

Interoperative Guidance  
via  
Medical Augmented Reality

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Diese Erklärung ist zusammen mit der Diplomarbeit beim Aufgabensteller abzugeben.

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**Abstract**

For the NARVIS project two critical stages of minimal invasive spinal trauma surgery have been identified that can be improved with advanced visualization of imaging data. The stages port placement and pedicle screw placement require anatomical imaging data in order give the surgeon sufficient information for performing his task.

Port placement is a very early stage of the procedure that determines the access to the operation site and the course of the whole surgery. To allow the surgeon for an optimal access to the operation site we want to provide an intuitive guidance making him find adequate places of the ports.

Pedicle screw placement is one of the critical parts of the surgery since their alignment and position decides on success outcome of the surgery to stabilize the spine without harming surrounding tissue.

For both stages 3D guidance of surgical instruments can support the surgeon. The aim of the guidance can either be guiding to a certain position and orientation of the instrument or avoiding critical anatomical structure during the procedure.

The guidance will be achieved by in-situ visualization with a head mounted display (HMD) and visualization of preoperative CT data and intraoperative imaging data.





# 1 Augmented Reality

Augmented Reality (AR) is a technology emerging in many fields, such as medical applications, video games or military applications in which the users perception of the real world is augmented by additional information from a computer model [4]. Augmented Reality is part of Mixed Reality as described by the reality-virtuality continuum introduced by Milgram [14]. This continuum is split into four main sections that account for the influence of virtual generated content in the scene.

- Real Environment
- Augmented Reality – The real world scene is augmented through virtual signals/objects
- Augmented Virtuality – The virtual world is augmented by real world signals/objects
- Virtual Environment

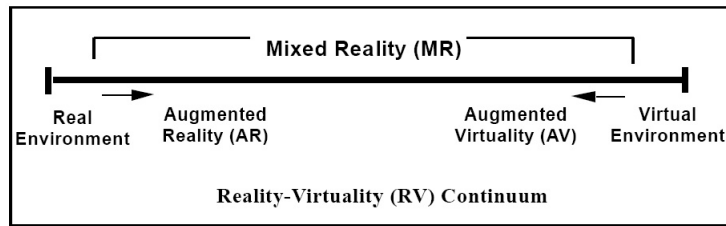


Figure 1: Simplified representation of a RV Continuum [14]

When talking about Augmented Reality in most cases only visual enhancement is meant, however virtual augmentation can be categorized in multiple sets, with the three main areas being:

- Visual – Perception is augmented through virtual models or data generated through computer models, e.g. green lines showing the run of a curve in a foggy environment.
- Audio – Additional sounds enhance the perception, e.g. a Geiger Counter making radiation perceivable
- Haptic – The users perception is amplified by giving a haptic feedback, e.g. using a glove with haptic feedback to allow the user to “feel” a virtual object

This augmentation enables the user to perceive the world very differently and may make information available that otherwise would not be accessible to the user in this manner. The emphasis in this thesis is on visual augmentation.

In order to give correct information for visual augmentation a few things are needed. In order to display virtual generated content at the intended position

tracking algorithms and sensors are needed. The process of registration is prone to errors from multiple sources [12] that have to be either eliminated or corrected as far as possible. Accurate tracking of the users viewing orientation and location are crucial for registration in AR [1]. These systems usually operate indoors because outdoor environments still pose significant challenges that yet have to be overcome. AR systems depend on real-time hardware in order to give the user augmented views for live environments.

Graphical representations can be done through head mounted displays (HMD) or projectors [4]. HMDs are separated into optical see-through and video see-through. Optical systems use mirrors and semi transparent surfaces to display the virtual content to the user while video systems shield the users eyes and use small monitors to display a composite video stream that has to be recorded through cameras and processed by a computer.

## 1.1 Medical Augmented Reality

Augmented reality in the medical field can be used in various situations, such as planning of an operation, visualizing ultra sound images and guidance during an operation. The idea of medical AR is to support physicians and surgeons during their work and if possible ease it. Visualization is the main focus in medical AR and therefor suffers from perceptual issues as described in the next section. Medical AR, just as any other medical system, also has a set of prerequisites that must be met in order to be considered for daily use in the operation room, such as:

- High accuracy – The system must offer a high accuracy, e.g. when aligning a virtual model to a real world object the position of the virtual object has to be exactly where it is expected to be and the level of detail of virtual models have to be high enough to provide realistic visualization.
- Highly reliable system – The system may not be susceptible to bad handling or external factors such as exposure to chemicals or physical force which may be found in the areas where the system is designed to be used.
- Price – Advantages of the new system must outweigh the costs of development, replacement of the old system and maintenance costs for the new system.

Meeting these criteria can only be achieved by using state-of-the-art technology and requires technologies such as segmentation and registration algorithms, high speed cameras with high resolution and broadband networking to enable visualization in real-time.

