The Virtual Mirror: A New Interaction Paradigm for Augmented Reality Environments

Christoph Bichlmeier*, Sandro Michael Heining, Marco Feuerstein, and Nassir Navab

***Abstract*—Medical augmented reality (AR) has been widely discussed within the medical imaging as well as computer aided surgery communities. Different systems for exemplary medical applications have been proposed. Some of them produced promising results. One major issue still hindering AR technology to be regularly used in medical applications is the interaction between physician and the superimposed 3-D virtual data. Classical interaction paradigms, for instance with keyboard and mouse, to interact with visualized medical 3-D imaging data are not adequate for an AR environment. This paper introduces the concept of a tangible/controllable Virtual Mirror for medical AR applications. This concept intuitively augments the direct view of the surgeon with all desired views on volumetric medical imaging data registered with the operation site without moving around the operating table or displacing the patient. We selected two medical procedures to demonstrate and evaluate the potentials of the Virtual Mirror for the surgical workflow. Results confirm the intuitiveness of this new paradigm and its perceptive advantages for AR-based computer aided interventions.**

***Index Terms*—Augmented reality (AR), interactive systems, medical information systems, mirrors, mixed reality, user interface human factors, reflection.**

I. Introduction

AUGMENTED reality (AR) has been the topic of intensive research in the last decades. Many scientific and commercial fields identified AR as a promising technology to improve existing solutions and to enable new applications that were not possible without AR. Beside the gaming and entertainment community, and different industrial engineering branches, medical engineering determined the potential of AR for being applied to preoperative diagnoses, intraoperative navigation, and postoperative control.

Intraoperative navigation systems for orthopedic surgery like spine, knee or hip surgery present the imaging data and the navigational information on monitors somewhere in the operating room (OR). In such systems the navigated surgical instrument and the patient's anatomy is localized by a tracking system. Together with slice views of the volumetric data, the instrument is presented as an icon on the monitor. This means that the physician has to deal with several focuses of attention namely the patient and the remotely presented medical imagery and navigational information. All visual information has to be mentally combined and mapped on the patient for accomplishing the navigational task. Furthermore, interaction for adjusting the visualization parameters of the data, such as brightness and contrast, is performed by further surgical staff with classical user interfaces, for instance mouse and keyboard or specific buttons.

Motivated by the increasing amount of imaging data, which can make the analysis of 2-D imagery inefficient, current researchers investigate efficient 3-D volume rendering techniques for presenting CT or MRI data. Recently, importance-driven volume rendering techniques have been proposed that highlight crucial information in the region of interest [1]–[3].

AR can prevent the surgeon from the difficult task of finding mentally corresponding regions in the image space and on the patient. The 3-D visualization of medical imaging data and an icon for the navigated instrument is registered with and superimposed on the real patient or his/her organs and the real instrument in an AR scene. The resulting AR scene can either be presented from the natural point of view with head worn devices such as video see-through head mounted displays (HMD) or on a monitor by augmenting the view of endoscopic systems.

With the combined view on the real operation site and the medical imaging data, AR visualization can provide perceptive advantages. However, one of the reasons for the absence of AR technology in today's ORs might be the deficient interaction of surgeons with visualized 3-D data to get all desired views on the region of interest. When observing the AR scene with head worn AR systems such as HMDs, simply changing the view position by walking around the patient becomes impractical. Space around the operating table in the OR is usually extremely scarce due to further surgical staff and all kind of equipment. Views from beneath the operating table onto the registered medical data is not possible at all and repositioning the patient is no option. Classical interaction methods for transformation parameters known from 2-D interfaces can not be applied anymore. In this case, the advantage of presenting imaging data registered with the patient would lapse and mental mapping of image information with the real anatomy is again necessary.

Regarding endoscope augmentation, the freedom of movement of endoscopic cameras inside the patient's body is extremely restricted due to only a few ports to the inside of the patient. Unfortunately, this extremely limits the number of perspectives on the virtual geometry superimposed on the anatomy.

Manuscript received November 03, 2008; revised January 30, 2009. First published March 24, 2009; current version published August 26, 2009. *Asterisk indicates corresponding author.*

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Digital Object Identifier 10.1109/TMI.2009.2018622

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To allow intuitive interaction with and observation of virtual objects with having only one or a few points of view on the AR scene, we take advantage of an interaction paradigm, which is strongly used in our everyday life, however novel for AR applications.

We introduce an interactively guided Virtual Mirror for generating additional views from any desired perspectives on the virtual part of an AR scene [4].

Overall, we determined four important benefits for Virtual Mirrors in AR scenarios.

1) **Visually accessing physically restricted areas:** Whenever a virtual object can not be viewed completely because the observer's viewpoint is physically restricted from a region of interest, the Virtual Mirror can provide the desired perspective.
2) **Improving navigational tasks:** The Virtual Mirror is not restricted by physical barriers. For this reason, it can enter for instance the patient's body to provide helpful additional views for navigational tasks in several intra-operative procedures.
3) **Understanding complex structures:** Whenever a complex 3-D structure can be observed from only a few points of stereo or monocular views for analytical or navigational tasks, a Virtual Mirror is capable of integrating additional perspectives on that structure into the original view. This can help to better understand hidden or self occluding structures such as complex blood vessel trees.
4) **Improving depth perception:** Simple superimposition of virtual anatomy on the patient or on organs inside the patient results in misleading depth perception of involved objects. Virtual anatomy seems to be located outside the patient's body or the organ surface. A tangible Virtual Mirror with the mirror image reacting on user interaction is capable of communicating information about relative and absolute positions of affected objects.

Before we take a look at the perceptive advantage of mirrors in Section III, we provide an overview of the related work in Section II. In Section IV-A, IV-B, and IV-C we describe the used AR systems. Section V introduces two exemplary medical applications and discusses for each of them the clinical significance of AR and the Virtual Mirror.

II. Related Work

The following section provides an overview on related work regarding navigation systems using AR for medical purposes and the mirror as an interaction paradigm in virtual and augmented worlds.

A. AR in Medical Navigation Systems

Beside medical navigation techniques based on AR [5], various other concepts have been proposed for image guided surgery. Some of these concepts optimized for particular surgical interventions became products and are now strongly used in the ORs. Peters [6], [7] provides an overview on approaches for image guided surgery and covers the full spectrum of systems. Cleary *et al.* [8], [9] review approaches in image guided surgery focusing on surgical robotics.

Only a few surgical systems for image guided surgery follow the AR concept and report on a satisfying navigation method exploiting the potentials of combining the real and the virtual domain.

