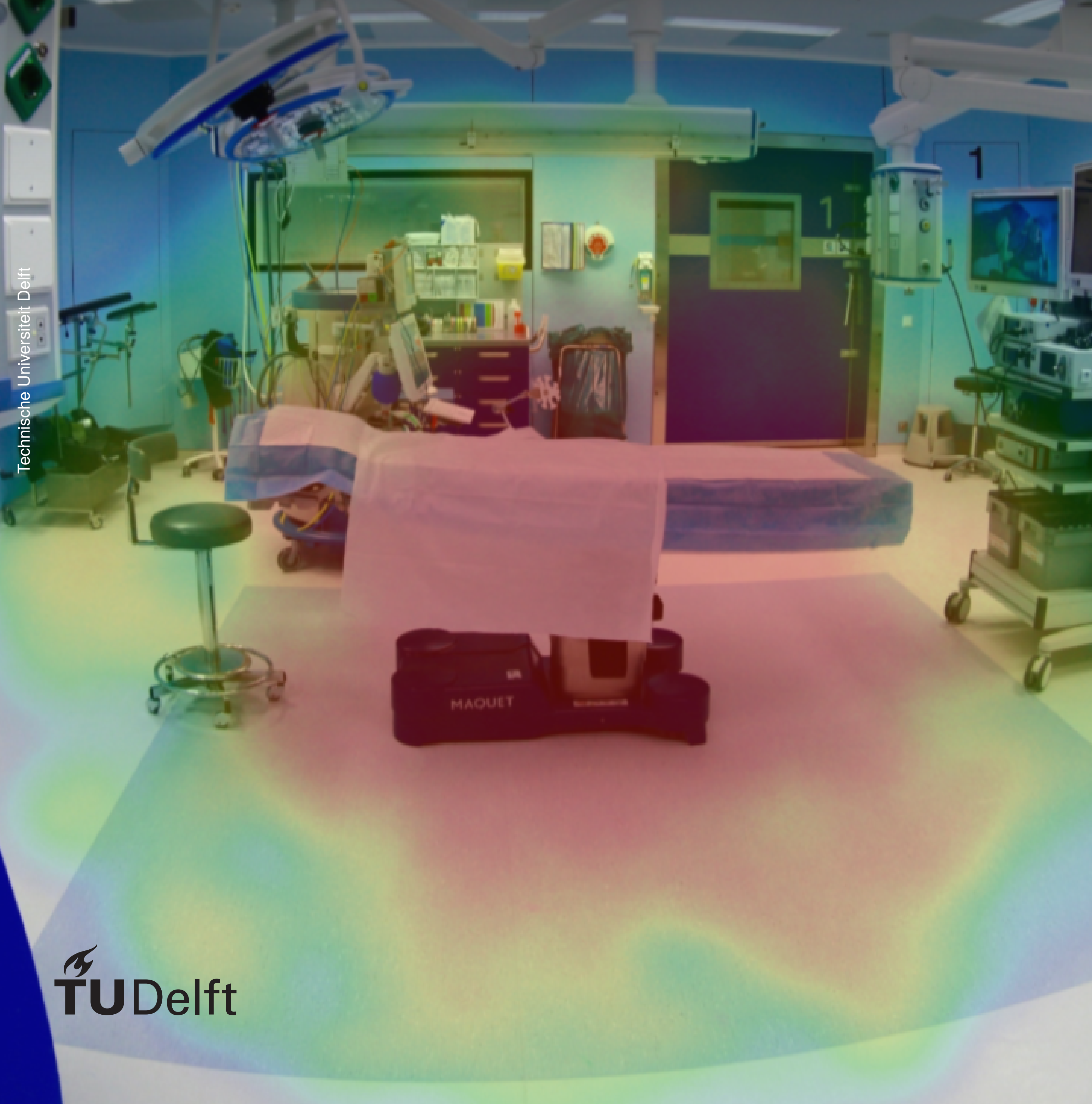
Radio Frequency Identification in the Operating Room

A systematic approach to test the feasibility of RFID in the operating room for surgical phase recognition.

S.G. Hengst



Technische Universiteit Delft

TU Delft

Radio Frequency Identification in the Operating Room

A systematic approach to test the feasibility of RFID in the operating room for surgical phase recognition.

by

S.G. Hengst

to obtain the degree of Master of Science
in Biomedical Engineering
at the Delft University of Technology,
to be defended publicly on Tuesday December 17, 2019 at 13:00 AM.

Supervisor:	Prof. dr. J.J. van den Dobbelsteen	TU Delft
Thesis committee:	Prof. dr. J.J. van den Dobbelsteen	TU Delft
	Dr. M. van der Elst	TU Delft, Reinier de Graaf Gasthuis
	P.E.A. Hermsen Msc	TU Delft

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

TU Delft

Abstract

Hospitals are facing enormous financial pressure over the last years. To achieve lower costs, hospitals should invest in smart ways of working to make optimal use of the scarce capacities. A solution can be digitising processes in the hospital to prevent it from making more costs. In line with this founding, planning and scheduling of the operating room (OR) program during a day is a process that could be improved by digitising. Overtime and idle time are consequences of inaccurate planning and are both expensive elements that do not contribute to satisfaction of hospital personnel and patients. Radio Frequency Identification (RFID) is proven and proposed in previous research to be used to acquire data for surgical phase detection. Up until now, the detection accuracy for this model is too low and requires optimization before it can be implemented in the OR. This research uses a systematic approach to investigate the feasibility of implementation of RFID in the OR in Reinier de Graaf Gasthuis (RdGG) in Delft for the purpose of surgical phase recognition.

The systematic approach is divided in four parts: theory, design, testing and evaluation. The first part presents an analysis of the OR in RdGG and the RFID technology and is used in the design part to compile a list of of design requirements. This list presents criteria that must be met in order to achieve succesful implementation of RFID in the OR. Based on the requirements an optimal position of the antenna is chosen above the surgical table, in the center of the plenum ventilation area and on a distance of 1.5 meter of the surgical table. On the basis of the optimal antenna position, an antenna, tag and reader is chosen. The proposed RFID system is tested in the MISIT-lab at the TU Delft and in an OR in RdGG. The goals of the experiments were to visualise the detection field and to compare the effect of the environment on the RFID performance. In the MISIT-lab, the antenna was able to detect a vast majority of tags up to a perpendicular distance (from the antenna to the surgical table) of 1.3 meter. At longer distances of 1.4 and 1.5 meter the antenna was still able to detect tags but to a lesser extent. The OR experiment yielded poor results compared to the laboratory experiment. None of the tags was detected on the predeterimined distances. The antenna was only able to detect tagged instruments on a distance of approximately 0.8 meter. The results are evaluated in the last part of this research. Normally, when facing poor performance of an RFID system the performance can be improved by increasing the antenna gain or choosing stronger RFID tags. These choices are both constrained by the dimensions of the antenna and the tag. An RFID antenna with a large surface cannot be placed in the airflow above the surgical table because this increases the risk on infections and large RFID tags do not fit on surgical instruments.

The most probable reason for the decrease in performance between the two experiments is electromagnetic noise from surrounding electrical equipment and wires in the floor and ceiling. In conclusion, it is not possible to implement an RFID system in the OR for phase recognition purposes. RFID technology is fast evolving and new technologies can offer a solution. It is certainly possible that RFID can be implemented in the future when tags and antennas are more powerful while retaining small dimensions. In future, it is recommended to perform on site tests of RFID in the OR before further developing an application.

Contents

Abstract iii

List of Figures vii

List of Tables ix

1 General Introduction 1
- 1.1 Problem analysis . . . 1
- 1.2 Thesis Structure . . . 3

I Part 1: Theory 5

2 Operating Room Environment Analysis 7
- 2.1 Operating Room Complex . . . 7
- 2.2 Operating Room Components . . . 9
  - 2.2.1 Surgical Table . . . 10
  - 2.2.2 Surgical Lights . . . 10
  - 2.2.3 Ceiling Supply Systems. . . . 11
  - 2.2.4 Monitors . . . 11
  - 2.2.5 Plenum Ventilation System . . . 11
- 2.3 Surgical working area . . . 13

3 RFID Technology Analysis 15
- 3.1 RFID Technology . . . 15
- 3.2 Performance Metrics . . . 16
- 3.3 RFID Antenna Characteristics . . . 17
- 3.4 RFID Tag . . . 18
- 3.5 RFID Reader . . . 18
- 3.6 Electromagnetic Field . . . 18
- 3.7 Electromagnetic Interference . . . 19

II Part 2: Design 21

4 Implementation Requirements 23
- 4.1 Criteria. . . . 23
- 4.2 Wishes . . . 25

5 Design Scenarios 27
- 5.1 Design Scenario 1 . . . 27
- 5.2 Design Scenario 2 . . . 28
- 5.3 Design Scenario 3 . . . 29
- 5.4 Design Scenario 4 . . . 30

6 Winning Scenario 33
- 6.1 RFID Antenna . . . 33
- 6.2 RFID Tag . . . 36
- 6.3 RFID Reader . . . 36

III Part 3: Testing 37

7 Introduction 39
- 7.1 Experimental Goals . . . 39
- 7.2 Materials . . . 40

8 MISIT-lab Experiment **43**
8.1 Experimental Set-up 43
8.2 Experimental Protocol 44
8.3 Data Analysis 44
8.4 Results 44
8.5 Discussion and Conclusion 47

9 Operating Room Experiment **49**
9.1 Experimental Set-up 49
9.2 Experimental Protocol 50
9.3 Data Analysis 50
9.4 Results 50
9.5 Discussion and Conclusion 50