There are limits as to what objects can and should be visualized due to their physical properties. Objects that are constantly changing or are subject to changes are not suitable for augmentation because the time delays between, e.g. an MRI or CT scan and the actual visualization compared to the real object could be large enough to result in tremendous differences. This means that the feasibility of soft tissue visualization has to be decided on a case by case basis while e.g. bones generally can be visualized without much of the problems mentioned earlier. Because of the fact that patients that are not moving between the scan and visualization do not cause the bones to shift or alter positions. For

this thesis the spine is the area of interest. Since the CT scan is done during the operation where the patient is already narcotized the registration for the visualization is not that difficult, because the patient doesn't move and is not moved by the surgical staff either.

## 1.2 Perceptual Issues in Augmented Reality

The perception and understanding of 3D space is generated through various sources supplying consistent and distinct information. These sources have physical and mental backgrounds, and are categorized in depth cues [6, 19, 4, 8]. Physical sources, such as "convergence" which occurs when an object is very close to the observer and his eyes turn slightly inward, or mental, when objects "overlap", where the object blocking out the other appears to be closer for the observer. These depth cues are broken in AR through technical limitations, e.g. virtual objects not always being occluded appropriately when real world object are actually in front of them in three dimensional space.

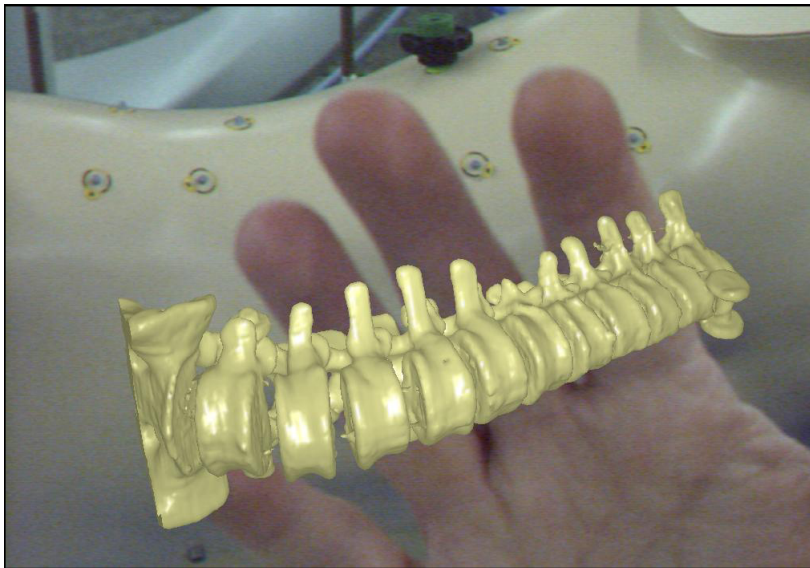


Figure 2: Visualization of a spinal column superimposed on a thorax phantom [3]

The Necker Cube is a popular example of how the brain interprets a two dimensional line drawing. The observer looking at the picture will be able to flip back and forth between two valid interpretations for the cube [8].

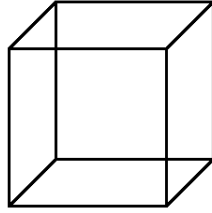


Figure 3: Necker Cube

Occlusion is another factor where the experience and knowledge show the observer which object is in front of the other in a three dimensional space. Since not all objects are occluded appropriately this information is to be used with caution in AR.

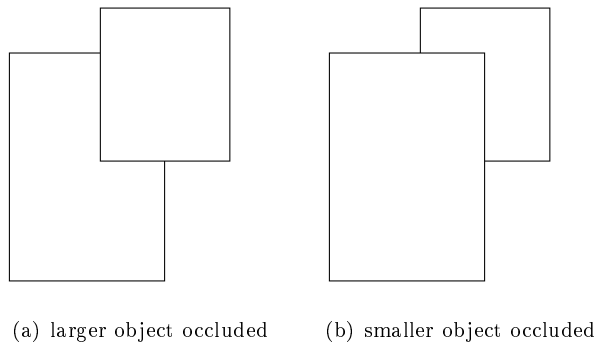


Figure 4: Occlusion

Given these factors, the loss of depth perception in AR is a problem that is currently not solved and needs aids to support the user to operate and navigate in certain situations and environments. The loss of depth perception is the major motivation for the guidance system described in this thesis. The system itself is attempting to solve the specific problems of navigating the drill into the correct position with five degrees of freedom and support the surgeon with a recommendation as to where the incisions for the drill access port are to be made.

## 2 Application: Spinal Surgery

With AR being subject to research and development in various fields, medical applications pose as one of the more interesting. This thesis takes a closer look at spinal trauma surgery with the aid of image guidance via medical AR and attempts to show a new guidance system opposed to those currently used in the operation room.

Trauma surgery is done shortly after an accident where damage of the spine occurred. This specific operation is done in order to reinforce and stabilize a damaged part of the spine and allow the patient a normal life without constant pain. Damage to the spine in this case is generally a fractured or jolted vertebrae which makes life without pain impossible and can lead to paralysis if not treated immediately.

