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VIRTUAL REALITY, AUGMENTED REALITY AND ROBOTICS IN SURGICAL PROCEDURES OF THE LIVER

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Medical image processing led to a major improvement of patient care. The 3D modeling of patients from their CT-scan or MRI thus allows a better surgical planning. Simulation offers the opportunity to train the surgical gesture before carrying it out. And finally, augmented reality provides surgeons with a view in transparency of their patient which, in the future, will allow to obtain automation of the most complex gestures. We present our latest results in these different fields of research applied to surgical procedures of the liver.

1. Introduction

During the 20th century, medicine witnessed the appearance of a new tool, which revolutionized it : 3D medical MRI (Magnetic Resonance Imaging) or CT (Computer Tomography) imaging. Though acquisition techniques keep on evolving, reading and understanding these images often remain highly complex skills. Progress achieved in computer technology allowed to solve part of these reading difficulties by translating the information contained in the image into a 3D or 4D (i.e. 3D + time) image of the patient anatomy and pathologies.

Thanks to an improved preoperative knowledge of each patient's internal anatomy, practitioners can today establish an improved diagnosis and a better planning of the best suited therapy for a given case. Therefore, 3D modeling of a patient is generally used for diagnosis support or surgical planning tools. The other use is patient follow-up over time, easing visualization of therapy efficiency. However, surgical simulation still remains limited to virtual models, without really exploiting medical data of patients. Thus, to simulate an intervention on a virtual patient reconstructed from his/her medical image is nevertheless a major research which would allow to noticeably reduce medical mistakes thanks to an optimized preoperative training.

Intraoperative use, which allows to improve the surgical gesture, has to be added to the preoperative use of 3D patient modeling. In this domain, augmented reality offers a more efficient steering of the surgical gesture, by superimposing preoperative information on the patient. Most applications have been developed in neurosurgery and in orthopedic surgery, since non-mobile bone landmarks are very reliable and allow an eased registration of the virtual

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patient on the real patient. The few works that have been carried out on the abdominal region provide only little accurate information, because of possible organ movements due to breathing.

In order to overcome limitations of 3D medical image analysis, preoperative simulation and augmented reality on organs and pathologies of the digestive system, we have been developing a set of tools over the last 8 years. Their objective is to provide support to surgeons of the digestive system, both before and during the surgical intervention. We are presenting those tools hereinafter.

2. 3D modeling of organs and surgical planning.

The 3D reconstruction of patients from their CT-scan or MRI medical imaging is one of the main research topics in the field of medical image processing. Most systems allow to reconstruct anatomical and pathological structures from interactive systems, except for some of them, that propose automated systems allowing a real use in clinical routine, where processing time has to be kept at a minimum. The digestive system is one of the most complex regions to analyze, because of the great number of neighboring soft organs, that all have a very close density.

In the case of the liver, main organ of the digestive system, radiologists use CT-scans, which are realized 60 seconds after the intravenous injection of a contrast medium. Theses images allow to visualize hepatic tumors, that are hypodense in the images, contrasted vessels are green as well as the liver, which has an intermediary grey level whereas it usually is higher than the one of surrounding organs. Despite these visible variations, liver delineation remains a highly complex procedure since its localization and its shape can vary considerably (its average density can vary between 70 to 150 HU). Several authors have proposed to delineate the liver with automatic [1-3], or semi-automatic methods [4-5]. These methods provide bad results in atypical-shaped liver or when the liver contains big capsular hepatic tumors, the only health parenchyma being detected.

We have developed a novel method [6] which detects parenchyma and tumors from techniques developed in the works of Bae et al. [3]. In order to obtain reliable and automatic results, we have added the prior segmentation of neighboring organ. This way, we obtain a more efficient and still automatic method, which provides within 15 minutes from a CT-scan with a 2mm thickness and that has been taken 60 seconds after injection of a contrast medium : skin, bones, lungs, heart area, aorta, spleen, kidneys, gallbladder, liver, portal vein and hepatic tumors from 5 mm diameter [6].

