

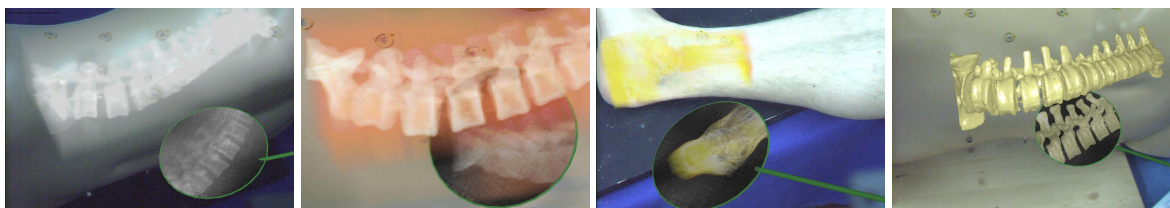
The Tangible Virtual Mirror: New Visualization Paradigm for Navigated Surgery

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ABSTRACT

Real-time in-situ visualization of virtual data overlaid on its real counterpart is getting increasing attention. Augmented Reality (AR) for intra-operative visualization and navigation has been a subject of intensive research and development during the last decade [2], [9], [12]. Besides accuracy and speed of the system one of the challenges to improve acceptance of medical AR systems is the lack of appropriate visualization paradigms that exploit the potential of these new 3D visualization technologies. In-situ visualization offers a higher degree of freedom for the programmer than classical visualization on a screen. The existing paradigms for interaction with 3D objects are however not satisfactory since the majority of them rotate and move the object of interest. The classic manipulation of virtual objects cannot be used while keeping real and virtual spaces in alignment. Other classic medical imaging user interfaces provide multiple orthographic views of virtual objects, which do not reveal spatial relationships if points of interest are not by accident in the same slice. This paper introduces a simple and efficient interaction paradigm allowing the users to interact with 3D objects and visualize them from arbitrary viewpoints without disturbing the in-situ visualization, or requiring the user to change the viewpoint. We present a virtual, tangible mirror as a new paradigm for interaction with 3D models. The concept borrows its visualization paradigm in some sense from methodology used by dentists to examine the oral cavity without constantly changing their own viewpoint or moving the patients head. The paper also presents a medical application for the hand-held virtual mirror in order to demonstrate its crucial role in intra-operative AR visualization for computer aided spine surgery. Results not only include simulated optical mirrors but also introduce the concept of medical imaging mirrors reflecting volume rendering. This new concept can be easily combined with all kinds of visualization techniques, e.g. digitally reconstructed radiographs (DRR), which is highly interesting since mirroring X-rays is not physically possible, but could be perceptually accepted and extremely useful for 3D medical in-situ visualization.

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techniques—;

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1 INTRODUCTION

The increasing amount of data provided by medical 3D imaging devices to surgeons makes new visualization technology necessary that reveal more information at a glance than a stack of 2D slices and that is less cumbersome than browsing through these stacks. As opposed to 2D images 3D data does not have a direct representation on a screen, but it needs a recalculation to visualize it. Ideally, the visualizations are embedded into the context of their use and not far away from the operation site as in current practice.

In order to take full advantage of the spatial relations in the 3D data, visualizations must convey the spatial information. The information perpendicular to the viewing direction is commonly preserved, however the absolute and relative depth information is gone on an ordinary 2D display. A promising technology in that direction is augmented reality. However technology alone is not sufficient to provide a compelling spatial experience. This problem has been identified as early as 14 years ago in one of the first publications about medical augmented reality [1]. Several systems [13, 2, 8] that are custom made for medical procedures tend to meet the requirements for accuracy and to integrate their display devices seamlessly into the operational workflow. Another challenge to push the break through for medical AR is the lack of useful visualization paradigms that enable the full potential of the system rather than classic visualization adapted to AR.

