Vuthea Chheang, Patrick Saalfeld, Tobias Huber, Florentine Huettl, Werner Kneist, Bernhard Preim, Christian Hansen

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Vuthea Chheang, Patrick Saalfeld, Bernhard Preim, Christian Hansen

Faculty of Computer Science,

Otto-von-Guericke University Magdeburg, Germany

christian.hansen@ovgu.de

Tobias Huber, Florentine Huettl, Werner Kneist

Department of General, Visceral and Transplant Surgery,

University Medicine of the Johannes Gutenberg-University Mainz, Germany

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Vuthea Chheang
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany

Patrick Saalfeld
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany

Tobias Huber
University Medicine of the
Johannes Gutenberg-University
Mainz, Germany

Florentine Huettl
University Medicine of the
Johannes Gutenberg-University
Mainz, Germany

Werner Kneist
University Medicine of the
Johannes Gutenberg-University
Mainz, Germany

Bernhard Preim
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany

Christian Hansen
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany
christian.hansen@ovgu.de

***Abstract*—Virtual reality (VR) has been used in many medical training systems for surgical procedures. However, the current systems are limited due to inadequate interactions, restricted possibilities of patient data visualization, and collaboration. We propose a collaborative VR system for laparoscopic liver surgical planning and simulation. Medical image data is used for model visualization and manipulation. Additionally, laparoscopic surgical joysticks are used to provide an opportunity for a camera assistant to cooperate with an experienced surgeon in VR. Continuous clinical feedback led us to optimize the visualization, synchronization, and interactions of the system. Laparoscopic surgeons were positive about the systems' usefulness, usability, and system performance. Additionally, limitations and potential for further development are discussed.**

***Index Terms*—Collaborative virtual reality, liver surgery, surgical training, laparoscopic procedures, human-computer interaction, medical visualization**

I. Introduction

Virtual reality (VR) technology has advanced to a point that it can be used to visualize complex medical data in an effective way that leads to a significant impact on medical training [1]–[3]. VR is currently used for surgical training to improve the psychomotor skills of surgical trainees, such as spatial orientation and hand-eye coordination [4], [5].

A decade ago, liver surgery was performed mainly as open surgery. Nowadays, it is performed more frequently as laparoscopic interventions [6], [7] where the operation is performed in the abdomen using small incisions with the aid of a camera. These interventions are beneficial because they result in less pain and shorter healing times for the patients. However, these interventions pose high demands on surgeons since they cannot see the operation area directly and operate within small holes with elongated instruments. Thus, surgery planning is an essential task for mental preparation and training. Patient data, including the liver, tumors, vascular structures, and related information, are required. Current simulations for surgical training are limited due to the usage of conventional monitors with an out-of-context environment, lacking the realism of tasks, using abstract graphic design, interactions, and collaboration [8]–[11]. Additionally, laparoscopic simulators provide accessible simulation training for surgical trainees at low-cost [12]. The integration of laparoscopic simulators with a virtual environment supports the immersion of surgical trainees with an in-context training environment [13]. Nonetheless, the integration of video output from the simulator and VR head-mounted display (HMD) is limited due to material preparation and difficulties in remote collaboration [14].

Collaborative VR allows multiple users to join and manipulate virtual objects together in the same virtual environment, whether they are co-located or remote. Thus, surgical trainer and trainees can perform collaborative training inside a shared virtual environment [15]. In this paper, we introduce a collaborative VR system, *CollaVRLap*, for planning and simulation in laparoscopic liver surgery. CollaVRLap allows multiple users to explore the patient organ model reconstructed from computed tomography (CT) dataset. The use of realistic patient data is useful for laparoscopic procedures to make a plan for surgical intervention. In laparoscopic liver surgery, an experienced surgeon controls surgical instruments while a camera assistant holds the camera. Therefore, surgical joysticks (Simballs) are used in our laparoscopic simulation in a virtual operating room. Moreover, using Simballs can enable the surgeon and *camera assistant* to cooperate, practice communication, and improve their psychomotor skills. Continuous clinical feedback and evaluations from laparoscopic surgeons comprised an essential part of the system development. Our contributions are as follows:

- Concept, design, and implementation of a collaborative VR-HMD system for laparoscopic liver surgery training.
- Usage of real medical image data for laparoscopic procedures, including cutting and bleeding simulation.
- Insights from system performance, evaluation, and clinical feedback reveal the limitations of the presented system for future investigation.

II. Related Work

A. Simulation in laparoscopic surgery

Training of surgical procedures is required with numerous training sessions to minimize the risk of the intervention. A variety of VR simulators are developed and used by many surgeons to improve the psychomotor skills and practice surgical techniques [4]. VR-based training proposed by Qian et al. [11] integrates a soft tissue deformation, collision detection, and dissection. Most of the training scenarios of VR simulations use an abstract graphic design instead of using patient data. Jung et al. [16] developed a web-based team meeting system for medical image data visualization and exploration. However, the system did not provide an immersive environment. The immersion of training environments could lead users to strong and realistic experiences. Huber et al. [17] showed the use of VR for laparoscopic training by combing a video output from a laparoscopic simulator with the HMD. However, there are still limitations for collaborative training and the availability of advanced surgical training scenarios.

B. Co-Presence

Co-Presence can be distinguished into two ways of understanding: the sense of being together with other users in a *remote environment* and the sense of being together with others in a *shared virtual environment*. The feeling of being together in a shared virtual environment can influence the experience of social presence [18].

Co-presence is relevant because it provides human experiences in the virtual environment. Thus they can communicate and collaborate as they would do in the real world as well as human locomotor behavior. Rios et al. [19] developed a collaborative VR and experimented with users' locomotor behavior when two participants share the same virtual space. The results showed significant differences in users' locomotor behavior between the real and VR world. Podkosova et al. [20] studied the co-presence and proxemics in a shared walkable virtual environment. They found that the perception and proxemics of users concerning co-located and distributed users are different. Salimian et al. [21] presented a mixed reality collaborative environment toolkit by linking a physical environment to virtual reality. Despite this, the results of users' preference did not show that this was preferred over other collaborative approaches.

