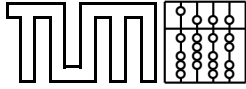


Advanced 3D Visualization for Intra Operative Augmented Reality

Christoph Bichlmeier

Diploma Thesis in Computer Science



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Submission Date: March 31, 2006

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Computer Aided Medical Procedures and Augmented Reality**

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Ich versichere, dass ich diese Diplomarbeit selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel verwendet habe.

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Abstract

Dorsal surgery, e.g. herniated intervertebral discs, is a medical domain that can benefit from new techniques for visualization of medical data. On the way to the spinal column the surgeon has to pass several tissues. Reaching the operation site during an intervention is a difficult and sometimes hazardous undertaking and a direct view onto the vertebrae is nearly impossible. If possible, nowadays interventions concerning the spinal column are performed via keyhole surgery. Because there is only a small hole through the skin, the surgeon has to navigate his instruments according to the images created by the camera of the endoscope and screened on a monitor.

One group of the chair for computer aided medical procedures and augmented reality (CAMPAR) works on the navigation- and AR-visualization system (NARVIS) that employs effects of computer graphic, techniques of visualization, a video see-through head mounted display (HMD) and an optical tracking system to enable a stereoscopic in-situ representation of CT data. Data can be aligned with the required accuracy and the surgeons can get an intuitive view onto and „into“ the patient.

Current technology to represent medical data with this system suffers from a serious lack. Virtual imagery, such as a volume rendered spinal column, can only be displayed superimposed on real objects. If virtual entities of the scene are expected behind real ones, like the spinal column inside the human thorax, this lack implicates incorrect perception of the viewed objects respective their distance to the observer. The powerful visual depth cue interposition is responsible for this misinformation about depth.

This thesis aims at the development and evaluation of methods that improve depth perception in stereoscopic AR. Its intention is to provide an extended view onto the human body that allows an intuitive localization of visualized bones and viscera such as vertebrae, muscles, ribs and blood vessels. Therefore various approaches were implemented and designed to create or intensify helpful depth cues within the workspace of a surgeon.

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1. Introduction

This diploma thesis was arranged by Christoph Bichlmeier at the Chair for Computer Aided Medical Procedures and Augmented Reality at the Technical University of Munich and completed in January, 2006.

Augmented Reality (AR) is an upcoming technology in many fields of research like gaming industry, aviation industry, automobile industry and medical application.

This diploma thesis concerns medical AR used for preoperative analysis and during surgical intervention. A custom video see-through head mounted display (HMD) enables the surgeon a stereoscopic view onto and into the patient [32], [43]. Virtual models like viscera and bones extracted from medical, tomographic data volumes shall be perceived intuitively by the surgeon at their proper position inside the human body of the patient lying on the operating table.

It is possible to position virtual objects at certain coordinates of the real world, e.g. within the workspace and the field of vision of the surgeon. Accurate positioning is essential for medical AR, however, it is not sufficient to provide an exact combination of virtual and real positions. There are problems concerning design of virtual objects, which should not look too artificial and technical restrictions of AR that have to be handled. One of the main shortcomings of representing virtual data within an AR-scene is the following.

In the former visualizations, virtual objects always superimpose real ones even though virtual objects are positioned behind real ones respective a coordinate system of the real world. This side effect provides misinformation for visual perception especially for depth perception. Powerful visual depth cues like interposition and motion parallax are misinterpreted and become useless. The observer cannot intuitively perceive anymore, where objects are located and how they are related to each other.

If we consider AR in surgery, we get an easily understandable example how perception and organization of visible objects is affected. If a virtual model of the spinal column is posed at its right position, it occludes areas of the skin and seems to be located in front of the human body and not inside. Figure 4.1 shows the problem. Some approaches try to handle this problem by drawing virtual objects transparent to diminish the interposition, e.g. Edwards et al. use it [20]. There are also proposals to clip parts of virtual objects, if they are positioned behind a real object, but this method requires expensive image analysis [11].

This diploma thesis describes different methods how to integrate virtuality to reality using an HMD based AR system and how to improve depth perception in order to enable surgeons to perceive intuitively augmented bones and viscera at their proper position.

Chapter 2.1 gives an introduction to AR 2.1 and its medical application 2.2. Chapter 3 describes the needed and utilized components of the AR system like the HMD and other hard- and software entities, which represent the basic technology of all features realized within the scope of this diploma thesis. Chapter 4 concerns the human, visual perception. All cues, which provide information sources for depth perception are described in detail.

Chapter 5 describes the ideas, their realization of the components of the system, which were developed as the practical part of this diploma thesis. For further description about the system, the application is called from now on „VISUALSPINAL“. Chapter 6.1 presents an experiment concerning depth perception in AR and an evaluation of all methods of VISUALSPINAL. We have invited 20 surgeons to evaluate seven different visualization techniques using a head mounted display (HMD). The evaluation has been divided into two parts. In the first part, the depth perception of each kind of visualization is evaluated quantitatively. In the second part, the visualizations are evaluated qualitatively in regard to user friendliness and intuitiveness.

2. Merging Virtuality and Reality

The following chapter introduces Augmented Reality. It includes a short historical review, a classification of the techniques that merge virtuality and reality and an overview of the field of application of AR. Furthermore it describes more detailed the use of AR in the surgical context.

2.1. Augmented Reality

AR is a growing field of computer research. It concerns the extension of the view on a real scene with virtual objects. Virtual objects can be placed at certain coordinates respective the real world and behave like real ones. That means, the observer can move around the virtual objects and they keep their orientation and stay at their location.

Several scientists engaged in AR for applications in various domains. One of the pioneers is Ivan Sutherland, who developed a working optical see-through head mounted display and used a tracking system to register graphics with the real world [36]. He labeled his work Virtual Reality. In 1992 Michael Bajura, Henry Fuchs, and Ryutarou Ohbuchi published a paper about medical AR that describes the use of a head mounted display and a tracking system within the surgical context to „merge virtual objects with the real world“ [4]. They did not declare any denomination for this kind of visualization (e.g. Virtual Reality or Augmented Reality), however they already worked on attempts to improve depth perception in their system. Krueger M. used AR for art performance in 1991 [41]. Wellner was one of the researchers who coined the term „Augmented Reality“. He differed AR from Virtual Reality (VR) and defined a classification for the field of research concerning the combination of reality and virtuality by evaluating the rate of virtuality or reality within a scene [44]. In 1997, Azuma defined that an AR system combines real and virtual, is interactive in real time, and is registered in 3D [3].

According to the Reality-Virtuality Continuum introduced by Milgram [27] in 1994, AR is a part of Mixed Reality. Considering the virtual grade of a scene, the following subsections of Mixed Reality can be itemized:

1. Virtual Environment: The goal of Virtual Reality is to position the user into a complete virtual scene and enable interaction in this virtual world.
2. Augmented Virtuality: Rate of virtuality exceed rate of reality.
3. Augmented Reality: Rate of reality exceed rate of virtuality. The aim of an AR-system, is to extend the real scene with virtual objects, generated by the computer that augments the real scene with additional virtual information.
4. Real Environment

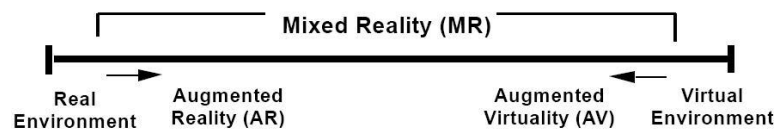


Figure 2.1.: Virtuality Reality Continuum

All items listed above belong to the class Mixed Reality as shown in figure 2.1, which was taken from the paper of Milgram [27].

In 1998 the international IEEE ¹ workshop IWAR was founded to constitute an official and central institution where to present and publish progresses in AR. IWAR became later ISAR ². ISAR fused with ISMR ³ and became ISMAR ⁴, which is today to most important international annual conference for AR.

A well known example for AR are the virtually augmented lines and numbers on the soccer field at certain situations during a soccer match on TV. The augmentation provides information e.g. about distance between goal and ball. Because the viewer, watching television cannot interact with the scene, this example does not conform to the definition of Azuma [3]. Anyhow it shows the enrichment of visual information by augmenting a real scene with virtual entities. Some more applications of AR in process and under industrial use are listed below.

- Visualization of hidden features: Computer-Aided Surgery, Industrial Plant Maintenance, Mechanical Repair [31], [28], [32], [1]
- Looking into the future: planning and preparation; Interior Design and Modeling ([12]).
- Looking into the past: reconstruction of historical buildings ([40],[30]).
- Entertainment: Television broadcasts and movie industry, games ([2],[34]).
- Art: Art, performances, museum exhibitions ([46]).

This list is definitively incomplete but it offers an overview of different fields of application for AR. Look at the augmented-reality.org homepage and at the homepages of ISMAR⁵ to find more applications for AR.

2.2. Medical Augmented Reality

This thesis concerns AR in medical usage in particular for surgical support. It assists pre-operative analysis of the operation site and augments vision while intervention to view

¹Institute of Electrical and Electronics Engineers, iee.org/

²<http://www1.cs.columbia.edu/graphics/isar2001/>

³<http://www.mr-system.com/ismr/2001/>

⁴IWAR became International Symposium on Mixed and Augmented Reality ISMAR05

⁵<http://wwwnavab.informatik.tu-muenchen.de/twiki/bin/view/ISMAR/>,
<http://studierstube.org/ismar04/>



Figure 2.2.: Radiographs of a spinal column

physically covered and therefore hidden viscera and bones in order to assist navigation of surgical instruments. The surgeon is able to get a view inside the patient.

The motivation of medical AR in this context is to enable vision on medical data intuitively. Surgeons don't have to look away from the patient to merge content of medical images like radiographs or ultrasound images as shown in figure 2.2 pinned somewhere on the wall with their proper position at the patient. The medical images can be visualized three dimensionally with various techniques of rendering. They are displayed at the correct position inside the patient. Visual enrichment enables e.g. keyhole surgery, which implicates reduction of operating time, less pain for the patient and diminishes the duration of hospitalization. All the advantages help to reduce costs. Medical technology in general has to fulfill stringent conditions. In particular AR systems have to satisfy the following requirements.

1. High and dependable accuracy: Virtual objects have to be positioned within reality at the exact position where they are expected by the surgeon. Furthermore, the level of detail of virtual models representing e.g. viscera or bones has to be high enough in order to provide realistic visualization. High and dependable accuracy concerns computational accuracy, quality and rapidness of synchronization of the virtual and real imagery, resolution of imagery taken by the camera and displayed by monitors.
2. Robustness: In an OR all technical entities like the components that belong to the AR-system have to resist physical and chemical exposure, i.e they have to work reliable under laboratory conditions.

2. Merging Virtuality and Reality

3. Price: The advantage of employed technology has to legitimate development costs, operating costs and costs of maintenance.

Not every real object, which is represented by its virtual counterpart is convenient for accurate augmentation because of the physical properties of an objects. Augmented viscera is hardly applicable for surgery because their position, shape and size changes in all probability between taking the tomographic imagery at the radiology in an hospital and the intervention performed at an other location in the OR. The surgeon cannot be sure about an exact overlay of virtuality and reality. If there are any deviations respective the overlay, the risk increases that the intervention ends disastrously.

Visualization of bones is the better application. Dorsal surgery is a reasonable field in surgical AR. All visualizations implemented within the scope of this diploma thesis show the virtual spinal column, which is superimposed on its plastic counterpart inside a plastic thorax model.

The real spinal column inside the human body is positioned, orientated and fixed by muscles and joints and accomplishes its stabilizing function as the pillar upper part of the body. It hardly changes its position or shape, if the patient keeps in the same position, e.g. lying supine, when the tomographic images are recorded and the intervention in the OR takes place.

Further information about visualization and computing the right position of the spinal column provides chapter 3.

3. Technology

The following section presents the technical entities of the complete system that is used to perform stereoscopic AR. It starts with a short overview about the AR system and describes later certain hard -and software components of the system. Section 3.4 engages the techniques how three dimensional medical imagery taken from CT-Data can be visualized. The AR system includes the following hardware entities.

- Head mounted display (HMD) (section 3.1.1) and a custom made single camera tracking system (section 3.1.2) to perform stereoscopic AR.
- Four tracking cameras mounted on a framework under the ceiling of our laboratory to track targets within the workspace of the surgeon (section 3.2). At least two of the cameras have to view a target to make it trackable.
- Computer to render 3D graphics, compute and include tracking data, synchronize and combine virtual and real imagery: Intel Xeon(TM), CPU 3,20 GHz, 1,80 GB RAM, NVIDIA Quadro FX 3400/4400.
- Various targets tracked by the tracking cameras, e.g. the patient, the observer, surgical instruments.

The following software components are used for implementation and planning.

- CAMPAR is a software platform developed at the Chair for Computer Aided Medical Procedures and Augmented Reality, TU Muenchen, Germany (section 3.3). It provides functionality to develop software for medical image processing, AR, volume rendering and geometric calculation.
- RAMP: Software for inside-out tracking performed by the HMD and the tracking target (section 3.1.2).
- IDE: Microsoft Visual Studio .NET 2005
- Amira: Software used for visualization and conversion of e.g. medical data types, e.g. DICOM.

The following sections afford more detailed information about the components of the system.

3.1. Stereoscopic AR

Fusion of virtual and computer graphic images can be performed via visualization on monitors. This technique provides only monocular or pictorial perceptual information to

estimate distances to viewed objects.

This project aims at the stereoscopic representation of medical imagery within an AR scene in order to provide an augmented and enriched intuitive vision for the observer.

Information about

1. distances between objects,
2. distance from observer to objects and
3. information about shape, i.e. spatial expansion, of objects

can be perceived because of the so-called *binocular disparity*. Viewing a scene with both eyes produces slightly different projections of the scene onto the retinas because of the horizontal displacement of the two eyes. The brain is able to calculate information taken from the two dimensional projections on the retinas and generates information about the third dimension of objects viewed with both eyes. This enables the observer to perceive shape and depth. Human visual perception is described extensively in section 4.

3.1.1. HMD

The head mounted display employed in this project enables wearable AR and stereoscopic vision. In general two types of HMDs are used:

- Optical see-through HMDs: Computer graphic images like three dimensional models of viscera or bones are projected onto a partial transparent mirror placed in front of the users eyes. Real environment can be perceived through the mirror without any latency, highest resolution, bright colors and correct accommodation distance, which seems to be an advantage. However the representation of virtual objects suffers from technical restrictions like the limited resolution of the projected image on the mirror. The optical difference between real and virtual entities increases and virtuality appears even more artificial. While using the HMD or when the wearer takes the HMD off and puts it on again, the position of the HMD changes and it cannot be guaranteed that the eye-to-HMD transformation is kept constant. Constance of this transformation is essential in order to be able to place accurately virtual objects at a real world position. This problem can be handled by a permanent active calibration mechanism, which detects deviation respectively to the user's eyes and the mirror of the HMD.
- Video see-through HMDs (figure 3.1): The HMD used in this project simulates the displacement of the two eyes with two cameras mounted on the HMD. Their directions of view direction cross at a predefined focus in front of the user within his or her workspace, ca 1 m. Imagery of the real world recorded by the cameras and virtual ones generated by computer graphic software are synchronized and merged with the same image quality. Real parts of the images and virtual ones can be displayed separately and combined. Difference in position of the cameras and the displays in front of the eyes can cause distortion of depth. These components have to be adjusted one time and no further calibration efforts are necessary.

Further evaluation and description about different types can be obtained at [35], [25], [24].

3.1.2. RAMP

As the vision should appear realistic, the AR system must be able to sense exactly movements of the wearer of an HMD. After measuring this information, the system has to determine what effect these movements will have on the virtual part of the scene. Changes have to be updated by the system to reposition the virtual objects according to the movements of the observer.

This is done by the RAMP¹ system developed at SCR². RAMP is an AR project designed for support of medical procedures in order to visualize medical imagery at its proper position right inside the patient. The RAMP systems consists of the following entities:

- Color cameras: Two color cameras simulate the view of the eyes and record the images in order to display them on the monitors of a video see-through HMD.
- Tracking via infrared camera: Visual, fiducial based tracking with a infrared camera mounted on the HMD. The infrared spectrum is used in order to be able to control light conditions in it and to avoid not desired influences for the user's view. It has a fish-eye lens, which extends its angle of vision to stabilize tracking and visualization. The choice of number and design of passive markers being tracked by the infrared camera contributes accuracy and robustness to the system. The reflective markers are placed on a custom made reference frame. Each marker has a flat, circular shape. This reference frame is called the *RAMP-arc* and has to be placed within the field of vision of the infrared camera. The infrared camera is mounted on the HMD above the color cameras as shown in figure 3.1 .
- Dual processor and graphics card with acceleration for 3D computation as described above in this section.

RAMP performs inside-out tracking. Extrinsic parameters of the infrared camera are computed permanently. The RAMP software evaluates the images recorded by the infrared camera and computes distances between the markers. The distances vary respective movement of the camera position and enable the reconstruction of the extrinsic camera parameters. The origin of the world coordinate system is defined at a certain fiducial marker.

This thesis focuses perceptual challenges in an operating AR. So description of the HMD stops here. Further details about the RAMP system can be obtained at [33].

3.2. Optical Tracking System

In addition to the RAMP inside-out tracking system an optical outside-in tracking system developed by the German company ART³ is used to track targets like surgical instruments, the patient, etc. within a room of the dimensions of about 3x3x3 meters. A so-called *tracking target* has to be attached to every object that is supposed to be tracked. These

¹Real Time Augmentation for Medical Procedures, Augmented Reality Project

²Siemens Corporate Research, founded in 1977, sub department of CT (Corporate Technology) - one of the research and development department of Siemens AG, research interests in imaging and software engineering, for more information refer to scr.siemens.com.

³A.R.T. GmbH. ar-tracking.de



Figure 3.1.: HMD

tracking targets consist of at least four markers. The markers of each target are positioned in unequal distances to avoid ambiguous interpretation. Figures 5.1, 5.13 show targets, which are tracked by the optical tracking system.

At least two cameras enable reconstruction of 3D information from 2D information via epipolar geometry [47]. The RAMP arc can be tracked as well by the ART tracking system. Transformations between the ART coordinate system and the RAMP coordinate system can be computed as shown in figure 3.2. Figure 3.3 shows the system adopted to the

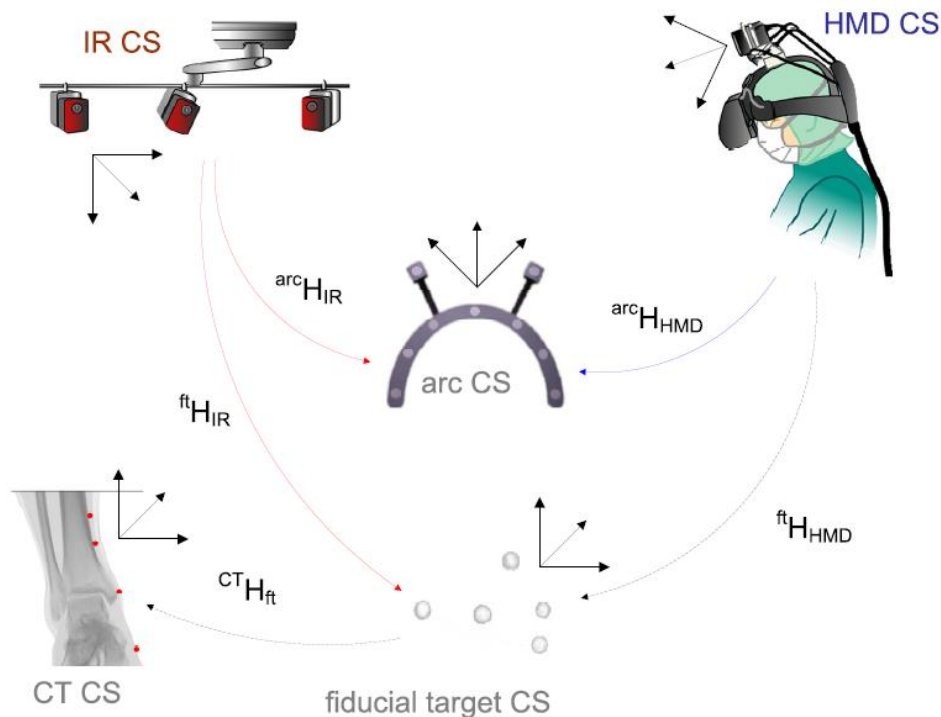


Figure 3.2.: Tracking system: ART optical tracking system + RAMP system

surgical environment.

