

Laparoscopic Virtual Mirror

New Interaction Paradigm for Monitor Based Augmented Reality

Nassir Navab*

Marco Feuerstein[†]

Christoph Bichlmeier[‡]

Chair for Computer Aided Medical Procedures and Augmented Reality (CAMP)
Technische Universität München, Munich, Germany

ABSTRACT

A major roadblock for using augmented reality in many medical and industrial applications is the fact that the user cannot take full advantage of the 3D virtual data. This usually requires the user to move the virtual object, which disturbs the real/virtual alignment, or to move his head around the real objects, which is not always possible and/or practical. This problem becomes more dramatic when a single camera is used for monitor based augmentation, such as in augmented laparoscopic surgery. In this paper we introduce an interaction and 3D visualization paradigm, which presents a new solution to this old problem. The interaction paradigm uses an interactive virtual mirror positioned into the augmented scene, which allows easy and complete interactive visualization of 3D virtual data.

This paper focuses on the exemplary application of such visualization techniques to laparoscopic interventions. A large number of such interventions aims at regions inside a specific organ, e.g. blood vessels to be clipped for tumor resection. We use high-resolution intra-operative imaging data generated by a mobile C-arm with cone-beam CT imaging capability. Both the C-arm and the laparoscope are optically tracked and registered in a common world coordinate frame. After patient positioning, port placement, and carbon dioxide insufflation, a C-arm volume is reconstructed during patient exhalation and superimposed in real time on the laparoscopic live video without any need for an additional patient registration procedure. To overcome the missing perception of 3D depth and shape when rendering virtual volume data directly on top of the organ's surface view, we introduce the concept of a laparoscopic virtual mirror: A virtual reflection plane within the live laparoscopic video, which is able to visualize a reflected side view of the organ and its interior. This enables the surgeon to observe the 3D structure of, for example, blood vessels by moving the virtual mirror within the augmented monocular view of the laparoscope.

Keywords: Interactive AR Visualization, Depth Perception, Medical Augmented Reality, Laparoscopic Surgery.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction styles; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; J.3 [Life and Medical Sciences]

1 INTRODUCTION

This paper introduces a new paradigm for interactive visualization of the augmented 3D data in a monocular optical or video see-through augmented reality system. In particular, the paper focuses on providing a 3D interactive visualization method for a monitor

*e-mail: navab@cs.tum.edu

[†]e-mail: feuerste@cs.tum.edu

[‡]e-mail: bichlmei@cs.tum.edu

based augmented reality system. In such systems, at each moment the user observes the real world from one viewpoint. When the real scene is augmented with aligned virtual data, the user's view is still two dimensional. In order to leverage the 3D nature of the augmented data, the existing interaction paradigms are not satisfactory. They usually require the user to displace or rotate the 3D object out of registration with the real world or to move around the real object, which is often not possible or practical. For example, while repairing a car the technician does not have the possibility of positioning his head under the engine and when rotating the virtual model of the engine loses the advantages of direct real/virtual registration. This is also the case in many computer aided surgery applications, where the surgeon cannot move freely to observe the virtual data from arbitrary viewpoints.

We propose a new paradigm for interactive AR visualization and improved depth perception in monocular optical or video see-through systems. To demonstrate the full advantage of this new AR interaction paradigm, our system is integrated into a medical application, which was desperately in need of such interactive visualization. However, the medical AR system itself is also newly developed. Therefore, in this paper we also need to describe the main elements of this system, which, because of its intra-operative performance allows us to integrate the new visualization solution as a complementary component.

Medical Application Laparoscopic surgery started to evolve after the first successful laparoscopic cholecystectomies¹ in 1983, 1985, and 1987, respectively. In 1987, Mouret used four trocars² to insert the laparoscope along with a set of minimally invasive instruments into the patient's abdominal cavity [24]. In the following years, laparoscopy steadily advanced. Compared to traditional open surgery, several benefits were reported such as less post-operative complications and smaller scars. However, operating through small incisions also prevents the surgeon from palpating organs, vessels, and tumors during the intervention. The surgeon's dexterity is required to deal with the restricted intra-operative view and working space. Additionally, the target region often lies inside the organ, i.e. below the organ's surface as seen in the laparoscopic video. Therefore, advanced visualization techniques are needed to support the surgical staff during the intervention [17].

Several groups started to utilize pre-operative imaging data to guide the surgical staff intra-operatively. Therefore, a tracking system is used, in which the patient and their pre-operatively acquired data set coordinate frame are both registered. This registration can be achieved, for example, by using a tracked probe to identify anatomical landmarks or fiducials, or a tracked surface scanner and stereo camera system to reconstruct the patient's skin [14]. All these registration techniques can easily be applied to orthopedics and neurosurgery, where mainly rigid structures are involved. Additionally, in orthopedics and neurosurgery commercial systems for image-guided surgery are readily available for purchase.

¹A cholecystectomy is the surgical removal of the gallbladder.

²A trocar is a sharply pointed cylinder that may be used to insert instruments into the body cavity (various shape types of a trocar's sharp tip exist, e.g. pyramidal or conical).

