualization plane.

An augmented visualization, based on fiducial points, allows obtaining a correct positioning of the virtual organs built from CT images of the patient. To allow a proper integration of the virtual scene in the real one, an appropriate chain of rigid transformations and a registration phase have been implemented.

Furthermore, in order to provide the visual impression that the virtual organs are properly positioned inside the body and not on its surface, a partial view of these is provided using a virtual window sliding on the patient's body surface. The obtained result provides a realistic visualization and a correct impression of depth. The system can be used as support for an image-guided surgery.

As future work is in progress the building of a complete Augmented Reality system with the acquisition in real time of the real patient's video and the integration of virtual organs; these information will be dynamically overlapped the patient's body taking into account the surgeon point of view and the location of medical instrument.

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