IV Evaluation **51**

10 Discussion **53**

11 Conclusion **55**

Bibliography **57**

A Experimental Study **61**
A.1 Introduction 61
A.1.1 Background 61
A.1.2 Research Question and Hypotheses 61
A.2 Methods 62
A.2.1 Experimental set-up and Materials 62
A.2.2 Variables and Constants 63
A.2.3 Experimental Protocol 63
A.2.4 Data Processing 65
A.2.5 Data analysis 65
A.3 Results 65
A.3.1 Processed data 65
A.3.2 Statistical Analysis 68
A.4 Discussion 70
A.4.1 Interpretation of the results 70
A.4.2 Limitations of experiment 70
A.5 Conclusion 71

B Sketches of Surgical Layouts **73**

C Slices of Experimental Results **75**

D Run Template for Operating Room Experiment **79**

List of Figures

1.1 Test setting during in-vivo tests in study of Meeuwsen and Koffeman [1][2]. 2
1.2 Thesis structure 3

2.1 Blueprint of the OR complex in RdGG in Delft. 7
2.2 Basic layout of an OR in RdGG [3] 8
2.3 Furnished OR 9
2.4 This image is confidential and can not be made public. 9
2.5 This image is confidential and can not be made public. 9
2.6 Blueprint of an OR in RdGG with the OR table (red), the mounting position of the Central Supply Systems (blue circle), the Central Supply Systems (blue rectangle), the mounting axis of the surgical lights (black circle and the surgical lights (black rectangle. 10
2.7 The 3-fold central axis of the surgical lights [4]. 11
2.8 Schematic representation of plenum ventilation system used in RdGG. 12
2.9 Schematic representation of an OR procedure. In the green zone the surgical working area and in the red zone the Mayo-stand. 13

3.1 Basic RFID structure [5]. 15
3.2 Main lobe and side lobes of the radiation pattern of a directional antenna [6]. 17
3.3 Linear polarisation and circular [7]. 18
3.4 Radiation of the antenna in far field[8]. 19
3.5 Electromagnetic waves perpendicular to each other[8]. 19

5.1 Sketch of design scenario 1. 27
5.2 Sketch of design scenario 2. 28
5.3 Sketch of design scenario 3. 29
5.4 Sketch of design scenario 4. 30

6.1 Schematic representation of the antenna facing the surgical table at its highest and lowest point (on scale). 34
6.2 Schematic representation of the beam width of the antenna facing the surgical table. 34
6.3 Sketches of the RFID antenna [9]. 35
6.4 Proposed version of aerodynamic housing for the RFID antenna. 35
6.5 Dimensions of the Xerafy Dash-On XS tag[10]. 36

7.1 Variations in RSSI values among eighteen different measurements of each 20 seconds. 40
7.2 All tagged and labelled instruments in instrument tray. 40
7.3 Surgical instrument with Xerafy Dash-On XS tag fixed to it. 41
7.4 Surgical cloth as template for positioning of the ten tagged surgical instruments 41

8.1 Experimental set-up in MISIT lab at TU Delft. 43
8.2 Barplot visualising the number of detections of two test measurements for ten different tags. . . 45
8.3 Number of detections per tag on different heights covering the whole length of the surgical table (mirrored). 46
8.4 Number of detections per tagged instrument in two directions. 46
8.5 RSSI values per tag on different heights in two directions 47

9.1 Experimental set-up during the test in the OR. 49
9.2 Overview of detections during OR tests. 50

10.1 Sketch of the surfaces of antenna with 8.5 dBi (inner) and 12 dBi (outer 54

A.1 Experimental set-up RFID equipment 62
A.2 Tagged surgical instruments. From left to right: Xerafy Pico-On Plus, Xerafy Dot-On XS and Xerafy Dash-On XS. 63
A.3 Multiple instruments. 64
A.4 Experimental set-up with rope with tape as an indication line for the different distances. 64
A.5 Boxplots of the measurements for every experimental condition. 66
A.6 Barplot visualizing the number of missing values per experimental condition for th three different tags. 66
A.7 Tagged instruments under an angle of 34.5°compared to tagged instruments straight under the antenna. 67
A.8 RSSI values of tag with multiple instruments compared to that of a single instrument. 67
A.9 Differences between the three different tags 68

C.1 Slices of the mirror 3D per read range 75
C.2 Slices of the different distances between antenna and tags 76
C.3 Slices of the RSSI 3D model 77

D.1 Template of the measurements. Six blocks all represents half of the surgical table. The six blocks are each measured at 6 different heights. 80

List of Tables

2.1 ORs with their surgical specialties and the surface and dimensions of the room (based on blueprints). 8
2.2 ORs with their surgical specialties and the surface and dimensions of the pleunum ventilation area (based on blueprints). 11

5.1 Harris Profile of design scenario 1. 28
5.2 Harris Profile of design scenario 2. 29
5.3 Harris Profile of design scenario 3. 30
5.4 Harris Profile of design scenario 4. 31

6.1 Commercial available antennas with different characteristics. 33
6.2 Specifications of the RFID antenna [9] 34
6.3 Autoclavable, on-metal Xerafy RFID tags[10]. 36

8.1 Example of retrieved data by the RFID reader. 44
8.2 UID of the used tags and their RSSI value at zero distance from the antenna (not fixed to instrument). 45

A.1 Specifications of the used RFID tags. [10] 63
A.2 Run table of distance measurement. ECD stands for experimental condition distance. 64
A.3 Run table of angle measurement. ECA stands for experimental condition angle. 64
A.4 Run table of measurements with multiple instruments. ECM stands for experimental condition multiple instruments. 65
A.5 One-Way ANOVA between the different distances for the Distance, Angle and Multiple Instruments measuremnets. 68
A.6 One-Way ANOVA between the reference and angle measurements. 69
A.7 One-Way ANOVA between the Reference and Multiple Instruments measurements. 69
A.8 One-Way ANOVA between the three different tags at different distances straight under the antenna. 70

1
General Introduction

Hospitals are facing enormous financial pressure over the last years. To achieve lower costs, hospitals should invest in smart ways of working to make optimal use of the scarce capacities. This can be done by digitalizing processes in the hospital to prevent it from making more costs [11]. In line with this founding, planning and scheduling of the operating room (OR) program during a day is one of those processes which can be improved by digitalizing. Overtime and idle time are the consequences of inaccurate planning and scheduling and are both expensive elements. Overtime means longer use of the OR than expected and results in longer waiting times for patients and dissatisfaction of OR personnel. Idle time is when the actual duration of a surgery is shorter than expected and leads to 'holes' in the daily OR schedule which could be filled up with other surgeries. In addition, the fact that the OR accounts for more than 40 percent of the hospital's total revenue and costs while hospitals are aiming on an increase of patient satisfaction and safety, the OR needs an optimal scheduling solution [12][13].

Radio Frequency Identification (RFID) is a tracking technology which uses an antenna to detect tagged objects that enter the radiation field of the antenna. It is known as a tracking technology in, for example, manufacturing places, retail industry or libraries. Healthcare is the next upcoming market for this technology. Some examples of applications of RFID in healthcare are: tracking patients during their hospital stay, tracking instruments during sterilising processes and tracking blood bags [14].
This thesis aims on implementation of RFID in the OR to track surgical instruments for the use of surgical phase recognition.

1.1. Problem analysis

As described, RFID has a broad field of application and is an often used technology to track objects. An example of an application of RFID in the OR is tracking of surgical sponges. Different research has been conducted in this field by Rivera et al. [15]. A reason to implement RFID in the OR was that in 1 of the 1500 cases a surgical sponge or equipment is left behind in the patient. In order to avoid these human errors, Rivera et al. presented a system that tracks surgical items before and after surgery. They used a check-in and check-out station to make sure every item that goes into the patient also goes out. In case a sponge or other object was missing at the end of surgery, a handheld patient RFID scanner was used to check whether the object was localised in the patient. The study showed reliable and accurate results with the presented system and showed a minimised chance on human errors [15].

A study from Kranzfelder et al. presented an RFID-based approach for real-time tracking of laparoscopic instruments [16]. Their system consisted of surgical instruments equipped with RFID tags and an antenna which was positioned on the Mayo stand. The antenna detected instruments which were on the Mayo stand and thus not in-use. When instruments left the Mayo stand and thus entered the interrogation zone (zone RFID tags can be detected in), it was considered as in-use by the surgeon. The reason to choose for detecting instruments which were not in-use was that there was no properly antenna available which can be positioned directly under the patient. Other disadvantages of tracking instruments which are not in-use instead of tracking instruments that are in-use, is that in many procedures the instruments do not return to the Mayo stand when they are not in-use. In this situation an instrument will be marked as in-use while it is not in-use [1].

