Virtual Reality and Augmented Reality in Digestive Surgery

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Abstract

Medical image processing led to a major improvement of patient care by guiding the surgical gesture. The 3D modeling of patients from their CT-scan or MRI thus allows an improved surgical planning. Simulation offers the opportunity to train the surgical gesture before carrying it out. These two preoperative steps can be used intra-operatively thanks to the development of augmented reality (AR) which consists in superimposing the pre-operative 3D modeling of the patient onto the real intra-operative view of the patient. AR provides surgeons with a view in transparency of their patient and can also guide surgeons thanks to the virtual improvement of their real surgical tools that are tracked in real time during the procedure. In the future, by combining augmented reality and robotics, these image-guided robotic systems will provide the automation of the surgical procedure, the next revolution of surgery.

1. Introduction

Modern medical imaging provides an essential preoperative knowledge of patient anatomy and pathologies. However, the patient is represented on a set of 2D images (MRI or CT-scan), and their interpretation often remains a difficult task. One of the major goals of computerized medical imaging analysis is to automatically detect, identify and delineate anatomical and pathological structures inside 3D medical images in order to guide the surgical procedure. Thus, by translating the medical information contained in images into a set of 3D models, this analysis allows to develop the concepts of Virtual Reality and of Augmented Reality.

The use of Virtual Reality in medicine consists in creating a virtual patient thanks to the 3D modeling of anatomical and pathological structures. It then lead to an easier and more extensive visualization and exploitation of images through immersion, interaction and navigation. 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, the simulation of an intervention on a virtual patient reconstructed from his/her medical image represents a major research field, which would allow to reduce medical inaccuracies thanks to an optimized preoperative training. The Virtual Reality concept limits the patient to a virtual world, even if this world is a virtual copy of reality.

In order to overcome this limit, a solution consists in combining information from the virtual world with information from the real world. In medicine, this concept will be translated into two major axes : computer-assisted guiding systems that use real information to control the virtual world, and Augmented Reality systems that superimpose virtual information onto view of the real world. These two axes require a first registration between the pre-operative virtual model of the patient and the real patient in the operative-room. This first step allows to have a single spatial reference frame linking the virtual world and the real one.

Computer-assisted guiding systems consist in tracking surgical tools in real-time in order to use their spatial coordinates to control the virtual copy of these tools in the virtual world. These systems are the most developed ones and are currently being sold by several companies for neural surgery (LandmarX™ Evolution Navigation System from Medtronics, VectorVision™ station from Brain Lab, etc...), or orthopaedic surgery (StealthStation from Medtronics, OrthoPilot™ from aesculape, Surgetics from Praxim, Navitrack™ from OrthoSoft inc., etc...). Indeed, in such surgical procedures, bones are used as efficient and accurate landmarks, which is impossible for the thoraco-abdominal area. This technique is thus restricted to research developments in abdominal surgery [8].

In opposition, Augmented Reality systems consist in superimposing information of the virtual world onto the real one. Augmented reality then offers a view of the real world that is enhanced by superimposed information which are computed in the virtual world. These information could be the 3D model of the patient or a virtual tool. The visualization is commonly based on the use of see-through interfaces like augmented reality glasses, but it can also be realized from a classical screen. These systems have essentially been developed in neural surgery [4, 10] and are currently used in routine (MKM systems and OPMI Neuro from Karl Zeiss, Surgivision system from Elekta). The few works that have been carried out on the abdominal area [5, 3] provide only little accurate information, because of possible organ movements due to breathing.

Through the use of Virtual Reality and Computer-assisted guiding systems, surgeons can improve surgery, but they need to build a mental relationship between a virtual image representing their patient, and the real patient. This image-guided surgery is easier with augmented reality, the virtual information being superimposed onto the real view of the patient. But this guidance remains limited to gesture precision and accuracy of surgeons.

Currently, computer assisted surgery has essentially been developed for neural and orthopaedic surgery. In abdominal surgery, several limitations still limit its use : 3D modeling of abdominal organs and pathologies from medical images remains a time consuming interactive process; Augmented Reality seems difficult to realize due to no real fixed landmarks in a deformable organ area; and efficiency of robotic control remains limited to patient movements.

In order to overcome these limits, we have developed several methods combining virtual reality and augmented reality in abdominal surgery.

2. 3D modeling of abdominal anatomical and pathological structures.