Initial attempts were made to superimpose pre-operative volumetric data acquired by computed tomography (CT) or magnetic resonance imaging (MRI) directly on the endoscope or laparoscope [16, 19]. However, it is difficult to apply a rigid registration procedure on the basis of pre-operative data to laparoscopic surgery, where the retroperitoneum³ individually deforms due to patient and port placement⁴, carbon dioxide insufflation, respiratory motion, and the intervention itself. Instead, interventional imaging modalities need to be considered, for instance laparoscopic ultrasound sonography [6, 12] or intra-operative computed tomography [9]. Be it in 2D or 3D, the major drawback of ultrasound is its coarse resolution, hampering the precise identification of target regions. Fichtinger et al. propose an image overlay system, which is based on computed tomography and intended for needle insertion [9]. Their system requires a certain amount of space and only displays single 2D slices. This makes it difficult to be used for a number of laparoscopic interventions, where usually more than one surgeon is involved and volumetric 3D data is essential, for instance for vessel augmentation during liver resection.

Therefore, we use an optically tracked cone-beam CT-capable mobile C-arm [22] during the intervention to reconstruct a high-resolution 3D volume of the target region. This volume is directly augmented on the live video of a tracked laparoscope. By means of ex-vivo perfusion studies⁵, we have shown its benefit for liver resection [7], where it is essential to the surgeon to identify the correct vessels to be clipped in order to avoid bleeding. After patient positioning, placement of the trocars, and insufflation of carbon dioxide, an iodinated nonionic contrast agent is administered to the patient. A C-arm acquisition is started immediately and synchronized with the contrast agent's penetration into the liver vessels. The contrasted liver vessels are clearly visible in a reconstructed volume.

Since C-arm and laparoscope are tracked as well as calibrated in a common coordinate frame, as described in section 2.2, our system is registration-free, i.e. *patient or patient imaging data is not used for the registration*, but is intrinsically registered to the tracking system. The intrinsic registration enables us to augment the contrasted vessels directly on the laparoscopic video. This augmentation is intended for the intra-operative planning of a liver resection, so the co-registered augmented view is only needed for a short period of time. During cutting and clipping, registration cannot be guaranteed, even during patient exhalation, as the organ will have been moved by the surgeon. However, if the radiation and contrast agent exposure is justifiable, another scan can be performed to re-align the augmentation.

One drawback identified during our experiments, as with any standard laparoscopic intervention, is the missing depth perception. This disadvantage is especially true for monoscopic laparoscope systems. Current solutions to this drawback consist of acquiring base-line stereo images and displaying them either on a stereo head-mounted display or on 3D monitors. Because of the small keyholes in laparoscopic surgery, stereoscopic laparoscopes have a small base-line and provide limited 3D perception. The limited space for positioning two independent cameras within the body prevents truly 3D images. In a quantitative evaluation of tasks which are feasible in both monoscopic and stereoscopic systems, the stereoscopic system did not provide better task performance than a standard monoscopic laparoscopic system [25]. Thus the advantages of stereoscopic systems for their use in conventional laparoscopic interventions are put into question – there are some tasks however that can only be performed with a stereoscopic view. Even when

³Retroperitoneum is the anatomical space behind the abdominal cavity.

⁴Port placement is the process of placing trocar incisions ("ports") to access the surgical site.

⁵In these ex-vivo perfusion studies, the portal vein of a freshly harvested pig's liver was catheterized. Contrast agent was conveyed into the liver by the pump of the perfusion system.

3D vision is available, once the visible anatomy (e.g. surface of the liver), and 3D virtual data (e.g. reconstructed contrasted blood vessels) are superimposed, it is extremely hard to study the 3D structure of the augmented anatomy. When augmenting a monoscopic laparoscope, which is the usual case, the 3D volume is projected onto the laparoscope's image plane, so one dimension is totally lost, leading to even more limited perception of 3D shape and depth during superimposition. However, particularly for interventions targeting the inside of organs, shape information is crucial, for instance when identifying vessel bifurcations, which can be ambiguous due to overlaps and occlusions in 2D.

Laparoscopic Virtual Mirror To recover this lost shape information, we avail ourselves of a virtual mirror, which is placed inside the augmented view. Radkowski and Krebs lately developed a nifty virtual mirror to augment both rear-view and side-view mirrors in cars [18]. Their prototype is limited to a fixed, immovable position. Our Laparoscopic Virtual Mirror (LVM) is able to virtually reflect the 3D volume as well as the laparoscope or any other modeled and tracked instruments. When dexterously placing the LVM on the side of the target region, missing shape information can be revealed through the perceptually familiar concept of a reflection onto the mirror. As the LVM can also be manipulated by a tracked interaction device, the user could move it within the personal space, similar to the tangible and movable virtual lenses proposed by Looser et al. [13]. Their inventive lenses can be used for zooming and information filtering. The nature of lenses, however, makes them unsuitable for looking at objects from behind or from the side to reveal occluded or spatial information.

The visual feedback provided by the reflection of our virtual mirror depends on the exact position and motion of the laparoscope and the mirror. Therefore, the observer senses spatial information of the objects through proprioception [10] – the ability to sense information about the position of his/her limbs in relation to his/her spatial environment. This information is gathered from stimuli of sensory receptors, called proprioceptors, found in muscles, tendons and joint capsules. Through movement, this additional sensory information allows the user to better perceive the augmented 3D volume, its depth, exact dimensions, and complex structures. This new concept presents itself as an attractive alternative to more complex solutions based on stereo view and 3D displays.

The purpose of this paper is twofold: First (in section 2), to provide a deep insight into our image-guided laparoscopic surgery system and the needed steps to calibrate and register it. Second (in section 3), to describe the benefits of our new interactive visualization paradigm. We also describe the basic elements of the system combining advanced imaging, tracking, and interactive visualization using LVM. Sections 4 and 5 present the first results and our current conclusions.