This thesis is part of a larger project about RFID in the OR and is conducted in collaboration with TU Delft and Reinier de Graaf Hospital in Delft (RdGG). Previous performed research by Meeuwsen used an RFID system in the OR which detected instruments that are in use by the surgeon to gather data for a surgical phase recognition model [1]. This model can detect phases during a surgical procedure based on instruments use. The information about the phase of a procedure can be communicated to a central planning system to track the progress of the procedure and estimate the start of next procedures. In Meeuwsen's research named "Safe Surgical Signature" a pilot study called "Intraoperative monitoring of surgical instrument use with RFID" is conducted. In this study, RFID technology was used to detect instruments which were used by the surgeon during a laparoscopic totally extra-peritoneal (TEP) inguinal hernia repair [1]. The work is different from the work from Kranzfelder et al. because they detected instruments which were not in-use. Meeuwsen tested an RFID system in a controlled test-setting (empty OR) where two researchers mimicked a procedure and during a real TEP-procedure performed by a surgical team. The controlled test yielded accurate detection rates for the surgical phase recognition model (86 percent). The results of the in-vivo test were not as good as the controlled test. This test achieved an average detection rate of 15 percent. The main reason for this significant difference in the average detection rate between the two tests is the position of the RFID antenna with respect to the surgical table. As can be seen in figure 1.1, the reader antenna is fixed to an intravenous pole and is positioned next to the surgical table and the surgeon. The RFID reader and the RFID laptop are placed on a mobile table which is placed outside the area the medical personnel is working in. The antenna is connected with the reader via a coax cable, the reader is connected with the laptop via an ethernet cable and the reader is connected to an electric point. When looking at the position of the antenna in the current setting in figure 1.1, the antenna is placed close to the area the surgeon is working in. The used RFID equipment should achieve a read range of around one to two meters. However, the performance of an RFID system can be affected by many factors. The environment plays an important role. While RFID is known by the fact that it does not require line-of-sight and thus can read through most materials, the body of the surgeon or the patient does disturb the RF signal in a way that the antenna was unable to detect the tagged instruments. Figure 1.1 also shows that the right arm of surgeon number 1 is in front of the antenna. Furthermore, the reader antenna is fixed at a certain height and after placing a sterile bag on it, it can not be changed in height anymore. When the surgeon decides that the surgical table has to change in height, the antenna can not change along with it. This can lead to a change of interrogation zone and can make the tagged instruments undetectable. A solution of other research by Haring for this problem was to fix the antenna to the rail on the side of the surgical table. This seemed to be an impossible solution because the RFID system should be used in many different surgeries and thus also surgeries where the rail is used for its original purpose [17].

Figure 1.1: Test setting during in-vivo tests in study of Meeuwsen and Koffeman [1][2].

The first pilots of Meeuwsen led to a proof-of-principle of RFID in the OR for the use of surgical phase recognition. She recommended to optimise the position of the antenna in order to ensure a reliable radiation field of the antenna which is able to acquire more accurate detection rates during a surgical procedure [1].
The study of Meeuwsen did not investigate the optimal position and optimal RFID equipment for the application.

This thesis will do that. A systematic approach towards implementation of an RFID system in the OR will be presented. The RFID system should be able to acquire accurate data of the used instruments during surgery in order to be used for surgical phase recognition. The goal is formulated as follows:

> *Investigate the feasibility of implementation of RFID technology in the OR in Reinier de Graaf Gasthuis in Delft for the use of surgical phase recognition.*

1.2. Thesis Structure

To achieve this goal, four steps are undertaken divided in four parts: Theory, Design, Testing and Evaluation (figure 1.2). The first part will start with analysing the technical and medical part of the problem. Chapter 2 gives an overview of the application domain RFID has to be deployed in. Chapter 3 gives an overview of RFID technology and includes an explanation of the working principle of RFID and its components, performance metrics and the electromagnetic field which is produced by the RFID equipment.
Based on the theoretical framework from part 1, the second part will include the design process. Chapter 4 presents a list of design requirements an RFID system in the OR should comply to and chapter 5 presents four different design scenarios. Evaluation of the scenarios in combination with the requirements yielded one winning scenario. This scenario is tested in part 3. In this part, the RFID system is tested in a controlled environment and in an OR environment.
Finally, the results of the study are evaluated and presented in the last part.

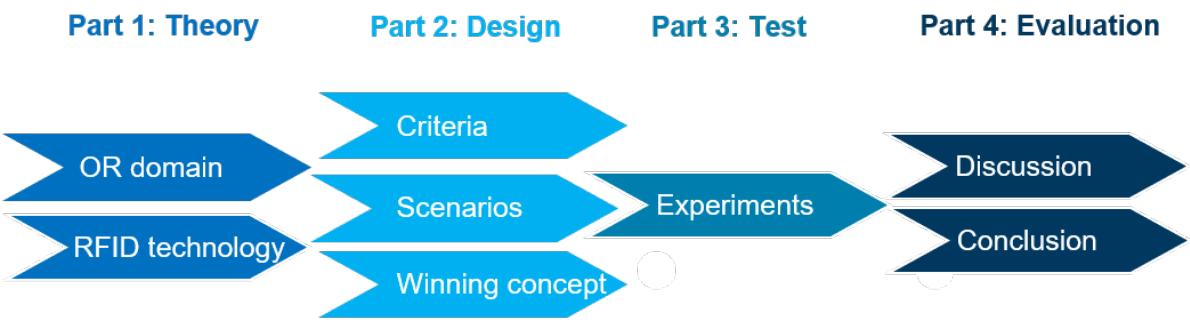


Figure 1.2: Thesis structure

I

Part 1: Theory

2

Operating Room Environment Analysis

This chapter describes the application domain for RFID technology: the OR complex in RdGG in Delft. Every room in the OR complex, present equipment and operating room layout during different procedures will be analysed. Blueprints of the hospital, pictures of an OR, sketches of the setting during different surgical procedures and documents of different equipment will be used to gather information for this analysis. Beside these documents, an OR was visited in order to get a real experience of the room. The blueprints, pictures and sketches of layouts of ORs are retrieved from RdGG.
The goal of this chapter is to create an overview of the objects in the OR and to map possible locations for RFID equipment. A thorough analysis of the environment and the technology has to be performed to prevent the implementation process from problems in a later stadium [18]. When looking at deployment of RFID in every OR in RdGG, it is important to get an overview of the whole OR complex and possible differences between the different ORs. Furthermore, equipment in the OR has to be explored to make sure the RFID equipment will not interfere or obstruct devices in the OR.

2.1. Operating Room Complex

RdGG hospital is rebuild in 2015. The OR complex is situated at the fourth floor of the hospital (figure 2.1). The complex contains eight ORs (red) and in 2020 two new ORs will be build at the roof of the parking garage which will bring the total number of ORs at ten [3] [19]. The rooms are build around two setting rooms (blue). A setting room is a clean room where instrument trays are prepared for surgery. Every OR has two doors, one door where patients enter the room and one door between the setting room and the OR. Before and after surgery, patients stay at the holding/recovery room (orange).

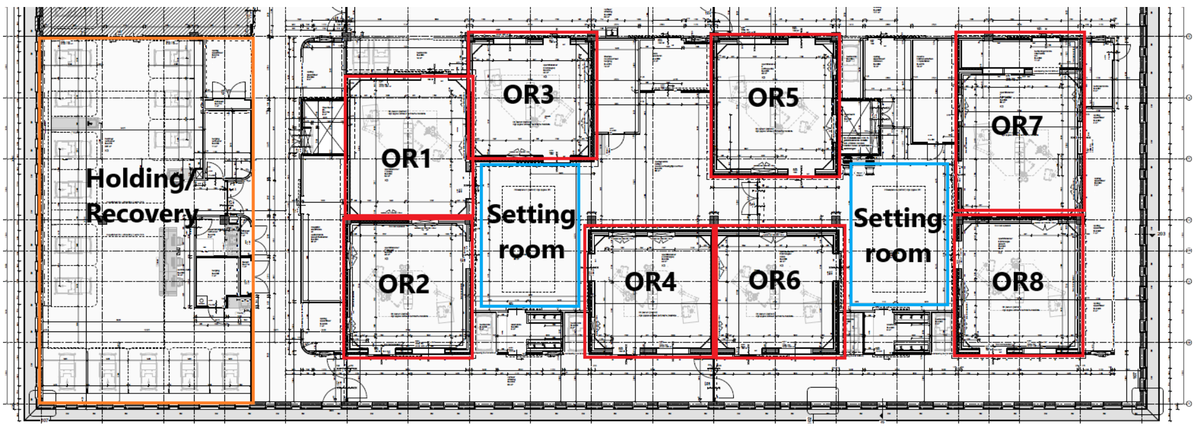


Figure 2.1: Blueprint of the OR complex in RdGG in Delft.

The eight rooms are build the same way in order to gain flexibility in planning of surgeries. Most rooms can be used for different surgical specialties. This is an advantage in case problems occur during surgery and another room has to be used. Furthermore, in case of emergency procedures it does not matter in which room this will be done [3]. Figure 2.2 shows a picture of the basic layout of an OR without furniture. Every OR has fixed equipment as the surgical lights, monitors, central supply systems and a plenum ventilation area (indicated in blue on the floor in figure 2.2).

Figure 2.2: Basic layout of an OR in RdGG [3]

Although this basic layout is almost equal in every OR, the ORs all have their own focus domain. Table 2.1 shows the eight ORs with their surgical specialties, surface area and dimensions. Each OR covers an area between 44 m^2 and 56 m^2 and has a height of 3 m. The blueprints do not show much differences between the eight rooms. Figure 2.3 shows a furnished OR. The center of the room is the plenum ventilation area with the surgical table positioned in it. The surgical tables in RdGG are not fixed to the ground and can be moved in multiple directions. This makes the ORs flexible and usable for different procedures. Around the centered plenum ventilation area, multiple arms are fixed to the ceiling. Two arms are used for surgical monitors which can be used for endoscopic procedures or other imaging material for the surgeon. The large column on the right side of the surgical table which is mounted to the ceiling with two arms is a fixed central supply system. This system has an outlet for power and medical gasses which are the connections for anaesthesia equipment, electrical surgical instruments and endoscopy equipment. Beside the blueprints, 28 pictures of sketches of the OR layout during different surgeries are received (appendix B). These sketches show more devices like the DaVinci surgical robot, an endoscopy column, an X-Ray bow, an ultrasound device, instrument tables and a surgical microscope. Most of these devices are positioned at the edge of the plenum ventilation area. The use of these devices during a procedure probably determines which of the eight rooms will be used.

Table 2.1: ORs with their surgical specialties and the surface and dimensions of the room (based on blueprints).

