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Integration and Usability Evaluation of a Mechatronic Navigation System for Orthopaedic Surgery

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Contents

Abstract

We integrated a Mechanical Tracking Arm (MTA) into a navigation software for 3-D surgical navigation. The navigation software was extended to use both optical and mechanical tracking with SDC. A reachability estimation was added, that supports the user in their understanding of the MTA's physical limitations.
A user study was conducted, in which the usability of the MTA and an optical tracking system were evaluated and compared for the placement of pedicle screws. The results were that the optical system provided a better usability and the MTA's accuracy is not precise enough.
However, we see potential for the MTA to be a valid option for surgical navigation, if the accuracy. For its usability to increase, some of the provided feedback needs to be addressed. This includes an increased range of motion and an easier connection process.

Überblick

Wir haben einen mechanischen Messarm (MTA) in eine Navigationssoftware für 3D chirurgische Navigation eingebunden. Die Navigationssoftware wurde so erweitert, dass sowohl optisches Tracking, als auch der MTA, über SDC genutzt werden können. Zusätzlich wurden Funktionen hinzugefügt, die dem Nutzer eine Einschätzung der räumlichen Grenzen des MTAs ermöglichen.
In einer Nutzerstudie wurde die Usability des MTAs mit der eines optischen Trackingsystems für die Platzierung von Pedikelschrauben geprüft und verglichen. Hier haben wir herausgefunden, dass die Usability des optischen Systems der des MTAs überlegen ist. Außerdem hat sich herausgestellt, dass der MTA noch nicht genau genug ist.
Insgesamt kommen wir zu dem Schluss, dass das Konzept des MTAs Potenzial für das navigierte Platzieren von Pedikelschrauben hat, wenn die Genauigkeit verbessert wird. Um die Usability zu erhöhen, sollten unter anderem die Freiheit der Gelenke erhöht und der Verbindungsprozess vereinfacht werden.

Acknowledgments

I would like to thank Noah Wickel and Sarah Sahabi for their kind guidance as supervisors during this thesis.

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Furthermore, I would like to thank all of the participants of the user study for their time.

Chapter 1

Introduction

According to Deyo et al. [2004], Rajaee et al. [2012] and Phillips et al. [2020], the placement of pedicle screws is a fairly common treatment for various spinal diseases and injuries, like scoliosis, fractures, and the repercussions of tumors and infections. While this surgery has historically been done in an open fashion, recent advancements in technology allow for a minimally invasive approach. According to Phillips et al. [2020], minimally invasive placement of pedicle screws requires some form of surgical navigation. This can either be done the more traditional way, by using 2-D fluoroscopy to estimate the position of a tool with the help of multiple X-ray scans, or with the newer approach of 3-D surgical navigation, which simplifies the workflow and allows for higher precision.

Minimally invasive surgeries for pedicle screw placement require some form of navigation.

Multiple technologies for 3-D navigation exist and are common in different medical fields. According to Mehta et al. [2018], electromagnetic tracking, in which a tool is tracked using slight differences in a magnetic field, is useful for bronchoscopy, as it does not require a line of sight. However, according to Wagner et al. [2002] it cannot be used in the proximity of ferromagnetic tools or other magnetic objects, as these influence its accuracy.
For these reasons, Phillips et al. [2020] use the more common optical tracking for the placement of pedicle screws. While optical tracking offers great accuracy and flexibility,

3-D surgical navigation can be achieved with different technologies. The most common method is optical tracking.

Glossop [2009] see its main problem in its dependence on a clear line-of-sight between the camera and the tracked tool.

The mediTec proposes the MTA as a solution to the line-of-sight problem. It is a small, lightweight, wireless tracking arm.

This is where the Mechanical Tracking Arm (MTA), a novel tracking solution designed by the mediTec, steps in. Its goal is to deliver constant tracking in situations where optical tracking would suffer from interruptions due to the line of sight problem. Furthermore, it differentiates itself from other mechanical tracking systems, like the ones designed by Hayashi et al. [1998] and Watanabe et al. [1987], by being smaller, lighter, and wireless, which allows the MTA to be mounted closer to the working area and directly on the patient. This is intended to reduce the cumbersomeness of older mechanical tracking solutions and accelerate its registration process.

This thesis integrated the MTA into a navigation software and designed its workflow for the use in pedicle screw placement surgeries. A user study was performed to evaluate its usability.

During this thesis, we integrated the MTA into an existing navigation software, designed two methods that should help users understand where the MTA's limitations are, and wrote the code required for the MTA to work.
The MTA's workflow in the use-case of pedicle screw placement was explored, defined, and then tested in a user study. The user study revealed, that participants rated the MTA's usability lower than that of an optical tracking system. However, the MTA's usability rating was not much lower than that of the optical tracking, and we see potential to further improve its usability. The direction of improvement can be derived from insights gained during the user study. Lastly, we came to the conclusion that the MTA is currently not accurate enough. This is the case for various reasons, but the most prevalent reason is the inaccuracy of the used magnetic encoders.

Chapter 2

Background Knowledge

2.1 Pedicle Screws for Spinal Fusion

Spinal fusion is a process in which two or more vertebrae are joined together. This hinders any relative movement between these. According to Deyo et al. [2004], Rajaee et al. [2012] and Phillips et al. [2020] indications for spinal fusion include scoliosis, tuberculosis, fractures, spinal degenerative disorders, spinal disk disorders, tumors, and infections.

One common method of spinal fusion is the insertion of pedicle screws. In this method screws are inserted into each vertebra that needs to be fixated. Specifically, the screws go through the pedicle into the vertebral body. These screws are then connected by a metal rod, that locks the position of the vertebrae relative to each other. An image of the resulting construction can be seen in Figure 2.1.

Spinal fusion involves fixing multiple vertebrae together. This can be done to combat a variety of spinal problems. One common method for this are pedicle screws, which are screws, that go into the vertebrae and are then connected via a metal rod.

This surgery can be done as an open surgery or as a percutaneous surgery, but according to Kim et al. [2005] the percutaneous method causes less muscle damage and blood loss. For this reason, percutaneous methods have become standard techniques. However, as pedicels are relatively small, threading a screw through them is no easy task. For this reason, surgeons use some method of navigation in order to gain the necessary precision. Phillips et al. [2020] explain two navigation approaches for percutaneous pedi-

Percutaneous pedicle screw surgeries require some form of navigation to achieve a higher precision. The exact process surgeons use to place pedicle screws varies, but a few common steps can be identified.

cle screw placement, using 2-D fluoroscopy for guidance and using a 3-D navigation system, which are further explained in section 2.2.1. In this thesis the focus is on percutaneous pedicle screw placement using 3-D navigation, which can be accomplished with a multitude of slightly different procedures. Phillips et al. [2020] for example, use a navigated Jamshidi needle to create a hole in the pedicle, while a surgeon of the RWTH Aachen University Hospital interviewed during this thesis uses a drill. Furthermore, the interviewee confirmed that most hospitals and surgeons have their own procedures that differ slightly in some aspects. However, most of these methods have the following steps in common:

1. Determine an optimal incision point, that makes the pedicle easy to reach, by using navigation outside of the skin.
2. Make the incision using a scalpel.
3. Use a needle, a drill, or another tool capable of puncturing bone to create a hole in the pedicle. For an increased precision, this is done using navigation.
4. Insert an unnavigated Kirschner-wire into that hole.
5. Thread a cannulated pedicle screw over that Kirschner-wire without navigation.

Once all screws are placed, the metal rod is threaded through their heads in order to fix their relative position.

2.2 3-D Surgical Navigation

3-D surgical navigation, is a process in which the position and orientation of a tool is tracked in real-time. This information is then displayed relative to a previously recorded 3-D image of a patient.

3-D surgical navigation is a method in which the position of a surgical tool is tracked. This position is then shown to the surgeon on a screen in relation to a 3-D image of the patient, which is acquired prior. According to Phillips et al. [2020], this method gives surgeons access to views during surgery that are not accessible using classical 2-D

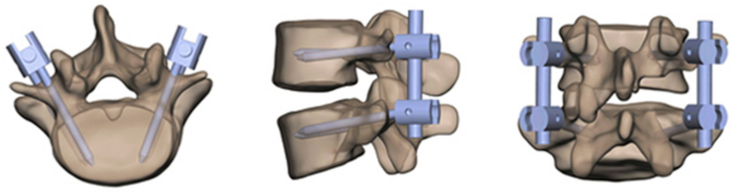

Figure 2.1: This image shows one possible arrangement in which pedicle screws can be inserted through the pedicle. The two images on the right additionally show the rods, which are used to connect multiple screws together. This figure was derived from Yang et al. [2023].

fluoroscopic imaging. Furthermore, it increases the accuracy of specific percutaneous surgeries, as shown by Kosmopoulos and Schizas [2007].

There are different techniques of tracking tools, which all come with advantages and disadvantages. Electromagnetic tracking can be used in situations where the tool is not rigid or completely inside of the patient. This makes it, for example, useful for bronchoscopy, as stated by Mehta et al. [2018]. However, Wagner et al. [2002] come to the conclusion that larger ferromagnetic tools or other magnetic objects may reduce the accuracy of electromagnetic tracking, limiting its use-cases. Other methods include the widely used optical tracking, discussed in Section 2.2.1, and the so far rarely used mechanical tracking, discussed in Section 2.2.2.

Multiple tracking methods exist, these include electro magnetic tracking, optical tracking and mechanical tracking. However, all of these methods have advantages and disadvantages.

2.2.1 Optical Tracking

Optical tracking typically works with two cameras, that point to the same position. A specific object can then be recognized on both camera images. Based on the position within these images, the position of the object in the space relative to the camera can be triangulated. By also tracking a reference position that is fixed to the patient, a relative position of the object with regard to the patient can be de-

In optical tracking two cameras are used to triangulate the position of objects.

termined. The specific camera setups and tracked object can differ between different optical tracking techniques.

Optical tracking can be performed with multiple different techniques. The most common techniques are based on passive reflective markers.

Multiple different techniques of optical tracking exist. One technique, described by Ma et al. [2020] and Li et al. [2021], is markerless navigation, which relies on the recognition of anatomic landmarks or the shape of tools.
The more common tracking techniques use markers, which are specifically designed to be easily recognizable on a camera image. These markers are then attached to the patient and tools. Methods with markers can be differentiated into two categories. On the one hand, there are active methods, which use light-emitting markers that can be recognized on the camera image, as, for example, described by Yang et al. [2012].
On the other hand, there are passive methods. These include methods where QR-code-like markers on patients and tools are tracked, as proposed by Xie et al. [2023], which have the advantage that they do not significantly alter the shape of tools and also don't need any additional surgical procedures to attach markers to the patient. However, this method is currently significantly less accurate than the more common passive reflective methods. These are based on small infrared light-reflecting spheres, as introduced by Klimek et al. [1999]. This method is widely used and therefore chosen as the baseline during this thesis.

Passive reflective methods are based on light reflecting spheres, which are arranged in groups to form arrays.

In these passive reflective methods, each object that is tracked has an array of reflective markers attached to it. These arrays enable the tracking system to calculate not only the position of the object, but also its orientation. Furthermore, each tool uses a slightly different array, such that based on the relative positions of markers to each other, the specific object can be identified. An example of such arrays can be seen in Figure 2.2.

According to Glossop [2009] the main drawback of any optical tracking system is the required line-of-sight. If an object comes in between an array and the camera, and occludes too many markers, the array's pose can no longer be calculated. This problem also occurs if the array is rotated away from the camera, in such a way that it blocks line-of-

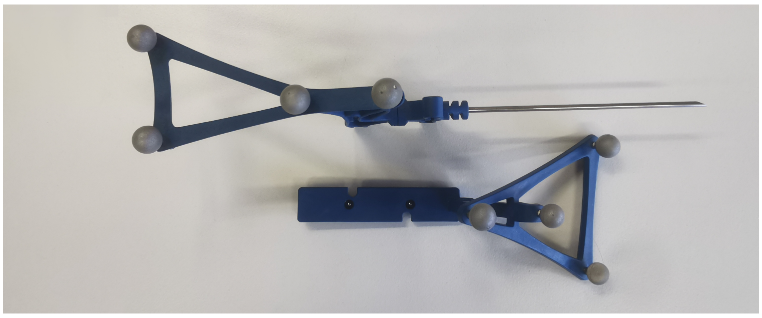

Figure 2.2: This figure shows two marker arrays used for passive reflective optical tracking. The top one is a marker array that is permanently fixed to a tool and the bottom one is a reference marker that is used to track patients. These two arrays have different marker configurations, which allows the optical system to distinguish them. Both arrays are models made by Surgivisio.

sight to its own markers. Depending on what caused this problem, the camera or the array need to be repositioned in order to regain tracking.

Solving the line-of-sight problem is an ongoing research topic, that is further explored in Chapter 3.2.

Glossop [2009] mentions another problem of passive reflective optical tracking, which is its space usage on the tool. As a marker array needs to be attached to each tracked tool, this makes them bigger and less easy to wield. Furthermore, the camera itself may also use up valuable space in the vicinity of the operating table, depending on the way the tracking camera is setup. This is something that was mentioned by a surgeon we interviewed during this thesis.

The main drawback of optical tracking systems is their reliance on line-of-sight. Additionally, the space usage of the marker arrays and the camera can be considered as a problem.

2.2.2 Mechanical Tracking

Mechanical tracking for image-guided surgery has a long history. One of the first uses was by Brown [1979]. They created a stereotactic head frame, which could be used to track the position of a tool during brain surgery. However, its rigid design, meant that it had a limited number of use cases. Mechanical tracking became more flexible with the first frameless system by Watanabe et al. [1987]. This system used a mechanical tracking arm with six degrees of freedom, which measured the angles in each joint using potentiometers. It achieved a reported accuracy of $5mm$. Hayashi et al. [1998] used a mechanical tracking arm with an accuracy of $2.9mm$ in the late 90s, and while further mechanical tracking arms, with better accuracy, were developed since then, their use in the surgical field was, according to Smith et al. [2025], overshadowed by the rise of optical tracking, mainly because, when compared to optical tracking, they were cumbersome to use. Additionally, as shown by Zhang et al. [2019], optical tracking systems are capable of tracking multiple tools at once, something common mechanical systems can not, which is another reason, why optical tracking is the currently more prevalent technique.

2.3 Service-oriented Device Connectivity (SDC)

SDC encompasses a family of standards, that define a manufacturer independent communication protocol for medical devices. Providers can offer metrics and operations to consumers. The standard defines certain units, use-cases and risk levels for metrics.

Service-oriented Device Connectivity (SDC), is a standard family made up of the core standards 11073-20701 [2020], 11073-20702 [2017] and 11073-10207 [2024]. Its purpose is to enable manufacturer-independent intercommunication between medical devices. SDC is based on a provider-consumer architecture. This means one medical device can host a provider, which publishes certain metrics and offers certain operations, while another medical device can host a consumer, which subscribes to the metrics of the provider or triggers one of their operations. In order to communicate to the medical devices in the network, what a provider offers, it publishes a model representation of itself, which describes all of its features. This description is standardized and consists of metrics and operations with predefined uses, units, and levels of risk.

To facilitate exchangeability between devices of the same category, SDC defines device profiles.

While this allows for communication between multiple medical devices, the SDC family of standards aims to do more. Medical devices of the same category, should be interchangeable inside of a system made up of multiple medical devices. For example, if a patient monitor uses SDC to communicate to a respirator, it should need no additional configuration, if the respirator is replaced for one of a different brand. This is achieved with standardized device profiles, that define which metrics and operations a device of a certain category needs to offer. These device profiles are defined in additional standards.

Chapter 3

Related Work

3.1 Surgical Navigation with SDC

A device profile for surgical navigation systems is still missing in the SDC standard. Before it can be developed, matrices need to be supported as metric type.

As described in Chapter 2.3, the SDC family of standards describes device profiles for different types of medical devices. However, currently these do not cover all types of devices, and devices for 3-D surgical navigation fall under this category.

Wickel et al. [2023], explore the requirements of a device profile for controlling a surgical arm, which also includes a device profile for surgical navigation systems. One problem this device profile is facing, is that it cannot be properly implemented, because the current specifications of SDC do not support matrices as metric types. These are vitally important for transmitting transformations, which describe a tool's pose. Current workarounds include implementing matrices as strings.

3.2 Solving the Line-of-Sight Problem

Solving the line-of-sight problem has been a research focus. One study tried to automatically readjust the cameras position.