Additionally, Gugenheimer et al. [22] proposed a system to enable co-located experiences for VR between HMD and no-HMD users. They found that the enjoyment of non-HMD users was higher than HMD. Christensen et al. [23] conducted a study on player experience in a VR and non-VR multi-player game. The results showed that player experience in VR was rated higher than non-VR. There is also work studying the different strategies to steer players from each other for reducing the collisions [24].

Understanding users' behaviors in a collaborative environment can help us to improve the design and make the system more efficient and feel more natural.

C. Collaborative VR simulations

Recently, collaborative VR emerged as an essential research topic. However, there are still not many collaborative VR applications with HMD for medical specialties [25], especially in laparoscopic liver surgery.

Diaz et al. [26] introduced a collaborative networked virtual surgical simulator that allows collaborative training of surgical procedures. The results showed that packet loss, bandwidth, and network delay have a significant effect on the consistency of the shared virtual environment. Paiva et al. [27] proposed a collaborative VR-based simulator for surgical education and discussed the networking issues for the 3D medical image in the collaborative virtual environments [28]. Papagiannakis et al. [29] presented an HMD-based system for medical education and training. The proposed system can be used to provide an immersive environment and allow cooperative users to perform on a knee arthroplasty simulation. Christensen et al. [8] proposed a team training in VR for robot-assisted minimally-invasive surgery. However, the system was not ready for use in actual training due to real-life feasibility.

In addition, Cecil et al. [30] presented a network-based virtual reality simulation for orthopedic surgery training by comparing haptic simulator and immersive simulator. The results showed that the immersive simulator was rated higher in terms of user experience. Elvezio et al. [31] presented a low-latency interaction of collaborative VR for motor rehabilitation. They found that the collaboration is effective when the network latency is below 15ms, and it improves further at 3-7ms of latency. Additionally, Brun et al. [32] proposed a shared view of mixed-reality hologram for heart surgery. The results demonstrated that mixed-reality holograms for surgical planning as collaboration might have a high diagnostic value and contribute to understanding complex morphology. In this work, we propose a VR-HMD system to make possible for collaboration and training in the laparoscopic liver surgery.

III. System Design and Implementation

A. CollaVRLap system

CollaVRLap enables multiple users to join together in the same virtual environment and manipulates the same patient organ model. We develop two modes for specific laparoscopic procedures: *exploration mode* and *surgery mode* in the virtual operating room.

The system architecture of the CollaVRLap system is shown in Fig. 1. For a development environment, the game engine Unity (version 2018.2.14) is used because it provides native support of the HTC Vive as well as several tools, including Virtual Reality Toolkit (VRTK) for fundamental interactions in VR. Unity networking (Unet) is used for making the collaborative VR possible. The surgical instruments are connected and only used in the surgery mode. The HTC Vive controllers are used in both modes, but the use in surgery mode is for teleportation. Also, we connect the Simball grasper, cutting tool, and the foot pedal to user 1 (surgeon) while the Simball camera instrument connects to user 2 (camera assistant). In

