Delft University of Technology

Faculty of Electrical Engineering, Mathematics and Computer Science

RFID-Enhanced Surgical Tool Interfacing

BSc Graduation Project
EE3L11

BAP Group G.1

Authors:
Simon Klappe (5397480)
Glenn Vriesman (4780647)
Jesse Wessteijn (5289998)

July 1, 2024

Abstract

This report entails the design process and development of an RFID (Radio Frequency Identification) system that must serve as a user interface for a surgical tool developed by SLAM Orthopedic. The goal of the user interface is to allow a surgeon to make selections as input for the surgical tool. The RFID interface is specifically designed to fit into the device, which leads to several design constraints like power consumption and size. The RFID system uses a coil antenna which was tuned for a specific frequency with the help of a Vector Network Analyser and Smith Charts. A prototype for the system was made but not finalised, however, results of the tuning process and research on RFID technology showed that an RFID system could be a promising interface for this surgical tooling.

Preface

This thesis is presented as part of the Bachelor Graduation Project from the Bachelor of Electrical Engineering at the TU Delft. The project was made with close involvement from the project proposer, SLAM Orthopedic. This project was carried out by six students, divided into 2 subgroups. Each subgroup had the same problem but tried to develop a different solution. Where this subgroup settled on RFID, the other subgroup chose to implement a Hall sensor as an interface.

We would like to thank our supervisor dr. Massimo Mastrangeli, who was not only closely involved but also very enthusiastic about our project. Secondly, we want to thank the proposers of our project, Bart Kölling and Tijs Moree from SLAM Orthopedic. Their help with the project, the option to work at YES!Delft and the demonstrations of the ADEPTH system made this thesis possible. Lastly, we would like to thank Dr. Chris Verhoeven for his assistance during circuit tuning and guidance in understanding the Vector Network Analyser (VNA).

Simon Klappe, Glenn Vriesman and Jesse Wessteijn
Delft, June 2024

Contents

List of Figures

List of Tables

1 Introduction

During Plate Osteosynthesis, metal plates are fixed to the bone with screws to properly heal broken bones, an example can be seen in Figure 1 [1]. To ensure the proper functioning of the screws and plates, the screws have to be of the right length. This length can be determined by the depth of the hole drilled by the surgeon. To determine the depth of the hole, SLAM Orthopedic made a product called the ADEPTH [2].

Figure 1: Screws are placed in a broken bone to hold it in place Figure 1.

1.1 The ADEPTH

The ADEPTH is an innovative device that is added to the drill and fits in between the drill and the drill bit. The ADEPTH automatically measures the total distance drilled and the length of the screw needed. In order to determine the exact screw length, the ADEPTH needs to know the diameter and type of the screw before drilling. Together with the measured rotation speed, pressure and distance to the bone, the ADEPTH can calculate the precise screw length. This information is sent to the second part of the ADEPTH system called the bridge which displays the required length on a touchscreen. Currently, this touch screen is being used to show and select the screw type, this can be seen in Figure 3 [3].

1.2 Problem statement

SLAM aims to transition to using the overhead, non-touch screens already available in operating rooms. By doing so, SLAM can provide the ADEPTH as a standalone product to hospitals, eliminating the need to supply an additional screen to already crowded operating rooms.

This brings us to the purpose of this thesis: developing an alternative screw selection mechanism for the ADEPTH to replace the touchscreen.

Figure 2: A CAD model of the ADEPTH [2].

Figure 3: The ADEPTH in a demonstration [3].

1.3 Preliminary Research

Before a prototype can be designed, it is important to be aware of the limitations related to a hospital environment. This section will give a brief overview of important aspects to keep in mind during design: the structure of the operating room, sterilisation, drilling and intuitiveness.
The following acronyms will be used:

CA: Circulating Assistant

OR: Operating Room

OS: Operating Surgeon

SA: Sterile Assistant

1.3.1 Lay-out of the Operating Room

An orthopaedic OR consists of a sterile and non-sterile zone; the operating surgeon (OS) and the sterile assistant(s) (SA) are in the sterile zone. There are usually between 3 and 10 people present in an OR, of which 2 to 5 are sterile [4]. It is incredibly important that people do not switch between zones, as that severely increases the risk of infection in the patient. The instruments/tools used during the operation are placed in the sterile zone close to the SA. Everyone in the sterile zone is scrubbed (cleaned) and has protective, sterile, clothing to prevent contamination [5]. The screws used during the operation are stored in the non-sterile zone and are handed to the OS or SA by the CA, see Figure 4. Each time a new instrument is needed, the OS communicates this with the SA. This means that the instruments are constantly switched between the OS and SA and must also not leave the sterile zone.

1.3.2 Sterilisation

Sterilisation is critical in orthopaedic surgeries, where infections in the bone can be fatal to the patient. For this reason, all equipment is placed in metal racks and sterilised in a high-speed pre-vacuum steamer for five minutes, using steam with a temperature of around 134° C [6]. All equipment that will be sterilised must be able to withstand the vacuum and high temperature for the required time. Different cycles can be used for sterilisation [7]; some cycles don't pull the chamber vacuum, but instead frequently change between 33 and 30 PSIA. Because of this, the sterilised items deteriorate; for example, the ADAPTH only guarantees 20 uses per device. This is because the sterilisation damages the sensors and internal equipment and their accuracy is no longer guaranteed after 20 sterilisation.

1.3.3 Drilling in orthopaedic surgeries

In orthopaedic surgery, plates are used to stabilise fractured bones and are available in various sizes. The type of screw required can vary depending on the situation. To place these screws a hole has to be pre-drilled. During drilling, drill guides are placed on the bone to keep the drill stable. The most common types of screws used are:

- Cortical
- Locking
- Variable Angle (VA)

Concluding from the datasheet of plates given by SLAM Orthopedic [1], each type of screw uses a different guide: a locking screw uses a guide that secures it to the plate, while a cortical screw employs a guide with a handle to adjust the angle. Variable angle screws (VA screws) utilise a specialised guide that allows adjustment to various angles within the plate. Switching between different kinds of screws occurs frequently, the procedure for this can be seen in Figure 4. In practice, the correct guide is not always used for the screw type that is being placed. Sometimes, the procedure differs from the standard approach [8].

According to orthopaedic surgeon de Hartog [8], the drilling procedure starts with the SA switching to the correct drill bit onto the drill. Subsequently, it needs to be known for what screw type will be drilled, since the measurement of the ADEPTH depends on that. The drill and the drill guide will be handed over to the OS, who will drill the hole. With the measurement from the ADEPTH, the surgeon will ask the CA and the SA for the correct screw length, of the previously chosen type. Then, the drill will be passed back to the SA, who will switch the drill bit for a screw bit. The SA also receives the sterilised screw of the correct length and type from the CA. Both of these will be passed to the OS, who will screw in the screw with the drill. After the screw has been secured in place by the OS, the drill will be handed back to the SA. Now, this cycle can be repeated until all the different screws have been placed [8].

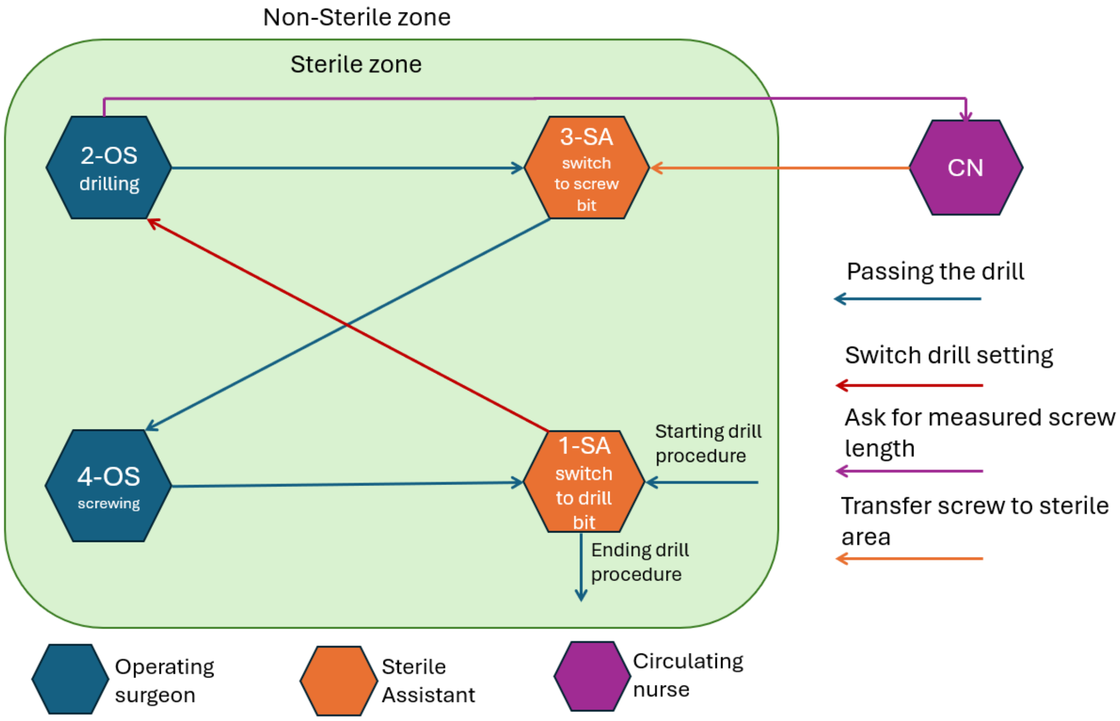


Figure 4: Communication during a drilling procedure in an orthopaedic surgery.

When looking at this procedure, it can be seen that either the SA or the OS can select the to-be-used screw type for the ADEPTH. This can be done after the SA places the correct drill bit on the drill. The CA should not be considered an option to select the screw type, because they are not involved enough in the surgery to know which screw type is used. If the CA has to select the screw types, the chances of human errors will most likely increase, which is undesirable. This is something that needs to be taken into account when designing a solution for the problem.

1.3.4 Intuitiveness

In an interview with plastic and orthopaedic surgeon John Barker (Appendix A.1), it became apparent that any new addition to a surgical procedure must be intuitive and simple to use. Surgeons are trained to follow specific methods and procedures, and, therefore, changing their established ways of working can be challenging. Thus, a good solution would be simple, intuitive, and user-friendly.