OR nr.	Surgical specialties	Surface (m^2)	Dimensions (m)
1.	Ear, nose and throat	54	6.7x8.0
2.	Emergency	49	6.7x7.3
3.	Urology	44	6.7x6.5
4.	General surgery	44	6.7x6.5
5.	Orthopaedic	49	6.7x7.3
6.	Urology/Ear, nose and throat	44	6.7x6.5
7.	Interventional	56 (+11)	6.7x8.3
8.	General surgery/emergency	49	6.7x7.3

Figure 2.3: Furnished OR

When analysing the blueprints another difference can be found in the walls of the rooms. OR number 2, 7 and 8 contain a 2mm lead equivalent wall, also known as a lead shield. This is meant to protect persons outside the room from radiation from imaging devices. Persons inside the room are wearing a lead apron to protect them from radiation. The reason why only three of the eight rooms are equipped with a lead shielded wall is because in these rooms devices are used which emit radiation which can be harmful for humans. The radiation shield creates a shield around the room preventing electromagnetic radiation in the room causing interference in nearby rooms and vice versa. Keeping the electromagnetic field inside the room should not affect the performance of an RFID system. Another difference can be found between OR number 7 and the other rooms. OR number 7 is by far the largest room with 56 m^2 and an additional part of 11 m^2. The main focus domain for this room is interventional surgery. This specialisation concerns minimally invasive image-guided surgeries. Image-guided surgeries require a larger room because of the size of the imaging devices. Every procedure asks for a different setting of the surgical table, OR personnel and surrounding equipment. An example of such a sketch can be seen in figure 2.4. This figure shows the layout of a basic surgery. Another example is figure 2.5, as you can see this procedure requires a complete different layout of the equipment and personnel. The center rectangle in pink presents the surgical table, the green 'umbrellas' the surgical lights, the blue rectangles are the instrument tables and the pink rectangles with an A in it present the anaesthesia equipment. Smileys are the surgical personnel and anaesthesia personnel. Appendix C shows the other 26 layout sketches.

images/confidential.jpg

Figure 2.4: This image is confidential and can not be made public.

images/confidential.JPG

Figure 2.5: This image is confidential and can not be made public.

2.2. Operating Room Components

Now the layout of different ORs and procedures became clear, the important equipment and medical devices present in the OR will be analysed. Looking at placement of an RFID system all devices in and around the surgical working area should be taken into account. Figure 2.6 shows the OR with the different components. Important equipment for this research are: surgical table, surgical lights, flexible central supply system, fixed central supply system, monitors and the plenum ventilation area. Technical documents regarding the specific components are used to gather more information. This information should create more insight in the particular devices which might be useful for the design scenarios and in the experimental phase of this thesis. At the end, the definition of the surgical working area is explained.

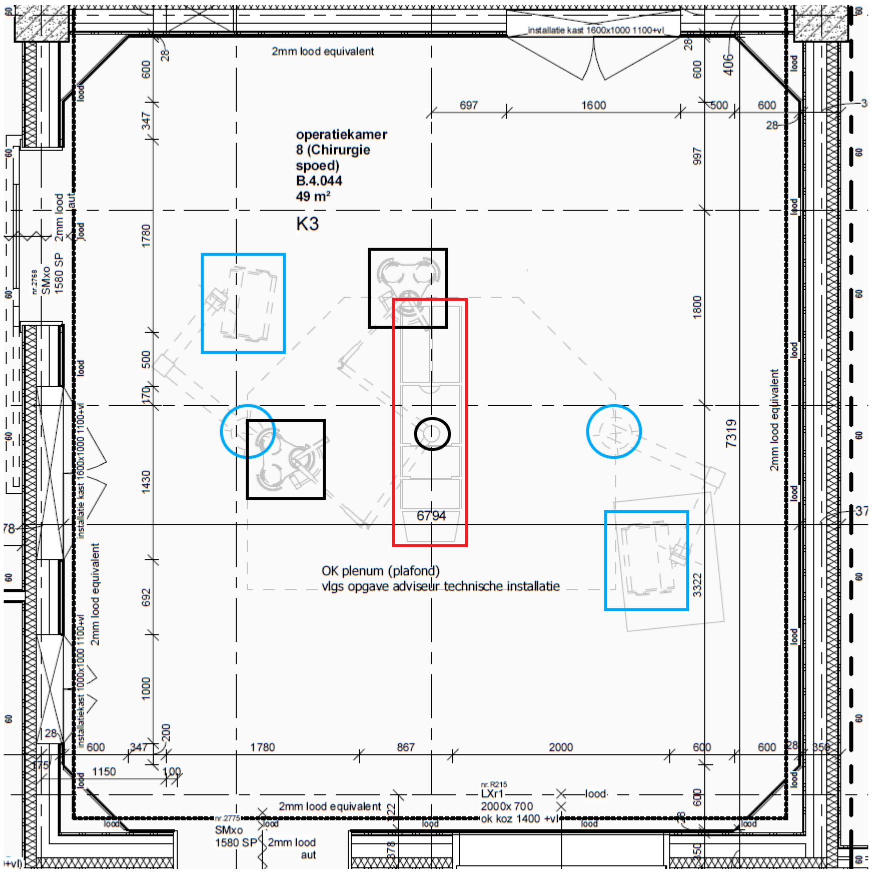


Figure 2.6: Blueprint of an OR in RdGG with the OR table (red), the mounting position of the Central Supply Systems (blue circle), the Central Supply Systems (blue rectangle), the mounting axis of the surgical lights (black circle and the surgical lights (black rectangle.

2.2.1. Surgical Table

The surgical table used in the RdGG is the 'Maquet Alphamaxx Mobile Operating Table' [20]. This is a mobile universal surgical table which means that it can be positioned at any place in the OR and can be shifted in different positions. This is useful for situations as figure 2.5 where a different orientation of the table is required compared to a general surgery (figure 2.4). The table can be shifted longitudinally up to 0.46 m and the height can be adjusted from 0.60 to 1.06 m from the ground. The height of the surgical table is important to take into account because in case the antenna will be placed above the table. The table height will determine the read range between the antenna and the tagged instruments on the table. The surgical tables have a width of approximately 0.55 m and a length of approximately 2.0 m. The length depends on the different kind of surgeries and patients. Many accessories are available to adjust the surgical table to a specific procedure. These accessories determine the length of the table. Following the sketches from the layout, the position of the surgical table is adjusted to the type of surgery and in most situations the surgical working area is positioned in the center of the ventilation plenum. Appendix B shows all the different layouts with the surgical working area encircled. The position of the surgical table is adjusted for different procedures and always close to the center of the plenum ventilation area. The position of the table is important for aiming the antenna in the direction the surgeon is working in.

2.2.2. Surgical Lights

The surgical lights are important to analyse because they can be compared to an RFID antenna. The lights are positioned above the table and in proximity of the surgical working area. Furthermore, the surgical lights offer some positions to mount the antenna to. The surgical lights used in the ORs in RdGG are the Dräger Polaris 600 [4]. The surgical lights have a 3-fold central axis which can be seen in the pictures of the OR. The figure below (figure 2.7) shows the central axis with the different options is sizes of the swivel arms. The ORs in RdGG have these 3-fold central axis but only two of the swivel arms are in use. Normally, the third arm can be configured with an extra monitor or an extra surgical light but in RdGG this third option is not used. The central axis of the surgical lights is positioned in the center of the plenum ventilation area (figure 2.6). The lights are mounted to swivel arms and this makes it possible move the lights freely around the surgical table. Another feature of the surgical lights is the use of an optional integrated Medview-camera in one of the surgical lights. The Dräger Polaris 600 is freely configurable and thus different components as display holders, external cameras, X-Ray protection shields or OR lights can be mounted on the three swivel arms. The length of the central axis differs between ORs. For example, OR number 6 has a central axis of 0.58 m and the central axis in OR number 8 has a lengthof 0.76 m. It has a diameter of 0.010 mm. The thickness of the swivel arms is 0.070 m and the surgical lights has a head diameter of 0.62 m [4].

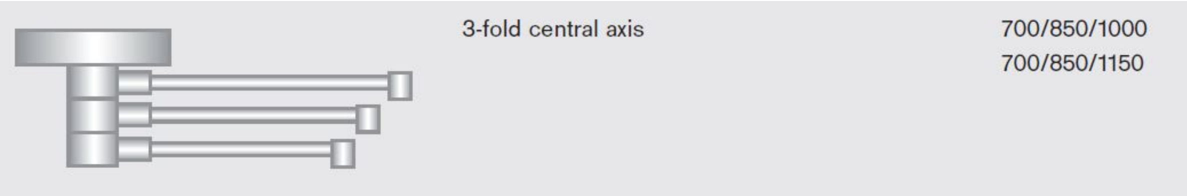


Figure 2.7: The 3-fold central axis of the surgical lights [4].

2.2.3. Ceiling Supply Systems

The ceiling supply systems are fixed at the edge of the plenum ventilation area and can be adjusted in position. Three ceiling supply systems are based in the OR. Two flexible systems which can be adjusted in position and one fixed system. The systems contain gas terminal units, electrical sockets, data ports and rails which enables the possibility to mount other equipment to it. The figure of OR number 1 (figure 2.3) contains one horizontal fixed ceiling supply system and two flexible systems. These systems can play an important role in implementation of RFID because they offer possibilities to mount RFID components to it. In addition, they can supply power to the reader and the laptop which is also important during the experiment. Furthermore, the data ports can be used in a later stadium to transfer data of detected instruments for the use of surgical phase recognition.

