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STEREOSCOPIC AUGMENTED REALITY FOR INTRAOPERATIVE GUIDANCE IN ROBOTIC SURGERY

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Augmented reality (AR) technology is increasingly adopted in the surgical field and recently it has been also introduced in robotic-assisted urologic surgery.
This work describes the design and development of an augmented reality intraoperative guide system with stereoscopic visualization (SAR, stereoscopic augmented reality) for the Da Vinci surgical robot. As major novelty, the developed SAR system allows the surgeon to have the virtual 3D model of patient anatomy superimposed on the real field, without losing the stereoscopic view of the operative field.
The workflow starts with the 3D model generation of the anatomical district of interest for surgery, from patient diagnostic imaging. Then, the 3D model is uploaded in the developed SAR application, navigated using a 3D space mouse, and superimposed to the operative field using computer vision algorithms.
The SAR system was tested during 30 robot-assisted surgeries, including 20 partial nephrectomies, 1 kidney explant, and 9 radical prostatectomies. The SAR guidance system received overall great appreciation from surgeons and helped in localizing hidden structures, such as arteries or tumoral masses, increasing the understanding of surgical anatomy with depth perception, and facilitating intraoperative navigation. Future efforts will be addressed to improve the automatic superimposition of digital 3D models on the intraoperative view.

Keywords: Stereoscopic Augmented Reality, Intraoperative guidance, 3D models, robotic-assisted surgery, urology.

1. Introduction

Robotic surgery utilization has increased over the years across a wide range of surgical procedures[1]. The Da Vinci robotic system, designed and manufactured by Intuitive srl, is the predominant platform around the world[2]. One of its main features consists of a 3D vision system on the surgeon console[1,2], which allows the surgeon to have a binocular perspective of the operative field, thus supplying a depth perception of the anatomical structures[3]. The physical principle behind depth perception from a stereoscopic view is called stereopsis[4] in which the brain automatically reconstructs a 3D structure given two slightly different images[4]. It has been demonstrated that a binocular view of the operative field improves surgical outcomes, the learning curve of novel surgeons, and overall comfort during the procedure[3].

To further help surgeons before and during the surgical procedure, patient-specific anatomical 3D models obtained from diagnostic image segmentation have been recently introduced[5–10]. Surgeons can study the anatomical 3D model before surgery and use it to explain to the patient the surgical procedure[11]. Moreover, with augmented reality (AR) applications which provide the superimposition of the digital 3D models on the real surgical scene, it is possible to guide the surgeon intraoperatively, showing hidden structures and allowing a neater view of the anatomical structures of interest. In recent years, many experiences of using AR for intraoperative guidance have been reported in urological surgery[12–16], as well as in other surgical specialties like maxillofacial[17–23]and neurosurgery[24,25].
As the binocular view of the operative field introduced many benefits to the surgical procedure [3], this paper describes the development of an application for stereoscopic augmented reality (SAR) applied to robotic surgery using the Da Vinci system. The SAR application provides the surgeon with a 3D visualization of both the operative field and the superimposed anatomical 3D model.

2. Materials and Methods

2.1. Patient-specific anatomical 3D model generation

The process started with the acquisition of contrast-enhanced computed tomography (CT) scan of a patient's abdomen, being treated at the Urological Surgery Unit of IRCCS Azienda Ospedaliero Universitaria di Bologna. Participants signed written informed consent. The study was approved by our Institutional Ethics Committee (IRB approval 3386/2018).
The image segmentation was performed using DICOM TO PRINT Software (3D Systems, Rock Hill, South Carolina) (Figure 1). A threshold-based interpolation segmentation was mainly used for the identification of the kidney parenchyma, tumoral masses, arterial and venous main branches, and excretory ways. Then the segmented masks were converted into meshes (saved as STL files) so as to obtain a 3D- model reconstruction of the preoperative patient kidney components. The resulting segmentation masks and 3D models were accurately checked and approved by a professional radiologist. The model was colored to give a semantic map of the components, and a navigable 3D model was generated from the STL files, using Autodesk Meshmixer (Autodesk, San Rafael, California). The navigable 3D model and some selected views were sent to the surgical unit for preoperative planning.