It became evident from the interviews with Doctors Barker and de Hartog (Appendix: A.1 & A.3) that each surgeon has distinct preferences for handling procedures. Doctor Barker prefers to manage tasks himself, whereas Doctor de Hartog wants the assistant to preset everything, allowing him to focus without interruptions. From the interviews, it was concluded that both the OS and the SA should be able to use the solution.

1.4 Possible solutions

In order to solve the given problem, it is important to stay open to all possible solutions. The research from the previous section has led to specific design limitations and recommendations. A key limitation is that the tool must be exclusively used in either the sterile or non-sterile part of the OR, not both. The decision was made to place it in the sterile area, as it would be operated by the operating surgeon and surgical assistant. This necessitates the product's ability to withstand sterilisation processes involving high temperatures, vacuum environments and water resistance. The primary design recommendations focus on intuitiveness, ergonomics and minimal disruption to the surgeon's existing workflow. Intuitiveness and ergonomics are crucial as they significantly affect the tool's effectiveness, error rates and user comfort. The emphasis on practicality is vital, as the surgeon might reject a tool that is not user-friendly.

The following potential solutions were evaluated:

- ID tracking - Using RFID (Radio Frequency Identification) or barcodes to identify tools and automatically apply the correct settings, ensuring efficiency and reducing manual input errors.
- Macropad - A sterilisable mini keyboard or a wrist-worn device that enables the selection of screw types directly within the sterile field, enhancing workflow efficiency.
- Foot pedals - Foot-operated controls to select screw types, though potentially prone to errors and ergonomic issues.
- Hand gestures - Utilising cameras or sensors to detect non-contact hand gestures for tool selection, although accuracy may be affected by lighting conditions.
- Rotary encoding - Implementing a rotary switch or hall sensors on the ADEPTH for tool selection, offering a reliable and intuitive solution, albeit with potential sealing challenges for mechanical switches.

1.5 Proposed solution

After considering all options against the design constraints and recommendations, barcode scanning, foot pedals and hand gestures were eliminated from consideration due to their impracticality for surgical use. Additionally, the macropad was discarded since it requires additional hardware and is difficult to sterilise effectively. RFID and rotary encoding emerged as the most promising replacements for the touchscreen. Since the OS and the SA alternate in using the drill, it is most convenient to integrate the solution in that step. This keeps the chosen solutions intuitive in use and easy to integrate into the existing ADEPTH system and workflow of the OS and SA. This thesis will focus on the implementation of an RFID-based selection method. This would allow the selected screw type to be detected automatically, without the surgeon or assistant giving any input.

2 Programme of Requirements

The following requirements were agreed upon with the project proposer, SLAM Orthopedic. During the project, there will be a differentiation between "The System" and "The Prototype Design". Due to the limited amount of time, it was deemed that a full design of 'The System' was not feasible and therefore a 'Prototype' Design is considered. The system is the solution that can directly be integrated into the ADEPTH and should comply with all the system requirements listed below. The prototype design serves as a 'proof of concept' to show that the solution developed in this paper could theoretically work as an interface for the ADEPTH. The prototype design does not have to fully comply with the system requirements, but in theory, could be further developed into a fully integrated solution. A block diagram of the system is given in Figure 5.

2.1 System Architecture

A system is proposed where an RFID reader is placed in the ADEPTH and RFID tags in the reflection plate. Each screw type has a corresponding reflection plate with a unique tag, the surgeon can then scan the tag to select a screw type. Ideally, the reader is only active during drilling so that the tag is read automatically when drilling. In case the read distance is not large enough the surgeon has to place the tag on the ADEPTH before drilling.

2.2 User Requirements

The system must have the following functionalities:

- The system shall select the correct screw during Plate Osteosynthesis procedures.
- The system shall require no input, or be controlled by the surgeon or the sterile assistant.
- The system shall be easy to use in the current workflow.
- The system shall be intuitive and ergonomic.

2.3 System Requirements

Global Requirements:

- The system shall integrate into the existing ADEPTH design by providing input to the ADEPTH Software.
- The system shall not compromise the airtightness of the ADEPTH Sensor.
- The system shall communicate with the ADEPTH sensor with a UART protocol.
- The system shall be resistant to reprocessing by steam autoclave sterilisation [7][6].
- The system should last at least 20 reprocessing cycles before a breakdown of any kind occurs.

Technical Requirements:

- The reader should have a range of around 20 cm to read the tag while drilling.
- The system shall not use a voltage higher than 12 V.
- The system shall not reduce the battery life of the ADEPTH Sensor by more than 25%, for a battery of 250 mAh.
- The system shall not use more than 125 mA for a pulse of 15 seconds.
- The system should not use more than 62.5 mA when on standby.
- The part of the solution inside the ADEPTH should be smaller than the inside diameter, 38 mm.

Optional Requirements:

- The reflector pieces could be reusable.
- The prototype could have an option to re-select the screw type afterwards.

- The prototype could be integrated with the actual ADEPTH.
- The tag should be smaller than 26 mm with a hole in the middle or smaller than 9 mm so it can fit on the reflector plate.

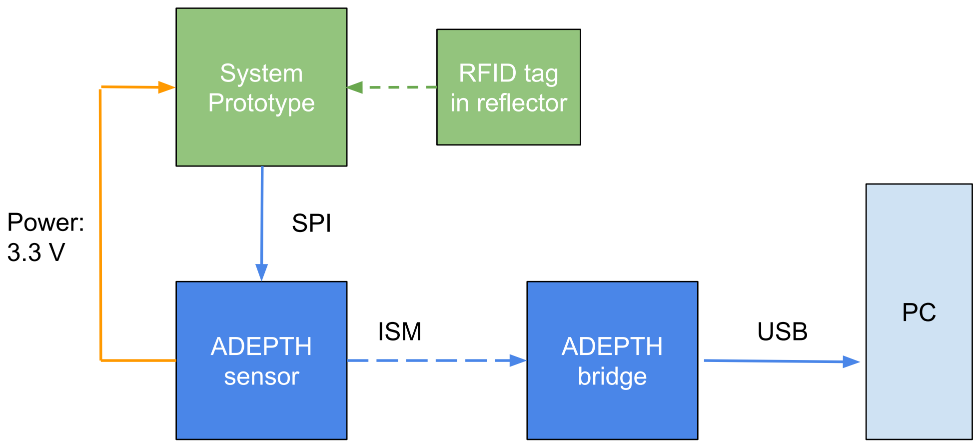


Figure 5: Block diagram for an ADEPTH with integrated RFID system.

3 Design

RFID (Radio Frequency Identification) is a technology for identification using radio waves, its main parts are an RFID identifier (a tag, also called a responder), a reader and a data system for handling the information. RFID tags, which include an antenna and a chip for information storage, are commonly installed on targets that need to be identified. The content of the chip can be read and written with an RFID reader. The technology is comparable to a bar code system, where a reader reads the information from a bar code. RFID systems can read and write tag information without a line of sight. This means that the information of a tag can be rewritten, whereas the barcode is immutable.

Taking into account the principles of a user-centred design [9], the system would be implemented as follows: each screw type of which the surgeon must make a selection has a unique drill guide that is used during drilling, each drill guide will be fitted with an RFID tag corresponding to a specific screw type, an RFID reader can then read the tag - without any input from the surgeon - and send the information of the tag to the ADEPTH bridge. An example of a drill guide is given in Figure 6 [2]. Each drill guide is fitted with a reflector plate that the ADEPTH system needs for measuring. The tags need to be placed on/in this reference plate, so the tags need to be small. The total solution has two components: an RFID reader and RFID tags, see Figure 7.

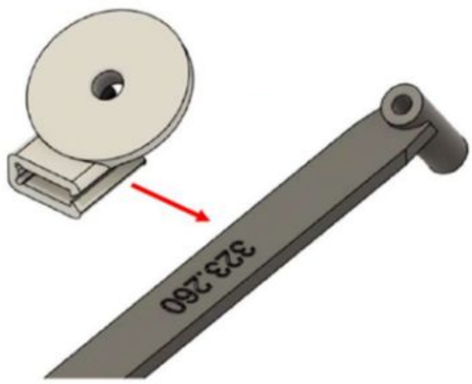


Figure 6: Drill guide with the reflector plate on which the tag will be placed [2].

The goal is that the reader is only active during drilling, this is done so that the surgeons do not have to change their current workflow to scan the tags. Another reason to only scan during drilling is to save power, if the reader would constantly sends signals the requirements for power in subsection 2.3 would not be met. When a surgeon starts drilling, the distance between the ADEPTH sensor and the drill guide is at most 20 cm, so we aim to have a read distance of around 20 cm. It takes only a few seconds for the surgeon to drill a hole, we assume that this will be more than enough time to read the tag because the amount of data the tag has to send is very small.

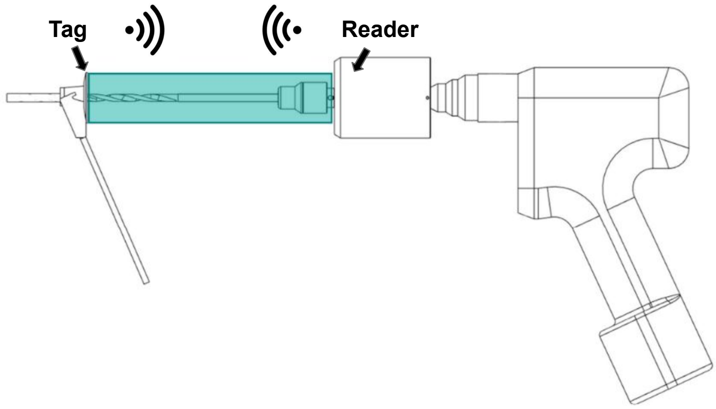


Figure 7: Design overview with the RFID-enhanced ADEPTH.

3.1 RFID Tag

A tag is the second part of an RFID system that stores the information that the reader wants to read or write. A tag can be passive or active and is usually tuned for a single frequency. There is a wide variety of commercially available RFID tags which differ greatly in size, cost and application. When an RFID reader emits an electromagnetic field, the RFID tag captures this field to power itself. It then transmits its data back to the reader, which receives the information.

