Introducing Virtual & 3D-Printed Models for Improved Collaboration in Surgery

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Abstract

Computer-assisted surgery and the use of virtual environments in surgery are getting popular lately, as they provide numerous benefits, especially for visualisation of data. Yet, these tools lack features for direct and interactive discussion with remote experts and intuitive means of control for 3D data. Therefore, we present a concept to create an immersive multi-user system, by using virtual reality, augmented reality and 3D-printed organ models, which enables a collaborative workflow to assist surgeries. The 3D models will be an interaction medium to provide haptic feedback as well as teaching material. Additionally, multiple depth cameras will be used to provide remote users in the virtual environment with a realistic live representation of the operating room. Our system can be used in the planning stage, intraoperatively as well as for training. First prototypes were rated as highly useful by visceral surgeons in a focus group.

Keywords: computer-assisted surgery, 3D-printing, virtual reality, augmented reality

1 Problem

Digital tools, such as visualization software, can be powerful instruments for surgeons to plan complex surgeries computer-assisted [7], [18], [21], [27]. While the planning data from these tools is available for the local surgeon, only few approaches exist to transfer the data into the intervention room or to allow for discussions and interactions with remote personnel and experts. Virtual and augmented reality (VR and AR) might provide help in various ways in the context of surgery, such as preoperative planning [7], [18], [21], [27]. Creating a *multi-user* immersive VR environment (or AR) for preoperative planning, intraoperative support, and training, comes with challenges, such as: (1) transmitting big amounts of data with high update rates and low latency, (2) creating a sufficient immersion and (3) an intuitive interaction, as the user experience is always a crucial factor. First examples for surgical applications using either VR or AR have been proposed [13], [16], but in general they restrict themselves to single parts of the process such as the visualization of CT (computer tomography) and MRI (magnetic resonance imaging) data [9], planning based on this data [18], or aiding the surgical intervention using this data [22], [25], [26].

In contrast, our research aims at creating a system which supports a broader spectrum of activities of the surgeon in the following three phases:

(1) *preoperative:* discussing radiological images and derived data, and planning the operation steps together with (remote) colleagues

(2) *intraoperative:* performing the surgery while having access to the planning data and if necessary being able to call in a colleague (via telepresence) to assist

(3) *training:* using the case data for teaching, training, in demonstrations, or patient education (beforehand)

To reach this goal, we will tackle the earlier mentioned challenges regarding data transfer, immersion, and (multi-user) interaction. In addition, most existing approaches are limited to displaying images and quantitative data on screens. Live discussions with remote experts based on the real organ or an accurate patient model do not exist to the best of our knowledge. Interacting with medical images, whether remotely or not, happens mostly on a 2D screen with a mouse. In the case of VR and AR environments or 3D displays, abstract gestures or handles are used for interaction [9], [17], [18]. But surgeons and physicians heavily rely on their tactile sensations and their visual thinking. Hence, one of their essential abilities is to use their anatomical knowledge to interpret the spatial relations of the case at hand based on the available radiological image data and on what they see and feel in the situs. Therefore, an obvious requirement for a surgical VR/AR system is to support this ability. To be best prepared for the real case, surgeons typically plan the intervention beforehand, which is also a critical stage in decision making [14]. 3D-printed organ models are already used for different purposes in medicine [12], e.g., prints of liver (parts) for planning [28]. Nevertheless, a review by Martelli et al. [12] found just 158 cases scientifically reported in a time span of 10 years (2005-2015). This leads to the conclusion, that the technique of creating a model from computed tomography (CT) (or MRI) data [23] is not common yet and requires further research. To summarize the research results: VR and AR miss the "realistic" sensation of what the users see, but offers a variety of options to show the important information from and in the image data. The 3D-prints just show a selected view of the images and do not provide any further displaying options. To get the "best of both worlds", we aim at combining both modalities to match the haptic perception and the rich visualization possibilities of VR and AR to increase the knowledge of the surgeon. As the AR technology develops quickly, AR will be treated as equal to VR while pursuing this aim.