In order to use this reconstruction, we have also developed a surgical planning system [7] working on a standard multimedia computer. Indeed, delineation of each organ allows us to deduce for each one of them a small

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triangular meshing and to display it on any 3D card that is compatible with the OPEN GL standard. Besides 3D visualization of delineated and modeled structures, this system allows to put each structure in transparency, to interact on them, to navigate anywhere and thus to simulate any kind of cœlioscopy. It also allows to realize virtual resections defined by interactively positioned cutting plans and to provide the volume of all visualized structures (figure 1). Because of its compatibility with current standards, this system can be used on a laptop fitted with a 3D graphic card and can thus be used during the intervention so as to improve the control of the carried out gesture.

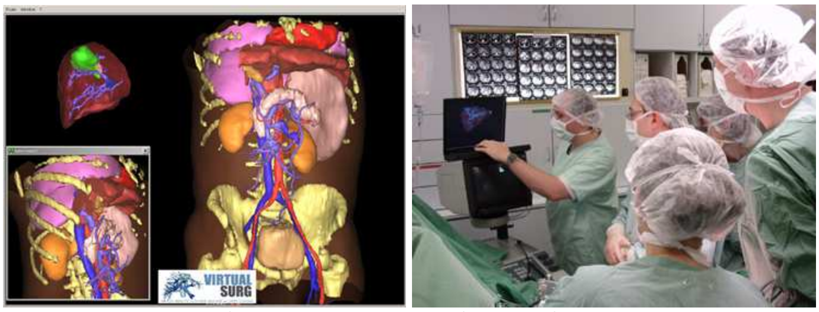

Figure 1 : Virtual resection of a 3D reconstructed liver of a patient from his/her medical images and intra-operative clinical use of the planning software on a laptop.

3. Surgical simulation.

Thanks to minimally invasive surgery, surgical simulation witnessed a very important expansion over the last years. This surgical technique consists in operating a patient with long instruments inserted into the patient's body, while looking at a screen linked to a camera for visualizing the interior of the operated cavity. Such a surgery offered thus a simulation favourable development field, since it is possible to replace the camera image by a virtual image of the patient. Furthermore, since the surgeon operates with instruments, it is also possible to link these instruments to motorized systems reproducing haptic sensations of force feedback.

The first simulator of this type is the Minimally Invasive Surgery Trainer (MIST), developed in 1995 by the company Virtual Presence Ltd, which is today commercialized by Mentice (www.mentice.com). Since then, a great number of companies took up surgical simulation. Some products propose deformable models, usually surfacic ones. The most used deformation model is the spring-mass model because of its easy implementation. If proposed, cutting only concerns surfacic organs. The most simulated surgery is the cholecystectomy, available on LapChole from Xitact (www.xitact.com), LapSim

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from Surgical Science (www.surgical-science.com), LapMentor from Simbionix (www.simbionix.co.il), or RLT from ReachIn (www.reachin.se).

Some of these companies have developed material platforms that can be used for simulating abdominal surgery, gynaecologic or arthroscopic procedures. Various scenarios are then available as separate modules. The increasing realism of visual rendering, due to the use of textures obtained from real images, and the progress in force feedback mechanisms enabled those products to acquire some maturity. All these simulators propose training exercises for learning basic gestures. Pedagogy follows a step by step training logic allowing in the end to realize a more complex gesture including a grading. Though they are attractive, these simulators are however limited to the simulation of restricted and determined virtual models in a set database. Thus, they do not exploit the 3D reconstruction of patients that can be realized from the medical image, and do not allow to prepare a surgical intervention on a copy of the patient. Furthermore, these simulators do not feature the opportunity to cut a voluminous organ like the liver and are in fact limited to learning basic gestures.

From the 3D patient modeling, we propose to realize a realistic simulator allowing to prepare and simulate a surgical intervention before actually carrying it out [8]. Thus, our objective is to realize and validate a highly realistic simulator for the laparoscopic surgery of the liver, including realistic physical and visual modeling of organs, real-time force feedback and the opportunity to change patient topology thanks to broad resections realized on any region of the reconstructed patient. In order to realize such a simulator, it is important to reproduce sensations linked to carrying out surgical gestures.

The first version described in [9] only allowed to simulate main prehension and resection gestures by applying an electric bistoury. In order to improve visual quality of the simulator, we worked on the realistic aspect of the cut region, by adding a local regeneration of the meshing that therefore provides a convincing simulation of ultrasound resection (figure 2 and [10]). We maintain meshing variety : this is the true novelty of this method [10]. This property is important since it allows us to compute the normal at each surface tip of the meshing, and thus to improve the stability of haptic interaction. Furthermore, this variety allows us to use a structure of simplified data for meshing, which is optimized for force computation.