While AR is used in many areas such as ultrasound visualization or virtual training, this thesis looks at a very specific operation that is already using the aid of image guided systems. The spine lies centrally embedded in the human body and is covered by muscles on some parts and surrounded by vital organs and pathways [16] reducing visibility of vertebrae for surgeons as well as making access difficult. Operations in this area are performed via open surgery or minimal invasive surgery.

The minimal invasive operation has two segments that are interesting for augmentation via medical AR and can benefit from it. Port placement is a stage very early in the operation where spots for the incisions are determined in order to gain optimal access to the operation site. There are restrictions to where the incisions can be made since organs and bone structures limit the access possibilities. While organs can be moved aside, bones should not be damaged or have to be dislocated as it is performed during open surgery. Later on into the surgery when access to the site has been established the second phase for augmentation becomes imminent. Pedicle screw placement requires the surgeon to drill several holes into the patients spine in order to fixate the stabilizing plate or plates. There are several systems in use for pedicle screw navigation employing computer aided navigation [15, 9]. Most systems however do not make use of medical AR for guidance.

Many of today's operation rooms are now equipped with C-arms allowing for CT navigation during surgery and also pedicle screw placement [9]. The CT data gathered from the C-arm however is also very interesting for visualization for a medical AR guidance system as described in this thesis.

The critical stage during this surgery is the placement of the pedicle screws. Current guidance systems offer reliable ways of placing the screws, but force the surgeon to focus on computer screens in the operation room for the navigation. The challenge is to place the pedicle screw in a specific position with a certain rotation in order to stay within the pedicle of the vertebra to retain its stability. Minimal shifts can damage the spinal cord or lead to instability within the vertebra causing pain and possibly fractures.

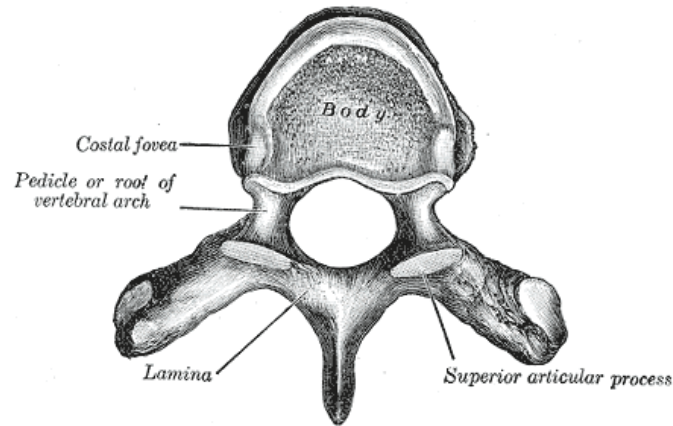


Figure 5: Anatomical view of a vertebra

adapted from Anatomy of the Human Body (online edition) <http://www.bartleby.com/107/>

## 2.1 Minimal Invasive Surgery

Beisse, et al. discovered [16] that the chronic pain syndrome showing in up to 50% of the patients is a result of profound and lasting damage caused by the access alone. In order to minimize this, minimal invasive surgery and standardized tools were developed.

Compared to open surgery, minimal invasive surgery has the major advantage of reducing recovery times and pain of patients experienced post operation [16] because of structural damage by opening access ports towards the operation site is kept minimal. Clinical studies also show a reduced risk of infection with the patients and wounds from the port incisions. Reduced recovery time is also an economic gains as it requires the patient to spend less time in the clinic as well as a faster return to a normal work life. This makes minimal invasive surgery the choice when it's applicable.

This special kind of surgery is usually performed with the help of small endoscopic cameras to allow surgeons to see what is happening inside the patient. Also embedded in the endoscope is a fiber optic that is powered through an external cold-light source that is either halogen or xenon based to allow for optimal illumination. The camera has a wide field of view to allow the surgeon to view as much area as possible in order to keep necessary camera movement to a minimum.

## 2.2 Problem statement / Motivation

Minimal Invasive Surgery however does also have its problems. The main concern in this area is the limited visibility the surgeon has due to image deformations through the camera, usually a fish eye deformation, and the area the camera can actually view. This makes hand-eye coordination extremely difficult.

Another problem is the fact that the surgeon does usually not look directly at the patient but has to closely watch the monitors with the camera video feed

and which is usually forcing the surgeon or an assistant to work with a mirrored view while not being able to directly look at the operation site.



Figure 6: Surgeons have to focus on monitors instead of the patient [18]

Accidentally injured blood vessels pose an extremely big problem, because the bleeding can only be stopped by repairing the vessels or clipping them. Should a vessel be cut or even severed the leaking blood is affecting the view very fast due to the size of the area and the amount of blood. Small areas can in the worst case be filled up instantly and force the surgeon to revert to open surgery.

Due to the fact that only a few ports are placed during minimal invasive surgery the mobility of the surgeon with the instruments is fairly limited. This goes hand in hand with the loss of tactile perception because only surgical instruments are entered through the trocars on the incisions, making it impossible for the surgeon to “feel” the structures inside.

Research in this field is ongoing and various systems were developed proposing solutions for the problem of guiding the surgeon towards a designated position [13, 5, 21, 11]. Traub, et al. attempted to compare various proposed navigation strategies and published their results in [21].