While the point of view does not change the general appearance of a 2D object, it is of crucial importance for 3D visualization. The user therefore wishes to either move around the objects or move and rotate the objects of interest. This is however not practical or intuitive for many applications. In particular for in-situ visualization, rotation or movement of the virtual object is not acceptable as it disturbs the real/virtual alignment. In many applications it is also impossible and impractical to move around the object. Whenever turning the object or moving around it is not desirable, the usual solution is to create another virtual view such as three orthographic views used in medical imaging. This approach is impractical when it comes to interaction. In addition, it prevents the users from taking full advantage of 3D visualization. In absence of better paradigm, this is however the visualization of choice for almost all intra-operative navigation systems in computer aided surgery.

A real mirror is a common, intuitively used tool in everyday life.

Mirrors enable sight on hidden areas or offer a second perspective on objects. Dentists use e.g. a stomatoscope for examination of areas inside the oral cavity of a patient without changing their viewpoint or moving the head of the patient. Here, we present a virtual, tangible mirror as a new paradigm for interaction with 3D models. To our knowledge, the use of an interactive virtual mirror for improving the perception of an AR scene is absolutely new. There is an approach called virtual mirror, which has also been used in the context of AR [4]. However, it aims at mirroring the real view by displaying a camera view on a screen for further augmentation. Our mirror strives for another goal. It was conceived to be able to mirror virtual objects, which cannot be seen because they are occluded by real objects, e.g. augmented spinal column within patient's body. This paper describes its implementation, and its application in particular in medical augmented reality visualization, where interaction and perception of depth have been identified as major issues to be resolved [11].

Section 2 presents our AR system. Section 3 describes the integration of the virtual, hand-held mirror. In section 4, we analyze the advantage of mirror reflection for perception of depth and layout. Section 5 presents a qualitative validation of the mirror. Therefore 22 surgeons of our clinical partner fill out a questionnaire.

2 METHOD

This section describes our AR system that consists of an optical outside-in tracking system for target tracking and an inside-out tracking system for head pose estimation.

2.1 AR System

First of all, we like to introduce our AR system that allows for in-situ visualization. Figure 1 gives a complete overview about an AR system in surgical use. For superior registration quality the system uses two synchronized tracking systems.

The single camera inside-out tracking system allows for a high rotational precision [5], which is necessary for tracking of the stereoscopic video see-through head mounted display (HMD). The hardware setup is similar to the one proposed by Sauer et al. [12] for medical augmented reality. Two color cameras rigidly attached to the HMD simulate the eye's view. An additional infrared camera mounted on the HMD tracks a marker frame, a static set of retroreflective markers, (figure 3.2) for head pose estimation [15]. 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" [14]. Second the system allows for more options 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. The optical outside-in tracking system from A.R.T GmbH (Weilheim, Germany) with four cameras fixed to the ceiling covers a large working area, i.e. 3x3x2 m. The system is capable of tracking the targets in our setup with an accuracy of $< 0.35[mm]$ RMS.

Both of the systems use the same kind of retroreflective fiducial markers offering a registration free transformation from one tracking system to the other. In order to recover the six degrees of freedom of a rigid body, the external optical tracking system requires at least four rigidly attached markers. Fiducial markers are attached to the tool positioning the mirror as well as on the patient lying on the operating table (see figure 3.2) and further surgical instruments. The marker frame target has an exceptional function as it enables the transition between the inside-out and the outside-in tracking systems. Both tracking systems calculate the same coordinate system respective the reference target. All augmentations of

tracked targets, which are tracked by the optical outside-in tracking system, have to be positioned respective the marker frame of the inside-out tracking system. The following equation calculates the transformation $^{anytarget}H_{frame}$ from the marker frame to an exemplary target ($^{to}H_{from}$).

$$^{anytarget}H_{frame} = ^{anytarget}H_{ext} * (^{frame}H_{ext})^{-1} \quad (1)$$

$^{anytarget}H_{ext}$ and $^{frame}H_{ext}$ are the transformations provided by the optical outside-in tracking system. The former describes the transformation respective 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.

A PC based computer is used to render 3D 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 mirror is implemented in C++ using the OpenGL.