Battery-assisted passive (BAP) RFID tags also require the carrier wave from the reader to operate. However, these tags are equipped with a battery, typically a button battery, which primarily powers the chip. This setup enhances the tag's performance and reliability.

3.1.1 Passive RFID Tag

A passive tag has no internal power source and uses the energy from the signal sent by the reader. The tag uses the signal to simultaneously power its electronics, read out the received instruction from the reader and store energy to send a signal back to the reader. Figure 8 [10] shows an example of a circuit for a passive tag. A tag consists of the following components; an antenna to receive and transmit information, a diode bridge to provide a DC voltage, power storage and an integrated circuit (IC). The antenna of an RFID tag is usually a coil and can be printed on a PCB or even a thin plastic label. The antenna is dual-purposed, it functions as a receiver and transmitter (transceiver). The diode bridge converts the AC voltage from the signal to a DC voltage to supply power to the IC and power storage. The IC contains a microprocessor and a memory bank to facilitate communication with the reader, the memory in the tag can be read out or even rewritten. The power storage (named power generation in the figure) stores the energy needed to send a signal back to the reader.

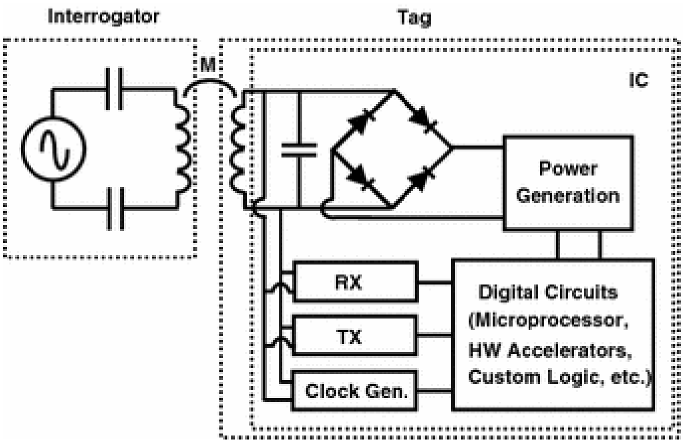


Figure 8: Example of an RFID tag circuit [10].

3.1.2 Active RFID Tag

Active RFID tags are equipped with their power source, typically a battery, which enables them to broadcast signals at much higher strengths compared to passive RFID tags. This intrinsic power supply allows active tags to be read from distances of up to 100 meters or more, depending on environmental conditions and the type of reader used.

Active RFID tags are commonly used in scenarios where long-range tracking is crucial. For example, they are employed in tracking large assets across extensive areas, such as containers in ports, vehicles in large manufacturing facilities, or equipment in sprawling hospital complexes. Due to their higher power and longer read range, these tags are ideal for managing logistics, enhancing security, and optimising asset utilisation.

Moreover, active RFID tags can support additional functionalities beyond simple identification. They may include sensors that monitor conditions such as temperature, humidity, or movement, making them valuable for applications that require environmental monitoring or condition-based maintenance. This capability makes active RFID technology a versatile tool in industries like healthcare, manufacturing, and supply chain management.

Even though the active tags would increase the read range, it was decided to use passive tags for the system. The reference plate is quite small so it would be difficult to fit a battery on the plate. These batteries are also highly specialised which makes them quite expensive.

3.2 Location

There are multiple options to place an RFID reader. One such location might be above the operating table. This would prevent any modifications to the ADEPTH itself but would require an external power supply due to the distance between the reader and the tag. Another potential problem could occur when there are multiple tags on or around the operating table. The reader would have to have an extremely focused sensing area in order to not detect multiple tags at once. Next to that, if the sensing area is too wide, it could interfere with other medical devices that might operate on the same frequency range[11].

A second option would be to place the reader in the front part of the ADEPTH, this way the antenna will be closer to the tag which will reduce the required power of the reader. This would prevent the need for an external power supply and thus allow for a compact design. Lastly, using this design would also allow for the ADEPTH to be shipped as a single device, instead of shipping multiple components.

After consideration of the requirements stated in subsection 2.3, it was decided to develop a prototype that would integrate with the existing ADEPTH.

3.3 Frequency

RFID systems make use of different frequencies and the properties of the system depend greatly on the used frequency. The most commonly used frequencies are low, high and ultra-high frequencies (LF, HF and UHF respectively). LF and HF systems are usually used for short-range applications and use a magnetic field (inductive coupling) for communication with the reader and tag. UHF are used for longer ranges and use backscatter coupling instead of inductive coupling. The frequency ranges along with the typically used values and the read range [12] are listed in Table 1.

Type	Frequency range	Typically used	Read range
LF	30 - 300 kHz	125 kHz, 134.2 kHz	10 cm
HF	3 - 30 MHz	13.56 MHz	30 cm
UHF	300 - 1000 MHz	passive: 433 MHz active: 860 – 960 MHz	30 m 100 m

Table 1: Relevant frequency ranges for RFID implementations.

Interference caused by metal objects depends on the used frequency, UHF is the most susceptible to interference while HF is only moderate. This might become a problem when taking into account the fact that the ADEPTH will have a drill bit attached to the front, see Figure 7, as this could have an impact on the resonating frequency of the antenna [13][14].

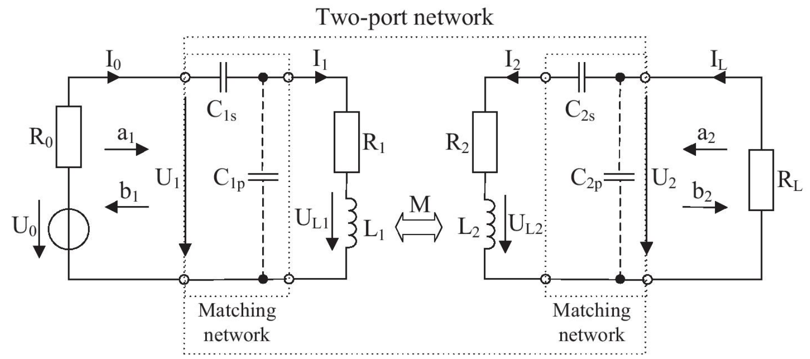


Figure 9: Simplified circuit of a reader and tag with inductive coupling [15].

As stated in section 2, the system will only have access to a limit amount of power. To determine the power usage for LF and HF the circuit in Figure 9 is used, this simplified circuit uses inductive coupling between the reader and tag. The capacitors are used for impedance matching and the inductors represent the coil antennas coupled by a mutual inductance (M). When a series matching on the secondary side is used the active power supplied to the load can be calculated by the formula described in Equation 1 and Equation 2 [15].

$$R = R_L, \quad X = \frac{-1}{\omega C_{2s}}. \tag{1}$$

$$P_L = |I_2|^2 R = |I_1|^2 \frac{\omega^2 M^2 R}{(R_2 + R)^2 + (\omega L_2 + X)^2}. \tag{2}$$

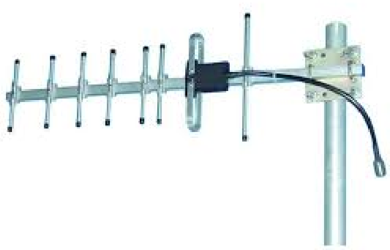
Here k is the coupling efficient and M is the mutual inductance. This method gives the power supplied to the tag as a function of the frequency. However, this power also depends on the inductance of both coils ($M = k\sqrt{L_1 L_2}$). Because the coils have a different number of windings depending on the used frequency it is difficult to compare the power usage of LF and HF based on frequency.

In conclusion, taking the power requirements as stated in subsection 2.3, distance requirements as stated in subsection 3.2 and the potential interference due to metal objects as indicated earlier in this section, it can be argued that HF has the most potential to give the desired result. Therefor, the most commonly used HF frequency, 13.56 MHz, shall be used.

3.4 Antenna

Ideally, the antenna in the reader should have a high gain in only the forward direction, but due to the limited space in the ADEPTH, there are some restrictions on the design of the antenna. As indicated in subsection 2.3, the maximum diameter of the antenna can be 38 mm.

One corollary from the proposed design is that an antenna with a very high gain in only one direction is desired because the tag will be directly in front of the reader when the surgeon starts drilling. Most RFID readers use a simple coil antenna, this antenna type has a high but also symmetrical gain. Since the reader will not have to read tags behind the drill, this part of the radiated power is essentially wasted. There are several antennas with the gain concentrated in only one direction, 2 examples are the Yagi and parabola antenna (shown in Figure 10 [16][17]). The Yagi antenna achieves a high gain by using reflector elements that superpose and interfere with the radiation [18]. The parabola antenna - also called disc antenna - uses a reflective disc to 'steer' the signals in a single direction.



(a) Yagi antenna [16].

(b) Parabola antenna [17].

Figure 10: Antennas with high directional gain.

The radiation patterns of the antennas in Figure 10 are given in Figure 11 [19]. The antennas have a high gain in only one direction, which would be very beneficial for the RFID system. Unfortunately, due to the physical design, they are impractical to implement in the ADEPTH. The Yagi antenna is quite long in the direction it sends the signal and the parabola antenna uses a disc which is much larger than the antenna part.

Figure 11: The radiation patterns of a Yagi and parabola antenna [19].

Most commercial RFID readers use a coil antenna integrated into a PCB, this antenna can be made very thin (depending on the number of windings and the thickness of the wire) which makes it a promising choice for the system. The implementation of the antenna on a PCB was deemed impractical due to the size constraints. Therefore, a coil antenna was chosen instead. The coil antenna has the advantage that it can easily be tailored to fit neatly inside the ADEPTH. The coil will be made of isolated copper with a thickness of 0.6 mm^2.

3.4.1 Power in RFID coil

The read distance of an RFID reader depends among other things on the power supplied to the reader. The power consumption of readers can range between 0.3 W for short distances and up to 15 W for a read distance of around 10 meters. The reader can send a signal in all directions with equal power (omnidirectional) or it can focus most of the power in one direction (directional).

For a reader, there is usually a distinction between near and far fields. The near field close to the antenna is inductive whereas the far field uses electromagnetic radiation, as can be seen in Figure 12 [12].

