Virtual Assistive System for Robotic Single Incision Laparoscopic Surgery

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***Abstract*—Single Incision Laparoscopic Surgery (SILS) reduces the trauma of large wounds decreasing the post-operative infections, but introduces technical difficulties for the surgeon, who has to deal with at least three instruments in a single incision. These drawbacks can be overcome with the introduction of robotic arms inside the abdominal cavity, but still remain difficulties in the surgical field vision, limited by the endoscope field of view.**

This work is aimed at developing a system to improve the information required by the surgeon and enhance the vision during a robotic SILS. In the pre-operative phase, the segmentation and surface rendering of organs allow the surgeon to plan the surgery. During the intra-operative phase, the run-time information (tools and endoscope pose) and the pre-operative information (3D models of organs) are combined in a virtual environment. A point-based rigid registration of the virtual abdomen on the real patient creates a connection between reality and virtuality. The camera-image plane calibration allows to know at run-time the pose of the endoscopic view.

The results show how using a small set of 4 points (the minimal number of points that would be used in a real procedure) for the camera-image plane calibration and for the registration between real and virtual model of the abdomen, is enough to provide a calibration/registration accuracy within the requirements.

I. INTRODUCTION

In open surgery of the abdominal areas, the resulting wound carries the risk of infection or dehiscence and can contribute to post-operative chest infection, ileus and immobility. Minimally Invasive Surgery (MIS) can improve the physiological and immune responses associated with open surgery, reducing the trauma to a minimum [1][2]. Single Incision Laparoscopic Surgery (SILS) has been advocated as the next step towards even less invasive surgery. However, SILS introduces some limitations: the surgeon's maneuverability is reduced due to the clustering of instruments in a single access port, which increases instrument collisions. Also the surgeon has to cross the instruments during the operation to achieve triangulation for tissue retraction. Moreover, the freedom of movement of the endoscopic cameras inside the patient's body is extremely restricted due to the single port access to the inside of the patient, decreasing the number of perspectives. Thus, structures of interest, as blood vessels or cancer areas, cannot be seen from different points of view, compromising the accuracy and safety of the surgery. The operative view is also restricted and the tactile sensing reduced, resulting in a long learning curve and increased operative times [3].

These drawbacks have motivated the recent development of advanced robotic systems for SILS [3]. Robotic-assistant may be able to restore the intuitive perception of the operation field to the surgeon. The commercial systems Da Vinci® and Amadeus® have been modified with a set up for SILS. And projects like SPRINT [4] are based on the concept of single port surgery. The main difficulties for the surgeon remain the loss of depth perception, in case of monocular endoscopic camera, and the restricted field of view of the endoscopic camera (usually 70° instead of 120° of the human eyes) [5]. Another issue to be considered in single port robotic surgery is the fact that the robot could be completely inside the abdomen. In vivo devices need automatic tracking and localization systems in order to know exactly their position and to better use the potentials of the surgical tools that are completely hidden to the eyes of the surgeons.

These disadvantages can be reduced by computer technologies by enhancing the view of the surgical field [6]. Information related to the pre-operative analysis of the disease and to the planning of the surgery can be fused with the intra-operative visualisation of the surgical field. This gives the surgeon all the necessary information to perform an accurate intervention. An Augmented Reality (AR) or Augmented Virtuality (AV) system allows to reduce the previously cited drawbacks and provide a more comfortable and efficient environment for the surgeon [7]. Motivated by the increasing amount of imaging data, which makes the analysis of 2D imagery obsolete, current researchers investigate efficient 3D volume rendering techniques for presenting CT or MRI data. There are multiple software packages allowing the segmentation of organs in CT/MR images and 3D modeling and visualization of patient anatomy. In [8] the authors developed an augmented reality computer guiding system combining the pre-operative 3D modeling with the intra-operative information provided by endoscopic cameras.

In this paper we propose a novel architecture for robotic SILS which easily allows the extraction of the a 3D model of the patient from a CT scan, acquired during the pre-operative planning, and the use of it during the intra-operative phase. This architecture allows the guidance of the surgical intervention improving the operative vision and the safety of the system. In this work we present a pipeline for the extraction of the surface rendering of abdominal organs and, the development and evaluation of the intra-operative assistive system. In a first implementation, the system accuracy required by our team of surgeons has to be inferior to 10mm, considering the motion of the organs due to heart beating and breathing. Future development has to take in account this important issue.