2.2.4. Monitors

The OR also offers three arms with monitors for imaging support for the surgeon. These monitor arms are fixed to the ceiling outside the plenum ventilation area and can be moved with swivel arms to the surgeons. A monitor arm can be a solution for fixing the antenna and make the antenna freely movable through the room.

2.2.5. Plenum Ventilation System

Every OR has a plenum ventilation area. The main goal of the plenum ventilation system is to keep the wound area free from contaminants. Table 2.2 shows the sizes and dimensions of the plenum ventilation areas for every OR in RdGG. The plenum areas are located in the center of the room with the fixed point of the surgical light in the center of it (figure 2.6).

Table 2.2: ORs with their surgical specialties and the surface and dimensions of the pleunum ventilation area (based on blueprints).

OR nr.	Surgical specialties	Surface (m^2)	Dimensions (m)
1.	Ear, nose and throat	11.8	3.5x3.4
2.	Emergency	10.1	3.5x2.9
3.	Urology	10.1	3.5x2.9
4.	General surgery	10.1	3.5x2.9
5.	Orthopaedic	11.8	3.5x3.4
6.	Urology/Ear, nose, throat	10.1	3.5x2.9
7.	Inverventional	13.8	3.5x4.0
8.	General surgery/emergency	11.8	3.5x3.4

Interflow BV. installed and validated the system used in RdGG (figure 2.8)[21]. The clean area around the surgical table is created by a vertical airflow originating from the ceiling. The air flows back through the return grilles in the corners of the room. The system is a unidirectional airflow system (UDF). This is also the most common system in Dutch hospitals [22]. The plenum ventilation areas in RdGG are between 10.1 and 13.8 m^2 and is marked in blue at the OR floor (figure 2.2).

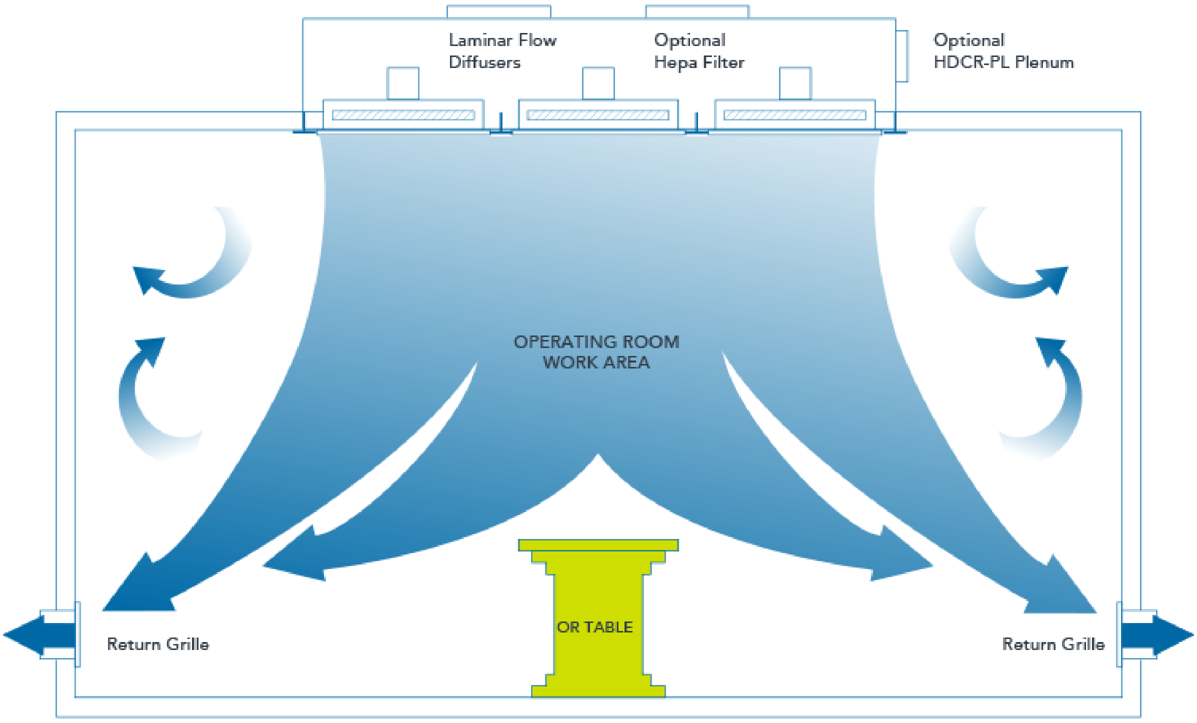


Figure 2.8: Schematic representation of plenum ventilation system used in RdGG.

The RFID system will be placed in proximity to the surgical working area. This will mean that it will probably be positioned in the plenum area since this area covers more than 10 m^2 of the OR. Some literature is searched to the use of plenum ventilation systems and the rules about positioning objects in this area. A study from Jain et al. reviewed the current airflow systems [23]. They concluded that the effect of airflow in the cleanliness of the air to prevent infections is multi-factorial. Multi-factorial in a way that the environment plays an important role. Jain et al. came up with a list of recommendations in order to achieve effective use of the laminar airflow. The number of personnel and the number of door openings must be minimised. Furthermore, surgeons should avoid allowing their heads above the surgical area and physical actions should be minimised near the surgical area. Lastly, devices that produce a lot of heat in the plenum must be limited. The airflow in the plenum has to be on the right temperature in order to reach the surgical wound area. In case the temperature increases, the air rises instead of flowing down to the patient. When the air is too cold the velocity of the airflow increases and can lead to turbulence [24]. This is important for placement of an RFID antenna because equipment placed in this area should not become too warm because this can negatively affect the flow pattern [25]. Zoon et al. state that an airflow system can be affected by the temperature distribution in the room, room dimensions, supply velocity and local disturbances as thermal plumes, objects disturbing the flow and OR personnel moving around the flow area. This study of Zoon et al. also state that the surgical lights are a critical factor in the performance of the flow system [24]. Surgical lights can serve as an example for an RFID system in the plenum area. When looking at the design of surgical lights designers should take the airflow into account. The Laminar Flow Index for surgical lighting (LFI) is often used in this process.

$$LFI = \frac{P \cdot A}{E^2} \tag{2.1}$$

P represents the electrical power of the light in *Watt*, A is the surface area in cm^2 and E is the illuminance of the light in *klux*. In this thesis, the surface area is of interest. This represents the physical obstruction of the airflow by the object. The study of Zoon et al. showed that the surface area of the lamp is a good indicator for infection risk. They conclude that, in their configuration, lamps with an area up to 0.1 m^2 do not disturb the airflow. The conclusion is that there is a relationship between the size of the object in the plenum area and the infection risk. This information can be used as a guideline for choosing the dimensions of the RFID antenna. The test setting in the experiment of Zoon et al. was much smaller than that of a real OR and thus the size as given in this research is lower than that in a real situation. In the experiment of Zoon they placed all the lamps horizontally and straight under the laminar downflow. They state that this is the worst case scenario. This means that the reader antenna should be positioned under an angle to decrease the detrimental effects on the flow pattern [24]. This is confirmed by the WIP-guideline [22]. They state that the surgical lights or other devices in the airflow should not be positioned horizontally and directly above the OR area. Beside these studies the WIP-guidelines also state that heat production, shape and size of lights or other devices can affect the flow pattern.

2.3. Surgical working area

The term surgical working area has been used in this chapter several times. A simple representation of this area can be seen in the figure below (figure 2.9). The green area represents the area the surgeon is working in and the red area is the area the instruments are located when they are not in use (instrument table). The position of the instrument table depends on the type of surgery. In some cases a Mayo stand is used and in other type of surgeries an instrument table is used which is positioned further away from the surgical table. In case the Mayo stand is used, the instruments are located more near the surgical area. This means the green and red zone of figure 2.9 are located close to each other which means that differentiating between instruments that are in-use and instruments that are not in-use more complicated. An estimation of the location of the surgical working area can be made based on the 28 sketches in appendix B. The red circle represents the location the surgeons are working in. In most procedures, the working areas are located in the center of the plenum (light green rectangle). This information is useful for positioning of the antenna in the OR.

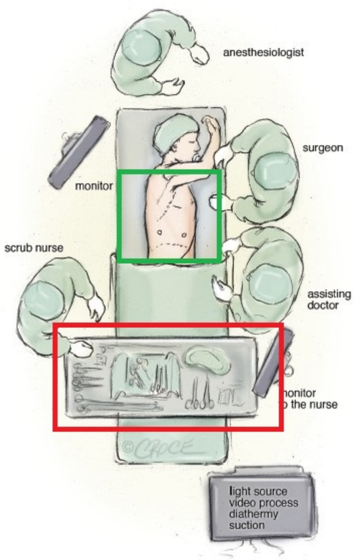


Figure 2.9: Schematic representation of an OR procedure. In the green zone the surgical working area and in the red zone the Mayo-stand.

3
RFID Technology Analysis

A small introduction to the basic principle of RFID is given in the general introduction of this thesis. This chapter will elaborate on the working principle of RFID technology and it will discuss the most important characteristics which are relevant for good performance of an RFID system in the OR. Furthermore, different performance metrics will be discussed, the electromagnetic field the RFID system produces will be discussed and the possible interference this field can cause will be explained. Technical understanding of the technology that will be implemented is a very important step in implementation to overcome miscalculations in a later phase.

3.1. RFID Technology

RFID is a tracking technology which also means information carried by radio waves. With RFID it is possibile to identify, locate and track people, animals and different objects [26]. This thesis uses passive RFID instead of active RFID. Explanation about this choice will be given further in this section. A basic passive RFID system contains the following components: host (laptop with software), a reader, an antenna and tags. The structure of an RFID system can be seen in figure 3.1. The antenna is connected to the reader with a coax cable and the reader is connected to the laptop with an ethernet cable. The reader is also connected to a power point.