### 3 Technology

The system [17] used was originally developed by Siemens Corporate Research in Princeton USA for use in medical applications. The AR system consists of a Head-Mounted-Display (HMD) which employs video see-through technology as opposed to optical see-through. Mounted on the HMD are three cameras.

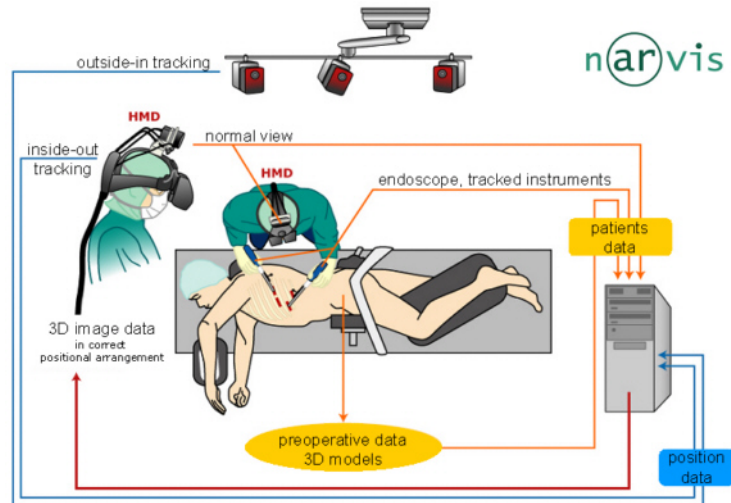


Figure 7: Overview of the system in an operation room

#### 3.1 Head-Mounted-Display

The Head-Mounted-Display is a video-see-through system that shows the user a composite of a video stream, usually a live stream, and a virtual stream containing the virtual objects that are being superimposed on the real world video stream. This composite stream is shown on two small screens before the users eyes.



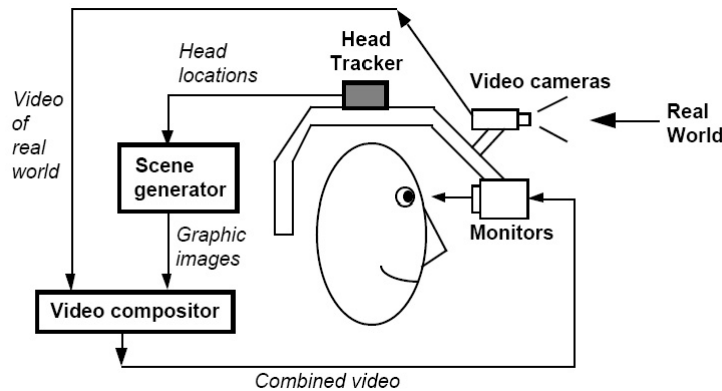


Figure 8: Video see-through HMD conceptual diagram [2]

Two of the three cameras mounted on the HMD are color cameras acting as artificial eyes for the user recording the real world. The third camera is a black and white capable of recording the infrared spectrum which is used for the tracking system. Attached to the black and white camera is also an infrared LED flash [17]. The infrared LED flash is synchronized with the tracker camera allowing for low exposure times in order to efficiently suppress background light in the cameras images. A video see-through HMD offers several advantages [2] such as:

- Flexibility in compositing strategies
- Real and virtual view delays can be matched and reduce ghost effects or video lag on the video feed shown to the user
- Additional registration strategies can be applied by using the video feed images for pattern recognition or other video/image processing appliances

Since two cameras are used a stereoscopic representation of the scene can be displayed and rendered for the virtual objects. This allows the user to regain some depth perception, meaning it becomes easier to perceive distances between objects, objects and the observer himself and additionally give information about the shape and spatial expansion of the object [3].

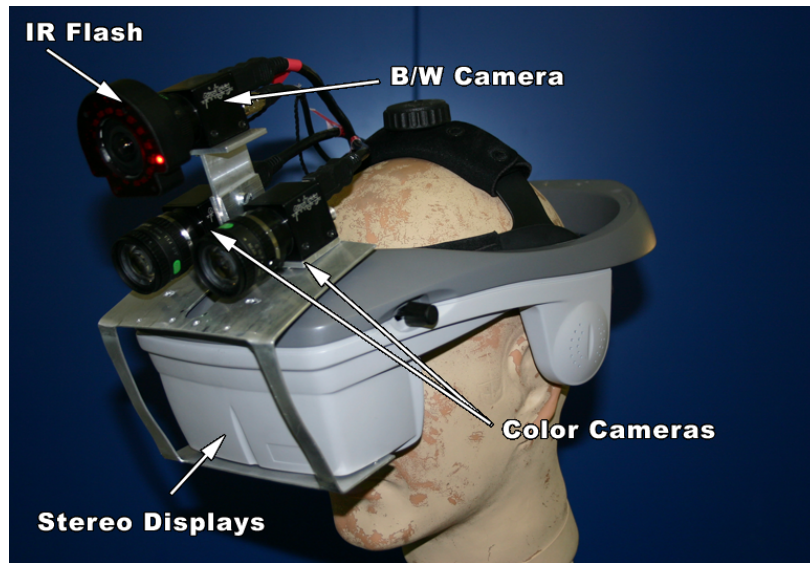


Figure 9: HMD currently in development at the NARVIS project

### 3.2 Optical Tracking System

Two optical tracking systems are used. The black and white camera mentioned earlier is used to calculate the users head position in a 6D space to align virtual objects accordingly, by utilizing single camera tracking on an arc with infrared light reflective markers.