Solutions to the line-of-sight problem, as described in Chapter 2.2.1, have been a focus in the research field of surgical navigation for years.

Schaller et al. [2011] tried to solve the line-of-sight problem, by automatically adjusting the camera position with a robot arm. While this improved the uptime of navigation, it did not completely remove the line-of-sight issue.

Multiple researchers attempted to solve the problem, by using more cameras. While this does help, it does not fully solve the problem.

A common attempt at solving the problem, which was also tested by Chen et al. [2025] and Pfeiffer et al. [2016], is the usage of an increased number of cameras. The intention is that when one camera's line-of-sight is blocked, another might have a clear view of a marker. Additionally, multiple cameras can be used to increase the working area, in which tools are tracked. However, this approach comes with an increased camera footprint, that takes up valuable space in the vicinity of the operating table. Both of these approaches improved the uptime of navigation, but do not guarantee an uptime of 100% because, depending on the situation, all cameras can be blocked. Nevertheless, according to Chen et al. [2025], multi-camera setups are already in use during real surgeries.

Using optical tracking to calibrate a magnetic tracking system, which then takes over navigation, when the camera loses sight, is another approach. It however, did not reach the same accuracy as optical tracking.

Birkfellner et al. [2002] proposed a combination of electromagnetic tracking and optical tracking. They use optical tracking to calibrate the electromagnetic tracking prior to the surgery. This is in an attempt to remove errors introduced by metallic or magnetic objects in the surrounding area. When the optical tracking loses sight of the markers, the position calculated by the electromagnetic tracking is used to bridge the time until a line-of-sight is reestablished. While this approach removed the line-of-sight problem, the electromagnetic tracking calibration could not fully compensate for the errors that were introduced, which meant the accuracy of the magnetic tracking was lower than that of an optical tracking system.

Another approach to solve the issue is the MTA, which is described in Chapter 3.3.

3.3 Mechanical Tracking Arm - MTA

This chapter gives an introduction to the Mechanical Tracking Arm (MTA), which is required to understand the capa-

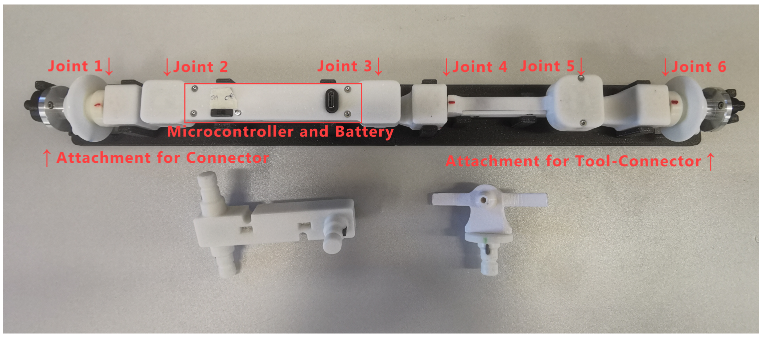

Figure 3.1: This image shows the MTA in the calibration rig at the top. The rig positions all joints in their predefined origin. For the first and the last joint additional calibration volumes can be seen, which are required to keep the MTA in the correct position. The bottom left shows the connector used for connecting the MTA to the Dynamic Reference Base (DRB). It has three connection points and can be rotated by 180° to provide three additional connection points. In the bottom right, this image shows the tool connector, which is attached to the MTA, so that tools can be slid through it.

bilities and limitations of the MTA and why certain decisions were made during this thesis.

The MTA, is a novel mechanical navigation system that can calculate its pose based on the measurements of magnetic encoders in all of its joints. An image of it can be seen in Figure 3.1. It is an ongoing research project at mediTec, which is why its concept and mechanical prototype have been designed and manufactured separately to this thesis. The goal of the MTA is to offer an alternative to the commonly used optical tracking systems. The main drawbacks of optical tracking are its required line-of-sight between the camera and the markers, as well as the space usage of the camera in the vicinity of the operating table. The MTA is an attempt at solving both of these issues. Instead of with cameras and markers, surgical tools can be tracked using the MTA, a small, lightweight wireless measurement arm. These attributes are what differentiate the MTA from existing mechanical tracking methods, as they are introduced in Chapter 2.2.2. They allow the MTA to be mounted directly

The MTA is a small, wireless, lightweight measurement arm, that can be connected between a patient and a tool, to determine the tool's position. It was designed as an alternative to optical tracking systems.

on the patient, in close proximity to the working area, with the intent to reduce the obstruction that it poses to the surgeon. This further alleviates the step of manually registering the patient's position relative to the arm's basis, as the arm is connected to a predefined position on the patient.

3.3.1 Mechanical Design

The MTA has six joints, which can not fully rotate. It therefor has 6 degrees of freedom with some limitations.

The MTA consists of seven segments that are connected by six joints. Joints one, four, and six rotate along the MTA's roll axis, while joints two, three, and five rotate along the MTA's yaw axis. Together these joints allow for movement with six degrees of freedom. However, the movement of these joints is limited to a rotation from $-137.5°$ to $137.5°$, because there are cables running through each joint. Further limitations stem from its length of $37.5cm$ and the fact, that the MTA may be blocked by objects in the vicinity or by parts of itself.
The prototype of the MTA used throughout this thesis was 3-D printed from plastic, but the final version is supposed to be out of aluminum.

The MTA has two adapters, which can be used to connect it to other objects. These adapters can only be connected in one orientation.

At both ends of the MTA are female adapters; these allow the connection to a male adapter, which is either mounted to a tool or a reference point at the patient. The male adapter has a metal pin, which can be best seen on the tool connector on the lower right side of Figure 3.1. The female adapter has a slit in which this pin can slide, which allows these adapters to only connect in one specific orientation. Furthermore, the female adapter has a spring-loaded mechanism, which can be pulled back to allow connecting or disconnecting the adapters. If the mechanism is not pulled back, the adapters stay locked together.

3.3.2 Electrical Design

In order to determine the angles of all joints in the MTA, the electrical system contains six magnetic encoders, of the model AMS_AS5038B[1]. These sense a magnetic field generated by a permanent magnet that sits on the opposing side of the joint. If the joint is rotated, the magnetic field rotates relative to the encoder, which translates this change to a rotation information.

The MTA contains six magnetic encoders which are connected to a microcontroller via I2C. The microcontroller has a WiFi module and an integrated battery management system.

This rotation information is transmitted using Inter-Integrated Circuit (I2C), a serial data bus designed for communication between two or more integrated circuits. I2C requires a total of two data lines, and the magnetic encoders require two additional power lines. This means four cables need to fit through each joint.

The recipient of the rotation information is an ESP32_S3[2], a microcontroller that comes with a WiFi module and a battery management system. This microcontroller runs the code required to receive the angle data and transmit them further via WiFi. It is powered with a small battery. Both of these components sit inside of the third segment of the MTA, which is marked in Figure 3.1.

3.4 Similar Research

Another mechanical tracking arm, with a similar approach to the MTA, has recently been published.

During the writing of this thesis, Smith et al. [2025] proposed a similar approach. They also designed a small, wireless mechanical tracking arm, that calculates its pose based on angular encoders in its joints. Furthermore, it is designed to be mounted directly on the patient to simplify the registration step, just like the MTA. Their design, however, was made for a different surgical procedure and consists of only four joints, because their use-case does not require a full six degrees of freedom.

While the reason for the conception of the MTA was the line-of-sight problem, Smith et al. [2025] proposed their mechanical tracking arm because they deemed it to be cost-effective and easier to learn than optical tracking.

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[1] https://ams-osram.com/products/sensor-solutions/position-sensors/ams-as5048b-high-resolution-position-sensor (15.12.25)

[2] https://www.seeedstudio.com/XIAO-ESP32S3-p-5627.html (15.12.25)

Chapter 4

System Design and Implementation

During this master's thesis, multiple software components were newly created or extended in order to accommodate both optical and mechanical tracking within one navigation suite.
As Figure 4.1 shows, the entire system is designed to be run on multiple devices, in order to facilitate flexible usage. While the setup of the camera comes as one unit, which includes the camera and a computer for the more complex calculations, the MTA' setup is split into two systems. The MTA comes with an additional unit, which hosts its own WiFi, performs the computationally complex calculations, and acts a as a bridge to the SDC network. This allows the MTA and the optical tracking camera to easily switch surgery rooms and connect to different instances of the navigation software.

For this master's thesis multiple software components were created or extended in order to facilitate the use of optical and mechanical tracking in one navigation suite. The software components are split up on multiple devices, that are distributed in the surgery room.

The navigation software used in this thesis is written by the mediTec for navigation using optical tracking. It has been extended to also enable mechanical tracking. Additionally, its usage has been simplified, and new features were added, that improve its use for the placement of pedicel screws. More about the continued development of the navigation software can be seen in Chapter 4.3.
The transformation calculator for the optical tracking is a software written by the mediTec, that calculates the trans-

The navigation software was extended during this thesis and the MTATransformer and the embedded code were newly created.

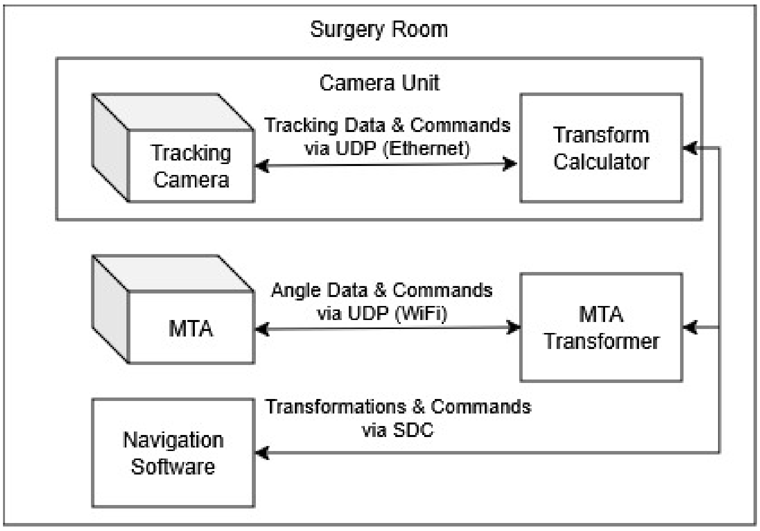

Figure 4.1: This diagram shows the physical distribution of all of the required software components and their communication methods. The tracking camera comes as one unit with a computer, which hosts a transformation calculation software. The MTA's setup consists of two systems, the MTA itself and a separate unit, which hosts the MTA-Transformer, and handles all of the calculations. It also acts as a bridge to SDC and hosts its own WiFi to which the MTA connects to. Both systems communicate via SDC with a navigation software running near the operating table. Components which are represented as cuboids, require specialized hardware and can not run on a normal computer.

formations for the optical system and functions as a bridge between the optical tracking camera and SDC. It has not been significantly altered during this thesis. For mechanical tracking, the MTATransformer acts as the middleman. It receives joint angles and calculates transformations, so that these do not need to be calculated on a microcontroller. Furthermore, it also hosts an SDC provider, presenting data in a format similar to that of the optical tracking system. The MTATransformer, as well as the embedded code running on the MTA are new developments and are further detailed in Chapter 4.2.

4.1 System Design

A workflow describing the optimal use of the MTA needs to be designed.

While different workflows for optical tracking in surgeries are already widely in use in hospitals all around the world, the workflow for the MTA still needs to be designed. This includes the entire use, from the MTA arriving in the surgery room, over optimally fixing it to the patient, all the way to using it with a navigation software. In order to figure out a decent first iteration of such a workflow, in the specific use-case of pedicle screw placement, multiple design phases commenced.

A first concept was designed, based on information gathered about optical tracking. This first iterations workflow however was very strictly ordered.

First, scientific literature about pedicle screw placement and 3-D surgical navigation was investigated, in order to evaluate the current workflow using optical tracking. The findings were compared with video footage of surgeries by Michael [2020] and Sheeraz [2017], which gave further insights into the handling of used tools and the situations these surgeries take place in.
Based on the gathered information, a first walkthrough of the entire use of the MTA and UI mockups for the navigation software were designed. These first designs had a focus on allowing different tools and methods for the surgery; however, a strong focus on preventing usage mistakes, meant that most parts of the workflow were very strictly ordered.

To gain further insights into the topic an interview with a surgeon was conducted.

With the first concepts in mind, an interview was conducted with a neurosurgeon of the RWTH Aachen University Hospital, to evaluate these concepts based on new insights, with a special focus on challenges created by the introduction of the MTA. While this surgeon usually performs pedicle screw surgeries on the cervical spine, we want to focus on the lumbar spine. We were of the opinion, that their insights were relevant, despite the differences in techniques that come with the different surgery locations. They are experienced in using optical 3-D navigation, and though they mostly do pedicle screw surgeries in an open fashion, they still had insights into minimally invasive methods. The interview was semi-structured and included a short presentation and demo of the MTA in an early state, followed by an open discussion about the

MTA's requirements. Some of their feedback was outside the scope of this thesis and is therefore worked into the evaluation in Chapter 5. Important feedback for the workflow design during this thesis included:

1. They see a problem in potentially reaching a joint's limit, while inside the relevant working area.
2. They want to be able to grab the tool's handle and a part of the MTA with one hand.
3. They do not want to change the position of the MTA for every screw.
4. They do not use additional reference screws in minimally invasive surgeries, which is something we assumed before.
5. They do not need a numerical value representing the accuracy of the system; visual confirmation on landmarks is more intuitive.
6. They see a significant problem in the potential of manipulating the patient's spine or the accuracy of the connection point due to forces applied through the MTA.
7. They first drill all holes and introduce the screws afterward in order to reduce inaccuracies due to the forces applied by the screw introduction.
8. They would like the system to have a small footprint, so that it becomes possible to operate as close to the reference point as possible.
9. They, as a surgeon, do not control software during surgery; this is done by an assistant.
10. They do not preplan the positions of all screws. Instead, they use navigation to move a virtual screw to the correct position without incising the skin. They can then choose the dimensions of the screw on-the-fly.

Based on this feedback and the previous designs, a new, more flexible, workflow was created. The workflow goes as follows:

Workflow: Preparations

The MTA needs to be fixed to the patient's spine in such a way, that the spatial relation between patient and connection point is known. For optical tracking, multiple different systems exist, that only need small incisions and are fixed to just one vertebra. However, they are sensitive to manipulation, as the interviewed surgeon confirmed. If they are touched during the surgery, their position has to be remapped with a new CT-scan. As we expect some forces to be applied to the connection point by the MTA, we decided to go with the DRB of the Surgivisio Platform[1]. It is a system designed for optical tracking and CT registration, that comes with multiple advantages for the MTA, which are utilized in this thesis. First of all, it connects three vertebrae together in order to form one connection point, which could propagate the applied forces more evenly and reduce the relative movement of the relevant vertebrae. Whether this is an actual solution to the interviewee's feedback-6 remains to be tested.

Connecting the MTA to the patients spine requires a more stable connection point than most systems used for optical tracking provide. For this reason the Dynamic Reference Base (DRB) of the Surgivisio Platform was chosen, which connects multiple vertebrae together.

As the DRB has not been designed with the MTA in mind, an additional connector is needed that can be attached to the MTA and the connection point made for the optical reference marker. Initial testing with the MTA revealed, that just one way of connecting the MTA will not yield the freedom to reach all points needed for a pedicle screw surgery. It was discovered, that it is advantageous, when the MTA's connection point is on the opposite body site of the intended working area. However, adding connection points that point to the side takes up a significant amount of space. Therefore, keeping the surgeons feedback-8 in mind, the number of connection points was kept to a minimum, while still offering a few options in order to further evaluate which connection points offer advantages. To increase the number of possible connection points without increasing the footprint, the connector was designed in such a way, that it can be flipped 180° to double the number of connection points. The final design can be seen in the lower left

The MTA requires multiple connection points to offer good freedom of movement on all relevant positions. Therefore, a connector was designed that can be rotated by 180° to offer more connection points without additional space usage.

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[1] https://www.ecential-robotics.com/media/images/Brochure-Commerciale_AA-0601-EN-F.pdf

corner of Figure 3.1. The CAD-design and printing of the connector were done by an employee of the mediTec.

The position of the connector can be located in the CT image, because the DRB of the Surgivisio Platform comes with a CT phantom.