We also merged two different deformation algorithms in a same meshing : an explicit method called mass-tenser and a pre-computed method [9]. Thus, the virtual organ is separated into several volumetric regions in which the deformation method (mass-tenser or pre-computed) is chosen according to the interaction nature with the virtual tool (no interaction, deformation, cutting). This method is based on the domain decomposition theory and is optimized so as to minimize the amount of communication between two neighbouring

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regions. Our current research works aim at parallelizing this method, what will allow to speed up computation time.

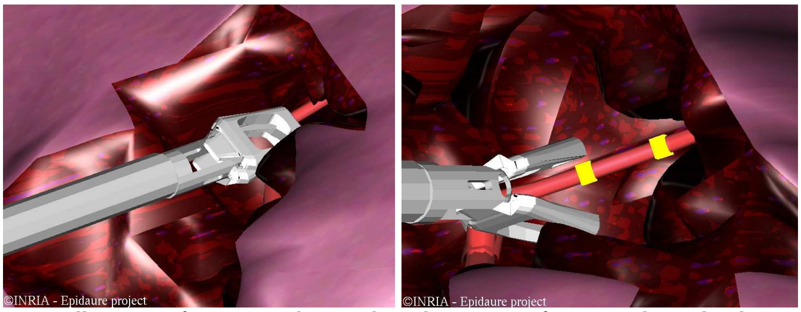

Figure 2: Illustration of a resection showing the realistic aspect of cutting and vascular clamping.

4. Augmented Reality: the transparent patient.

One of preoperative planning and simulation limitations is the difficulty of accurately reproducing the planed and simulated gesture on the real patient. This limitation can be overcome by superimposing preoperative data on the real patient during intervention. However, this superimposition is complex to achieve in practice since it requires the accurate correspondence of reference landmarks between the virtual and the real patient. We have developed a set of tools so as to obtain a reliable result that can be used in clinical routine. Therefore, we propose to offer a view in transparency of the patient by superimposing the 3D virtual patient reconstructed from MRI or CT medical images, on the video image realized during the intervention. In order to retrieve the constraint linked to deformation and movement of organs of the abdominal area due to patient breathing, the medical image and the video image can be realized under general anesthesia with a constant air volume inside lungs. Such a procedure is observed in practice for needle insertion interventions, such as radiofrequency thermal ablation of hepatic tumors. Thanks to these restrictions, abdominal organs have the same position between both acquisitions with a movement observed in vivo of less than 1mm. Registration can thus be limited to a 2D (video) – 3D (modeling) rigid registration of images.

To perform an accurate registration it is essential to have reference landmarks that are visible in both images. In the case of neurosurgery or orthopedic surgery, fiducials (their number varies between 3 and 6) are usually fixed on bones in order to ensure their motionlessness. In the case of digestive surgery, we place a greater number of fiducials on the skin, what allows to ensure greater stability and thus a more reliable registration (a total of 25 fiducials). These fiducials will automatically be modeled during skin segmentation and will automatically be segmented in the video image. In order

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to carry out this registration, we orient two tri-CDD digital color cameras conjointly calibrated on the model under two different points of view with an angle between 40° and 90° for an accurate stereoscopic registration [11]. These cameras are connected to a personal computer thanks to a Matrox Meteor II acquisition card allowing the simultaneous acquisition of two video sources. In order to superimpose the 3D model in the video images, fiducials located on the 3D reconstruction have to be positioned on those visible in video images. To do so, we use a 3D/2D registration according to our method described in [11] : 3D points are spatial coordinates of fiducials reconstructed from data stemming from the scanner, and 2D points are pixel coordinates corresponding to fiducials in both camera views. The experimental study [11] we carried out with an abdominal model showed that superimposition accuracy for targets located inside the model reaches an average of 2mm after fiducial registration.