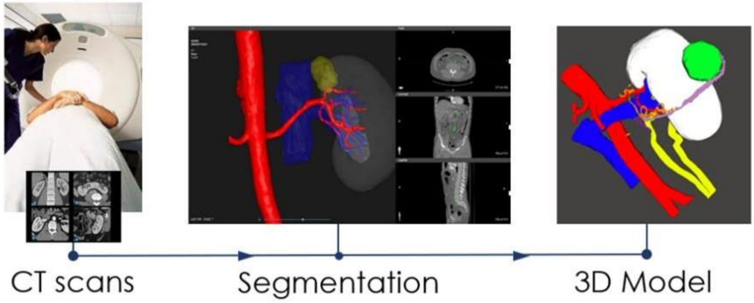


Fig. 1: Segmentation masks and 3D models of the preoperative patient kidney components.

2.2. Stereoscopic Augmented Reality (SAR) application

The application for SAR requires two slightly different images of the 3D model to be superimposed correctly to the feeds received from the robotic endoscope stereo camera. This has been achieved by generating a virtual stereo camera consisting of two virtual cameras in a digital environment at a fixed distance and relative angle. Each camera provides a visualization of the 3D model from its point of view, resulting in a digital copy of the endoscope stereo camera (Figure 2).
The parameters of the virtual stereo camera such as Near and Far clipping plane, focal point, and view up direction, as well as stereo camera parameters such as distance and relative angle of the two cameras have been initially guessed and then calibrated using the Da Vinci system 3D headset in the surgeon console.

The application was developed in C++, using the Visualization ToolKit (VTK) library to manage the virtual environment, i.e. to upload the STL files of the 3D models, to adjust virtual environment lights, camera settings and 3D model rendering; the OpenCV library was used to manage the images from the surgical endoscope and the superimposition between the 3D model views and the endoscope camera feeds.
The model views images were adapted in dimension to fit the endoscope camera feed, which is acquired using a dedicated thread to maintain a real-time constraint and minimize delays.
AR images were produced by blending the 3D model images with the endoscope camera images, managing the transparency of the model by keyboard input during surgery.
During the procedure the 3D model is manually aligned by a biomedical engineer using a 3D mouse (Spacemouse Wireless, 3DConnexion Inc., Germany) which allows to change the pose (translations and rotations) of the 3D model. Such an input system was integrated into the application using its own software development kit in order to get the raw data of the mouse pose.

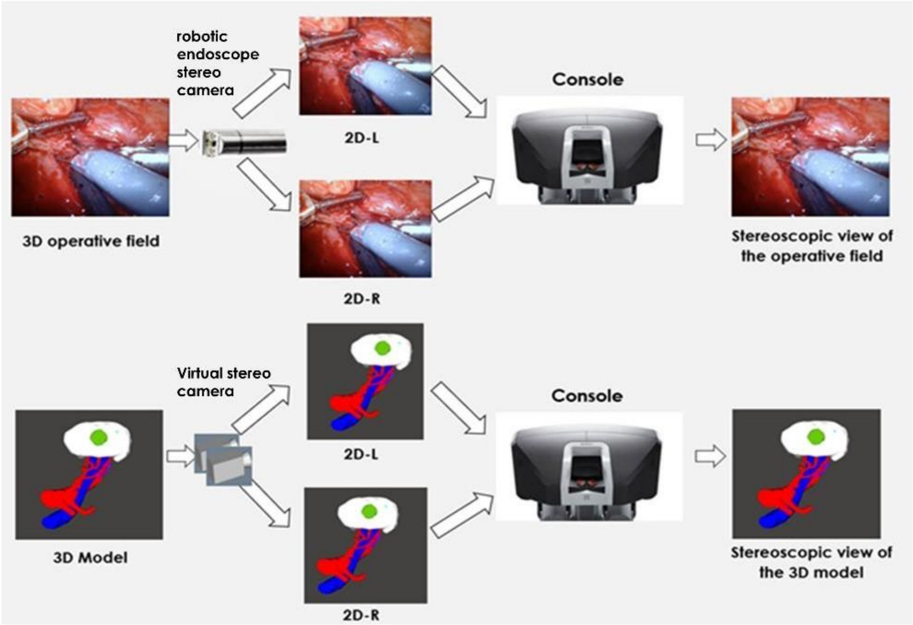


Fig. 2. The implemented digital 3D model stereovision that mimics the actual stereoscopic view of the robotic endoscope during surgery.

2.3. Hardware connections to implement the SAR system in the operative room

The Da Vinci system is composed of three main components: the patient cart, which consists in the robotic arms with tools operating on the patient; the video cart, which is the central node, managing the data flow, the endoscopic stereo camera, and electrifying the surgical tools; and the surgeon console, where the surgeon sits and carries out the procedure controlling the robotic arms via two controllers and seven pedals. During the robotic procedure, the surgeon looks at the operative field through a 3D headset which automatically merges the images from the endoscope stereo camera to give a stereoscopic view of the operative field.