II. SYSTEM DESCRIPTION

The following subsections describe the proposed virtual assistive system. In the pre-operative phase a pipeline developed in 3DSlicer [9] allows to create a virtual model of the specific patient. While in the intra-operative phase, the coexistence of virtual and real surgical environment enhances the information required by the surgeon.

A. Pre-operative Pipeline

Providing a 3D visualization of the pre-operative patient data is the first step to develop an enhanced vision system. It helps the surgeon to view the entire model of the abdomen and to identify and highlight important structures, such as main vessels or cancer areas. The extraction of such information is fundamental during the surgery. The main targets, suggested by surgeons with experience in abdominal surgery, are: liver, kidneys, spleen, gallbladder, aorta and main veins. A standardization of a workflow for segmentation and surface rendering of anatomical structures from pre-operative abdominal CT-scan was designed and developed, using already implemented modules of the open-source software 3DSlicer. The segmentation of the organs is initialized by drawing a seed on CT slices. An active contour model then evolves to segment the organ in the sagittal, coronal and axial planes [10]. The 3D surface model is computed through a marching cubes algorithm, using triangle reduction and triangle smoothing algorithms [11]. This process can be realized by a trained technician using only a few mouse clicks. An example of the different capabilities of this module is shown in Figure 1.

B. Intra-operative Virtual Environment

During the intra-operative phase, in our setup, the surgeon is performing the operation through a small incision using a robot. The arms of the robot are completely inside the abdomen and are controlled by the surgeon from a remote console. The surgeon lacks of direct visual feedback since he cannot view directly the robot arms. The feedback of the surgeon is provided only by the stereo cameras mounted on the robot. However, the field of view of the stereo-cameras is restricted with respect to the field of view of the human eyes, and the cameras show only a small portion of the surgical scene. This is not enough in case of robotic single port surgery, since single port robotic procedure requires to view the pose of the robot and of the tools with respect to the organs in order to perform surgery safely. Usually, Augmented Reality (AR) is proposed in order to superimpose pre-operative information on the real images, adding knowledge related to the pathology of the patient. This technique is used only in specific particular moments during the surgical procedure, because the physician prefers to work without superimposition for a long time. In our system we proposes the coexistence of virtual and real environment representing the surgical scene during the entire surgery, instead of AR. It consists of two main views, showed in Figure 2:

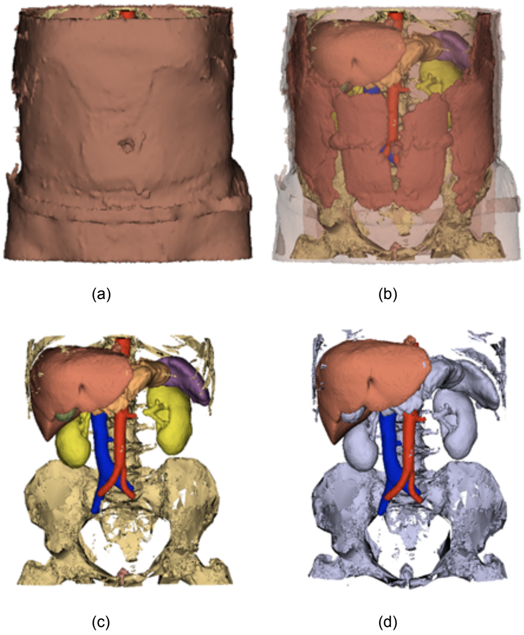


Fig. 1. Sample views of 3DSlicer showing different representations of a man abdominal model extracted from a CT scan. a) This image shows the model of the skin. b) The software allows to put the skin in transparency to visualise the internal structures. c) Representation of the internal structures with a color labeling code. d) It is also possible to highlight target structures (vein, aorta and liver).