Once the DRB of the Surgivisio Platform is attached to the patient's spine, an intraoperative CT scan is performed. The second advantage of using the DRB of the Surgivisio Platform is its CT-phantom which is a construction with metal balls at predefined positions that are easily visible on a CT scan and can be used for registration of its position. To achieve this, a transformation matrix between the CT image origin and the patient can be calculated, which provides us the information about the MTA's position in the CT image. However, this is done automatically by the navigation software and is of no concern to the user.

The MTA is delivered into the operating room in a special calibration rig, which holds all joints in predefined orientations.

Next up, the MTA needs to be calibrated. This requires all joints to be in a predefined position, which can be achieved by using a special rig in which the MTA is delivered into the surgery room. This means in order to calibrate the MTA, it only needs to be turned on, and then a button inside of the navigation software gives the command for calibration. Afterward, the MTA can be taken out of the rig, and two calibration volumes connected to each end of the MTA, which are needed to keep the MTA correctly positioned in the rig, can be removed. The calibration rig can be seen in Figure 3.1. In the same figure you can see the calibration volumes, which are the metal parts at both ends of the MTA.

An additional connector was designed, that is attached to the MTA's end and can hold tools.

The last step before the MTA is ready to use, is the attachment of the tool connector. To keep the system as open as possible for different tools, it consists of a small tube, through which any tool of a proper size can be slid. For tools that do not fit this format, a custom connector can be created. The method of tool attachment means that we lose all information about the tool's roll angle; however, this information is not required, because the used tool has rotational symmetry around the roll axis. Furthermore, to respect the surgeons feedback-2, the tool connector has a small handle that allows holding the tool and the tool connector with just one hand. The tool connector can be seen in Figure 3.1. The CAD-design and printing of the tool connector were done by an employee of the mediTec.

Workflow: Planning

While, according to the interviewee's feedback-10, preplanning of all screws is not necessary with the optical system, we came to the conclusion, that because of the MTA's joint limits and the resulting restrictions in movements, a rough planning of the screws and the optimal connection point used for them is required. This may reduce the chance of running into a joint limit while in a critical phase of the operation, which addresses the interviewee's feedback-1. Furthermore, this reduces the applied forces to the MTA's connection point, which could be especially high when a limit is reached, therefore at least partially addressing feedback-6.

We deemed some degree of planning necessary for the MTA, so that an optimal connection point can be chosen. This makes reaching the desired pose doable and reduces forces applied through the MTA.

However, with the intent to keep this system flexible and open to different approaches, this planning can happen in two different ways.
Option one is to just preplan what connection point is used for the MTA and not plan the final screw positions. With some experience in the use of the MTA this may be possible without any aid from software, but to gain this experience, the navigation software is extended to show areas in which the MTA can easily reach all poses. These areas are highlighted in the CT image and can be shown for all connection point and tool combinations.
Option two is to preplan all screws as exactly as possible. For this, the surgeon can add a screw, of the required dimensions, to the CT image and move it to its intended position. The software then suggests an optimal connection point for all screws and an optimal screw order that reduces the number of times the MTA has to be attached to a different connection point. The suggested screw order addresses the interviewee's feedback-3, while still maintaining a good reachability for all screws.
More on how these suggestions and the areas that the MTA can easily reach are determined can be found in Section 4.3.2.

The workflow allows for two degrees of planning: 1. Checking if a connection point is suitable to reach a position. 2. Preplanning all screws and receiving automatic suggestions.

Workflow: Navigation

For navigation the software needs to be told, which tool and connection point are being used. Navigation is then only used for pre-drilling the holes for all screws, the screws are then introduced unnavigated with the help of Kirschner wires.

Before a screw can be placed using navigation, the MTA needs to be attached to the correct connection point. Furthermore, the selected tool and connection point need to be set in the software, so that it knows which combination is used. If the screw was preplanned, it can be immediately placed; otherwise, the surgeon needs to first choose the correct screw dimensions using the navigation. However, the placement of the screw itself is not navigated. Instead, the pre-drilling of the screws path is. During this, the navigation software visualizes the end position of the screw, which is assumed to be at the tip of the tool. Afterward, a Kirschner wire is threaded into the hole, over which a cannulated pedicle screw is inserted in an unnavigated fashion. While this is the approach taken by the interviewed surgeon, there are other approaches that are possible using the designed workflow, for example, the method used by O'Donohoe et al. [2020], which skips the Kirschner wire.

4.2 MTA Software Implementation

The code required to run the MTA is split into two parts. The first part is the code running on the microcontroller, embedded in the MTA, that reads out sensor values and transmits them. The second part is the MTATransformer, which receives the sensor-values and calculates the resulting transformation based on the known proportions of the MTA.

4.2.1 Embedded Code

The embedded code for the MTA has to fulfill three goals:

1. Listen for a command to calibrate the MTA
2. Read out sensor data using I2C.

3. Send sensor data to a given receiver.

As none of these tasks are computationally complex, they are completed by an infinite loop without the use of interrupts. This allows for a simple code setup and a reliable execution order, while still having a fast enough reaction time for our use-case. The code is implemented using the Arduino programming language.

Sensor data is read using I2C commands. All angle values are collected and then send in one UDP packet to a predefined IP address.

Sensor data is always read one sensor at a time, by sending a command to the sensor, which triggers the sensor to respond with its current angle value. This is facilitated through the use of a library[2] written for communicating with the `AMS_AS5048B`[3] sensor. For this, it is required to know the I2C-addresses of all sensors, which have to be burned in prior. While the sequential reading order of the sensor data means that we never get a snapshot of all joint angles at once, the time difference between these data points is small enough not to be noticeable. All of these data points are then packed together into one UDP packet, which is sent to a predefined IP address.
Because this use-case does not require a reliable transmission protocol, UDP is used for all data communication. If a package gets lost in transmission, a repeated transmission, as would be the case with TCP, is redundant by the time it is received and unnecessarily slows down the communication. Furthermore, as UDP is not connection-oriented and sends data whether a receive is there or not, it is more reliable in the case of a short connection loss than TCP, because no new connection has to be established. The communication is handled using the Arduino WiFi Libraries[4].

The MTA calibration is triggered by an incoming UDP packet. The calibration is done using I2C commands, which tell all sensors to consider their current angle as zero.

Lastly, the MTA needs to be calibrated after every start-up, as the exact orientation in which the magnets are embedded in the MTA is not known. This means, that each sensor needs to be told which magnet orientation it has to consider as an angle of zero. During this calibration, the MTA needs to be fixed in a specific predefined pose, in which all the joint angles are considered zero per definition. While

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[2] https://github.com/sosandroid/AMS_AS5048B

[3] https://ams-osram.com/products/sensor-solutions/position-sensors/ams-as5048b-high-resolution-position-sensor

[4] https://github.com/arduino-libraries/WiFi

the sensors used in the MTA do support hard-burning this configuration once, we chose not to do this, as we considered the possibility that the relative orientation of magnet and sensor might drift over time. Though this step might be skipped in future iterations, if it can be shown that this effect does not take place. Calibration is triggered by sending the keyword "SETZEROPOS" to an open UDP socket of the MTA, which is polled during each loop iteration. Once triggered, commands are sent to all sensors via I2C, reading out their current angles and then setting these as their new zero angle.

4.2.2 MTATransformer

The MTATransformer is responsible for receiving the angle values, combining them with a virtual model of the MTA to get a transformation describing the tool's pose and then transmitting this information to the navigation software using SDC.

The MTATransformer executes the main processing required for the use of the MTA. It takes in all angles measured by the sensors, combines these with a digital model of the MTA to calculate a final transformation matrix, and sends the data to the navigation software.
Data communication from and to the MTA is handled using an UDP socket, which is constantly checked for new data and sends a calibration command to the MTA on demand. Communication with the navigation software is handled using an SDC provider, which uses numeric states to transmit the currently selected tool ID, the current timestamp, and an ascending frame number. These data points can be used to verify the timeliness of the received data on the receiving end. The most important transmitted part is the transformation matrix, which is transmitted as a string state, because SDC currently does not specifically support matrices as data points. All of these outgoing states are updated every time new data is received from the MTA. Additionally, the SDC provider also offers operations that can be triggered by an SDC consumer; there is one for triggering the calibration and one for setting the currently selected tool. These two operations are vital for configuring the system to be in the correct state.

The entire MTATransformer was designed as a C++ library with minimal dependencies, which allows for flexible usage. While it is currently used inside of a GUI application written with the QT Creator[5] it is designed in such a way, that it could be run on a small edge server without any graphical output. However, for purposes of testing and further development of the MTA the current GUI has some useful functionality. The user can easily upload an arbitrary URDF file, which defines the MTA's dimensions as explained in Chapter 4.2.2 and all IP-addresses and ports are easily configurable. Furthermore, the GUI can simulate the data sent by the MTA, for which it replaces every joint with a slider.

The MTATransformer was designed as a C++ library, for ease of use in different scenarios. It is however currently used inside of a small GUI application for testing purposes.

Model Configuration

In order to calculate the transformation of the tool relative to the MTA's base, a digital model of the MTA is required. This needs to represent every segment's length and every joint's orientation and rotation limits. One goal of making the model configurable is that it makes it easy to adjust, as the prototype's dimensions may change. For this reason, the Unified Robot Description Format (URDF) has been chosen. It is a format mainly used in the Robot Operating System (ROS) developed by Quigley et al. [2009], which allows for a standardized representation that can be easily adapted for various applications in future research work.

The exact dimensions of the MTA are given to the MTATransformer as URDF files. The format was restricted with additional rules to only allow the shape of an arm to be read.

However, the URDF is capable of describing significantly more complex systems than the MTA. For this reason a few restrictions were added to enforce the shape of an arm, consisting of an arbitrary amount of joints and segments without any branching segments. Furthermore, an arbitrary amount of tools can be defined, which can be swapped in and out. These are defined as fixed joints connected to the last segment. Specific naming restrictions for all joints and segments are applied, that simplify the evaluation of an URDF file when read in by the MTATransformer. These enforce segments to be called "segment_n" and joints to be called "joint_n" with n counting up. Furthermore, tools are to be called "tools_id", where id is a number that is unique for that tool.

This system restricts anyone who intends to change the

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[5] https://www.qt.io/product/development-tools

```
<robot name="MTA">
  <link name="base_link"> </link>
  <link name="segment_0"> </link>
  <link name="tool_207"> </link>
  <joint name="joint_0" type="revolute">
    <parent link="base_link"/>
    <child link="segment_0"/>
    <origin xyz="0 0.0 0.040" rpy="0 0 0"/>
    <limit lower="-2.39" upper="2.39"/>
    <axis xyz="0 0 -1"/>
  </joint>
  <joint name="tools_207" type="revolute">
    <parent link="segment_0"/>
    <child link="tool_207"/>
    <origin xyz="0.110 0.0 0.020" rpy="0 1.571 0"/>
  </joint>
</robot>
```

Figure 4.2: This figure is a minimal working example of a URDF to configure the MTA. This MTA would consist of only one joint and one possible tool.

URDF of the MTA to adhere to this format, which reduces the number of possible undetected errors caused by a wrong configuration. However, even without these restrictions, errors in the MTA configuration would most likely be detected during testing and are not of relevance for the end-user.
A minimum working example of an URDF file describing a version of the MTA with just one joint and one tool can be seen in Figure 4.2.

Each joint consists of a fixed relative position and orientation,as well as a rotation axis with limits to its angle for the flexible movement.

As can be seen in the example URDF in Figure 4.2, each joint has a preceding and succeeding segment, as well as an origin. The origin describes the position and rotation of the joint in reference to the pose of the last preceding segment. This position and rotation stay fixed during the use of the MTA. The movable part of the joint is described by the axis, around which the joint rotates in between defined limits. While tools are also defined as joints, they are fixed and do not allow adjustable rotation. Their origin should describe the working point of the tool and its forward direction.

Pose Calculation

The MTA's transformation is calculated based on a number of fixed transformation matrices that can be precalculated and a number of flexible transformation matrices that need to be calculated every time a new angle is received.

The pose of the tool relative to the MTA's base can be found by combining the predefined virtual model of the MTA with the angles sent by the MTA for each joint. This is done using a series of homogeneous transformation matrices. These can be used to represent translations and rotations to a vector, as described by Briot and Khalil [2015]. The end result should be a 4 by 4 transformation matrix M_t with the following properties:

$$p_t = M_t \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}, o_t = M_t \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \\ 1 \end{pmatrix}$$

where p_t is the translation of the tool's working point relative to the MTA's base, and o_t is a vector pointing in the tool's forward direction relative to the MTA's base.
For each joint and all tools of the MTA a transformation matrix is precalculated for its fixed rotation and translation. For a joint i with the following properties

$$p_i = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, r_i = \begin{pmatrix} r \\ p \\ t \end{pmatrix},$$

where p_i is its position, and r_i is its fixed rotation, relative to the preceding joint $i-1$, the transformation matrix T_i^{fixed} can be calculated as follows:

$$T_i^{fixed} = \begin{pmatrix} & & & x \\ & R_i^{fixed} & & y \\ & & & z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

with $R_i^{fixed} = R_z \cdot R_y \cdot R_x \cdot I_3$ and

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos(r) & -sin(r) \\ 0 & sin(r) & cos(r) \end{pmatrix}$$

$$R_y = \begin{pmatrix} cos(p) & 0 & -sin(p) \\ 0 & 1 & 0 \\ sin(p) & 0 & cos(p) \end{pmatrix}$$

$$R_z = \begin{pmatrix} cos(t) & -sin(t) & 0 \\ sin(t) & cos(t) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Furthermore, the transformation matrices T_i^{flex} for the flexible rotation of the ith-joint is calculated as follows every time new angles are received:

$$T_i^{flex} = \begin{pmatrix} & & & 0 \\ & R_i^{flex} & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

with

$$R_i^{flex} = \begin{pmatrix} a_x^2(1 - cos(\theta_i)) + cos(\theta_i) & a_x a_y(1 - cos(\theta_i) - a_z sin(\theta_i)) & a_x a_z(1 - cos(\theta_i)) + a_y sin(\theta_i) \\ a_x a_y(1 - cos(\theta_i) + a_z sin(\theta_i)) & a_y^2(1 - cos(\theta_i)) + cos(\theta_i) & a_y a_z(1 - cos(\theta_i)) - a_x sin(\theta_i) \\ a_x a_z(1 - cos(\theta_i)) - a_y sin(\theta_i) & a_y a_z(1 - cos(\theta_i)) + a_x sin(\theta_i) & a_z^2(1 - cos(\theta_i)) + cos(\theta_i) \end{pmatrix}$$

where the rotation axis of the joint i is given by

$$a_i = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix}$$

and the current rotation angle is θ_i.

With these transformations calculated, we can now calculate the transformation of the entire MTA. This is done by using these transformation matrices as basis transformations, changing the basis of the identity matrix joint after joint from being in tool-space to being in MTA-base-space:

$$M_t = T_0^{fixed} \cdot T_0^{flex} \cdot T_1^{fixed} \cdot T_1^{flex} \cdot \ldots \cdot T_{n-1}^{fixed} \cdot T_{n-1}^{flex} \cdot T_t^{fixed} \cdot I_4$$

where T_t^{fixed} is the fixed transformation of the currently used tool, and n is the number of joints of the MTA.