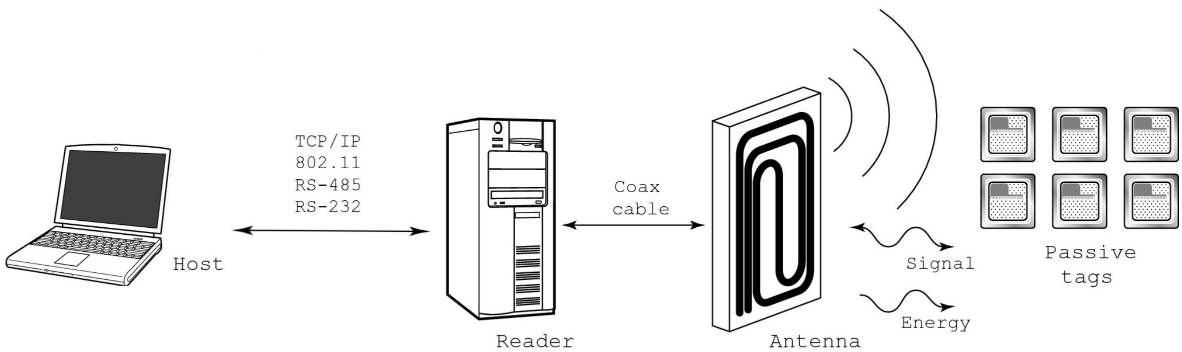


Figure 3.1: Basic RFID structure [5].

As said above, this project focuses on passive RFID instead of active RFID. This choice is based on the two types of tags, passive and active tags. An active tag has its own power supply and can transmit a stronger signal which results in a longer read range. These tags are often large and therefore not desirable to place on surgical instruments. Passive RFID tags are lighter, smaller and absorb energy from the electromagnetic field which means unlimited battery life. The small dimensions of the tags makes them more suitable for placement on surgical instruments.

The RFID reader and the RFID antenna create and radiate an electromagnetic field in which a tag can be detected. This radiated field is the interrogation zone [27]. When electromagnetic waves encounter the tag's antenna, energy is absorbed by the tag and the tag's integrated circuit. This integrated circuit chip generates a signal which is send back to the RFID antenna. The tag's integrated circuit switches between a load and an open/short circuit and by this it can control the encountered electromagnetic wave. By constantly changing from a good to a bad reflector the signal strength will vary and create a pattern. This pattern is unique and is detected at the reader as the unique identification (UID) code of the tag which is stored in the integrated circuit. This technique is known as backscatter modulation.

RFID can work in different frequency bands varying between approximately 100 kHz and 6 GHz. This range is divided in different ranges: Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF) and Microwave Frequency (MF) band. This project will use the UHF band. UHF is working in the frequency band of 865.6 and 867.6 MHz and works on a power of 2 W ERP. These two values are based on and limited by regulations which differ per country [28]. The choice for using UHF RFID technology is based on the fact that in this frequency it is possible to read tags on a longer distance compared to HF and LF. A higher frequency band as MF RFID is also suitable for long range applications. However, MF band is not used in many applications [5]. In addition, MF RFID uses mainly semi-passive or active tags which are more expensive than passive UHF tags and larger in size. Furthermore, MF RFID operates normally in a crowded frequency band and is therefore prone to interference which is not desirable in the OR [29].

3.2. Performance Metrics

The performance of an RFID system can be defined by different metrics. Widely used metrics are read range and read rate. Read range is defined as the maximum distance for detecting a tag by the antenna. Read rate is the percentage of tags that is in the operating distance of the interrogator and that is read by the interrogator relative to the total number of tags that is within the operating distance of the same interrogator [30]. Meeuwsen presented a model of surgical end-time prediction during a TEP-procedure [1]. In this research, read rate (or detection rate) was used as performance metric and defined as the percentage of time the instrument was detected by the system while the instrument was in use [1]. In this thesis the number of detections during a particular period will be used and these numbers will be compared among different tags.

Achieving a large read range is in this project important to detect tagged instruments which are used by the surgeon. By increasing the distance between the antenna and tags, the signal strength decreases. This can be derived from the Received Signal Strength Indication (RSSI) value [31]. The RSSI is an indicator of the strength of the signal received by the antenna transmitted from the tag. This value has a relation with the distance. When the distance increases, the RSSI value decreases. Thus, the higher the RSSI, the better the signal. The distance of the RSSI signal can be estimated by using the Log-Distance pathloss model. This model is as following:

$$RSSI = -10 \cdot n \cdot log_{10}(\frac{d}{d_0}) + A_0 \tag{3.1}$$

d is the distance between the antenna and the tag, n the signal propagation exponent which is often two in indoor environments. A_0 is the referenced RSSI value at a reference distance d_0 [32]. The closer to 0 dBm the stronger the signal. A decreasing signal strength can indicate an increase in read range. However, the RSSI value can also implicate that the environments is affecting the signal strength when the value is different while reading tags on equal distances. In practice, it seems that the distance is not always proportional to the RSSI value and that the environment plays an important role. Environmental causes will be further explained in this chapter. RSSI is in this thesis also used as an performance metric.

3.3. RFID Antenna Characteristics

The antenna has several characteristics which can affect the performance. A literature study showed that the following characteristics can effect the performance: radiation pattern, gain, beam width, directivity, front-to-back ratio, effective radiated power (ERP), polarisation and axial ratio [33]. The radiation pattern of the reader antenna is the graphical three-dimensional view of the power of the antenna. An isotropic antenna transmits power uniformly in all directions. The radiation pattern is actually never omnidirectional. In certain directions the power will always be more than in other directions. A radiation pattern consists of multiple lobes. The main lobe where the intensity is at its maximum and side lobes which point in different directions (figure 3.2) [27, 30].

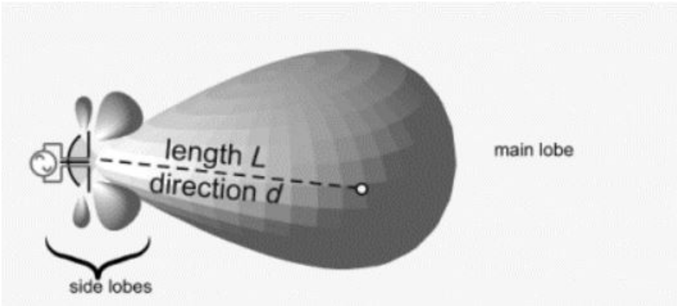


Figure 3.2: Main lobe and side lobes of the radiation pattern of a directional antenna [6].

This is where the term gain comes in, the gain is the ratio of the power transmitted in any direction d with respect to the power transmitted in that direction of an isotropic antenna. The higher the gain of a directional antenna the smaller the beam width [6]. The beam width is defined as the the angle between two points at which the power level falls to half of the maximum power. The size of the beam width is thus inversely proportional to the gain. A high gain and a low beam width ensures a better signal, a better read range and thus a more accurate signal [34]. However, it depends on the application whether this is desirable. In some cases where a small read range is sufficient, a low gain is desirable because this gives a shorter read range but also a larger beam width. The gain and the beam width are important factors in creating the right IZ for a specific application. For example, an antenna with a gain of 12 dBi has a beam width of around 45 °, an antenna with a gain of 8.5 dBi has a beam width of 69 °and an antenna with a gain of 5.5 dBi has a beam width of around 100 °. Increasing the gain also increases the physical dimensions of the antenna. A trade-off has to be made between these parameters [34].

Directivity of the antenna is a measure of how directional the radiation pattern is in reference to an isotropic antenna. A high directivity is required in a situation where it is desired to detect tags in a certain area. 0 dB means isotropic pattern and 3 dB gives the peak radiation. This peak radiation or peak directivity is equal to the beam width. The front-to-back ratio is related to the directivity of the antenna (the ratio of the forward and backward signal transmission). This ratio must be as large as possible to overcome signal noise and to increase the range and performance of the antenna.

The transmitted power by the antenna is given by the effective radiated power (ERP) and the effective isotropic radiated power. These two terms are important because they are always mentioned in the regulations about RFID. ERP is the product of the power of the antenna and the gain of the dipole antenna. While ERIP is the product of the power of the antenna with the gain of an isotropic antenna. In the Netherlands, the maximum ERP is set at 2 W [28, 35].

Another important characteristic of the antenna is polarisation, which determines the orientation of the electromagnetic field. The polarisation can be linear or circular. Linear polarised antennas create a horizontal or a vertical field while circular polarised antennas produce both a horizontal and a vertical field (figure 3.3). Normally, a linear polarised antenna has a better read range because of the more concentrated radiation pattern with respect to a circular polarised antenna. A drawback of linear polarisation with respect to circular polarisation is that all tags has to be in the same plane which is often not the case. In most applications a circular polarised antenna is used [36]. The axial ratio gives the quality of the circular polarisation. This is the ratio between the minor and major axis of the polarisation ellipse. An axial ratio of 0 dB is optimal and perfect but is not realistic. The axial ratio of an antenna is important when multiple tags have to be read at once [37].