The SAR system extracts the real-time feeds of the robotic endoscope cameras using two DVI-DVI cables connected to the Da Vinci video cart output ports. The signals are acquired by an operative room desktop computer (OR PC) through two video capture cards (Startech USB 3.0 StarTech Ltd., The Netherlands). The OR PC then processes the AR images and transmits them to the Da Vinci 3D viewer using the two TilePro input ports of the Da Vinci surgeon console. These AR images are automatically merged to obtain a stereoscopic vision using the TilePro 3D function of the Da Vinci system (Figure 3).

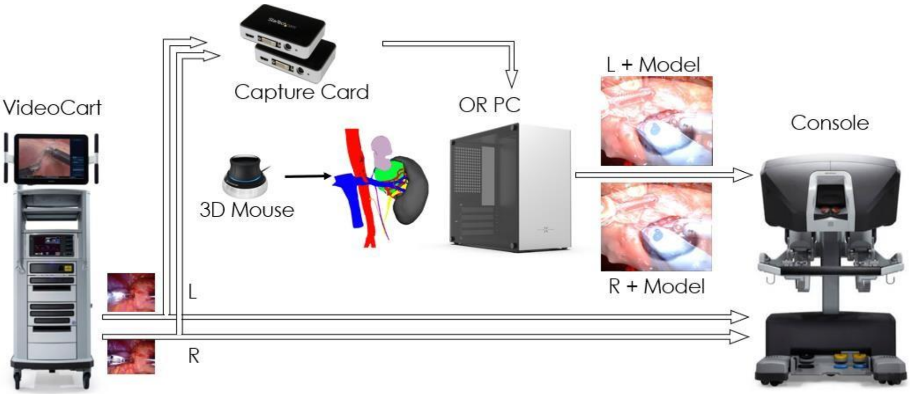
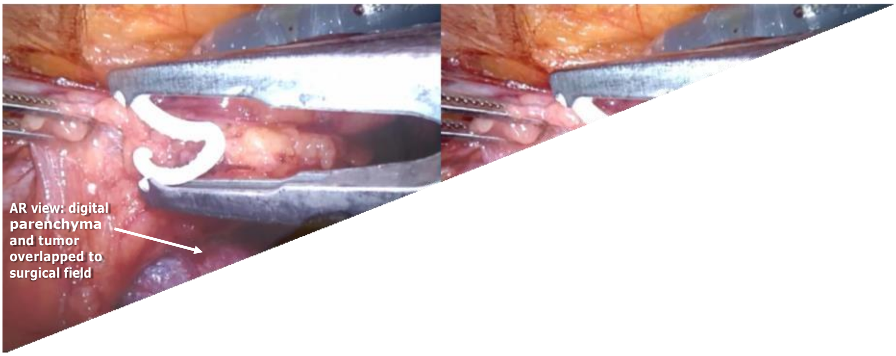


Fig. 3. Schematic representation of the hardware connections to implement the SAR system in the operative room.

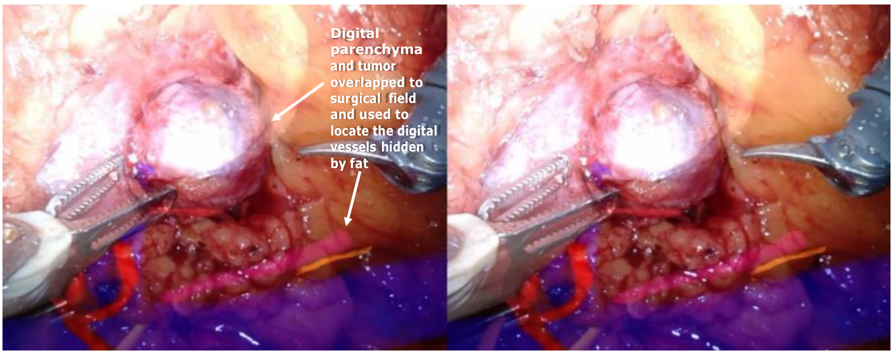
2.4. Experimental phase

The described SAR system has been tested by the Urological Surgery Unit of IRCCS Azienda Ospedaliero Universitaria di Bologna during 30 robot-assisted surgeries, including 20 partial nephrectomies, 1 kidney transplant, 9 radical prostatectomies (Figure 4). The 30 surgical procedures were performed by two urological surgeons with similar experience and skills in robotic-assisted surgical procedures dealing with kidney and prostate tumors.