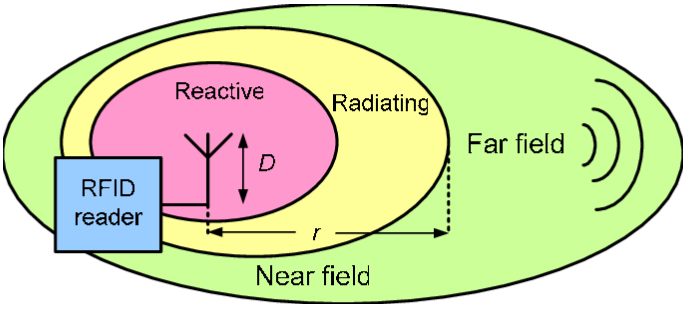


Figure 12: A visualisation of the near and far field radiation of an RFID antenna [12].

3.5 Integrated Circuit

A coil alone will not be sufficient. The coil needs a signal to transmit, and in the case of RFID, this signal needs to be tailored in such a way that not only information is present in the transmitted signal, but also that the signal has enough power to supply a passive tag with the power it needs to reply with a message. To achieve this purely with a circuit would be too complex and outside of the scope of this thesis, thus it would be practical to offload this work to a dedicated integrated circuit (IC). This IC will do the encoding and decoding while the antenna and supporting circuitry can be designed purely for transmission.

To drive the coil described in subsection 3.4, not only must the IC meet the requirements described in subsection 2.3, but it must also comply with a few additional requirements. Namely, it must be able to independently be able to convert a digital signal to an analogue signal, it must be able to drive the coil without an external power supply feeding the coil and it must be able to generate a signal at 13.56 Mhz (as per subsection 3.3). Taking these requirements in mind, the NXP MFRC522 was selected. According to the data sheet [20], it will be able to drive the antenna with minimal input from external circuits and thus meet all the requirements. A high-level system diagram for the circuit can be seen in Figure 13.

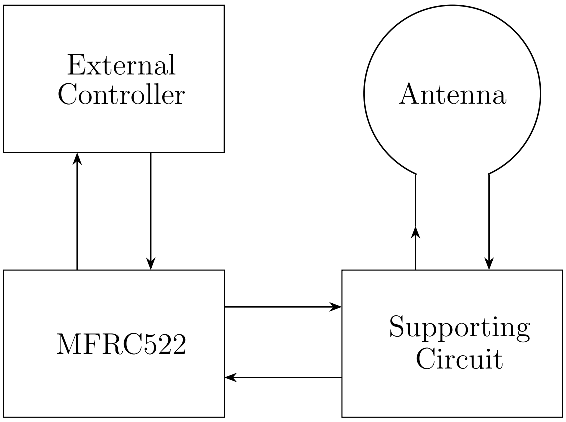


Figure 13: Interaction between IC and antenna.

3.5.1 Signal modulation

The IC needs to encapsulate all the information into the analogue signal in a way that the receiver can process it with minimal effort. For this, the MFRC522 uses Amplitude Shift Keying (ASK) modulation and a modified version of Miller encoding. A simple example of ASK modulation can be seen in Figure 14. The modulation technique is very intuitive, the carrier signal is only transmitted when the digital signal is high.

There are special waveforms which are used for power optimisation that can be used to increase the range of the reader [21]. However, the MFRC522 can only use ASK modulation so it was chosen not to use these methods.

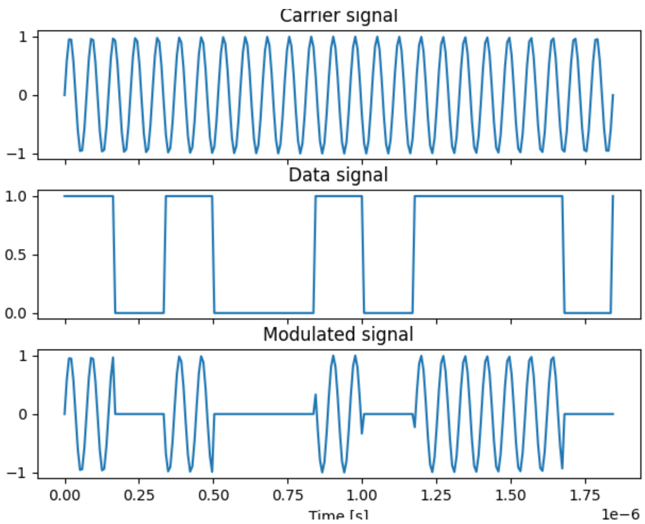


Figure 14: Example of ASK modulation on 13.56 MHz.

3.5.2 Digital Communication

To communicate with the MFRC522, there are several possible communication methods. Namely, I2C, SPI and UART. As per the requirements specified in subsection 2.3, the final design should make use of the UART protocol to communicate the tag selection, but for the prototype, any arbitrary protocol can be used as long as the final result is a message over UART. For this reason, I2C and SPI can be considered.

One of the key differences between SPI, I2C and UART would be the transfer speed. According to the datasheet[20], the MFRC522 supports SPI for up to 10 MBit/s, I2C supports at most 3.4 MBit/s in its highest speed settings and UART would support 9.8 MBit/s. In case of the prototype, there are no speed requirements, however judging purely based on speed it would suggest that SPI would be the best option as multiple sensors in the final system would all need to use an interface.

Another consideration to take into account would be the physical implementation of each protocol. I2C and UART both work with just 2 wires, whereas SPI requires 4 wires, a clock, a selector wire, a receiver wire and a transmitter wire. This might be an issue in extremely compact systems where every connector counts, but in the case of the ADEPTH this is not the case. For a system where the amount of wires is critical, a decision could be made to select I2C, however for the prototype this is not an issue. Therefor no protocol can be excluded based on physical constraints.

A final remark to consider is the current implementation of the ADEPTH. It already uses all three discussed protocols, but for high-speed measurements it uses SPI. A possible scenario would then be that all sensing components use the same interface, namely SPI, instead of using a mixture of different protocols. Moreover, the firmware of the ADEPTH would allow for easy integration of the new component into the system, with relatively limited lines of code to control the MFRC522.

Taking all these considerations into account, the decision to use SPI as the main interfacing method was made. This does have implications for prototyping, however, namely that there needs to be a microcontroller to simulate the ADEPTH during development. Which in turn can log the selected screw type over UART.

3.6 Supporting Circuit

The IC and antenna alone are not sufficient to transmit or receive a meaningful signal. To ensure that the antenna resonates at the right frequency and to ensure sufficient power transfer from the IC to the antenna, there needs to be a support circuit. Namely, a receiver, a matching circuit, a filter, and an oscillator. A reference starting point given by the manual for the MFRC522 [20] can be seen in Figure 15.

It should be noted that the design in the reference circuit is symmetrical, this will yield some problems when tuning the values of certain components. Therefore, two versions of the circuit should be made. One asymmetrical version, to be able to check the design with a Vector Network Analyser (VNA), and one symmetrical version which will be used as the actual circuit for the prototype.

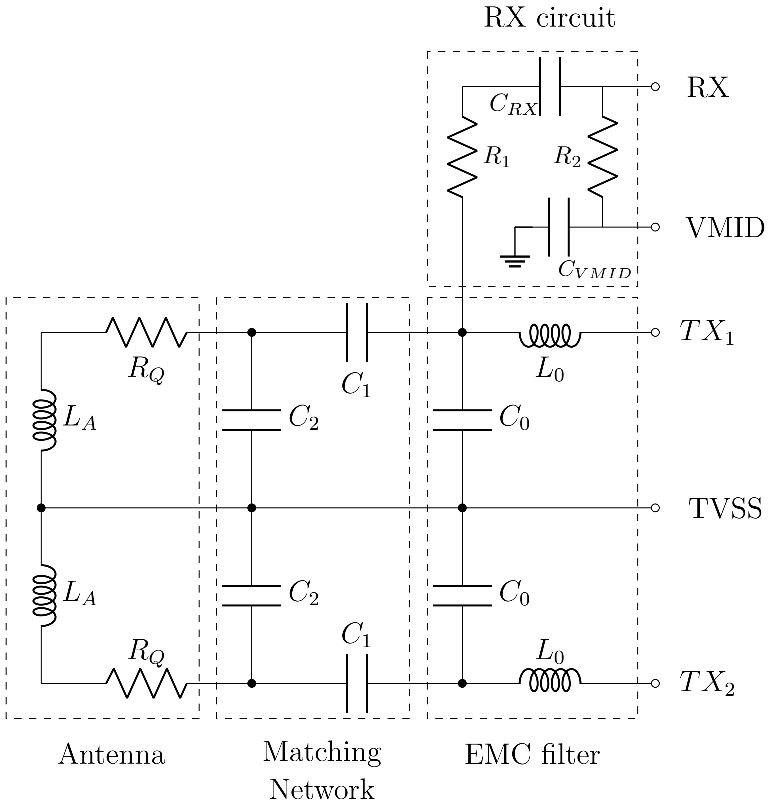


Figure 15: Supporting circuit containing the four sub-circuits needed to transmit and receive an RFID signal.

3.6.1 EMC Filter

Whenever you connect a device to a power source, there is bound to be some noise present on the signal. In the case where this noise can cause significant problems, it can be remedied by making use of a filter. Based on the selection made in subsection 3.3, the desired signal frequency is 13.56 MHz. This means that a bandpass filter can be designed to filter all signals that are not between 13 MHz and 14 MHz thus reducing harmonics and filtering out any DC offset.

In the reference circuit provided in Figure 15 a symmetrical design for the filter is used. However, for selecting the component values, a simpler asymmetrical design shall be used. Using this circuit would allow the circuit to be analysed with a VNA that is made for asymmetrical circuits. This does come with the caveat that this circuit needs to be transformed into its symmetrical variant before it can be used in the final antenna design.

3.6.2 Impedance matching

The antenna will be produced by winding a wire into a coil and thus will behave like a normal coil. This will turn the load into a complex load. To ensure maximum power transfer, the source impedance has to be equal to the complex conjugate of the load impedance [22]. This means that the supporting circuit needs to incorporate a matching circuit. This matching circuit will collaborate with the filter described in subsubsection 3.6.1 and antenna described in subsection 3.4 to ensure that the full impedance will be equal to the input impedance imposed by the IC described in subsection 3.5. The reference circuit can be seen in Figure 15.