Thus, we developed an efficient registration method, which allows to superimpose the 3D modeling of the patient on the real-time acquisition realized in the OR, thus providing a virtual view in transparency of the patient. For this transparency visualization to be useful, it has to be coupled with a visualization of tools that will be inserted inside the body, so as to make them visible during the whole intervention, and thus allowing to realize a precise targeting of the aimed tumor. Therefore, we developed a real-time tracking system of surgical tools allowing to superimpose a virtual instrument on the real instrument (figure 3). To do so, we have adapted the ARToolKit library [12] so that it works with the Meteor II acquisition card. Thus, tracking of the instrument is eased by adding a printed planar square, which is automatically recognized by the library, and permanent visualization of tool positioning is also possible.

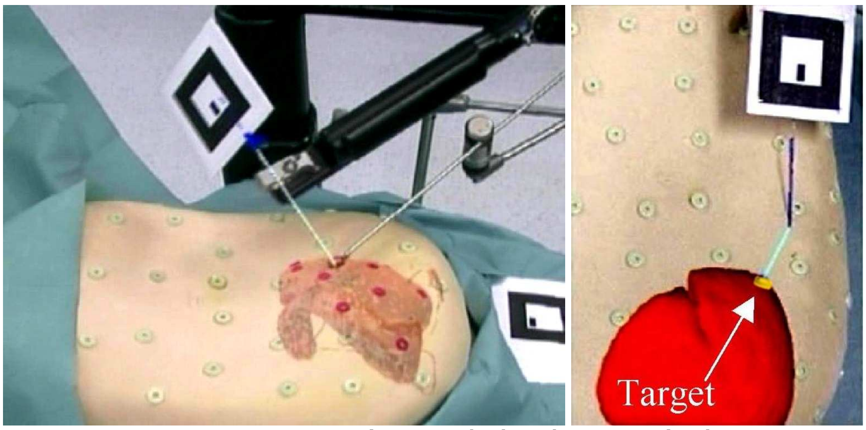

Figure 3 : Computer-assisted targeting thanks to the augmented reality vision.

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In order to validate the interest of such a system, we have realized a targeting which is similar to the one carried out during a radiofrequency ablation intervention. We modeled targets with radio-opaque fiducials stuck on the synthetic liver inside a model (cf. figure 3). To reach targets, the augmented view provides the virtual position of target and needle on both video images. Needle orientation is guided by the color of the target, which changes when the needle points towards the right direction. Furthermore, the software indicates the distance (in mm) between virtual needle tip and virtual target in real-time.

Two different users, software designer and expert surgeon, who did not participate in the software development, then carried out 50 targetings each. Targeting accuracy has been evaluated thanks to an endoscopic camera oriented towards target fiducials. Resulting mean distance and time to reach the target are indicated in Table 1.

Table 1 :Targeting results (mean value ± standard deviation).

	Total	Computer Scientist	Surgeon
Real mean distance (mm)	2.79 ± 1.41	3.6 ± 1.03	1.98 ± 1.27
Mean time (sec)	46.57 ± 24.64	38.5 ± 21.78	54.64 ± 24.88

These results clearly show an important targeting accuracy, since the expert has a targeting error of less than 2mm. Furthermore, comparison between targeting carried out by the software designer and the expert surgeon allows us to check that the system ensures a very high realism in usage, by favoring the expertise of gesture and not the expertise of the developed system. This is indeed a frequently encountered problem in computer-assisted surgical gesture systems, where knowledge of the system developed by the designer often enables him/her to carry out more accurate actions than the medical expert. The other advantage of this system is the time required for needle positioning. In clinical routine, such a positioning takes 5 to 10 minutes, due to the use of intra-operative imaging, such as ultrasonography or scanner, that prolongs intervention duration. Our experience shows that the gesture requires on average less than one minute to be carried out.

5. Conclusion

The various works carried out by our research teams led us to develop a set of tools for diagnosis support and surgical intervention planning. They also allow to simulate a complex procedure on a 3D virtual copy of the patient and to use preoperative information during intervention, in particular by superimposing the virtual image of internal organs and pathologies on the abdomen of the patient.

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These systems, at an experimental stage, are progressively being tested clinically, with the objective of eventually being used in clinical routine. They represent the first essential phase for surgical gesture automation, that will allow to reduce surgical mistakes. Indeed, intervention simulation will allow to do without all superfluous or imperfect gestures, using it as a programming of the final gesture. This gesture will then be transmitted to a surgical robot which, thanks to augmented reality, will be able to precisely reproduce optimized gestures of the surgeon. Tomorrow's surgery is on its way.

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