A second system consisting of four cameras attached to a frame that look into the tracked space from different positions and are doing a so called outside-in tracking. Objects have multiple infrared reflective spherical markers attached to them in unique multiplanar setups to allow for high accuracy when determining their position and alignment within the tracking space. In order to get a relation between the tracked data from the outside cameras and the images recorded by the camera on the HMD, the arc is used as a common feature. Due to this design the tracking is very stable and allows for an accuracy of less than 1 mm [17].

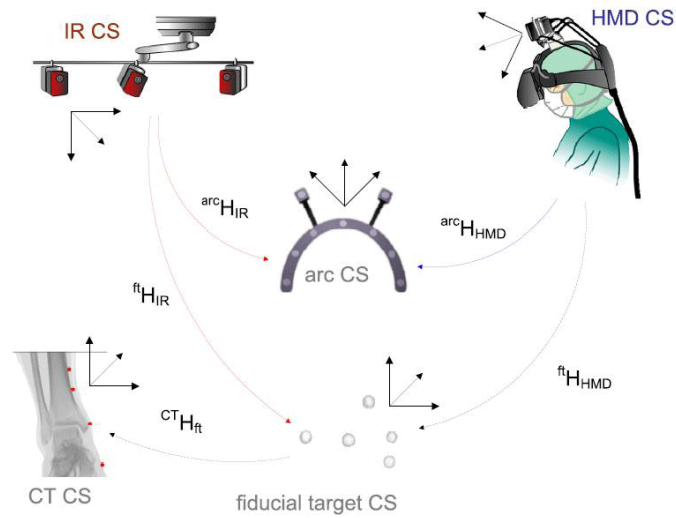


Figure 10: Tracking system overview

### 3.3 CAMPAR/CAMPLIB

The framework used for this project was being developed at the chair for Computer Aided Medical Procedures and Augmented Reality at TU München, Germany. It is the aim of the framework/library to improve quality, efficiency and safety in computer aided medical procedures for diagnosis and therapeutic procedures. This requires close collaboration between surgeons and physicians as well as computer and engineering scientists which is performed at the Klinikum rechts der Isar and Polyklinik in Munich where the chair has several laboratories and research groups. Research is currently done in the following fields:

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

The CAMPLIB library is written in C++ and offers broad spectrum functions for distinct tasks such as processing of medical images, segmentation, registration, visualization, etc. OpenGL is mainly used for the purpose of visualization where applications with a graphical user interface (GUI) are mainly written in *ftk* or *Qt*. CAMPAR is the framework specifically designed for the purpose of medical AR, with reliability, usability and interoperability, in mind [20]. The challenge for the framework's design was to find a balance between the reliability necessary for medical applications and flexibility when using the framework and the library beneath it and allow hardware vendor independent operation ability. Also supported by the framework are XML files to allow complex parameter and program changes at run time to reflect the vast flexibility offered. All external libraries used are freely available for download from their respective Internet sites.

## 4 Guidance System

The guidance system presented in this thesis attempts to offer a solution for two phases of minimal invasive spinal surgery, port placement and pedicle screw placement. The choice of where the incisions for the ports are to be made is essential for the course of the operation because it decides what areas are reachable and how well they can be accessed.

Pedicle screw placement is a critical stage of the operation because misaligning screws may cause problems for the patients later on. The screws fixate and support the plates that must be able to handle the stress of a daily life and even allow the patient to perform active sports without pain. It is vital to ensure these screws are placed at a specific angle. Misplacement may lead to fractures in the pedicle or in the worse cases may cause damage to the spinal cord resulting in disablement for the patient.

As mentioned earlier one of the main issues in AR is the loss of depth perception, which makes navigation very difficult. This thesis tries to offer a solution for the problem of guidance for the drill port incision and pedicle screw placement during spinal trauma surgery.