3.3. CAMPAR / CAMPlib

The chair „Computer Aided Medical Procedures (CAMP)“, TU Munich, Germany tasks study and modeling of medical procedures and introduction to advanced computer integrated solutions in order to improve their quality, efficiency, and safety. Intention of CAMP is to improve medical technology for diagnosis and therapeutic procedures, which requires close collaboration between physicians and surgeons, computer and engineering scientists and providers of medical solutions.

CAMP aims at keeping an intelligent balance between incremental, radical and fundamental research in following fields:

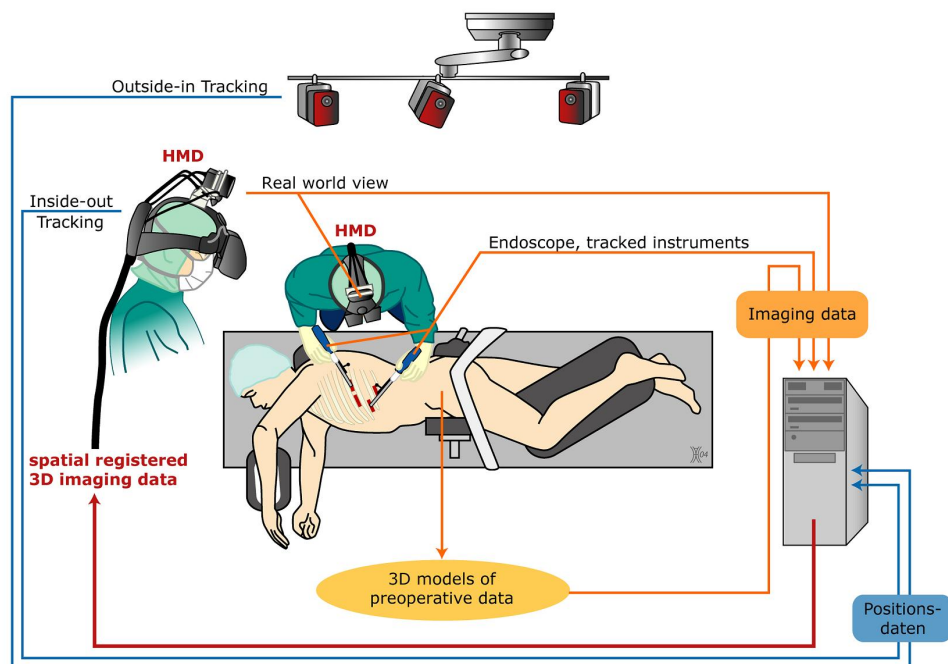


Figure 3.3.: Tracking system in a OI

- Medical Workflow Analysis
- Medical Image Registration and Segmentation
- Medical Augmented Reality

Staff and students at the chair integrate their algorithms into a common C++ library called CAMPLIB. In the meantime it contains a rich set of methods for the processing of medical images, segmentation, registration, visualization, computer vision, etc. . OpenGL is used for visualization, and the applications built on top of it mainly use fltk or Qt as GUI. CAMPAR is the framework for AR applications also created by students and members of the chair. It is highly customized on the demands of medical visualization and in particular medical AR. The main design requirements are reliability, reusability and flexibility. The challenge was to define an interface that offers the necessary flexibility while conserving the necessary reliability of a medical AR system. CAMPAR interfaces to all algorithms and data structures of CAMPlib efficient and highly abstract.

3.4. Visualization

The right choice of the visualization technique is deciding to get a nice and useful three-dimensional representation of medical, tomographic imagery. In general it can be distinguished between indirect and direct volume rendering. These two techniques were used to visualize the spinal column and to test, which method is more useful and generates more information for depth and shape perception.

The segmented and visualized data is taken from a three dimensional, tomographic image, which is stored by the Digital Imaging and Communication in Medicine (DICOM) format. Several useful and powerful libraries for developing applications in computer graphics are free available, e.g. [OpenGL](#)⁴, [DirectX](#)⁵, [Open Inventor](#)⁶ All code that enables the visualizations shown by the images within this paper is implemented in C++ and OpenGL. The next two sections describe the techniques of volume rendering. It is not the intention of this theses to evaluate, which technique is more applicable. During the evaluation (section 6.1) some physicians said that they prefer the direct volume rendered version because it is comparable to the radiographs they know. Observers, who are not familiar with the representation of medical data by radiographs preferred the surface models. Further information about the evaluation of the system and different types of data representation can be obtained at section 6.1.

3.4.1. Direct Volume Rendering

Each voxel, the smallest 3D unit, of a DICOM data volume is represented by its position within the volume and a measurement that is scaled to a gray value, . If we watch slices of a radiograph, the images consist of gray values. From now on the second variable of the DICOM data volume is called the gray value to emphasizes its task to visualize the data. Certain materials of a tomographic image have certain gray values. For example bones have brighter gray values than skin or muscles and physicians are able to interpret structures. One disadvantage is, that usually just one slide can be considered. Techniques of computer graphics and visualization permit a representation of the whole data volume. Methods of computer image processing are able to attribute values of transparency and color defined by a so-called *transfer function* to a certain gray value.

Therefore the render pipeline for volume rendering has to be considered. At the beginning a three dimensional structured grid represents a framework within the data volume. Every grid point is marked with a scalar value, the gray value, which represents the density of tissue.

In the next step of the pipeline the scalar values are classified and attributed to opacity- and color values.

Next step is the integration of a shading model that simulates the transport of light through the volume. Thereupon vertices between the grid points are computed by interpolation between the scalar values.

Last step is the composition of transparency and color values. Therefore the values of voxels, which are positioned behind each other in view direction, have to be accounted conveniently in order to calculate the resulting color value for the pixel on the monitor. [22]

By using direct volume rendering for visualization, the observer gets a detailed view into the data volume. All areas of the data volume can be visualized with the application of

⁴OpenGL is the premier environment for developing portable, interactive 2D and 3D graphics applications since its introduction in 1992.

⁵DirectX is a collection of APIs for easily handling tasks related to game 3D computer graphic programming on Microsoft Windows.

⁶Open Inventor, originally IRIS Inventor, is a C++ object oriented “retained mode” 3D graphics API designed by SGI to provide a higher layer of programming for OpenGL.

transparency. Choice of the right color and transparency is essential to represent certain areas of the human body intuitively. For example, bones are presented as white and nearly opaque objects and muscles are semitransparent and red colored. The disadvantage of direct volume rendering is that special effects adopted from computer graphics like shadow casting and other effects concerning lighting and reflection cannot be applied. These effects implicate visual feedback generated by user interaction in AR and provide powerful perceptive information 4.3.

3.4.2. Indirect Volume Rendering

Indirect volume rendering is another technique how to visualize three dimensional data like DICOM. Data is represented by surfaces of homogeneous areas within the DICOM data volume. Examples are the skin and surfaces of muscles and bones. Therefore an algorithm, usually the Marching Cube Algorithm [21], examines the volume. The algorithm detects voxels, which are located at the boundary layer of homogeneous areas, stores them as three dimensional vertices and triangulates surfaces over these vertices. Detailed information about the Marching Cube Algorithm is well described in standard Computer Graphics literature, e.g. [21].

The major part of the information provided by the volume data is removed and just the surface, which is the representative of a homogeneous area of the volume can be display. The user has to define exactly what he wants to visualize, everything else is taken away. This could be a disadvantage of this method. On the other hand sometimes too much visual information occludes relevant information.

Surface models allow for the realization and integration of special effects like shadow cast and reflection on surfaces, which let the virtual objects appear more realistic.

4. Depth Perception

This work is motivated by improving depth perception for stereoscopic AR via HMD. Up to now in most of the systems based on stereoscopic AR via HMD virtual objects superimpose real ones even if the real objects are positioned in front of virtual entities. Figure 4.1 shows a possible scene in surgical AR. The observer views an augmented spinal column, which seems to be placed in front of the thorax because it occludes parts of the thorax. Because of a long experience in business, the surgeon knows where the spinal column should be in reality. But as interposition or occlusion is a strong indicator for depth perception the process of perception is affected by this visual misinformation. Distance cannot be estimated intuitively anymore. Perception gets even worse if the surgeon moves his hand in front of his field of vision as shown in figure 4.1. The following section introduces the

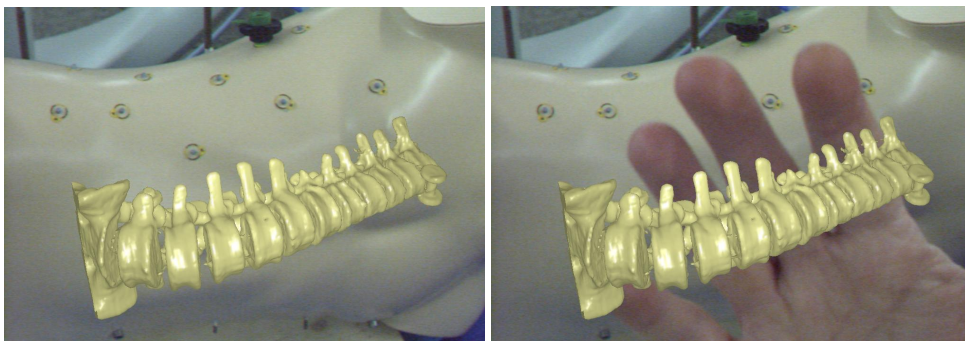


Figure 4.1.: Visualization of the spinal column is overlaid on real objects.

human visual perception. It contains an anatomic description of the eye, the human visual system for perception, and psychological cognition concerning visual perception and in particular visual depth perception. Section 4.3 engages proprioception, which is an additional source of information for depth perception.

4.1. Basics

The first section of this chapter provides a detailed anatomic description of the human eye and the introduction to the stages of human perception.

4.1.1. Human Visual System / The Eye

According to Zimbardo [29], vision is the most complex, highest-developed human sense. It enables orientation and supports the equilibrium sense. Without vision, i.e. if we close our eyes, we loose aplomb immediately [29].

Eye Anatomy

The eyeball consists of three chambers filled with fluid and further components, which differ respective their structure, function and tissue.

- Outer layer of the eyeball: This layer is called cornea, which is completely transparent. The resistant sclera, which encases the entire eyeball to protect it, is located immediately behind the cornea. Eye muscles are affixed to the anterior section of the eye e.g. in order to be able to focus objects located near to the observer. In addition, the eye is covered by the conjunctiva in the anterior section, which is a transparent membrane.
- Medium layer of the eyeball (uvea): The uvea consists of the choroid in the posterior section and the ciliary body in the middle section, which enables the deformation of the lens. The iris is located in the anterior section and exhibits an aperture in its center. This section is covered by many parasympathetic fibres of the annual musculature of the iris, which enable dilatation and stricture of the pupil.
- Interior membrane (retina): The retina consists basically of the photo receptors in the posterior section. The so-called blind spot is located in the front, which does not exhibit photo receptors.
- Lens: Connected with the ciliary body in the interior part of the iris.
- Anterior chamber: Located between iris and cornea.
- Small posterior chamber: Positioned between iris and lens and filled with fluid as the anterior chamber.
- Big posterior chamber: Located behind the lens. The so-called vitreous body is inside of this chamber.

Figure 4.2 shows the main components of the human eye.

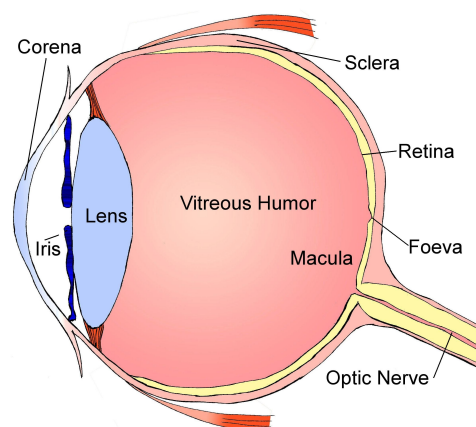


Figure 4.2.: eye

Functionality

The eye reacts to physical stimuli caused by the electromagnetic radiation. The human eye is able to perceive wave lengths in the range of 350 nm and 750 nm and the neural part of the visual system allocates light intensity and colors.

The image, which is perceived, the so-called *distal stimulus*, passes the iris and is projected on the retina. The retina consists of special light sensitive cells, the photo receptors, which encode the light and translate the electromagnetic stimuli to neural stimuli.

There are two types of photo receptors, rods and cones. The rods are more numerous, some 120 million, and responsible for low light levels, scotopic vision. They have a low spatial acuity and are not sensitive to color. The cones, in the range of 6 to 7 million, are active at higher light levels, photopic vision, and responsible for perception of colors and high spatial acuity. They are located concentrated in the central yellow spot, the macula. The fovea centralis, a 0.3 mm diameter rod-free area with very thin, densely packed cones is located in the center of the macula.

Iris and lens are responsible for the projection of the distal stimulus onto the retina. They handle accommodation and alignment to lighting conditions by the ciliar muscle, which is able to arch the lens. The iris can be compared with a camera and its components shutter and modulation of light intensity. [26]

The image projected on the retina, the so-called *proximal stimulus*, is an inversion of the observed scene, the distal stimulus. It is reinverted by the brain. Basically the left visual field, which is located on the posterior section of the brain, is responsible to process visual stimuli. Further information about eye anatomy, its functionality and neural processes can be obtained in every book about human anatomy and visual perception, e.g. [26], [29].

4.1.2. Stages of Visual Perception

Human perception is an important field of research in psychology. Its task is to examine interpretation and conversion of lots of sensory information received as a chaotic input that stimulates various receptors. The section above already described the projection of the distal stimulus onto the retina, the generation of the proximal stimulus by the receptors and finally its transfer to the human brain. This section goes into detail of psychological cognition concerning visual perception.

First of all a scenario shall be introduced to be able to refer to an example while describing the stages of perception and later the sources of information for depth perception.

We have to take into account that the patient has to be scanned by e.g. a computer tomograph at a certain station at hospital and later he is brought to the OR. In general viscera, bones and joints change their position, orientation and shape because of this transfer. The surgeon cannot be sure that the augmented objects are exactly overlaid onto its real counterparts. Accuracy and precision are fundamental attributes in medical technology. System errors can cause serious consequences first of all for the patient but also for acceptance in the surgical future workflow. The example focuses on dorsal surgery, because bones, e.g. the spinal column, keep their shape and stay approximately at their position in contrast to viscera such as the lung, which changes its size permanently.

A surgeon puts on an HMD before or while surgery to view the virtual spinal column at its right

4. Depth Perception

position on the patient who already lies on the operating table. The surgeon wants to know,

- which vertebra has to be treated,
- where to place the port on the patient' skin and
- how far away is an instrument guided by the surgeon or an assistant from the operation site, a certain vertebra.

Therefore a virtual surface model or a volume rendered representative of the spinal column has been generated from the CT data and positioned at its proper position inside the patient. The surgeon perceives the spinal column in front of the real body of the patient, because the virtual model superimposes the real objects as it is shown in figure 4.1

The process of human perception can be subclassified to three stages [29].

1. Sensation: The first step of perception handles the conversion of physical energy to neural coded information. If we consider the example introduced before, the images on the HMD-monitors placed in front of the surgeon's eyes are projected onto the retina receptors of his or her eyes. The projected image is already the combination of real and virtual entities, in this scenario the real patient and the augmented spinal column.
2. Organization: This step of the perception process provides the answer to the question: „How does the viewed object look like?“
The human visual system generates a so-called *percept* of the distal stimulus. The percept is a sufficient description of the exterior environment and includes information about simple, sensory attributes like hues, edges of viewed objects, lines, homogeneous areas, which are combined to one percept of a certain object. Due to the results of this synthesis, information about objects like shape, size, depth and movement already can be estimated in this stage of the process. Therefore experience values and actual sensory information are merged. In reference to depth perception, the observer already allocates distances between objects of a certain scene. An object A, which is partially occluded by an object B is placed behind B within the imagination of the observer. If we consider the example, the surgeon views among other things two homogeneous areas representing the spinal column and the body of the patient. In this stage he or she still does not know that one area is the spinal column and the other one the body but he or she perceives depth information because one area partially occludes the other.
3. Identification and classification: This step of the perception process provides the answers to the questions: „Which object is it?“ and „Which functionality has the object?“
Now all percepts get a signification. In reference to the example, the surgeon identifies among other viewed objects the two homogeneous areas as the spinal column and the patient. The visual system notices that the constellation of the objects was assessed wrongly. Imagination about the constellation of the viewed objects has to be adjusted because of experience values, which say that a spinal column should be located inside the human body.

After have run through the stages of the perception process the surgeon possesses all information about distal stimulus engendered by the viewed physical and virtual objects. However the stages „organization“ and „identification“ come into conflict. The consequence is, that the surgeon cannot get a satisfactory feeling about the constellation of objects within his or her field of vision. Within the scope of this diploma thesis, this conflict has to be resolved.

4.2. Visual Sources for Depth Perception

This section goes into detail of visual depth perception. The previous section already discussed „organization“ as the first stage of the perception process that enables estimation of distances and depth. Now all information sources, which are responsible for the sensation of depth will be itemized and described.

A very strong, monocular depth cue is interposition or occlusion. It causes the conflict between the stages of the perception process described above.

Perceiving depth is very intuitive and natural exercise. People don't loose time to think about why they are able to drive a car without crashing permanently into the car, which drives in front of oneself. They just use perception and rely on what they see. Visual illusions published to confuse the observer about his depth perception can be found in the internet. Examples are the Ames Room [5] or the objects shown in figure 4.3.

Depth cues can be arranged respective their effectiveness in areas around the observer.

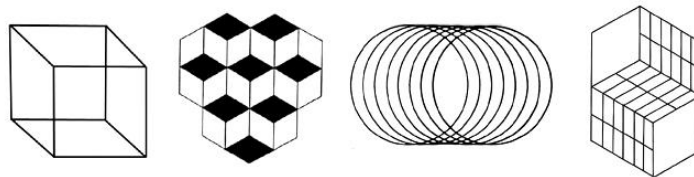


Figure 4.3.: Illusions about depth.

Cutting [8] differs three areas.

- Personal space (Up to 1-2 m): That's for example the workspace of the surgeon in an OR. The focus of this thesis is on depth cues with high effectiveness within this area.
- Action space (1-2m to 10-30 m): Driving a car in the city or throwing a basketball.
- Vista space (10-30 to ... m): Playing golf or driving a car on the freeway.

Some of the following depth cues seem to be obvious and well known. Others might be unfamiliar or /and unnoticed and require further explanation.

4.2.1. Oculomotoric Criteria for Depth

The oculomotoric criteria contributes to depth perception because we usually use two eyes to perceive a scene. Each eye perceives a slightly different, two dimensional representative

4. Depth Perception

of the scene. The brain is able to combine ocular, sensory information, the so-called *binocular source*, and generates information about depth, distances and constellation of objects within a viewed scene.

Stereopsis

Human eyes are positioned in average about 6 cm away from each other. Therefore two slightly different images taken from different positions are projected onto the retina and stimulate different receptors. This deviation of stimulated, corresponding receptors enables the generation of information about three dimensionality and depth. This depth cue is called *stereopsis* or interchangeable *binocular disparity*. Figure 4.4 shows the images projected on the retinas of both eyes. The observer closes the right eye and views the ball with his left eye. He or she positions two fingers within his field of vision in front of the ball in order to create a frame for the ball. That's the distal stimuli for the open left eye, which is shown in the left image. If the observer now closes the left eye and opens the right one, fingers and ball stay at their position, he or she views the right image, which is obviously different to the left one.

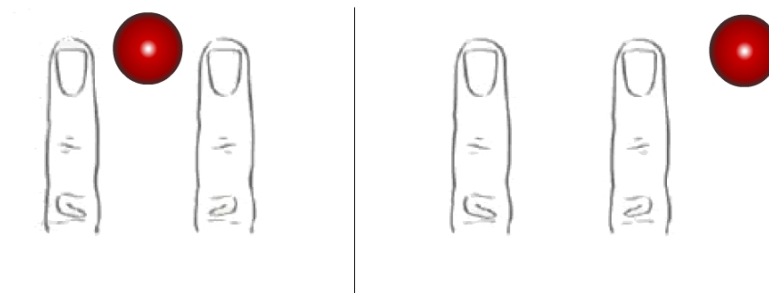


Figure 4.4.: View on the scene with the right and the left eye.