It is important to note that the entire support circuit has to be matched, it is not possible to design the matching circuit separately from the other components. Furthermore, to be able to analyse the circuit with a VNA, an asymmetrical version should be built. This should then be converted to a symmetrical circuit to achieve a functional antenna.

3.6.3 Oscillating Circuit

For the MFRC522 to be able to generate a proper signal at the desired frequency, an external reference clock is needed. This clock will ensure that the internal clock, used to generate the signal, is properly timed at 13.56 MHz. The required frequency of the oscillator is twice the desired frequency. In the case of 13.56 MHz, the oscillator has to have a nominal oscillating frequency of 27.12 MHz.

To enable quick prototyping, a through-hole component that can be quickly replaced is desired. This leads to the selection of the LFXTAL036075 Crystal oscillator [23] as the external clock. This oscillator does require two capacitors connected to the ground, as can be seen in Figure 16. For optimal functioning of the external clock, a capacitance close to the load capacitance of the crystal should be used.

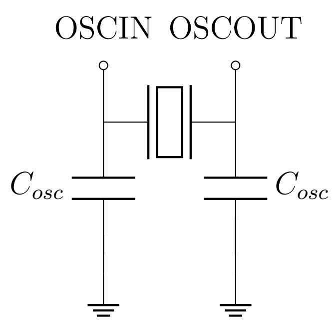


Figure 16: Supporting clock circuit.

3.6.4 Receiving Circuit

To be able to read the incoming signal, a small receiving circuit is required. This consists of a voltage divider, a decoupling capacitor C_{vmid} and a DC blocking capacitor C_{RX}. The values of the resistors are determined by calculating the voltage drop over the capacitor C_0 in the EMC filter to ensure that the voltage on V_{RX} is 1V. To measure the voltage drop over the C_0 capacitor, a probe with less than 2pF capacitance is required, which necessitates specialised equipment [24]. With this value determined, the values of the resistors can be calculated.

3.7 Tuning procedure

To achieve a resonance frequency of 13.56 MHz, the values of the capacitors, resistors and inductors need to be chosen precisely. While this can be done through trial and error, a much more effective and precise method would be to use a Smith chart. By plotting a Smith chart, it can quickly be seen if the values of any of the capacitors need to be changed. By iterating a few designs, a matched circuit can be achieved.

3.7.1 Quality factor

For the system to have a strong enough signal transferred to the tag, the antenna needs to have a quality factor of around 35 [20]. This can be achieved by picking a value of R_Q and recalculating the value of the quality factor.

3.8 Microcontroller

Since the MFRC522 will not do anything without proper control, a separate microcontroller is needed to simulate the ADEPTH. To simulate the behaviour correctly, it needs to comply with the requirements defined in section 2. One microcontroller that would meet the requirements, is the Adafruit Feather 32u4 [25].

3.8.1 Wireless communication

In order to transmit relevant information from the ADEPTH to the screen currently present in the OR, the ADEPTH utilises the ISM band to communicate between the ADEPTH and a bridge connected to the screen. For the design of the prototype, the 868 MHz part of the ISM band shall be used.

4 Implementation

In this section, the details of the process regarding the creation and testing of the prototype for our system will be discussed. This includes the construction of the prototype, the development of the antenna circuit and the evaluation of the prototype's performance. The use of the Feather 32u4 microcontroller, the construction and tuning of the antenna circuit and the results obtained from the prototype testing will be discussed.

4.1 Prototype

The prototype serves as an initial physical implementation of the system using the design choices made in the previous section. The prototype design shall be used to demonstrate the functionality of the final system in a simulated environment using a Feather. As stated before in section 2, the prototype design does not have to comply with all of the system requirements, but the system requirements should be achievable in further iterations of the design. The prototype must be able to send information to the ADEPTH bridge. It shall provide input to the ADEPTH software through a separate data channel, with a 868 MHz ISM data command. The prototype will function as shown in the block diagram in Figure 17.

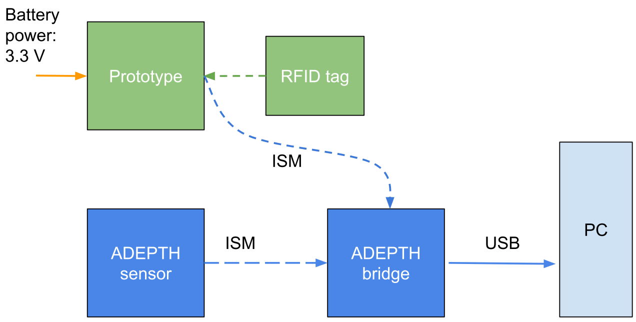


Figure 17: Block diagram RFID prototype.

4.1.1 Microcontroller

As stated before, the microcontroller used is a Feather 32u4, the exact model that SLAM used for their prototype. It has an ISM band radio transceiver, allowing the microcontroller to simulate ADEPTH and send data to the bridge. The MFRC522 RFID chip is connected to the microcontroller using SPI. To control the MFRC522 RFID chip, Arduino code has been written which can be found in Appendix B. This code is tested with a reference RFID Arduino board module [26]. This board was used for the first prototype. Once communication with the MFRC522 RFID chip was established, an RFID tag could be read. Only the ID is important and this data must then be transmitted to the bridge. The transmission is facilitated by the onboard ISM 868 MHz module on the Feather 32u4. The ID stored in the tag is then sent over the ISM band to the bridge.

The chip also has a continuous wave mode. In this mode, the chip will send continuous waves over the TX channel. This is useful to test and measure antenna circuits. The code to achieve continuous wave mode can be found in Listing 1.

4.1.2 Antenna Circuit

To initiate the prototype development, a coil must be wound. The coil can be seen in Figure 18, constructed from insulated copper wire, specifically with a cross-sectional area of 0.6 mm^2, and wound to fit the dimensions of the front of the ADEPTH device. The coil consists of 2.3 turns and has an inductance of 0.385 mH, with a series resistance of 13 $m\Omega$. This configuration yields a self-resonance frequency of 71.2 MHz. A Vector Network Analyzer (VNA) is used to obtain these measurements. Upon obtaining these measurements, further calculations for the rest of the circuit can be conducted. The intended circuit design is referenced in Figure 15. Initially, the circuit will be designed asymmetrically, as illustrated in Figure 19. An EMC filter is selected for a resonance frequency of 14.6 MHz. Subsequently, the values of the matching capacitors are determined using the Smith chart shown in Figure 20. This Smith chart is created with an online tool [27].

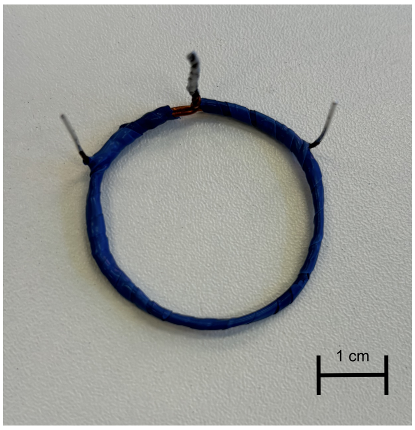


Figure 18: Coil used for the prototype.

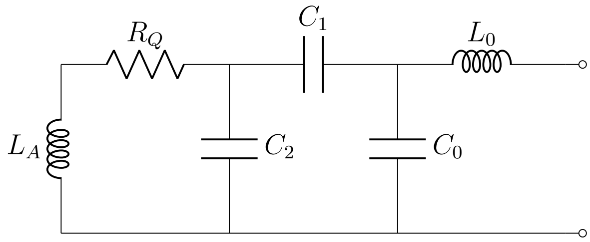


Figure 19: Antenna circuit first Iteration.

Initially, a matched circuit was created using the Smith chart shown in Figure 20. The black lines show the impact of the circuit components on a frequency of 13.56 MHz, while the red line represents the circuit's response at 13.56 MHz ±13 MHz. The Smith chart appeared correct, resulting in the values shown in Table 2. This circuit was then created and tested using a VNA, with the test results displayed in Figure 21. As observed, the charts in Figure 20 and 21 are quite similar. The real values proved to be favourable, and the Smith chart exceeded expectations. However, when later tested with the chip, the circuit did not function.

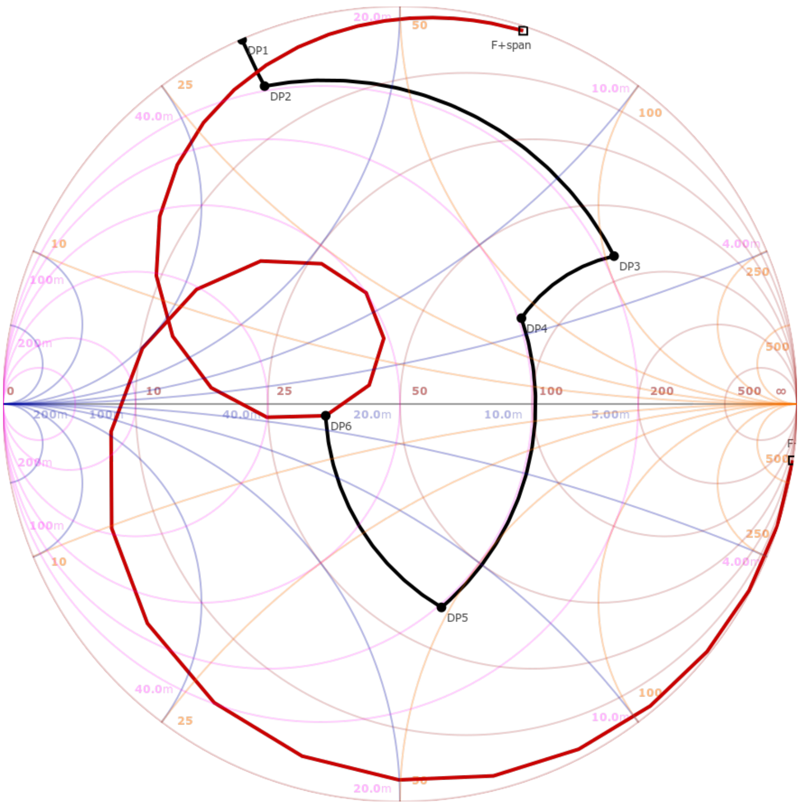


Figure 20: Smith Chart of the first design.