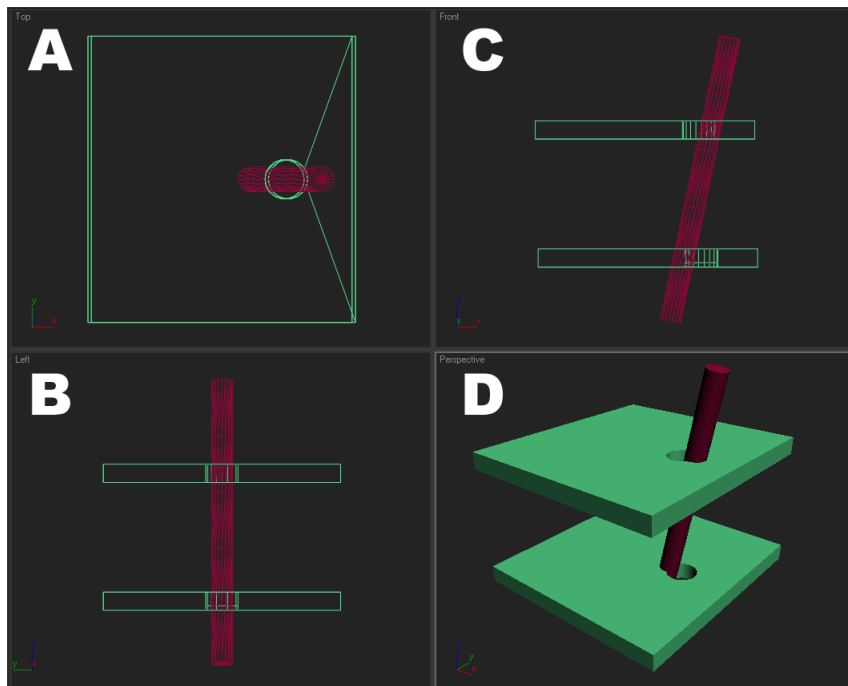


Figure 11: Placement appears to be correct in views (A) and (B) but looking at (C) and (D) reveals the holes were only barely hit

## 4.1 Navigation

Various systems using medical AR have been proposed, focusing on needle biopsy as a research subject [22, 7]. These systems employ navigation that operates with 3 degrees of freedom (DOF), which for the nature of their problem is sufficient because the entry points can be chosen at will.

Pedicle screw navigation however needs at least 5 DOF due to the fact that the screws have to be placed at specific angles within the vertebrae to ensure stability and no damage to the patient, which makes the navigation complex.

The main problem is how to balance navigation of the position and the rotation while visualizing it in a comprehensive way, yet retaining as much visibility as possible for the surgeon. The next section will attempt to present a solution on how navigation with 5 DOF can be achieved for spinal trauma surgery with the aid of medical AR by introducing virtual work planes as navigation aids.

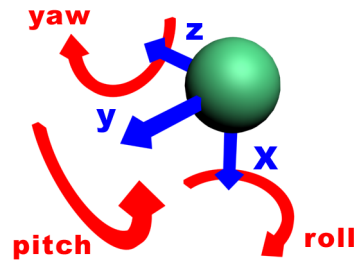


Figure 12: Rotation along local axes relative to an object

## 4.2 Design

This system attempts to connect both phases mentioned earlier through virtual placement of a pedicle screw. The idea is that in order to determine the best possible position to make the incisions, information is needed as to where and how the pedicle screw is to be fixated at the end of the operation. In order to do this the surgeon extracts the virtual spine from the patient with the press of a button. The virtual spine is a surface and volume model that needs to be generated through segmentation from on-site CT data that is created by, i.e. a fluoroscope based C-Arm [9].

When the spine is extracted it will be attached to a tool the surgeon can freely move around so that it allows for a free 6D movement. This will allow the surgeon to bring the spine into a position that makes it easy for him to place the virtual screw.

After the virtual spine is fixated the surgeon takes a tool representing a virtual pedicle screw. This screw can then be placed within the virtual spine by the aid of slice rendering to give more information about the correct positioning of the virtual pedicle screw. The slices displayed show a two dimensional perspective view of the CT data along the instrument.

After the placement has been done it is possible to release the spine again and check the screws positioning from any perspective for correct placement. If the surgeon is satisfied with the result he can put the virtual spine back into the patient. He can now operate in either port placement mode or pedicle screw placement mode.

If port placement is chosen, a small cone will mark the area on the patient where the incisions for optimal access towards the planned pedicle screw should be made. The incision point marked allows perpendicular access to the virtual

pedicle screw. In order to show these points however a surface model needs to be generated from the previously taken CT data. After the ports have been opened the surgeon can switch to pedicle screw placement mode.

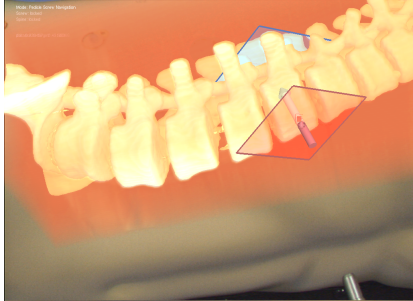


Figure 13: Volume rendering combined with a surface model displaying entry and exit planes

The idea here is to generate two planes representing an entry- and exit-plane for the drill. These planes are color marked where the red plane represents the entry-plane and the blue plane represents the exit-plane.

Both planes have small spheres at their center representing the optimal drill hole points based on information from the placement of the virtual pedicle screw. Since the blue plane is behind the spine it is brought to the front to allow easy navigation without having to step back and forth to verify the positions of the drill. In order

to position the drill the surgeon gets information as to where in the planes he would currently enter and exit should he choose to start drilling. If the drill is outside the marked plane a colored circle for each plane in its respective color coding will appear telling the surgeon that he is too far off the plane.