In the field of telemedicine, most research focused on remote-controlled minimal-invasive operations [24] and rarely on systems supporting the actual procedure [15]. There are two commercial telemonitoring systems available [2], [20] and both use video streams to the remotely working medical staff. Even systems with AR support use tablets and video streams [3]. Research on the effect of such systems shows, that there is no difference if there is a remote or a local mentor [19] and the system use leads to better results but takes longer [4]. The reason might be the technology, as most proposed systems rely on using depth cameras for skeleton tracking, which are mapped onto avatars [5] in the application. Avatars are important, as their quality has an influence on behaviour and team performance [8], [10] . However, the need for extensive pre-processing and the big data volumes make the usage in real-time VR and AR applications difficult [1], [6].

As pointed out in the previous paragraphs, to reach our aim of a multi-user VR/AR environment to support surgeons along with different phases a lot of basic research needs to be done, and the presented paper will not solve these problems yet. But in the following sections, we will present our approach and initial steps towards a solution. To get started, we ran a focus group with five visceral surgeons. We got valuable feedback, especially about the interaction part and which aspects are important for the surgeon's work.

2 Material and Methods

Our general goal is to assist surgeries, from the planning stage to the actual intervention, and also during education and training of becoming a surgeon, using and combining VR and AR as well as 3D-printed organs as tangible user interfaces. In the following two sections we will first present details on our technical concept of our idea and then shortly present the procedure of a focus group we ran to evaluate our concept idea.

2.1 Technical Concept

To reach our goal of supporting surgeons to work collaboratively and effectively on the same set of data, sharing and visualizing information in real time and over distant locations is crucial. The creation of the data that forms the basis for the virtual environments and the 3D-prints involves the following steps:

1. medical image acquisition (CT, MRI) at the clinical site
2. medical image data analysis by medical-technical radiology assistants, including delineation of relevant structures (organs, vessels, tumors) and planning of resection planes
3. deriving tissue qualities including disease state and softness
4. conversion into 3D models (polygonization) and application of textures to visualize the disease state
5. creation of 3D-printed models under consideration of the derived textures and tissue softness values

These steps are carried out as a separate process before the data is actually used and may take days including the 3D-printing. As a long term goal, this process should be automatized as far as possible. Furthermore, high standards in data security including anonymization and secure data transfer need to be established.

As possible hardware to view the data in all three phases mentioned in section 1, recent VR and AR devices like HTC VIVE[1] and Microsoft HoloLens[2] are of interest. The HoloLens will be used by the surgeons

[1]https://www.vive.com

[2]https://www.microsoft.com/de-de/hololens

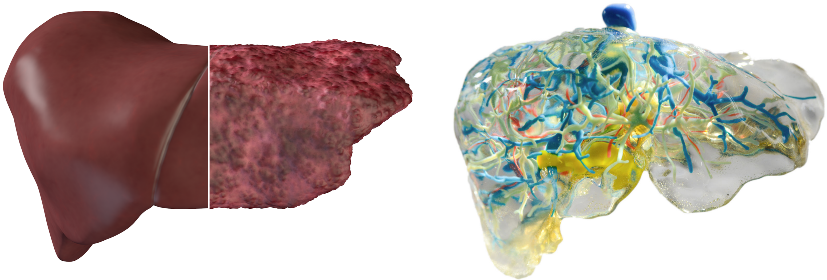

Figure 1: *Left: Exemplary textured 3D model showing varying liver tissue states (left: healthy, right: cirrhotic) Right: a transparent 3D-print of a liver*

in the operating room (OR) to explore the data and to interact with it. The HTC VIVE, in turn, will be applied by the remote personnel or experts in a way that they can discuss and interact within the multi-user virtual environment. Based on virtual representations of patient specific organs, all users will then be able to collaboratively examine and annotate the model. Also, VR and AR components of our architecture are coupled, which enables a seamless communication between them, e.g., displaying planning results and annotations made in VR on the AR-glasses during a surgical intervention. For the realization of such a shared immersive AR/VR environment we need to tackle the following technical challenges:

- realistic rendering of the anatomical models including textures to illustrate the tissue state (Fig. 1 left)
- creation of a realistic 3D environment for the telepresence user in the intraoperative phase

For the rendering of anatomical structures we will explore both, surface rendering and volume rendering, to determine the best possible visualization of the relevant anatomical structures and the resection proposals for the various application scenarios and display technologies. Common to both approaches is the need to focus on the relevant information. Hence, we will carry out studies to determine for each scenario which structures should be visualized in which way. Furthermore, we will investigate technologies for realistic rendering to raise the level of immersion. In the case of AR, this will also necessitate to explore methods for streaming as the hardware of the HoloLens is not suited for advanced volume rendering. To provide a realistic looking live 3D environment for the telepresence user in the intraoperative phase, we will use multiple depth cameras which record and stream the surgical intervention into the virtual environment. Here, a three-dimensional representation of the fused data, which includes the color as well as the depth information, is shown in form of a point cloud. Since the streaming of the data of multiple depth cameras over network needs a considerable amount of bandwidth, we will make heavy use of compression algorithms, although it is important to keep the computational complexity and therefore the latency low. We plan to enhance the current algorithms and develop specialised ones in the future to further reduce the needed bandwidth and latency. In this regard, we will also explore different transmission techniques and formats as well as filtering algorithms. Depending on the use case, the 3D-printed organ models used as tangible user interfaces need to be for instance deformable, and/or transparent. Since for some use cases, tactile feedback should be as realistic as possible, we need to conduct studies to measure organ softness depending on the respective disease. Furthermore, as the 3D-printed organ models need to be integrated into the VR, tracking using reflective markers will also be employed. Hardware solutions are for example OptiTrack[3] or Brainlab[4].

2.2 Focus Group

In order to investigate the potential of our approach, we performed a focus group with five physicians from the University hospital for Visceral Surgery in Oldenburg. The experts were a head physician, two chief residents and two residents of the visceral surgery department. The system was introduced to the physicians through a verbal description and three accompanying prototypes. One was a 3D-printed liver model (see Fig. 1 right) and material probes with different properties in terms of softness to introduce the haptic component of our idea. The second was a VR prototype with a virtual model of the same liver. The liver model was attached to a VR controller and could be inspected by turning the controller. With the second controller participants could annotate the virtual model. Additionally, the physicians could explore an application on the HoloLens, showing a human skull. The discussion of the focus group was recorded and analyzed descriptively afterwards.

[3] `https://optitrack.com`
[4] `https://www.brainlab.com/de/`

3 Results

The discussion in the focus group revealed that the presentation of the organ is a central aspect. The surgeons requested functionalities like marking, scaling, and changing the views, for instance by hiding vessels, or showing surrounding tissue. As for the 3D-printed organ model, they did not care about the colour when the model is used for controlling in the VR. When talking about training, they favoured two versions: an abstract visualization and a realistic visualization. The abstract one should be used mainly for the surgery planning in order to learn about the spatial arrangement of structures in the organ. The realistic visualization aims at forcing users to use their haptic senses to explore the model. The surgeons additionally suggested to overlay the relevant structures with AR.

The 3D-printed model was accepted very quickly and the surgeons expressed a huge benefit of soft models with embedded hard structures as tumors for education purposes. Landmarks, such as the ligament of the liver, should also be visible and palpable in a 3D-print. The participants were divided over the benefit for patient individual models, also in a soft print fashion, as they discussed the costs/benefit ratio and the environmental aspect. Additionally, the size was discussed intensively, as a real sized model might be beneficial for educational aims, but as an interaction device it was judged as too big and heavy.

The 3D-printed model also led to valuable observations regarding the interaction, as surgeons turned the model and pointed with their finger while showing their fellow colleagues the details of the presented model. One participant's suggestion was to record the planning process to inform the staff in the operation room beforehand of the procedure. Asked about planning with remote colleagues the participants were enthusiastic about the idea as current solutions involve screen sharing and Skype[5] or similar services, which is not a "safe solution according to good clinical practice" and brings with it high concerns with regards to patient data confidentiality.