2.2 In-Situ Visualization

Our system allows for different kinds of visualization techniques such as volume rendering or isosurfaces (see figures 6). In-situ visualization requires the following preparations.

1. At least four fiducial markers have to be attached to the object of interest, e.g. thorax or foot. These markers have to be visible for the tracking cameras in the OR.
2. Then the object of interest, e.g. thorax or foot (figures 6), has to be scanned via CT or MRI to get a three dimensional data volume.
3. Registration: The fiducial markers are segmented automatically from the data volume to be able to align the virtual data with the real tracked object.
4. Choose type of visualization.

The technique direct **volume rendering** displays every part of the data volume with a certain value for color and transparency. Therefore a predefined number of planes parallel to the image plane are clipped against the volume boundaries. All planes are rendered by interpolating within the volume and blending appropriately. Intensity values in the volume domain are mapped to the three dimensional color space using transfer functions. This enables accentuation of interesting structures.

Indirect volume rendering concerns the extraction of **surface models** from the data volume. Areas of interest, e.g. bones or blood vessels can be determined due to their intensity values in the volume domain. The marching cube algorithm is parameterized with a certain threshold to segment a homogeneous area within the data volume and generates a surface model. Surface models can be designed with color, transparency and textures.

The presentation of volume rendered objects is more computationally expensive than display of surface models. Our system renders the volume rendered spinal column with 5-6 fps and its surface model with 30 fps.

Positioning the visualization of the spinal column inside the thorax within our AR scenario can be described by the transformation $^{visual}H_{frame}$.

$$^{visual}H_{frame} = ^{visual}H_{thorax} * ^{thorax}H_{ext} * (^{frame}H_{ext})^{-1} \quad (2)$$

$^{thorax}H_{ext}$ and $^{frame}H_{ext}$ are the transformations provided by the optical outside-in tracking system. $^{visual}H_{thorax}$ represents the registration matrix to align virtual data with the real tracked object.

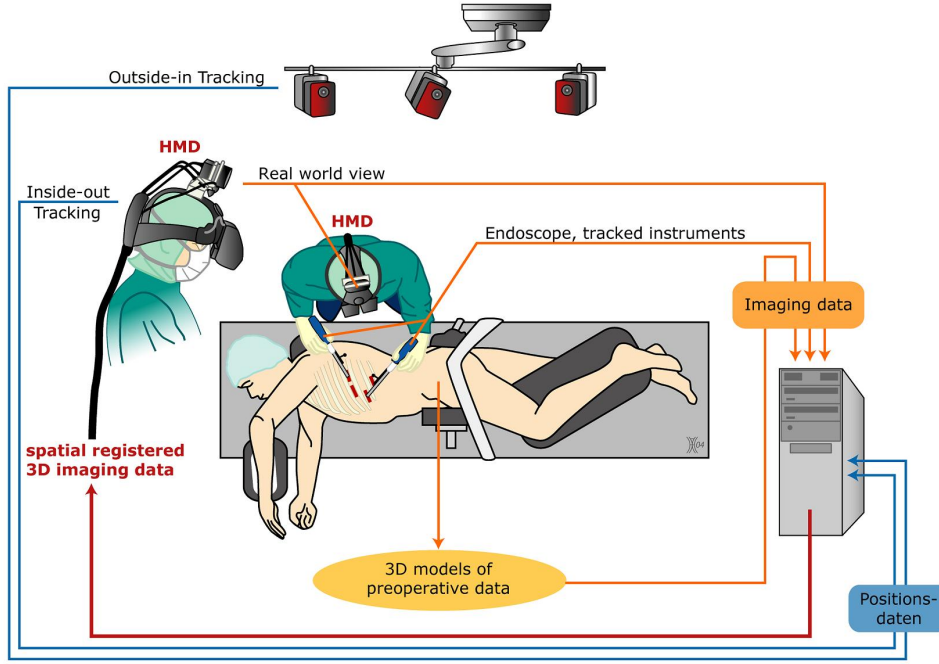


Figure 1: Augmented reality tracking system.