2 SYSTEM OVERVIEW

In order to augment the laparoscope with intra-operative C-arm data and the virtual mirror, an elaborate system was set up in our clinical partner's animal operating room, as shown in Fig. 1.

2.1 System Components

One of the driving components of our image-guided laparoscopy system is an optical outside-in tracking system (ARTtrack2, ART GmbH). It consists of four infrared cameras, which are mounted beneath the ceiling of the operating room. They are positioned in each corner of a rectangle, so occlusions can be avoided to a large extent. The system is able to localize the 3D position of retroreflective spherical markers in a defined tracking coordinate frame (here referred to as the world coordinate frame). Combining at least three markers to a target, the target's rotation can be measured as well. The tracking system is connected to a desktop PC equipped with



Figure 1: Experimental setup in the hospital's animal operating room.

tracking software that sends 6D tracking data over Ethernet to our augmentation workstation.

For intra-operative image acquisition, we use a prototype mobile C-arm with cone-beam CT imaging capability based on a Siemens PowerMobil, which incorporates a workstation deployed with X-ray acquisition and 3D volume reconstruction software by Siemens. It is also connected over Ethernet to our augmentation PC, so we are able to directly access any reconstructed volumes. The augmentation workstation is equipped with 2 GB main memory, an Athlon 64 3500+ CPU, and an NVIDIA GeForce 6800 Ultra graphics card with 256 MB memory. It incorporates a frame grabber that captures the live video of our laparoscope with 30° optics (KARL STORZ GmbH & Co. KG) with 30 frames per second. A standard light source is connected to the laparoscope. A marker target is each attached to the laparoscope, a pointer, and the flat panel detector of the C-arm. We employ a helical BB phantom⁶ mounted on a stand for geometric C-arm calibration. The operating table is made of carbon to get as little imaging artifacts as possible during a series of X-ray acquisitions.

2.2 Calibration

As illustrated on Fig. 2, each of the described system components has its own coordinate frame. All of them need to be brought into the same world coordinate frame to successfully augment the laparoscopic video. The optical tracking system provides the transformations from each target coordinate frame to the world coordinate frame: flat panel to world (${}^W T_F$), pointer to world (${}^W T_P$), and laparoscope to world (${}^W T_L$). The C-arm software reconstructs a 3D volume relative to the isocenter coordinate frame F_I . To augment the laparoscopic view, a virtual camera needs to be placed at the same location as the laparoscope's camera center (F_C). Hence, the following transformations need to be computed: isocenter to flat panel (${}^F T_I$), camera center to laparoscope (${}^L T_C$), and the cam-

⁶Phantom does not refer to a PHANTOM[®] by SensAble Technologies, but rather to a model. The helical BB phantom is a set of 54 shot pellets ("BBs") of two different diameters cast in a hollow, cylindrical plastic housing and arranged as a helix.

era's perspective projection geometry along with its distortion coefficients.

All of the calibration steps can be performed off-line and remain valid for a long time – unless the marker targets are rearranged. A detailed description of all necessary calibration steps can be found in our previous work [8, 7].

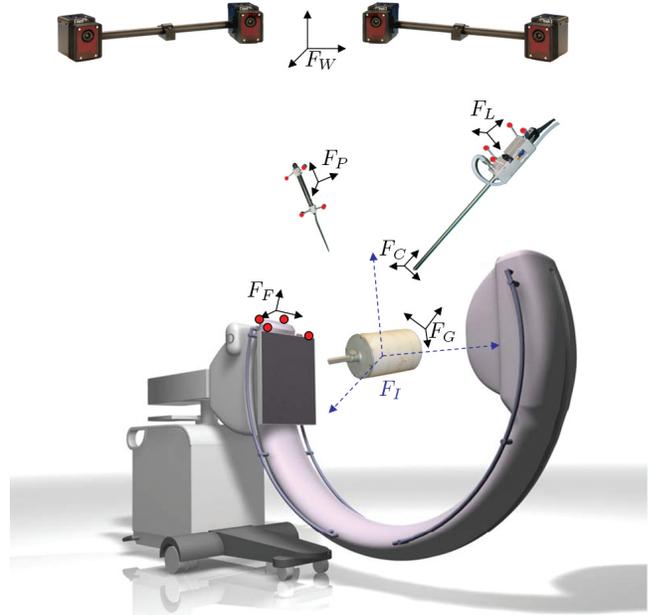


Figure 2: All involved system components' local coordinate frames.

2.3 System Accuracy

The major contributor to the overall system error is the optical tracking system. A typical setup with four ART cameras has a root mean square (rms) error of 0.4 mm for the target location and 0.12 degrees for the target orientation and a maximum error of 1.4 mm for locational and 0.4 degrees for orientational measurements[1]. As shown previously [7], both navigation accuracy with a tracked pointer and augmentation accuracy when superimposing a reconstructed C-arm volume directly on the laparoscopic view are around 1 mm, which is sufficient for laparoscopic liver resection. This obviously also holds for the virtual mirror. For a detailed description of the equations and errors involved in tracking distal tips of long instruments refer for example to recent results presented by West and Maurer[26] and Bauer et al.[4].