4.3 Navigation Software Extension

The navigation software used as a base structure in this thesis is an in-house production by the mediTec. It is capable

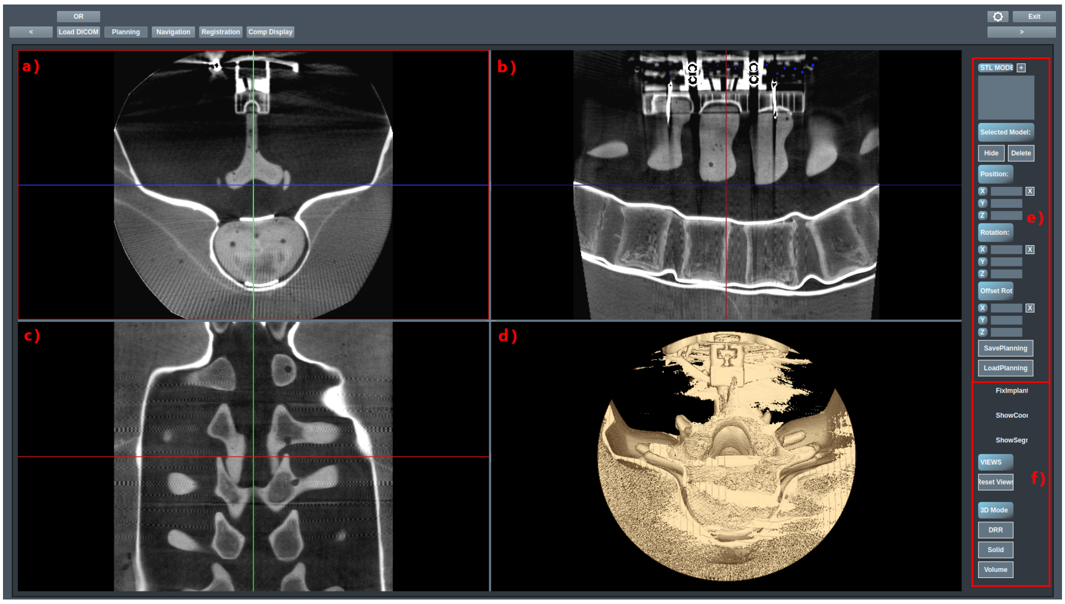


Figure 4.3: This image shows the planning screen of the navigation software prior to its redesign. a), b) and c) are different views of the CT image. d) is a 3-D rendering of the CT image. e) includes options for adding, removing and positioning screws. f) includes rendering settings.

of visualizing DICOM (Digital Imaging and Communications in Medicine) files, which is a standard image format for medical imaging. In this case it is specifically used for CT images. Furthermore, it is capable of planning screws in a CT image and supports navigation using optical tracking systems. An image of the navigation software prior to this thesis can be found in Figure 4.3. During this thesis, support for the MTA was added. Additionally, smaller features to improve its capabilities for pedicle screw placements were implemented. The redesign of the navigation software is further specified in Chapter 4.3.1. Furthermore, the navigation software's SDC interface was adjusted to allow for both optical and mechanical tracking; more on that in Chapter 4.3.3.

The navigation software is an extension of an already existing navigation software. Changes were made to support mechanical tracking, simplify its use, clear up its visual identity and improve its usefulness for the placement of pedicle screws.

4.3.1 Redesign

While Chapter 4.1 already described the design of the MTA's workflow, this chapter will focus on the necessary changes and additions to the navigation software, that come as a consequence of this workflow. As well as additional improvements that were made, that do not directly follow from the workflow.

Visuals

The navigation software went through an extensive visual redesign, to clear up its visual language and make it easier to add new elements.

The initial version of the navigation software, as can be seen in Figure 4.3, has a graphic style in which it is not always clear what an UI element is supposed to be. Some buttons have white outlines, and some have a 3-D effect; meanwhile, some labels also use a 3-D effect, while other labels use a plain text without a bounding box. This means that an inexperienced user of the software may miss buttons, because they are mistaken for labels, or click on labels, expecting something to happen. Furthermore, unchecked checkboxes are invisible, which means users will likely not even learn of their existence. Lastly, mutually exclusive options, are not identifiable as such.

To remedy this, the design has been simplified. Now, only buttons use a 3-D effect, while labels are always just plain text without a bounding box. Checkboxes are now always visible, and mutually exclusive options were turned into radio buttons. The color scheme was switched to black and white with the goal of making the visuals more consistent and the system easier to extend, as UI changes under the previous color scheme were relatively time-consuming due to its implementation.

Results of these visual changes can be seen in Figures 4.4.

Planning

The navigation software was adjusted to allow for all levels of planning.

As discussed in Chapter 4.1 planning is optional and may not be necessary; however, we deem it useful, especially in the context of the MTA's limitations. The intent is to enable all degrees of planning a surgeon could want; it should be possible for them to plan nothing, plan all screws in advance, or just plan the next screw they want to place. Therefore, the planning screen of the navigation software received an overhaul, the result of which can be seen in Figure 4.4.

The software was redesigned to not only include screws, but also connection points. These are shown in their own lists and are now easier to modify.

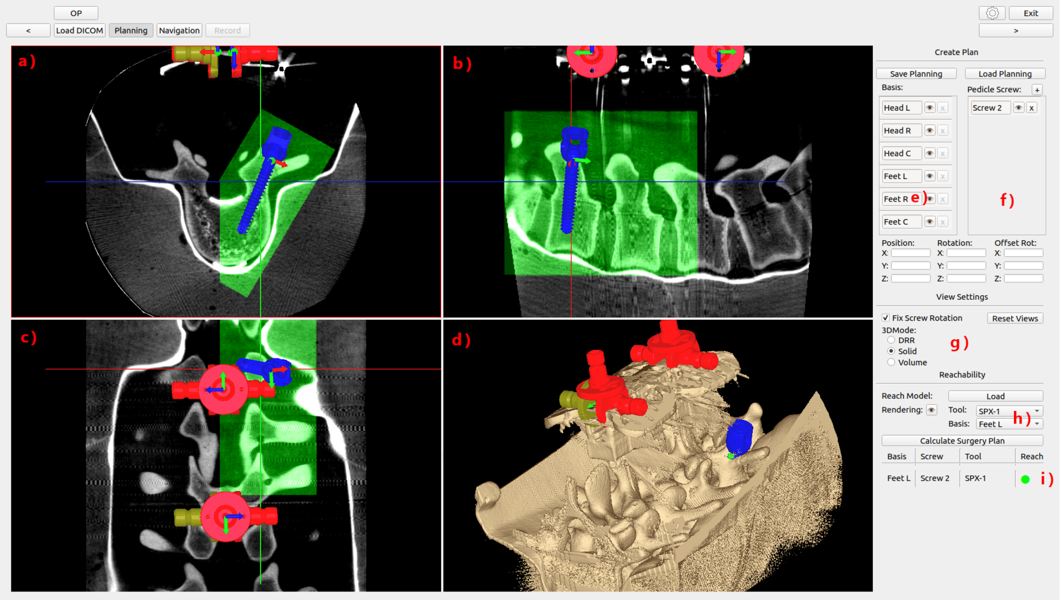
In the original version of the navigation software, all objects that were planned ended up in the same list, in which there was no way to tell what function the object served. Within this new design, there are two lists, one for objects added by the user and one for connection points, which are automatically added based on the selected navigation type. The objects now all have their own delete and hide button in order to decrease the number of necessary clicks. Furthermore, objects that are added by the user are now enumerated and can be renamed to make it easier to identify their purpose. While it is still possible to add any 3-D mesh to the visualization, it is intended for the use with specific 3-D models of pedicle screws, of which there are now many more, offering different combinations of diameter and length.

The UI changes may seem small on the surface, but they required extensive rewrites of the backend to add the possibility to load, select, and plan objects of different kinds. This could aid further development of the navigation software, especially for use-cases where multiple object types are necessary.

Connection points for both optical and mechanical tracking are automatically added to the planning. Their position is determined by an automatic registration.

While, for optical tracking, there are just two different ways the reference marker can be oriented on the DRB; there are six different connection points for the MTA, for reasons explained in Chapter 4.1. As mentioned previously, these connection points are automatically added based on the used navigation type. The exact position of these can be determined, because their poses relative to the DRB are known and its pose can be calculated.

In order to calculate the pose of the DRB, it comes with a CT-phantom, which contains fiducial markers that are visible in a CT image. This allows us to calculate the transformation from the CT image origin to the mounting point origin. The first step in this calculation, is to determine the position of all fiducial markers in the CT image using common computer vision algorithms, like region growing. Next, the transformation between the found positions and the known positions in the fiducial marker array is calculated using the generalized solution of the orthogonal Procrustes problem



☑ Fix Screw Rotation

● Solid

Tool: SPX-1

Basis: Feet L

Basis	Screw	Tool	Reach
Feet L	Screw 2	SPX-1	●

Figure 4.4: This screenshot shows the navigation software's planning screen after the redesign. a),b) and c) are different views of the navigation screen. They include a planned screw in blue, connection points in red and a selected connection point in gold. Additionally they show a reachable area, as explained in Chapter 4.3.2, which was determined with the manual method. d) is a 3-D rendering of the CT image. e) and f) are lists of connection points and screws respectively. Options for adding, removing and posting screws are next to or in f). g) includes a few rendering settings. h) are the option, which reachable area to render. i) shows a table with the reachability of all screws and a suggested connection point. This feature is further explained in Chapter 4.3.2.

proposed by Schönemann [1966]. This calculation returns the translation and rotation of the mounting point relative to the CT image origin. Large parts of this calculation already existed in the code base and were just properly utilized for this thesis.

When using the MTA an additional visualization is added, which suggests the use of certain connection points and visualizes the areas the MTA can reach from a connection point with a given tool. As this is a more intricate topic, it is further discussed in Chapter 4.3.2.

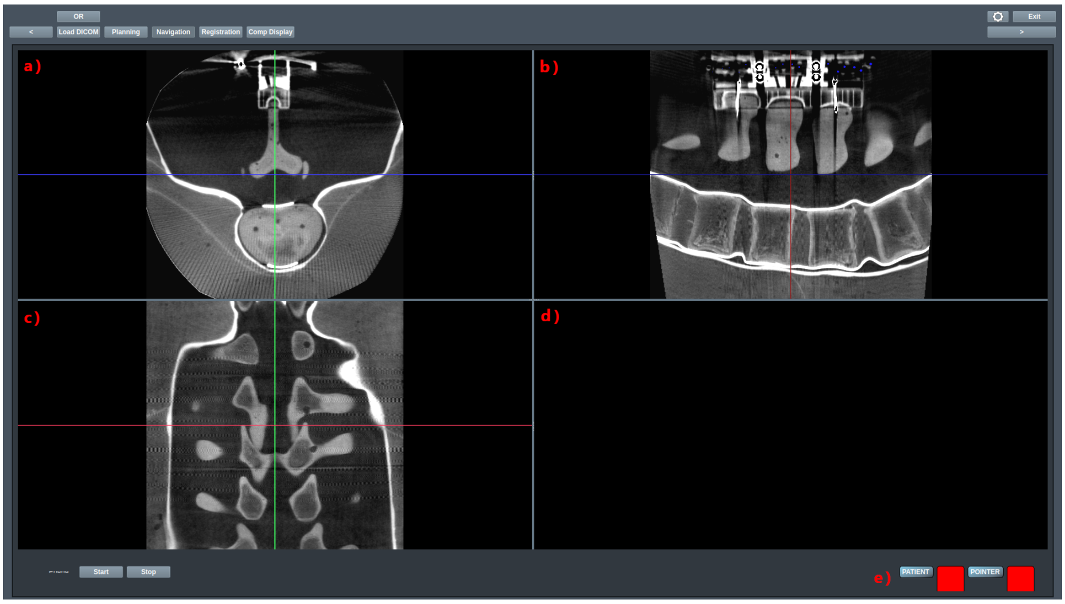


Figure 4.5: This image shows the navigation software's navigation screen prior to its redesign. a), b) and c) are views of the CT image, that move with the tracked tool. d) is a compensatory display, which shows the tracked tools relative position to a planned screw; however, as this screenshot was taken without tracking data the view is blank. The compensatory display can be seen in Figure 4.6. e) includes two indicators, that tell wether or not racking data is received for the tool or reference marker. They are red, because no data is arriving.

Navigation

In the original version of the navigation software, the actual navigation screen, as can be seen in Figure 4.5, is minimalistic; it has three views of the CT-image, which move with the tracked tool and can optionally also be rotated with the tool. In the lower right there is a compensatory display, a visualization that helps with the orientation of the tool, by showing the tool's tip and handle position relative to the axis of a planned screw. Lastly, there are two indicators, that represent if the tool and the reference marker are successfully tracked by the optical tracking system, by turning red and green.

The navigation screen of the initial navigation software was simple and did not offer a wide array of functionality useful for pedicle screw placement.

Based on this, the UI is redesigned with a focus on adding functionality for the placement of pedicle screws and the MTA. The final version of this redesign can be seen in

The navigation screen was redesigned adding functionality for live planning of screw sizes and increasing the information rendered in the CT-images. Furthermore, options were added to freeze the navigation and add or remove planned screws.

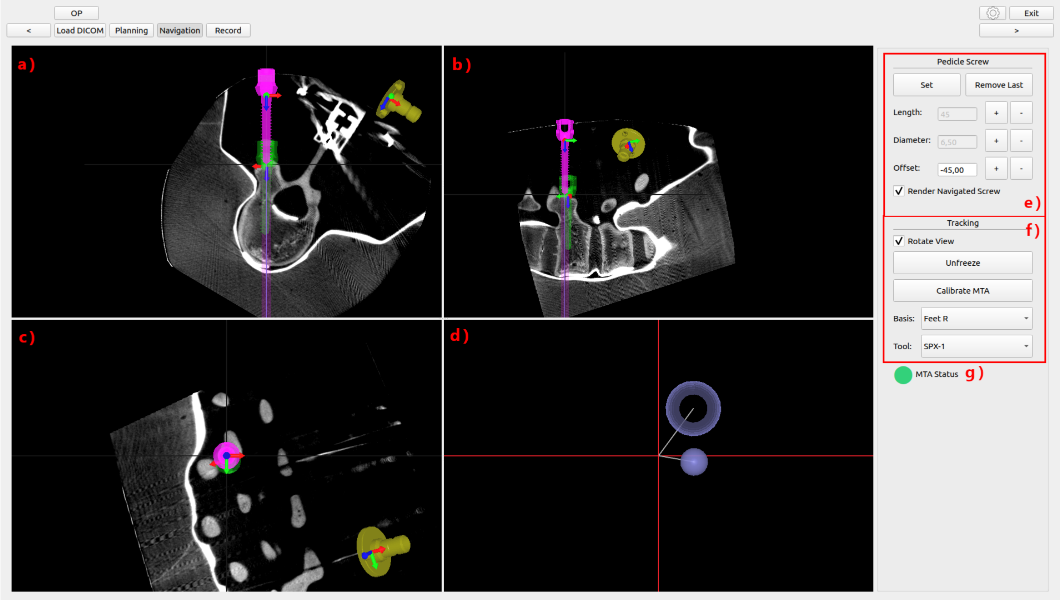
Figure 4.6. As the new features require more screen space, the toolbar was moved from the bottom to the right side. Here, the first feature is one requested by the surgeon for the use in surgery without preplanning, as seen in their feedback-10. The software renders a virtual screw at the position of the tool; options are added for changing the length and diameter of this screw. Furthermore, the image can now be frozen in time, and the screw can be digitally moved along the axis of the tool, which can help with selecting the correct screw size, by visualizing the screw in its final position. The rendering of the screw in the CT image also changed for this reason. It now renders the screw, with the screw's tip at the tool's tip, the screw's trajectory as a line, and the screw's diameter along this trajectory. A screw that has been selected and positioned in this manner can be stored with the press of a button and is then always visible in a different color. It is also editable in the planning screen. Another button is added, that can remove the last screw that was stored, so that there is a fast method of undoing a potential error.

Both optical and mechanical tracking require operations during setup that were added as buttons to the navigation screen. Furthermore, the selected tool and connection point can now be selected on this screen.

Full support for both the MTA and optical tracking requires additional options. Such as the selection of the used connection point and the used tool for both systems. But also a button to calibrate the MTA. As the camera for optical tracking does not need calibration every time it is used, this button is replaced in the optical tracking mode with a button that helps with adjusting the camera's view area. While not all optical tracking cameras have them, some have integrated laser pointers, that can be used to visualize their focus point. This button sends a command to the optical tracking software telling it to toggle these on and off. When using the MTA, the previously mentioned indicators of the tracking availability are replaced with just one indicator, that is green if data of the MTA has been received in the last few milliseconds and red otherwise.