4 Discussion

The results from our focus group show that the concept idea of our system is received very well by the participating physicians. They all agreed that our system would improve the current workflow and the combination of AR/VR with haptic models opens up new possibilities. Consistent with literature findings [14], the surgeons highlighted the benefit of better spatial perception by using a 3D model. Based on their interaction with the model and how they discussed the model at hand, it was obvious that this way of visualization and interaction encourages exchange between the experts.

The results of the focus group can be used to differentiate the use of technology between the three scenarios or phases of section 1: preoperative planning phase, intraoperative phase and the training scenario.

In the *preoperative planning phase* the surgeon can review patient's data and plan the surgery, either in VR or in AR. Especially in VR the 3D-printed model, either a general or case-specific model, will aid as an interaction device to control the virtual model. But also in AR the 3D-printed model can be used for the same purpose and might be overlaid with additional information, as the physicians positively discussed. Finding the optimal rendering solution for VR as well as AR, i.e. the HoloLens, will be an important aspect for the success of the system. As our goal is to create a multi-user application, the interaction using a 3D-printed model at one location and the purely virtual model at another location simultaneously will be a strong research focus. Research on how to present several users adequately and with low latency accompanies this research aspect. Also the size of the organ model will be of research interest, to ensure an interaction that is not fatigueing, which was a concern of the participants.

The information from the planning phase will be available in the *intraoperative setting.* In the OR AR technology will be used to ensure the surgical staff has a clear view of the situs. At the same time the surgeon can view the planning data whenever needed and interact with it with hand gestures. As the surgeons stressed the benefits of being able to bring in remote experts who get a realistic impression of the current situation in the OR, an important research topic will be how to transfer point cloud data between different locations with low latency. This will enable remote experts to view the live situation of the OR in 3D and they will be able to get all spatial information necessary to support the surgeon. This technology can give surgeons the possibility to consult specialists who can help with complicated or unusual situations and give valuable advise as they are aware of the current state of the intervention.

As the *education* of future physicians and the *training* of surgeons is an important aspect for our future, the third application area of our concept focuses on these topics. Thereby all technology developed for the scenarios preoperative planning and intraoperative support can be used to train on real cases. Furthermore, the 3D-prints can be used for a variety of use cases: First, transparent models in real size can be used to teach and

[5] `https://www.skype.com/de/`

train the spatial relations of internal structures of the organs as the participants highlighted the importance of this ability. Second, opaque haptically realistic models with varying softness can be used to train visual and tactile diagnostic skills. These models can either be general examples or case-specific models, which will be reused from a real case. Printing haptically realistic models matching a liver with cirrhosis or tumors inside is challenging. Research has shown, that current 3D-printing material is not soft enough to mimic human tissue and just workarounds like air pokes and vents in the 3D-print can get (nearly) satisfactorily results [11]. Biological materials like collagen are not suitable, as our models are supposed to be long lasting for repetitive used in lectures. Therefore, creating a realistic and long lasting 3D-print will be of research interest together with proper didactic integration.

5 Conclusion

Computer-assisted surgery becomes more common and is required by surgeons to help them plan complex surgeries, but the respective tools are lacking collaborative features as well as haptic feedback. In this work we presented a concept idea of a system, that can be used to support planning and execution of the surgery as well as training and education. We will combine a multi-user virtual and augmented reality environment with 3D-printed organ models as tangible user interfaces. Additionally, depth cameras will be used for a live reconstruction of the surgical intervention, so surgeons and remote personnel will be able to collaboratively view and manipulate detailed 3D data interactively in an immersive environment. In addition to describing the concept, we presented results of a focus group with five visceral surgeons, who tested first partial prototypes. The surgeons rate the approach as highly useful and highlighted the advantage of easier grasping the spatial relations and discussing with remote colleagues, which would greatly improve the planning phase of surgery and further steps.

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