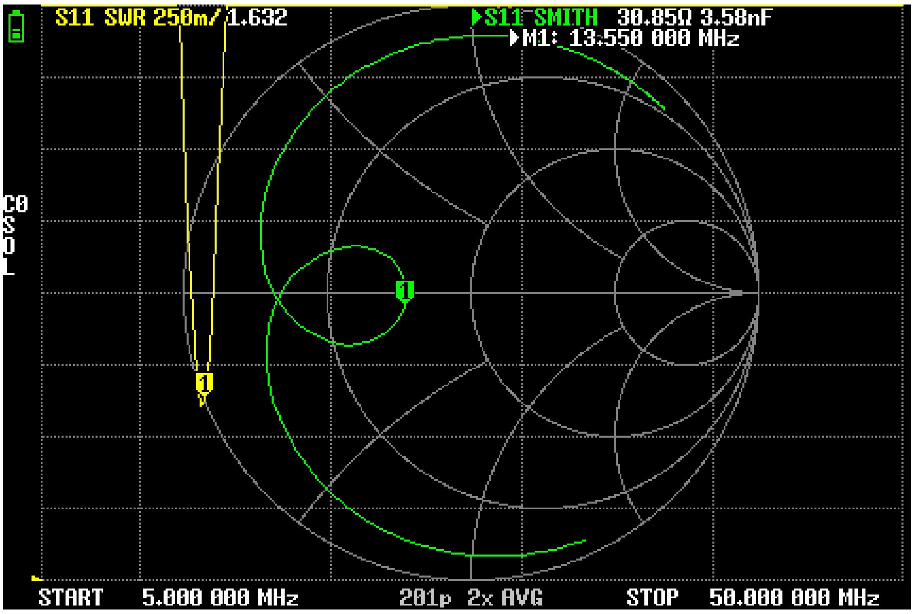


Figure 21: Vector Network Analyser on the antenna prototype circuit.

After some investigation, the next step involved returning to the simulations. LTspice was used to simulate the circuit with an AC sweep, resulting in the Bode plot shown in Figure 22. The simulation was performed using a 1 V AC power supply without current limitation, making the dB scale on the y-axis incorrect compared to the chip. The red dotted line indicates the required resonance frequency.

Component	Values
L_A	$192.5\ nH$
R_A	$13\ m\Omega$
R_Q	$4\ \Omega$
L_0	$540\ nH$
C_0	$220\ pF$
C_1	$180\ pF$
C_2	$280\ pF$

Table 2: Values for the first iteration of the antenna circuit.

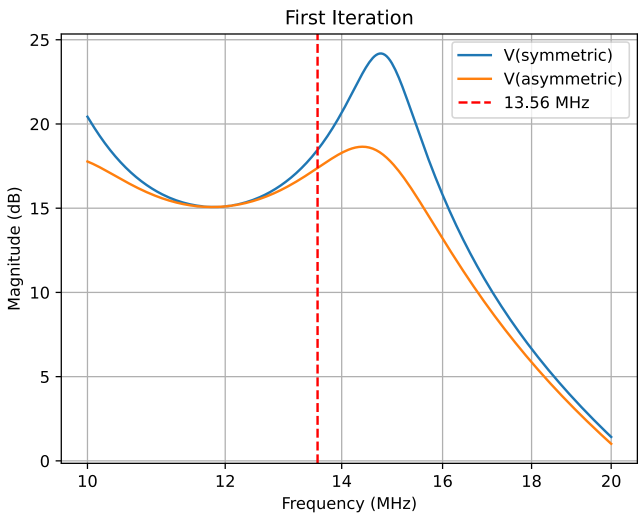


Figure 22: Bode plot of first design.

The Bode plot indicated that the resonance frequency was incorrect, which could explain why the circuit did not function properly. Since the MFRC522 RFID chip provides only a small current, it may not be sufficient to drive the circuit. Therefore, the circuit was not tuned correctly. A new calculation was necessary, beginning with the resonance calculation of the coil and parallel capacitor, followed by tuning the values in LTspice. This adjustment resulted in a promising Bode plot, as shown in Figure 23.

Component	Values
L_A	$192.5\ nH$
R_A	$13\ m\Omega$
R_Q	$4\ \Omega$
L_0	$540\ nH$
C_0	$220\ pF$
C_1	$500\ pF$
C_2	$390\ pF$

Table 3: Values for the second iteration of the antenna circuit.

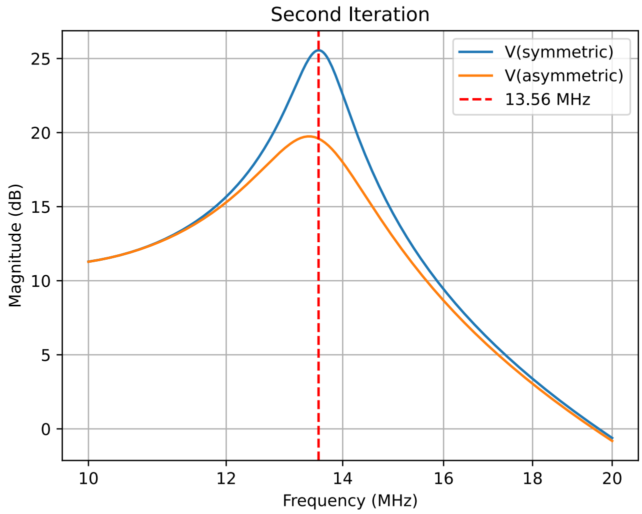


Figure 23: Bode plot of second design.

The values of this circuit that produced this Bode plot can be seen in Table 3. The quality factor denoted as R_Q, remains unchanged, as does the resonance of the EMC filter. In theory, this was already correct. After this redesign, the circuit response was checked using the Smith cart simulator [27]. The result can be seen in Figure 24. The matching seems off and will be around 25 Ω in the complete symmetric design. The last black dot should be around 25 Ω on the horizontal axis. The matching will then result in 50 Ω. To be sure this circuit has to be built and tested using a VNA.

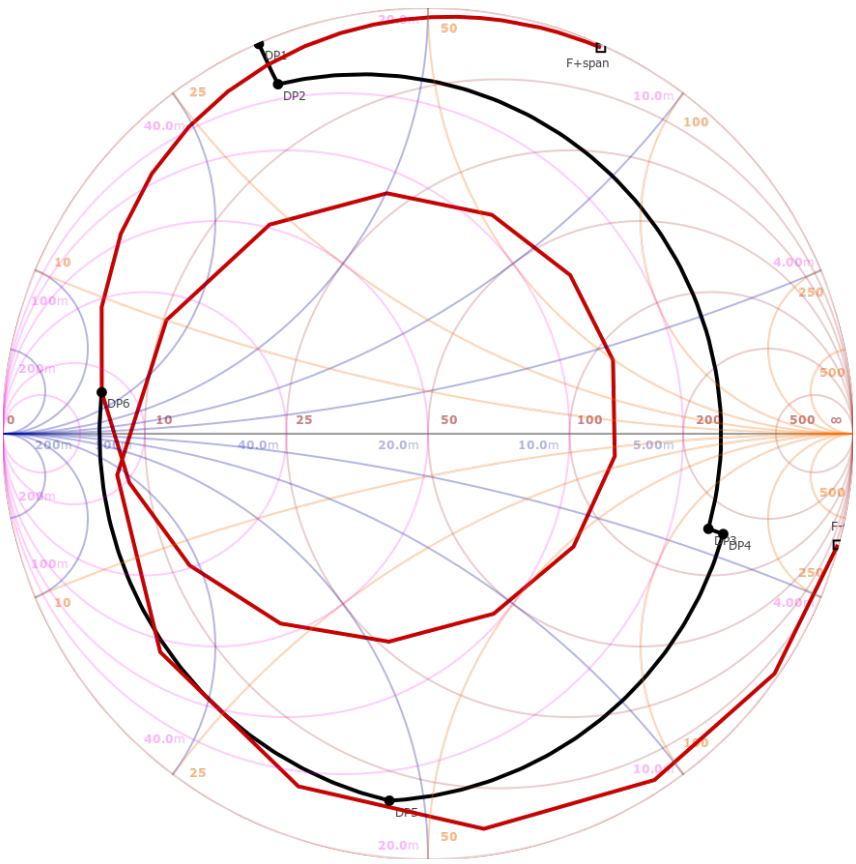


Figure 24: Smith Chart of the second design.

In theory, the circuit should respond when connected to the chip. The values provided in Table 3 can be used to achieve a fully symmetric design of the antenna, as illustrated in Figure 15. The next step would be to implement the RX circuit. It should start by connecting the circuit of Figure 15 without the RX-part to the chip and putting the chip in continuous wave mode. The chip will then send a 13.56 MHz continuous wave over the antenna. Then the voltage drop over the 220 pF capacitor needs to be measured. This can be done with a < 2 pF differential probe. The RX circuit can be found in Figure 15.
Predefined components:

- $C_{RX} = 1$ nF: DC blocking capacitor
- $C_{VMID} = 100$ nF: Vmid decoupling capacitance
- $R1 = 1\ k\Omega$: Predefined part of the voltage divider

With these values, the voltage divider resistor R_2 can be calculated using Equation 3. With a U_{RX} of 1 Volt the R_2 value can be found after measuring.

$$R_2 = R_1 * \left(\frac{U_{c0}}{U_{RX}} - 1 \right) \tag{3}$$

This has not yet been done due to the time constraints of this project.

4.1.3 RFID tags

Due to the limited time for the project, it was decided to leave the implementation of the tag in the ADEPTH system for further research. Because the tags will be used in an operating room they need to be sterilised, this means that the tags need to be able to withstand a temperature of 134°C. Commercial RFID tags that can withstand these temperatures are widely available but are hard to fit on the reference plate because it has a hole in the centre (Figure 6). It would also be possible to design and develop the tags with a hole in the middle so they can neatly fit on or in the reference plate. However, this will require the tags to be tested to verify that they can survive the high temperature. The tag also has to be tuned for a specific frequency. It could also be possible to increase the efficiency of the tag by placing it above a metal plate [28], but this might not be practical for the reflector plate.

The only design choice made for the tag is to place it on the reflector plate and to use a passive tag due to the size constraints and costs.

