Augmented Reality in Minimally Invasive Surgery

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***Abstract*—The advantages of the Minimally Invasive Surgery are evident for the patients, but these techniques have some limitations for the surgeons. In medicine, the Augmented Reality (AR) technology allows surgeons to have a sort of "X-ray" vision of the patient's body and can help them during the surgical procedures. In this paper we present two applications of Augmented Reality that could be used as support for a more accurate preoperative surgical planning and also for an image-guided surgery. The first AR application can support the surgeon during the needle insertion for the Radiofrequency Ablation of the liver tumours in order to guide the needle and to have a precise placement of the instrument within the lesion. The augmented visualization can avoid as much as possible to destroy healthy cells of the liver. The second AR application can support the surgeon in the preoperative surgical planning by means of the visualization of the 3D models of the organs built from patient's medical images and in the choice of the best insertion points of the trocars in the patient's body.**

Keywords - Augmented Reality, medical images, minimally invasive surgery, laparoscopic pediatric surgery, RF ablation

I. INTRODUCTION

One trend in surgery is the transition from open procedures to minimally invasive interventions, where visual feedback to the surgeon is only possible through the laparoscope camera and direct palpation of organs is not possible. Minimally Invasive Surgery (MIS), such as laparoscopy or endoscopy, has changed the way to practice the surgery and, as a promising technique, the use of this surgical approah is nowadays widely accepted and adopted as an alternative to classical procedures.

These techniques offer the possibility to surgeons of reaching the patient's internal anatomy in a less invasive way and causing only a minimal trauma. The diseased area is reached by means of small incisions in the body and specific instruments and a camera are inserted through these ports; during the operation a monitor shows what is going on inside the body.

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 and, if the advantages of this surgical method are evident on the patients, these techniques involve some limitations for the surgeons. In particular, the imagery is in 2D and the surgeon needs to develop new skills and dexterity in order to estimate the distance from the anatomical structures and work in a very limited workspace.

The acquisition of medical images (CT or MRI) associated to the latest medical image processing provides an accurate knowledge of the patient's anatomy and pathologies and could lead to an improvement in patient care by guiding of the surgeons during the surgical procedure.

The emerging Augmented Reality (AR) technology has the potential to bring the direct visualization advantages of open surgery back to minimally invasive surgery and can increase the physician's view with information gathered from the patient's medical images.

AR technology refers to a perception of a physical real environment whose elements are merged with virtual computer-generated objects in order to create a mixed reality. In addition to a mixture of real and virtual information, an AR application has to run in real time and its virtual objects have to be aligned (registered) with real world structures. Both of these requirements guarantee that the dynamics of real world environments remain after virtual data has been added [1].

In medicine the AR technology makes it possible to overlay virtual medical images of the organs on the real patient and it allows the surgeon to have a sort of "X-ray vision" of the patient's internal anatomy. In order to register the data and fuse virtual and real imagery in real time, special devices are used in the AR platform.

An advantage of using AR in surgery could be found in a better spatial perception and in the duration of the surgical procedure that could be shorter than in conventional way.

The aim of this paper is to present two AR applications that could be used as support for a more accurate surgical preoperative planning and also for an image-guided surgery. The first application can support the surgeon during the needle insertion in the radiofrequency ablation of the liver tumours; the second one allows the surgeon to choose the more appropriate points for the insertion of the trocars a pediatric laparoscopic procedure.

II. PREVIOUS WORKS

Motivated by the benefits that MIS can bring to patients, many research groups are now focusing on the

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development of systems in order to assist the surgeons during the minimally invasive surgical procedures.

Furtado and Gersak [1] present some examples of how AR can be used to overcome the difficulties inherent to MIS in the cardiac surgery.

Samset et al. [3] present some decision support tools based on concepts in visualization, robotics and haptics and provide tailored solutions for a range of clinical applications.

Bichlmeier et al. [4] focus on the problem of misleading perception of depth and spatial layout in medical AR and present a new method for medical in-situ visualization.

Navab et al. [5], [6] present a new solution for using 3D virtual data in many AR medical applications and introduce the concept of a laparoscopic virtual mirror, a virtual reflection plane within the live laparoscopic video.

De Paolis et al. [7] present an AR system that can guide the surgeon in the operating phase in order to prevent erroneous disruption of some organs during surgical procedures. They provide distance information between the surgical tool and the organs and they use a sliding window in order to obtain a more realistic impression that the virtual organs are inside the patient's body.

Nicolau et al. [9] present a real-time superimposition of virtual models over the patient's abdomen in order to have a three dimensional view of the internal anatomy. The authors have used the developed system in an operating room and to reduce the influence of the liver breathing motion they have tried to simulate the patient's breathing cycle.