3 VIRTUAL MIRROR

The following section introduces the virtual mirror that reflects the virtual part, volume rendered objects and surface models, of the AR scene and creates intuitively an additional perspective on visualized medical data.

3.1 Mirroring Technique

The method implemented in our application to realize real-time reflection takes advantage of the stencil buffer. The buffer is used to create a mask that separates the frame buffer into two domains A and B.

1. First of all the stencil buffer is initialized with a certain reference value and the frame buffer is reset. Then the mirror plane is rendered and affected areas of the frame buffer are marked on the stencil buffer. These areas are enabled for further rendering and belong to domain B. All other areas belong to the domain A.
2. The complete scene that is composed of the medical volume data and virtual 3D models of surgical instruments is mirrored respective the mirror plane. Values of the frame buffer can only be changed within domain B. Objects and parts of objects located within domain A are clipped away. A stencil buffer test decides for every pixel, if it belongs to domain B where rendering can modify the values of the frame buffer, i.e. the mirrored scene is only rendered within the borders of the mirror.
3. For the further steps, the stencil buffer is no longer needed. The mirror itself is a transparent texture mapped plane, which is bordered by a colored frame.
4. Finally the original scene is rendered at its proper position.

3.2 Mirror Control

The virtual mirror can be guided by a hand-held device to a certain position within the AR scene. In our setup this device is a customary remote mouse pointer with a marker tree attached to it (figure 3.2). In our implementation, the mirror is positioned along a virtual extension of the pointer in order to be able to access physical restricted areas like the inside of the human body. The following equation describes the transformation ${}^{mirror}H_{frame}$ from the marker frame of the inside-out tracking system to the mirror.

$${}^{mirror}H_{frame} = {}^{mirror}H_{pointer} * {}^{pointer}H_{ext} * ({}^{frame}H_{ext})^{-1} \quad (3)$$

${}^{pointer}H_{ext}$ and ${}^{frame}H_{ext}$ are the transformations provided by the outside-in tracking system as described in section 2.1. ${}^{mirror}H_{pointer}$ is the transformation that positions the virtual mirror 30 cm away from the physical pointer to be able to guide and place the mirror also inside the thorax. Figure 2 shows a tracking diagram that includes all mentioned transformations. The mirror can be detached and fixed to its current pose by a key stroke. For further guidance, it can be reorientated for instance by mouse interaction on the monitor or using the buttons of the remote mouse controller.

While guiding the mirror the user is able to observe and study the relative positions of medical visualization, other augmented, overlaid surgical instruments and the mirror.

3.3 Mirror Design

While moving the mirror through the AR scene, the observer has to be able to accurately perceive position, dimension, orientation, 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 virtuality.
- The shape of the mirror can be set to quadratic or circular. Note that simple and familiar shapes provide better cues for perceiving the actual orientation of the mirror.