4.2 Results

This project resulted in two prototypes: an antenna and a reference prototype. The antenna does not yet work with the MFRC522 RFID chip, but it resonates at the correct frequency and shows potential. Additionally, there is a working reference prototype constructed from a standard MFRC522 Arduino module [26]. This board was used to test the Arduino code and demonstrate the potential usage of the complete system. The antenna requires further development to achieve compatibility with the MFRC522 RFID chip, while the reference prototype is fully operational, validating the system's potential and serving as a proof of concept.

Both prototypes have promising implementations. In theory, the system will select the correct screw during plate osteosynthesis. The system does not require input and is easily integrated into the workflow, making it intuitive and ergonomic.

The RFID reader can easily be integrated into the existing ADEPTH, as the circuit can be seamlessly added to the existing PCB. Consequently, the airtightness remains unchanged. The MFRC522 chip can withstand temperatures above 134° C, ensuring that the ability to sterilise and durability across multiple cycles of sterilisations are maintained. However, the read range of the RFID system is an important requirement that has not yet been validated. Therefore, the prototype has the potential to comply with all requirements, but further testing is required.

4.2.1 Parasitic in Breadboard

During the project, there were some challenges related to prototyping. The initial approach involved using a breadboard for prototyping. However, this method proved problematic when working with small capacitors, as the breadboard itself has an inherent capacitance of approximately 1.5 pF. Taking into account the small values of various capacitors in the supporting circuit, this had a significant impact on the functioning of the prototype. After switching to a direct wire method, this issue was resolved.

4.2.2 Power Requirements

The MFRC522 RFID chip operates on 3.3V, meeting the required driving voltage. Due to the antenna not being compatible by the end of the project, it was not possible to measure the power consumption of the complete reader system. However, in theory, the power consumption should meet the requirement. According to the datasheet of the MFRC522 chip, the maximum current during typical operation is below 100 mA, ensuring it will not exceed the maximum current of 125 mA for a pulse of 15 seconds. Furthermore, some measurements can be taken to reduce the power usage and increase the range for which the system can detect a tag [29] [30].

5 Discussion

The results of our study indicate that the proposed circuit is valid and performs as expected under theoretical conditions. The simulations and calculations have shown that the circuit meets the desired specifications, demonstrating proper impedance matching and efficient power transfer. However, it is important to note that while the theoretical analysis is promising, practical implementation remains to be validated.

In the current situation, two of the three types of screws use the same guide. Occasionally, the same drill guide is used for different screw types. A crucial aspect of implementing this solution is the use of specific drill guides for each type of screw. This step is necessary to ensure the correct screw selection for calculating the appropriate length. This requirement introduces an additional step in the instructions for ADEPTH. The instructions should include detailed guidance on using different drill guides for each screw type.

6 Conclusion

The goal of this thesis was to propose an interfacing method to replace an existing touchscreen in an operating room. This thesis focused on utilising RFID technology to minimise interaction between people and machines. This led to the proposal of integrating a custom-made antenna and readout circuit into SLAM Orthopedic's product, the ADEPTH.

A prototype with an impedance matched at 13.56 MHz has been theorised, however, there was insufficient time to test the implementation fully and thus there is no data about the read range of this prototype. Regarding size constraints, it has been shown that the proposed design could fit inside the current version of the ADEPTH and that a fully developed system would meet all the requirements set by the project proposers.

This leads to the conclusion that an RFID reading in combination with tags situated on the drill guide is viable. Still, thorough testing is needed to determine if the system will perform at the desired distance.

7 Recommendations

Before this project, the project group had no understanding of Smith charts from Bachelor courses, but a substantial amount of knowledge has since been gained on the subject. This resulted in a slow and difficult start when creating the circuit. A team with more experience with Smith charts and or Vector Network Analysers could potentially develop a functional antenna based on this thesis.

While this thesis has focused primarily on the antenna and readout circuit, great care should be taken when designing the custom tags. Since they are a crucial component of the proposed system, they should be reliable. Research could focus on how the tags behave when exposed to the conditions in surgery.

Another topic that should be further researched is the experience of the surgeon when using the proposed system. One focus of the study could be the effects on the ergonomics of the drill after the addition of the RFID system. Another study could focus on the selection speed compared to the old, analogue measurement and selection.

References

[1] "Va lcp™ ankle trauma system 2.7/3.5," DePuy Synthes, Tech. Rep. [Online]. Available: https://synthes.hs.llnwd.net/o16/LLNWMB8/INT%20Mobile/Synthes%20International/Product%20Support%20Material/legacy_Synthes_PDF/164640.pdf.

[2] *User manual adepth system*, Mar. 2024.

[3] SLAMORTHOPEDIC, Tech. Rep. [Online]. Available: https://www.slamortho.com/adepth.

[4] J. Barker, *Interview with a plastic and orthopaedic surgeon*, Online Interview, Apr. 2024.

[5] A. Gupta, "Operation room techniques for the surgeon," *Prof BS Rana Memorial Oration*, p. 181,

[6] W. A. Rutala and D. J. Weber, "Guideline for disinfection and sterilization in healthcare facilities, 2008. update: May 2019," 2019.

[7] M. Dion and W. Parker, "Steam sterilization principles," *Pharmaceutical Engineering*, vol. 33, no. 6, Jan. 1, 2013. [Online]. Available: https://www.ispe.gr.jp/ISPE/07_public/pdf/201504_en.pdf.

[8] B. de Hartog, *Interview with a orthopeadic surgeon and co-founder of slam orthopedic*, Online Interview, Apr. 2024.

[9] M. S. Hallbeck, "How to develop usable surgical devices–," *Advances in Human Factors and Ergonomics in Healthcare*, p. 286, 2010.

[10] F. Bo, D. Yujie, and Xiaoxing, "Low power clock recovery circuit for passive hf rfid tag," *Analog Integr Circ Sig Process*, 2009.

[11] Y. Ying, D. Fischer, and U. Hölscher, "Electromagnetic interference with rfid readers in hospitals," in *World Congress on Medical Physics and Biomedical Engineering, September 7-12, 2009, Munich, Germany: Vol. 25/7 Diagnostic and Therapeutic Instrumentation, Clinical Engineering*, Springer, 2009, pp. 872–875.

[12] P. Nikitin, K. Rao, and S. Lazar, "An overview of near field uhf rfid," Apr. 2007, pp. 167–174. DOI: 10.1109/RFID.2007.346165.

[13] S. A. Weis, "Rfid (radio frequency identification): Principles and applications," *System*, vol. 2, no. 3, pp. 1–23, 2007.

[14] K. Arora, H. Mallinson, A. Kulkarni, J. Brusey, and D. McFarlane, "The practical feasibility of using rfid in a metal environment," in *2007 IEEE Wireless Communications and Networking Conference*, 2007, pp. 1679–1683. DOI: 10.1109/WCNC.2007.316.

[15] C. Degen, "Inductive coupling for wireless power transfer and near-field communication," *EURASIP Journal on Wireless Communications and Networking*, vol. 2021, no. 1, p. 121, 2021.

[16] Ventev, Tech. Rep. [Online]. Available: https://ventevinfra.com/product/824-960mhz-11dbi-lte-yagi-h48-v40-antenna-with-1-n-style-connector/.

[17] M.Minderhoud, "Satellite dish," Tech. Rep., 2004.

[18] P. P. Viezbicke, *Yagi antenna design*. US Government Printing Office, 1976, vol. 688.

[19] "Antenna types and parameters," *Circuit Design, INC.*, [Online]. Available: https://www.cdt21.com/design_guide/antenna-types-and-parameters/.

[20] *Standard performance mifare and ntag frontend*, MFRC522, Rev. 3.9, NXP Semiconductors, Apr. 2016. [Online]. Available: https://www.nxp.com/docs/en/application-note/AN1706.pdf.

[21] M. S. Trotter, J. D. Griffin, and G. D. Durgin, "Power-optimized waveforms for improving the range and reliability of rfid systems," in *2009 IEEE International Conference on RFID*, 2009, pp. 80–87. DOI: 10.1109/RFID.2009.4911196.

[22] M. Thompson and J. Fidler, "Determination of the impedance matching domain of impedance matching networks," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 51, no. 10, pp. 2098–2106, 2004. DOI: 10.1109/TCSI.2004.835682.

[23] *Quartz crystal specification*, LFXTAL036075, V1.0021, IQD, May 2023. [Online]. Available: https://www.farnell.com/datasheets/3966826.pdf.

[24] *Antenna design guide for mfrc52x*, NPX, Jun. 2018. [Online]. Available: https://www.nxp.com/docs/en/application-note/AN1445_An1444.zip.

[25] *Adafruit feather 32u4 with lora radio module*, RFM9x, Adafruit, Jun. 2024. [Online]. Available: https://cdn-learn.adafruit.com/downloads/pdf/adafruit-feather-32u4-radio-with-lora-radio-module.pdf.

[26] "Rc522 rfid module for arduino," keyestudio, Tech. Rep. [Online]. Available: https://www.data-media.gr/files/KS0067.pdf.

[27] W. Kelsey, *Online smith chart tool*. [Online]. Available: https://www.will-kelsey.com/smith_chart/.

[28] L. Mo and H. Zhang, "Rfid antenna near the surface of metal," in *2007 International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, 2007, pp. 803–806. DOI: 10.1109/MAPE.2007.4393746.

[29] B. Jiang, J. R. Smith, M. Philipose, S. Roy, K. Sundara-Rajan, and A. V. Mamishev, "Energy scavenging for inductively coupled passive rfid systems," *IEEE Transactions on Instrumentation and Measurement*, vol. 56, no. 1, pp. 118–125, 2007. DOI: 10.1109/TIM.2006.887407.

[30] X. Xu, L. Gu, J. Wang, and G. Xing, "Negotiate power and performance in the reality of rfid systems," in *2010 IEEE International Conference on Pervasive Computing and Communications (PerCom)*, 2010, pp. 88–97. DOI: 10.1109/PERCOM.2010.5466989.

[31] F. Meeuwsen, *Interview with a medical docter*, Online Interview, Apr. 2024.