LiverPlanner [10], [11] is a virtual liver surgery planning system developed at Graz University of Technology that combines image analysis and computer graphics in order to simplify the clinical process of planning liver tumor resections. The treatment planning stage enables the surgeon to elaborate a detailed strategy for the surgical intervention and the outcome of pre-operative planning can then be used directly for the surgical intervention.

Maier-Hein et al. [12] present a system developed for computer-assisted needle placement that uses a set of fiducial needles to compensate for organ motion in real time; the purpose of this study was to assess the accuracy of the system in vivo.

Stüdeli et al. [13] present a system that provides surgeon, during placement and insertion of RFA needle, with information from pre-operative CT images and real-time tracking data.

III. THE USED TECHNOLOGIES

A reconstruction of the 3D model of the anatomical and pathological structures of the patient is required in order to improve the standard slice view. An efficient 3D reconstruction of the patient's organs is generated by applying some segmentation and classification algorithms to medical images (CT or MRI) of the patient. The grey levels in the medical images are replaced by colours that are associated to the different organs [14].

Nowadays there are different software used in medicine for the visualization and the analysis of scientific images and the 3D modelling of human organs; Mimics [15], 3D Slicer [16], ParaView [17], and OsiriX [18] play an important role among these tools.

In our application we have used 3D Slicer for the building of the 3D model of the patient's organ; 3D Slicer is a multi-platform open-source software package for visualization and image analysis and in Fig. 1 is shown a 3D model built from CT images of a two-year-old child with a benign tumour of the right kidney.

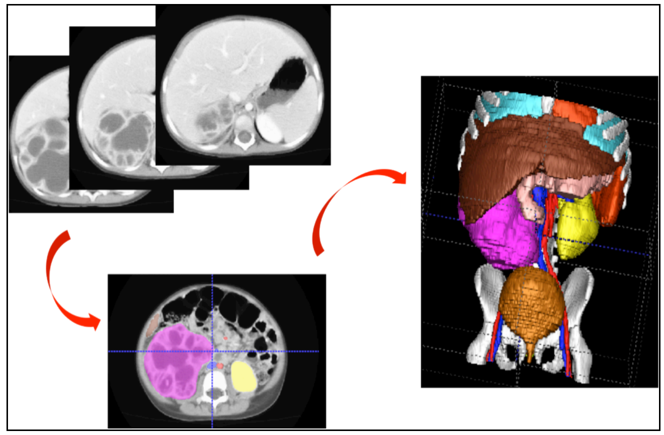

Figure 1. 3D model from the CT dataset

In the developed AR platform it is also necessary to use an optical tracker that is able to detect some intentionally introduced retro-reflective spheres (fiducials) placed on the surgical tools. In this way it is possible to know the right position and the orientation of the surgical instruments used during the surgical procedure. The tracking system is also used in order to permit the overlapping of the virtual organs on the real ones providing an augmented visualization of the scene. This registration phase is one of the most delicate step in an AR system for surgery.

We have used the Polaris Vicra optical tracker that provides precise and real-time spatial measurements of the location and orientation of an object or tool within a defined coordinate system [19].

For the visualization the Image-Guided Software Toolkit (IGSTK) that is a set of high-level components integrated with low-level open source software libraries and application programming interfaces has been used. IGSTK builds on the InsightToolkit (ITK) and the Visualization Toolkit (VTK) [20].

IV. AR FOR THE RF ABLATION OF THE LIVER TUMOUR

A. The Liver Tumour

Hepatic cancer is one of the most common solid cancers in the world. Hepatocellular carcinoma (HCC) is the most common primary hepatic cancer. Unless primary hepatic cancer is quite rare, liver is second only to lymph nodes as a common site of metastasis from other solid cancers [21]. The liver is often the site of metastatic disease, particularly in patients with colorectal adenocarcinoma.

The use of chemotherapy for malignant form of liver cancer rarely led to good results in long-term survival rate. We have also to consider that chemotherapy produces negative effects in the lifestyle of the patient.

Today surgery is the best approach to avoid the death of the patient and the reversion of hepatic cancer. Unfortunately only from 5 to 15 per cent of HCC or hepatic metastasis patients diagnosed again undergo a potentially curative resection of the liver cancer [22], [23].

Patients with confined disease of the liver could not be candidates to resection because of multifocal disease, proximity of tumor to key vascular or biliary structures that preclude a margin-negative resection potentially unfavourable in case of presence of multiple liver metastases. Very often the tumor is also associated to a pre-existent cirrhosis that can reduce resection margins.

Liver transplant is the only radical therapy that eliminates the risk of recurrence but it can't be always used. So, since most of patients with primary or malignancies confined metastatic at the liver are not candidates for surgical resection, we should use different approaches to control and potentially cure liver diseases.