Convergence

The depth cue *convergence* concerns the demand of ocular musculature. If an object is positioned near to the observer, three meters at maximum, and focused with both eyes, the view directions of the eyes converge and cross at the focal point.

Information of convergence is gained from the movement of the eyes measured by certain receptors of their musculature. These receptors transfer the stimuli to the brain, which can estimate by experience values the distance to the focal point, i.e. where the focused object is positioned.

If the focal point is located at distances greater than three meters, axes of view direction are more or less parallel. The movement of musculature gets too slight and convergence becomes irrelevant for depth perception.

If we consider perception via the displays of the HMD and its cameras, convergence is predefined by the extrinsic camera parameters because the adjustment and orientation of the cameras cannot be changed by the user while he or she observes a scene.

4.2.2. Motion Induced Depth Cues

The following information sources for depth perception require movement of the visual system respective the observed scene, e.g. the observer is sitting in a train and watches the landscape passing outside the window.

Motion Parallax/Motion Perspective

„The relative movement of the projection several objects stationary caused by observer movement is called motion parallax“ [8]. This depth cue can be described by the following example. The driver of a car looks through the side window and observes the landscape. Viewed objects, which are located far away, e.g. a mountain peak at the horizon, pass slower the field of vision than objects positioned near to the car, for example a person on the pavement beside the road.

Even distances between these objects can be estimated, if the observer knows about the their size. Motion perspective ([18] [17]) provides the same information for depth perception as motion parallax. In contrast to motion parallax, the whole field of viewed objects moves and the observer stays at his or her position. Figure 4.5 shows from bird eye's view the observer, the disk, who stays at his or her position and two objects, the quads, that move to the right. The object, which is farer away, seems to move less distance than the object that is nearer to the observer, although they move exactly the same distance.

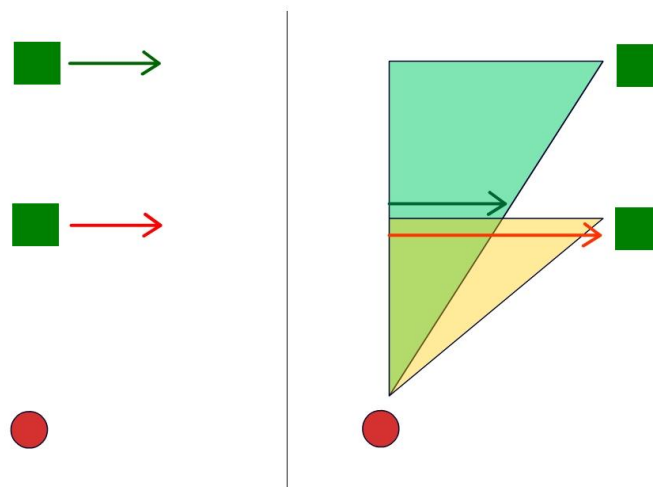


Figure 4.5.: Motion perspective

Cover and Uncover Planes

Another dept cue, which is very similar to motion parallax can be explained by the following observation. If the observer moves respective two plains, e.g. two house walls, these walls seam to move relatively to each other. The wall A in the front covers or uncovers

the wall B, which is located behind A. Also declarations about distances between objects are possible. This effect does not occur, if the observer moves perpendicular to the planes. Figure 4.6 shows from bird eye's view the observer, the disk, who moves sideways respective two fixed walls. The semi-transparent plains representing the visual field show, which parts of the walls are visible for the observer.

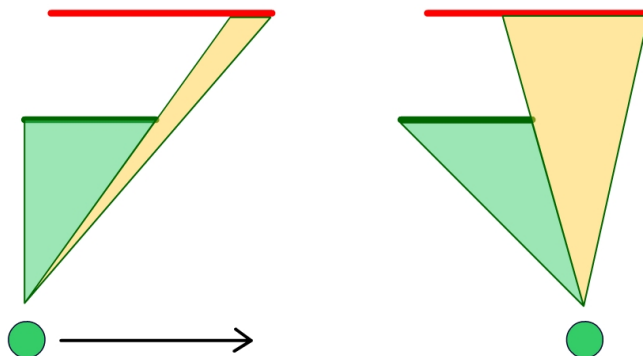


Figure 4.6.: Cover and uncover planes

4.2.3. Monocular, Pictorial Criteria for Depth

The sources of information for depth perception described above imply that both eyes view the scene or the observer and viewed objects move relative to each other. There are further depth cues, when the scene is observed with just one eye. Using these cues to generate an impression of depth and distances has a long tradition in painting and drawing.

Interposition/Occlusion

If there are two objects and object A occludes parts of the object B, we get the impression that the partially occluded object B is positioned more distant than object A. As Cutting [8] mentioned, occlusion „exceeds all other information“ for depth perception. „The effectiveness of occlusion does not attenuate with distance“ of the objects to each other or to the observer. This depth cue is quite similar to „cover and uncover planes“ (4.2.2). However interposition does not provide absolute information about distance between the objects and to the observer. It just allows for cognition, which object is nearer to the observer.

Exactly this depth cue confuses the vision of the surgeon. The observer perceives the spinal column in front of the thorax and not inside as shown in figure 4.1. Even if the observer moves his head and depth perception is generated from correct motion parallax (4.2.2), the observer is still confused about constellation of the viewed objects, because the visual

effect caused by interposition produces the stronger depth cue. Figure 4.7 shows a simple example that illustrates interposition.

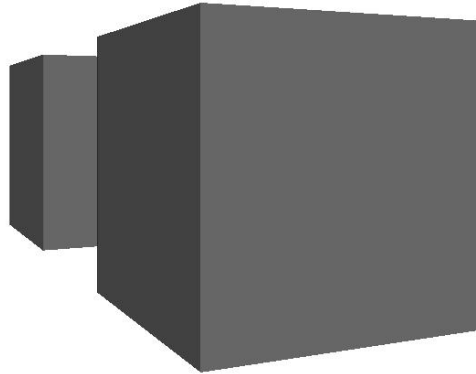


Figure 4.7.: Interposition/Occlusion, Relative Size, Shape from Shading, Linear Perspective

Relative Size

The source of information, relative size, concerns the relation between size and distance to physically similar sized objects. The objects, positioned in variable distances to the observer, create different sized two dimensional images on the retina. If the observer does not have any knowledge about the natural size of the viewed object at least two objects have to be present in order to perceive distances between them. If the objects are known to the observer, for example coins, one object is sufficient to estimate absolute distance to the observer. In that case the terms „familiar size “or „assumed size“ are often used [14], [15]. The objects in figure 4.8 are unknown to the observer, however smaller disks seem to be located more distant than bigger ones. Familiar size can cause illusions about distances. For example, if the viewed objects are trees of a certain species and some of them are younger than others, they don't have the same size but look similar [6].

Texture Perspective/Relative Density

A group of similar objects, which create all together again some kind of pattern provide information for depth perception. Texture perspective or „Relative density concerns the projected retinal density of a cluster of objects or textures, whose placement is stochastically regular, as they recede into the distant“ [8]. Figure 4.9 shows such a cluster of objects that forms a texture. Another example would be a corn field that gets a more and more densely and finely woven structure into the distant. Near regions appear detailed and coarsely meshed.

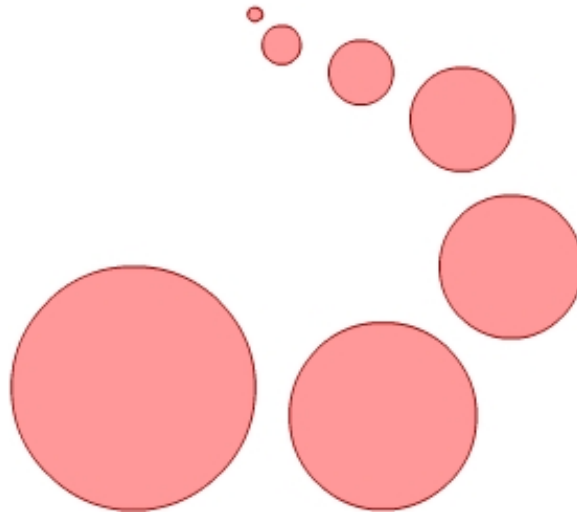


Figure 4.8.: Relative size

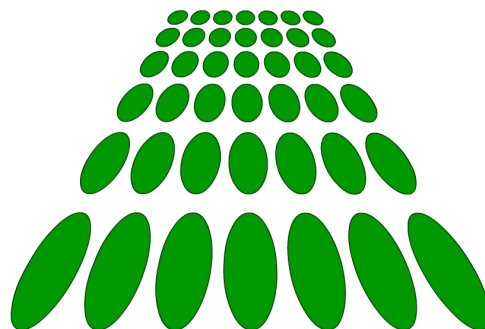


Figure 4.9.: Texture perspective

Linear Perspective

Linear perspective is a depth cue that combines relation of size and distance. If an observer looks along parallel lines, e.g. rails, which lead to the horizon or the borders of a straight road, the lines seem to converge somewhere at the horizon line (figure 4.9). Linear perspective is a „systematic combination of several other sources of information“ [8]. It includes effects of relative size and textures. In any case, this depth cue requires distance and nearly does not contribute to depth perception in the personal space given for example in an OR.



Figure 4.10.: Linear perspective

Relative Height/Height in Visual Field

This depth cue results from the position of objects relative to the horizon line. For objects above the horizon line we perceive the following. Objects positioned higher appear nearer to the observer and objects closer to the horizon line appear more distant. If we compare objects beneath the horizon line, we perceive the opposite effect. Objects positioned higher seem to be positioned more distant than objects in a lower position (figure 4.11). Relative height or height in visual field gives absolute information about distances. However, this depth cue does not provide useful information within the personal space and its effectiveness to estimate depth decreases with distant unlike occlusion or relative size.

Distance Fog/Aerial Perspective

Small particles, moisture or /and pollution, in the air let distant objects appear blurred and diffuse and their color seems to be less intensive. Objects, which are positioned closer to the observer, have intensive colors, seem to be more detailed and rich in contrast. Painters use this effect for centuries to create pictorial effects for depth. Figure 4.12 shows a landscape. Distant objects like the peaks „appear blue and almost of the same hue as the atmosphere itself“ (Leonardo, [37]) in contrast to the lusciously colored trees located in the

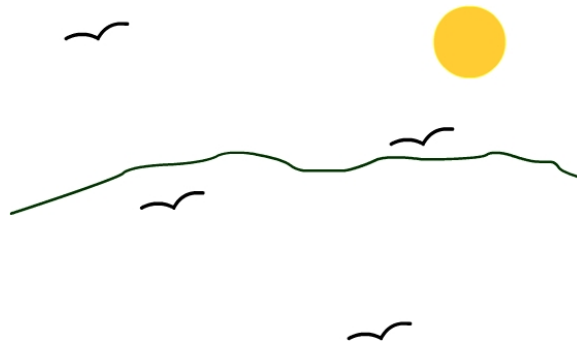


Figure 4.11.: Relative height

foreground. Unlike the depth cues presented above, effectiveness of aerial perspective increases with distance. However, with too great distance the objects become indistinct or nearly invisible and the depth cues becomes ineffective. The concept of particles that manipulate colors and create depth impression can be applied to the perception of underwater worlds and transparency in general. Section 4.4.3 addresses transparency. Within the personal space, distance fog hardly contributes to depth perception and to handle the problem introduced by the example above. However, representation of medical data with the technique of volume rendering (3.4.1) and a well defined transfer function shows, how depth information within the data volume can be generated by colored particles, in this case certain voxels, and transparency.

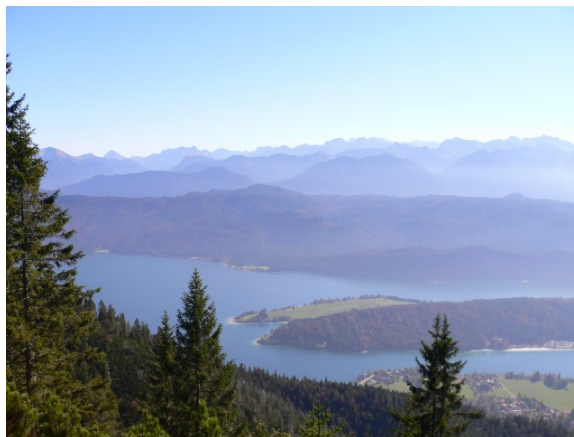


Figure 4.12.: Distance fog/Aerial Perspective

Chromostereopsis

The characteristics of the human visual system allows for allocation of distances to different colors. It is not possible to estimate distance values. However, we can achieve information about the relative position of uniformly colored objects. This is possible because of the visual phenomenon chromostereopsis. Light is refracted „in a color dependent manner, so that light rays with different wavelength ... are projected onto different positions on the

retina“ [42]. The stimulation of the different areas of photo receptors is aligned with depth information by the brain. Chromostereopsis is the reason why we perceive red areas of a red and blue pattern in the foreground. The so-called Open CyberHolographicTM and ChromaDepth Standard of Chromatek¹ defines an order for the colors. „On a black background, red will appear closest, blue furthest, and the other colors will fall in-between according to their place in the rainbow (red, orange, yellow, green, blue)“. Knowledge about chromostereopsis is important to define the right colors to design a visualization. A bad choice of colors, e.g. combination of red and blue, can fatigue the observer. It can be also helpful to create impression of depth. Figure 4.13 shows the effect. Red disks seem to be located closer than blue ones.

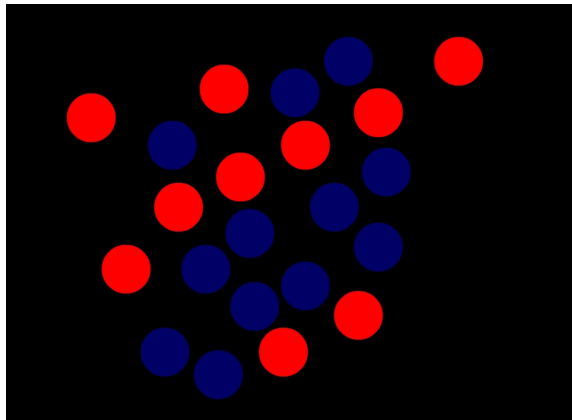


Figure 4.13.: Chromostereopsis

4.3. Proprioception/Kinesthesia

Proprioception or often used interchangeably kinesthesia is the sense that provides information about the position and orientation of parts of the body. 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. Proprioceptors give feedback about

- tonicity and muscularity,
- motion of joints respective deflection,
- velocity and direction of motion and
- position of parts of our extremities.

Muscle memory and hand-eye coordination result from kinesthesia and can be trained. This enables equilibrium as well as fine motor skills. Bathyesthesia is the deep sensibility stimulated by pain, movement and pressure and merges all proprioceptive cues.

¹<http://www.chromatek.com/>

In our setup interaction does not result in haptic feedback. In some cases it is not wanted at all to keep the patient abacterial, in other cases it is simply not possible because collision of virtual objects cannot be transferred to haptic information. However, there are some approaches that enable visual feedback for user interaction (sections 5.6.2, 5.6.3 and 5.5).

4.4. Perception of Layout and Relation of Objects in a Certain Scene.

The following section mainly discusses attributes, which help to perceive layout of objects, i.e. shape and dimensions, and their relative position within a scene. Focus is not anymore on depth perception. Some attributes can be influenced by user interaction. This includes for example interaction that manipulates the light condition of the scene, e.g. shadows cast, and interaction dependent appearance of surfaces, reflection or specular highlights.

4.4.1. Texture Gradients

The texture gradients size and density, explained above in sections 4.2.3 and 4.2.3, provide information sources about depth.

James T. Todd, Lore Thaler, Tjeerd M.H. Dijkstra analyzed the use of textures with a special structure to generate a three dimensional impression, which helps to distinguish the shape of objects.

Among other things the paper examines the effect of textures, which consist of simple, round, black disks with a white background. Many of these disks are positioned like grid points on the texture and form a uniform pattern. Disks have a simple shape. It is eye-catching, if their shape changes when their orientation is modified. The eye interprets a spatial rotation of the disk, which is ambiguous respective direction of rotation, if just one disk is presented as shown in figure 4.14. Many grouped disks create a unambiguous

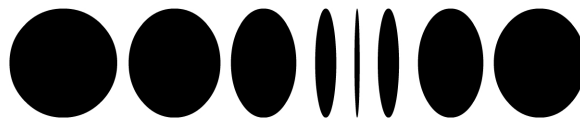


Figure 4.14.: Round disks as texture primitives

impression about the three-dimensional shape of the textured object (figure 4.15).

4.4.2. Lighting and Shading

In computer graphics, three types of light [10] can be distinguished. Ambient light does not exist in the real world. However, it is used in computer graphics to approximate light that comes uniformly from the sun and arrives onto a surface by bouncing off so many other surfaces that it might as well be uniform.

Diffuse light has a particular point source, e.g. the sun, and hits surfaces with an intensity that depends on whether they face toward the light or away from it. Once the light hits a surface, it is reflected equally in all directions.

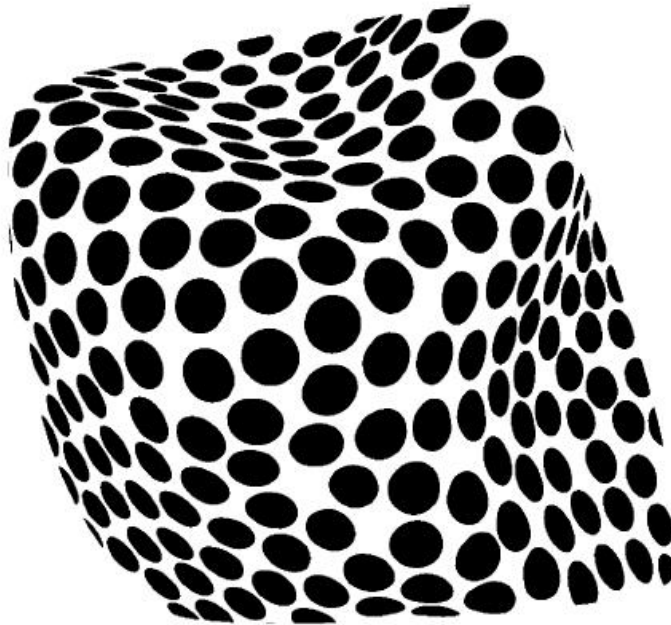


Figure 4.15.: Different orientated round disks as texture primitives illustrate shape of an object (image taken from [38]).

Specular light comes from a point source and produces highlights on smooth surfaces because it reflects the incoming light like a mirror in a particular direction defined by the surface shape. Intensity of those highlights depends on the material parameters of the illuminated surfaces and the specular ratio of a light source that illuminates the scene. For example, we get more intensive effects on a glass bottle than on a tennis ball. On a sunny day, sunlight contains more specular light than on a cloudy day, when light is mainly diffuse.

If the observer is able to guide the light source, he or she gets visual feedback by color changes on the illuminated surfaces due to diffuse and specular light. This visual feedback includes information about the shape of the objects because of „shape from shading“ [7], which is shown in figure 4.17. The color of a certain point on the surface of an object depends on the gradient of this point respective orientation and position of the light source. Extremal values are areas on the surface, which light can't reach because the object casts a shadow on itself and areas, where the gradient of the point on the surface is parallel to the direction of the light and highlights can be seen.

If the illuminated surface is not plane and the light source moves independently of observer interaction above the scene, information about the position of the light can be estimated. A half moon gives information about the position of the sun.

A spotlight also provides visual feedback because the light can now be associated with a shape, usually a round cone. The shape of the projected cone, usually a distorted disk, gives information about shape of an object (only if the light direction is not the same as the view direction), position of the light source and direction of the light. Spotlights are usu-

4. Depth Perception

ally used as a single light source to direct the observers attention to a certain location, for example to the stage of a theater. Layout information gathered from spotlights decreases, if additional light illuminates the scene. If the spotlight can be guided interactively by the observer, e.g. hand-held or head mounted, he or she is able to direct the spot through the scene and can explore the constellation of objects. Figure 4.16 shows a light cone that illuminates two walls. Due to the shape of projection, the observer is able to determine, which wall is the front. The first wall hit by the light shapes the light cone and influences the projection on the wall in the background. If there is not just ambient light that illumi-



Figure 4.16.: Spotlight illuminates two walls. The wall in the front influences the shape of the spot that hits the wall in the background.

nates the scene, lighting usually causes shadow cast. Shadow provides information about constellation of objects placed in a scene. So the scene is divided up in two domains. The first domain includes areas, which are directly illuminated by a certain light source. The other one includes areas, which are not illuminated directly by any light source but by light reflection from other objects, the so-called diffuse and ambient light. If an object A

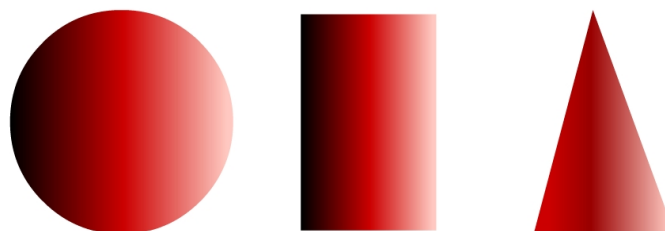


Figure 4.17.: Shape from shading

casts a shadow on an object B, the observer can estimate a spatial relation between objects A and B but also between objects and light source. If the light source or objects can be moved interactively by the observer, the shadow casts change and the observer gets visual feedback and is able to gather information about constellation of the illuminated objects.