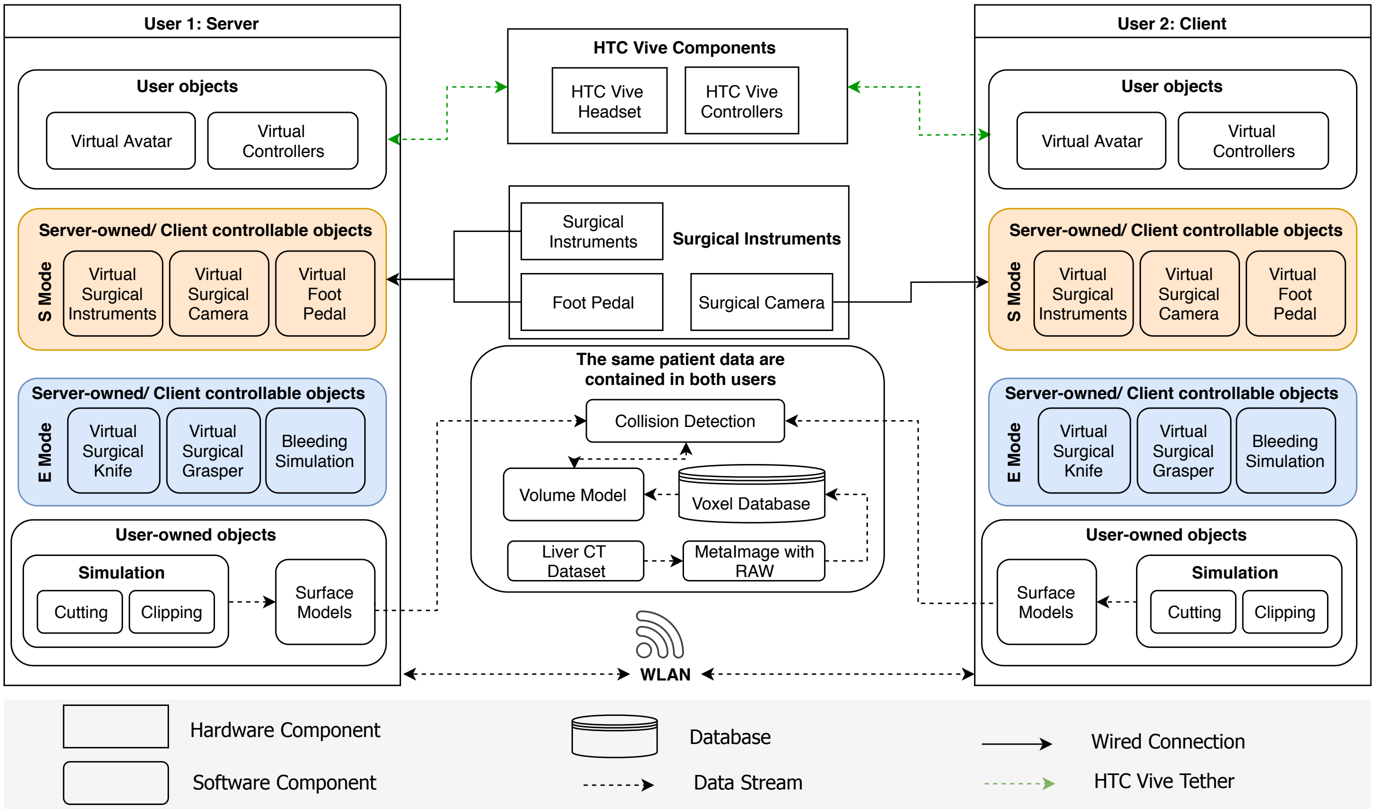


Fig. 1: System architecture of the CollaVRLap (*E*: exploration mode, *S*: surgery mode).

exploration mode, both users have their controllers to interact with the same virtual patient 3D organ model. User objects are referred to the objects, including virtual user avatar and virtual controllers, that spawn after completing a matchmaking process of Unet networking. Server-owned/client controllable objects are owned by the server, but the objects can be controlled and updated by any clients on the network. Moreover, user-owned objects are referred to as the objects which are computed on each device of the users. The idea is to minimize the network latency and computation on the server.

B. Patient data and pre-processing

Data preparation is focused on generating and reconstructing the model of patient data from a CT dataset. We used the dataset which is used in the liver surgical routine. The original dataset was a series of DICOM files, separately segmented into different structures, i.e., the liver, portal vein, hepatic vein, hepatic artery, gallbladder, tumor, and inferior vena cava. The image resolution was $512 \times 512 \times 1261$. The data is imported into MeVisLab software (MeVis, Germany) and smoothed with a GaussSmoothing filter. Then, the images are cropped to contain only the boundaries of the liver, resulting in an image resolution of $242 \times 223 \times 350$.

Two different CT datasets of the liver were tested, the test relates to the coordination of the model within the phantom for surgery mode in Unity. Several image resolutions were tested as well to analyze their impact on system performance.

C. Cutting, Bleeding, and Clipping simulation

We assembled technologies, including Cubiquity, Nvidia FleX, and Unity, to create useful features of cutting, bleeding, and clipping simulation. According to requirements from physicians, a deformable model was not implemented because its physical behavior was not sufficiently realistic when performing a cutting simulation. Thus, a low-quality simulation was considered confusing.

We use the Insight Segmentation and Registration Toolkit (ITK) to read and write the image dataset. Each dataset was exported from MeVisLab as metadata and raw image. Furthermore, we use the Cubiquity library to generate volumetric models for each dataset. The volumetric model preserves the volume density, which represents the internal model structure in an occupancy grid data structure. And, it is connected with a voxel database.

Collision detection between sample points on the model occupancy grid and a virtual surgical tool (cutting/grasper tool) is applied during the simulation of cutting and clipping. During the cutting simulation, the model is checked frequently whether the mesh representation is synchronized with the volume data. If there is a modification, the system will regenerate the volumetric mesh based on the Marching cubes algorithm with volume data stored in the voxel database. The cutting simulation of the volumetric model is implemented with a surface painting of layered texture. The MaterialSet of Cubiquity is used to represent material with the layer of textures. Finally, mesh smoothing is applied to smooth around the cutting area.

Bleeding simulation is implemented for CollaVRLap. The bleeding is realized by using the fluid simulation of Nvidia FleX, a particle-based simulation framework. We simulate cutting and a possibility to clip vascular structures. For example, during cutting on the liver, surgeons should be cautious of vessels inside the liver. If they accidentally cut onto the vessel, bleeding occurs from the cutting point.

To stop the bleeding, the surgeon can use the virtual grasper of the SimBalls to place a clip onto the bleeding vessel. As long as the clip is placed above the bleeding, it will stop. To support surgeons in training, it is also possible to render the liver in a semi-transparent manner. This semi-transparent liver reveals the inner vessels and allows easier cutting.

D. Hardware

Fig. 2 shows the setup of the CollaVRLap system for laparoscopic liver surgery training. Two computers are used for testing the CollaVRLap. The computer that starts the application first acts as a server (user 1) and the following computer performs as a client (user 2). The computer for user 1 (server) is equipped with an Intel Corei7-8700K CPU @3.70GHz (12 CPUs) processor, an NVIDIA GeForce GTX 1080 (8GB VRAM) graphics card, and 32GB of RAM. The computer for user 2 (client) is equipped with an Intel Core i7-7820HQ CPU @ 2.90GHz (8CPUs) processor, an NVIDIA Quadro M2200 (4GB VRAM) graphics card, and 32GB of RAM. We set up the room with the trackers of HTC Vive. NETGEAR WiFi Router (Model: R6120) is used for sharing a local network connection. For interactions, laparoscopic surgical joysticks (Simball 4D joysticks) with a double foot-switch (G-coder Systems) are used as well as HTC Vive controllers. The left and right instruments (grasper and cutting tool) of Simball, and foot pedal are connected to the user 1 while only the Simball camera instrument is connected to the user 2. The Simball joysticks'laser-marked ball joints, with three degrees of freedom (DoF), allow real-time calculations of the exact 3D angular position and orientation; therefore, this device is used commonly for laparoscopic training.

E. Exploration mode

The patient medical image data is reconstructed and visualized as an enlarged 3D organ in a virtual room. The virtual room is set up with a table in the center and the enlarged 3D organ model. On the table, a virtual knife and a virtual clipping tool are placed. Fig. 3 demonstrates a liver exploration of the collaborative surgeons in the exploration mode.