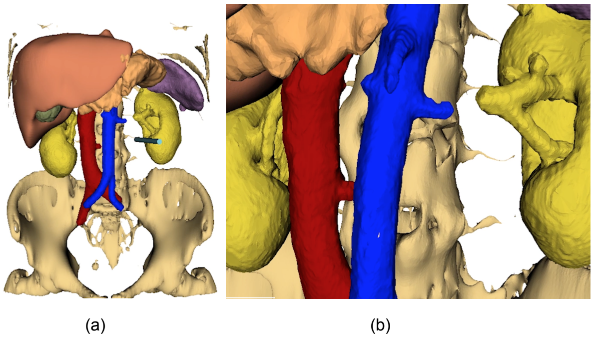


Fig. 2. This figure represents the virtual environment viewed by the surgeon during the surgical operation. a) The view of the entire abdomen makes possible to visualise at run-time the motion of the surgical tools inside a virtual abdomen patient-specific. b) The virtual camera image plane shows the structures visualized by the camera form the same point of view in the virtual environment.

- **view of the entire abdomen**: In this view, the reconstructed 3D patient abdomen anatomy is displayed to the surgeon intra-operatively. The system allows to add or remove structures; to rotate and translate the model in order to view the structure of interest from different points of view; and to change the transparency of the organs to see the internal vessels or cancer areas. Moreover, the virtual robot and its camera can be added to the reconstructed patient model. If the real pose of the robot is known, the virtual model of the robot can be mapped to the real one. The surgeon views in the virtual environment the same elements of the reality navigating in the patient abdomen following its real motion.

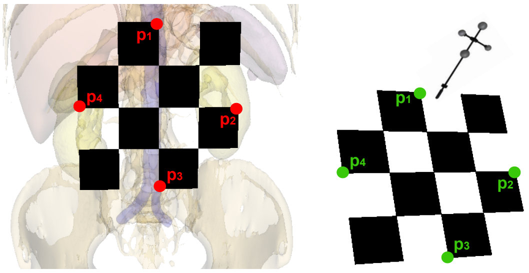
- **view of the virtual camera**: Alongside the view of the entire abdomen, the image plane of a virtual camera is used to mimic the point of view of the real camera. In this work, we simulate the camera attached to the robot with a simple webcam, that is tracked by an optical tracker. In order to know the position of the real image plane, a *camera-image plane calibration* is computed. First, a planar chessboard is used to compute the intrinsic parameters of the camera. On the same chessboard, four points are identified both by the camera, using image processing, and by a pointer tracked by the optical tracker. Using the positions of the same corners in the reference frame $\{ImagePlane\}$ and $\{Tracker\}$ it is possible to compute the transformation $T^{ImagePlane}_{Tracker}$. But $T^{ImagePlane}_{Camera}$ still has to be known. Knowing the position of the camera in $\{Tracker\}$, the transformation $T^{ImagePlane}_{Camera}$ is computed, as shown in Equation 1. Figure 4 explains the relation between the different reference frames. In order to have correspondence between the real and virtual model, a *virtual-real 3D/3D registration* is computed. It consists in the rigid point based registration [12] of the virtual model on the real abdomen of the patient. The same fiducial landmarks are selected on the virtual model, positioning virtual fiducial points and on the real patient pointing the same landmarks with a tracked pointer, as shown in Figure 3. Using three or more points the transformation between the two model is computed and the virtual model is re-oriented. In the evaluation of the virtual assistive system we simulate a patient using a simple chessboard and we decided to use a minimum number of points in order to simulate as much as possible the real procedure executed by the surgeon during the surgery. However, in real scenario the surgeon could choose external anatomical landmarks easily identifiable.

$$T^{ImagePlane}_{Camera} = (T^{Camera}_{Tracker})^{-1} * T^{ImagePlane}_{Tracker} \quad (1)$$

III. EVALUATION

The evaluation of the system is done by testing the *virtual-real 3D/3D registration* and the *camera-image plane calibration*. These procedures affect the accuracy of the guiding system.

Regarding the registration between the real and the virtual model, a virtual and real planar chessboard is used to evaluate the registration error. 12 corners are selected in $\{RealWorld\}$ using a pointer tracked by the optical tracker and in $\{VirtualWorld\}$, adding points on the chessboard in the virtual environment. The $T^{VirtualWorld}_{RealWorld}$ is used to re-project the 12 points selected from $\{RealWorld\}$ to $\{VirtualWorld\}$. The registration error is calculated with the Root Mean Square Error (RMSE) of the point distances, as shown in Equation 2.