4.4.3. Color in Combination with Transparency

If an object B is opaque or transparent and placed partially behind an transparent object A, the observer can get depth information from a special case of the monocular depth cue „interposition“ described above.

If B is completely behind A and the observer does not know about the color of the objects, which is occluded completely, he or she cannot be sure whether A is behind B or contrariwise. Figure 4.18 shows two transparent objects in different constellations to each other. Experience values about color composition enables the visual system to organize them, if they occlude each other partially. Provided that the observer does not know about the color of an object placed inside of the other one, it is not possible to decide with reasonable certainty, which object is nearer to the observer.

However, regarding the scenario introduced above, this ambiguity is a progress. That

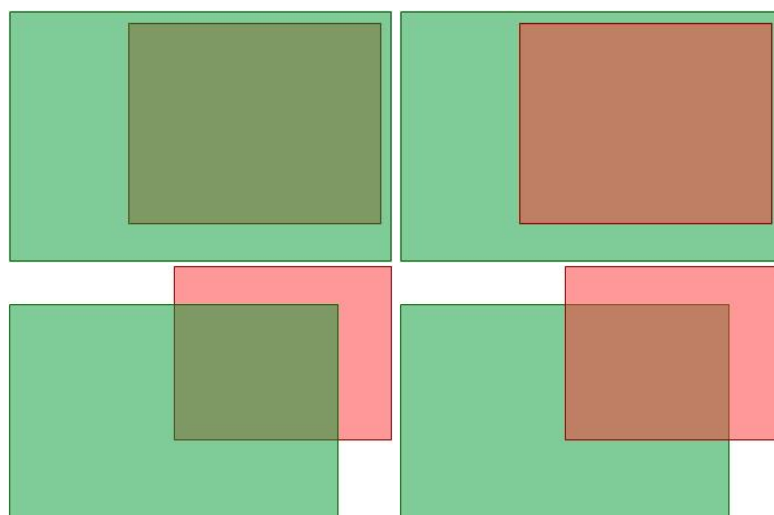


Figure 4.18.: Perception of transparency objects.

means, if we render a transparent augmented spinal column instead of its opaque counterpart (figure 6.2), we get better results for depth perception. This was shown with the evaluation presented in section 6.1. Figure 4.19 shows such a semi-transparent representation of a volume rendered spinal column. The real skin of the patient is the background of the virtual spinal column, so the visual effect is comparable to the figure 4.18. But perception still is not definite! Some papers [16], [23] mention, that the concept of aerial perspective 4.2.3 is justifiably applied to the perception of transparency. They concern the study of the depth order of two or more colored transparent sheets. Instead of the air, the sheets become the medium that generates information for depth perception.

Johnson published a study concerning depth perception in surgical AR. Their system ren-

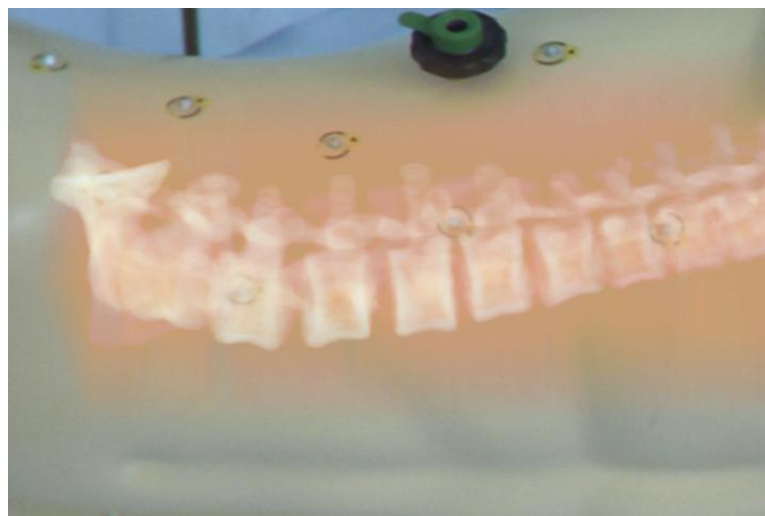


Figure 4.19.: Volume rendered spinal column.

ders virtual, medical imagery under a transparent surface, e.g. the skin of the patient, but they don't give further information, how to do that. They mention that „the presence of transparent surfaces diminishes the surgeon's ability to use the stereo information effectively and get an accurate sense of depth“ [9]. In any case the application of transparency is a good attempt to provide a view into the patient.

4.4.4. Perception of Glass/Mirrors

The following section discusses, how the special material glass as a transparent surface can contribute to perception of depth, if the observer interacts with a scene.

Provided that the specular portion of the light source is high enough, appearance and the rate of transparency of a glass bottle is changed by highlights at certain areas. Objects inside a transparent bottle can be perceived more or less undistorted. This depends on the material parameters, the shape and uniformity of the thickness of the glass.

Achromatic glass does not influence the color of the objects inside or behind the bottle. But highlighted areas on the surface of the bottle change the color of these objects. At some areas they even occlude parts of the inside as shown in figure 4.20.

Occlusion or interposition 4.2.3 is a weighty information source for depth perception. In this case, the specular highlight on smooth, glass surfaces occludes objects in the background. Glass is a familiar material in everyday life. The decision, if a bee is outside or inside the bottle of lemonade, is made very intuitively because we are able to perceive slight distortion and color changes and create an imagination about the order of viewed objects.

There is another effect enabled by a glass or a surface with similar material parameters. If there is an other object close to our bottle, it is mirrored on the glass surface. The reflection provides information about the position of the reflected object relative to the bottle even if the reflection is distorted because of the shape of the bottle.

If we consider mirrors - to simplify matters plane mirrors in order to get undistorted reflec-

tion - we get a second perspective of the scene that allows for a better idea about constellation of objects within a scene. A mirror is a plane as a part of a scene and a snapshot that is taken from a certain position behind the plane is mapped onto it. From the stationary point of view the mirror is an image and constellation of the figures shown in the image can be perceived with the aid of pictorial depth cues 4.2.3 in the stage „Organization “ of the perception process 4.1.2. Knowledge that the image is not static but dynamically generated can be obtained, when the observer interprets the displayed figures and cognizes them as reflected objects of the scene. Identification and classification of objects takes place in the last stage of the perception process 4.1.2. Depth should be perceived in the stage „Organization “. Even when the observer identified the mirror, he or she must determine its orientation and position to be able to interpret additional information about the constellation of the objects within the scene. That means several steps of interpretation have to be taken until pictorial cues can contribute to depth perception of the scene.

However a mirror is an instrument in everyday life that is used intuitively in many applications. In most cases the reflection on a mirror is perceived while either the mirror itself or the observer moves. Drivers steer a car backwards with the help of rear-mirrors and dentists use a stomatoscope to examination of the oral cavity.

Dynamic interaction with the mirror helps to explore a scene and to generate information about distances and locations of objects. The mirror can be located statically and reflections on the mirror plane change relative to the movement of the observer. Hand-held, free navigateable mirrors like the stomatoscope that allow for full control of position and orientation support exploration of directly invisible areas. Even though this device is not as effective and intuitive as the depth cues described above the mirror can contribute to layout and depth perception of a scene.

Reflection produced by the mirror and the glass surface but also shadow cast are light effects, which can be enabled by interaction with the scene. For example, if the observer moves his or her hand above the bottle he or she views its reflection. In addition to the visual feedback about the position of his hand he or she gets information about depth gained from proprioception (4.3).

4.5. Conclusion

Visual cues described above enable perception of depth. Distance from the observer to objects of a scene as well as distances among objects can be estimated intuitively. The human visual system is also able to perceive the layout of objects like shape, orientation and dimension due to cues provided by texture gradients and light effects. Effects like shadow cast and reflection on surfaces enrich information about the constellation of objects within a scene. Interaction with objects of a scene adds information about depth and distances gathered from proprioception. This information can be provided as haptic feedback as well as visual feedback. The latter comes into effect in AR systems, where virtual objects can be visually added to the scene but not physically.

It has to be mentioned that not just one but many information sources are combined unconsciously. Visual cues are mainly processed in the stage „organization “ of the perceptive process [29]. Every projection of a distal stimulus on the retina, which results to the proximal stimulus, as well as stimuli from receptors of muscles, tendons and joint capsules

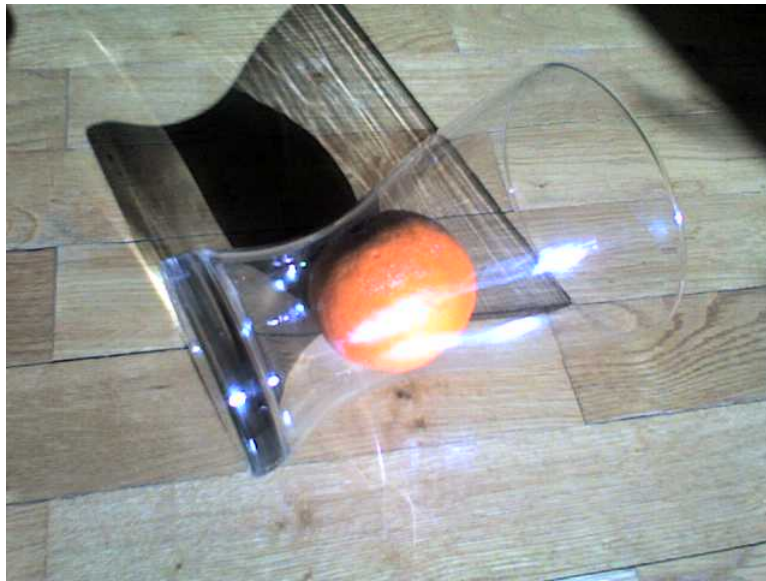


Figure 4.20.: Perception of glass.

include information for depth perception.

Cutting [8] classifies certain visual depth cues, which play a role within the personal space, i.e. two meters around the observer. The personal space conforms to the work space of surgeons in an OR. It is claimed that within this area interposition, binocular disparity and motion parallax are the most effective visual depth cues in contrast to linear perspective, which is nearly useless. Space for proprioception is limited by the length of extremities or e.g. dimensions of hand-held instruments.

In general all cues, concerning spatial information, are combined to one single, coherent, three dimensional interpretation of the environment.

5. Results

The following section presents the results of this diploma thesis. Various approaches were implemented and tested that task the misleading depth perception caused by superimposed virtual images on real ones. Some of the ideas that were evaluated as the most effective ones are presented in this section.

The methods base on light effects adopted from computer graphics, completely new augmented devices but also concepts how to use colors, textures and transparency to improve the design of certain virtual entities for a better visual perception.

In general, there are two approaches how to use visualization techniques and effects of computer graphics to integrate virtual objects to reality.

- Use visualization techniques and effects of computer graphics to let virtual objects appear as realistic as possible. The intention of this attempt is to provide homogeneous images on the displays of the video see-through HMD. Perception of the observer should not be confused or hindered by differences in the quality of virtual and real imagery. If one of the two components offers better quality than the other, the fusion of real and virtual appears too artificial. This also includes the level of detail of virtual objects, i.e. surface models should not appear laminar where they should be round. Also light effects have to be inserted faithful.
- Use deliberately abstract design to distinguish virtuality. The observer should identify virtual objects as fast as possible in order to adjust perceptive misinformation easily without getting confused. For example Edwards suggested triangle meshes as the representation of virtual objects [13]. Also accessory objects provide additional helpful information, which cannot be perceived, even if virtual objects are designed and integrated as realistic as possible. For example sensory information, which cannot be perceived visually.

This thesis also presents approaches that employ visual effects created by interaction as an additional source of spatial information. Interaction with virtuality of the AR scene excludes haptic feedback because they cannot be reached and touched physically by the observer. However, it is possible to create visual feedback, e.g. like reflection on a glass surface, caused by interaction, for example when the user guides an augmented instrument through the scene. This enables also proprioceptive information about distances to certain objects.

Another effect, providing spatial information about single objects but also about the constellation of objects, is shading. Therefore, a virtual light source can be placed at the same position as a real light source and real and virtual shadows can be combined.

We suggest the following methods giving visual feedback for interaction.

- Shadow cast by objects, which can be moved through the system.

- Reflection of objects on glass surfaces.
- A hand-held virtual mirror, which reflects virtual objects.
- A head-mounted light, that can be configured as a spot light and emits intensive specular light to produce highlights on smooth surfaces.

All of these methods were implemented within the scope of the diploma theses.

Another approach how to increase information about depth is to employ and intensify certain depth cues, which contribute intensively to depth perception within the personal space of the observer. These cues were introduced in section 4. I suggest a vision panel that is placed onto the skin of the patient and occludes areas outside its frame. The observer gets the impression to get a view through the vision panel or window on viscera or bones inside the patient. The virtual window is described in section 5.3.

Due to time and technical constraints, not all ideas were applied to visualization of medical data. Some of them are presented by more primitive virtual objects than e.g. the virtual spinal column. The implementation of these effects within the surgical context could be the task of a continuative project.

5.1. Anatomy

This section introduces to the visualized anatomy. As mentioned before, dorsal surgery is a reasonable field of application for surgical AR. The spinal column keeps at its position while the patient's transfer from radiology to the OR. It can be visualized with the required accuracy.

It has to be mentioned that all visualizations were generated from a tomographic data volume of a plastic thorax. The plastic thorax consists of its surface representing the skin and an internal attached model of a plastic spinal column. Both, the skin and the spinal column are made of almost the same material, which complicated the segmentation of homogeneous areas of the data to separate the skin and the spinal column. However, this is just a model to test different visualizations and segmentation was performed manually. If the data volume is taken from a real human body, all wished structures of the data volume can be extracted automatically by setting the right parameters in the segmentation methods, e.g. the so-called *Hounsfield Units*, certain transfer functions for volume rendering, definition of the right cube size if the marching cubes algorithm is used to realize surface models.

Tracking can be performed in two ways. One possibility is to attach a marker tree to the spinal column, which enhances accuracy of its position because the tracked target is directly affixed to the operation site. The other possibility is to attach at least four markers, in our case nine fiducial markers¹, onto the surface of the thorax. In a real application the most reasonable solution would be to mount a marker tree directly onto a fixateur the spinal column, because this means that the visualized spinal column itself is tracked and e.g. breathing does not bother accuracy of the virtual overlay too much. However, the optical tracking system is able to track the thorax model either the marker tree attached to

¹We tried to use the thorax target as the reference target for inside-out tracking to be able to replace the reference frame as another tracked object wasting space.

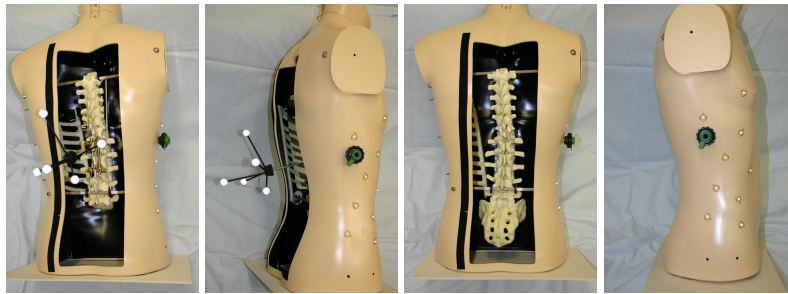


Figure 5.1.: Spinal column can be tracked by a separate marker tree or by the markers attached to the surface of the thorax model.

the spinal column or the fiducial marker set attached to the skin of the thorax.

Figures 5.1 show the thorax model with and without a marker tree attached to the spinal column. In both cases fiducial markers are attached to the skin of the model. But they are only used, if there is no marker tree.

Skin and spinal column were virtually visualized. The spinal column can be displayed by a volume renderer and an adequate transfer function but also as a colored, opaque or transparent surface with adequate material parameters (figure 5.2). The skin is visualized as a transparent surface with special material parameters to let it appear like glass (figure 5.2).

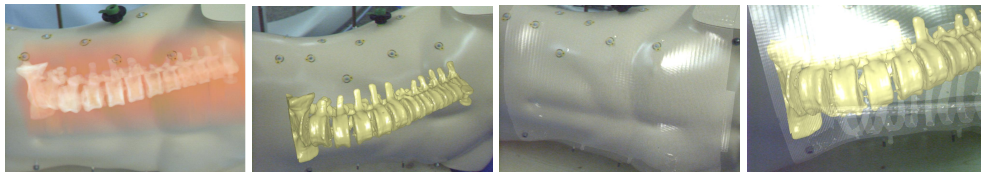


Figure 5.2.: Volume rendered spinal column, surface model of the spinal column, glass skin, surface models combined

5.2. Light

Light is an essential component of a scene. Due to different types of light like diffuse, ambient, specular light or spotlight, the visualized objects appear more realistic and three dimensional.

Virtuality of the introduced AR scene is illuminated by two light sources, which can be turned off and on.

```
//Material
GLfloat mat_ambient[] = { 0.2f, 0.2f, 0.2f, 1 };
GLfloat mat_shininess[] = { 100.0f };
GLfloat mat_specularhigh[] = { 0.8f, 0.8f, 0.8f, 1.0f };
glMaterialfv(GL_FRONT, GL_SPECULAR, mat_specularhigh);
glMaterialfv(GL_FRONT, GL_SHININESS, mat_shininess);
glMaterialfv(GL_FRONT, GL_AMBIENT, mat_ambient);
//Fixed light
GLfloat light_ambient0[] = { 0.5, 0.5, 0.5, 1.0 };
```

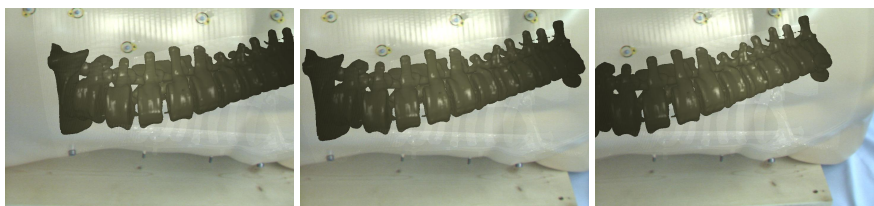


Figure 5.3.: Sequence shows the spotlight that moves over the spinal column.

```

GLfloat light_diffuse0[] = { 0.5, 0.5, 0.5, 1.0 };
GLfloat light_specular0[] = { 0.5, 0.5, 0.5, 1 };
GLfloat light_position0[] = { 0.0f, 1.0f, 70.0f, 1.0f };
glLightfv(GL_LIGHT0, GL_AMBIENT, light_ambient0);
glLightfv(GL_LIGHT0, GL_DIFFUSE, light_diffuse0);
glLightfv(GL_LIGHT0, GL_SPECULAR, light_specular0);
glLightfv(GL_LIGHT0, GL_POSITION, light_position0);
//Head-mounted light
GLfloat light_ambient1[] = { 0.2f, 0.2f, 0.2f, 1.0f };
GLfloat light_diffuse1[] = { 0.2f, 0.2f, 0.2f, 1.0f };
GLfloat light_specular1[] = { 0.6f, 0.6f, 0.6f, 1.0f };
GLfloat light_position1[] = { 0.0f, 50.0f, 1.0f, 1.0f };
glLightfv(GL_LIGHT2, GL_AMBIENT, light_ambient1);
glLightfv(GL_LIGHT2, GL_DIFFUSE, light_diffuse1);
glLightfv(GL_LIGHT2, GL_SPECULAR, light_specular1);
glLightfv(GL_LIGHT2, GL_POSITION, light_position1);

```

Specular light in combination with the right material parameters for surface models create highlight effects. Surfaces appear very smooth like glass. This is helpful for some methods presented in the following sections.