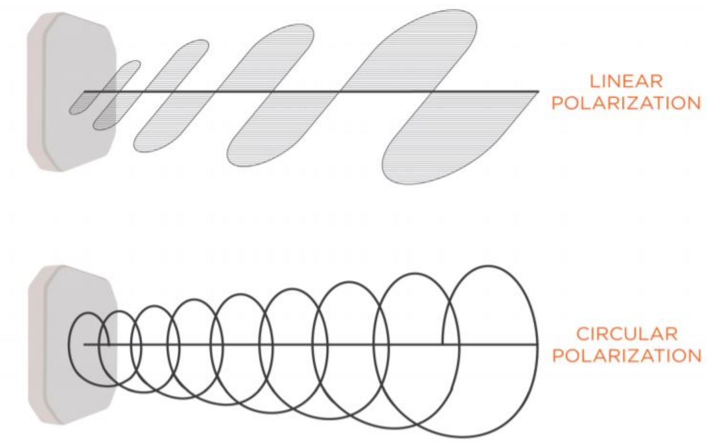


Figure 3.3: Linear polarisation and circular [7].

3.4. RFID Tag

The size, orientation, read angle and polarisation of the tag are factors that can affect the read range between the tag and the antenna. The tag choice for a certain application depends on different factors. The larger the size of the tag the better the read range. In the application where tags will be fixed to a surgical instrument, a trade-off has to be made between size and performance. The tag should fit on the surgical instrument and must not bother the surgeon in certain movements. The tag orientation and read angle of the tag with respect to the RFID antenna can also affect the read range between the tag and the antenna. Tag orientation is only important for linear polarised antennas. In this application a circular polarised antenna must be used and tag orientations should not matter. The read angle does matter. The instruments are often made of stainless steel and therefore tags are required which make it possible to be detected when fixed to metal. These tags are called on-metal tags. When tags are placed on surgical instruments permanently, they will also go through the cleaning process of surgical instruments. This means that the tags should withstand this process of cleaning. These tags are called autoclavable tags. After implementation an attachment has to be designed which makes it possible to attach and de-attach the tag. The attachment should not affect he performance of the tag.

3.5. RFID Reader

The RFID reader is connected to the RFID antenna with a coax cable. The RFID reader creates the electromagnetic signal that is radiated by the RFID antenna. Beside the role in transmitting signals, the reader is important in receiving the signals. An analog signal is received by the antenna and transported to the reader. The analog response of a tag is transformed by the reader in a string of zeros and ones [5]. The reader is less important than the antenna and tag in effecting the performance of the RFID system. Therefore, this thesis mainly focuses on the antenna and tags.

3.6. Electromagnetic Field

As aforementioned, the reader and the antenna together create and radiate an electromagnetic field. From this field the tag absorbs energy and sends back a signal to the antenna. To understand the propagation of the waves and the possible interference some basic knowledge about the electromagnetic field is required. An electromagnetic field consists of electric and magnetic waves. A magnetic field is produced if there is a changing electric field. A changing magnetic field is also able to create a changing electric field. This changing electric field will create a changing magnetic field and so on. This results in an electromagnetic field. The electromagnetic wave is the net results of these two interacting changing fields and can travel through space. This radiated electromagnetic field is send out by the antenna [8]. Below, a schematic representation of the electromagnetic field for far-field antenna. Figure 3.4a shows the propagation of the waves. Red represents the electric waves and perpendicular on the electric waves the magnetic waves in blue. Further in the radiated field the behaviour of the waves is like figure 3.4b. Electric and magnetic waves are always at right angles to each other. Figure 3.5 shows the two fields perpendicular on each other. The waves travel in phase with each other. This means that they equal zero and their peak at the same time [8]. The electrical and magnetic fields are always perpendicular to the direction of the wave.

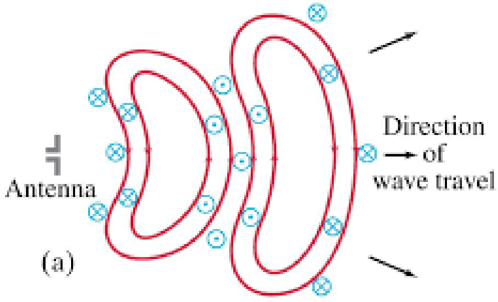


Figure 3.4: Radiation of the antenna in far field[8].

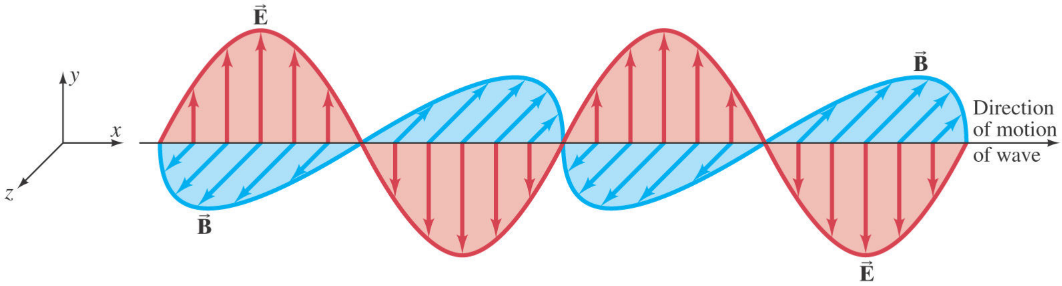


Figure 3.5: Electromagnetic waves perpendicular to each other[8].

3.7. Electromagnetic Interference

Electromagnetic interference occurs when multiple waves travel through the same space. These multiple waves are also called electromagnetic noise.

This can happen in case of a multiple antenna configuration, bistatic antenna configuration, reflection of waves or external waves. Interference is defined as the distortion caused by the radio waves of a device when interfering with the radio waves of the RFID system [30]. When the waves travel in the same phase constructive interference occur and when they propagate out of phase destructive interference occur. Constructive interference can be advantageous when the signal at the tag is multiplied but it can also lead to detections outside the interrogation zone which means false detections. Destructive interference can cause null spots in the interrogation zone. These null spots or dead zones are areas in the interrogation zone the tag can not be detected [30]. Electromagnetic interference in medical environments is covered in different studies. Following Calcagnini et al. the distance between the a RF portable device (RFID antenna) and a life-support medical device can be estimated with the following formula [38]:

$$D = 23\frac{\sqrt{P}}{E} \tag{3.2}$$

And the distance between the RFID equipment and not-life supporting medical devices can be estimated with:

$$D = 7\frac{\sqrt{P}}{E} \tag{3.3}$$

With D the distance in *meters*, P the rated maximum output power of the transmitter in *Watt* and E the medical device immunity level of the life supporting or not-life supporting device in *V/m*. This approach of estimating the distance is an approach based on International standards and European Regulations on medical devices. Immunity is defined as the ability of an electronic product to operate as intended without performance degradation in the presence of an electromagnetic disturbance [39]. With a minimum level of immunity of 10 V/m for life supporting devices (established by the IEC/EN 60601-1-2:2007) and a minimum level of immunity of 3 V/m for not-life supporting devices, the minimum distance is estimated at 3.3 m for both life and not-life supporting devices[39, 40]. Different researches investigated the effect of electromagnetic interference between RFID and medical devices and used different distances. Koffeman searched different work from other researchers which led to conflicting results [2]. A study from van der Togt et al. showed that UHF RFID can lead to interference with medical devices. They found that interference can occur on a median range between the antenna and the medical device of 30 cm with a range of 0.1 to 600 cm [41]. This is a large difference with the estimated distance of Calcagnini et al. [38]. Another study tested if there RFID was interfering with implantable devices as pacemakers. Only for the LF band and HF band interference occured and not for the UHF band [42]. A study of Houliston et al. tested if RFID was interfering with an infusion pomp and found that interference occured only for high power systems of 4 W. In the Netherlands only 2 W RFID readers are allowed. At this power no interference occured [43]. The studies all advice to test the possible interference of RFID and medical devices before implementation. Koffeman did this in his thesis in ORs in RdGG [2]. He concluded that it was unlikely that interference occurs between the devices on a distance of 1.5 m. Because this test is performed in the OR in RdGG, 1.5 m is used as the minimal distance between the antenna and critical equipment in the OR.

Interference can also cause distortion of RFID equipment. In the OR different environmental factors can affect the performance of RFID. As aforementioned, reflective environments can cause multipath propagation which can cause constructive or destructive interference. Both not desirable.

A study of Poulin and Amiot aimed to quantify the interference sources in an OR to evaluate their impact on a location tracking system [44]. They give three different sources of interference in a normal OR. First, background noise originating from ambient electrical devices. As example of this first source they give wires in the floors or in ceilings, lights and MRI devices in a nearby section. Secondly, the electromagnetic fields of electrical OR equipment and lastly the ferromagnetic behaviour of metal instruments and tools. The location of the radiology department (MRI location) in the RdGG is located at the ground floor of the hospital and the OR complex at the fourth floor. Therefore, MRI should not affect the RFID equipment in the OR. Chapter 7 will test an RFID system with the electrical equipment turned on and off. Metal instruments will be attached with an on-metal tag meaning that the tag results in better performance when attached to metal. However, the metal instruments can still affect the performance of the antenna.

Electrical magnetic noise is different from destructive and construtive interference. IT

II

Part 2: Design

4
Implementation Requirements

This chapter presents a list of requirements the RFID system should comply to in order to be implemented in the OR. The requirements are based on the previous chapters. Chapter 2 presented the application domain and chapter 3 presented the background of RFID. The combination of the technology and the medical setting is an important step in research in the field of Biomedical Engineering. In case this problem is approached from the technical site only multiple problems can occur in a later stadium of implementation. The list of requirements will be used in the next chapter where possible positioning options will be presented. The requirements are divided in criteria and wishes. The criteria are the ones that must be met and the wishes can be beneficial for the performance of the RFID system in the OR but are not necessary for successful implementation.

4.1. Criteria

1. *The RFID antenna should produce a circularly polarised pattern.*
   As described in chapter 3, the pattern can be linear and circular. A circularly polarised antenna is able to detect tags in a three dimensional plane. A surgeon uses instruments in a three dimensional field and the location of the surgical working area will differ per procedure. A three dimensional interrogation zone is necessary for this application.