The collaborative users can join in the VR room and virtually perform the surgical intervention. Through the enlarged representation of an interactive 3D organ model, it provides a basis in liver surgical procedures such as planning to remove the tumor (see Fig. 3a). Furthermore, with the use of HTC Vive controllers and VRTK, the users can easily make interactions and teleportation. There are several options on the controller touch-pad to choose the visualization methods of

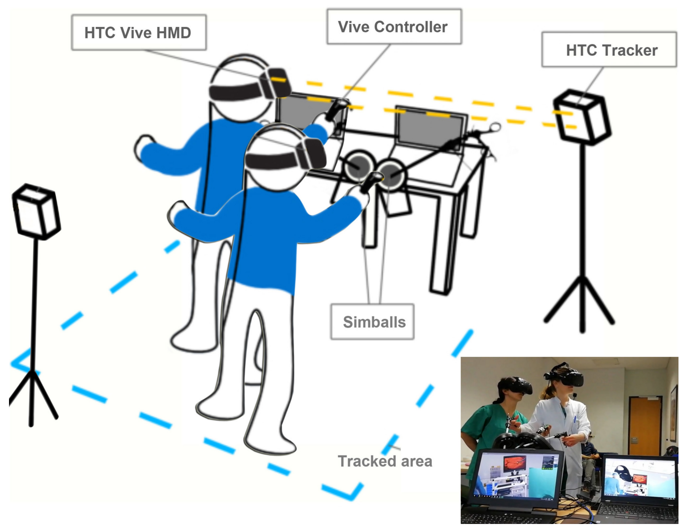


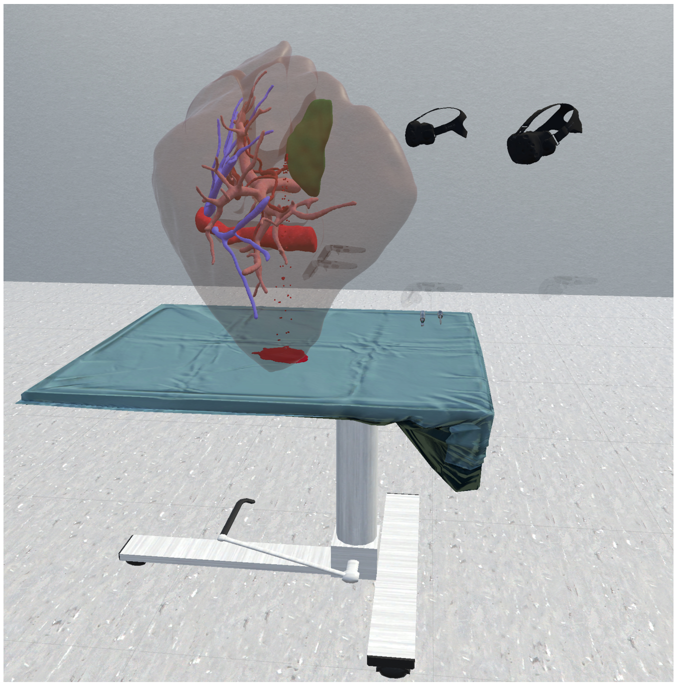
Fig. 2: The setup of the CollaVRLap system. Room-setup is equipped with the HTC Vive hardware. Two computers and surgical joysticks (Simballs) are used in the system. The bottom-right figure shows two surgeons that testing our system with the use of Simball joysticks.

the 3D organ model. For example, change the livers texture from solid to semi-transparent, enable/disable vessels, change the environment to the surgery mode, and reset the whole 3D organ model. The user can also grab the virtual knife and virtual clipping tool to perform the cutting and clipping simulation on the vessels.

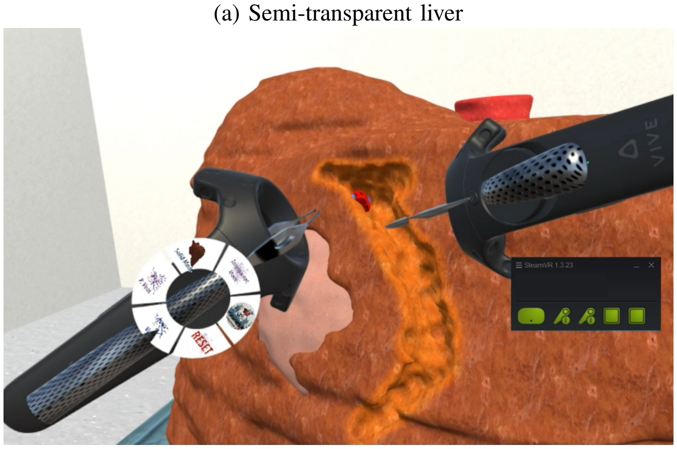
Fig. 3b illustrates the patient organ model, which is reconstructed and visualized as an enlarged 3D organ model. During pressing the trigger button of the right Vive controller while there is a collision between the virtual knife and occupancy grid data, the volume data will be modified, and the volumetric mesh will be regenerated for the cutting area only. Moreover, the cutting surfaces of the volumetric mesh are painted with another layer of texture. The bleeding simulation will also occur if the virtual knife collides with one of the vessel's mesh, and its position will synchronize with other users. To stop the bleeding, the user can employ the left Vive controller with the clipping tool to clip on that vessel.

F. Surgery mode in the virtual operating room

The virtual operating room (OR) is developed based on a commercial modular 3D asset kit (Vertigo Games, Rotterdam, Netherlands). The asset kit contained a fully equipped virtual operation room with surgical instruments. The virtual OR was designed and re-positioned according to feedback from our clinical partners. The Simball joysticks and foot pedal are used in this mode. The patient organ model is placed inside an OpenHELP phantom [33]. The model is *filmed* by the Simball camera instrument that controls the virtual camera. The captured view is projected to a virtual monitor in the virtual operating room (see Fig. 4a). The position of Simball instruments in the real world is tracked to match with the

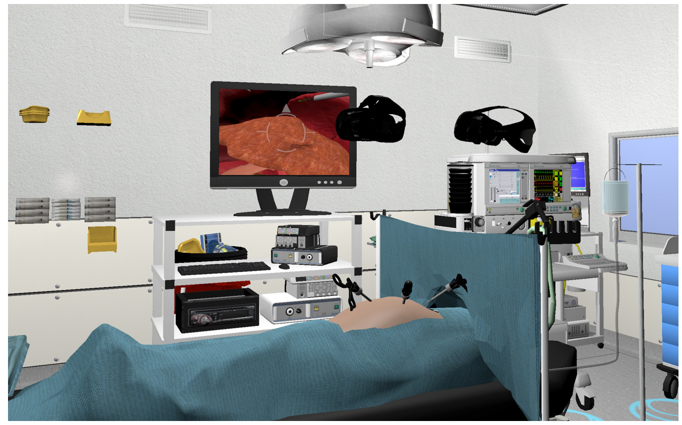


(a) Semi-transparent liver



(b) Cutting, bleeding, and clipping simulation

Fig. 3: Two surgeons are using the exploration mode to explore and make surgical planning on the patient data.



