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Augmented Reality-based Robot Control for Laparoscopic Surgery

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Abstract: Minimally invasive surgery is the standard for many abdominal interventions, with an increasing use of telemanipulated robots. As collaborative robots enter the field of medical interventions, their intuitive control needs to be addressed. Augmented reality can thereby support a surgeon by representing the surgical scene in a natural way. In this work, an augmented reality based robot control for laparoscopic cholecystectomy is presented. A user can interact with the virtual scene to clip the cystic duct and artery as well as to manipulate the deformable gallbladder. An evaluation was performed based on the SurgTLX and system usability scale.

Keywords: Computer Assisted Surgery, Augmented Reality, Cognitive Surgical Robotics, Robot Control

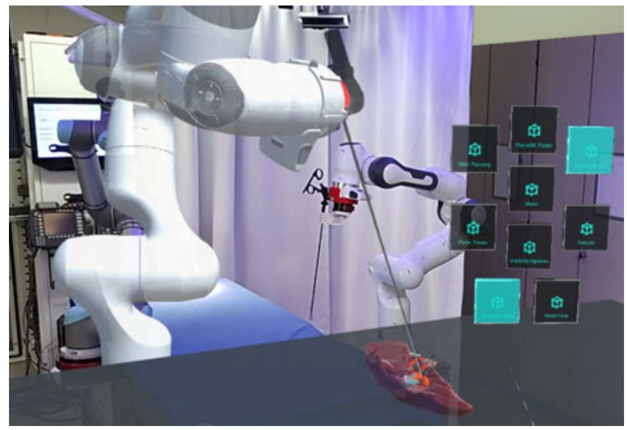

Fig. 1: Virtual scene with robot and menu in the foreground, and real operating room table and robot in the background.

1 Introduction

Minimally invasive surgery (MIS) offers many advantages for patients, such as faster healing times and reduced access trauma [1]. For the surgeon, however, MIS comes with several limitations in usability. Vision is limited to the endoscopic camera stream and hand-eye coordination becomes increasingly complex because the surgeon shifts attention from the own hands to the motion of laparoscopic instruments. In addition, a lack of haptic perception is noticeable. Compared to open surgery, the three-dimensional depth is missing [2], which makes it difficult to interpret the surgical scene. Recently, new head-mounted displays (HMDs) have been introduced, significantly advancing the state of the art and presenting systems that can be used in the operating room (OR). With augmented reality (AR), it is possible to visualize the surgical scene in its original scale as holograms that can be superimposed over the patient or placed freely in the OR. Thus, AR can assist by intuitively visualizing 3D environments or support in training surgeons in these procedures. Here, we focus on the removal of the gallbladder from the liver, i.e. cholecystectomy, as an exemplary surgical procedure. Towards automation of single tasks in laparoscopic surgery, a next step is the use of a context-sensitive robotic system that is able to manipulate surgical instruments and can be used in close cooperation with the surgeon. An intuitive approach to control the robot is through a HMD.

AR assistance have been applied to several medical applications. Park et al. [3] presents a system utilizing the HoloLens 2 to place biopsy needles for lesion treatment. Schneider et al. [4] proposed a system for AR assisted ventricular drain placement and reached a higher success rate in comparison to the standard of care. AR visualization for laparoscopic procedures was originally introduced by Fuchs et al. [5] in 1998, but was limited by hardware. The ARAMIS system was introduced by Qian et al. [6], which provides real-time x-ray transparency in laparoscopic surgery. In the study, users preferred ARAMIS to endoscopic vision due to a better depth perception and hand-eye coordination. Zorzal et al. [7] applied a Meta 2 HMD to visualize the endoscope video stream in front of the laparoscopic instruments to provide better ergonomics during surgery.

In this work, we present a novel approach for augmented reality-based control of a collaborative surgical robot (as depicted in Fig. 1) that enables intuitive perception of the surgical scene during laparoscopic interventions.