The first light is fixed at a certain position above the scene. The second one is virtually mounted on the head of the observer. It generates visual feedback because of highlights on surfaces reflect the light dependent to the motion of the observer's head. Visual effects caused by light and the interaction of the observer is a powerful tool to get a feeling about three dimensionality. The head mounted light emits intensively specular light. It can also be configured as a spot light like a head mounted lamp used e.g. by a speleologist (figure 5.3). Light essentially contributes to integration of virtuality to reality. If real and virtual light sources have the same attributes like brightness, color, proportion of specular light, position and direction of light, they influence illuminated objects, real ones and virtual ones, in the same manner.

5.3. Window

A window is a visual port, which provides a bordered view onto the world at the other side of the window. If we consider a glass window, the observer cannot pass his or her head through the frame of the window to view the environment on the other side by turning his or her head. However, the observer can move within his or her environment to look at different areas of the world, which are seen through the window as shown in figure .

Surgeons shall view objects like viscera or bones inside the human body. Section 4.1.2

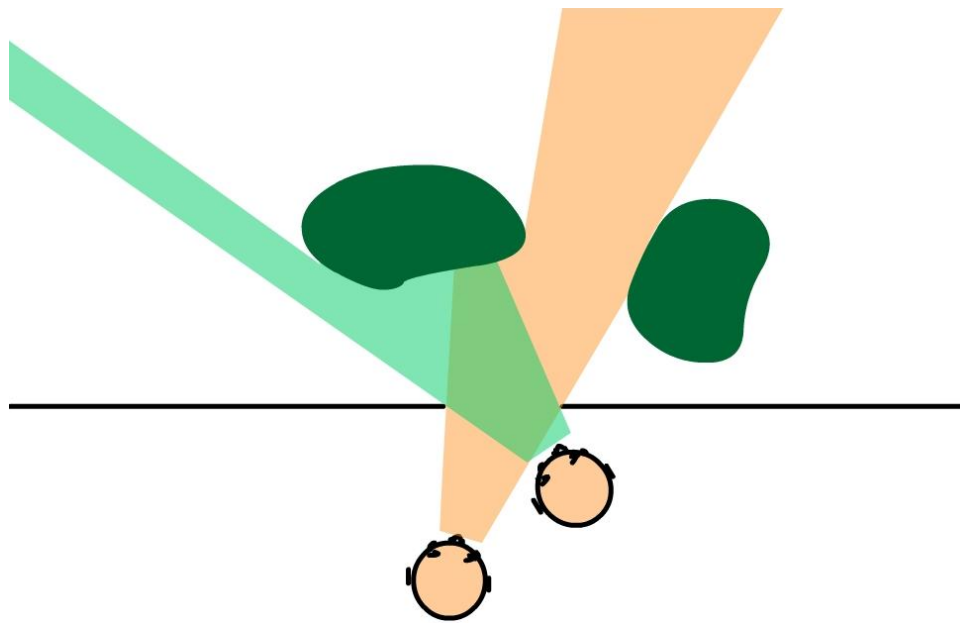


Figure 5.4.: Two observers see through a window from different positions and view different objects outside.

describes the conflict within the perceptual process caused by the technical restriction of AR, that virtual objects always superimpose real ones. In this application the virtual representative of the spinal column is displayed at its proper position within the AR scene. But it is not perceived inside the body because it occludes the real thorax, i.e. the skin of the thorax is perceived behind the spinal column.

The virtual window provides a view from one environment, the visible personal space of the surgeon, to the other environment, the inside of the human body. It is perceived as a visual bordered port to the anatomy of a body. Regarding depth perception, a window realizes the effective depth cue occlusion within virtuality to rectify the wrongly perceived constellation of objects.

5.3.1. Design and Perceptive Gain

Design of the window is essential to perceive its position within the AR scene. The observer may notice that it is overlaid onto the surface of the body. That means, it has to adopt the shape of the skin within the area, where it is positioned.

The window exhibits the following design features.

- The window is not just a hole into the inside of the thorax. It is a surface like a real glass window. The glass pane that reflects specular light and shows highlights at certain areas dependent to the light position. Because there is a virtual head mounted light source, highlights are created interactively due to the motion of the observer's head. Definition of the right parameters for material and light enable the glass effect.
- In addition to the glass effect, a texture was mapped onto the surface of the window. The texture supports perception of window shape and serves as a reference for mo-

tion parallax 4.2.2. If the observer moves his head, he perceives the pattern of the texture on the glass surface in front of the virtual spinal column because the components of the window, pattern and borders, move relatively faster than the spinal column.

- The green, opaque frame of the window distinguish the borders of the vision panel and the curved shape of the window, which is overlaid onto the thorax. The frame occludes parts of the spinal column positioned inside the thorax, which is a powerful depth cue as described in section 4.2.3. When the observer moves his or her head sideways, parts of the spinal column are covered and uncovered by the frame of the window and effects motion parallax like the texture on the surface of the window (section 4.2.2 and 4.2.2).

Also the thickness of the glass window is simulated. A parallel frame is placed at a certain distance behind the window. This second frame is covered or uncovered (4.2.2) dependent the view direction of the observer.

Figures 5.5 show the design features listed above. The figures 5.7 shows the monocular

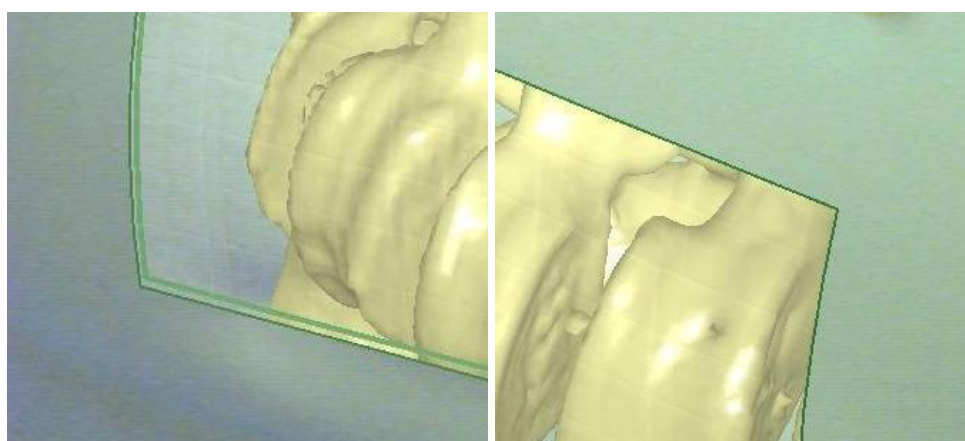


Figure 5.5.: Textures on the window surface and parallel frame inside of the body, shape of the window adapts to the shape of the thorax

view on the window while the observer moves his head.

5.3.2. Setting up the Window

The set-up of the virtual window can be performed without touching the patient and no additional instruments are needed. That means, the patient keeps abacterial and no further instruments bother freedom of movement and work flow.

In this implementation, the creation of the window requires a virtual model of the skin. This can be done automatically by a Marching Cube Algorithm (see section 3.4.2). Provided that no other virtual objects are positioned in front of the virtual skin, a so called *picking algorithm* that calculates the values of the depth buffer at certain two dimensional positions of the frame buffer. These positions are grid points of a two dimensional structured mesh, which can be positioned somewhere within the viewport of one color camera

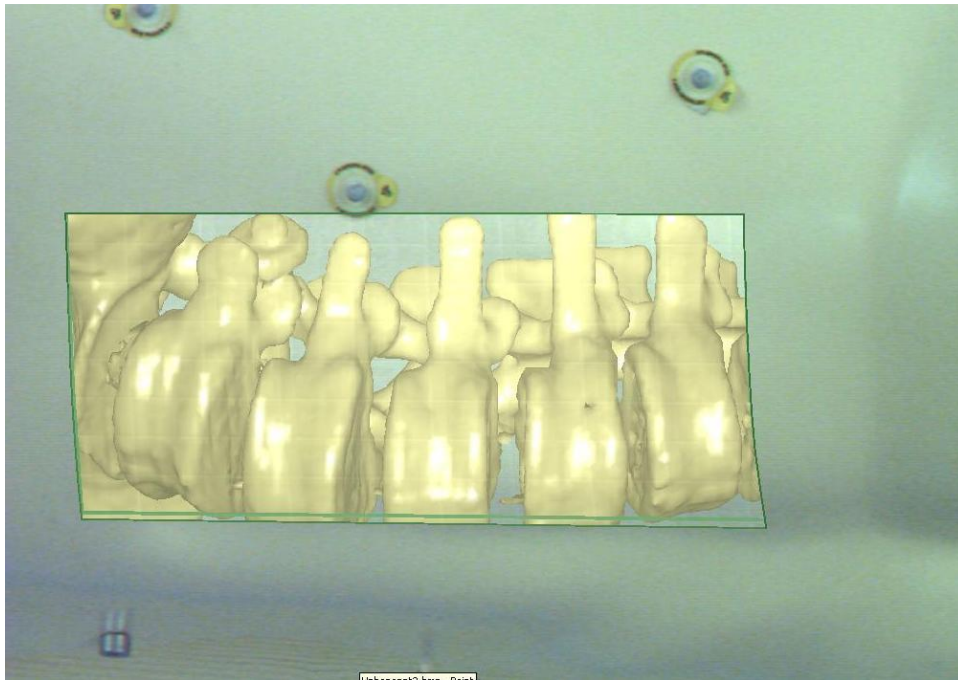


Figure 5.6.: The window.

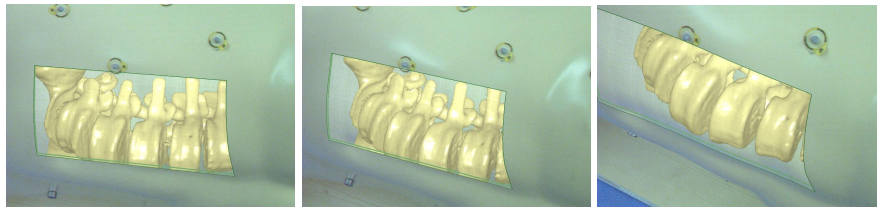


Figure 5.7.: Sequence shows the window viewed by the observer from different positions.

attached to the HMD. Figure 5.8 shows the frame of the window overlaid on the surface while navigating the mesh to find the right position for the window. If certain grid points result in invalid depth values, like the maximal depth value at the far plane or too big differences of neighbored grid points, the window cannot be locked and the frame gets red as shown in figure 5.8. The mesh can be scaled by mouse motion, which defines the dimensions of the virtual window. Regarding the work flow in an OR, this can be done by an assistant viewing the surgeons vision on external monitors. The window can be navigated to a certain position by moving the head with the HMD on it. If size and position of the window are adjusted, the grid points of the mesh are logged and the window and its design features are created.

Picking is a method, which is usually used to select certain objects of a 3D scene by mouse click. That means 3D information can be recalculated from the 2D position of the mouse or any other position on the screen. Therefore the depth buffer value can be read at a certain 2D position of the frame buffer. Picking can be realized with the following code.

```
CAMP::Vector3<float> VisualSpinal::pick3DPosition(int mousex, int mousey) {
```

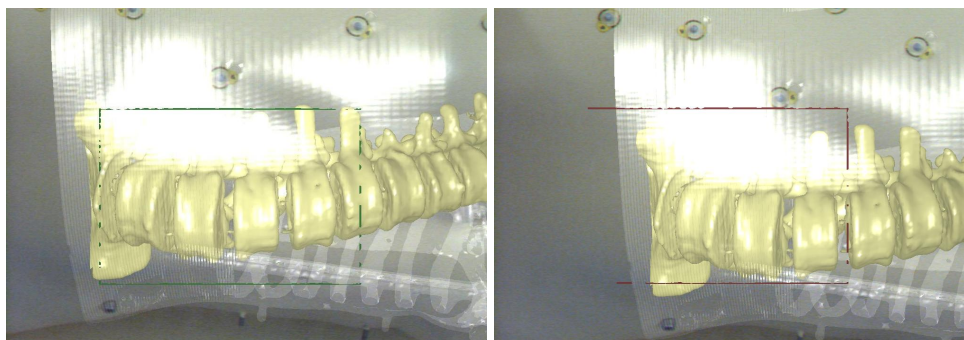


Figure 5.8.: Setup the window.

```

float depthgaga[1];
GLdouble modelm[16], projm[16], poswer[3];
int viewgaga[4];
CAMP::Vector3<float> retadad;
glGetDoublev( GL_MODELVIEW_MATRIX, modelm );
glGetDoublev( GL_PROJECTION_MATRIX, projm );
glGetIntegerv( GL_VIEWPORT, viewgaga );
glReadPixels( mousex, mousey, 1, 1, GL_DEPTH_COMPONENT,
GL_FLOAT, depthgaga );
gluUnProject( mousex, mousey, depthgaga[0], modelm,
projm, viewgaga, &poswer[0], &poswer[1], &poswer[2] );
retadad[0] = (float)poswer[0];
retadad[1] = (float)poswer[1];
retadad[2] = (float)poswer[2];
return retadad;
}

```

The creation of a smooth surface requires computation of the normals of each grid point. The normals are also used at the borders to position the second frame behind the window to simulate thickness of the glass. Additionally the texture coordinates are calculated for texture mapping.

After the window is created, the virtual skin is not longer needed and excluded from the scene.

the observer is now able to perceive the spinal column at its right position due to the window. However, all progress is vitiated when the real hand moves through the scene as shown in figure 5.9

5.4. Instruments

Augmentation of real instruments like endoscopes or other surgical instruments supports their navigation inside the human body while surgery. Especially if instruments enter the patient through a very small port like it is performed in keyhole surgery and no direct view onto the operation site is possible, the virtual counterparts of real instruments provide e.g. information about their distance to the operation site. Therefore an exact virtual copy of the real instrument has to be constructed and overlaid onto the real endoscope.

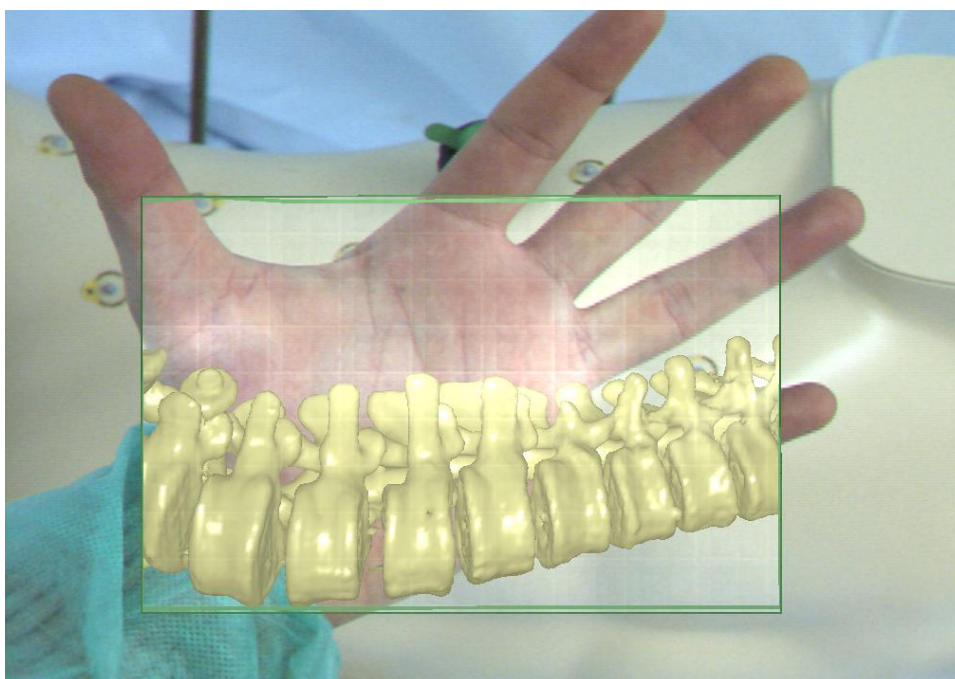


Figure 5.9.: Window that should be positioned in front of the window is superimposed on the real hand.

Additional design features can be attached to these virtual copies or extensions of the surgical instruments in order to optimize its usability as a new augmented, virtual surgical instrument. The idea is to map a certain pattern to the instrument in order to generate information how deep the instrument is inside the human body. Like a red and white scale, which is used to measure water depth at certain spots at the riverside, this kind of pattern can be used for our application. If the skin is visualized as a transparent surface and the patterned instrument is positioned partially inside the human body, the observer gets visual feedback how deep the instrument sticks inside the body. Composition of colors of the pattern and the color of the transparent skin divides the scale into two parts. The one, which is outside and the other one, which is inside the human body. The patterned virtual instrument is partially transparent. The virtual design has to be chosen carefully to avoid too artificial appearance of the instrument. This effect is shown in figure 5.10.

Another partially virtual instrument was developed. The instrument is a virtual cylinder, radius 2 cm and length 40 cm, which is attached to a real target tracked by the optical tracking system. It enables the surgeon to pass physical borders and position a virtual mirror inside the human body to provide a second perspective on the augmented spinal column. Further details about the mirror can be obtained in section 5.5.

5.5. Mirror

If we consider a real mirror, it is a common, intuitively used tool in everyday life. For example, drivers of a car navigate their vehicle with the aid of rear-view and side-view mirrors but also mirrors positioned at complex crossings to make enable a view directly

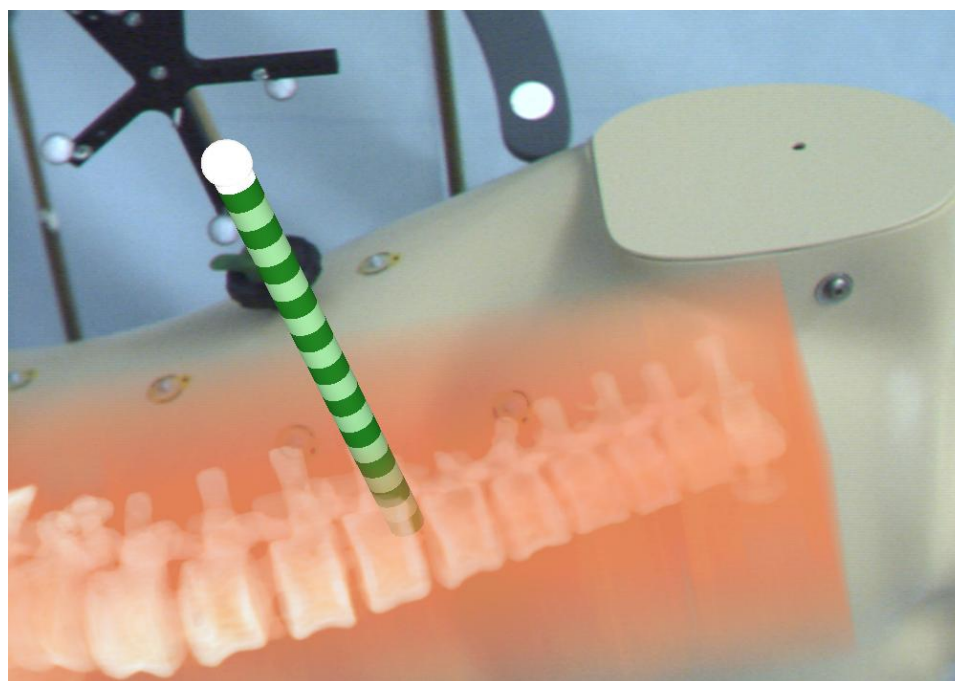


Figure 5.10.: Virtual instrument is overlaid on a real one.

invisible road users.

A mirror can also be designed as an instrument for specific professional intention. Dentists use a stomatoscope to augment for examination of areas inside the oral cavity of a patient. There are a lot of examples that show the practical gain of a mirror. They enable sight on hidden areas or offer a second perspective on objects.

Respective to the psychological point of view, the human visual system uses the visual information provided by a mirror, a mirror-inverted image of a certain scene, intuitively to extend visual information in order to get a better idea about constellation and properties of objects within a scene. This information concerns depth information respective distance of the observer to objects, distances between objects, addition of not directly visible areas, shape and dimension of objects. As a component in an AR scene, a mirror can be a powerful component to integrate virtuality in reality. This device is in addition to the visual information given by the stereoscopic perception another feasibility to interact with a scene consisting of virtual and real objects. Perception realized by interaction, in this case with arms and hands, is called Proprioception or Kinesthesia. This concerns perceptive information taken from tonicity and receptors of joint. In most stereoscopic systems the observer visually explores a scene by moving his head with the HMD on it around the virtual and real objects. So he or she views different perspectives on the scene and gets an idea about constellation and spatial properties of all visible objects.