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, which 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 [12, 6, 1], or semi-automatic methods [16, 7]. 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 new method [18] which detects parenchyma and tumors from techniques developed in the works of Bae et al. [1]. In order to obtain reliable and automatic results, we have added the prior segmentation of neighboring organ. Each organ segmentation is based on the translation of human knowledge used to manually delineate organs in morphological, topological and geometrical constraints. Thus, we have a more efficient and still automatic method, which provides within 15 minutes from a CT-scan with a 2 mm 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 [18] (see figure 1). We have also adapted this method for cholangio MRI, which provides thus a 3D modeling of the biliary tract and its internal stones [17].

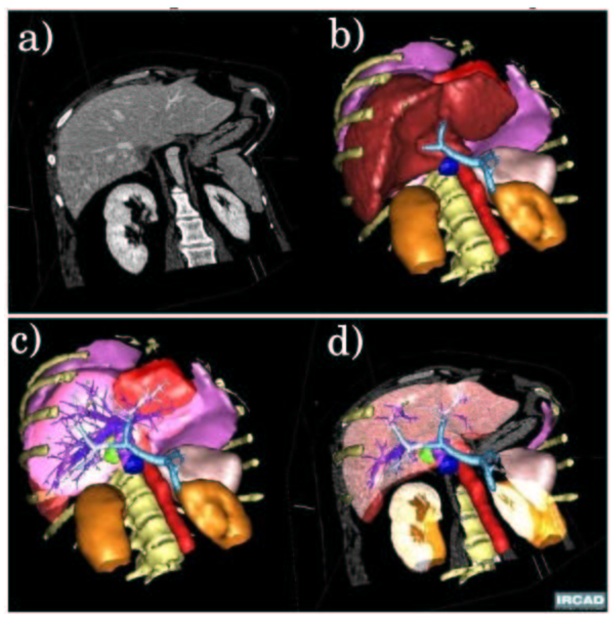

Figure 1. From the CT-scan of the patient (a), automated 3D modeling of the anatomical and pathological structures of the patient (b and c). Superimposition of the CT-scan shows the accuracy of the result (d).

3. 3D visualization system for planning and intra-operative use

In order to use the 3D modeling of a patient, we have developed a surgical planning system [9] working on a standard multimedia computer. Indeed, delineation of each organ allows us to deduce for each one of them a small 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 add virtual surgical tools, to realize virtual resections defined by interactively positioned cutting planes and to provide the volume of all visualized structures (see figure 2). 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 gesture being carried out.

One possible use of this software consists in superimposing the resulting 3D visualisation on the real intra-operative view of the patient. To obtain a good result, we use rib landmarks to manually position the virtual patient in the same position as the real one (figure 3.a). Interactive Augmented Reality requires then to move the virtual tools in real-time in the same position as the real ones according to the patient landmarks. Once virtual surgical tools are in the same position as the real ones, the virtual laparoscopic view is similar to the real one. It is thus possible to obtain an augmented reality view for minimal invasive surgery (figure 3.b and 3.c).

Such an augmented reality is necessarily user-dependant due to manual positioning. Therefore, it is impossible to ensure accuracy for this first interesting image-guided surgical tool, that can only be used for an easier understanding of patient anatomy using pre-operative data.

4. Automatic Augmented Reality

One of Interactive Augmented Reality limitations is the difficulty of accurately reproducing on the virtual patient the real surgical gesture performed by surgeons. This limitation can be overcome by automatically superimposing preoperative data on the real patient during intervention and by automatically tracking surgical tools in real-time. However, this superimposition is complex to achieve in practice, since it requires the accurate correspondence between the two reference frames in which are defined 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, onto the video image realized during the intervention. In order to retrieve the constraints linked to deformation and movement of organs of the abdominal area due to patient breathing, two solutions can be proposed: the medical image and the video image can be realized under general anesthesia with a constant air volume inside lungs, and the superimposition can be limited to fixed anatomical structures such as aorta or vena cava. Constant air volume is observed in practice for needle insertion interventions, such as radiofrequency thermal ablation of hepatic tumors. Furthermore, fixed anatomical structures are often difficult to find and crucial for an efficient surgery. Because of these restrictions, visualized abdominal structures will have a similar position between both acquisitions with an in vivo observed movement of less than 1mm. Registration can thus be limited to a 2D (video) - 3D (modeling) rigid registration of images.