Regarding HMD-based *in situ* visualization, Sauer *et al.* [10] evaluate an approach for navigated needle biopsy. Guidance of the augmented needle to an augmented target disk is supported by small shaded virtual tori. Here, information from the intersection of objects and switching the color of virtual objects from green to red provides visual hints for correct navigation. Birkfellner *et al.* [11] report on the advantage of stereo vision in AR guided interventions for depth perception of target objects inside a skull phantom using a "varioscope AR, a prototype of a miniature head-mounted operating microscope." The user guides a bayonet probe superimposed with its virtual counterpart to a target object represented as a small cylinder. When the probe comes close to the target object, its render mode changes from solid to wire frame to provide a visual hint during the navigation procedure. The same visual hint was presented in a similar system setup by Wanschitz *et al.* [12] for oral implant surgery. Aforementioned approaches [10], [11] give basic feedback about absolute distances, however, provide no or only weak information communicating relative positions of instrument and target object. Traub *et al.* [13] evaluate different visualization modes presented in a video see-through HMD for orthopedic and trauma surgery. According to the authors, their most promising navigation interface combines three orthogonal slice views lined up close to the field of action within the AR scene with the so-called "instrument aligned orthoslice view." The latter component shows two orthogonal slices registered with a surgical drill whereas the intersection line of the slices corresponds to the drill axes. The approach of Traub *et al.* [13] utilizes the surgeons' familiar data presentation namely the slice view. For controlling drill depth and orientation, however, the surgeon has to combine information from several sources. Side views on "the instrument aligned orthoslice view" (normals of slices are orthogonal to the line of sight) communicate drill depth and the lineup of orthogonal slice views shows drill direction.

Endoscope augmentation has been proposed for different medical applications like brain surgery [14], liver surgery [15]–[17], transbronchial biopsy [18], and cardiac surgery [19] to support different procedures such as port placement and navigation of instruments inside the patient. Fuchs *et al.* [20] introduce a system for laparoscope surgery displaying data with a head mounted display instead of an external monitor. The mentioned approaches only allow monocular or fixed baseline stereo viewing of the AR scene. Furthermore, the freedom of movement of endoscopic cameras is restricted to only a few ports inside of the patient, which extremely limits the number of perspectives on an augmented geometry. Thus, an entire exploration of objects such as complex blood vessel structures can not be performed satisfactorily. Wendler *et al.* [21] introduce a system for tumor resection using laparoscope augmentation. Information of a 4-D vector containing position and activity measured by an interventional beta probe is presented first visually with a generated color encoded surface map of the scanned activity superimposed on the real anatomy and second acoustically like a traditional Geiger counter. Acoustic

signals complement visual cues, however, visual perception is still restricted to monocular depth cues that do not provide an entire observation of the vessel structure from arbitrary points of view. Nicolaou *et al.* [22] "digitally detected, enhanced and re-displayed" shadow, which is cast by an endoscopic instrument but invisible to human perception. Results of their method show the potential allowing more accurate navigation of the instruments. Shadow provides strong depth cues for navigation and can help to understand a complex 3-D structure. However, in this scenario, shadow is only cast on the surface of the organ but not on inner structures like blood vessels.

Sophisticated image composition of real and virtual entities is an important research topic to allow for correct depth perception of all involved objects in an AR scene. Fischer *et al.* [23] report on handling the occlusion among real and virtual objects with an anatomy model. Further recent work on improving depth perception in AR environments has been published in [24]–[26]. In [27] Fischer *et al.* present an interaction paradigm for manipulating the AR scene that does not require the integration of classical or additional interface devices. Basic gestures performed with a tracked surgical instrument are recognized as input information to modify the content of the AR scene. However, the problem of getting visible access to physically restricted areas remains.

The idea of registering and visualizing ultrasound imagery in medical AR scenes for navigational purposes, instrument control and diagnoses is reported e.g., in [28]–[33]. Ultrasound serves as a precious real-time image source during the intervention and does not expose the patient to radiation.

Fuchs *et al.* [34] present an HMD-based AR system for ultrasound-guided needle biopsies. Needle guidance can be controlled by a tracked ultrasound device whereas its imaging data is presented within the AR scene. They also report on an augmentation of the tracked needle including a differently colored projected path working like a laser pointer to control the trajectory of the needle to a visualized target object. Wendler *et al.* [32] report on fusion of ultrasound and gamma probe data for navigated localization of liver metastases. Information is visualized and presented by laparoscope augmentation. The FOV of the gamma probe is visualized with the augmentation of ultrasound images to improve the detection of tumorous tissue. Imaging data of the ultrasound device can be visualized and registered with the gamma probe to provide helpful information for navigation particularly in medical applications. This approach follows a different concept of visualizing navigational information than the Virtual Mirror, however, we believe that a fusion of both concepts, the integration of ultrasound together with a Virtual Mirror, can lead to promising advanced methods.

B. Mirrors

Mirrors are well known and widely used in computer graphics to enhance the realism of virtual scenes. Within "virtual worlds in the context of desktop workstation environments" the perceptive advantage of a "magic mirror" is discussed in [35]. In this paragraph, we provide an overview of work employing the mirror as an interaction interface. However, none of these will present an interaction paradigm compatible to the present Virtual Mirror.

The mirror metaphor combining reality with an augmentation of virtual objects has been presented for different commercial issues. The customer is able to view oneself in a stationary mirror-like display that augments for instance clothes (http://www.iconnicholson.com). Eisert *et al.* [36] and Vigano *et al.* [37] present stationary, large mirror-like displays to augment new customized sneakers on the user's feet. François *et al.* [38] introduce a "handheld virtual mirror" consisting of a camera mounted on a display monitor and a magnetic tracking system. The recorded camera images are presented on the display and provide the mirror-like reflection, however, they do not report on registration of virtual objects to create an AR scene with the mirror. Darrell *et al.* [39] describe a system that integrates a face tracking algorithm and different image processing techniques to realize a stationary mirror display that is capable of distorting the mirror reflection.

The mirror concept was already determined to provide the driver of a car beside the information from the traditional rear view mirror with additional information in a mirror-like display that is not directly visible. Pardhy *et al.* [40] report on the idea of extending the rear view mirror in a car with additional information from a DGPS (Differential Global Positioning System), "an onboard geo-spatial database" and "radar or inter-vehicle communication" to provide the driver with an entire knowledge about position, distance and speed of other vehicles and objects close to his or her own car. Donath from the same group filed a patent on this topic and called it "virtual mirror." Kojima *et al.* [41] work on a similar concept "to provide views of hazardous areas that drivers can not see directly."

All of the mentioned mirrors referred to mixed or augmented reality applications used as a real display reflecting the world like a mirror. Some of them are capable of augmenting the reflected world with additional information registered with real objects. Our requirements on a mirror for medical AR scenarios differ from the concepts mentioned above. For our applications the mirror is one registered object among others within an AR scenario presented on a display device such as a monitor or the display of an HMD. The mirror can be guided like a dentist mirror through the AR scene having the advantage of accessing also areas inside real objects like the patient. Our mirror is completely virtual and is capable of reflecting virtual objects only. It can be attached to and guided with any tracked object, for instance a mouse pointer, a surgical drilling device, or a laparoscope. For this reason, the user can guide the mirror to a suitable position according to the particular application. Even though the mirror can only reflect virtual objects of the AR scene, virtual counterparts of objects relevant for a particular navigational tasks can be registered and visualized within the AR scene to be reflected in the mirror image like the surgical drill, the endoscope see Fig. 9, or the endoscopic instrument.

III. Perceptive Benefit of Mirror Reflection

Mirrors provide us with an additional perspective on regions of interest for fast decision making in traffic situations, to support hand–eye coordination for shaving the beard, for exploring physically restricted areas like to oral cavity. The present section will take a closer look at the perceptive advantage of mirror reflection.