The new SAR system was evaluated by collecting the two surgeons' feedbacks through a questionnaire, based on a Likert 5-point scale, regarding aspects, such as the 3D model fidelity, the usefulness of the 3D anatomical model in the preoperative phase, the usefulness of the intraoperative SAR guidance, the impact of this technology on the procedure time.



a



b

Fig. 4. Two examples (a, b) of SAR view in the operative field. Left and right images of the SAR tool are sent to the left and right screen of the surgeon console respectively and merged using the TilePro 3D function of the Da Vinci system to provide a stereoscopic view to the surgeon.

3. Results

The 3D anatomical modeling and SAR system received overall great appreciation from surgeons who used it.

The two surgeons' feedbacks, as resulting from the questionnaire, were collected in Figure 5.

For partial nephrectomy, the usefulness of SAR guidance was perceived as very satisfactory (score 5) in half of the procedures, and satisfactory (score 4) for the remaining half of the procedures (Fig. 5a). The fidelity of the 3D anatomical model, its usefulness in the preoperative phase, and the perceived accuracy of digital-to-real alignment were rated rather satisfactory (80% score 5 + 20% score 4, 75% score 5 + 25% score 4, and 60% score 5 + 40% score 4, respectively) (see Fig. 5b-d).

For prostatectomy procedures, we obtained similar results of overall good satisfaction regarding the SAR usefulness (55% score 5 + 45% score 4, see Fig. 5a), and a very satisfactory feedback (100% score 5) regarding the 3D model fidelity and its usefulness

in preoperative phase (Fig. 5b-c). Instead, a lower score was collected for the perceived accuracy of digital-to-real alignment (90% score 4, see Fig. 5d).
For the single case of kidney transplant, there was slightly less enthusiastic feedback regarding the SAR usefulness, the 3D model fidelity and its usefulness in preoperative phase (Fig. 5a-c), while the accuracy of digital-to-real alignment was rated very satisfactory (Fig. 5d).

For other aspects such as the hardware encumbrance of SAR system in the OR, its ease of use, the perceived lag of SAR view superimposed on the real field and the impact of the digital-to-real alignment on OR times, very positive feedback (score 5) were collected for all three types of procedure (Fig. 5d-g).

4. Discussion

In this study, we successfully introduced a stereoscopic augmented reality (SAR) view used as intraoperative guidance, based on patient-specific anatomical 3D models in both robot-assisted partial nephrectomy and robot-assisted radical prostatectomy. All surgical procedures were conducted without intraoperative incidents and without switches to radical nephrectomy.

The introduced tool offers the possibility to visualize and navigate the anatomical 3D model alone or superimposed to the operative field, using the implemented SAR application, directly in the Da Vinci surgeon console 3D viewer.
Interfacing with the Da Vinci system was feasible, and such a system has proven fit to augmented reality applications, being provided with a high-quality endoscopic stereo camera and a 3D viewer.