3 ADVANCED VISUALIZATION

In order to achieve augmentation of the laparoscopic view in real time, several requirements need to be fulfilled. Most importantly, the rendering needs to be fast, therefore our augmentation software is implemented in C++ using OpenGL[2]. Furthermore, the tracking data needs to be synchronized to the laparoscopic video images within a few milliseconds, so no temporal offset between reality and virtuality is perceptible during the augmentation, which can be achieved by synchronizing all involved PCs' clocks via NTP (network time protocol). All these features are provided by our medical augmented reality framework CAMPAR [21], which is used throughout the implementation of our system.

3.1 Laparoscope Augmentation

During the intervention, the laparoscopic view is augmented with intra-operatively acquired C-arm data. For the liver resection, we

focus on the augmentation of contrasted blood vessels. Using this augmentation, the surgeon can estimate where to cut the tissue to reach the vessels to be clipped. A typical laparoscopic augmentation of a porcine liver's blood vessels can be seen in Fig. 6(a).

Using the CG shader language[3], the volume reconstructed from a series of intra-operative C-arm projections can be rendered in real time as view aligned 3D textures. The live laparoscope video is undistorted and augmented with this volume rendering at the same time. To visualize certain tissues only, specific colors and opacities can be interactively assigned to the rendered textures, provided by a graphical transfer function editor. Additionally, default transfer functions can be loaded, for instance, one tailored for contrasted vessels. Alternatively, the volume could be segmented to generate and render polygonal models. Segmenting essential parts of the reconstructed volume however is very time-consuming. Therefore, we mainly focus on fast direct volume rendering techniques that only require the surgeon to adjust a few parameters in the transfer function editor, taking only a few seconds.

In any case, relying on the two-dimensional augmentation, makes it difficult to identify bifurcating or overlapping vessels. This limitation hampers the perception of 3D structure, which is actually available in the reconstructed 3D volume. Therefore, we introduce the concept of a virtual laparoscopic mirror.

3.2 Virtual Mirror

In addition to the visualization of the volume data, we introduce a virtual, controllable mirror reflecting the virtual part of the scene, adding a second perspective on the visualized virtual data.

3.2.1 Technique and Design

The virtual mirror utilizes a two-pass rendering approach, which is realized by the real-time computer graphics technique called *render-to-texture*. Initially, the scene that is composed of the medical volume data and a virtual 3D model of the laparoscope is reflected respective to the mirror plane. Then, a snapshot from the point of view of the laparoscope camera is stored as a perspective projection to a designated mirror texture. After that, the scene, now composed of the volume data and the mirror with the mirror texture mapped onto it, is drawn from the point of view of the laparoscope camera. The mirror texture is mapped onto the mirror plane using the OpenGL operation:

```
glTexGeni (gl_x, GL_TEXTURE_GEN_MODE, GL_EYE_LINEAR)
```

with `GL_S`, `GL_T`, `GL_R`, `GL_Q` values for `gl_x` set to create the correct reflection depending on the position and orientation of the observer and the mirror plane.

Mirror Control The virtual mirror can be guided by the laparoscope to a certain position within the AR scene. In our implementation, it is positioned along a virtual extension of the laparoscope. If desired, by a key press the mirror can be detached and fixed to its current pose. It can then be repositioned and reorientated for instance by mouse interaction on the monitor.

Furthermore, the mirror can be guided by an additional hand-held device. This allows the user to observe and study the relative positions of virtual objects, the augmented laparoscope and the mirror. Alternatively, the virtual mirror's position may also be fixed to another laparoscopic instrument, e.g. orthogonal to the instrument axis close to its tip, to have a total haptic control during the positioning of the virtual mirror.

Mirror Design While moving the mirror through the AR scene, the observer has to be able to accurately perceive position, dimension, and boundary of the mirror. The following design features were implemented to optimize this perception:

- The mirror plane is planar and provides undistorted reflection of the virtual world.

- The shape of the mirror can be set to square or circular. Using simple and familiar shapes provides better cues for perceiving the actual orientation of the mirror.
- The mirror plane is mapped with a texture, which is a simple structured pattern, to improve the perception of mirror's orientation relative to the virtual scene [23].
- The borders of the mirror are made clearly visible, by using a colored, opaque, non-reflective frame.
- If the mirror is guided with an additional hand-held device, the device and the mirror can be connected with a virtual, colored, opaque cylinder. This creates the sensation of navigating the mirror like any other laparoscopic instrument. If the mirror was positioned directly at the real target, it could not be moved within the human body to reflect the visualization of inner organs. Without a visible connection, the positioning of the mirror would be confusing. The virtual handle helps to understand the direct relation between the movements of the device and the mirror.
- The mirror's reflection plane can be made either fully opaque, e.g. colored black, or transparent to simulate a glass effect.
- The mirror can be locked to a certain position. Mirror reflection now changes depending on the point of view. While interacting with the AR scene by moving the head, the observer gets visual feedback about relative position of objects and himself/herself due to the mirror.

The mirror is able to reflect volume rendered objects as well as surface models. Fig. 6(b) illustrates these rendering modes for the dorsal surgery example application. Using the virtual mirror, perspectives such as from beneath the operating table can be viewed. The following section more clearly shows the perceptive advantages of this device positioned within an AR scene.