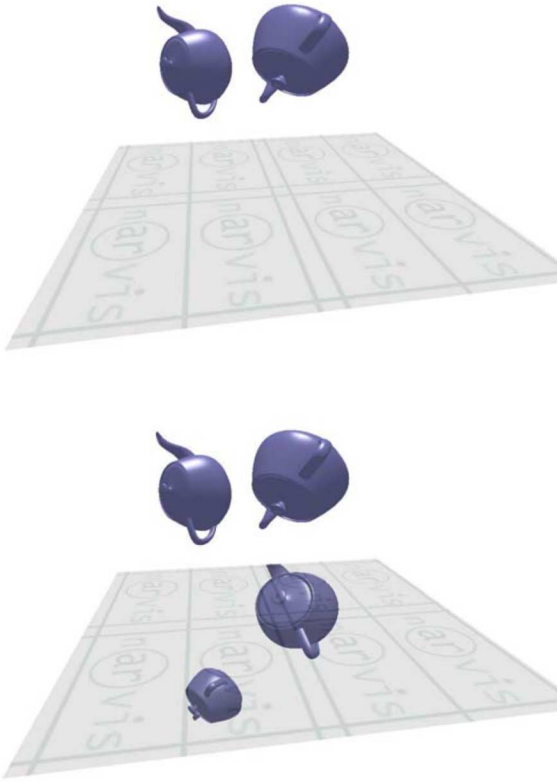


Fig. 1. Illusion about depth. Without the mirror floor the bigger teapot seams to be located nearer. Using the reflection information about depth can be corrected. The figures prove that the mirror reflection provides stronger depth cues than the depth cue relative size.

Depth perception is still a major problem in many AR systems when virtual entities can be displayed only superimposed on real imagery. Cutting *et al.* [42] summarized the most important binocular and monocular depth cues. *Relative size* is one of the most effective depth cues within personal space. The combination of visual information from the mirror image and the observer's point of view enrich information about the order of the objects impressively. Fig. 1 shows two similar looking teapots and a plane that can be changed to be reflective. The teapots have the same color but not the same size. Due to the depth cue *relative size*, the upper image without the reflecting floor tells the observer that the right teapot is closer because it appears bigger than the left one. However, the reflection tells the true position of the teapots as shown in the bottom image with the mirroring floor. Also the borders of the mirror plane that cut off the mirror image help to locate the objects. When motion comes into play the interactively repositioned mirror provides even stronger depth cues due to visual feedback in the changing reflection image.

Motion parallax or *motion perspective* can support the perception when the observer moves either his or her head with the HMD on it or the mirror. Also the cue occlusion/interposition contributes to perception of depth when the visualization partially occludes the mirror plane. According to Cutting *et al.* [42] *motion parallax* and *occlusion* are the most effective monocular depth cues within personal space. Both cues can be perceived again in the mirror image from another user-defined point of view.

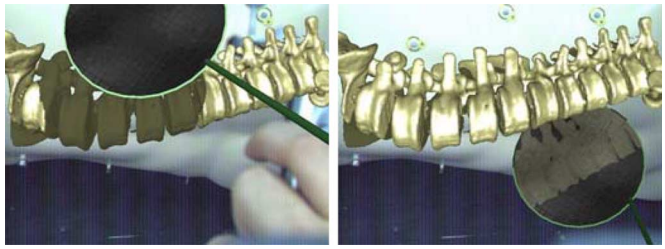


Fig. 2. Both light effects shadow and reflection cause visual cues to enhance information about relative position of objects in an AR scene. Here, a spinal column is registered and superimposed on a plastic thorax phantom. The Virtual Mirror guided with a remote mouse pointer casts virtual shadow on the vertebrae.

In 1994, Kersten *et al.* [43] 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 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 3-D trajectory of objects 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" [44]. They found out that "shadows were perceptually most relevant for the recovery of spatial arrangement, especially when the shadow is in motion." Both, reflections on the mirror plane and shadows, are projections of the scene onto another surface, except that the mirror image contains much more information about the scene, such as color, shading, shape, and structure of complex objects, as well as information about the order of mirrored objects gained from the depth cue *occlusion*. Fig. 2 shows the combination of both projective light effects with one of the first versions of the Virtual Mirror.

In addition, the mirror image has the advantage of being a function of AR viewpoint, while the shadow is a function of secondary light source position. When the user moves the viewpoint, he or she perceives additional 3-D information. Shadows provide less informative information when moving the viewing position and orientation. Fig. 3 shows a similar setup as the mentioned 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, the well-known teapot. In the middle and lower images, the floor reflects the teapot like a mirror, depending on its position. As one could 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 bottom of the teapot can be seen. In addition to visual cues, the observer senses spatial information of the objects from proprioception [45]. This information is gathered from stimuli of sensory receptors, the

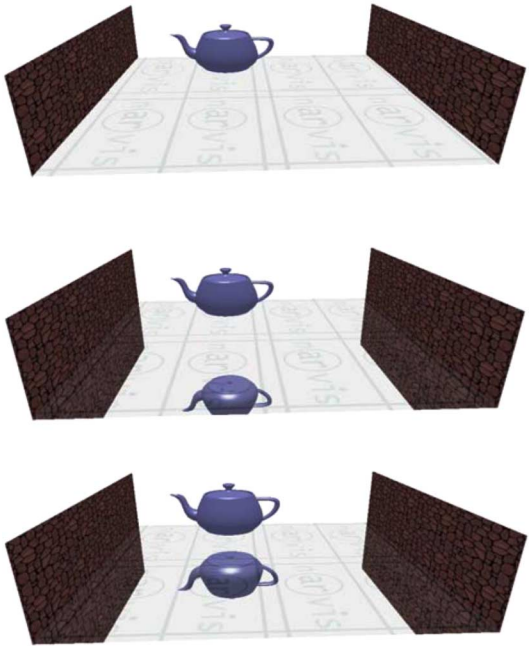


Fig. 3. Modified virtual ball-in-box scenario to distinguish the importance of reflection for spatial perception. Reflection considered as a projection of a scene onto a surface includes even more information than shadows. In this case, from the current perspective certain details of the teapot can only be seen in the mirror image.

so called proprioceptors, found in muscles, tendons and joint capsules, and generates sensation about the observer's position in relation to his or her spatial environment. The Virtual Mirror can be guided by a tracked device within the personal space. Moving the mirror through the AR scene and changing its orientation generates a combination of visual and proprioceptive cues for perceiving depth variations within 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.

IV. Methods

The following sections describe the AR system consisting of an external optical tracking system and two different types of devices capturing video images of the reality and displaying the AR scene. The first system is based on the stereo video see-through HMD presented in Section IV-B. Two color cameras mounted on the HMD simulate the eyes view. Recorded video images are fused with virtual entities to compose the AR scene, which is finally presented on two display devices in front of the user's eyes. The second system records video images with a laparoscopic camera (see Section IV-C) and presents the AR scene on an external monitor. Both systems employ an optical tracking system for specific purposes (see Section IV-A).