The mirror as a fixed device expands visual information sources and combines them with information generated from proprioception. In our system the observer is even able to interact with the scene by moving his arms and hands. Binocular, visual information about the scene increases because of the second perspective on the scene for each eye reflected by

the mirror. Figure 5.11 shows the user, wearing a HMD and navigating the mirror within the body of a patient lying on the operating table. Figure 5.12 shows the user's view on the AR scene through the HMD. The mirror was conceived to be able to mirror virtual



Figure 5.11.: View from outside.

objects, which cannot be reached physically because their are covered by real objects, e.g. the augmented visual spinal within a real human body.

5.5.1. Method

The virtual mirror is attached to a off the shelf laser pointer with wireless mouse functionality, which is tracked by the optical, outside-in tracking system. This offers a small set of user interaction features by moving the mouse or pressing certain keys. A marker tree consisting of 5 markers is mounted on this device and makes it easily trackable (figure 5.13). The planar mirror is able to reflect all virtual entities. Virtual objects are rendered with various visualization techniques. We propose complex surface models and volume rendered objects as shown in figure 5.14. Visualization via volume rendering and a certain

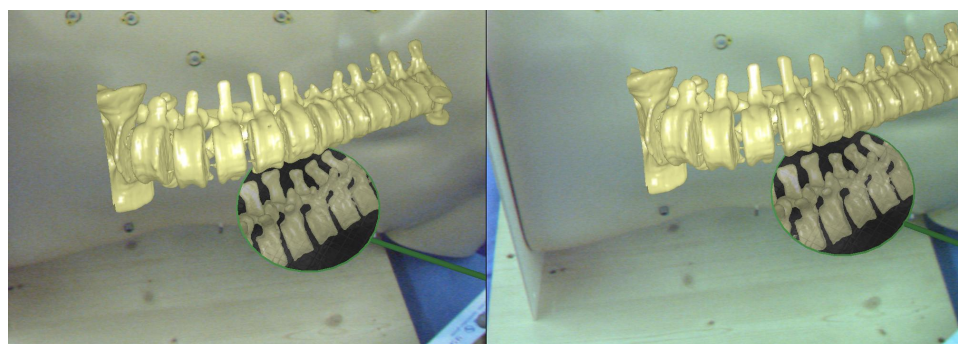


Figure 5.12.: Stereoscopic view onto the AR scene.

transfer function allows for digitally reconstructed radio graphs (DRR), which is a familiar representation of the medical data for a surgeon. In order to create an intuitive device, the origin of the coordinate system of the target and the mirror are connected by a virtual handle. In this way, the user perceives the mirror as physically attached to the hand-held laser pointer.

The reflection plane can be rotated around the end point of the virtual cylinder by mouse interaction using the buttons on the laser pointer. Every target for the inside-out and the outside-in tracking system has its own coordinate system. Realization of the mirror requires that all virtual objects be positioned relative to the coordinate system of the inside-out tracking system. The outside-in and inside-out tracking systems provide the following transformations:

- $^{inst}H_{IR}$: Transformation from the coordinate system of the optical, outside-in tracking system to the coordinate system of the marker tree mounted on the laser pointer that navigates the mirror (figure 5.13). The orientation of the mirror plane, in particular the direction of its normal is defined independently of its position. In the beginning, the mirror plane is parallel to the xy plane of the coordinate system of the reference system. All rotations of the mirror are performed around the axes of this coordinate system.
- $^{spine}H_{IR}$: Transformation from the coordinate system of the optical, outside-in tracking system to the coordinate system of the marker tree or set of fiducial markers attached to tracked objects like the thorax model (figure 5.13)
- $^{arc}H_{IR}$: Transformation from the coordinate system of the optical, outside-in tracking system to the coordinate system of the reference frame of the inside-out tracking system.

These further transformations have to be calculated manually:

- $^{inst}H_{arc}$: Transformation from the coordinate system of reference frame to the coordinate system of marker tree mounted on the laser pointer. Note that the inside-out and outside-in tracking systems use the same fiducial marker set for the reference frame and create the same coordinate system for this target. The former tracks the

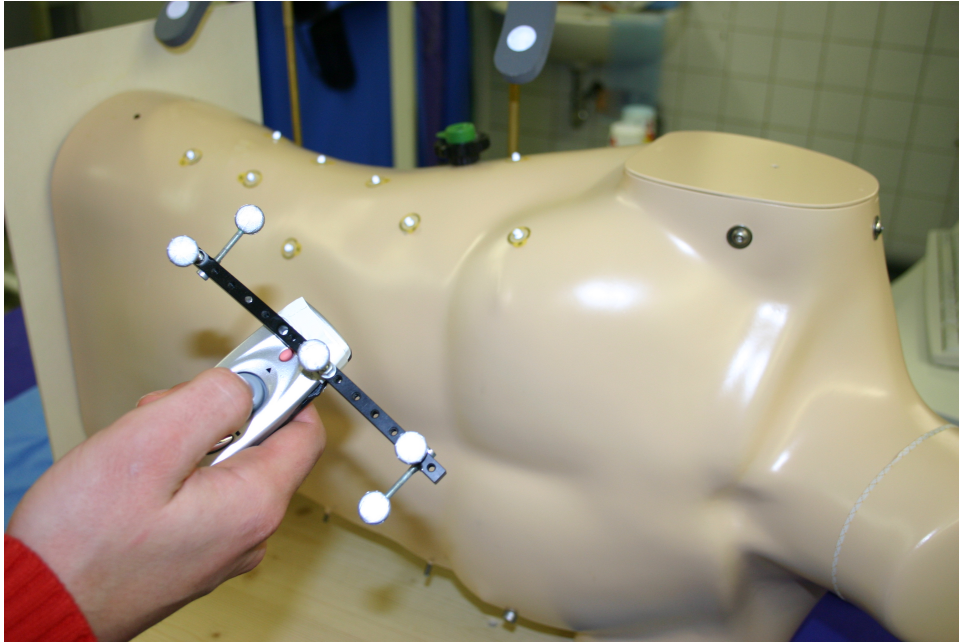


Figure 5.13.: Two targets: The remote laser pointer, which navigates the virtual mirror with a marker tree and a thorax phantom with fiducial makers attached to its surface.

frame as just another target and the latter calculates the position of the HMD from it.

$${}^{inst}H_{arc} = {}^{inst}H_{IR} * ({}^{arc}H_{IR})^{-1} \quad (5.1)$$

- ${}^{mir}H_{inst}$: A virtual extension, a cylindrical handle, is used to position intuitively the mirror into space. This enables the user to enter physical objects, e.g. human body in the medical application, and position the virtual mirror inside. ${}^{mir}H_{inst}$ includes the translation from the hand-held laser pointer to the end point of the cylindrical handle, where the virtual mirror is mounted.
- ${}^{mir}H_{arc}$: Transformation from the coordinate system of the reference frame to the mirror. This transformation results from the combination of the above transformations:

$${}^{mir}H_{arc} = {}^{mir}H_{inst} * ({}^{inst}H_{arc})^{-1} \quad (5.2)$$

- ${}^{spine}H_{arc}$: Every virtual object, which is part of the scene, has to be positioned respective the coordinate system of the reference frame of the inside-out tracking system. In this application, a set of fiducial markers is attached to the thorax phantom, which includes the spinal column model. Similar to the laser pointer that navigates the mirror, the thorax model is also tracked by the optical, outside-in tracking system. The transformation from the coordinate system of the reference frame of the inside-out tracking system to the thorax is defined as:

$${}^{spine}H_{arc} = {}^{spine}H_{IR} * ({}^{arc}H_{IR})^{-1} \quad (5.3)$$

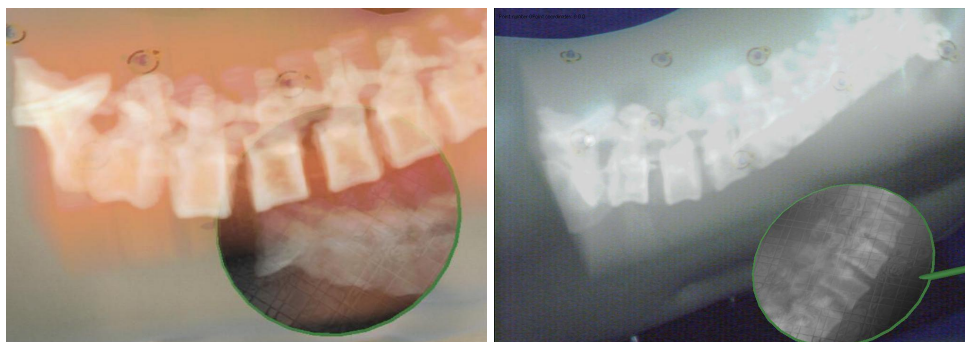


Figure 5.14.: Volume rendering with two different transfer functions. Right image shows digitally reconstructed radiographs(DRR)

Note again, that the inside-out and outside-in tracking systems use the same fiducial marker set as the reference frame.

Figure 5.16 shows a tracking diagram with all transformations required for the implementation of the mirror. Generally, there is more than only one method to implement a realistic, planar mirror in a virtual world, but each of them requires the scene to be rendered twice. One possible method works with a dynamically generated texture. Before every rendered frame the virtual camera moves to a certain position behind the mirror and takes a snapshot of the scene. The snapshot is stored to a texture and mapped onto the reflection plane. Another method takes advantage of the stencil buffer. This buffer is used to create a mask exactly where the mirror modifies the frame buffer. The mirrored scene is rendered behind this mask. After that the mirror itself is rendered as a transparent, textured bordered plane. Finally the original scene is added to the scene. There are various tutorials in the internet and in Computer Graphics books that describe implementation of a mirror. In general, realization of the mirrored scene requires that all transformations are performed contrarily respective the original scene. The following code shows the transformations to position and orientate a certain object.

- Multiply translation $(C_x^1, C_y^1, C_z^1 - ThicknessOfGlass)$ to position the mirror.
- Multiply rotations $R^1, R^2, R^3, \dots, R^n$ to orient the mirror.
- Draw Scene (This is the real one!)

The following code is necessary to mirror the position respective the Z plane.

- Multiply rotations R^n, R^{n-1}, \dots, R^1 .
- Multiply translation $(-C_x^1, -C_y^1, -C_z^1)$.
- Draw scene (This is the mirrored one!)

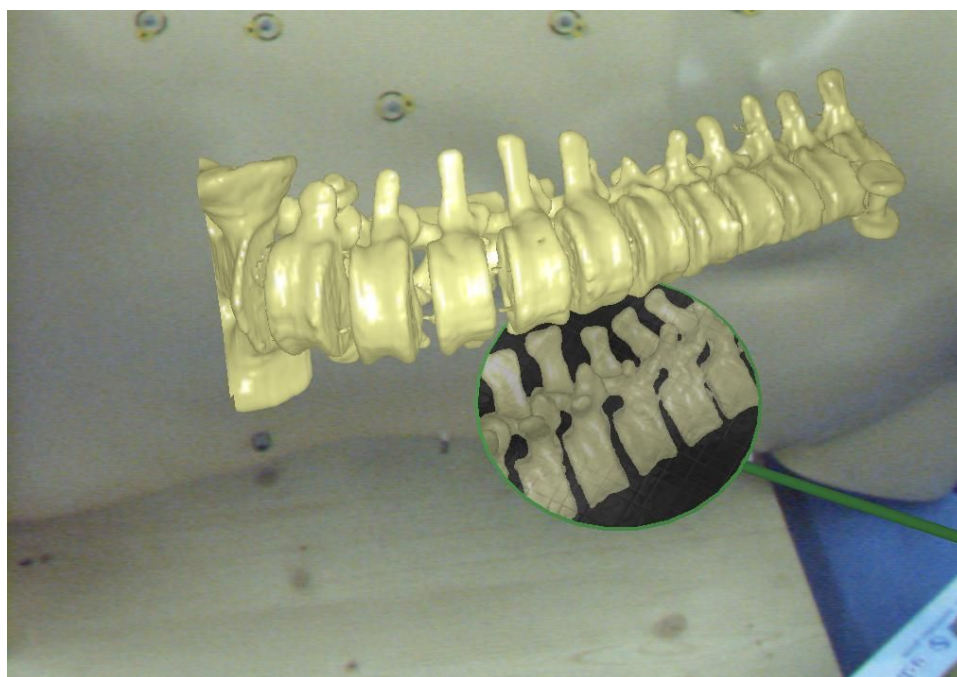


Figure 5.15.: Surface model

5.5.2. Design

The virtual mirror was developed as a tool for surgeons wearing an HMD, which allows for interaction with 3D visualization within an AR scene. While guiding the mirror through the AR scene, the observer has to be able to perceive accurately the position, dimension, orientation and boundary of the mirror. I suggest the following design features to optimize perception:

- The mirror plane is planar and provides undistorted reflection of virtuality.
- Shape of the mirror can be set to polygonal or circular. Note that simple and familiar shapes provide better cues to perceive the actual orientation of the mirror.
- The mirror plane is mapped with a simply structured texture, which also helps the perception of the orientation of the mirror [39].
- In order to make the borders of the mirror clearly visible, it is designed with a green colored, opaque, non-reflective frame.
- A virtual handle, a green virtual cylinder, connects the real hand-held pointer and the virtual mirror. This creates the impression of a navigable instrument. If the mirror was positioned directly at the real laser pointer, it could not be moved within the human body to reflect viscera and bones. Without a visible connection, the navigation of the mirror would be confusing.
- Only virtual objects can be reflected by the mirror. The mirror can be either set transparent or the background of the reflection in the mirror is colored black.

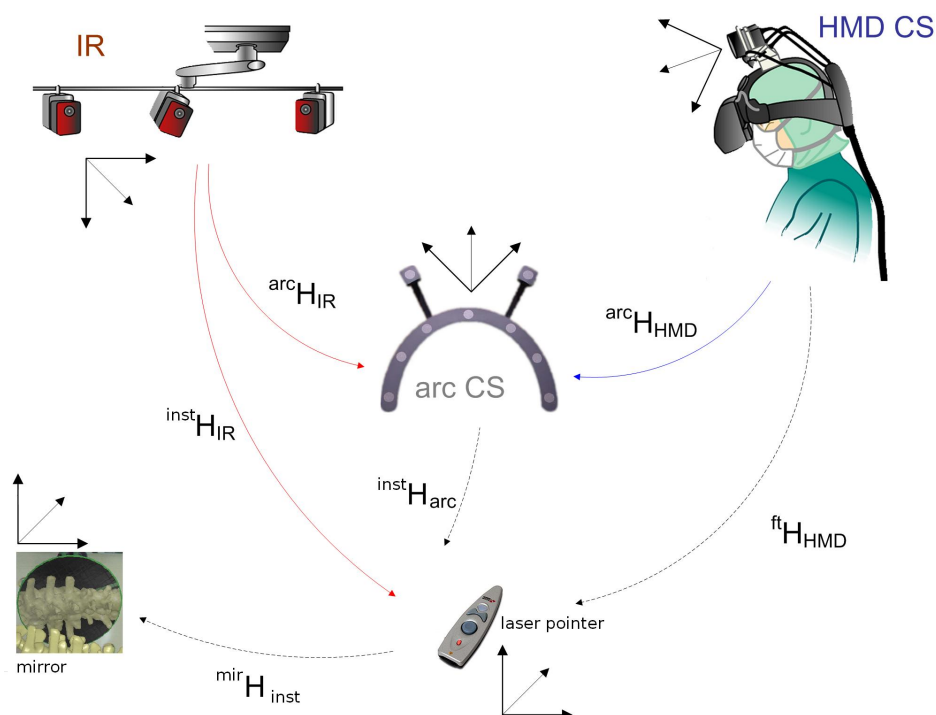


Figure 5.16.: Tracking diagram shows all transformations concerning the mirror and the coordinate systems of both tracking systems of the AR system.

- A real, conventional mirror is a glass plane of a certain thickness, which is silver plated in the back. The thickness of the transparent glass is simulated. Two parallel layers are placed 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 can be put to a certain position and interacts visually with virtual entities of the scene as a fixed object.

Some of the added effects and features are shown in figure 5.17 and 5.5.2. However, most of them are self-explanatory.

5.5.3. Perceptive Gain

After the technical description, this section initially attends the gain in information sources concerning visual and proprioceptive perception and the combination of both due to the mirror.

Development of the mirror was motivated by the creation of further depth cues within an AR scene. Up to now an observer explores a scene by moving his head with the HMD on it, in order to analyze different perspectives and to get an idea about three dimensionality and the constellation of all visible objects. Depth perception depends on the movement of the visual system, the HMD or the head. The mirror provides additional depth cues,

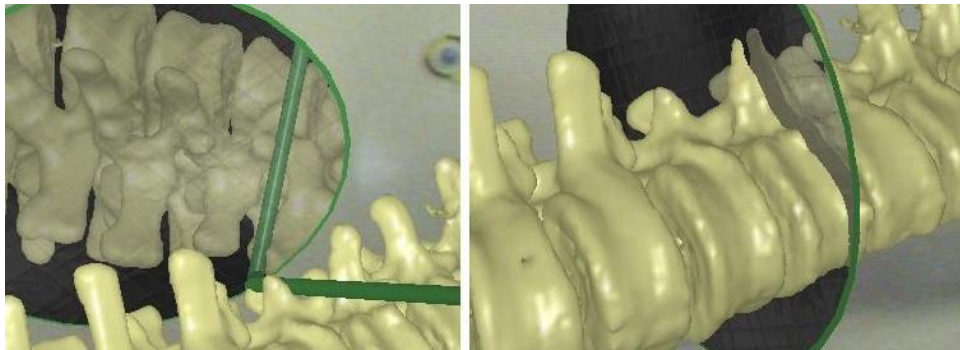


Figure 5.17.: Details of the mirror, detection of the gradient by the texture, thickness of the glass.

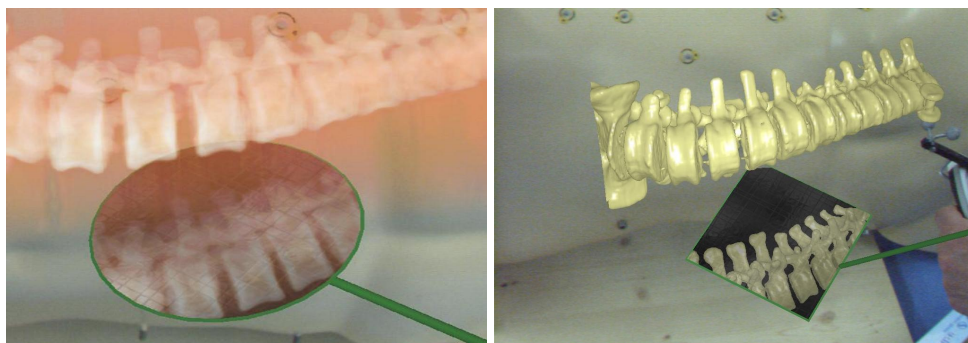


Figure 5.18.: Round and rectangular mirror

which let the observer perceive shape and the dimension of viewed objects, distances between objects and distance from his or her point of view to visible objects.

Within the space, where the mirror can be moved and positioned, interposition and motion parallax are the most powerful depth cues [8]. Because of the stereoscopic view on the AR-scene via HMD, the observer gets additionally to the both perspectives of each eye another two perspectives on the scene generated by the reflection on the mirror plane. The mirror does not only provide pictorial or monocular depth cues like a image on the wall. The projection on the mirror plane is for each eye slightly different. Figure 5.12 shows the stereoscopic view extended by the mirror.

Most of the visual depth cues are duplicated by the mirror and some of them are even intensified. For example the borders of the mirror cover and uncover areas of the reflected scene, if the observer moves his head around the fixed mirror (figure 5.19). Via proprio-

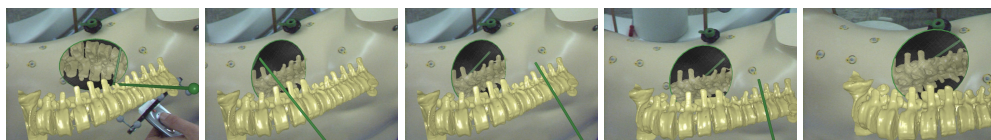


Figure 5.19.: Sequence shows the mirror that is positioned and fixed. The mirror target can be taken away and the observer moves around the fixed mirror.

ception the observer is able to palpate depth by moving the mirror within an AR-scene (figure 5.20). The user does not get haptic feedback by reaching a physical border with his hand or instrument. However, reflection of the scene on the mirror depending on motion of the observer generates a feeling about distance to and between objects.