3.2.2 Extended Vision

The imagery seen by the laparoscopic camera provides only a monocular view of the operation site. Therefore, the perception of the three-dimensional shape of the augmented volume data is difficult. Certain structures of the visualization cannot be seen from a static perspective. For example, liver resection views of blood vessels, in particular those near bifurcations, can occlude each other. The observer cannot be sure about the position of blood vessels to be clipped. Even if the laparoscope is reorientated slightly inside the patient, exploring the structure around the blood vessels the perception of 3D information, in particular the order of blood vessels, will not be convincing.

The mirror enables an additional perspective on the area of interest. For example, the reflection on the mirror plane provides information about the arrangement of blood vessels, which could not be observed in a classical monitor based augmentation. A virtual model of the laparoscope overlaid onto the real one is also reflected in the mirror. This provides helpful information for navigating the laparoscope. The same can be done for using the mirror to improve the navigation of other surgical instruments to the operation site. In addition to the extended vision on details of the visualized structure, the mirror provides a view from physically restricted perspectives. Equipment and workflow restrict the freedom of movement of the surgeons. They can not radically change their position to get a dramatically different view onto the patient anatomy. Because the mirror is virtual and not positioned directly on the tracked target, its freedom of movement is not constrained by physical boundaries like the patients body. It can be placed as close to virtual objects as desired.

Depth Perception Depth perception is still a major problem to be solved in many AR systems when virtual entities can be displayed only superimposed on real imagery. Cutting and Vishton summarize the most important binocular and monocular depth cues [5]. The presented AR scene is "perceived" monocularly by the camera and displayed on a monitor. This excludes binocular depth cues like stereopsis. However, pictorial and monocular motion induced depth cues are available. The virtual mirror enriches information about depth because the observer can interact with the mirror and the scene and receive visual feedback. The reflection on the mirror plane can be interpreted intuitively because a mirror is a familiar device, e.g. during navigation of a car, or putting one's eye makeup on. Regarding professional life a mirror is a well-known tool used by dentists to examine the oral cavity.

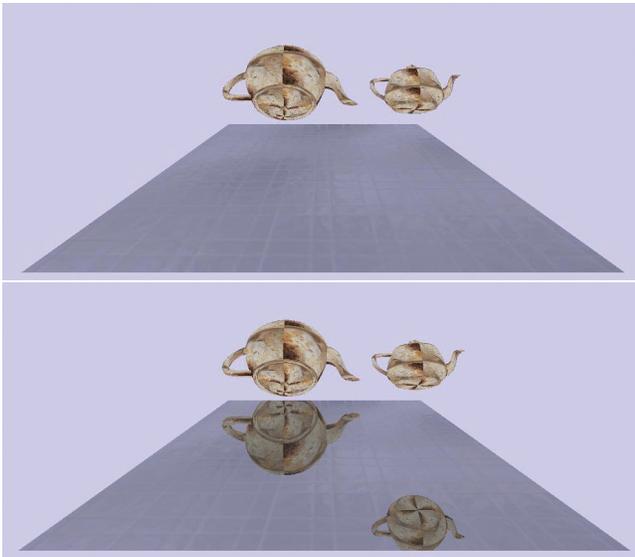


Figure 3: Illusion about depth.

The depth cues *motion parallax* or *motion perspective*⁷ provide information about depth when the observer moves either the laparoscope camera or the mirror. Also the occlusion/interposition depth cues contribute to perception of depth when the visualization partially occludes the mirror plane. According to Cutting and Vishton, these two sources of information are the most effective monocular depth cues within personal space [5]. Both cues can be perceived monocularly in the mirror image from another, user-defined, point of view. The combination of visual information of the mirror image and the camera viewpoint enhance information about the respective locations of the objects, as shown in Fig. 3, where two teapots with a varicolored texture and a mirror plane beneath the objects are visualized. The teapots have the same color and pattern but not the same size. Due to the depth cue *relative size*, the upper image without the reflecting floor tells the observer that the left teapot is nearer because it appears bigger than the right one. However, the reflection tells the true position of the teapots as shown in the bottom image with the mirroring floor. The borders of the mirror plane that cut off the mirror image also help to locate the objects.

In 1994, Kersten et al. [11] arranged a psychological experiment with the so-called ball-in-box scenario to distinguish the importance of shadow cast for spatial perception. The authors claim that

⁷The relative movement of the projections of stationary objects due to observer movement is called motion parallax. If the projection changes because of the movement of the whole field of objects the cue is called motion perspective. Both cues indicate that distant objects seem to move slower than near objects.

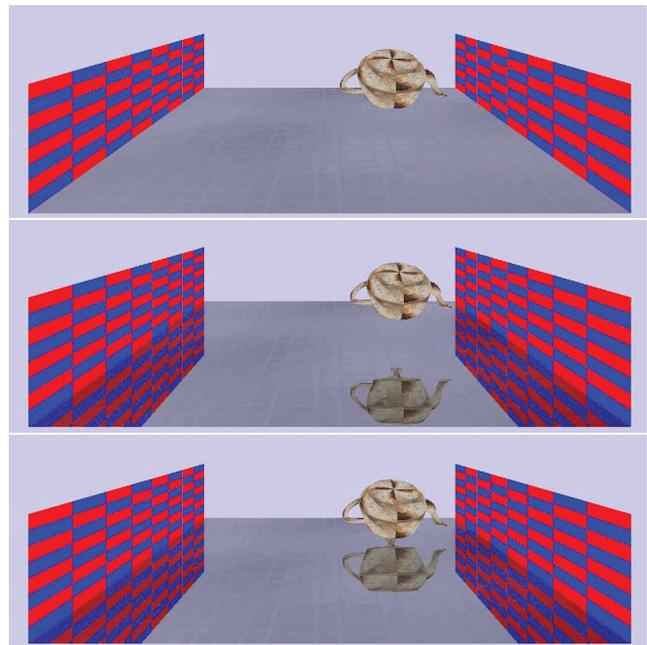


Figure 4: Modified virtual ball-in-box scenario to distinguish the importance of reflection for spatial perception. Reflection includes even more information than shadows. From the current perspective, certain details of the teapot can only be seen in the mirror image.