A. Shared Hardware Setup of Both Systems

To locate the patient and further surgical instruments within the surgical workspace, we use an optical outside–in tracking system (A.R.T GmbH, Weilheim, Germany) with four infrared cameras fixed to the ceiling covering a large working area ($3 \times 3 \times 2$ m). In this case sensor cameras are rigidly fixed for observing the tracking volume. They receive signals sent from markers attached to tracking bodies. After an initial calibration procedure the outside–in tracking system provides accurate tracking as long as the tracking cameras remain at their position. The system is capable of tracking the targets in our setup with an accuracy of <0.35 [mm] rms. The tracking system uses retro-reflective fiducial markers. To recover the six degrees-of-freedom of a rigid body, the external optical tracking system requires at least three rigidly attached markers. Fiducial markers are attached to the surgical instruments, the phantom/patient and on specific targets enabling the calculation of the optical center of an imaging device, such as an HMD or an endoscope camera, capturing the real scene.

Our AR software framework CAMPAR provides methods for synchronization, registration, image processing and visualization of medical volume data such as CT or MRI using different rendering techniques [46]. For the experiment described in Section V-A we segmented the bone region from the original CT data volume and triangulated the corresponding voxel positions to create a polygonal surface model of the vertebrae. The polygonal surface model of three vertebrae consists of 8114 triangles and is rendered as a OpenGL display list. The experiment described in Section V-B uses GPU based direct volume rendering, which has been implemented with view-aligned OpenGL 3-D textures and a 1-D transfer function. Both approaches show a frame rate of more than 20 fps, which is accepted by the participants of the experiments since the nature of the experiment tasks does not require fast motion.

A PC based computer is used to render 3-D graphics, to compute and include tracking data, to synchronize and combine imagery of virtual and real entities. The specification is Intel Xeon(TM), CPU 3,20 GHz, 1,80 GB RAM, NVIDIA Quadro FX 3400/4400. The Virtual Mirror and further computer graphic objects are implemented in C++ using OpenGL (http://www.opengl.org) and Cg (C for Graphics is a high-level shading language developed by NVIDIA).

B. Head Mounted Display System

See through head mounted displays provide the physicians with a simulated X-ray view through the patient. *In situ* visualization of the anatomy, which means that the anatomy is registered with the patient and presented from the natural point of view, is considered to be the most intuitive way of presenting the data. This eases the hand–eye coordination while navigating (augmented) instruments to the operation site in an intraoperative AR scenario. *In situ* visualization using HMDs minimizes the number of workspaces and shows the patient, imaging data and information from different systems such as vital signs and navigation data in only one field of action.

Within the scope of the present and also earlier experiments [47], we asked the surgeons to give feedback about the usability of the HMD based AR system. In general, surgeons approve the concept of presenting navigational information and medical imaging data from the natural point of view when being integrated in their work flow. They claim that they would not use the proposed system during the whole surgical procedure. However, for the critical steps like the resection of tumors or navigated

drilling they consider *in situ* visualization as an advantageous solution. An important factor for the surgeons is the ability to quickly remove the system in emergency cases or when it is not needed anymore. A cumbersome and time-consuming procedure to put the HMD on and off would strongly affect the acceptance of the HMD.

One major concern of surgeons addresses the weight of the HMD. In contrast to the prototype system that was built to show the feasibility and potentials, the HMD would undergo a major redesign process in order to meet also usability requirements when becoming a product. For upcoming research related to evaluations with the present system, we are currently developing different concepts. One solution addresses a hanging HMD that is mounted like an OR lamp to a flexible arm construction attached to the ceiling. The surgeon can pull the HMD onto his head when AR views can be helpful and push it away when being obstructive. A primary solution for this is currently developed by our partners at Simiosys (http://www.simiosys.com). In addition, we currently started the development of a system that captures and analyzes the surgical workflow. This will allow us to determine and communicate automatically situations during the operation, when AR technology can be helpful for a particular surgical task [48]–[50]. Regarding the problem of relatively small field of views due to HMD hardware restrictions, which is often criticized in the literature, we do not get negative feedback for the surgical workspace. Surgeons' field-of-view (FOV) is directed at the patient unless he/she has to deal with additional sources of information like monitors showing medical imaging data. However, exactly this problem can be solved by HMD based *in situ* visualization.

For our research topics and experiments we use the RAMP system consisting of tracking software and a stereo video see-through head mounted display presented by Sauer *et al.* [51]. For superior registration quality, a second tracking system is synchronized with the external tracking system described before. The single camera inside–out tracking system allows for a high rotational precision [52] necessary for tracking the stereoscopic video see-through HMD (see Fig. 4). In this case the sensors are attached to the body to be located, e.g., the HMD, while receiving and measuring signals from external senders. Two color cameras rigidly attached to the HMD simulate the eye's view. An additional infrared camera, mounted on the HMD, realizes inside–out tracking. This infrared camera tracks a reference frame, which is a static set of retro-reflective markers, to estimate the head pose for the registration of both the virtual and the real world. The reference frame enables the transition between the inside–out and the outside–in tracking systems since both tracking systems calculate the same coordinate system for the reference frame. There are two major reasons why to choose a video see-through system. Real and virtual imagery can be optimally synchronized to avoid time lags between the images of the camera, which would lead to undesirable and for the user fatiguing effects like "perceivable jitter or swimming" [51]. Second the system allows for more options on how to combine real and virtual imagery like occluding real objects since we have full control over the real images while optical systems offer only a brightening augmentation. All augmentations on targets, which are tracked by the optical outside–in tracking



Fig. 4. The used video see-through head mounted display [51] consists of two color cameras simulating the eye's view and an infrared camera for inside–out tracking.

system, have to be positioned respectively to the reference frame of the inside–out tracking system. The following equation calculates the transformation $H^{\mathrm{t}}_{\mathrm{ref}}$ from the reference frame to an exemplary target $(H^{\mathrm{to}}_{\mathrm{from}})$:

$$H^{\mathrm{t}}_{\mathrm{ref}} = H^{\mathrm{t}}_{\mathrm{ext}} * \left(H^{\mathrm{ref}}_{\mathrm{ext}}\right)^{-1}. \tag{1}$$

Transformations $H^{\mathrm{t}}_{\mathrm{ext}}$ and $H^{\mathrm{ref}}_{\mathrm{ext}}$ are provided by the external, optical outside–in tracking system. The former describes the transformation respective to the origin of the tracking system to a target, the latter one is the transformation from the origin of the tracking system to the marker frame for inside–out tracking. The transformation for *in situ* visualization can be described by $H^{\mathrm{CT}}_{\mathrm{ref}}$.

$$H^{\mathrm{CT}}_{\mathrm{ref}} = H^{\mathrm{CT}}_{\mathrm{phan}} * H^{\mathrm{phan}}_{\mathrm{ext}} * \left(H^{\mathrm{ref}}_{\mathrm{ext}}\right)^{-1}. \tag{2}$$

The optical outside–in tracking system provides the transformations $H^{\mathrm{phan}}_{\mathrm{ext}}$ and $H^{\mathrm{ref}}_{\mathrm{ext}}$. We attached CT markers (Beekley Corporation, http://www.beekley.com) coated with retro reflective material to the phantoms used in our experiments. Compared to the usual content of CT images showing the patient's anatomy of interest, these markers have a distinguishably high intensity value. For this reason, these markers can be segmented automatically from the volumetric imaging data unless there is further material such as metal screws with similar intensity values within the targeted image space. Correspondence of segmented positions and tracking data results in a registration matrix $H^{\mathrm{CT}}_{\mathrm{phan}}$ that aligns the data volume with the tracked object.