A Preparatory Interviews

A.1 John Barker

On the 23rd of April, an interview was held with John Barker who is a plastic (soft tissue) and orthopaedic (hard tissue) surgeon active in both clinical and research [4]. The interview started with an explanation of the project, what the product from SLAM is measuring, and what needs to be changed about it. During this interview, questions were asked to give more insight into how the OR (Operation Room) is operated and the rules. To make this conversation readable, some paraphrasing was used.

Q: Do you know before surgery which screws and plates you get, and do you get different lengths?
A: Before surgery they know the size of the screws they want to use from scans from x-rays, MRI, and CT scans. From those scans, they choose 3 to 4 sizes of screws they want to take into the OR. They don't know the dimensions of the plates exactly. During surgery, they select the screw that would fit, and if it's a bit too long they take it out en pick a different screw. For each surgery and situation, they pick which ones they need to use; so every surgery has a different set of screws.

Q: How many people are in the OR?
A: In an orthopaedic room there are 3 up to 10 people. The amount of people scrubbed in is a smaller number, somewhere between 2 and 5 people are sterile. The people in the OR who would be handling the touch screen would probably be around 4.

Q: Who would preferably select the screw type on the screen?
A: Preferably the surgeon if they have the freedom to do so. If you imagine building a house and having to ask someone else to do an action it's better to do it yourself.

Q: Which non-technical limitations should we take into account?
A: The surgeons are not prone to change anything in the OR or the way they want to do things. So the solution has to come with very little change in the OR. The surgeon already has to deal with a lot of information so nothing too overwhelming with data. The solution also needs to take into account that the errors due to mobility don't increase.

Q: What are some OR specific limitations for orthopaedic surgery?
A: In orthopaedics, unlike urology, is infection a big risk and lots is done to prevent infections. This means that the surgeon is double-gloved and in a kind of space suit to prevent any germs from getting near the bone. The dexterity of the surgeon is significantly lower and the buttons on the device should be big and fairly easily accessible. The device should also have a rough/textured and grippy surface, because during the operation there will be blood on the gloves. They can clean their hands during the surgery with gauze or a cloth, but it is still something to keep in mind.

Q: Regarding the robustness of the tools, what happens if it fails? is there a backup system?
A: The surgeons are like carpenters, they will find solutions to all problems. They are very versatile and resourceful, they will figure it out and make it work. Failure of a device is not a total emergency, but it is if the heart stops.

The interview ended with John asking us whether or not we wanted to see how such an operation unfolded.

A.2 Frédérique Meeuwsen

On the 24th of April, an interview was held with Frédérique Meeuwsen [31]. She is a pathology resident from Erasmus MC in Rotterdam. She did her PhD in Biomechanical Engineering at the University of Technology in Delft. She researched the use of RFID tags on medical instruments to improve efficiency. To make this conversation readable some paraphrasing was used.

Q: Is the research regarding the RFID tags on tools still ongoing?
A: Yeah I believe so, but still in scientific research.

Q: What kind of RFIDs are used?
A: A special-made RFID was created (van Straaten Medical). These RFIDs are sterilizable and tig welded to the tools. These RFID tags are then sterilised with the tools. There are one or two sets of instruments with tags.

Q: Do surrounding assistants have time for giving input?
A: Yeah, the surrounding assistant does have enough time to do things asked. They can interact with the screens of input devices.

Q: How are the RFIDs scanned?
A: The RFIDs are scanned during the procedure to know in what part of the surgery they are, and to do research afterwards.

A.3 Bas de Hartog

On the 26th of April, an interview was held with Bas de Hartog [8]. He is an orthopaedic surgeon and co-founder of Slam Orthopedic. Slam Orthopedic was there to support us. To make this conversation readable some paraphrasing was used.

Q: How is communication managed inside the operating room, and how aware is the surrounding assistant of the situation, or are they busy with other tasks?
A: In a typical operation, there are three sterile team members, including two assistants and a surgeon. The operating room also has one surrounding assistant. The surrounding assistant's role is relatively minimal if the procedure is proceeding smoothly. Their main responsibility is to pass items like plates and screws from the non-sterile area to the sterile area upon the surgeon's request.

Q: Is there a different guide for every screw?
A: Whether a different guide is needed for each screw depends on the drill size, as the drill determines the guide.

Q: How are instruments passed by the sterile assistant?
A: The method of passing instruments varies; there is no universal technique. Each situation may dictate a different approach.

Q: Who might need to interact with electrical devices during a procedure?
A: The circulating assistant might not always be fully aware of the ongoing situation and could theoretically be replaced by a robot. In contrast, the sterile assistant is highly attuned to each step of the procedure, often anticipating the surgeon's needs and preparing for each step in advance without needing to be asked.

Q: Is the diagram in Figure 4 correct?
A: Yes, that's about right.

Q: What do you think about having a rotating disk on the ADEPTH?
A: It seems like a practical idea; it could streamline the workflow. The assistant could adjust the settings as needed, allowing me, as the surgeon, to focus solely on the procedure without concerns about adjusting the equipment.

Q: What would be the impact of using RFID tags in drill guides, implying the use of different guides for various types?
A: Incorporating RFID tags in drill guides could be a beneficial solution. However, if the RFID tags require close proximity to function, or if they must be attached to the guides around the drill, this could pose a limitation.

Q: Do you, as a surgeon, choose the screw when you need it?
A: Not every plate is compatible with all types of screws, the plate determines which can be used. I communicate what I'm doing, and the circulating assistant needs an active request to fetch the correct screw. Typically, we start with two cortical screws, followed by locking or variable angle locking screws.

Q: You already know the type of screw you're going to use, right?
A: Yes, knowing the correct type of screw in advance helps reduce waste. If we retrieve the wrong length or type of screw, it cannot be used and must be discarded.

Q: What if there was an external device that could communicate with the bridge, something like a numpad?
A: Integrating something on the ADEPTH itself would be more beneficial. Our trauma drill already has two settings, showing it can interact with buttons on the drill, so adapting it into the workflow could be effectively managed.

Q: What do you think of foot pedals?
A: Foot pedals are not commonly used and require a period of adjustment. They aren't inherently bad, but there are certainly more user-friendly options available. They likely wouldn't be the best solution for streamlining our workflow.

Q: What if an RFID tag needs to tap the ADEPTH?
A: It would be better if tapping isn't necessary, but rather just detecting within a certain range.

Q Bas: What if you display every type of screw on the screen?
A Slam: That could be overwhelming, considering three types of screws and two thicknesses, that's six variations. We believe displaying all these options might increase the likelihood of errors.

Q Bas: What about colour detection or QR code?
A Slam: Color detection can be unreliable because the guide might get dirty, altering how colours are perceived. QR codes require a high scan rate; currently, the ADEPTH handles 6 readings per cycle.

Bas: Sometimes we only have one hand free, and we need to manage the drill with that hand. Please take this into consideration.

Q: What about using a small remote controller?
A: A remote controller is a separate device, similar to a numpad. It could work, but a more elegant solution might be the rotary encoder. Every new solution requires some adjustment, so any option could be effective if designed properly. A straightforward, Apple-like solution would be ideal. However, simplicity is key.

B Arduino code

B.1 Continuous wave mode

```
#include <SPI.h>
#include <MFRC522.h>

// Define pins
#define RST_PIN     10
#define SS_PIN      9
// MISO D12
// MOSI D11
// SCK D13
// SDA D9
// RST D10

MFRC522 mfrc522(SS_PIN, RST_PIN);  // Create MFRC522 instance

void setup() {
    // Initialize serial communications with the PC
    Serial.begin(9600);
    // Initialize the Led pin as an output
    pinMode(LED_BUILTIN, OUTPUT);
    // Do nothing if no serial port is opened (added for Arduinos based on ATMEGA32U4)
    while (!Serial);
    SPI.begin();            // Init SPI bus
    mfrc522.PCD_Init();     // Init MFRC522
    delay(10);
    // Turn on the built in Led to indicate that the RFID reader is ready
    digitalWrite(LED_BUILTIN, HIGH);

    // Continuos Wave
    SPI.transfer(0x14);
    SPI.transfer((1<<3));
}

void loop() {
    if(Serial){
        // Show details of PCD - MFRC522 Card Reader details
        mfrc522.PCD_DumpVersionToSerial();
        delay(2000);
    }
}
```

Listing 1: Arduino Code for continous wave mode of MFRC522 chip.

B.2 Arduino RFID operation Code

```
#include <SPI.h>
#include <MFRC522.h>
#include <RH_RF69.h>

// Define pins
#define RST_PIN         9
#define SS_PIN          10
// MISO D12
// MOSI D11
// SCK D13
// SDA D10

MFRC522 mfrc522(SS_PIN, RST_PIN);  // Create MFRC522 instance
RH_RF69 rf69(8, 7); // Adafruit Feather 32u4

void setup() {
    // Initialize serial communications with the PC
        Serial.begin(9600);
    // Init SPI bus
        SPI.begin();
    // Init MFRC522
        mfrc522.PCD_Init();
        delay(4);
        if serial:
        // Show details of PCD - MFRC522 Card Reader details
                mfrc522.PCD_DumpVersionToSerial();

        if (!rf69.init()){
        while (1){
            digitalWrite(LED_BUILTIN, HIGH);
            delay(500);
            digitalWrite(LED_BUILTIN, LOW);
            delay(500);
        }
    }
    digitalWrite(LED_BUILTIN, HIGH);

    // ISM frequency, in MHz
    if (!rf69.setFrequency(868.0)){
        digitalWrite(LED_BUILTIN, LOW);
    }

    // The encryption key has to be the same as the one in the client
    rf69.setEncryptionKey((uint8_t*)"thisIsEncryptKey");
}

void loop() {
        // Reset the loop if no new card present on the sensor/reader. This saves the entire
        ↪  process when idle.
        if ( ! mfrc522.PICC_IsNewCardPresent()) {
                return;
        }

        // Select one of the cards
        if ( ! mfrc522.PICC_ReadCardSerial()) {
                return;
        }

        // Dump debug info about the card; PICC_HaltA() is automatically called
        mfrc522.PICC_DumpToSerial(&(mfrc522.uid));
        rf69.send(&(mfrc522.uid), sizeof(&(mfrc522.uid)));
        rf69.waitPacketSent();
}
```

Listing 2: Arduino Code for normal operation of MFRC522 chip.