their "results support the hypothesis that the human visual system incorporates a stationary light source constraint in the perceptual processing of spatial layout of scenes" and "the information provided by the motion of an object's shadow overrides other strong sources of information and perceptual biases, such as the assumption of constant object size and a general viewpoint". The authors examined the perception of the 3D trajectory of each object due to the shadow cast caused by the moving objects. The same group claimed, in 1996, that an observer is able to gain information about "the shape of the object, the shape of the background surface and the spatial arrangement of the object relative to the background" [15]. We do not present shadows in this paper. However, a reflection on the mirror plane is, such as the shadow cast, a projection of the scene onto another surface, except the mirror image contains much more information about the scene, like color, shading, shape, structure of complex objects, and information about constellation of mirrored objects gained from the *occlusion* depth cue.

In addition, the mirror image has the advantage of being a function of the AR viewpoint, while the shadow is a function of secondary light source position. Therefore, when the user moves the viewpoint, e.g. location and/or orientation of the laparoscope camera, he or she sees additional 3D information. Shadows provide less informative information when moving the viewing position and orientation. Fig. 4 shows a setup similar to the ball-in-box scenario. It illustrates the consistency of the two effects and its perceptive results. The upper image shows the setup without a reflective floor. We exchanged the ball with a more complex object, namely our well-known teapot, mapped with the same texture as in Fig. 3. In the middle and lower images, the floor reflects the teapot like a mirror, depending on its position. As one can not tell with certainty where the teapot is located in the upper image, the added reflection in the two lower images provides strong information about the location of the reflected object. Due to the mirror, certain details of the reflected object like the lid of the teapot can be seen.

It is important to note that, as the mirror can also be guided by

a tracked device within the personal space and the visual feedback provided by the reflection depends on position and motion of the laparoscope and the mirror, the observer also senses spatial information of the objects from proprioception [10] (see section 1). The user can move the mirror around and change its orientation. This provides a combination of visual and proprioceptive estimations of the depth of the augmented virtual data. Based on the application and the magnification factors of the imaging apparatus, the displacement can be mapped directly or through adaptive magnification factors.

4 EXPERIMENTAL RESULTS

For our experiments, we built a model ("phantom") to simulate contrasted blood vessels inside the liver. The phantom consists of copper wires in the shape of a vessel branch containing bifurcations. It was inserted into a plastic bottle and filled with an opaque silicone rubber casting compound that is usually used to create dental models. After drying of the compound, the plastic bottle was removed. Due to the bluish opaque color of the silicone rubber, the wires inside the cast could no longer be seen, similar to the real case for actual liver vessels. The phantom can be seen on Fig. 5 and 7. The phantom was placed on the carbon operating table, an orbital scan was performed by the C-arm, and a 3D volume was reconstructed from 200 X-ray projections⁸.

For augmenting the simulated vessels, a suitable transfer function was defined to only visualize the copper wire, which has a very high Hounsfield unit and whose reconstructed voxels consequently have a very high intensity. Utilizing this transfer function inside our AR visualization software, the vessels could be directly superimposed on the laparoscopic video in real time. Additionally, a virtual pointer was augmented for our visualization and interaction experiments.

One experiment mainly focused on the perception of depth. As visualized on Fig. 7, a tracked pointer was therefore slightly inserted into the silicone rubber to find and touch a wire. Of course it is almost impossible to find a certain wire without augmentation. Being limited to a sole 2D augmentation, to ensure that the pointer intersects with the correct wire, the axis of pointer insertion needs to be collinear with a ray going through the camera center. However, this is impracticable in almost every intra-operative situation, since the operating region would be fully occluded by the instruments. Adding the virtual mirror to the augmentation, the pointer and vessels can be well visualized and their relative depth can be intuitively estimated. One can therefore determine, how many and which vessels lie beneath the pointer tip.

Information gained from the upper image in Fig. 5 results in observation of one blood vessel at the position where the tip of the instrument touches the phantom. However, from the mirror image the observer can identify at least three blood vessels that occlude each other within the augmented view.

We also built a phantom consisting of wires and a plastic ball simulating a tumor surrounded by blood vessels. This structure was filled with polyurethane foam, creating a stable phantom covering the vessel structure. We made a CT scan of the phantom and augmented its camera views. This second phantom experiment aims at demonstrating the benefit of the mirror for tumor resection. In this case the surgeon needs to perceive the spatial relationship of blood vessels surrounding or going through the tumor, see Fig. 8.

In addition, within the scope of a previous experiment concerning depth perception in AR the virtual mirror was presented to 20 surgeons [20]. Therefore we introduced different rendering techniques for in-situ visualization of the spinal column using a stereoscopic video see-through head mounted display. Having no expe-

⁸Note that the red trace on the table on the left side of the bottle seen in the augmented images in Fig. 5 and 7 is only an artifact of the cone-beam reconstruction.