Recording Point Clouds

A new screen was designed, which can be used to record point clouds based on the received tracking data. This is of



Length: 45

Diameter: 6,50

Offset: -45,00

☑ Render Navigated Screw

☑ Rotate View

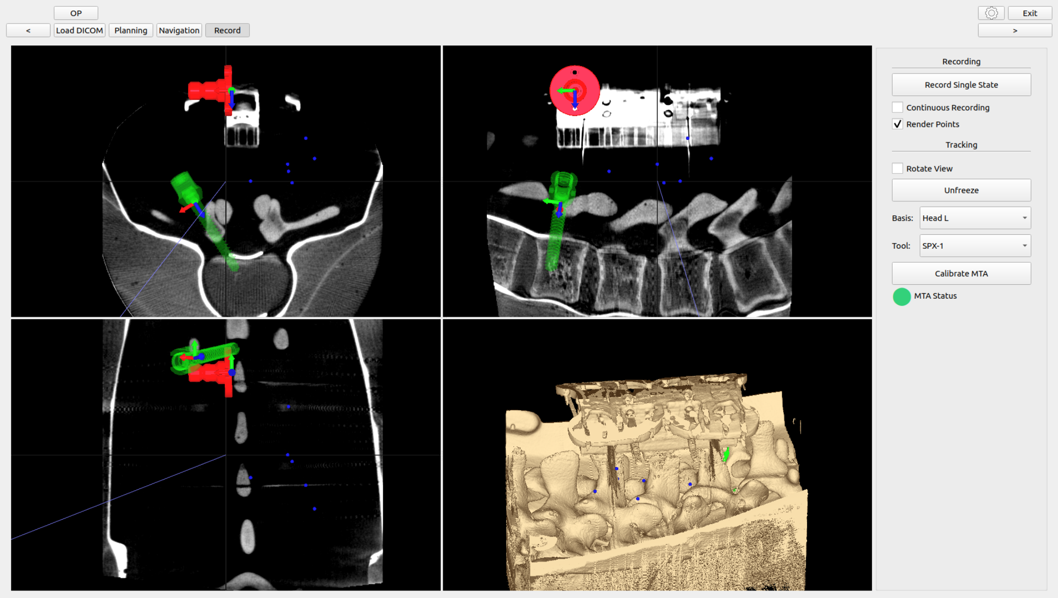
Basis: Feet R

Tool: SPX-1

Figure 4.6: This screenshot shows the navigation software's navigation screen after its redesign. a), b) and c) are views of the CT image, that move relative to the tracked tool. In them one can see a rendering of a screw at the position of the tool in pink, a planned screw in green, and the selected connection point in gold. d) shows a compensatory display, which displays the relative position and orientation of the tool to the planned screw's axis. If the torus and the sphere are both in the center the tool and screw are perfectly aligned. e) shows several settings for live planning of the screws dimension. f) has relevant options for the used tracking system. One can freeze the current tracking state and calibrate the MTA. If an optical system was used this would show a button to toggle the cameras laser pointers. Additionally, the used tool and connection point can be set. g) is an indicator showing that data is received from the MTA.

no use for surgeons, but can be helpful for further evaluation of the MTA or an optical tracking system. There are two options for recording new points. The first one is to press a button every time a point should be recorded. The second one is a checkbox, which, if checked, causes a new point to be recorded every time new tracking data is received. All of these points can be visualized in the CT image and are stored in a log file with their positions and orientation as well as timestamps. An image of the point cloud recording screen can be seen in Figure 4.7.

A new screen was added, that allows users to record point clouds with both tracking methods.



☐ Continuous Recording
☑ Render Points
☐ Rotate View
Basis: Head L
Tool: SPX-1

Figure 4.7: This screenshot shows the navigation software's point cloud recoding screen. It can be used to record single points or if one wants it can record a point for every new position data that is received. It functions mostly the same as the navigation screen in Figure 4.6.

4.3.2 Reachability Estimation

Even if there are multiple ways to reach a pose, it is not always clear, how the user needs to rotate all of the joints to get to that pose. We deemed it to complicated to tell the user exactly how to rotate each joint and therefore implemented methods that estimate how easy to reach a pose is.

The MTA cannot reach all positions with equal ease, due to the rotation limits of the joints, the shape of the tool, the dimensions of the arm segments, and the possibility of it being in its own way. However, this strongly depends on the connection point the MTA is connected to. The fact that the mount for the tool allows for rotating the tool without moving the MTA means, that the poses in the case of the MTA are only in five dimensions instead of the common six dimensions. For this reason, there are many different joint orientations that can be utilized to reach a specific pose. A problem arises because, due to the mentioned limitations of the MTA, the proper joint orientations needed to reach a position are not always obvious. Whether a certain pose is reachable heavily depends on the orientation of the first few joints. But different screw position and connection point combinations differ in how many of these wrong joint orientations exist and how many joint orientations exist, that can be used to reach the screw. While the exact rotations needed for each joint to reach a certain position are difficult to communicate clearly, it is possible to communicate to a user how likely it is that they will not have any problems reaching a point. As a way of communicating this likelihood, and the resulting best connection point, two new features were added to the planning screen of the navigation software.

The first feature is a change to the CT images, where the areas that are easily accessible by the MTA are highlighted by a green tint. The areas depend on the selected tool and connection point, and their intensities depend on how easy they are to reach. The ease of reachability used here is an average value for the surrounding area, because a point is only easily reachable, if there is also an easy way to navigate towards it. As the CT image is represented in 2-D slices, there is no good way of representing how easy each orientation is to reach at a given position. Therefore, the reachability shown is also the average reachability of all, for pedicle screws relevant, orientations in the surrounding area.

One approach we implemented is to highlight areas in the CT image depending on their reachability.

The second feature suggests which connection point to use for a preplanned screw. For this purpose a table is added at the bottom of the planning screen in which this information is displayed. This table lists all screws and tool combinations, with the suggested connection point and an indicator that changes its tone of green depending on how good the reachability is. This indicator turns red if the screw is not reachable from any connection point. The table sorts the screws in such a way, that the number of times the surgeon has to reconnect the MTA, as well as the number of times the connection adapter needs to be flipped, is minimized. If a screw is reachable from multiple connection points with equal ease, the connection point is chosen based on this minimization.

The second approach is an automatic suggestion, which tells the user which connection point to use for which screw.

Both of these features build upon the knowledge of how easy it is to reach a pose. While the common and efficient solution for calculating the angles for each joint required in order to reach a specific pose is inverse kinematics by Pieper [1969], this approach does not fulfill our requirements. This is the case, because we need to know how

For performance reasons a precalculated reachability estimation for all relevant poses is required. We tried two approaches.

```
def calculateReach(int jointID, matrix4x4 transform)
 if(jointID is a joint){
  transform = transform * fixedTransform(jointID);
  for(all angles within limits and with a step Size){
   tempTransform = transform * flexTransform(jointID,angle);
   calculateReach(jointID + 1, tempTransform);
  }
 }else{
  for(allTools){
   transform = transform * toolTransform;
   if(tranform in relevant area){
    store(transform);
   }
  }
 }
```

Figure 4.8: This is a pseudocode representation of the automatic reachability estimation for the MTA. It calculates the MTA's transformation matrix for all possible joint configurations in a recursive manner.

many solutions there are and not necessarily which solutions, so that we can estimate the reachability. Furthermore, this information is required for thousands of poses and not just for one, so that it can be rendered for all points in the CT image. As calculating all of these poses is computationally too complex to do in real-time, the reachability for all poses is precalculated. For this precalculation, two approaches were implemented during this thesis.

Automatic Reachability Estimation

An automatic reachability estimation was implemented, that is based on the idea of estimating how many joint configurations can reach a certain pose. However the resulting visualizations of this estimation were difficult to interpret.

This approach automatically approximates the easily reachable areas, based on the URDF described in Chapter 4.2.2, for all tools in this URDF file. The intended benefit of this is, that this approach could be easily scaled to numerous different tools and surgeries.

The algorithm used for this is a recursive method where each possible joint configuration, with a certain step size, is tested and stored; its implementation is akin to depth-first search. The idea is to gain an estimation as to, how many joint configurations can reach a certain pose. If broken down to its most basic form, the algorithm works as described by the pseudocode in Figure 4.8.

In this implementation, the fixed and flexible transforms are calculated as described in 4.2.2 and optimizations are implemented, that split up the first joint into multiple threads, significantly improving calculation time. The calculated data is stored in a multidimensional grid, with three dimensions for the position and three dimensions for the orientation, where the value stored is an integer counting how often this position and orientation combination has been reached. The orientation is stored as a vector pointing in the forward direction of the tool. In order to decrease memory cost, all six dimensions are binned, and poses that are either too far away from the patient or point away from them are dismissed. All the remaining poses are stored to a file.

The first iteration of this algorithm only calculated how often each pose is reached. However, this led to fairly homogeneous data, that was difficult to interpret, even with the knowledge of how this calculation worked. Especially, since a pose can be easily reachable with multiple configurations, while still being restrictive in its movement around that pose.

For this reason a second iteration was designed with the goal to alleviate this drawback. The second iteration not just counts how often the pose can be reached, but instead additionally respects how much freedom each joint configuration offers. This is accomplished by calculating the distance each joint has to its closest limit in a configuration and summing these up. This value replaces the count of how often a pose has been reached. While the resulting data represents more accurately how easy a pose feels to reach, it can still be difficult to interpret.

The resulting visualization of the reachability can be seen in Figure 4.9, which already includes an attempt to increase its readability, by splitting the reachability into discrete color steps, instead of showing them with their exact value. The idea behind this is to make it simpler for users to identify at which level a reachability value is good and which areas are practically not reachable.

In order to improve the readability of the reachability estimation, the resulting values are discretized to just a few levels of reachability.

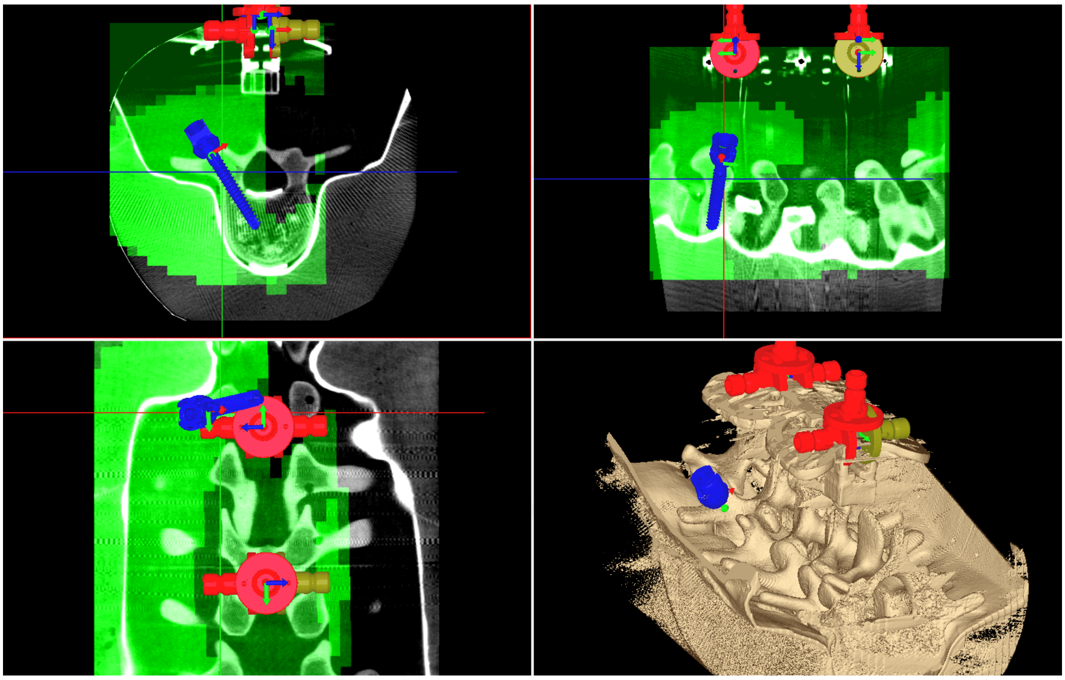


Figure 4.9: This image shows the results of the automatic reachability calculation, as it is visualized in the planning screen of the navigation software. The more intense the green tint gets the higher the reachability.

An attempt to improve the readability of the data can be seen in the following Figure 4.9, where the data is not displayed as a smooth gradient of reachability, but instead split into fixed categories of ease of reach represented by different tints of green.

Manual Reachability Estimation

Because the automatic reachability estimation did not satisfy our usability standards, as it was difficult to interpret, a second approach was designed. Instead of calculating the easily reachable areas, an experienced user defines areas, in which they would recommend the use of the MTA for each connection point and tool combination. This approach depends on the experienced user to define easily readable areas.

In an attempt to keep the displayed areas easy to read, they can only be made up of rectangular cuboids, with a

customizable scale, orientation, and reachability level. If a shape other than a cuboid is required, a second cuboid can also be used to cut the shape of the first cuboid. While more shapes might be useful for representing the areas the MTA can reach more precisely, cuboids were deemed sufficient for the tools and tasks used during this thesis.
The resulting visualization can be seen in Figure 4.4. This approach greatly improves the readability of the system, as the user sees clearly defined areas, in which they know for certain, that the system is easy to use. However, it requires an experienced user to take the time and set it up, which makes it less scalable than the automatic approach. In this thesis the ease of readability was more important, which is why this approach was chosen as the main method.

A manual approach to reachability estimation was implemented, in which an experienced user defines areas that they suggest the MTA to be used in. While this approach is not as scalable it produces results that are easier to understand than those of the automatic approach.

4.3.3 SDC Connection

The navigation software receives its tracking data over SDC. However, the received data and offered functionality differ between the provider of the optical system and the provider of the mechanical system. Therefore, the redesign of the navigation software has two modes, one in which it supports optical tracking and one in which it supports mechanical tracking. The mode is selected on startup and determines which consumer is used. While it was outside the scope of this thesis, following the idea of SDC and its usability in an actual hospital setting, in which surgeons switch between optical and mechanical tracking on a per-surgery basis, it would be logical for the navigation software to start up in a neutral mode and offer the selection between all fitting SDC providers in the network.

The navigation software receives its tracking data via SDC. To which kind of SDC provider it connects is decided at start up, because optical and mechanical tracking require a different set of metrics and operations.

While the SDC providers of both tracking systems need to offer system-specific parameters and operations, the core of them is the same. Both of them need to provide the transformation matrix, timestamps, frame numbers, and an ID of the used tool.
The difference is that while the MTA's provider offers operations for setting the tool or calibrating the MTA, as described in Chapter 4.2.2, the provider for optical tracking needs to offer just one operation for toggling the guide

SDC providers for both tracking systems need to transmit the same base data, however both require a few system specific features.

lasers, which can be used to visualize the camera's focus point.
Furthermore, the optical tracking provides metrics describing the current accuracy of its pose estimations and is capable of providing pose estimations for multiple objects.

A generalized SDC provider for mechanical and optical tracking should be possible, with more generalized SDC operations.

Despite these differences, it should be possible to generalize an SDC model, that fits both of these use-cases. This could be accomplished by adding a few generalizable operations to the provider, which could then be used for different purposes by all navigation systems. Additionally, the MTA would need to send a predefined accuracy estimation of the MTA's pose estimation.
A generalized SDC provider would have the advantage, that every SDC-capable navigation software could handle both systems without the need to write additional code for each system.

Chapter 5

Evaluation

The evaluation of the MTA is split into two parts, first a short evaluation of the MTA's technical functionality in Chapter 5.1 and then a usability evaluation on the basis of a user study in Chapter 5.2. As preliminary tests revealed an insufficient accuracy, which should be reduced with further constructive development of the MTA, we refrained from further technical benchmarks.

5.1 Technical Evaluation

Technically relevant factors for the MTA's success are the data delay, the data frequency and the measurement error.

From the technical side, there are three important measures for the MTA.

The delay between the MTA being moved and the navigation software reflecting this movement is important for good hand-eye coordination. No exact measurements were performed, but the delay is not noticeable and feels on par with that of the optical tracking system used during this thesis.

According to Coudiere and Danion [2024], data frequency has a big impact on a user's hand-eye coordination; infrequent data makes movement less smooth and less accurate. However, Consoli et al. [2025] found that, at least for telesurgeries, frame rates as low as 15fps were still rated as acceptable by users. The data frequency of the MTA,

in combination with the navigation software, is on average 114 updates per second, which is high enough to be perceived as a fluid motion. As this is far above, the previously mentioned, 15fps we deem it sufficient.
Last, but certainly not least, the accuracy of the system is critical, as just slight errors in the position or the rotation of the tool can lead to severe mistakes by a surgeon, with the potential to seriously harm the patient. Currently, the MTA is not accurate enough to be used in a real surgery. While the exact error has not yet been conclusively determined, we estimate the maximum position error to be around two centimeters. This estimation is based on experience using the system, combined with the calculation of the theoretical maximum error in Chapter 5.1. The goal would be an accuracy of at least $0.1mm$, which would make the MTA competitive with modern optical tracking systems. Some known factors of its inaccuracy include:

1. **Bending of tools**: The dimensions of the tool are predefined but could slightly change due to bending. This is most likely in those situations in which the tool is in contact with the patient, the exact situations in which accuracy is especially relevant. However, this cause of inaccuracy is not unique to the MTA and is also a problem when using optical tracking.