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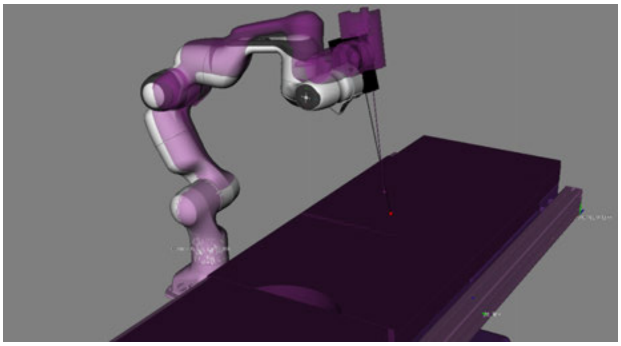

Fig. 2: Visualization of the planned trajectory. Old robot state in original colors, new state in magenta.

2 Material and Methods

For the proposed system, we utilize a Microsoft HoloLens 2 (Microsoft Inc., Redmond, USA) and a workstation (Ubuntu 20.04, Intel i7 9700K, 32 GB RAM) running ROS Noetic (ros.org). The patient models (liver and gallbladder) are taken from the OpenHelp dataset [8].

2.1 Path Planning

The AR visualization is executed on the HoloLens 2, while the path planning is calculated on the external workstation. Two different motion planning algorithms are implemented. The first enables free 6-DOF motion planning with collision detection. The second enables a pivot-based path planning to allow robot control in minimally invasive surgical scenarios. The execution of the path planner is visualized in Fig. 2. The tool center point (TCP) of the mounted instrument can be defined by placing an instrument tip model at the desired location in the virtual scene. The trocar is set by moving the TCP in free mode to the desired location outside the patient's body and can then be saved as a parameter. This is followed by switching to pivot-based planning to support trajectories inside the human body during laparoscopic interventions (Fig. 3 a).

2.2 Augmented Reality Support

Here, we consider the surgical application scenario of laparoscopic cholecystectomy. The AR application supports two tasks of this procedure: the clipping of the cystic duct and artery, as well as the manipulation of the gallbladder. In the presented prototype, the scene and the robot are represented in simulation. In future work, we will utilize the proposed control method with the real robot.

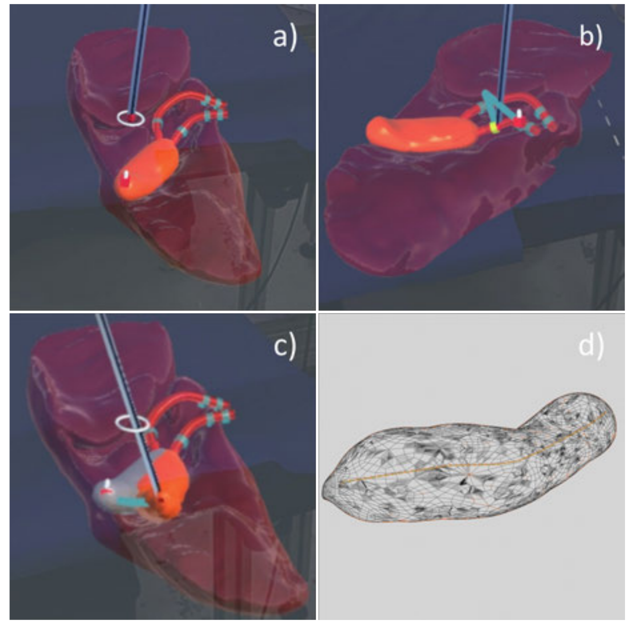

Fig. 3: Tasks represented by the system: a) trocar placement, b) clipping, c) gallbladder manipulation. d) Skeleton structure inside the gallbladder.

For the initial positioning of the AR scene, a Vuforia marker (PTC Inc., MA, USA) is used. The scene can then be placed on any desired position.