(a) Surgeons virtually cooperate in the VR

(b) Surgeons perform in the real world

Fig. 4: Two surgeons are performing in the surgery mode with the use of the Simball joysticks.

virtual surgical instruments. Therefore, there is an angle while users are looking to the virtual monitor (see Fig. 4b).

In surgery mode, the experienced surgeon controls the Simball joysticks and uses the foot pedal while the camera assistant controls only the Simball camera, as shown in Fig. 4. The synchronization of virtual instruments over the network allows both users to see the captured view from the virtual camera, including the virtual grasper and the cutting instrument. A blue button of the foot pedal is required to press to activate the cutting. In case of bleeding, the user is recommended to give a clip on the bleeding vessel to stop the bleeding. In order to complete this task, the user is required to move the grasper instrument to collide on that bleeding vessel and press the yellow button of the foot pedal.

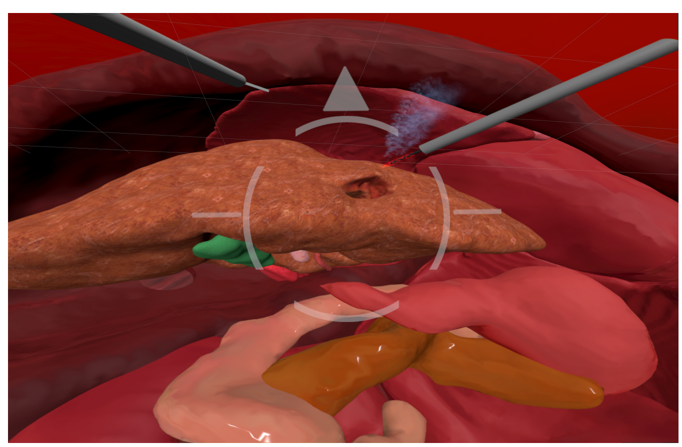


Fig. 5: Cutting and clipping simulation in the surgery mode.

Fig. 5 shows the view of the patient organ model, which is projected on a virtual monitor. In this model, the cutting simulation is performed. The position and orientation of the virtual surgical instruments, including virtual cameras, are synchronized over the network to all users. One user performs as a *camera assistant*, and an experienced surgeon controls the cutting and clipping instruments. The main idea is to provide an immersive experience in laparoscopic liver surgery on the real patient data for the collaborative surgeon and camera assistant. Not only improving psychomotor skills, but surgeons can also improve the communication skills for laparoscopic procedures because it is crucial in reality.

IV. Evaluation and Results

A. Usefulness and Usability

A qualitative study was carried out to evaluate the first prototype of the exploration and simulation mode in laparoscopic procedures. The aim was to determine the usefulness and usability of the system as well as feedback for further improvement. The first prototype was shown to surgeons from the surgical department of University Medicine of the Johannes Gutenberg-University Mainz, Germany. Three laparoscopic surgeons (one female) with previous experience with the VR laparoscopic simulator participated. According to the Think Aloud method, participants were asked to do all the interactions and actions. A pre-introduction and an explanation of how to use the system were incorporated before performing all interactions. For evaluation, participants were asked to answer the user experience questions (module I) of the meCUE questionnaire [34]. The questionnaire was divided into two subsections for exploration mode and surgery mode concerning the usefulness and usability of the system. The answer is rated with a seven-point rating scale from ”strongly disagree” to ”strongly agree”. The results of the first prototype with user experience questions of the meCUE questionnaire gave an average rating for exploration mode from 5.33 ± 0.33 in terms of usability and 4.67 ± 1.45 in terms of usefulness. For surgery mode, the score was 4.33 ± 1.73 in terms of usability and 4.33 ± 1.73 regarding usefulness.

The score of usability in the exploration mode is higher than the surgery mode because the visualization of the patient 3D organ model is easily explored and visualized with the additional models, especially vessels inside the liver. Hence, the semi-transparent display of the liver is useful for viewing the vessel structures and tumors. Moreover, the cutting, bleeding, and clipping simulation is implemented to simulate necessary steps before going through to laparoscopic simulation.

Surgeons assessed the surgery mode as a good basis for understanding and communication during the surgery. The handling of laparoscopic instruments is subject to the fulcrum effect (endpoints of tool move in the opposite direction to the surgeon’s hand), thus combining Simball joystick with VR is helpful for motor skill training. Nevertheless, while holding the instruments, hand tracking would be helpful and increase the immersive of the system.

For both modes with collaborative users in the follow-up, the surgeons were positive about CollaVRLap that provides abilities to explore, interact, and perform the simulation on the patient data. Moreover, the ability to use the patient medical image data has been considered as an advantage compared to known simulators.

In particular, our CollaVRLap system provides the immersive experience with collaborative users in the contextual training environment. Hence, it will be a basis for making surgical plans and training in laparoscopic liver surgical procedures - for example, planning of tumor resection in the liver.