2. **Bending of the MTA segments**: In addition to tool bending, the MTA's individual segments can also bend slightly during use. While this was a suspected cause of inaccuracy during this thesis, in which a 3-D printed version was used, it should not be relevant with the aluminum version, which has been developed in parallel.

3. **Slack in the joints**: A test of the MTA's joints, done separate to this thesis, in which the impact of a joint's slack on the measured angle was evaluated, came to the conclusion that the current joint design leads to high inaccuracies. This results in inaccurate calculations for that joint and all following joints.

4. **Inaccurate virtual model**: Due to production or measurement errors, the virtual model of the MTA and

the used tool has the potential of not accurately reflecting reality. This would mean that the tool's pose is calculated with wrong dimensions, causing a consistent error in the calculated position and rotation.

5. **Spine manipulation**: As the MTA is attached to the patient's spine, it is to be expected that at least a small amount of force is applied to the spine when the MTA is used or attached. If this force is strong enough, it could cause relative movement in the spine, which causes the CT image to not mirror reality anymore. While, according to Phillips et al. [2020], this is also a known concern for optical tracking methods, the likelihood of manipulation seems higher with the MTA, because of its mechanical connection to the patient. Though the actual influence remains to be evaluated.

6. **Slack of the connector**: Because the connector is designed to be flipped by 180° it is not statically fixed to the mounting point. This causes a bit of slack in the connection, which materializes mostly in small rotations to the patient's left and right side. While this might be an unintended way to decrease the forces applied to the patients' spine, it can cause wrong measurements if this rotation is not noticed.

7. **Inaccuracy in the registration**: The relation between CT image and MTA is based on image registration. While this is also being used for optical tracking and should yield sufficient accuracy, a slight inaccuracy can be caused by image distortion or a wrong model of the registration phantom.

8. **Faulty calibration**: The MTA needs to be told which sensor values it should assume as angles of zero degrees. To accomplish this, the MTA is fixed in a registration rig during calibration. The current iteration of the MTA and the registration rig leave little room for slack and inaccuracies during calibration. However, this is only the case if it is used correctly, which is not guaranteed, as the user study in Chapter 5.2 showed. If just a single joint is wrongly rotated, it causes drastically wrong calculations of the MTA's pose.

The manufacturer of the magnetic encoders does not offer a clear definition of its accuracy. We got to assume an error of up to $1.2°$

9. **Inaccuracy of magnetic encoders**: The accuracy of the used magnetic encoders is not clearly defined and depends on multiple circumstances. According to the manufacturer's website[1] the accuracy of the encoders is 0.5°, however this is not confirmed by the datasheet [2018]. The datasheet mentions the sensor's resolution of 14 bit or 0.0219° and a root mean squared measurement noise of 0.06°. Additionally, nonlinearities in the measurement are mentioned that depend on the temperature and magnet alignment. With optimal magnet alignment and a temperature of 25° the encoder has a maximum error of 0.8°. With uncertain temperature conditions and a magnet misaligned by $707\mu m$ the maximum error grows to 1.2°. As such a misalignment, especially with the previously mentioned joint slack, seems likely it has to be assumed that the angle measurement error in the current version of the MTA may reach up to 1.2°.

Theoretical Maximum Accuracy

Based on the information given by the manufacturer of the magnetic encoders, we can calculate the maximal deviation between measured and real position, under the condition that they are the only source of error. We calculate a maximum error of $17,23mm$, from which we conclude, that the currently used magnetic encoders are not suitable for the MTA.

Under the assumption that only the measurement of the magnetic encoders is inaccurate and all other problems mentioned above do not occur, we can calculate the theoretical maximum accuracy of the MTA. For this, the maximum deviation of the MTA's tool position is calculated using the formulas listed in Chapter 4.2.2. In order to evaluate the joint orientations that yield the maximal deviation from the correct position, all possible combinations of a deviation of plus and minus α are applied to all joints. The deviation is calculated with a tool applied, which has the dimensions:

$$xyz = \begin{pmatrix} 0.11 \\ 0 \\ 0.02 \end{pmatrix}, rpy = \begin{pmatrix} 0 \\ 1.571 \\ 0 \end{pmatrix}$$

These are the same dimensions as those of the tool used during the user evaluation. As the accuracy of the encoders is up for debate, as mentioned in point 9 of the above enumeration, the deviation is calculated for $\alpha \in$

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[1] https://ams-osram.com/products/sensor-solutions/position-sensors/ams-as5048b-high-resolution-position-sensor (05.12.2025)

$\{0.5°, 0.8°, 1.2°\}$. However, as the magnets are most likely not perfectly aligned, the actual accuracy is assumed to be somewhere between the values for $\alpha = 0.8°$ and $\alpha = 1.2°$. The following maximal deviations Δ were calculated:

$$\alpha = 0.5° \Rightarrow \Delta = 7.16mm$$
$$\alpha = 0.8° \Rightarrow \Delta = 11,47mm$$
$$\alpha = 1.2° \Rightarrow \Delta = 17,23mm$$

However, the bigger nonlinear magnetic encoder errors, of $\alpha = 0.8°$ or $\alpha = 1.2°$ can in theory be partially compensated. Chuang et al. [2022] proposes a calibration method for magnetic encoders, that reduced the nonlinear error in their setup by a factor of 10. While this approach could reduce the nonlinear error of the MTA's encoders, it requires a redesign of the MTA or the design of additional calibration hardware, as each encoder must be calibrated in-place with a stepping motor attached to it.

Therefore, based on the information given by the manufacturer, the currently used magnetic encoders, are not suitable to reach the accuracy required for actual surgery. However, there are magnetic encoders on the market with higher accuracies, suitable for this use-case. One example would be the PT Series Magnetic Encoder by Mosrac, which, according to its datasheet [2023], has an accuracy of 0.01°. This would yield a maximum position deviation of $\Delta = 0.14mm$, which could be enough for the purpose of surgical navigation. Therefore, we see the potential of an accurate MTA and deem it desirable to evaluate its usability.

5.2 Usability Evaluation

While the technical values, such as accuracy and information delay, of a system like the MTA are important, in order to determine if it can be used for a specific use-case, the usability of the system is important to determine if it is desirable for the user to use it over another system. As the main reasons the concept of the MTA exists are inconveniences in the use of optical tracking, it was deemed important to evaluate the usability and potential pain points of the MTA. The following chapters will provide insights into the conception of a user study, its execution, and the insights gained from it.

5.2.1 Study Design

The user study intended to evaluate the MTA's usability. However, not all aspects of usability are equally relevant or evaluable during a single study. For these reasons we focused on a low error rate and satisfaction, but also evaluated learnability and efficiency.

Nielsen [1994] defines usability as a multidimensional property combined from the following five attributes:

1. **Learnability**: Learnability, describes how easy to learn the system is and how quickly a user can get to a sufficient level of understanding to work effectively with it.
2. **Efficiency**: Efficiency means, using the system, once the user learned how to handle it, should not take longer than necessary.
3. **Memorability**: Memorability means, even a user who has not used the system for a while, should still be able to use the system, without having to relearn its use.
4. **Errors**: The system should allow for as few user errors as possible, and in case they do happen, there should be ways to recover from them. Errors with catastrophic consequences should not be possible.
5. **Satisfaction**: Satisfaction means, the system should be designed in such a way that the users enjoy using it and are satisfied by its use.

These are the attributes we intended to evaluate for the MTA during a user study. However, not all attributes are equally relevant for the MTA. Especially important in the field of medical technology is a low error rate, as we do not want patients to be injured. Additionally, the satisfaction is of especial relevance for the MTA, as problems with the satisfaction of optical tracking are the reason for its existence. While efficiency is relevant for the use in surgery rooms, as the schedule for these can be tightly planned, it is difficult to evaluate with a system every user has to learn first; therefore, it was not a focus of this study. However, we deem it desirable to further evaluate efficiency in the future, when the MTA has been improved, as we see potential efficiency gains compared to optical tracking systems due to the reduced downtime. Learnability, on the other hand, is something that can be evaluated on a first tryout, even though it is of lesser relevance during the conducted study, because it can be expected that surgeons would only use the MTA with extensive prior training. Lastly, memorability cannot be evaluated in short-term studies and was thus neglected.

With the above-mentioned criteria in mind, a study was designed to evaluate these as accurately as possible. First of all, it was decided to evaluate both optical and mechanical tracking with the same study, so that we have a baseline to compare the MTA to. This lowers the influence of the environment and study design on our test results, as it would be factored into the evaluation of both systems. The tracking camera used for this study is a FusionTrack500[2], a commercial tracking camera with an accuracy of up to $0.08mm$. Its accuracy is comparable to most modern optical tracking systems, which makes it an adequate baseline for this study.

To reduce the influence of the environment and the study design on the results, we decided to use an optical tracking system as our base line, to which we compare the MTA.

The study simulated a pedicle placement surgery in the lumbar spine region, as, according to the interviewed surgeon, surgery further up the spine is more likely to be an open surgery, while the intent of this thesis was to evaluate the MTA for the use in a minimally invasive surgery. For this study we designed a small rig, that sits inside a pretend patient and simulates their skin surface. The patient's body is simulated using two styrofoam boards, which offer a bit of resistance, but can be penetrated using the correct tools and block the participants of the study from seeing the tool's tip, once it is inside. Additionally, it offers a mounting point, like the one of the DRB of the Surgivisio Platform, to which we can mount either the optical reference marker or the MTA. The rig was conceptualized as part of the study, but the CAD-design and 3-D printing were conducted by an employee of the mediTec. Initially, we intended to include a spine phantom in the pretend patient;

The study simulated the placement of pedicle screws in a minimally invasive manner on the lumbar spine. The patient was simulated using a special construction, which imitates the skin with styrofoam board and offers a mount for the MTA and the optical reference marker.

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[2] https://atracsys.com/product/fusiontrack-500/ (11.12.2025)

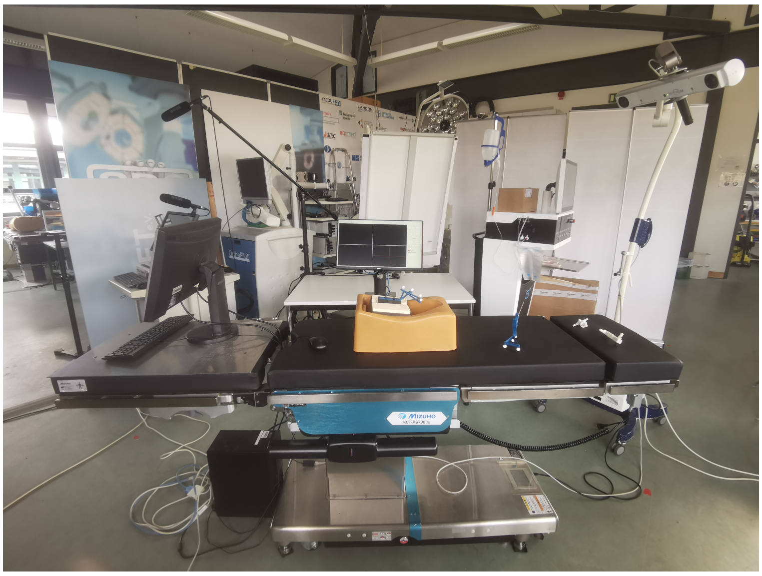

Figure 5.1: This is the setup used for the user study. In the back: A display showing the navigation software, which was moved to the other side of the patient if required. In the center: A surgery table with pretend patient to which the optical reference marker is attached. On the right: Optical tracking camera, which the participants could reposition if needed.

however, due to the inaccuracies of the MTA explained in Chapter 5.1 it was concluded, that accurately hitting a predrilled trajectory in the spine would be unlikely. While the spine would have given more realistic haptic feedback with an accurate system, not hitting the spine accurately would have probably caused more confusion than it would have done good. The setup used for the study can be seen in Figure 5.1. The pretend patient was positioned on a surgery bed with a screen for navigation in view of the participant. The screen was moved to the other side of the bed, whenever the surgery took place on the other side of the patient. Additionally, enough room was offered for the participants to move the camera to different positions.

As explained in Chapter 2.1, not all steps of placing pedicle screws are done using 3-D navigation. In particular, most methods do not place the screw itself under navigation and instead thread these over guide wires into holes that were created under navigation. For this reason, the study also only simulated the first step of creating a hole under navigation. Simulating the placement of a single screw in this study followed these steps:

To simulate the placement of a single screw a participant has to complete multiple steps.

1. **(Optional) Plan position of the screw**: The end position of the screw can be preplanned using the navigation software, as seen in Figure 4.4. This has benefits for orientation and planning with the MTA, but also has the drawback of requiring additional time. It was kept optional during this study, to see, if participants see this as a drawback of the MTA.

2. **(MTA only) Plan connection point**: The MTA requires some additional thought that needs to be put into its connection point. As explained in Chapter 4.3.2 there are multiple approaches that can be taken to accomplish this planning. It was kept open for participants to choose which, if any, method they wanted to use, so that their benefits and user preferences could be evaluated.

3. **Setup tracking**: Optical tracking and the MTA both require a bit of setup. For the optical tracking, this means correctly positioning the camera, so that it can see the reference marker and all markers on the tool. The MTA requires the user to connect it to the connection point of their choice.
   While the setup for the camera does not need to be repeated for every screw, if done correctly at the beginning, the MTA most likely requires a different connection point for different screws. However, the initial setup required for the MTA, which includes calibration and assembly, is only required once.

4. **Find incision point**: If the setup is complete, the participant is required to navigate to a point on the simulated skin, that is optimal as the incision point. This can be done using the 3 different CT views or, if a screw has been preplanned, with the help of the compensatory display. This step can be seen in Figure 4.6.

Participants can preplan the screw, if they are using the MTA, they must also plan its connection point, then the used tracking system needs to be set up. Afterwards, the participant can navigate to the goal position, puncture a hole through the styrofoam and advance to the required depth.

5. **Puncture the hole**: Lastly, participants need to puncture a hole through the styrofoam and advance the tool to the required depth.

Each participant placed four screws, two with each system, in specific vertebrae. The tracking system order and screw order was switched for every patient, to reduce the influence of learning effects.

Each participant was asked to simulate the placement of four screws, two with each system. These were, L1 on the left with system-1, L3 on the right with system-1, L1 on the right with system-2 and lastly L3 on the left with system-2. System-1 and system-2 refer to the MTA and the optical tracking system, the order of which were switched for every participant, while L1 and L3 are names of the vertebrae that the screws are supposed to be placed in. These positions were chosen for multiple reasons. First of all, L1 is the furthest vertebra from the mounting point, that is still inside the CT image, while L3 is the one closest to the mounting point. This allows for evaluation of the flexibility of both systems at certain ranges. The patient side is switched in between screws, because in actual spinal fusion surgeries the surgeons always work on both sides of the spine. In order to simulate some of the potential drawbacks the two systems might have regarding changing sides mid-operation, it was decided to include both sides with each system. Lastly, the switch in system order for each participant was conducted, so that potential learning effects or biases that stem from it have a lower impact on the overall study results.

Each participant was asked to fill out a SUS questionnaire for both systems, which can be used to measure and compare the usability of different systems.

After the test with each system, the participants were asked to fill out a System-Usability-Score (SUS) evaluation. The SUS is a method to evaluate the usability of a system, introduced by Brooke et al. [1996], which is useful in scenarios, in which the usability of multiple systems needs to be compared with a small time investment. It consists of ten statements, with which the participants have to state their level of agreement, on a scale from one to five. For this study a few of these questions were slightly altered to better fit the use-case of 3-D navigation:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.

4. I thought the system restricted my motion too much.
5. I felt like I improved at using the system during this study.
6. I think the setup process is too much work.
7. I think that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I did not trust the system to show me the correct position.

The SUS was chosen, because it can easily be adjusted and gives a good base for comparison of the usability of the two systems for a relatively small time investment.

To gain more insights into what the participants liked or disliked about both systems a semi structured interview was conducted at the end of the study. Additionally, the study was recorded for further analysis of the participants behavior.