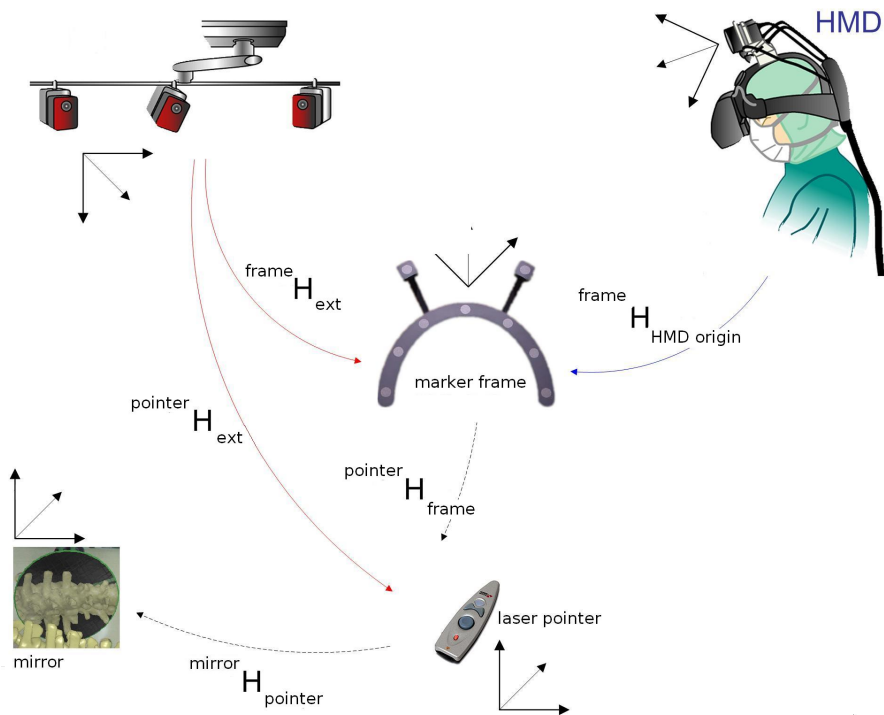


Figure 2: Tracking diagram.

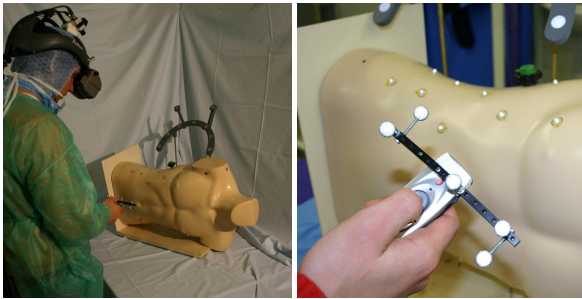


Figure 3: Our setup including the HMD, a model of the patient and the marker frame for the AR tracking system

- The mirror plane is mapped with a simply structured texture, which improves the perception of mirror's orientation relative to the virtual scene [17].
- In order to make the borders of the mirror clearly visible, it is designed with a colored, opaque, non-reflective frame.
- If the mirror is guided with the 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 surgical instrument which is augmented and therefore visible inside the body. If the mirror was positioned directly at the real target, it could not be moved within the human body to reflect the visualization of viscera. 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.
- A real, conventional mirror is a glass plane of a certain thick-

ness, which is silver-platted in the back. We simulate the thickness of the transparent glass by placing two parallel layers one after another in a certain distance. The first one is transparent and shows the mirrored scene. The rear one is opaque and also serves as the frame of the mirror. The distance between the two layers simulates the thickness of the glass of a real mirror.

- The mirror's reflection plane can be made either fully opaque, e.g. colored black, or transparent to simulate reflection on a glass plane.

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

4 PERCEPTIVE GAIN

This section describes the perceptive advantages due to the mirror reflection. The mirror provides an additional intuitive perspective on the operation site, supports guidance of surgical instruments to certain areas of interest and helps to understand the constellation of objects in a complex AR scene. We also show with a modified experiment that reflection provides stronger depth cues than some of the classical ones like relative size.

4.1 Extended Vision

The mirror enables an additional perspective on the area of interest. Even if the surgeon is able to get a view on bones and tissue inside the patient's body due to the in-situ visualization, most of his or her

points of view are physically restricted. Equipment and personnel in an operating room restrict the freedom of movement of the surgeons. They can hardly change their position to get a dramatically different view onto the patient anatomy. Moving the patient lying on the operation table is generally impossible. The mirror provides intuitively generated perspectives from any desired point of view e.g. from the bottom or the opposite side. Positioning the virtual mirror is not restricted by physical borders. It can also be positioned inside the human body due to the virtually extended device for its guidance.

The mirror can be used to improve the navigation of other surgical instruments to the operation site. Figure 4 shows an augmented surgical instrument inside the thorax. Mirror reflection provides information about the relative position of the instrument to the vertebra.