When the drill is within the entry and exit planes and close towards the optimal drill points the circles will disappear and the surgeon can see his current entry and exit points marked through small wire cubes. Once the spheres of the entry and exit points are within the cubes on each plane the drill is aligned in the position gathered from placement of the virtual pedicle screw.

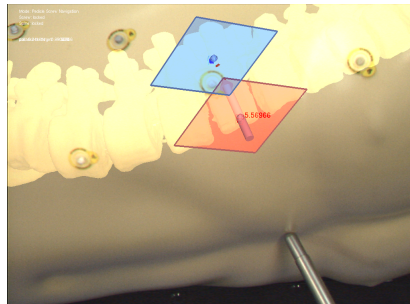


Figure 14: Drill tool aligned in the correct position

This system should allow the surgeon to focus on the patient and not be distracted by looking at monitors needed for operating other navigation systems. The attempt to connect both phases through the virtual placement of the pedicle screw is unique to this system and is currently not found in this form anywhere else.

### 4.3 Technical Aspect

Due to the design of the navigation guidance system it was clear that either collision detection or intersection detection would be required. After evaluating the coin3D intersection detection the decision was made to create a faster intersection detection system.

The idea of a collision detection system was dropped quickly due to the fact that it would be far more complex and require more computational power. Due

to the nature of the problem an intersection detection is only needed between two objects at any given time simplifying the problem even more for our case.

The idea here is to create a 2D projection of the object we want to intersect with along an axis of our second object. This projection is calculated once for every frame in order to allow for real time intersection detection. When the 2D projection of the first object is calculated, a point projection of the “tool” object is calculated. The projection position is then evaluated against all points of the 2D projection to find it’s nearest neighbors within a given threshold. Once this has been done for all points the resulting points are matched against a precomputed multimap containing relation of triangles and their points of origin. After this the tools projected point is checked to see if it’s inside a found triangle.

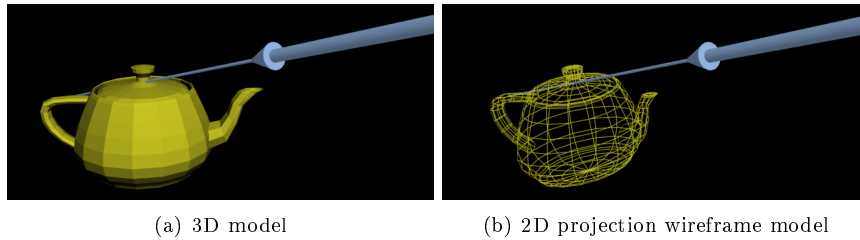


Figure 15: Projection of the teapot along the blue axis

Once a hit has been confirmed with a triangle it’s saved in a list of hit triangles. These triangles are then looked up against a list containing their original 3D coordinates to calculate the distance between the tools tip and the respective triangle. This allows the detection of the entry and exit point of the tool with the object as well as an exact distance. The time for the calculations for this is however highly dependent on the complexity of the models, especially the model that is being projected because it has to be calculated for every frame and can not be precomputed.

The models used here have approximately 5,100 points for the phantom thorax and 51,000 points for the spine. Computational time for projection of the spine is around 3 ms on a Intel CoreDuo 6600.

The virtual objects were composed in CoinDesigner and saved as OpenInventor files. CoinDesigner was chosen because it allows for rapid prototyping and has an easy to use interface to manage and modify OpenInventor files. In the OpenInventor file the items were arranged to resemble their connections and relation to each other, e.g. the spine is a sub object of the thorax model. Each model has several transformation matrices preceding each model node in the hierarchy to allow for registration and position correction transformations.

The models used where generated from previously scanned CT data that was processed in Amira where manual segmentation of the structures took place. Amira is a state-of-the-art visualization program that offers the possibility to visualize 3D image data such as CT and MRI scans as well as automatic and interactive segmentation of this data. The CT scans are layered image slices of the object. This data is also used to create volume rendering.



Another important fact is that the virtual objects needed to be registered onto the real objects. Registration is the process of correctly aligning the virtual view of an object to its real world object, e.g. correctly align a MRI brain scan to a patients head, here this was done with the surface model of the thorax and spine. This was done by using the CAMPLIB functions for automatic segmentation of markers from images and methods to calculate transformations between the previously recorded CT scan data and the tracked data from the ART system.

In order to save computational time the resulting matrix from the calculation was stored and used again. This can be done since the infra red reflective markers are fixated on the thorax and do not move from their relative positions on the thorax model even if the model itself is moved. This matrix is stored within the OpenInventor file mentioned earlier.

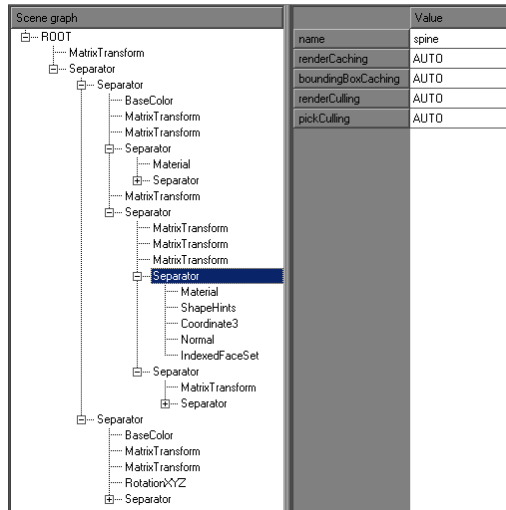


Figure 16: Expanded “spine” node in the OpenInventor file with prior matrices visible in the hierarchy

ability. This was necessary because no methods to render separate nodes or custom sub paths were implemented but required in order to work with OpenGL blending modes for various visualizations.