The clipping position and orientation is defined by placing the tip model in the virtual scene. After planning, the trajectory is visualized to the user before it is executed upon request. A user can make adjustments or start the execution by the robot. When a clipping point has been successfully reached, its color changes from green to yellow, followed by navigation to all desired clipping positions as visualized in Fig. 3 b. The second scenario covers the grasping of the gallbladder and its manipulation. The surgeon moves to the desired grasping position of the gallbladder and can then initiate a grasp. Subsequently, a new position of the instrument tip is set by the user and the grasped gallbladder is moved to the new desired location (Fig. 3 c). The gallbladder's deformation is modeled (Blender, blender.org) through a skeletal structure inside the virtual gallbladder as depicted in Fig. 3 d. The new deformation state and the path are visualized to the user who may initiate execution by the robot.

One challenge is the small surgical site without the use of a zoom or microscope. To address this shortcoming, the ability to enlarge a scene is implemented, allowing a better view of the surgical site than at its original scale. This allows a more accurate positioning of the tip model and a more detailed visualization of the scene. In this scenario, it seems favorable to position the virtual scene at a neutral position with more space (i.e. on a table) and not directly over the patient.

2.3 Experimental Validation

The AR robot control is evaluated in a user study. The participants were given a short period of time to familiarize themselves with the fundamental interaction possibilities (approx. 5-10 minutes). A technical expert assisted during that time and explained the basics to the participants. After the learning phase, participants were asked to perform two tasks: 1) Placement of the trocar and clipping of the cystic duct and artery, 2) Grasping of the gallbladder and manipulation from the center to the right, back to the center and to the left. This motion pattern was chosen as it emulates the holding task of the assistant surgeon during the removal of the gallbladder.

After system assessment, each participant was asked to complete the SurgTLX [10] and the system usability scale (SUS) questionnaire (see Tab. 1). Additionally, the participants were interviewed after the experiments. They were asked to state the positive and negative aspects of the AR control. The questions of the SurgTLX were rated from "very low" to "very high" demand and those from the SUS from "strongly disagree" to "strongly agree". The overall usability score is calculated from the answers as described by Brooke et al. [9]. The answers are rated in relation to a positive or negative meaning of the question. All questions with a positive meaning (odd) were rated from 0 to 4 and all with negative meaning (even) are scored from 4 to 0. The results were then summed up and multiplied by 2.5. A SUS value above 68 is considered good usability. The study was conducted with five participants (1 medical student, 3 medical and 1 technical expert). None of them had prior experience with AR interfaces. Solely the medical student had assisted a cholecystectomy in the last six month. All participants used the system for the first time with no prior knowledge about it.

Tab. 1: Questionnaire of the system usability scale [9].

Q1	I think that I would like to use this system frequently.
Q2	I found the system unnecessarily complex.
Q3	I thought the system was easy to use.
Q4	I think that I would need the support of a technical person to be able to use this system.
Q5	I found the various functions in this system were well integrated.
Q6	I thought there was too much inconsistency in this system.
Q7	I would imagine that most people would learn to use this system very quickly.
Q8	I found the system very cumbersome to use.
Q9	I felt very confident using the system.
Q10	I needed to learn a lot of things before I could get going with this system.

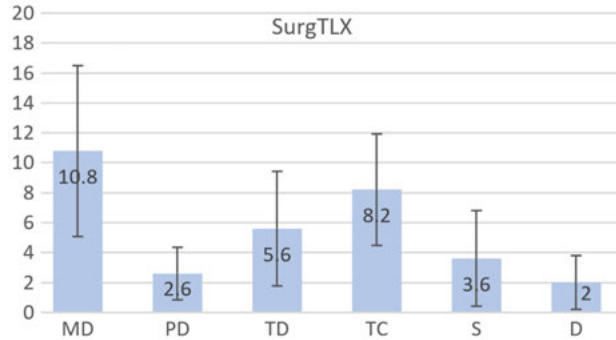

Fig. 4: Results of the SurgTLX evaluation.