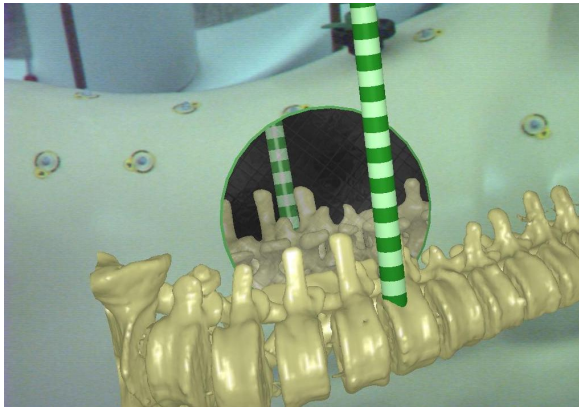


Figure 4: Mirror image supports guidance of an instrument to the operation site.

4.2 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 [16]. Cutting summarized the most important binocular and monocular depth cues [3]. The presented AR scene is perceived binocularly with the two color cameras mounted on the HMD. Stereopsis is realized by the slightly different perspectives of the two cameras. Convergence is predefined by orientation of the cameras. 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 gets visual feedback. The reflection on the mirror plane can be interpreted intuitively because a mirror is a well-known device supporting our everyday life, e.g. during navigation of a car, putting one's eye makeup on, or examination of the oral cavity with a stomatoscope. The depth cues *motion parallax* or *motion perspective* provide information about depth 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, these two sources of information, *motion parallax* and *occlusion*, are the most effective monocular depth cues within personal space [3]. Both cues can be perceived again in the mirror image from another user-defined point of view.

The combination of visual information of the mirror image and the observer viewpoint enrich information about the constellation of the objects impressively, as shown in figure 5, where two teapots with a varicolored texture and a mirror plane beneath the objects are vi-

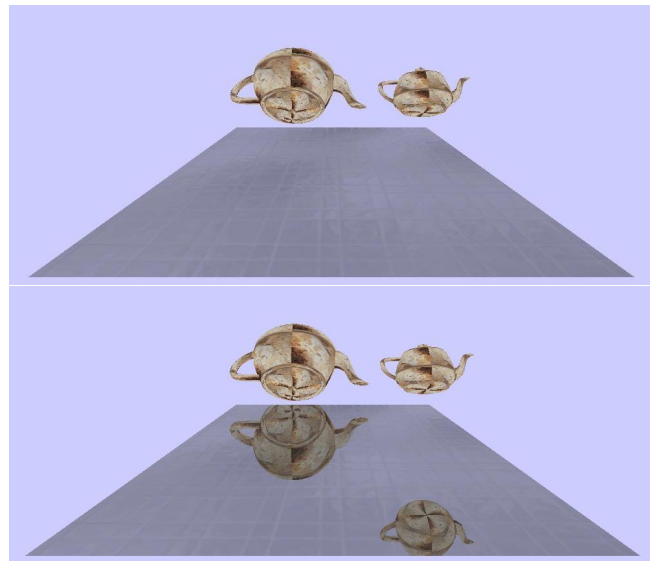


Figure 5: Illusion about depth: Without the mirror floor the bigger teapot seems to be located nearer. Due to the reflection information about depth can be corrected. The figures prove that mirror reflection provides stronger depth cues than relative size.

sualized. 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. Also the borders of the mirror plane that cut off the mirror image help to locate the objects. In 1994, Kersten et al. [7] 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 3D trajectory of 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" [10]. They found out that "shadows were perceptually most relevant for the recovery of spatial arrangement, especially when the shadow is in motion". 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 depth cue *occlusion*. 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.