C. Laparoscopic Camera System

Regarding the use of endoscopic cameras in different surgical interventions such as laparoscopy, arthroscopy, and gastroscopy,

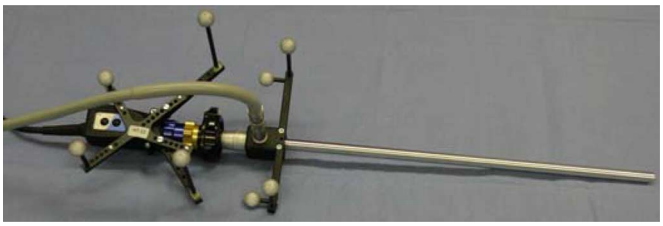


Fig. 5. The laparoscopic camera consisting of two marker targets tracked by the optical outside–in tracking system.

the recorded video images can be augmented with visualized medical imaging data. Such augmented video images can be presented on an external monitor. This supports the surgeon in defining the right place for the port for entering the patient with endoscopic instruments and the endoscopic camera. In addition, endoscope augmentation allows for the view on inner structures of organs to localize e.g., blood vessels and tumors. Such augmented views can be used for instance for planning the resection of tumorous tissue and consequential clipping and closure of blood vessels feeding the tumor.

The external outside–in tracking system described in Section IV-A spatially localizes the laparoscope (telecam SL ntsc by KARL STORZ GmbH & Co. KG). A standard light source illuminates the FOV inside the patient. To provide a correct image superimposition during rotation of the 30° camera optics, the laparoscope shaft as well as the laparoscope body containing the camera CCD are tracked independently. Therefore, one marker target is attached to each of them (Fig. 5) to determine the rotational offset between the components. To model this rotation and the camera geometry, the laparoscope is calibrated applying the techniques of Yamaguchi *et al.* [53].

D. Real Time Mirror Techniques

In computer graphics mirror reflection is a standard effect that can be performed in real time with basically two different techniques. Both require the virtual scene to be rendered twice, once for the reflected scene and another for the original scene. For this reason the frame rate for both techniques is similar and strongly depends on the rendering of the original scene to be reflected. Both techniques have been implemented using the OpenGL (http://www.opengl.org) library and tested with our Medical Augmented Reality software framework CAMPAR [46].

The first approach referred to as render-to-texture stores a snapshot of the reflected scene to a designated texture and maps it view-aligned onto the virtual object representing the mirror. This approach allows for manipulation of the mirror image for instance distortion to magnify reflected objects. Another approach to create mirror effects employs the stencil buffer that can be used to mask the frame buffer. The stencil buffer is an additional buffer besides the color buffer and depth buffer found on modern computer graphics hardware. It can be used for instance to limit the area of rendering. Within this context the mirror is rendered first to define the mask. The mask defines the area that is allowed to be modified by the first rendering pass drawing the scene reflected on the mirror plane within the mirror mask. In the second pass the stencil function is disabled and the original scene is added to the mirror.

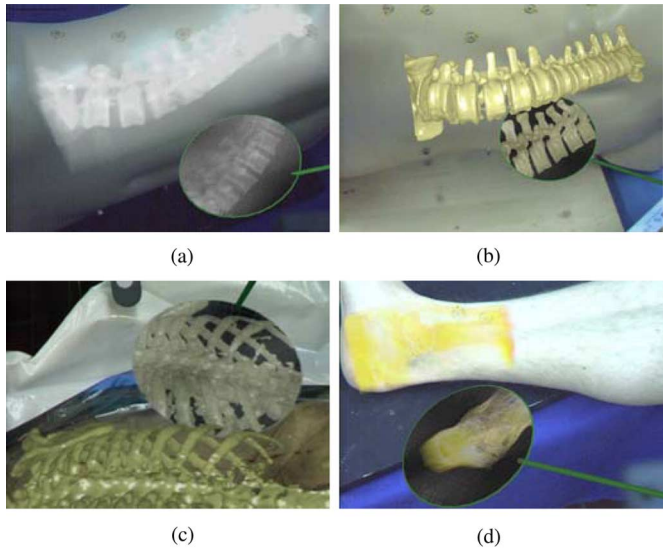


Fig. 6. The handheld Virtual Mirror reflects virtual objects rendered with different visualization techniques. (a) Digital reconstructed radiographs. (b) Polygonal surface models. (c) Cadaver study. (d) Direct volume rendered MRI data set.

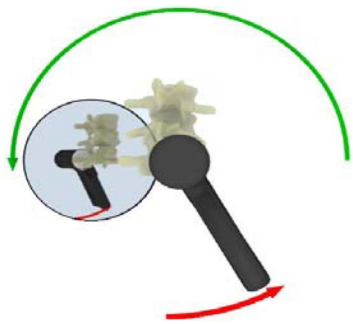


Fig. 7. The angle of the mirror rotation around the drill tip (green/bright arrow) is the multiplied rotation angle of the drilling device around the drill axis (red/dark arrow).

V. Evaluation for Medical Applications

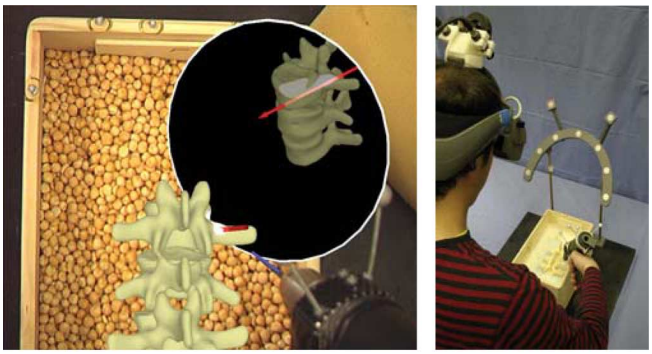
In 2006, our group presented the concept and prototype of a Virtual Mirror, which can be guided through an AR scene by a handheld, tracked, remote mouse pointer [54]. It was successfully tested on a phantom [Fig. 6(a) and (b)], a cadaver [Fig. 6(c)], and a patient [Fig. 6(d)]. At that time, however, we have not evaluated its usefulness for any kind of application.

This paper presents two user studies with their main focus on medical applications that can benefit from an additional view onto the region of interest using the Virtual Mirror.

A. Spine Surgery

The Virtual Mirror can be used in combination with the HMD based system [see Fig. 8(b)] described in Section IV-B for communicating navigational information in spine surgery. We determined the preparation of drill canals for pedicle screw implantation as a promising surgical application [55].