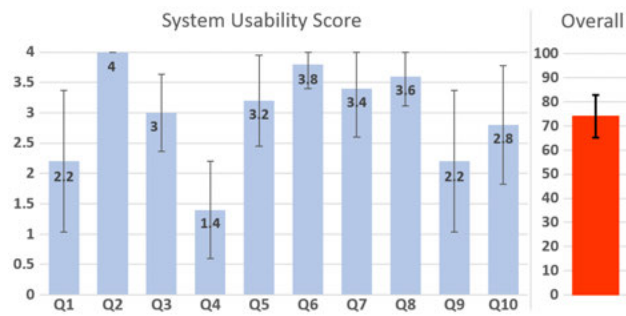

Fig. 5: Results of the system usability score evaluation. Left: individual questions results. Right: overall score of the system.

3 Results and Discussion

The results of the SurgTLX evaluation are depicted in Fig. 4 where a low score is preferred indicating lower stress of a user. The aspect with highest score is the 'mental demand (MD)' with a score of 10.8±5.7. Followed by the aspect 'task complexity (TC)' (8.2±3.7) and 'temporal demand (TD)' (5.6 ± 3.8). The 'situational stress (S)', 'physical demand (PD)', and 'distractions (D)' were rated with 3.6±3.2, 2.6±1.7, and 2.0±1.8, respectively.

The system usability score was rated according to Fig. 5, while a higher rating means a better experienced usability. The lowest ratings were given for question four (Q4) with 1.4. The participants stated that they would require support of a technician during the use of the evaluation study. Questions one (Q1) and nine (Q9) were both rated with 2.2, which indicates that a user requires training to obtain confidence to use the system in the OR and that a benefit is visible. Question ten (Q10) was rated with 2.8, also indicating that training is necessary for the system. All other questions were rated with at least 3.0. In summary, the AR control was rated as easy to use, with well integrated functions (e.g. tip placement) and no inconsistencies. A high learning curve could be observed. An overall usability score of 74 ± 8.6 was reached where an SUS value above 68 is considered good usability. Values above 80.3 are considered as an excellent usability. Three of the five participants rated the system with ≥ 80.

Interaction with the HoloLens 2 was rated as good, however, in some cases the finger tracking failed, leading to unrecognized gestures, e.g. during the re-placement of the tip tool. As no participants had prior experience with augmented reality devices or head mounted displays, the hand-eye coordination was sometimes described as difficult. Interaction with the virtual holograms can be cumbersome without experience and requires training. One possibility to address this challenge in the future could be the additional visualization of the user's hand in the virtually superimposed scene.

The main result of the user evaluation was that the AR system is challenging to use by first-time users. However, study participants stated that they experienced a steep learning curve when training. Summarizing, the visual impression of the holograms were rated as good and the interaction with the virtual scene was intuitive. The control of the tip tool was easy and worked most of the time sufficiently well. When the AR scene is displayed in its original size, the interaction seems difficult as the anatomical structures are small. Therefore, the zoom capability of the scene was rated as excellent as it enables a user to interact even with very small anatomical structures. The possibility to grab an object and release it by hand control was also rated as good and intuitive to use. The preview of the new gallbladder deformation state helped the participants to evaluate and approve the new position before execution by the robot control.

4 Conclusion

In this work, we propose a solution to control a robot with an AR device. Two process steps of the cholecystectomy were modeled. First, the clipping of the cystic artery and the cystic duct were modeled. Second, we investigated the manipulation of the gallbladder in space by the assistant gripper. We evaluated the system with the SurgTLX and SUS questionnaire. The system was rated with a high usability score, but training is required to learn intuitive interaction with the system as AR devices present a new interaction modality to many users. Presumably, this is the main reason why the system was rated as mentally demanding. The presented method enables the realistic and intuitive representation of the surgical scene. Future work will investigate intuitive control of a cognitive surgical robot using augmented reality by providing a way to inspect a subsequent robot motion as suggested by a machine learning algorithm.

Author Statement

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