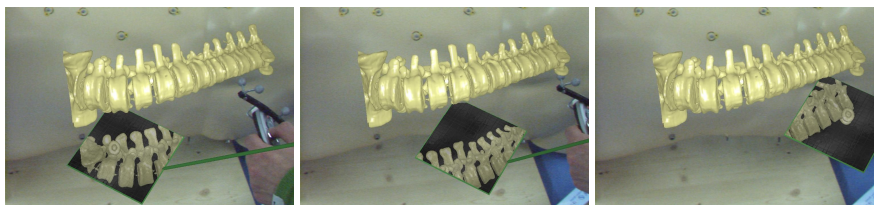


Figure 5.20.: Sequence shows the mirror that is navigated through a AR scene.

5.5.4. Practical Use

The practical aspect of an augmented mirror is to provide the observer a second, intuitive perspective on objects.

Figure 5.21 shows a typical scene in an OR. The patient lies on the operating table in the center of the room surrounded by surgeons, assistants, tables with surgical instruments on it and other devices like flourosopes, C-arm etc. . The advantages of this new interaction paradigm are listed below:

- Equipment and workflow restrict the freedom of movement of the surgeons. They can hardly change their position to get a view of an other perspective on the patient. The mirror can be fixed at a certain position and with a certain orientation and enables a second view on augmented viscera and bones also from e.g. bottom or the opposite side. Because the mirror is virtual and not positioned directly on the tracked target, freedom of movement is not constrained by physical objects like the patient's body. It can be placed as near to virtual objects as it is desired. It can also be affixed to a certain position to have both hands ready for other tasks.
- Provided that the augmentation of virtual bones and viscera is accurate, the mirror can assist navigation of surgical instruments. If the surgeon has to drill a hole into a certain vertebra to affix a fixateur, he or she can use the second perspective available due to the mirror to check the position, orientation and the correct depth of the drilling.

5.6. Light and Color Effects

This section concerns the employment of color, transparency and certain effects produced by the influence of light to achieve better representation of virtual objects within the real scene.



Figure 5.21.: Typical scene in OR.

5.6.1. Transparency

Transparency is one approach to get an intuitive view into the patient.

Like certain visualizations of volume rendered anatomy show, homogeneous areas like skin, muscles and viscera get a specific color and a transparency value by the transfer function. Bones are usually opaque. So values skin and muscles can be seen and change the color of objects like the bones behind them and create therefore perceptive information for the observer. The observer is able to get an impression about the constellation of viewed objects, even if he or she does not know anything about anatomy.

In AR this is approach cannot be realized because single real objects of the scene like the thorax cannot be displayed transparent. However, it is possible to represent the virtual spinal column as a transparent surface or via a certain transfer function with a value for transparency using volume rendering (figures 6.2, 5.14).

Regarding the stages „organization “of perception described in section 4.1.2 the human visual system perceives the position of the spinal column ambiguously. Because the transparent spinal column is completely surrounded by body and the skin behind the spinal column is also visible, the user cannot decide, which viewed object is behind or in the front as described in section 4.4.3 .

Although visual information is ambiguous this approach is an improvement.

5.6.2. Glass Effect

Glass is a common, well-known material in our everyday life. Glass is usually used to separate physically two spaces, but it is possible to view from one space to the other. Information about the other space can only be achieved visually when the glass is transparent and

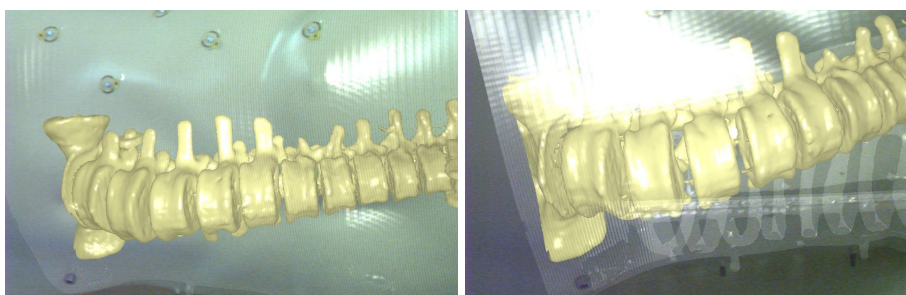


Figure 5.22.: Glass effect without viewing fragments of the skin in the background, occlusion by highlights

achromatic. Other sensory information, like feeling temperature or auditive information are normally blocked out. When we view glass, we intuitively know about its material, which is extremely smooth and hard. We also perceive and interpret light effects on its surface like highlights and reflection. Knowledge about attributes of glass was adopted to virtual objects to improve depth perception for our application.

Highlights

The skin of the thorax was augmented as a transparent, colorless surface - like glass. The virtual or real skin can be perceived at its proper position because it is directly visible. It does not suffer from the perceptive lack of AR described above like the spinal column. Within virtuality, it encloses the virtual spinal column. Highlights on the virtual skin produced by the fixed and the head-mounted virtual light source enable the depth cue interposition (section 4.2.3). At the highlighted areas, the virtual, glass skin changes degree of transparency, sometimes it gets even opaque. The skin occludes areas of the spinal column or influences its color. This effect can also be perceived, if the virtual skin and the spinal column are superimposed to the real thorax. The real skin is perceived as glass because its virtual counterpart equipped with the right material parameters. The best results can be achieved, if only these fragments of the model are displayed, which are directly visible but not those, which can be seen because of the transparency. The highlight effect is shown in figure 5.22. Usually, the skin can be extracted automatically from the thorax model and the Marching Cube Algorithm is able to generate a smooth surface. However, the skin thorax model is 0.5 cm thick, therefore this algorithm extracts two parallel layers. This leads to not desired transparency effects, which can be avoided if the skin was created from real anatomy. One of the future projects will be a cadaver experiment to test the features on a real anatomy.

Reflection

The surface of glass reflects objects, which are positioned close to it. If an observer moves his or her hands near to a glass bottle, he or she sees a reflection of the hands on the bottle as described in section 5.6.2.

This effect can be added with the so called technique *dynamic cube mapping* and was re-

alized within this thesis. This makes glass appear more realistic. In addition, it provides visual feedback for user interaction. This means, if the user moves for example an augmented, virtual instrument (section 5.4) close to the virtual glass surface, its reflection can be perceived. This enables depth perception via proprioception. The instrument is moved with arms and hands and visual feedback is generated dependent to the movement (section 4.3).

5.6.3. Shadow

Shadow cast is a well known phenomenon caused by a light source that illuminates an object (section 4.4.2). Shadow casting was implemented by an algorithm that bases on shadow mapping [45]. This technique allows the generation of shadow casts from complex objects like the virtual model of the spinal column within our application.

Light position that effects the shadow cast can be changed. Also objects like instruments, which can be moved through the AR scene by the observer influence the shadow effect. So this is another approach how visual feedback caused by interaction can contribute to depth perception and proprioception. Due to time reasons, shadow mapping was just implemented with a test scene in AR.

5.7. Additional Perceptive Approaches

Some ideas, which were partially or completely or not implemented within the scope of this thesis were evaluated as too ineffective for this application. Although they are described in the following sections.

5.7.1. Particle Engine

All particles created by a particle engine have the same attributes like size, color or texture, shape, speed, direction of motion and gravity. So they are all considered as objects of the same type. Particles are used for simulation of water or snow, flocking birds, butterflies or fishes, smoke and fire, clouds and trees and leaves of deciduous trees. Such a particle engine was implemented within the scope of this thesis.

Nearly everyone already tested the height of a bridge by spitting down into the river and waiting until he or she sees a splash or hears the impact. Knowledge about gravity and experience that all bodies fall with the same speed and acceleration the spitter can perceive somehow the height of the bridge.

Within the medical AR scene, a possible visualization could be lots of particles that move from the position of the head of the observer or another position toward the operation site, in this case a certain area of the spinal column. The moment, when the particles reach the virtual spinal column can be detected visually by the observer because the virtual spinal column let the particles temporary disappear when they collide.

This still does not solve the problem that the spinal column is perceived in front of the skin. Furthermore, the observer cannot get any intuitive information about the speed, acceleration depth of the particles except the particles fall perpendicular like the spittle into the river.

However, if a virtual, transparent skin is added to the scene, the skin changes slightly but recognizable the color of the particles before they are manipulated by the spinal column. This enables information about distance between skin and spinal column but the observer cannot detect distance between himself and the object, which is passed by abstract particles because he has no idea about the speed of particles that move in an arbitrary direction. According to Galileo Galilei all objects fall within a vacuum with the same speed. But frictional force of air slows down the velocity of fall, so we know that in our natural environment a snowflake falls slower than a stone and can estimate approximately time until these objects reach the ground. This implies that the objects move orthogonal toward the ground. Recognition of an object, if it is a snowflake or a stone, is part of the process of visual perception affiliated to the stage of „Identification and classification“ (section 4.1.2). Adoption of kinetic behavior to a certain object is an additional information taken from experience values. In fact, because of the additional abstract objects important information can be disguised.

Overall, we and also the surgeons, who tested this visualization, found that the presented medical application does not benefit from this concept.

5.7.2. Converging Lines/Relative Size

The third most powerful depth cue within the personal space of about 2 meters around the observer [8] is relative size. That means similar objects or objects considered as similar respective their shape, color or size create information for depth perception. The AR scene of this application does not contain many similar objects, which could provide information for the depth cue relative size. For this reason abstract objects, which don't have any relevance for the content of the images have to be included. For example coins are well known objects. If an observer views such a coin, he or she perceives size of it and is able to estimate distance to it. These coins can be positioned at two lines equidistantly from the two color cameras of the HMD to the operation site. These lines converge at the focus of the view directions of the camera. Because size of the coins depends on the distance to the observer, he or she can estimate depth.

Although the coins don't contribute satisfactorily for depth perception because of the same reason that was mentioned at the previous section.

First of all, the disks have to be perceived as coins. Additionally cognition of their values is important to get knowledge about the size of the coins. All this information is gained within the stage of „Identification and classification“ when the observer already adjusts misinformation about the constellation of virtual spinal column and real skin. In addition the images contain abstract objects that rather obscure than provide helpful information also for depth perception.

5.8. Extension for CAMPLib and Other Tools

While implementation of the methods presented above, some additional functions for the CAMPLib were developed and included.

5.8.1. VMRL Reader

Three dimensional surfaces can be rendered with a Marching Cube Algorithm. Experience has shown, that this approach is sufficient for opaque surfaces. If the surface is transparent like the glass skin, it does not appear smooth enough like glass is expected.

AMIRA² is a tool for advanced 3D visualization and volume modeling. We use this software to display and edit data volumes. After segmentation of the skin and generation of a surface with the functionality of AMIRA, it is possible to export the surface as different data types like a OI or VMRL model.

This model can be loaded by the VRMLReader, which was implemented within the scope of this theses. It creates an OpenGL list of the model, which can be manipulated individually by OpenGL functionality like transformations, color, material and transparency. Therefore the VRMLReader loads the vertex list, the normal list and the triangle list. The function can be used to load any model of the data type VRML. Obviously this is not the best solution to generate surface models from CT data, however, the task of this thesis was to create and test different visualizations, which could be done quickly with this approach.

5.8.2. Texture Loader

Textures are powerful design features to enrich layout of a three dimensional scene. A small method to load .bmp images of the size $2^n * 2^n$ stores images located at a certain local folder within the OpenGL context.

5.8.3. Picking

Picking is a technique to be able to get three dimensional information of a pixel on the screen. It is described in section 5.3.2.

5.8.4. PollMan

For the evaluation of different visualization methods and techniques and the virtual mirror, the online tool „PollMan“, was implemented in PHP and MySQL to create and manage online questionnaires.

- Polls can be defined by name, owner and description.
- Polls can be edited. Open and standardized questions can be added and deleted.
- Results of a polls can be shown → Up to now an average of standardized questions and a list of results of open questions.
- Polls can be chosen and started.

PollMan can be used for further online questionnaires initialized students and staff of the chair.

²Homepage: <http://www.amiravis.com/>

6. Evaluation

This chapter describes and evaluates novel visualization techniques that are designed to overcome misleading depth perception of trivially superimposed virtual images on the real view. The evaluation of the visualization methods is divided into two parts. In the first part, it is evaluated, which visualization offers the most reliable depth perception. In order to get quantitative results, the participants had to fulfill a task on a phantom and measure the accuracy of the performance and the time to fulfill the task. The second part concerns the user acceptance. The participants fill out a questionnaire regarding the usability of the system. This questionnaire has been filled out directly after the first part of the evaluation. Thus the experience with the AR system to be very present and pristine. The group of participants consists of 20 surgeons of the chair's partner hospital.

6.1. Evaluation of Depth Perception

The 20 surgeons took part at an experiment that evaluates the quality of depth perception for certain visualization techniques.

6.1.1. Setup of the Experiment

All participants had to fulfill the same task with different visualization techniques. The task consists of a pointer that has to be moved to a spot inside a body phantom. The body phantom consists of a plastic surface of a torso and a spinal cord model inside. The data model has been recorded with a CT scanner before.

During the test, each participant has to move a pointer to randomly located spots on the surface of the spine of the phantom as shown in figure 6.1. Each participant had to find twenty points for each visualization. For the tests, the model of the spine has been taken out of the body phantom in order not to get haptic feedback. The participant have to rely on their mere vision. The phantom guarantees that the participants do not have a direct view to the point of interest, which is also true for minimally invasive surgery. The participants have been asked to move the pointer to the target spot and tell if they are done. The spot has been marked with a small black point in order not to interfere with the current visualization (figure 6.1).

Each participant had two minutes time to get used to the HMD and AR visualization. After this, the participants were asked to fulfill the tasks above. The average time for the whole test was 16.4 minutes. This exceeds the expected usage time of the visualization system in the operating room. The following visualization modes have been tested in a random order in order to average out effects of learning and exhaustion. The table in figure 6.3 contains the visualizations in the same order as figure 6.2. Explanation of these follow in the order of figure 6.2. The visualization speed is denoted in brackets in frames per second.

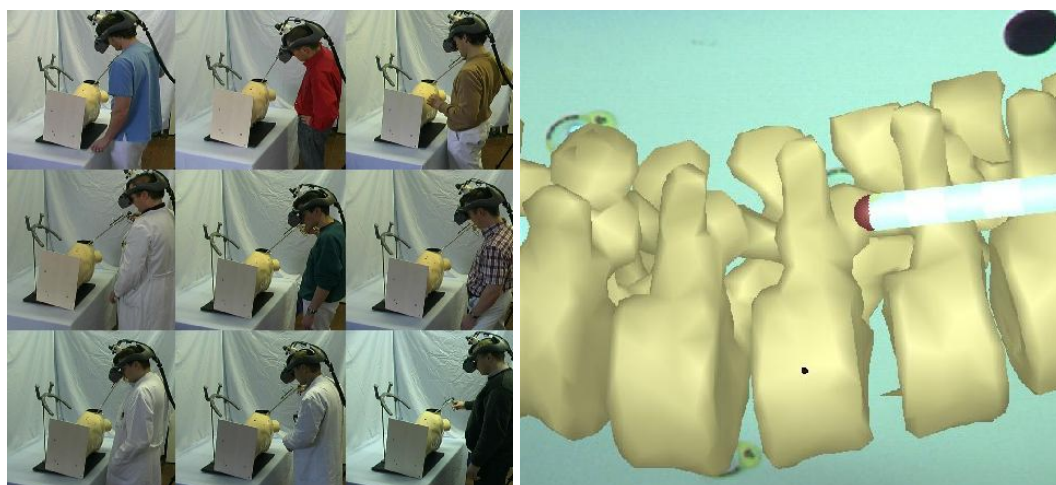


Figure 6.1.: 9 of 20 Surgeons, who were asked to touch a black spot on the surface of the virtual spinal column with the tip of the instrument.

Triangle mesh. The triangle mesh (see figure 6.2- 4) is a representation of the surface of the bone structure in the scene. The surface has been segmented from the CT scan before the evaluation. The surface is stored in the computer as a list of triangles. In this mode only the edges of the triangles are displayed. Edges in a higher distance to the viewer are displayed darker than closer ones in order to give a strong depth impression.

Surface rendering. The surface rendering (see figure 6.2- 1,2,3,6) is as the triangle mesh a representation of the surface of the bone structure in the scene. The surface has been also segmented from the CT scan. The surface is visualized with untextured, but shaded solid triangles.

Volume rendering. Volume rendering (see figure 6.2- 5,7) represents the whole volume rather than a surface. The data need not be segmented or prepared. Each voxel is rendered with a certain transparency according to its value. The transfer function that relates the value to its color and transparency has been chosen in a way that bone structure in the spine model is emphasized. The rendering is performed with the support of 3D texture hardware as suggested by Hastreiter et al. [19]

Glass effect. This effect is only applied to the surface of the skin, but not the vertebrae (see figure 6.2-6). The skin is rendered transparently and achromatically. Only reflections of a virtual light source to the skin are rendered. By this means the skin looks like glass. The idea is to provide a visual impression that the skin is in front of the bone model, since the reflections of the glass skin occlude slightly the bone model or influence its color at certain areas.

Virtual window. This effect is also only applied to the skin(see figure 6.2-3,5). In this visualization add-on we define a region on the skin, which we call the virtual window. The visualization of the bone can only be seen through the virtual window, but not outside. The window enables the effective depth cues *occlusion* and *motion parallax* because its frame occludes partially the spinal column in the background and the projections on the retina of these stationary objects move relative, which is caused by observer movement.

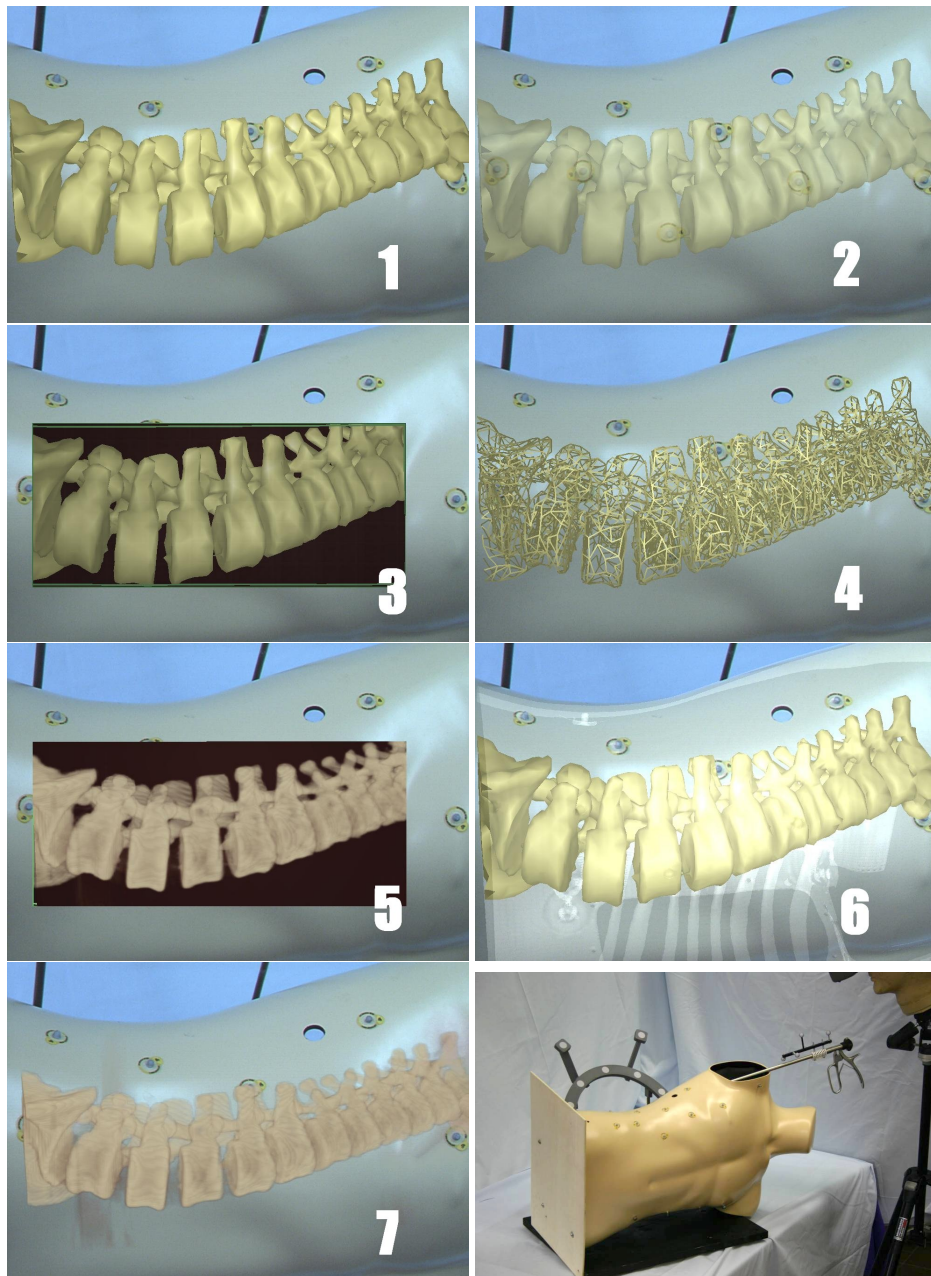


Figure 6.2.: The seven evaluated visualizations; bottom right: The setup

	Depth perception	Effectiveness	Qustionaire: Experience of Perception (1 = good, 5 = bad)	Frame-rate in our system
Surface rendering opaquely superimposed	o	+	2,2381	30 fps
Surface rendering transparently superimposed	+	+	2,5238	30 fps
Surface rendering through a virtual window in the skin	+	+	2,4762	30 fps
Triangle mesh	-	+	3,4211	30 fps
Volume rendering model through a virtual window in the skin	-	-	2,2857	9-10 fps
Surface rendering with a glass effect of the skin	-	-	2,8571	7-9 fps
Volume rendering superimposed	-	-	2,381	5-6 fps

Figure 6.3.: Table of tested visualizations including simplified results

6.1.2. Results

Overall, 2398 3D points that had to be touched in the model have been evaluated. It has to be mentioned that this evaluation is not intended to find out the accuracy of the system. Especially the exaggerated length of the pointer (64 cm) and its crude tip with a diameter of 9 mm has been designed to provoke errors due to interaction. A shorter pointer that is peaked at the end yields far more accurate results, but it would emphasize errors of the system and unwanted movements like tremor.