In order to create a relationship between the different tools tracked by the ART system, it is necessary to convert between the local coordinate systems of the separate objects. Here this can usually be done by a few matrix operations. The OpenInventor file used was created with this in mind, in order to make it possible to quickly see what matrices have to be used to get the positions in coordinates local to the relevant object.

A few core classes concerning OpenInventor file handling and rendering within the CAMPLIB had to be modified to allow for more flexibility.

#### 4.4 Rationale

Other concepts were also explored to see if there were any other methods for the guidance.

One of the systems explored was a guidance system using lines to show alignment of the drill towards a virtually positioned screw. A horizontal and vertical line would display the relative derivation of the drill from the drill axis and two additional horizons would display rotation around two axes. This concept was dropped very quickly because the number and sizes of line needed to display the information took up most space of the visible area. Also the lines were constantly moving which would confuse the operator of the system.

Another concept that was explored was a guidance system that sets up a three dimensional grid and highlights the sector the tip of the instrument is currently in and the target sector, with the grid changing its resolution as the instrument gets closer towards the final position. One of the main problems here was that even though there was a grid to visually aid depth perception there was no improvement of perception. The virtual grid might have been more effective if occlusion from real world objects would affect the grid. Also this system would need a separate display to show rotation and alignment of the drill, because the clusters highlighted within the grid would only show the position, but no rotation or derivation from the desired positioning.

## 5 Conclusion

Commercially available navigation systems as used in today's operation rooms are currently not employing the emerging technology of medical AR. These systems are restricted to pedicle screw navigation via inter operative MR or CT data displayed on computer screens, forcing the surgeon to look away from the patient and focus on the screens. None of the systems however offers guidance or aid for port placement. While Feuerstein et al. proposed a system for port placement with automatic patient registration [10] they only offer a solution for one of the two phases described earlier, again only for one of two phases that are interesting for augmentation via medical AR. With the flexibility of the NARVIS system, inter operative MR and CT data can be combined and visualized via a HMD for the purpose of medical AR.

Navigation in augmented reality is still a problem that needs to be resolved on a case by case basis depending on the requirements of the particular task. The task of navigation for the surgeon is not solved instantly by employing AR technology but requires a distinct guidance aid. Virtual work planes appear to be a suitable aid for navigation in three dimensional space via augmented reality and 5D navigation.

The navigation system proposed in this thesis employs virtual planes in order to solve the problem of 5D guidance for the particular task of pedicle screw placement. Due to the fact that planing is required for correct placement of the screws additional information is generated. This additional information enables the system to display a recommendation as to where the incisions for the ports could be placed in order to allow perpendicular access to the screws in their designated positions. No system proposed so far combines the phases of port placement and pedicle screw placement. This is a feature that is to this day unique to this system that is using state-of-the art technology for visualization.

The system in its current state is not ready for deployment in the operation room, but can be used for further research and development to improve the workflow and accuracy of pedicle screw placement.

## 6 Outlook

Work on guidance systems for augmented reality is not a closed topic. The system proposed in this thesis also needs more work and research.

Distance and derivation of the drill from the virtual model should be displayed and clearly visible at all times when in port placement mode. Currently only the distance between the virtual entry point and virtual screw are displayed. While the system is operational in its current state it still has missing features. One of the main features requested is the ability to adjust the screw by parameters once it's placed.

The system currently requires the operator to start again with the placement of the pedicle screw if the position is not satisfactory. A concept to adjust the screw here would be to manually move the entry and exit point along the surface in either a linked mode or separated mode. With the current implementation this is however not a simple task because this requires complex calculations to compute the transformation matrices for the virtual pedicle screw.

It would also be desirable to have adjustable virtual monitors floating above the patient supplying additional information about the pedicle screw placement in terms of distance to the target, current deviation and other views that might be interesting for the surgeon but not required to be displayed on the patient. Another possible view would allow the operator to virtually walk back and forth along the drill axis to see what areas might be traversed.

The navigation system might also be extended with haptic feedback to allow the operator to feel the penetration of the virtual screw with the virtual spine. Haptic feedback when operating outside the virtual mode however, is not recommended because this could easily lead to severe injuries or permanent damage to the patient.

While the visualization shows the required elements for the surgeon it might be possible to add more information that is not yet displayed, such as veins that are running across the spine and the aorta. Both could possibly be made evident via contrast agents to be clearly visible for the surgeon.

Most importantly though, this system will need to be evaluated by surgeons to gather feedback on the usability and accuracy of the system while placing the screws.

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