The Liver Radiofrequency Ablation (RFA) is a technique used since 1980's and consists in the placement of a needle inside the liver parenchyma in order to reach the centre of the tumor lesion. When the lesion is reached, an array of electrodes is extracted from the tip of the needle ant it is that expanded in the tumor tissue. From these electrodes is injected for a certain time a radiofrequency current in the tumor tissue that causes tumor cell necrosis for hyperthermia (the local temperature is higher than 60 °C and cancer cells are more sensitive to heat than normal cells).

One problem in using radiofrequency tumor ablation technique is the correct placement of the needle that should reach the tumor lesion. Today surgeons use ultrasound, CT or MNR acquired during the needle placement in order to correctly direct the needle to the tumor. The use of these two-dimensional images makes the procedure very difficult and requires sometimes more than one insertion.

There is a need of enhancing the prognosis by a better control of the area interested by the RFA and the accuracy of the needle insertion in order to avoid some areas (important vessels) during the intervention.

A sort of guidance of the needle in tumour ablation procedures can be obtained using Augmented Reality technology. With the superimposition of the virtual models of the patient's anatomy (liver, cancer, etc) exactly where are the real ones, it is possible to make the needle placement less difficult.

B. AR in RF Ablation of the Liver Tumours

The purpose of this AR application is to provide a guidance system that can help the surgeon during the needle insertion in liver RFA.

To overlap the virtual tool over the real one we track the position and the orientation of the real tool using some reflective spheres detected by means of an optical tracker. In this way the position and the orientation of the real tool are measured and used in IGSTK to set the position and the orientation of the virtual tool.

To achieve a correct augmentation it is necessary to have a correspondence between the virtual organs and the real ones. This task is very difficult in an image-guided surgery application because a very small error in the registration phase can cause a serious consequence on the patient.

The registration process is carried out just before starting the surgical procedure and the applied method is based on the placement of fiducial points on the patient's body before the CT scanning and the detection of these in the 3D model built from the acquired medical images.

The optical tracker by means of a tool placed on the patient's body detects some possible movements of the patient over the operating table.

The application is provided of an user interface designed to be simple and functional at the same time. In the left side of that interface we have put the application control bottons; in the right-top window we show the 3D model and the augmented reality scene and in the right-bottom the three smaller windows where are placed the axial, coronal and sagittal views of CT dataset.

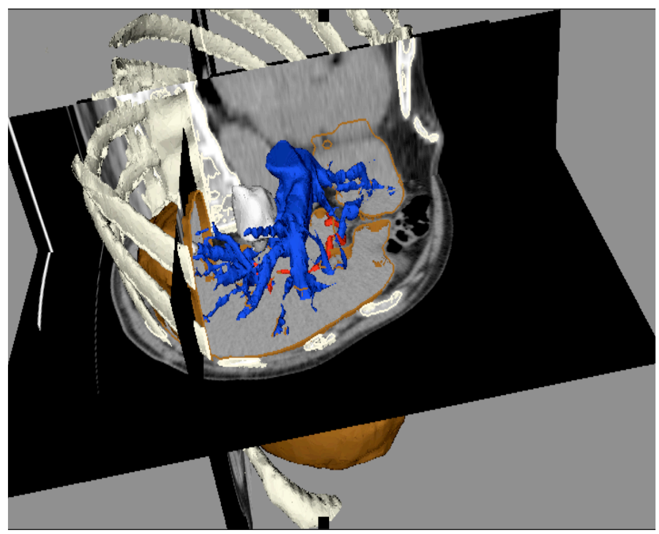

Figure 2. Clipping visualization applied to the liver and thoracic cage

There is the possibility to apply the clipping modality that permits the surgeon to dissect the model and to study its internal structure changing the opacity of the organs (Figure 2). The dissection could be made along the three principal axes.

The application features described till now are part of what we consider the pre-operative planning task. During this task the surgeon can use the application to study the pathology in a more simple and natural way than that provided by simple CT slice visualization.

For the navigation and augmentation task the surgeon needs to use the optical tracker and to carry out the registration task. When the registration process is complete, the virtual tool is shown in 3D view and is coupled with the real one so it follows the movements that real tool makes.

In Figure 3 is shown the augmented visualization of the 3D virtual model over the patient's body (a dummy). This visualization can guide the surgeon during the needle insertion in the radiofrequency ablation of the liver tumour.