However, while the SUS can give meaningful insights for the comparison of two systems, it is not good at finding specific attributes that make a system favorable or difficult to use. For this reason we also used the following qualitative evaluation methods. The study ended with a short, semistructured interview, in which participants were asked about their likes and dislikes of each system. Additionally, a few suspected pain points were questioned, like the positioning of the MTA, the relevance of joint limits, and the influence of line-of-sight problems. Furthermore, participants were asked to mention any thoughts they had about the tested systems during the study, and their behavior was analyzed. Participants were recorded visually and audibly during the entire study so that these clues could be evaluated afterward. While the recordings were not watched with the participants, any interesting behavior or comments that were noticed during the study execution were brought up in the interview.

To facilitate a more data-driven, quantitative analysis of potential problems of both systems, the used software was adjusted to log the time it took to position a screw, how much time was spent in a joint limit, and how much time was spent without line-of-sight.

5.2.2 Study Execution

The study was performed with 10 participants, some of them with minor experience regarding optical and mechanical tracking. None of them had a medical background.

The study was performed over the course of three days with a total of ten participants. Each iteration of the study required roughly an hour. Nine of the participants were students or employees of the mediTec and one was a visitor of the chair. Some of the participants had minor previous experiences with optical tracking, and a few had experience with the MTA. As experience with both systems was present to a similar degree, it was concluded that it should not skew the results in a meaningful way. Medical background knowledge for all participants was limited to technical knowledge. An evaluation with professionals was intended, but was not possible due to planning constraints.

A few relevant technical issues came up. The first joint broke and was as a consequence no longe restricted in its motion. The MTA broke into two parts twice during this study. The inaccuracies of the MTA made repositioning the planned screws, in some cases, necessary.

During and prior to the evaluation, a few technical issues came up, that could have an impact on the results. In a test run of the study shortly before the actual study, a pin in the first joint experienced irreparable damage. The consequence of which was, that the first joint is no longer restricted in its motion and can perform a 360° rotation. While this causes no problems in the current version of the MTA, as there are no cables running through this joint, it is not the intended behavior.
The other issue was, that after the second participant, the MTA broke into two parts. It was glued back together, but likely caused a decrease in accuracy for all the following tests. The same spot broke again right at the end of the evaluation of the fifth participant. It was glued back together and remained intact for the remainder of the study.
The inaccuracy of the MTA also posed some unexpected problems, in that sometimes the calculated position was so far off, that the tool would be outside the styrofoam area, when the navigation software showed it at the position of the screw. In these scenarios the planned screw was moved further inside of the area, even if this meant that it was no longer planned in the medically correct location. This allowed the participants to once again follow the navigation.
Lastly, logging data for one participant was incomplete and is therefore ignored in the analysis.

All participants were asked not to factor in the MTA's inaccuracy for their evaluation, as the goal of the evaluation was to gain insights into the MTA's usability when its inaccuracy problems are resolved. Furthermore, most participants spent a majority of their time trying to plan the screws in the correct position. This was surprising, as the user experience of planning the screw was not meant to be a focus of the study. However, the participants were asked not to include this step in their evaluation when filling out the SUS, as most of them did this for both mechanical and optical tracking.

Participants were asked not to include the MTA's inaccuracy and the planning step in their evaluation.

5.2.3 Results

The user study gave numerous insights into the usability of both the optical tracking system and the MTA. The following evaluation, however, mostly covers the MTA and only uses the results of the optical tracking system as reference.

Evaluation: System Usability Score

We ran a SUS evaluation during the study, the results of which can be seen in Figures 5.2 and 5.3. If we look at it from a broad perspective, we can see that 5 out of 10 people rated the optical system higher than the MTA, while only 4 people preferred the MTA. The optical system is also the preferred system if we compare the average score. However, according to Lewis and Sauro [2018] the standard SUS score goal in the industry is 80, which would be an above-average user experience. This means neither system had an exceptionally good rating. Nevertheless, the fact that the MTA, despite of its current accuracy issues, managed to gain an average score close to the optical tracking system, and in the opinion of some people even performed better than the optical tracking, shows that the MTA's usability could compete with that of the optical tracking system if the MTA gets further refinements. As previously mentioned, the participants were asked not to factor in the accuracy in their evaluation; however, an influence of the accuracy on

Overall, the optical tracking system is rated as more usable than the MTA. However, 4 out of 10 people preferred the MTA and the average score is only 6.75 points away from that of the optical system.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Average
S1	4	3	3	1	2	4	3	1	2	4	2.7
S2	3	4	3	2	4	4	3	2	3	3	3.1
S3	3	2	2	1	1	4	4	0	3	2	2.2
S4	2	4	2	3	2	4	4	1	1	4	2.7
S5	3	4	2	3	3	4	3	3	3	3	3.1
S6	4	4	3	3	4	2	3	2	3	3	3.1
S7	3	3	3	1	4	4	3	1	3	3	2.8
S8	3	3	3	2	1	2	3	1	2	3	2.3
S9	3	2	1	2	2	4	4	0	1	1	2
S10	3	3	3	1	2	4	4	4	2	4	3
Score	77.5	80	62.5	47.5	62.5	90	85	37.5	57.5	75	67.5

Figure 5.2: SUS results for the MTA. S1 - S10 are the statements of the SUS, and can be clicked for easier referencing. Ratings per statement are in the range from 0 to 4, where a higher number is a better usability, no matter if the statement is phrased positively or negatively. Scores are in the range from 0 to 100.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Average
S1	4	2	3	3	3	0	3	4	2	3	2.7
S2	4	3	4	3	4	4	3	4	2	3	3.4
S3	2	4	3	3	4	4	3	3	1	2	2.9
S4	4	4	3	4	4	4	3	4	1	4	3.5
S5	3	4	4	0	1	4	4	4	4	3	3.1
S6	4	3	4	3	4	0	4	4	2	3	3.1
S7	2	4	4	3	4	1	3	3	2	2	2.8
S8	2	3	3	3	3	4	4	4	1	1	2.8
S9	1	4	2	4	4	0	3	3	0	2	2.3
S10	0	4	4	4	4	0	4	4	3	4	3.1
Score	65	87.5	85	75	87.5	52.5	85	92.5	45	67.5	74.25

Figure 5.3: SUS results for the optical tracking system. S1 - S10 are the statements of the SUS, and can be clicked for easier referencing. Ratings per statement are in the range from 0 to 4, where a higher number is a better usability, no matter if the statement is phrased positively or negatively. Scores are in the range from 0 to 100.

the results is still likely, as it caused frustration and trouble with positioning for some participants. For example, it caused more people to run into issues with joint limits, because they had to go out of the suggested working area in order to navigate to their planned screw.

The optical tracking system has the lead or is rated as equally usable in all statements. The individual ratings vary greatly within one statement and seem to often correlate with problematic experiences.

A more thorough review reveals that the optical systems received ratings that are either equivalent to or higher than those of the MTA for all statements. The optical system has the biggest lead in Statement 4, which means participants on average favored the freedom of motion the optical system gave them, though the freedom of motion for the MTA is also not rated terribly. The second highest difference in rating exists for Statement 3, which tells us, that the average participant thought the optical system was a lot easier to use.

However, as with most of the statements, the ratings of the participants, regarding the ease of use of the MTA, vary greatly, with two participants rating it with the highest score, while another rated it with the lowest. These extreme differences in rating probably occurred, because some participants experienced problems others did not. In the case of the ease of use, the eighth participant was one of the only participants that spent a long time searching for the general area, in which they planned their screw, while under navigation. During this time, they did not work in the suggested area, which is the reason, why they had so many problems with joint limits not letting them move further into a direction. Most of the other participants managed to find the correct area a lot quicker, which let them have fewer problems with joint limits. This probably influenced their rating regarding how easy the MTA is to use. Similarly, participant six rated the optical system relatively badly in multiple categories, because the tracking system did not track their tool consistently for the entire time it took them to place the first screw. While participant 4, who had basically no navigation losses at all, rated it much better in most categories. These are just two examples of how problems that not everyone experienced, could have caused drastically different ratings.

Interestingly, the setup process for both systems, rated in Statement 6, was rated the same, even though the MTA's setup contains more steps. This seems to be the case, because most participants struggled with correctly adjusting the camera, so that even if it was just one step, it was seen as an equal amount of work.

Evaluation: Setup

As mentioned above, the SUS showed that the participants rated the setup process of the MTA and the optical tracking as an equal amount of work. While the optical tracking only has one setup step that caused most participants a bit of frustration, because they found it difficult to correctly orient the camera, the MTA needs multiple setup steps, a few of which caused trouble.

Calibrating did not pose significant challenges for the participants. The rig's design was intuitive enough, as long as they did not have to put the MTA into the rig on their own.

The calibration step was fairly easy for most participants. Pressing the calibration button and taking the MTA out of the calibration rig posed no trouble for any participant. Taking out the additional calibration volumes was also no problem once it was shown to them how the adapter mechanism works. However, during the study some special situations required a recalibration. If the participants had to put the MTA into the rig on their own, they were unable to do this. The rig does not make it clear which way all the joints need to be rotated for the MTA to fit. It is also not intuitive which way around the MTA needs to be put inside. Furthermore, some of the participants managed to fit the MTA into the rig, while one of its ends was sticking out. Lastly, the aforementioned broken first joint meant, that it could be placed seemingly correctly in the calibration rig, when it was in fact rotated by 180°. A wrong calibration like this could lead the surgeon to work on the wrong side of the patient, potentially causing severe injuries.

Connecting the MTA to the patient base connector, was made more difficult due to the connection point's proximity to the patient surface. Additionally, if the connector was not taken of before mounting or dismounting the MTA it was visible, that forces were applied to the patient.

Connecting the MTA to the patient base connector also posed a few challenges. These can be split into two main categories: trouble with the connector and trouble with the adapter mechanism of the MTA.
Most participants left the connector on the patient, when connecting the MTA. This posed a challenge for some of them, as there was not enough room for their hands to work freely, because the surface of the patient is close to the connector. One of the participants suggested changing the connection points to stick out at a 45° angle, as this would make connecting the MTA easier. The implications of this on the reachable areas would need to be determined and considered. However, it was also observable, that this pro-

cess applied forces to the patient, that we would like to reduce. Some participants opted for removing the connector from the patient, then attaching the MTA, after which they put the connector back in place. This removed the space restrictions other participants mentioned and also reduced the amount of visible force applied to the patient. Similar problems also occurred when participants tried to remove the MTA. One of them accidentally ripped the connector off of the mount, applying a big force to the patient. It may therefore be the advisable method, to take off the connector before attaching or removing the MTA.

Correctly differentiating the connection points posed a challenge for many participants. Multiple possible approaches were suggested.

Multiple participants struggled with correctly recognizing which connection point of the connector is the correct one. Some of them confused left and right, while one misunderstood the terms "head" and "feet" in this context and thought the center connection point of the connector had to show in the direction of the head or the feet. While most of them noticed their error, when the navigation software did not show the screw in the expected position, this could have catastrophic consequences if it goes unnoticed. Participants suggested color-coding or marking the connection points in different ways, instead of using the terms "left" and "right." This may however still be confusing when the connector gets rotated. It was also suggested to show the correct connection point using LEDs, though this would add additional technical challenges, and the connector would need to be able to recognize which way around it is mounted.

The adapter mechanism of the MTA caused some problems, because participants struggled to find the correct rotation for it. Furthermore, many participants found it hard to pull the mechanism back, because they had nothing they could press against.

The second category of challenges was caused by the MTA's adapter mechanism. It consists of a pin, that allows just one rotation to be correct, and a spring-loaded mechanism that needs to be pulled back during attachment and holds the connection in place afterward. Multiple people had problems correctly rotating the pin, as it cannot be seen in which direction it needs to be rotated during attachment. One participant suggested changing the mechanism in such a way, that the correct orientation can be assured, before the spring mechanism is pulled back. This might allow the user to see which way the MTA needs to be rotated.

This would be especially helpful, because a few participants struggled to apply force to the spring mechanism, especially for a longer duration, as they did not have anything to apply pressure against. They would have needed some position against which their thumb could have pressed. This was worsened, by the fact, that the connection point that was being used was almost always on the other side of the patient's body, which meant that the participants had to pull back the mechanism while it was facing away from them. This caused one of the participants to always move around the table anytime they had to attach the MTA, as it was easier for them to control the mechanism that way. This, however, would not be necessary if the connector was always taken off, as suggested earlier.

The MTA when it is not being used and si still attached has a tendency to be left laying on the patient.

Lastly, it often happened that the MTA was left dangling on the patients, when the participant was attaching or removing it from the connector. This also happened quite a few times, when they got distracted. While it had no consequence during this study, the impact might be problematic during a real surgery. The MTA could get entangled with a previously inserted Kirschner wire or come in contact with an open wound. Additionally, if the tool is still inserted in the MTA, it could harm the patient. This is a unique problem of the MTA, because the tool used under optical tracking can just be put to the side.
Professionals, would probably handle the MTA differently and would not just place it on the patient. However, in a time-critical situation, they could need to prioritize other tasks, which might require getting rid of the tool or the MTA quickly; this seems easier with optical tracking systems, and could cause surgeons to leave the MTA dangling as well.

Evaluation: Planning

Almost all screws were placed with prior planning and while most participants disliked the planning step they deemed it as necessary.

Planning was included and kept optional in the study, to see if the participants see it as a downside of the MTA or prefer to do it anyway. However, out of 40 simulated screw placements, only three were placed without prior planning, by two participants. All of them were placed with the optical tracking system. However, only one of those instances was a conscious decision; the other two screws were placed by a participant who later mentioned that they did not un-

derstand that preplanning was also an option available for optical tracking. While most participants disliked the process of planning the position of the screws in the software, they still mentioned that they would have been lost without the preplanned screw during the navigation phase.
However, this is one of the steps that was likely influenced the most by the fact that none of the participants had a medical background, as navigating a CT image without prior knowledge is difficult. For these reasons we conclude, that we can draw no conclusion if preplanning is seen as a drawback of the MTA. We did, however, gather insights into the design of the navigation software from this, which are mentioned in Chapter "Navigation Software".

We come to the conclusion, that we can draw no conclusion on whether or not preplanning is seen as a disadvantage of the MTA.

Planning for the MTA also includes determining the optimal connection point to use for a specific position. As mentioned in Chapter 4.3.2 the navigation software aids in this process using two methods.
The simpler of the two is the display of the area in which the use of the MTA is recommended. Most participants did not fully utilize this feature. When asked about it, they said, that they understood what it was showing them and could see it being useful, if they had not preplanned their screws. One participant mentioned, however, that they did not like the fact, that they had to click through all connection points one by one in order to display the areas. It may therefore be an interesting idea to test out a mode in which the areas for all connection points are displayed at the same time in different colors. While most participants did not use this feature, some used it to verify the suggestions they received for a screw, by the second feature.

The feature that renders the easily reachable areas in the planning screen, was not fully used by most participants. However, they could see it being useful when one does not preplan a screw.

The suggestion feature was used by all participants. When asked in the interview, multiple participants mentioned that they trusted the suggestion blindly and did not question its correctness. Most of the participants were of the opinion, that this feature or a feature like this is necessary for a good usability of the MTA. However, most of them came to the conclusion, that the feature is especially useful during a training phase and assumed that they could determine the optimal connection point on their own if they had more experience in the use of the MTA. One participant stated, that even if they had experience in the use of the MTA and knew which connection point should be the

The feature that suggests a good connection point, based on a preplanned screw, was used by all participants. Furthermore, most of them said that a feature like this is necessary for the use of the MTA or at least helpful during the learning process.

best for reaching a position, they would still use this feature to double-check their decision.
Multiple participants forgot to check the suggested connection point, prior to connecting the MTA, which led to them being confused about where to connect it and testing out multiple different connection points until they were satisfied or remembered the suggestion. Two participants mentioned, that they would have never expected the best connection point to be one pointing to the other side of the patient. Both of these insights further highlight the relevance of a connection point suggestion feature for the MTA.

Telling the navigation software how the MTA or the optical reference marker was connected, is something most participants forgot on their first screw. This could have dire consequences, which is why participants suggested several approaches to address this issue.

Most participants forgot to select the connection point they used for the MTA or the connection direction of the reference marker in the software on their first iteration of the study. This can cause the navigation to feel right, while it is actually flipped or rotated. If it is not noticed, this can have severe repercussions for the patient. For this reason it might be advisable to force the user to explicitly choose a connection point or orientation before they can start the navigation. Alternatively, an automatic recognition of the chosen connection point could be implemented. Participants suggested the following two methods. Using a verification step in which a user has to navigate to a known landmark or adding additional hardware in the connector, that can recognize where the MTA is connected and which way around it is mounted. Lastly, multiple participants wished for a feature, where they could click on a suggested connection point in the suggestion table and automatically switch to the navigation view with this connection point selected.