4.1. An optimal model registration

To perform an accurate registration, it is essential to have reference landmarks that are visible in both images. In the case of neurosurgery or orthopaedic 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 radio-opaque markers on the skin, that allows to ensure greater stability and thus a more reliable registration (a total of 25 fiducials). These fiducials, visible in both CT-scan and video images, are automatically extracted and matched thanks to several robust algorithms that were validated in [14]. In order to carry out this registration, we orient two tri-CDD digital color cameras jointly calibrated toward the patient with an angle above 20^o for an accurate stereoscopic registration [15]. These cameras are connected to a personal computer thanks to a Matrox Meteor II acquisition card allowing the simultaneous acquisition of two video sources. To superimpose the 3D model in the video images, we could use the classical least square 3D/2D criterion that simply position the CT-scan fiducials on those visible in the video images. However, this criterion abusively supposes that the noise corrupting the 3D data is negligible. Since we need the best possible accuracy, we use instead the *Extended Projective Points Criterion* (EPPC) that we developed in [15], and that is optimal in the case of noise on both 2D and 3D markers extraction. In this context, 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, carried out with an abdominal phantom showed that superimposition accuracy for targets located inside the model reaches an average lower than 2 mm after fiducial registration [15].

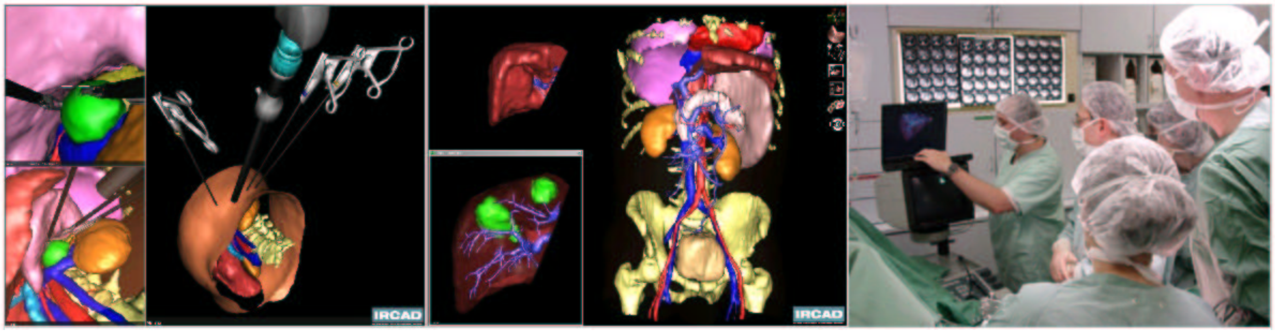

Figure 2. From medical images of a patient, virtual laparoscopic tool positioning for an adrenal tumour resection (left), resection of a 3D reconstructed liver of a second patient (center) and intra-operative clinical use of the planning software on a laptop (right).

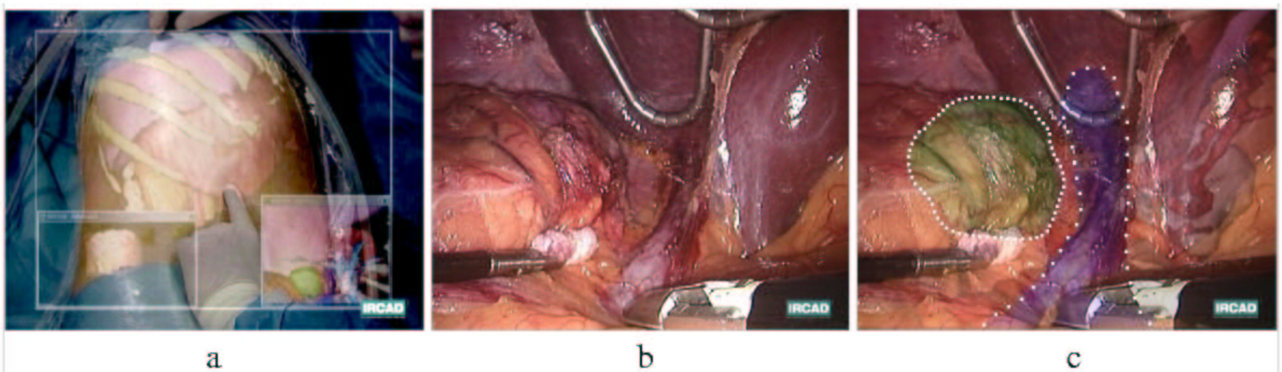

Figure 3. Interactive Augmented Reality allows to superimpose (c) the virtual laparoscopic view onto the real one (b) from an initial manual registration of the virtual patient (a). In (c), superimposed virtual structures are emphasized with a dotted line.

4.2. A submillimetric needle tracking

We developed an efficient registration method, which allows to superimpose the 3D modeling of the patient on the real-time acquisition realized in the operative room, 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 an accurate real-time tracking system of surgical tools by enhancing the ARToolKit library [2]. Eventually, it allows to superimpose a virtual instrument on the real instruments. An accuracy evaluation, realized in simulated clinical conditions, proved that the superimposition average error of a radiofrequency needle was below 1 mm.