B. System performance

The system performance is evaluated with both two computers for each mode. Maximum synchronization (maxSync) refers to synchronized times per update of Cubiquity in play and edit mode of Unity. A higher value of maxSync would lead the volumetric model to synchronize the collision and regenerate the volumetric mesh quickly in the update function of Unity. However, a small value of maxSync will result in a better frame rate, while the volumetric cutting is being performed. Therefore, we minimize the maxSync per updated frame of volumetric mesh synchronization in the play mode for system stability and a better frame rate.

Nevertheless, the rendered mesh and collision synchronization noticeably lagging behind the modifications of cutting, which are being performed. Volumetric cutting without painting on the cutting surface will also lead to a better frame rate. Nonetheless, physicians preferred the cutting with surface painting with another texture to show and be aware of the cutting area.

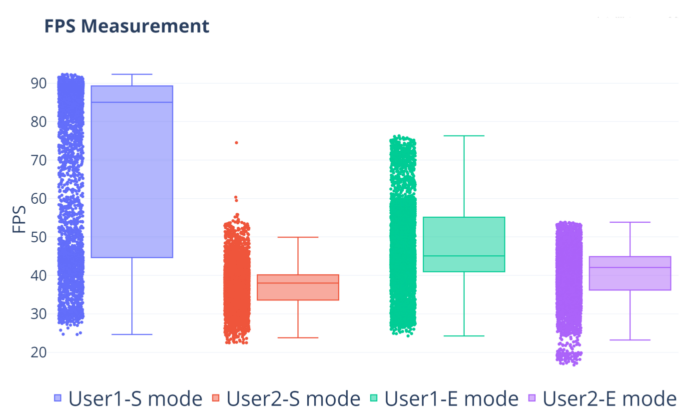


Fig. 6: The system performance of the collaVRLap in the exploration mode (E) and surgery mode (S).

Fig. 6 illustrates the preliminary performance results of our system. We gave a maxSync value of the cutting simulation to one with the surface painting during the experiment. The frames per second (FPS) were tracked for each mode and each user. The specification of one computer (user 1) was better; thus, the results varied. Moreover, the results of testing showed that the cause of a low frame rate is due to volumetric cutting.

The resolution of image data also results in a noticeable computation of the voxel occupancy during the cutting simulation.

We used the user 1 computer to test the cutting performance with options of maxSync and without surface painting in the surgery mode. Fig. 7 shows a comparison of volumetric cutting performances between the value of maxSync and the cutting without paint another texture on the cutting surface. The results of maxSync 4 and 8 are tested with surface painting, while the results of cutting performance without surface painting are tested with maxSync 1. Network latency was tracked for each mode with the wireless connection speed 130 Mbps. The average latency in surgery mode is 34.92 ms (min: 4, max: 51), and exploration mode is 32.06 ms (min: 3, max: 42).

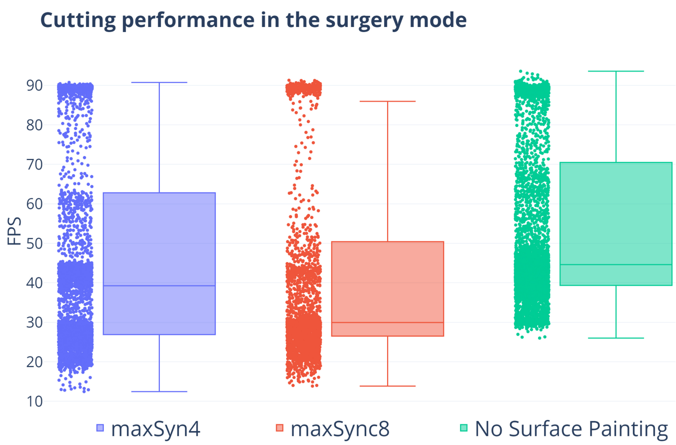


Fig. 7: A comparison of volumetric cutting performance.

V. Discussion

Both modes of our system were evaluated positively in terms of usefulness and usability. This work is a basis and indicates the potential for further development with a qualitative assessment. Valuable insights were gained from the results of the Think Aloud protocol. In contrast to most laparoscopic simulators that are presented on a conventional 2D monitor in an out-of-context environment; CollaVRLap provides the experience of exploring patient data and perform a laparoscopic simulation in an immersive surgical environment. Moreover, the current system allows collaboration with multiple users, whether remote or co-located in a local network. The over distance collaboration and assessment is needed for planning of laparoscopic procedures. According to system requirements and feedback from clinical partners, two modes of surgical procedures are developed for exploration and simulation of laparoscopic liver surgery.

In the exploration mode, the surgeons were able to cut on the liver by using the Vive controllers. The bleeding simulation and clipping functionality were acceptable; however, the blood flow should be investigated for further improvement [35], [36]. A comparative model with physical behavior when cutting and clipping should also be investigated with the proposed method of Bargteil et al. [37]. In the surgery mode, CollaVRLap enables collaborative training for laparoscopic simulation with the use of Simball joysticks. Our system can apply with different datasets, however, the coordination of the model needs to be adjusted with the phantom in Unity. Our goal was to provide essential practice for surgeons and camera assistants to collaborate, communicate, and improve their psychomotor skills on real patient data. The development of integrating the Simball joysticks with the virtual surgical instruments in VR was evaluated positively. However, visualizing a whole avatar with hand tracking and haptic feedback while controlling the Simball instruments may increase spatial awareness and proprioception [38], [39]. The results of Hagelsteen et al. [40] showed that haptic feedback in the VR laparoscopic simulator has limited fidelity. However, it resulted in less stretch damage with haptic feedback enabled.

VI. Conclusion and Future Work

We have presented the CollaVRLap system for exploration and simulation in laparoscopic liver surgery procedures. This new generation of collaborative VR will enable clinical trainees to study and evaluate the impact of VR. Furthermore, this system will enable the surgical trainer and trainees to join as a collaborative surgical training in VR. We have introduced the system architecture, technical setup, and laparoscopic procedure modes. In particular, the collaboration in the exploration mode of patient data will enable surgeons to organize precise surgical planning. The same patient data used in exploration mode is also used for laparoscopic surgical simulation in the surgery mode. Hence, surgeons can practice, communicate, and improve surgical skills with the use of the Simball joysticks.