One participant, who struggled with correctly orienting all the joints, wished for a feature that could give them insights into the correct configuration. However, as already mentioned in Chapter 4.3.2, this would probably be difficult to communicate clearly. However, it might be an interesting idea to add a visualization of which joints are currently at their limit to the navigation software.

Evaluation: Navigation

Most participants stated that the navigation loss with the optical tracking system was an annoyance, even though the environment offered perfect conditions for the optical tracking system. There were no assistants walking through the line of sight, and the camera could be moved nearly everywhere so that the participants hands were not in the way; however, most participants still experienced significant navigation loss. Figure 5.4 shows the percentage of time participants spent without navigation for each screw. On average, participants spent 17.6% of the time without navigation, but the average time participants spent with navigation increased from their first screw, which was either L1L or L1R, to their second screw, which was either L3L or L3R. This shows a clear improvement, which was mostly caused by a better-adjusted camera, though some participants also learned to hold the tool in a more favorable angle. This, however, was mentioned in the interview as a downside of the optical tracking. Participants did not like having to keep in mind how to hold the tool for optimal tracking. One caveat of this measurement is the fact, that navigation loss happened very frequently, but every time it did occur, it only occurred for a short time. Thus, the actual time the navigation was practically unusable was higher than 17.6%.

Even though the study conditions were perfect for optical tracking, most participants struggled with navigation losses. This was mainly caused by poor camera positioning, which improved for many participants on their second screw.

Contrary to the optical tracking system, the MTA does not have any situations in which a navigation loss can occur. This was seen by many as a clear upside of the MTA. Additionally, most of them enjoyed the fact that they did not need to think about how they needed to hold the tool for optimal tracking. However, the study revealed an interesting behavior shown by all but one participant. They usually used one hand on the tool to navigate and had a second hand further back on the MTA. When asked about it, most participants stated that they did this subconsciously, while others said they did this because they felt like it made the MTA easier to control or more accurate. One participant specifically mentioned that they did this to reduce the influence of the MTA's weight on their motion. Using one hand further back on the MTA and one hand on

All but one participants held the MTA with two hands, one on the tool and the other one further back on the MTA. This was mostly a subconscious decisions, but multiple reasons were given by the participants.

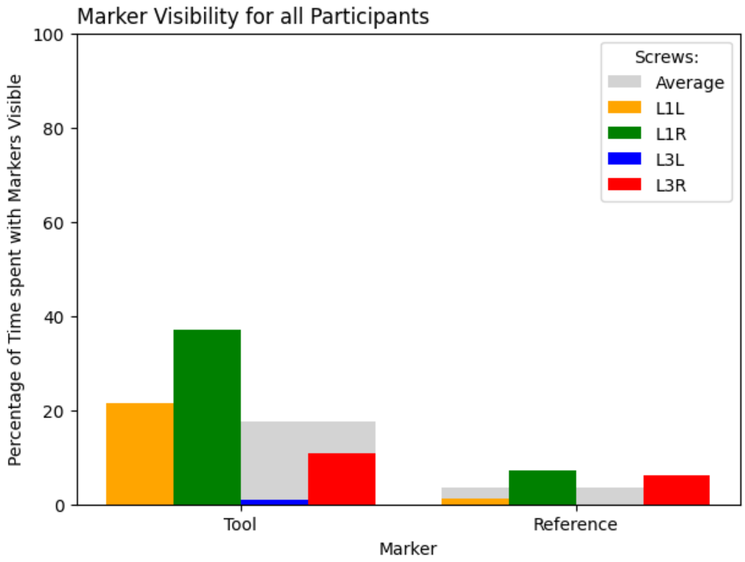

Figure 5.4: This graph shows the average time, in percent, the tool and reference markers where not tracked by the optical tracking system. L1L, L1R, L3L and L3R stand for different screw positions.

the tool, means that participants had both hands already in use. This stopped them from using a technique most of them used with the optical tracking, that is also used by the interviewed surgeon, which is to use the second hand to navigate the tool at its tip. This allows for easier fine control.

Another issue with with holding the MTA and the tool that revealed itself during the study, is that participants did not always realize that they needed to hold the tool together with the tool mount. Instead, a few of them let the MTA slide down the tool and then wondered why the navigation software showed them a wrong position. As a consequence of this, multiple participants wished for the capability to fix the tool to the mount so that this cannot happen and they gain greater freedom to hold the MTA as they feel comfortable with.

The study also provided insights into the consequences the MTA's joint limits have on its usability. There was no consensus among the participants on whether the MTA's joint

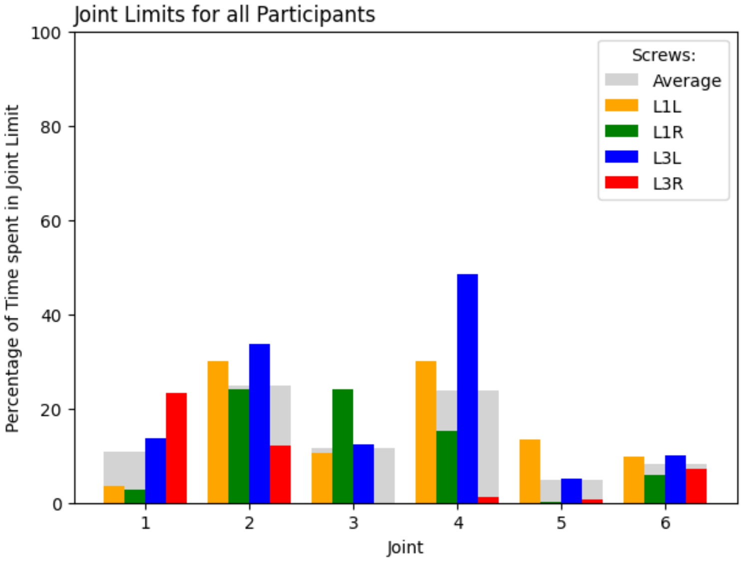

Figure 5.5: This graph shows the average time participants spent in the limit of different joints in percent. L1L, L1R, L3L and L3R stand for different screw positions.

limits hindered its usability. Multiple of them mentioned that they had not really noticed them whenever it was relevant; others had an issue with them, because they did not manage to reach their desired location. As all of them used the planning feature of the navigation software, the limits were not a big problem in the actually relevant areas; however, the inaccuracy of the MTA and differences in planned screw poses meant that some participants had to venture further out of these recommended areas for the navigation to fit their planning. In these outer areas, hitting joint limits became more prevalent. This, however, was also described as an advantage by one participant. They at first had a hard time relating their movement to the navigation shown on screen and quickly noticed that every time they hit a joint limit, they were moving away from their actual goal. The joint limits basically defined a working area for them.

Some participants thought the joint limits were a problem, others did not find them hindering. The chance of running into joint limits was increased due to the accuracy of the MTA.

Moving to a data-driven insight on the MTA's joints shows, that the average time spent in each joint's limits varies greatly per screw and joint. Figure 5.5 shows the average time all participants spent at the limit of each joint. Un-

The percentage of time joints spent in their limit varies greatly from joint to joint. For some of them we can explain why they spent that much time in a limit.

surprisingly, the time spent in joint-2's limits is high, as it needs to be at almost 90° or more, for the MTA to reach over the connector to the correct side of the patient, which means even in an ideal joint configuration, it is always close to its limit. However, it also did not matter so much if joint-2 hit a limit, because the same task can be taken over by joint-3 which rotates along the same axis and spent a lot less time at its limit. Joint-4 was also one of the joints that spent the most time in a limit. For joint-4 this can be explained by its significant contribution to the MTA's degrees of motion. Its rotation axis allows the MTA, in combination with joint-5, to reach a greater number of orientations. This means that for numerous poses, this joint needs to be fully utilized, which leads to more time spent in joint limits.

A comparison between the data of two participants shows, that the time spent in each joint varies greatly for each participant. However, the time spent in joint limits and the participants opinion on whether or not joint limits are a problem does not correlate.

However, if we compare the data between two participants, we can see that they utilized each joint in very different manners. Figure 5.6 shows the time spent in joint limits for the first and ninth participants. If we look at this one-by-one comparison, which was chosen for its extreme difference, we can see that one participant only hits the limit of three joints and for screw L1R only of one joint, while the other participant went into the limit of almost every joint for all screws. Interestingly, despite what these figures might lead one to believe, in the interview only the first participant mentioned that they were annoyed by the joint limits. The ninth participant said that the limits were not really a problem. In total, most participants came to the conclusion, that the limits are only a slight bother and are mostly annoying if they are in a entirely wrong orientation, in which one cannot even get close to the correct pose. This was seen by multiple participants as part of the setup process and not as a problem during navigation. However, there was one participant that despised the use of the MTA because of its limits and few that were annoyed by them. When watching the study, it was noticeable, that in multiple situations a correct position was just barely not reachable; therefore, an increase of the joint's rotary freedom by a few degrees might significantly increase its usability.

We conclude that the damage to the first joint did not influence the data of the study to a relevant degree.

Figure 5.5 also shows that the average participant spent 10.8% of their time at the limit of the first joint. As mentioned in Chapter 5.2.2, the first joint was broken during this study and allowed for 360° rotation. Because of the

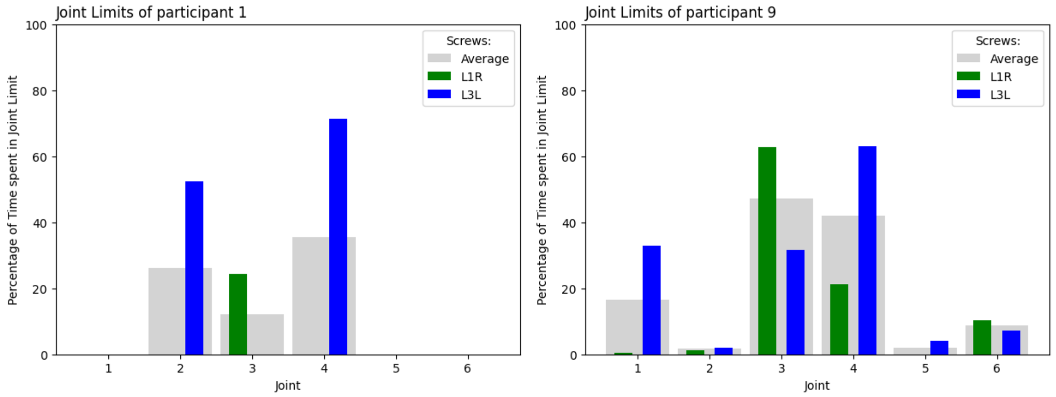

Figure 5.6: This Figure shows the time spent in each joint limit for the first participant on the left and the ninth participant on the right. L1L, L1R, L3L and L3R stand for different screw positions.

low percentage of time spent in this limit and the fact that rotation far outside this joint's usual rotation range does not yield favorable MTA poses, we come to the conclusion, that the insights collected during this study are not relevantly influenced by the joint's damage.

Once the first joint of the MTA came in contact with the styrofoam area, which in a real surgery would have been the skin of the patient. This caused the joint to be harder to move, because of the caused friction, which was seen as a problem by the participant that experienced this.
Another very severe problem occurred, because of the MTA's contact with the patient. Three different participants managed to switch the MTA off, because the On/Off switch came in contact with the edge of the styrofoam. While this might be less likely with real skin, as it is much smoother, the fact that it can happen accidentally is a problem. This always happened in the most critical phases, when the tool was already inserted into the patient, as the MTA needs to be almost parallel to the patient at this point of the surgery. After the MTA is turned off, it needs to be recalibrated, for which the MTA has to be dismounted again. This whole procedure takes a few minutes for inexperienced users, and all participants that experienced this were of the opinion that this must not be possible.

Contact of the MTA with the patient can cause problems. The most relevant of which is the chance of the MTA being turned off during its use.

An issue that only occurred once, but was also perceived as problematic by the participant, was that a connection point of the connector stood in the way of the tool. This likely only happened, because the MTA was inaccurate and the suggested reachable area was chosen a bit too big. However, it could be completely avoided, if the connector was to be redesigned so that both sideway connection points were on the same side of the patient. This would allow for the same amount of connection points, but with a bigger working area.

While the reason for a navigation loss of the optical tracking system was often unclear to the participants, two of them said, that they felt like errors with the MTA were a lot easier to understand. This was the case, because most of the time the cause was something they could see, like a wrongly oriented joint or the wrong connection point.

Evaluation: Navigation Software

Many participants struggled with rotating views or how the views are rotated during the navigation phase.

The participants also provided feedback regarding the navigation software, which was not MTA related. As its continued development was part of this thesis and the feedback might be interesting for future work on the navigation software, all the gathered insights into the software's usability are collected in this chapter.
Many participants struggled with rotating the CT views or a loaded object in the planning screen. Currently one needs to hold the right mouse button and then move the mouse up or down. Most participants tried to move the mouse horizontally.
The rotation of the CT views in the planning screen and the navigation screen are not synchronized; this was criticized by multiple participants, as it caused confusion as to what they were seeing in the individual views.
The CT views in the navigation screen can optionally be set to rotate with the tool. While some participants preferred this setting, most were confused by it, because they then had to think about how to hold the tool so that the navigation software showed them the CT image from the expected sides. A similar issue was solved during this thesis for the

compensatory display, and the solution could also be applied to the CT views. The views would be easier to read, if the rotation around the roll axis of the tool was canceled out for the calculation of the view's rotation.

The colors for the navigated screw and the planned screw were difficult to differentiate for one participant. It might therefore be a good idea to change these or add options for colorblind people.

Chapter 6

Summary and Future Work

Our work provides the software integration for a small, lightweight, wireless mechanical tracking arm. We created a flexible software stack, that can adjust to different environments and versions of the MTA. An extended navigation software offers support using the MTA. This is done through a reachability estimation we designed. Two different methods of defining reachability as well as two different methods of communicating this reachability were explored. The navigation software has been designed to support both optical and mechanical tracking, which simplifies the future comparisons between these two methods.

We integrated the MTA into a navigation software. This included the addition of a reachability estimation.

A user study was conducted to evaluate and compare the usability of the MTA for pedicle screw placement with that of an optical tracking system. This included a SUS evaluation of both systems, which revealed that most participants preferred the usability of the optical system. However, it also indicated that the MTA could become viable, if its usability is further improved.

A user study showed promise for the MTA, but also revealed that optical tracking currently has a higher usability.

User observation and their comments during and after the study revealed benefits and downsides of the current designs of the MTA and navigation software. One key insight is that joint limits, even though they hindered participants in many scenarios, were not seen as a major problem by

The user study revealed benefits and downsides of the MTA and the navigation software.

most participants. The study also revealed, that most participants used the MTA with two hands, which limited their fine control of the tool's tip. The reasons for this differed from participant to participant, but most of them did this unconsciously. Another key issue was the handling of the MTA's adapters, as many participants struggled with the mechanism and correctly rotating it, when connecting it to the patient.

The suggestion as to which connection point to use, was universally trusted. However, many participants forgot to tell the software that they were going to use the suggested connection point and had trouble with correctly identifying connection points on the patient.

A short technical evaluation revealed potential causes of inaccuracy, as the MTA with its current accuracy could not be used in a surgical environment. Prevalent reasons include inaccurate magnetic encoders and slack in the joints.

6.1 Future Work

We conclude that future work should first focus on ensuring the MTA's accuracy and the consequences of forces being applied to the patient through the MTA.

Future work must first address the open technical challenges that could still stop the MTA from being a valid alternative to the optical tracking. The MTA must incorporate more accurate rotation encoders, as the currently used encoders were shown to be insufficient for high accuracies.
Furthermore, an evaluation of the forces that are applied through the MTA needs to be conducted to gain insights into its effects on the spine, as strong forces might invalidate the CT image and the registration of the MTA's position.
The identification of connection points suggested by the software on the connector needs to be improved to reduce the error rate. User errors could be reduced by clearer markings, and an automatic recognition of whether the MTA has been correctly connected could prevent consequences caused by mistakes.

Another interesting topic for future work could be an improvement to the automatic reachability estimation. If the

MTA is supposed to be used as a flexible tool for more than just one specific surgery, a better implementation of this concept could significantly reduce the workload of configuring the MTA for a new scenario. A special focus should be put on the readability of results.

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