The objective of pedicle screw implantation is to install an internal fixateur for stabilization of injured vertebrae. In the proposed system, vertebrae are first segmented from volumetric CT



(a) (b)

Fig. 8. The anatomic situation for the navigated preparation of the drill canals is simulated with a phantom consisting of three vertebrae, (a) The virtual part of the AR scene shows the vertebrae, the drill, the drill canal and the Virtual Mirror. (b) Our colleague Augustiner wears the HMD and guides the surgical drill to the vertebrae.

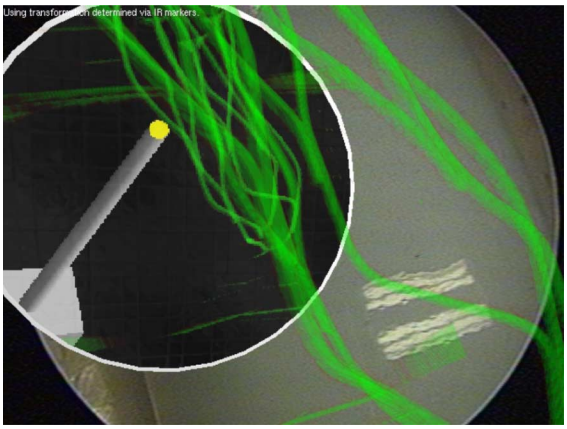


Fig. 9. Reflection of a virtual counterpart of the laparoscopic camera on the mirror image provides helpful visual feedback to estimate relative positions of devices and anatomical region of interest.

data and then visualized *in situ*. A surgical drilling device is virtually extended with a Virtual Mirror for intuitive planning of the drill canal, control of drill direction, and insertion depth. The corresponding AR scene is shown in Fig. 8(a).

We suggest to divide the procedure of drilling preparative holes for the pedicle screws into two steps. First, a drill canal is planned and defined, second the drilling procedure itself is performed.

The virtual components of the AR environment include a polygonal surface model of the vertebrae, a red arrow supporting the interactive planning of the drill canal, the Virtual Mirror, and a blue cylinder representing the tracked drill [see Fig. 8(a)]. Depending on the position and orientation of objects, a virtual model of the drilling device is visible in the mirror image as well.

During the planning stage, the Virtual Mirror can be rotated on a circular path around the drill axis (radius $= 10$ cm) by rotating the drilling device around its axis. For ease of use the rotation angle of the drilling device is multiplied by an adjustable factor to change the position of the mirror. This enables the surgeon to move the mirror around the target while only rotating the drill by a small angle. Thus only a slight motion of the drilling device can provide all desired side views on and into the transparent augmented vertebrae (see Fig. 7).

TABLE I
TWENTY DRILL-HOLES HAVE BEEN COMPARED FOR EACH METHOD. VIRTUAL MIRROR/HMD BASED METHOD SHOWS HIGHER ACCURACY, HOWEVER TAKES LONGER

	method	mean	std. deviation	std. error mean
accuracy	Virtual Mirror	1,3500	0,74516	0,16662
	monitor based	1,7	0,86450	0,19331
time	Virtual Mirror	173,75 sec	84,125 sec	18,811 sec
	monitor based	168,952 sec	103,589 sec	23,163 sec

The first step of the procedure is the insertion of a red arrow that extends the drill at its tip into the augmented vertebrae. Then the position of the planned drill canal can be controlled with the mirror reflection. When the correct canal pose has been found, it can be locked and remains at its designated position inside the vertebra during the next steps of the procedure.

Before the drilling is started, the surgeon places the mirror at a suitable position that enables a view onto the exit point on the bottom of the vertebra and also allows for control of insertion depth. A virtual spot light is attached to the drill tip and oriented towards the drill direction in order to provide additional information for navigation. The spot light illuminates the entry point at the pedicle as well as the exit point on the opposite side of the vertebra, which is visible only through the mirror [see Fig. 7, Fig. 8(a)].

Regarding the surgical task, the drill has to be aligned with the defined drill canal at the entry point using visual cues due to the spot light and intersection of drill, vertebra, and drill canal. This means that the drill has to be reoriented until the visible spot light is aligned with the exit point on the back of the vertebra seen through the mirror.

In order to evaluate the AR navigation system, a first user study with five surgeons compares a classical monitor based navigation system with the present AR based approach. Analysis of 20 drill-holes for each method shows promising results (see Table I).

According to the surgeons the planning stage enables a final check of the canal position and allows for collaborative decision making before the vertebra is drilled. We refer to [55] for further details of this work.

B. Minimally Invasive Tissue Resection

We also integrated the Virtual Mirror into an AR system intended for enhanced visualization and perception of complex structures during laparoscopic resection of tumor affected liver tissue. For liver resection, blood vessels supplying the tumor have to be closed and cut before tumorous tissue can be removed and finally extracted using a laparoscopic forceps such as the one illustrated in Fig. 10.

In our prior work [56] we reported on an exemplary setup showing that the additional perspective of a Virtual Mirror can provide an improved perception of depth, structure, and spatial relationship of vessels.

In order to evaluate the Virtual Mirror technique quantitatively and qualitatively for advanced visualization during minimally invasive liver resection, we asked 12 surgeons of our partner clinic to participate in another experiment to evaluate



Fig. 10. The endoscopic surgical instrument is tracked by the external optical tracking system and has to be guided to the target spots.

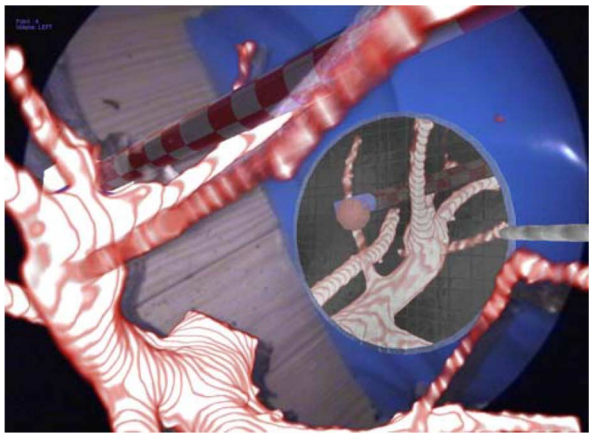


Fig. 11. The tracked endoscopic instrument reaches a target spot. In this case this can only be controlled with the Virtual Mirror. A blue plastic foil blocks the view on the second branch.

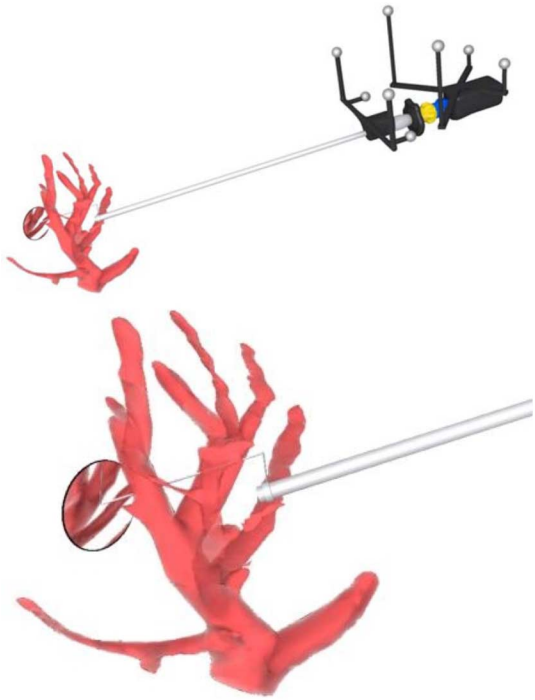


Fig. 12. Illustrative view on the mirror attached to the camera. The Virtual Mirror is positioned in front of the laparoscope camera and oriented toward the optical center.

the usefulness of the mirror for improved perception of complex structures [57].