(a) (b)

Fig. 3. a) This figure shows the virtual model of the chessboard used for the simulatation of the registration process. In 3DSlicer the surgeon selects the fiducial landmarks, in this case four corners. b) The same fiducial landmarks are pointed on the real model with a pointer tracked by the Optical Tracker.

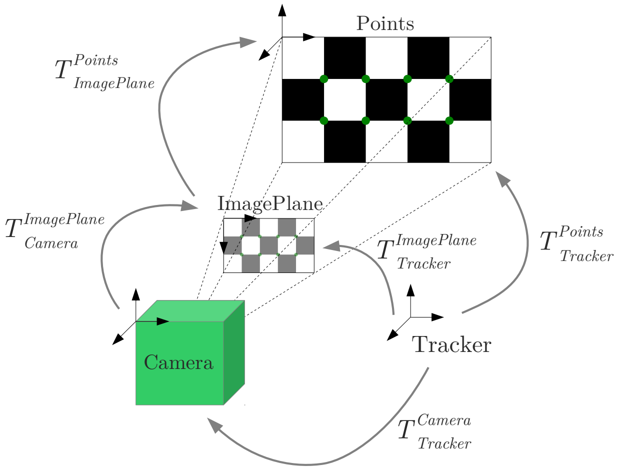


Fig. 4. Relation between the different reference frames used during the camera-image plane calibration.

$$RMSE = \sqrt{\frac{\sum_{n=1}^{12}(p_x^2 + p_y^2 + p_z^2)}{n}} \quad (2)$$

In Table I we can see the results of the registration procedure, which was executed 10 times. The mean of the registration error was $4.13mm$.

TABLE I
EXPERIMENTAL MEASUREMENTS OF THE REGISTRATION ERROR

Trial	1	2	3	4	5
RMSE (mm)	3.65	4.15	4.29	4.39	4.12
Trial	6	7	8	9	10
RMSE (mm)	3.65	3.40	4.17	4.22	3.79

The same evaluation was performed to test the *camera-image plane calibration*. 8 points were selected in $\{ImagePlane\}$ using image processing function for the corners detection and in $\{Tracker\}$ using a tracked pointer. Table II shows the calibration error in 10 trials. The median value of the error was $1.72mm$.

TABLE II
EXPERIMENTAL MEASUREMENTS OF THE CAMERA-IMAGEPLANE CALIBRATION ERROR

Trial	1	2	3	4	5
RMSE (mm)	2.25	2.32	2.03	1.09	1.07
Trial	6	7	8	9	10
RMSE (mm)	1.58	1.90	1.84	1.61	1.43

Note that the registration and calibration errors are affected by several factors: the accuracy of the optical tracker, the accuracy of the pointer, the human error in the positioning of the pointer and the precision of the recognition of the chessboard corners. The optical tracker used for the experiments was an Optitrack Motion Capture System (NatualPoint). In our setup, it was composed by four cameras, covering a volume of around $1m^3$. The obtained mean error of system calibration was $0.2mm$.

The position of the tip of the pointer was computed using the pivoting method. In this method the tip of the pointer is maintained in a fixed position, while the pointer is rotated along two perpendicular axes. Consequently, the position of the tip of the pointer is calculated as the center of the sphere described by the markers. The maximum residual error of this procedure was $0.59mm$.

IV. DISCUSSION AND CONCLUSION

The system presented in this paper is aimed at enhancing the information that the surgeon receives during robotic SILS. Using the pre-operative pipeline, the surgeon can extract 3D surface models from CT scans of the patient with a few mouse clicks. During the surgery, semi-automatic point-based registration of the virtual abdomen on the real patient creates a connection between reality and virtuality. The virtual environment, composed of the view of the entire abdomen and the view of the image plane of the virtual camera, makes possible to visualize at run-time the motion of the robot and of the surgical tools inside a virtual abdomen specific for each patient. The possibility to change the transparency of the skin allows the surgeon to plan the entry point, adjusting the access region with respect to the target to reach. Moreover, the virtual camera image plane shows the structures visualised by the camera from the same point of view in the virtual environment. Adding or removing organs in the virtual patient enables the visualization of the behind structures using transparencies and to zoom out if the surgeon desires to view a wider field of view.