Based on the clinical feedback and evaluation, we identified the elements that could be improved. The surgeons were positive about its usability and usefulness. They evaluated the developed system as a reasonable basis for training and further clinical evaluation. Using the real patient data and the visualization of vascular structures and tumors inside the liver model are considered as useful for surgical training. The system performance was evaluated by tracking the FPS of each user and each mode. Low FPS happens during the cutting simulation. The computer for user 1, with its specification, was provided a better frame rate. The image resolution also results in the considerable computation of the voxel occupancy grid for real-time cutting. Finally, the developed prototype offers a basis and potential for future development. It enables a new direction for planning and simulation of liver surgical procedures in a collaborative VR.

Future work aims to improve system performance, interaction, network latency, supplement additional scenarios for collaborative laparoscopic procedures, and evaluate the remote collaboration. This work builds a basis for more extensive clinical evaluation, transfer to other surgical disciplines, and opens new directions for surgical training in the future.

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References

[1] H. Adams, J. Shinn, W. G. Morrel, J. Noble, and B. Bodenheimer, "Development and evaluation of an immersive virtual reality system for medical imaging of the ear," in *Med. Imaging: Image-Guided Proc., Robotic Interventions, and Modeling*, vol. 10951, 2019, p. 1095111.

[2] Y. Pulijala, M. Ma, M. Pears, D. Peebles, and A. Ayoub, "Effectiveness of immersive virtual reality in surgical training–a randomized control trial," *Journal of Oral and Maxillofacial Surgery*, vol. 76, no. 5, pp. 1065–1072, 2018.

[3] J. Marescaux, J.-M. Clément, V. Tassetti, C. Koehl, S. Cotin, Y. Russier, D. Mutter, H. Delingette, and N. Ayache, "Virtual reality applied to hepatic surgery simulation: the next revolution." *Annals of surgery*, vol. 228, no. 5, p. 627, 1998.

[4] M. Alaker, G. R. Wynn, and T. Arulampalam, "Virtual reality training in laparoscopic surgery: A systematic review & meta-analysis," *International journal of surgery (London, England)*, vol. 29, pp. 85–94, 2016.

[5] C. A. Linte, J. White, R. Eagleson, G. M. Guiraudon, and T. M. Peters, "Virtual and augmented medical imaging environments: Enabling technology for minimally invasive cardiac interventional guidance," *IEEE reviews in biomedical engineering*, vol. 3, pp. 25–47, 2010.

[6] B. Descottes, D. Glineur, F. Lachachi, D. Valleix, J. Paineau, A. Hamy, M. Morino, H. Bismuth, D. Castaing, E. Savier *et al.*, "Laparoscopic liver resection of benign liver tumors," *Surgical endoscopy and other interventional techniques*, vol. 17, no. 1, pp. 23–30, 2003.

[7] 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.

[8] N. H. Christensen, O. G. Hjermitslev, N. H. Stjernholm, F. Falk, A. Nikolov, M. Kraus, J. Poulsen, and J. Petersson, "Feasibility of team training in virtual reality for robot-assisted minimally invasive surgery," in *Proceedings of the Virtual Reality International Conference - Laval Virtual*. ACM, 2018, pp. 8:1–8:4.

[9] J. Zhang, Y. Lyu, Y. Wang, Y. Nie, X. Yang, J. Zhang, and J. Chang, "Development of laparoscopic cholecystectomy simulator based on unity game engine," in *Proceedings of ACM SIGGRAPH European Conference on Visual Media Production*. ACM, 2018, pp. 4:1–4:9.

[10] H. Kolivand, B. Tomi, N. Zamri, and M. Shahrizal Sunar, "Virtual surgery, applications and limitations," in *Medical Imaging Technology*, ser. Lecture Notes in Bioengineering, 2015, vol. 9, pp. 169–195.

[11] K. Qian, J. Bai, X. Yang, J. Pan, and J. Zhang, "Virtual reality based laparoscopic surgery simulation," in *Proceedings of ACM Symposium on Virtual Reality Software and Technology*. ACM Press, 2015, pp. 69–78.

[12] E. Thinggaard, F. Bjerrum, J. Strandbygaard, L. Konge, and I. Gögenur, "A randomised clinical trial of take-home laparoscopic training." *Danish medical journal*, vol. 66, no. 1, pp. 1–5, 2019.

[13] T. Huber, M. Paschold, C. Hansen, T. Wunderling, H. Lang, and W. Kneist, "New dimensions in surgical training: immersive virtual reality laparoscopic simulation exhilarates surgical staff," *Surgical endoscopy*, vol. 31, no. 11, pp. 4472–4477, 2017.

[14] T. Huber, M. Paschold, C. Hansen, H. Lang, and W. Kneist, "Artificial versus video-based immersive virtual surroundings: analysis of performance and users preference," *Surgical innovation*, vol. 25, no. 3, pp. 280–285, 2018.

[15] J. Lacoche, N. Pallamin, T. Boggini, and J. Royan, "Collaborators awareness for user cohabitation in co-located collaborative virtual environments," in *Proceedings of ACM Symposium on Virtual Reality Software and Technology*. ACM, 2017, pp. 15:1–15:9.

[16] H. Jung, Y. Jung, D. D. Feng, M. Fulham, and J. Kim, "A web-based multidisciplinary team meeting visualisation system," *International journal of computer assisted radiology and surgery*, pp. 1–11, 2019.

[17] T. Huber, T. Wunderling, M. Paschold, H. Lang, W. Kneist, and C. Hansen, "Highly immersive virtual reality laparoscopy simulation: development and future aspects," *International journal of computer assisted radiology and surgery*, vol. 13, no. 2, pp. 281–290, 2018.

[18] C. S. Oh, J. N. Bailenson, and G. F. Welch, "A systematic review of social presence: Definition, antecedents, and implications," *Frontiers in Robotics and AI*, vol. 5, p. 114, 2018.