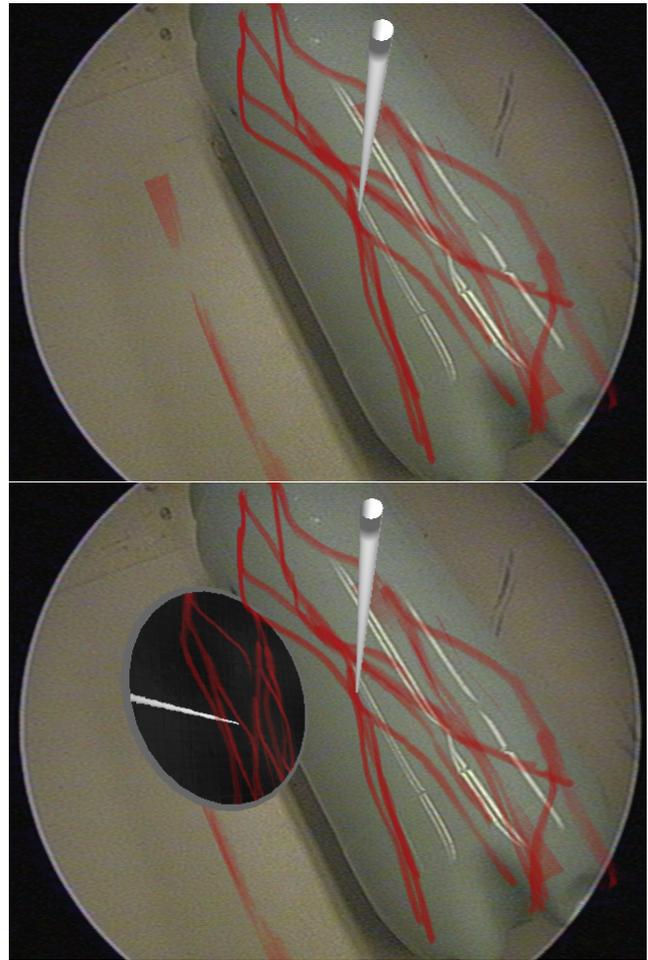


Figure 5: In the upper image the number of branches and the 3D structure of the augmented blood vessels is hard to analyze. The mirror image however shows clearly that three blood vessels occlude each other in the laparoscopic view at the position where the pointer touches the phantom.

rience with an AR system before the experiment, the participants were able to use the virtual mirror without any particular instructions. After the surgeons tested the mirror we asked them to fill out a questionnaire. Surgeons evaluated statements concerning acceptance of and potential applications for the mirror. Table 1 presents the results of the questionnaire (with questions translated from German). The surgeons were also asked for which purpose they would use this kind of visualization. Most of the participants thought of monitoring and verification of surgical cutting and drilling. They were interested in using the virtual mirror for better visualization of the position and orientation of instruments during surgical procedures. Almost all participating surgeons suggested at least one clear application for the virtual mirror.

5 CONCLUSION

In this paper, we introduce a new interactive visualization paradigm enabling the user to take full advantage of the available 3D data within an augmented scene. In particular, this is of great value for monitor based augmentations, which are restricted to monoscopic views captured often by a single camera. By means of an interactive virtual mirror, the reflected virtual view within the AR scene reveals occluded structures and adds depth information. This is ex-

The mirror helps to estimate the position of the spinal column.	2.0952
I can imagine that the mirror helps to position pedicle screws.	1.8571
I can imagine using the mirror to achieve further perspectives on the operation site.	1.6667
The mirror is an exciting instrument, but it is too cumbersome and time consuming to use.	3.8095

Table 1: Results of the questionnaire (*I strongly agree = 1 ; I agree = 2 ; I am undecided = 3 ; I disagree = 4 ; I strongly disagree = 5*).

tremely useful for laparoscopic interventions, where the surgeon is restricted to monocular views that only show the surface of an organ or one projection of contrasted vessel structures. The surgeon however needs to perceive the 3D structure, e.g. for identifying blood vessels to be clipped during liver resection. In general, the virtual mirror (1) can be used for navigational tasks, e.g. implantation of pedicle screws, (2) improves the 3D visual perception of complex structures, e.g. blood vessel trees, and (3) provides an additional view from physically restricted areas of interest, e.g. from beneath the operating table. By combining this visualization paradigm with a registration-free augmentation system for laparoscopic surgery, a powerful medical augmented reality system becomes possible, which could make such minimally invasive surgeries easier and safer to perform.

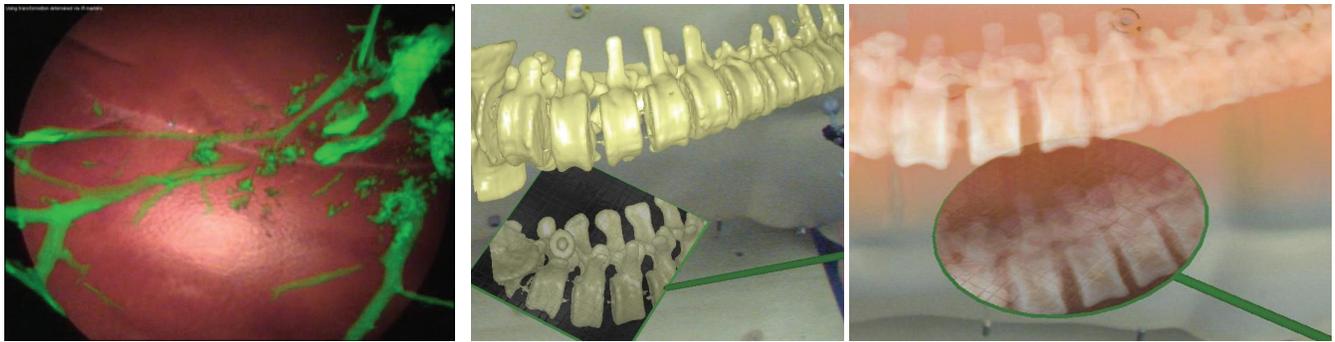
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(a) Augmentation of a porcine liver's blood vessels. (b) The mirror used in an experimental setup that addresses dorsal surgery. The top image shows a surface model of the spinal column, reflected in a familiarly shaped mirror. The bottom image shows a volume rendered vertebrae with its reflection.