The results obtained form the *virtual-real 3D/3D registration* and the *camera-image plane calibration* are within the specification requirements of the surgeon (accuracy below 10mm). Regarding the *virtual-real 3D/3D registration* results, it has to be considered that we used only four points for the registration of the models, in order to simulate as much as possible the real procedure executed by the surgeon during the surgery. In a real scenario, the number of available reference points would be very limited, so the system was tested under that assumption. However, there are several sources that influence the accuracy of the registration, such as the inherent error of the Optical Tracker and the tool calibration, which can be improved in future developments.

V. FUTURE WORKS

The presence of a virtual environment representing the reality during the surgical operation is an additional tool, which could improve the safety of the robotic surgery. Future tests will be aimed to evaluate the usability of the virtual environment.

Considering the drawbacks of organs motion due to breathing, blood circulation, and surgical tool interaction, a future goal is to track abdominal structures and to adjust at run-time the registration of the virtual model. The final system will consist also in a 3D reconstruction of the surgical field using stereo cameras and in the definition of dynamic active constraints, which will adapt in real-time to compensate for tissue motions and deformations.

REFERENCES

[1] J. E. Varela, S. E. Wilson, and N. T. Nguyen, "Laparoscopic surgery significantly reduces surgical-site infections compared with open surgery," *Surgical endoscopy*, vol. 24, no. 2, pp. 270–276, 2010.

[2] R. H. Taylor and D. Stoianovici, "Medical robotics in computer-integrated surgery," *Robotics and Automation, IEEE Transactions on*, vol. 19, no. 5, pp. 765–781, 2003.

[3] G. Taylor, J. Barrie, A. Hood, P. Culmer, A. Neville, and D. Jayne, "Surgical innovations: Addressing the technology gaps in minimally invasive surgery," *Trends in Anaesthesia and Critical Care*, vol. 3, no. 2, pp. 56–61, 2013.

[4] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastri, A. Menciassi, and P. Dario, "Design of a novel bimanual robotic system for single-port laparoscopy," *Mechatronics, IEEE/ASME Transactions on*, vol. 15, no. 6, pp. 871–878, 2010.

[5] M. Baumhauer, M. Feuerstein, H.-P. Meinzer, and J. Rassweiler, "Navigation in endoscopic soft tissue surgery: perspectives and limitations," *Journal of Endourology*, vol. 22, no. 4, pp. 751–766, 2008.

[6] S. Nicolau, L. Soler, D. Mutter, and J. Marescaux, "Augmented reality in laparoscopic surgical oncology," *Surgical oncology*, vol. 20, no. 3, pp. 189–201, 2011.

[7] S. Nicolau, L. Goffin, and L. Soler, "A low cost and accurate guidance system for laparoscopic surgery: Validation on an abdominal phantom," in *Proceedings of the ACM symposium on Virtual reality software and technology*. ACM, 2005, pp. 124–133.

[8] C. Bichlmeier, S. M. Heining, M. Feuerstein, and N. Navab, "The virtual mirror: a new interaction paradigm for augmented reality environments," *Medical Imaging, IEEE Transactions on*, vol. 28, no. 9, pp. 1498–1510, 2009.

[9] S. Pieper, M. Halle, and R. Kikinis, "3d slicer," in *Biomedical Imaging: Nano to Macro, 2004. IEEE International Symposium on*. IEEE, 2004, pp. 632–635.

[10] Y. Gao, A. Tannenbaum, and R. Kikinis, "Simultaneous multi-object segmentation using local robust statistics and contour interaction," in *Medical Computer Vision. Recognition Techniques and Applications in Medical Imaging*. Springer, 2011, pp. 195–203.

[11] J. Rossignac and P. Borrel, *Multi-resolution 3D approximations for rendering complex scenes*. Springer, 1993.

[12] B. K. Horn, "Closed-form solution of absolute orientation using unit quaternions," *JOSA A*, vol. 4, no. 4, pp. 629–642, 1987.