[19] A. Ríos, M. Palomar, and N. Pelechano, "Users' locomotor behavior in collaborative virtual reality," in *Proceedings of International Conference on Motion, Interaction, and Games*. ACM Press, 2018, pp. 1–9.

[20] I. Podkosova and H. Kaufmann, "Co-presence and proxemics in shared walkable virtual environments with mixed colocation," in *Proc. of ACM Symposium on Virtual Reality Software and Technology*, 2018, p. 21.

[21] M. Salimian, S. Brooks, and D. Reilly, "Imrce: A unity toolkit for virtual co-presence," in *Proceedings of the Symposium on Spatial User Interaction*. ACM, 2018, pp. 48–59.

[22] J. Gugenheimer, E. Stemasov, J. Frommel, and E. Rukzio, "Sharevr: Enabling co-located experiences for virtual reality between hmd and non-hmd users," in *Proceedings of CHI Conference on Human Factors in Computing Systems*, 2017, pp. 4021–4033.

[23] J. V. Christensen, M. Mathiesen, J. H. Poulsen, E. E. Ustrup, and M. Kraus, "Player experience in a vr and non-vr multiplayer game," in *Proceedings of the Virtual Reality International Conference - Laval Virtual*, 2018, pp. 10:1–10:4.

[24] M. Azmandian, T. Grechkin, and E. S. Rosenberg, "An evaluation of strategies for two-user redirected walking in shared physical spaces," in *IEEE Virtual Reality*, 2017, pp. 91–98.

[25] R. Anthony J. de Belen, H. Nguyen, D. Filonik, D. Del Favero, and T. Bednarz, "A systematic review of the current state of collaborative mixed reality technologies: 2013–2018," *AIMS Electronics and Electrical Engineering*, vol. 3, no. 2, pp. 181–223, 2019.

[26] C. Diaz, H. Trefftz, L. Quintero, D. A. Acosta, and S. Srivastava, "Collaborative networked virtual surgical simulators (cnvss) implementing hybrid client–server architecture: Factors affecting collaborative performance," *PRESENCE: Teleoperators and Virtual Environments*, vol. 23, no. 4, pp. 393–409, 2014.

[27] P. V. Paiva, L. S. Machado, A. M. G. Valença, T. V. Batista, and R. M. Moraes, "Simcec: A collaborative vr-based simulator for surgical teamwork education," *Computers in Entertainment (CIE)*, vol. 16, no. 2, p. 3, 2018.

[28] P. V. Paiva, L. d. S. Machado, J. C. de Oliveira, and R. M. de Moraes, "Networking issues for 3d medical collaborative virtual environments: Design and applications," *SBC Journal on Interactive Systems*, vol. 8, no. 2, pp. 89–97, 2017.

[29] G. Papagiannakis, N. Lydatakis, S. Kateros, S. Georgiou, and P. Zikas, "Transforming medical education and training with vr using m.a.g.e.s." in *SIGGRAPH Asia*, 2018, pp. 83:1–83:2.

[30] J. Cecil, A. Gupta, M. Pirela-Cruz, and P. Ramanathan, "A network-based virtual reality simulation training approach for orthopedic surgery," *ACM Trans. Multimedia Comput. Commun. Appl.*, vol. 14, no. 3, pp. 77:1–77:21, Aug. 2018.

[31] C. Elvezio, F. Ling, J.-S. Liu, and S. Feiner, "Collaborative virtual reality for low-latency interaction," in *ACM Symposium on User Interface Software and Technology Adjunct Proceedings*, 2018, pp. 179–181.

[32] H. Brun, R. Bugge, L. Suther, S. Birkeland, R. Kumar, E. Pelanis, and O. Elle, "Mixed reality holograms for heart surgery planning: first user experience in congenital heart disease," *European Heart Journal-Cardiovascular Imaging*, vol. 20, pp. 883–888, 2018.

[33] H. Kenngott, J. Wünscher, M. Wagner, A. Preukschas, A. Wekerle, P. Neher, S. Suwelack, S. Speidel, F. Nickel, D. Oladokun *et al.*, "Openhelp (heidelberg laparoscopy phantom): development of an open-source surgical evaluation and training tool," *Surgical endoscopy*, vol. 29, no. 11, pp. 3338–3347, 2015.

[34] M. Minge, M. Thüring, I. Wagner, and C. V. Kuhr, "The mecue questionnaire: a modular tool for measuring user experience," in *Advances in Ergonomics Modeling, Usability & Special Populations*. Springer, 2017, pp. 115–128.

[35] M. I. Holland, S. R. Pop, and N. W. John, "VR cardiovascular blood simulation as decision support for the future cyber hospital," in *International Conference on Cyberworlds*, 2017, pp. 233–236.

[36] M. K. Mokhtar, F. Mohamed, and M. S. Sunar, "Real-time rendering blood flow visualisation using particle based technique," in *Asian Simulation Conference*. Springer, 2017, pp. 645–655.

[37] A. W. Bargteil and T. Shinar, "An introduction to physics-based animation," in *ACM SIGGRAPH*, 2019, pp. 2:1–2:57.

[38] J. Achenbach, T. Waltemate, M. E. Latoschik, and M. Botsch, "Fast generation of realistic virtual humans," in *Proceedings of ACM Symposium on Virtual Reality Software and Technology*, 2017, pp. 12:1–12:10.

[39] M. E. Latoschik, D. Roth, D. Gall, J. Achenbach, T. Waltemate, and M. Botsch, "The effect of avatar realism in immersive social virtual realities," in *Proceedings of ACM Symposium on Virtual Reality Software and Technology*, 2017, pp. 39:1–39:10.

[40] K. Hagelsteen, R. Johansson, M. Ekelund, A. Bergenfelz, and M. Anderberg, "Performance and perception of haptic feedback in a laparoscopic 3d virtual reality simulator," *Minimally Invasive Therapy & Allied Technologies*, pp. 1–8, 2019.