Therefore, when the user moves the viewpoint, he or she sees additional 3D information. Shadows provide less informative information when moving the viewing position and orientation. Figure 6 shows a similar setup as 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-

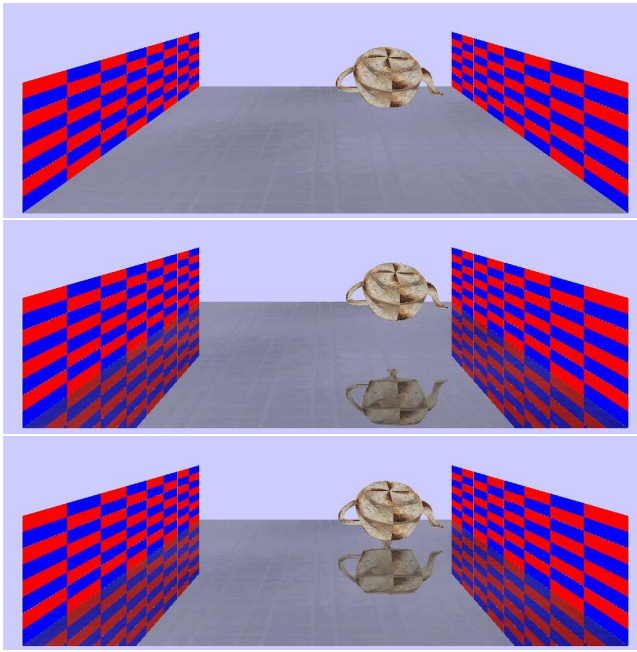


Figure 6: Modified virtual ball-in-box scenario to distinguish the importance of reflection for spatial perception. Beside depth cues reflection provides even more information about the shape and further details of objects than shadows. From the current perspective, the lid of the teapot can only be seen in the mirror image.

known teapot, mapped with the same texture as in figure 5. 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 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 observer and the mirror, the observer senses spatial information of the objects also from proprioception [6]. This information is gathered from stimuli of sensory receptors, the so called proprioceptors, found in muscles, tendons and joint capsules, and generates sensation about the observer’s position in relation to his/her spatial environment. The user can move the mirror around and change its orientation. This provides a combination of visual and proprioceptive estimates of the 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.

5 RESULTS

Figure 6 presents the results of the mirror. The images show the virtual mirror while interacting with the volume rendered spinal column, its surface model and the virtual anatomy of a real foot of one of our colleagues, Joerg Traub.

Within the scope of an experiment [16], we presented the virtual mirror together with the visualized spinal column to 22 surgeons of our clinical partner. Having no experience with an AR system before the experiment, the participants were able to use the virtual mirror without any instructions other than telling that it is a virtual mirror.

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 to use 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 utilize it.	3.8095

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

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. We have also asked for which purpose they would use this kind of visualization. Most of the participants thought of monitoring and checking cuts and drills. Both, checking position and orientation of drills and further surgical instruments were of interest in multiple answers. Only a few did not suggest a concrete scenario.

As we can not provide a quantitative validation of the mirror yet, we like to arrange an experiment and invite surgeons of our clinical partner. Therefore we plan the development of a concrete application including the mirror that supports positioning pedicle screws. Visualization of vertebra will be enriched by several virtual mirrors.

6 CONCLUSION AND DISCUSSION

This paper introduces a virtual, hand-held and freely navigateable mirror for in-situ visualization. The mirror is able to reflect all virtual entities of an AR scene. The observer of an AR scene, e.g. wearing a video see-through head mounted display (HMD), is able to move and position the mirror with a real hand-held tool, which is tracked e.g. by an optical tracking system. The mirror is a completely new paradigm in AR, which enables interaction with augmented, virtual objects and provides direct visual feedback. The reflection on the mirror provides powerful, additional sources of information for visual perception of layout and depth.

While interacting with the scene, there is no haptic feedback because the mirror is completely virtual and not hindered by physical borders, however, the observer gets visual feedback on the reflection plane caused by moving the mirror. Because of the interaction with augmented virtual objects, the observer senses information about depth from proprioception. This information is gathered from stimuli of sensory receptors, the so-called proprioceptors, found in muscles, tendons and joint capsules and generates sensation about the observers position and layer in his/her spatial environment.