Figure 6: In situ visualization for liver and dorsal surgery.

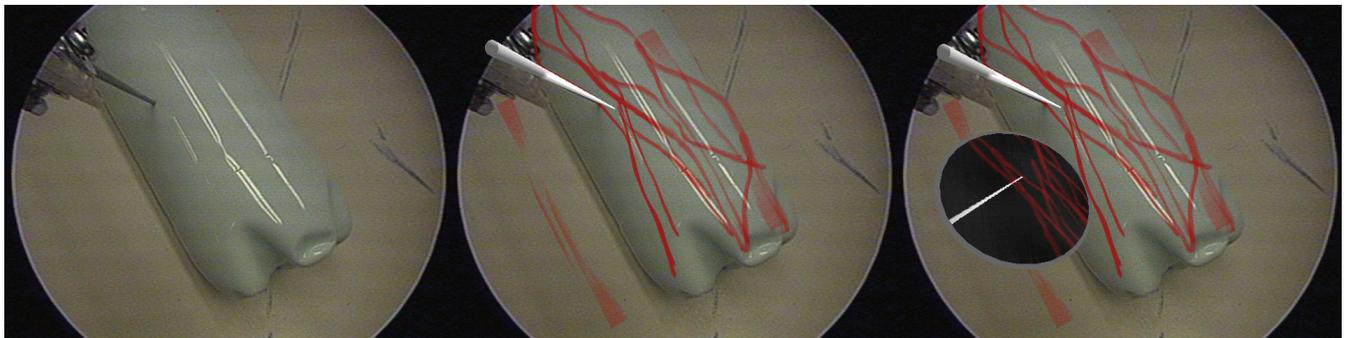


Figure 7: Silicone rubber phantom with cast-in wires to simulate blood vessels inside the liver, seen by the laparoscope. A tracked pointer is inserted. From left to right: the vessel phantom in the laparoscope image, augmentation of the pointer and the reconstructed wires simulating blood vessels, and provision of an additional mirror to estimate depth and structure of vessels.

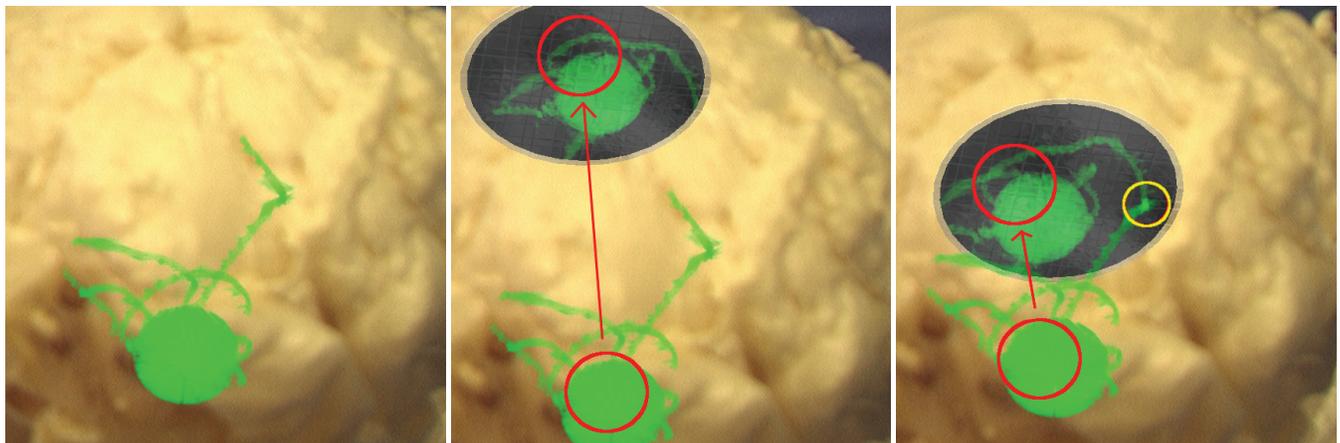


Figure 8: Polyurethane foam phantom with cast-in wires and a plastic ball to simulate blood vessels going around and through a tumor inside the liver (red and yellow annotations added manually). As shown on the left image, from certain points of view a particular blood vessel cannot be distinguished from going through a tumor or not. The virtual mirror provides an additional perspective and allows for a better understanding of the spatial relationship between vessels and the tumor, as illustrated on the right images. The reflection shows that the blood vessel, which cuts the mirror plane (see yellow circle in the right image), first passes by the tumor keeping a certain distance and later enters the tumor on its right side, which is not visible in the left image. The red circles annotate the same region.