The AR visualization for minimally invasive abdominal surgery is based on medical volumetric data acquired by (cone beam) CT, which is registered to the patient and overlaid onto the live camera images of a laparoscope tracked by an optical tracking system [16]. An injected contrast agent enables the discrimination and emphasis of vascular structures. To avoid in vivo studies for the simulation of the visual properties of a blood vessel tree during image acquisition, we designed a phantom consisting of wooden branches.

Quantitative results of the experiment show the advantage of a mirror in certain cases, when blood vessels can not be directly seen from the camera point of view due to self-occlusion of the structure. Results of a questionnaire filled out by the surgeons after the experiments confirm the acceptance of AR technology for particular medical procedures (see Table III).

1) Experimental Setup: The phantom (Fig. 14) consists of a wooden box with six retro-reflective CT markers attached to the upper border of the box, so it can be localized by the optical tracking system. We installed two branches inside the box and separated them physically by a plastic foil, so once inserted, only one branch is visible by the laparoscopic camera. The phantom was scanned by CT and prepared for visualization. To simulate the spatial layout during visualization, the two branches are separated virtually by clipping planes. During the experiment the box was covered with a wooden board. Twelve holes were drilled into the plate for each branch serving as ports to the inside of the box. After the CT scan, for either volume we defined five target spots, each of them visualized as a polygonal sphere colored slightly differently than the direct volume rendering and Cg (C for Graphics) of the branches. The augmented surgical instrument of Fig. 10 had to be guided to the target spots (Fig. 11).

The experiment compares two visualization modes. The first visualization mode (*ViNoMir*) consists of a tree structure augmented on the laparoscope view, the second one consists of the augmented tree structure including the Virtual Mirror (*ViMir*).

For *ViMir*, the mirror is installed 165 mm in front of the laparoscopic camera and oriented 45° toward the point of view (Fig. 12). The mirror can be placed at four different positions (left, right, top, bottom), whereupon the center of the mirror is moved orthogonally 70 mm away from the view axis of the laparoscopic camera according to the respective position. The Virtual Mirror reflects the visualized branches as well as the virtually extended surgical instrument. The background of the reflected scene is black. Furthermore, the mirror is flat, textured, and bordered and has a round shape. A textured cylinder connecting the mirror with the camera provides visual cues about the spatial position of the mirror respective to the camera position.

For evaluation, two visually separated different tree structures were used to avoid learning of the structure of one branch while working with the first visualization mode and using this knowledge for the second visualization mode. The visualization of volume data augmented on video images of the laparoscopic camera was presented on a monitor positioned in the working space of the subjects as shown in Fig. 13.

Every subject had to reach five spots for each of the two branches. For every target spot, we predefined one of 12 ports, which had to be used for the insertion of the laparoscope camera. The selected ports provided a restricted view onto the target spot



Fig. 13. Six of 12 surgeons of our clinical partner guide the surgical instrument inside the phantom using the video images of the laparoscopic camera presented on a monitor.

TABLE II
TENDENCY OF MEASURED DATA GIVEN AS AVG(STD) SHOWS HIGHER ACCURACY USING THE VIRTUAL MIRROR BASED METHOD

mode	dist	time
ViNoMir	$14.29mm(5.28)$	$69.70sec(64.45)$
ViMir	$13.45mm(4.79)$	$87.49sec(82.20)$

TABLE III
RESULTS OF THE QUESTIONNAIRE POSED IMMEDIATELY AFTER THE EXPERIMENT

The scale of the multiple choice questionnaire was *I strongly agree(1)* ↔ *I agree(2)* ↔ *I am undecided(3)* ↔ *I disagree(4)* ↔ *I strongly disagree(5).*	AVG(STD)
The system is useful to understand the structure of blood vessel trees even though an exact overlay of virtual and real blood vessels can not be guaranteed	1.81(0.57)
Position of the mirror reduces my view on the work space, however, the additional visual information provided by the mirror image to locate the surgical instrument and to understand the structure of blood vessel trees is beneficial	1.91(0.51).
An additional mirror positioned anywhere within the scene is restricting my view and provides no advantages	4.27(0.62)
The position of the mirror in front of the camera restricts the view on my work space and is not helpful	4.0(0.43)
Augmentation of the 3D structure including the mirror provides an advantage compared to the classical visualization of CT data on a monitor.	1.91(0.79)
The augmentation of blood vessels without the mirror is more helpful	3.73(0.86)
Do you think that the experimental setup is capable to simulate the real medical intervention sufficiently?	2.73(1.05)

due to self-occlusion of the branches. The surgical instrument could be inserted through an arbitrary port. The combination and order of branches and the visualization mode changed for every subject. When subjects reached the target spot they asked the investigator to lock the result to measure time and accuracy. Overall 12 surgeons participated and 60 spots were analyzed. Accuracy was measured virtually. Therefore, a predefined, constant error has to be taken into account composed by the tracking error and the manually designed virtual clamp, which does not exactly conform to the real clamp of the surgical instrument.

Before a subject started the experiment, we provided the following information.

1) Wooden branches simulating a complex structure were installed inside the box. We made a CT scan of the phantom and visualized the imaging data in 3-D.
2) AR visualization means that virtual objects such as CT data can be superimposed onto the laparoscopic camera images using our AR system. For this reason, the visualization of wooden branches is registered with the real branches.
3) You have to reach visualized spots, small red spheres, on the branch structure with the surgical instrument.
4) The laparoscope can only be inserted into the box through one specific port for each target spot. Start position of the laparoscope and the instrument for every new target spot is the entry of a port. For the surgical instrument, you are allowed to use any port.
5) We compare two different visualizations each on a different structure: Augmented structure only and augmented structure plus Virtual Mirror. We measure time and accuracy.
6) In the mirror-based visualization, the Virtual Mirror is positioned 165 mm in front of the laparoscopic camera and oriented 45° toward the camera. The mirror can be repositioned at four different locations by request (left, right, top, bottom).
7) Please do not pull or push too hard to avoid breaking the branches!
8) Before we start, you will test the system with an augmented dummy object.

Immediately after the experiment, we asked the subjects to fill out a questionnaire for qualitative evaluation of the system.

2) Results: It needs to be mentioned that the quantitative results are valid for particular situations when a region of interest of the structure can not be seen directly from a certain point of view limited by the port for the laparoscope camera to the inside of the patient. Results do not show significant differences between the visualization modes. However, from the calculated means we assume that subjects guided the instrument with higher accuracy to the predefined target spot using the *ViMir* mode. However, using the *ViNoMir* mode takes less time (see Table II).