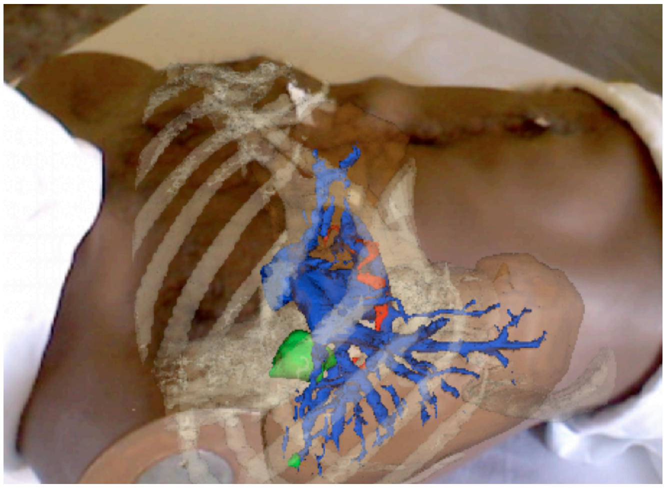

Figure 3. Augmented visualization in the RF ablation of the liver tumour

The application has been tested previously on a dummy and afterwards a first test has been carried out in the operating room in order to evaluate the system accuracy.

We are taking into account the possibility to include in the system also the simulation of the virtual model deformations due to the breathing of the patient.

V. AR FOR PEDIATRIC LAPAROSCOPY SURGERY

This application has the aim to provide support to the surgeons in a pediatric surgical procedure and, in particular, in the choice of the trocar entry points and the simulation of the interaction of the surgical instruments inside the patient's body.

Sometimes, using the standard insertion points for the surgical tools, also a simple surgical procedure can be very difficult due the difficulty to reach the organs. In this case the surgeon has to choose another insertion point in order to be able to carry out the surgical procedure in the most suitable way. Our aim is to avoid the occurrence of this situation and to provide a platform that allows to plan the insertion of the surgical tools on the virtual model of the patient's organs.

In this application we use the AR technology in order to visualize on the patient's body the precise location of the insertion points selected on the virtual model of the patient. Using the augmented visualization, the chosen entry points of the trocars are visualized on the patient's body in order to support the physician in the real trocar insertion phase.

For the augmented visualization, in order to have a correct and accurate overlapping of the virtual organs on the real ones, a registration phase is carried out; this phase is based on some fiducial points.

Figure 4 shows the specific section of the user interface for the choice of the trocar insertion points.

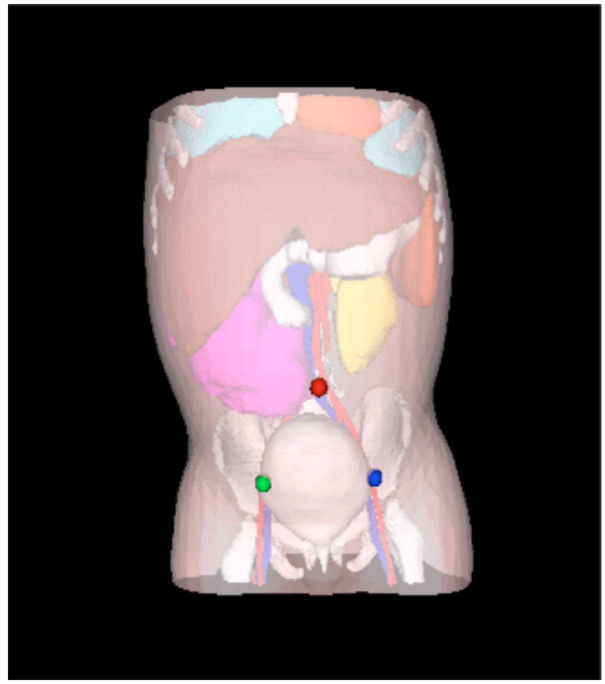

Figure 4. Interface for the choice of the trocar insertion points

Figure 5 shows the augmented visualization of the trocar's insertion points on the patient's body (a dummy).

The platform has been tested on two study cases (a two-year-old child with a benign tumor of the right kidney and a twelve-year-old child with a tumor of the peripheral nervous system) already operated by the surgeon; the future work will be the validation of the developed application on new real study cases.

Figure 5. Augmented visualization of the trocar's insertion points

VI. CONCLUSIONS AND FUTURE WORK

In this paper we present a guidance system for needle placement in radiofrequency ablation of the liver tumour and an AR platform for laparoscopic pediatric surgery.

The application for the RFA of the liver tumours has been tested in the laboratory on a specific testbed and, in order to start the validation of the system, a first test has been carried out in the operating room during an open surgery procedure for the liver tumour resection.

Operating rooms are overloaded of systems and devices and an efficient use of space is mandatory. In this first test the correct position of the devices close to the operating table has been chosen and a precise definition of the more appropriate fiducial points used for the registration phase has been decided. In Figure 6 is shown a phase of the first test in operating room.

As future work we are planning to add some improvements in the visualization of the organs taking into account the latest suggestions of the surgeons and to measure the precision of the image-guided application on a pig liver.

Figure 6. First test in operating room of the RF ablation application

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