The volume rendering visualization proved to have a performance that can be displayed in a current PC based AR system even with a large data volume. However other kinds of volume visualizations that need prior segmentation showed a faster and more precise interaction. Even though the surgeon liked the volume rendering and reported a good perception of depth (see figure 6.3).

The triangle mesh mode did not perform as good as expected. The reason might be that the visualized model has a complex structure of many self occluding surfaces that confuse the viewer when rendered with transparent triangles.

Figure 6.4 (top right) shows the performance in the course of time. The participants were able to work with the video see-through HMD without losing performance during the whole experiment that took 16.4 minutes in the average. The graphs show no indication of exhaustion during the test. The accuracy and speed of interaction improved over the whole experiment. In the beginning of the experiment the participants trade accuracy for interaction speed. This can be interpreted as an indicator for getting used to the test and to the unfamiliar system.

Figure 6.4 (top left) shows the performance of each visualization mode. The numbers are according to figure 6.2 and 6.3. The different visualizations modes have a clear impact on the interaction precision and speed. In our experiments the frame rate seems to be an important factor for the performance. The participants complained about slow visualization modes and had slower and less precise performance using these. The graph shows the average error as well as the error splitted up into x and y and the z-plane that is parallel to the viewing direction. The fast modes using surface rendering show clear better result than the fast one using triangle mesh or the slow one using volume rendering or surface rendering. The two best visualization modes for interacting with a 3D model in medical AR are the transparent surface rendering or the one with the virtual window. It would be quite exiting to find out, if a combination of these could even improve the performance.

Figure 6.4 (bottom left) shows the performance of each individual surgeon. Comparing the graph depicting speed and the accuracy, one can see that these do not correlate with each other. That means, that the performance depends on the skills and not on the attitude of going fast or slowly.

6.2. Questionnaire

This section presents the complete questionnaire and its results. All questions were posed in German immediately after the experiment. The questionnaire was performed via a on-line interface in the same room where the experiment took place. The questionnaire includes two kinds of questions, open questions and standardized questions (figure 6.5).

6. Evaluation

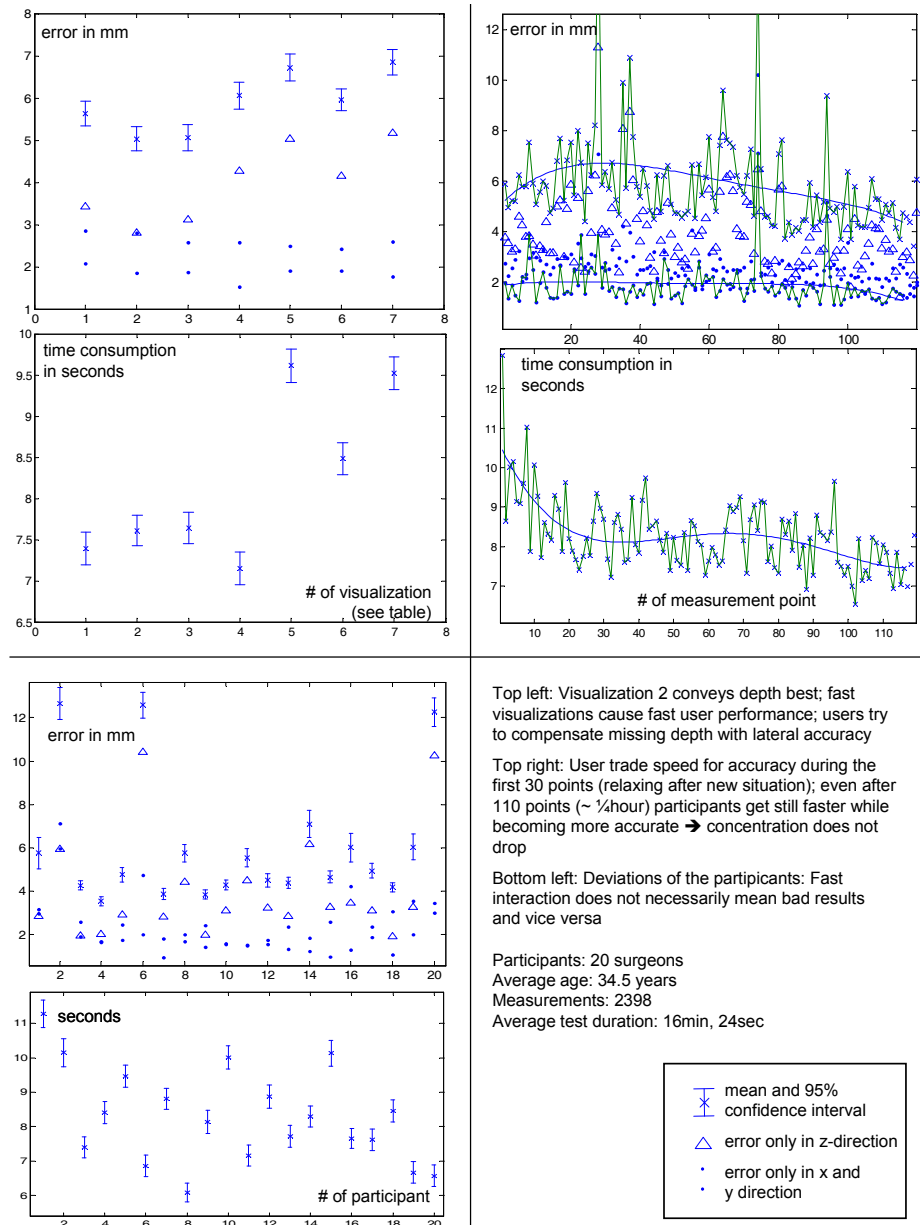


Figure 6.4.: Figures of the evaluation

The image shows two parts of a questionnaire interface. The top part is an open question section with a blue header 'Question' and the text 'In welchem Fachgebiet sind sie spezialisiert?'. Below the text is a large empty text input area and a 'Submit' button. The bottom part is a standardized question section with a blue header 'Question' and the text 'Wie bewerten Sie folgende Aussagen? (stimme sehr zu - stimme nicht zu)'. It contains seven rows of statements, each with five radio buttons for rating. The statements are: 'Ich interessiere mich für neue Technologien in meinem Berufsfeld.', 'Ich besuche regelmäßig Fortbildungen.', 'Ich versuche in Fortbildungen gelerntes bei meiner Arbeit in die Praxis umzusetzen.', 'Die Präsentation der 3D Modalitäten (CT, MRI, ...) ist verbesserungswürdig.', '-Ich setze am liebsten auf klassische Methoden während der OP.', 'Ich verwende Navigationssysteme im OP.', and 'Ich nutze privat Computer regelmäßig.'. At the bottom of this section is an 'Anfrage abschicken' button.

Figure 6.5.: Open questions and standardized questions.

Standardized questions can be evaluated from 1 (very good, I agree) to 5 (very bad, I don't agree). If the candidates did not know the names of the visualization techniques or the other unfamiliar and unknown terminology of certain questions, they were allowed to ask.

Most of the surgeons (20) of our clinical partner, specialized in many fields [see appendix .1], participated in the experiment. The average age of all candidates, 19 male and one female, was 34,47 years. The candidates had in the average 7,19 years professional experience.

Most of the candidates say that they are interested in new technology within their field of professional activity (1.2381) and they are motivated to increase their knowledge (1.9524) and adopt it for their work (1.6667). However, they still don't use navigation systems while interventions (4.1429). Surgeons agree that the presentation of 3D modalities have to be improved (2.1429) [see appendix .5].

Most of the surgeons (2.8571) already read up on the application of augmented reality in surgery, however only few of them tested this (4.2857) or a similar system (4.5000) personally before the experiment [see appendix .6].

In general, all surgeons can imagine to use the system as a useful support for their work (1.3810). They would use it while intervention for certain activities like controlling and positioning surgical instruments (1.2381), placing the ideal port (1.6190), positioning pedicles (1.2381) and keyhole surgery (1.3810)[see appendix .7].

Most of the surgeons can imagine to use in the future this system as the only source of information for visualization of medical data while their work (2.5238). However, the average value tells us that some of the surgeons won't renounce traditional visualization techniques. Anyhow, they would favorite the AR-system for certain tasks (2.1429)[see appendix .8].

The surgeons had a lot of proposals, how the system could support their work [see appendix .8].

The candidates preferred the surface model (figure 6.2) (1.7143). Second place is volume rendering (2.1429). It has to be mentioned that the layout of this visualization technique depends extremely on the choice of the right transfer function. A certain transfer function enables e.g. digitally reconstructed radiographs (DRR) or let the data appear like the surface model. The representation of the CT data by volume rendering suffers from the lack of performance and causes a frame rate that is much slower than the representation of surface models[see appendix .8]. The surgeons chose the opaque surface model of the spinal column (2.2381) as the best visualization to perceive depth correctly. This is contrary to what we expected, however, in the experiment this visualization is one of the faster methods that came in third. The best results of the experiment show the transparent surface model and the opaque surface model behind the window. However, the candidates evaluated these two methods in questionnaire to be at the fifth place (window + opaque surface model) and sixth place (transparent surface model) in contrary to the results of the experiment, even if these methods had high frame rates [see appendix .8].

All candidates liked the mirror and said that this tool can become a helpful tool in medical AR to perceive depth (2.0952), to position pedicles (1.8571) and simply to get a second perspective on the operation site, which can possibly be physically restricted [see appendix .8]. The surgeons had many proposals, how to use the mirror to support their work [see appendix .8].

7. Conclusion

This diploma thesis attacks the lack of depth perception in a present AR system for medical application. Within our AR system, virtual images used to be superimposed on real ones. The introduced medical application realizes an in-situ visualization of the spinal column with the desired accuracy and speed. However, the virtual spinal column occludes the real thorax of the patient and is therefore perceived in front of the patient and not inside. Regarding this problem, section 4 analyzes the human visual system, the stages of visual perception and in particular all kinds of depth cues that contribute to depth perception. Based on the present video see-through AR system, various approaches were implemented (section 5) and some of them were later tested and evaluated within the scope of an experiment (section 6.1). One of the main results of this thesis is a virtual window on the skin that allows for a bordered view into the human body (section 5.3). The window can be set without touching the patient. That means, if the system is used while surgery, no further instruments have to be kept abacterial, waste space or bother the surgical workflow while setting up the window. The window exhibits strong depth cues like occlusion and motion parallax that adjust the misleading perception. The window was one of the winners in the evaluation (section 6.1.2).

Another main result is the virtual mirror, which is a completely new interaction paradigm in medical AR. This device offers like a stomatoscope additional, intuitive perspectives on the operation site, which normally are physically restricted. Due to proprioception, an observer interacting with a scene is able to perceive depth. Even though the observer does not get haptic feedback, he or she gets visual feedback on the reflection plane by moving the mirror through the scene.

Finally, an evaluation of various visualization techniques were tested within an experiment in order to determine the most reasonable techniques. Some of them were already presented in earlier papers about AR in general and medical AR others were new methods developed within this diploma theses (section 6.1). with 20 surgeons of the Klinikum Innenstadt, München, Germany. Further approaches of techniques and effects like shadows and reflection that provide visual feedback while the observer is interaction with objects of a AR scene were implemented. Among other things, the development and optimization of these methods will be the topic of further projects.

7. Conclusion

8. Acknowledgments

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¹<http://www.scr.siemens.com/>

8. Acknowledgments

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A. Original Questionnaire in German

.1. In welchem Fachgebiet sind sie spezialisiert?

- 8x Chirurgie
- 7x Unfallchirurgie
- 1x Chirurgische Intensivmedizin
- 4x Viszeralchirurgie:
- 1x Endoskopische Chirurgie
- 1x Schulterchirurgie
- 2x Traumatologie
- 2x Fusschirurgie

.2. Wie alt sind Sie?

Durchschnittsalter: 34,47619047619047619047619047619.

.3. Geschlecht (m/w)

Es nahmen 19 Männer und eine Frau an der Umfrage teil.

.4. Wieviele Jahre haben sie Berufserfahrung?

Durchschnittlich hatten die Kandidaten 7,1904761904761904761904761904762 Jahre Berufserfahrung.

.5. Wie bewerten Sie folgende Aussagen?(stimme sehr zu - stimme nicht zu)

- Ich interessiere mich für neue Technologien in meinem Berufsfeld. 1.2381
- Ich besuche regelmäßig Fortbildungen. 1.9524
- Ich versuche in Fortbildungen gelerntes bei meiner Arbeit in die Praxis umzusetzen. 1.6667

- Die Präsentation der 3D Modalitäten (CT, MRI, etc.) ist verbesserungswürdig. **2.1429**
- Ich setze am liebsten auf klassische Methoden während der OP. **3.2857**
- Ich verwende Navigationssysteme im OP. **4.1429**
- Ich nutze privat Computer regelmäßig. **1.4286**

.6. Wie bewerten Sie Ihre Kenntnisse zu Augmented Reality in der Chirurgie (In- Situ- Visualisierung)?(stimme sehr zu - stimme nicht zu)

- Ich habe mich bereits über den Einsatz von Augmented Reality in der Chirurgie informiert. **2.8571**
- Ich habe dieses System vor diesem Experiment selbst ausprobiert. **4.2857**
- Ich habe ein anderes System selbst ausprobiert. **4.5000**

.7. Wie bewerten Sie die folgenden Aussagen?(stimme sehr zu - stimme nicht zu)

- Ich kann mir gut vorstellen, dass ein solches System meine Arbeit unterstützen könnte. **1.3810**
- Ich kann mir vorstellen das System zur präoperativen Analyse außerhalb des OPs einzusetzen. **1.8095**
- Ich kann mir vorstellen das System zur präoperativen Analyse innerhalb des OPs einzusetzen. **1.6190**
- Ich kann mir vorstellen das System zu bestimmten Zeitpunkten während des Eingriffs, z.B. zur Kontrolle der Position von Instrumenten bezüglich des Operationssitus, einzusetzen. **1.2381**
- Ich kann mir vorstellen das System zur Navigation von Bohrern, um z.B. Pedikelschrauben einzusetzen. **1.2381**
- Ich kann mir vorstellen das System zu Beginn einer OP einzusetzen, um den idealen Port festzulegen. **1.6190**
- Ich kann mir vorstellen das System zur Visualisierung von Instrumenten bei einem minimal invasiven Eingriff einzusetzen. **1.3810**

.8. Wie bewerten Sie die folgenden Aussagen?(stimme sehr zu - stimme nicht zu)

- Vorausgesetzt die medizinischen Daten werden an der exakt richtigen Stelle angezeigt, und dass der Tragekomfort zufriedenstellend ist, dann könnte ich mir vorstellen, die Visualisierung medizinischer Daten ausschließlich von einem solchen System zu beziehen. **2.5238**
- Ich würde für bestimmte Aufgaben eine in-situ Visualisierung einem traditionellen Navigationsinterface vorziehen. **2.1429**

Bei welcher Art von Eingriff könnten Sie sich vorstellen das System anzuwenden, um einen Arbeitsvorgang zu erleichtern? (Alle Organe und Knochen können visualisiert werden.) Results will be the topic of further work at the chair CAMPAR.

Stellen sie sich vor, dass dieses System standardmäßig in OPs genutzt wird. Probleme wie akkuraten Positionierung der CT-Daten, komfortable Benutzung des Systems sowie Unterbringung der Komponenten des System im OP sind gelöst. Wie brauchbar finden Sie die folgenden Arten der Visualisierung der Wirbelsäule?(sehr brauchbar - unbrauchbar)

- Komplettdarstellung: Volume Rendering. **2.1429**
- Komplettdarstellung: Oberflächenmodell. **1.7143**
- Einzelne frei definierbare Schichtbilder. **2.2381**
- Pseudoröntgenbilder (DRR). **2.5263**
- Orthogonale Schichtbilder. **2.3500**

Bei welcher Darstellung empfanden Sie die Wahrnehmung der Position der Wirbelsäule am besten (abgesehen davon dass sie wissen wo sie sein sollte)?(sehr gut - schlecht)

- Volume Rendering ohne Fenster. **2.2857**
- Volume Rendering mit Fenster. **2.8571**
- Undurchsichtiges Oberflächenmodell ohne Fenster. **2.2381**
- Undurchsichtiges Oberflächenmodell mit Fenster. **2.4762**
- Glashaut. **2.3810**
- Transparentes Oberflächenmodell. **2.5238**
- Gittermodell **3.4211**

Wie bewerten Sie folgende Aussagen?(stimme sehr zu - stimme nicht zu)

- Das Fenster hilft zwar die Wahrnehmung zu verbessern aber verdeckt zu viel von der Wirbelsäule. **2.7143**
- Die Festlegung der Position und der Größe des Fensters ist gut gelöst. **2.8095**
- Der Spiegel hilft die Position der Wirbelsäule besser einzuschätzen. **2.0952**
- Ich kann mir vorstellen, dass der Spiegel bei der Positionierung von Schrauben helfen kann. **1.8571**
- Ich kann mir vorstellen, den Spiegel einzusetzen, um eine erweiterte Perspektive auf den Operationssitus zu erhalten. **1.6667**
- Der Spiegel ist zwar ein interessantes Instrument, es ist jedoch zu umständlich und zeitaufwendig ihn einzusetzen. **3.8095**

Haben sie eigene Vorschläge, für welche Aufgaben man den virtuellen Spiegel einsetzen könnte? Results will be the topic of further work at the chair CAMPAR.

Was sind die größten Probleme bei der Sicht durch das HMD? (in Ordnung - sehr problematisch)

- Das Gewicht ist problematisch für dauerhafte Anwendung. 3.0000
- Das Gewicht ist problematisch für eine Anwendung von maximal 5 Minuten. 3.1905
- Die Auflösung der virtuellen Bilder. 3.1905
- Die Auflösung der realen Bilder. 3.0500
- Ein Display zwischen dem Operationssitus und dem Auge fühlt sich ungewöhnlich an. 3.0000
- Das Gesamtbild fühlt sich unnatürlich an. 3.0476