5. Result of augmented reality guided targeting

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 15 mm diameter radio-opaque fiducials stuck on the synthetic liver inside an abdominal phantom. To reach targets, the augmented view provides several windows (see figure 4) corresponding to: a superimposition of the virtual model on the real video of the patient (figure 4.a); a virtual camera localized at the tip needle and oriented along its axis (figure 4.b) ; and a computer-assisted guiding view (figure 4.c) that shows the real position of surgical tools on a virtual modeling of the patient. Furthermore, the software indicates the distance (in mm) between virtual needle tip and virtual target in real-time.

Seven participants each performed 10 consecutive needle targetings of the model tumors. During the positioning, the operator placed the needle and stopped his movement when

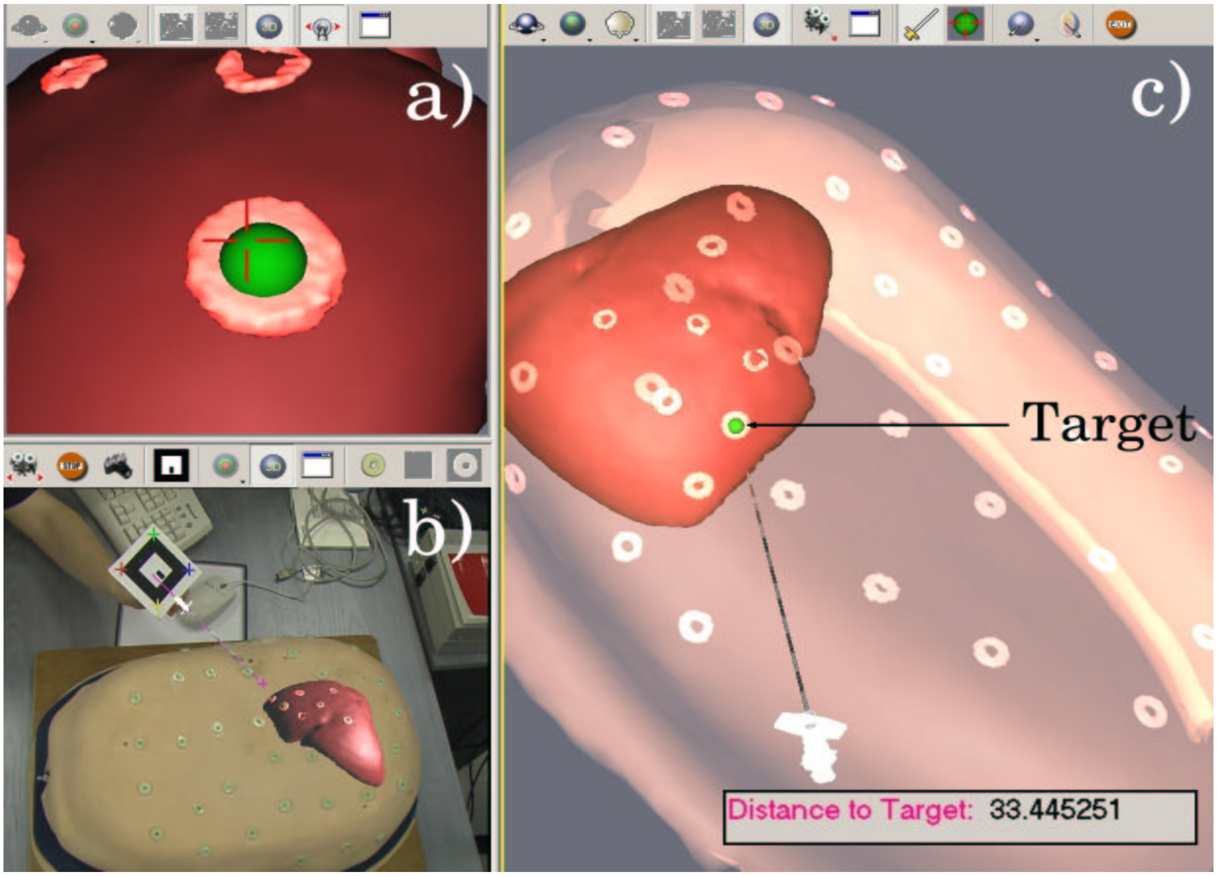

Figure 4. Example of the augmented view provided to the user. (a) virtual view of a camera positionned at the tip needle and oriented toward its axis. (b) the 3D reconstruction of the liver and the virtual needle are displayed on the video frame. (c) virtual view displaying the real position of the needle with respect to the model of the abdominal phantom. We indicate in its corner the virtual distance in mm that separates the tip needle to the target (in this case, a marker center).

he thought that he had reached the tumor center. After each trial, the time required to position the needle was recorded, and the accuracy of the hits was verified by an independent observer using an endoscopic camera introduced into the phantom and focusing on the targets. Accuracy and time results are shown in Table 1.