After exclusion of outliers deviating three times the STD from AVG, a total of 106 target spot measurements, in detail 54 *ViNoMir* and 52 *ViMir* ones, were analyzed. In addition to the Euclidean distances, we also analyzed individual x, y, and z distances from the spot to the tip of the instrument relative to the instrument coordinate system with z being the instrument axis. Comparing the two visualization modes, measured distances in x and y direction do not differ significantly ($x = 0.84$ mm, $y = 0.38$ mm), however, in z direction the difference of distances is $z = 1.64$ mm. We assume that the view along the instrument axes without using a mirror does not provide sufficient visual information for position control.



(a) (b) (c) (d)

Fig. 14. Two wooden branches are installed on the bottom of the box and visually separated by a plastic foil. For the experiment the box was closed with a plane having twelve ports to each branch.

Occlusion effects tell subjects when they reached the target spot with the instrument. However, we noticed an interesting effect during the experiment, which was also confirmed by a participating surgeon after the experiment. When surgeons had problems to reach a spot due to physical barriers because of the branches and the tip of the instrument was already close to the target, they rather stopped and asked to lock the result instead of keeping on trying to move the clamp to the correct position. In contrast, when using the mirror to get an additional view on the target, motivation increased to keep on trying until both perspectives, the direct view and the mirror image, proved to have successfully located the spot. This delayed finishing the task, however, navigation got more accurate.

According to the results of the questionnaire the average age of the participating surgeons (ten male, two female) was 32 and they had 5.8 years of work experience.

One participant said that the mirror is useful to find the target spot, however, he would not use it to navigate the tip of a laparoscopic instrument to the target region. Nevertheless he would use the additional perspective provided by the mirror image for a final check before he clips or cuts the blood vessel. Participants also suggested to manipulate the size, the orientation, and the position of the mirror with foot pedals, rather than asking an assistant for repositioning. During the experiment some surgeons asked for the ability of scaling and reorientation of the mirror. In addition an adjustable distance to the camera point of view was required. Suggestions of the surgeons to use such an AR system range from all types of laparoscopic surgery such as cholecystectomy and adrenalectomy to advanced control of oncologic surgery in resection of colon and rectum and lymphadenectomy. Furthermore, arthroscopic surgery, minimally invasive spine surgery, and neurosurgery were mentioned.

Surgeons can imagine using the Virtual Mirror for visualization of 3-D data sets in all procedures where currently 2-D monitor control is performed: laparoscopy, arthroscopy, thoracoscopy, and even procedures using flexible endoscopes.

3) Discussion: In order to be able to draw statistically correct conclusions, the number of surgeons N participating in this study has to be increased. Based on the qualitative feedback from the questionnaire, we assume that bigger N will also show the hypothesized significant advantage of the mirror mode.

The visualized part of the phantom (the wooden branches) are rigid in contrast to the real scenario where deformable soft tissue is clipped. In the real scenario, in most cases, the pose and shape of soft tissue will change between data acquisition and surgical intervention. Even though data is acquired intraoperatively using e.g., a mobile C-arm, surgeons can not rely on the accurate augmentation due to breathing, pushing, and pulling tissue with surgical instruments and manipulation of the tension of tissue as cutting modifies its structure. However, some basic characteristics of the structure like relative position and order of blood vessels, vessel size, and branches remain in spite of all extraneous, deforming influences. Information about these characteristics can be used to plan the next step in the surgical workflow, for instance to decide where to cut next. In most cases, structure can be understood satisfactorily from the monocular point-of-view of the laparoscopic camera. The experiment evaluated the suitability of a Virtual Mirror to create a mental model of such a structure for navigating through it.

Creating a reproducible phantom fulfilling all the conditions to simulate a realistic anatomical environment for such an experiment is quite difficult. In a real scenario a direct view on the blood vessels is not possible. Regarding liver resection, physicians have several visual hints on how to locate a certain liver segment e.g., due to the pose of the patient, recognized organs around the operation site, and shape of the liver. However, we assume that the phantom providing limited access to a closed body is suitable to evaluate visualization modes for understanding the topology of structures like blood vessel trees.

After the experiment, we asked surgeons to propose ideas to improve the experimental setup. One surgeon suggested to insert a deformable tree-like structure into "Leberkäse"[1] and bake it in a pan shaped like a liver. Another surgeon proposed hiding the structure under granulate material like sand to restrict the direct view.

VI. Conclusion

Mirrors considered as an interaction interface provide us with additional perspectives for many tasks of our everyday life. Also AR considered as a 3-D interaction interface has been determined as a promising technology for many applications to provide the user with additional perspectives, for instance a view on hidden structures, for guidance, navigation, and control.

We assume that integrating a mirror into an AR environment combines the advantages of both interfaces and can even provide space for new applications that have not been possible before. The major advantage of Virtual Mirrors in AR scenarios

[1]Special German, Austrian food consisting of fine ground beef, bacon, and onions. Everything is baked as a loaf in a bread pan.

is their unlimited moving space. Such mirrors can be positioned at any helpful location to offer additional visual cues supporting the accomplishment of the user's task. The Virtual Mirrors can be attached to tracked objects, for instance tools that are already used for a classical procedure such as a drilling device or a laparoscope camera. This avoids the need to introduce new interaction devices to control the position of the mirror.

The present mirror reflects only virtual entities of the AR scene. However, this does not limit the benefit of the present device since virtual counterparts of the most relevant objects in the AR scene like the drilling device or the anatomy of interest can be registered with and superimposed on the real object.

Together with the surgeons of our clinical partner, we determined the first two medical applications of the Virtual Mirror:

1) navigated drilling of preparative canals for pedicle screw implantation in spine surgery;
2) minimally invasive resection of tumorous tissue for instance in liver surgery.

Regarding these medical applications, two experiments were arranged evaluating the accuracy and duration time of the procedures, the usability and the clinical acceptance of the proposed AR systems.

Although the number of subjects and accordingly the number of measurements are too few to draw strong conclusions, it is important to note that all experiments are performed by practicing surgeons. The quantitative results of the experiments done by these surgeons show promising tendencies for the suggested medical applications. Regarding the positive feedback of the surgeons participating in the experiments and the qualitative results of questionnaires filled out by the surgeons immediately after the experiments, both endoscope augmentation and *in situ* visualization corroborate our belief that AR can find its way into various clinical applications to improve surgical procedures. As a matter of fact it shows the importance of design and development of novel visualization and interaction paradigms, which integrate smoothly into the surgical workflow and allow surgeons to take full advantage of the additional 3-D data provided to them by medical AR systems.

ACKNOWLEDGMENT

The authors would like to thank F. Sauer, A. Khamene, and S. Vogt from Siemens Corporate Research (SCR) for the design, setup, and implementation of the *in situ* visualization system RAMP they provided us. The authors would also like to thank A. R. T. GmbH for providing cameras and software for the outside–in tracking system. The authors would like to thank the radiologists and surgeons of Klinikum Innenstadt Muenchen for their precious contribution in obtaining medical data and evaluating our systems. The authors would also like to thank J. Traub, T. Sielhorst, M. Rustaee, S. Holdstock, and P. Stefano of the NARVIS group for their inspiration and support.

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