The observer of an AR scene is able to move and position the mirror within his workspace. This improves the perception of the relative depth of virtual objects and their layout in an AR scenario and enables the observer to view areas, which are not directly visible from the user’s point of view. The mirror can become a inherent tool for stereoscopic AR to enforce perception of constellation, dimension and shapes of virtual entities of an AR scene. This new paradigm is applicable to many domains, where the augmentation extends human vision to include hidden and unreachable objects, where change of viewpoint or moving virtual objects are impractical or unintuitive.¹

¹Permanent URL to online video:
<http://ar.in.tum.de/files/publications/bichlmeier2006mirror.video.avi>

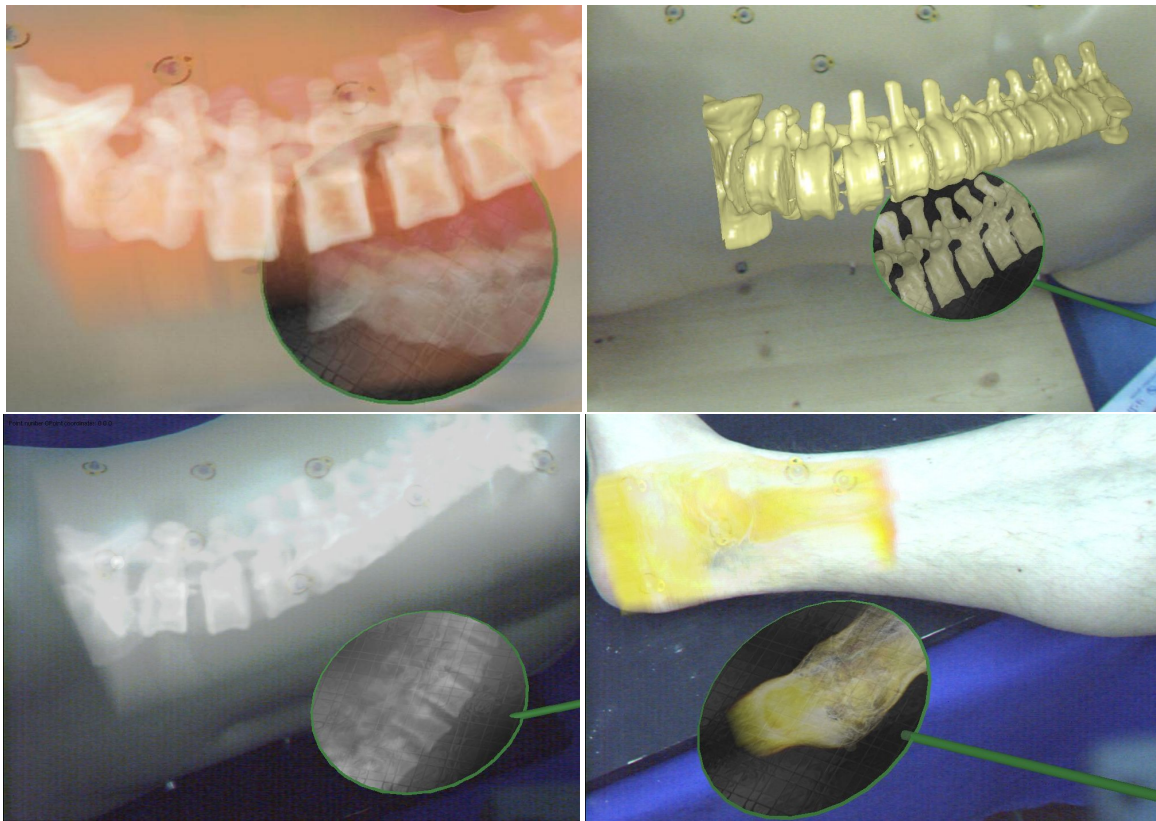


Figure 7: Four exemplary visualizations of the spinal column in combination with the virtual mirror. The upper, left image shows the volume rendered spinal column with a transfer function that adds color and transparency to the visualization. The upper, right image shows a surface model of the vertebrae. The lower, left presents digitally reconstructed radiographs (DRRs) enabled by volume rendering and a special transfer function. The lower, right image shows again volume rendered tissue and bones of a real foot.

7 ACKNOWLEDGMENT

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