According to surgeons, the overall accuracy of this system has to be less than 5 mm to provide significant help. Therefore, the results of our experiments clearly show an important targeting accuracy, since the less accurate user has a targeting maximal error of 5 mm with an average of 2.9 mm. 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 with an average time of less than 30 seconds.

We have thus obtained a fully efficient and accurate image-guided surgical tool for abdominal procedures.

6. Future Works

From these first results, we now aim at developing automated image-guided robotic surgical procedures, by combining augmented reality and robotics (see figure 5). Indeed, by computing the real 3D location of anatomical and pathological structures, it is easier for the computer to reach the target. The great progress in robotics also allows to use high-precision robots like Zeus of Computer Motion. The surgeon will then use a surgical simulator in order to program the robot that will reproduce and improve his/her movements by removing trembling and by reaching the target faster. Our current work consists thus in the develop-

	Average distance (mm) ± std.	Minimum distance	Maximum distance	Average time (sec.) ± std.
Engineer 1	0.95 ± 0.67	0	2	25 ± 5.6
Engineer 2	1.7 ± 0.97	0	3	14 ± 2.0
Engineer 3	1.8 ± 0.84	0	3	18 ± 5.5
Surgeon 1	2.2 ± 0.57	1	3	32 ± 12.2
Surgeon 2	2.9 ± 1.25	0	5	22 ± 3.1
Surgeon 3	1.3 ± 1.16	0	3	32 ± 3.7
Professor	0.84 ± 0.48	0	1	32 ± 6.4
All	1.8 ± 0.7	-	-	23.8 ±7.3

Table 1. Accuracy and time results obtained by each user. The average distances, always below 3 mm, prove that our system provides an important targeting accuracy. Moreover, the time needed is under 1 minute whereas an expert needs routinely 10 minutes for such intervention.

ment of automated suturing [13] and automated radiofrequency ablation [11]. Such a system could be available in only one year for radiofrequency ablation procedures or for laparoscopic surgery by restricting the superimposed information to fixed structures. The next step will then be to provide similar results for deformable organs. Finally in the near future, patients will become virtually transparent and robots will become the new surgical instrument of surgeons, thus offering great progress in all surgical procedures (see figure 5).

7. Conclusions

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 use preoperative information during intervention, in particular by superimposing the virtual image of internal organs and pathologies on the abdomen of the patient. 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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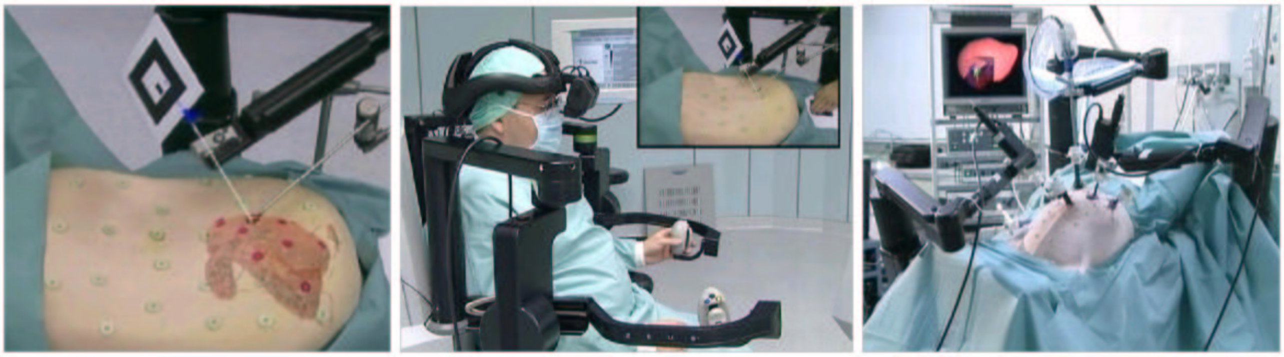

Figure 5. By combining Augmented reality (left) and robotics (center) accuracy of image-guided surgery will be improved and will lead to the future automated surgery (right).

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