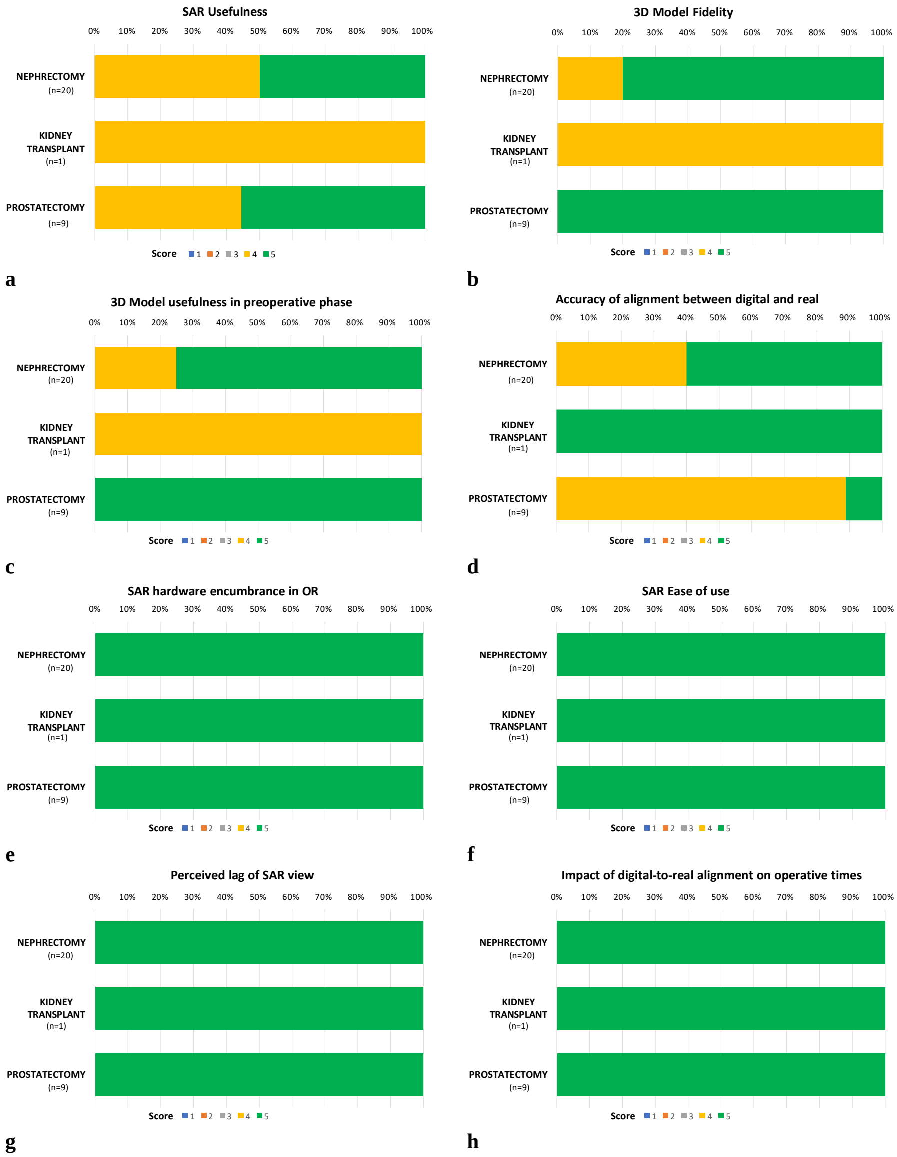


Fig.5. Results collected from the questionnaire based on 5-point Likert scale rating. 1: very unsatisfying; 2: unsatisfying; 3: neutral; 4: satisfying; 5: very satisfying.

The results of the questionnaire clearly showed that the digital anatomical 3D model is user-friendly and aids the surgeon during various phases of the operation. Preoperative planning using 3D models creates improved visualization of the exact location of tumors relative to renal vascularization branches and urinal calices, that may result in a change of the robotic tools pathway during the procedure. The SAR guidance helped in localizing hidden structures, such as arteries or tumoral masses, increasing the understanding of surgical anatomy with depth perception, and facilitating intraoperative navigation. Moreover, the digital 3D models allowed intraoperatively quick measurements of the anatomical dimensions using Autodesk Meshmixer software. This was deemed helpful by the surgeon for tumor enucleation and vascularization isolation. The most positive feedbacks were collected for nephrectomy procedures, while it seems that in prostatectomy a greater difficulty was perceived in real-time alignment between the 3D digital model and the real field (lower score of accuracy in alignment, Fig. 5.d). This can probably be explained by the fact that during the prostatectomy procedure the organs (e.g. the prostate or the neighboring structures) are frequently displaced by the robotic arms (e.g., overturned), so it is more difficult to follow those movements and correctly reposition the digital model on the real anatomy. Indeed, when surgery involves soft tissue organs as in this case, one of the major critical points is that the digital anatomical model is not deformable since it is generated from preoperative images. Future efforts should be devoted to implementing a deformable 3D model to be stretched, bent and aligned to the real anatomical structures of the surgical environment.

Although the results from this feasibility study seem promising, larger case-matched or randomized trials, with clear surgical endpoints (e.g., blood loss, length of hospital stay) or oncologic endpoints (e.g., resection margin status, recurrence-free survival and overall survival) are required to examine whether preoperative planning and intraoperative guidance using stereoscopic augmented reality in robot-assisted partial nephrectomy and radical prostatectomy leads to change in surgical management (e.g. reduce the operation time and/or decrease the blood loss) and subsequently improves patient's outcome.

Another limitation of this study is that, although this SAR application provides a real-time visualization, the alignment between real patient anatomy and the digital 3D model is achieved manually. Every time the surgeon moves the endoscope or the organ, the alignment is lost and needs to be reinitialized by an operator in the OR.
As future improvement, research efforts should be addressed to develop and test automatic or semi-automatic algorithms (e.g. based on artificial intelligence) to automatically adjust the overlapping of the 3D virtual model to the surgical view while the surgeon is operating.

5. Conclusion

This work introduces the next step toward an innovative AR-based intraoperative guiding system for robotic surgery, focusing on the 3D visualization of the anatomical structures in stereoscopic augmented reality (SAR). Future efforts will be addressed to improve the automatic or semiautomatic superimposition of digital anatomical 3D models on the intraoperative field view.

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