2. *The axial ratio of the antenna should be as close as possible to 0 dB.*
   The lower the axial ratio the better the antenna. In addition, a low axial ratio gives the antenna the ability to read multiple tags at once because more power is generated in the field [37]. This is important because multiple tagged instruments can be used simultaneously.

3. *The front-to-back ratio of the antenna should be as high as possible.*
   A high front-to-back ratio means that the forward power is higher than the backward power which results in better performance of the antenna. Strong forward power is required to achieve a strong interrogation zone in the surgical working area and means less leakage at the backside of the antenna [45].

4. *The distance between the RFID antenna and the surgical table must be not more than 1.5 meters.*
   This is a reasonable distance when looking at the RFID equipment available for this application. Previous tests with different tags showed a maximum read range of around 1.3 m (appendix A).

5. *A single RFID reader antenna should be used.*
   An RFID antenna which is able to read small tags has to be positioned in proximity of the surgical working area. As described before, the plenum ventilation area is 3.4 x 3.0 m. The maximal read range between the tag and the antenna is estimated at 1.5 m. Based on this it can be assumed that the antenna is positioned in the plenum ventilation area. In case objects are placed in the plenum ventilation area they should be small in size and multiple antennas cover more space than a single antenna. Beside this consideration, multiple antennas can cause multipath propagation causing interference which can decrease the performance of RFID.

6. *A monostatic RFID antenna configuration must be used.*
   This consideration came forward from literature and can play an important role in the performance of RFID [33]. A monostatic antenna is an antenna which is able to receive and transmit EM waves and a bistatic antenna configuration consists of a seperate transmitting and receiving antenna [36]. Literature showed that a bistatic antenna configuration could results in a longer read range but this would also require a lot of space in the room of implementation [33] Therefore, a monostatic antenna is preferred over a bistatic antenna for this application.

7. *The RFID antenna has to be as small as possible.*
   The larger an antenna the better the performance. But an antenna which is too large also causes more turbulence in the plenum ventilation area which is undesirable. A trade-off between performance and size has to be made. The location of the antenna will also determine the maximal size of the antenna. Literature in chapter2 stated that an object with a maximal surface area of 0.1 m^2 can be placed in the plenum ventilation area.

8. *The RFID antenna has to be working in the Ultra High Frequency band.*
   UHF band is the frequency band of 865-858 MHz and in this frequency band it is possible to achieve read ranges of more than a few meters. This is required in this application.

9. *The ERP should not be over 2W*
   This is according to the rules and regulations of RFID in Europe [28].

10. *The RFID system should not interfere with medical devices in the OR.*
    The RFID system should never interfere with other medical equipment such as anaesthesia equipment or endoscopy equipment because this can affect their function and performance. Care should be taken with the position of the antenna. Based the test of Koffeman the minimal distance between the antenna and medical devices is set at 1.5 m [2]. This should be a safe distance to prevent the systems from interfering with each other.

11. *The RFID reader antenna should not produce heat.*
    Heat production by the antenna can warm-up the environmental temperature. This is not desirable because it can affect the airflow pattern.

12. *Line-of-sight between the antenna and the surgical working area is required.*
    Normally, an RFID system does not require line-of-sight to detect tags. In our application line-of-sight is required because this was the problem in previous research. Due to blockage of human bodies the antenna was not able to detect tags. Besides, the tagged instruments will be in hands of the surgeon and this can lead to a situation where the RFID tags are not in line-of-sight with the antenna. In case another object is also in the line-of-sight the signal strength decreases and it would be difficult to achieve detection of a tag.

13. *The gain and the beam width of the RFID antenna should fit the interrogation zone.*
    The choice for the gain and the beam width of the antenna depends on the position of the antenna and desired interrogation zone. As described before, the higher the gain the lower the beam width and vice versa. In this application we have to cover an area in the center or the plenum ventilation area with different height because of different table heights.

14. *In case the antenna is placed in the plenum ventilation area the RFID antenna has to be positioned under an angle with respect to the laminar airflow.*
    When the antenna is positioned above the surgical table in the plenum ventilation area it can be compared with the surgical lights. Regulations for safe use of surgical lights describe that they have to be positioned under an angle in order to reduce the effect of turbulence [22].

15. *The RFID reader antenna should be positioned on a height of minimally 2.10 meters above the floor.*
    The antenna may never obstruct the surgeons in their work and therefore the antenna must be positioned at a height where it will not bother them. The estimated maximum height of a surgeon is 2.10 meters and therefore the antenna should not be placed below this point.

16. *The antenna and its mounting arm should not block movements of monitors or surgical lights.*
    The antenna and its mounting arm should be able to move in all degrees of freedom without blocking movements of other equipment and surgeons.

17. *No shadow forming by the antenna.*
    When the antenna will be positioned in proximity of the surgical lights, it may never be in the illumination field of the surgical lights.

4.2. Wishes

1. *Exactly cover the interrogation zone which is the surgical area.*
   The interrogation zone is the zone tagged instruments can be detected in. In case this zone does not exactly cover the surgical working area for a specific procedure, it does not mean that the system can not be used. This problem can be solved by setting RSSI limitations or by tracking changes in RSSI values which would mean the tag is moving.

2. *The tags on the instruments should be replaceable and sterilizable.*
   For this phase, it is not a criteria because the principle of the RFID system has the focus. In a later stadium it is desirable that the instruments can be sterilised while tagged and that tags can be detached and attached.

3. *It should be able to clean the RFID antenna easily.*
   After every procedure the OR is cleaned. The antenna should be cleaned easily. This requires a smooth surface and there should be no places where dirt can stick to easily.

4. *Re-positioning of the RFID antenna should be possible.*
   It should be possible to change the position of the RFID reader antenna by the OR personnel. Flexibility is important to make sure the antenna is always aiming in the right direction.

5 Design Scenarios

This chapter presents design scenarios for placement of the antenna in the OR. The requirements from the previous chapter are taken into account to sketch the design scenarios. For every scenario a Harris profile is made. This is a tool to visualise the strengths and weaknesses of the different design scenarios [46]. The winning concept will be chosen based on this Harris profile. The design scenarios are mainly based on the position of the RFID reader antenna (criteria 4, 10, 12 and 14-17). Choices regarding the RFID equipment will be based on the optimal position and these choices will be further elaborated in the next chapter.

5.1. Design Scenario 1

The first scenario of placement of the antenna is on the position where normally a monitor can be attached. This is at the third arm of the surgical lights. The analysis of the OR domain did not show a third swivel arm at the surgical lights. This can be an advantage because it is not used for monitors and thus available for an antenna. It can also be a disadvantage in case it is not possible to attach this third swivel arm. A sketch of this first design scenario is given in figure 5.1 where red gives the component where the antenna should be attached to and black gives the antenna with the radiation direction.

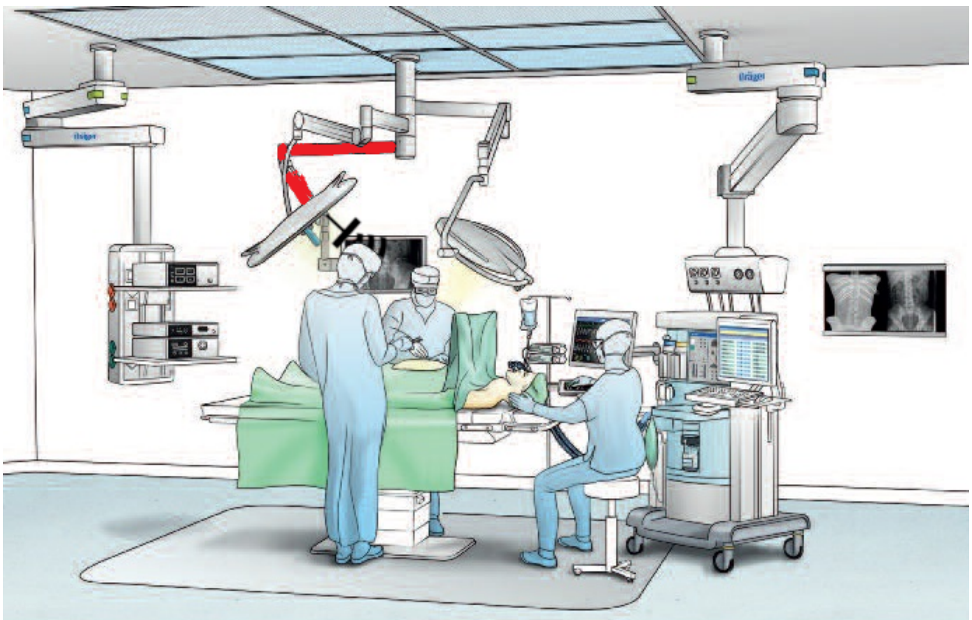


Figure 5.1: Sketch of design scenario 1.

The distance between the antenna and the surgical working area in this scenario is smaller than 1.5 m. The antenna has free line-of-sight to the tagged instruments because it is positioned in close proximity of the surgical working field. The antenna can be positioned under an angle when attached to this arm. Normally, a monitor can be attached and thus it is expected that this is in line with the regulations around the airflow. The antenna is not placed at a height of 2.10 meters and thus it is in the field of the surgeons. At this position the antenna is not in close proximity to medical equipment which is a plus. The optimal position of the antenna can interfere with the optimal position of the surgical lights. In that case, the lights will always have priority and thus the antenna will not has its optimal position. Adjusting the position of the antenna also has its downside because the OR personnel have to be informed about how to position the antenna the right way. In this scenario, the antenna can obstruct the surgical lights and surgical personnel in movements. In addition, shadow can arise in this scenario.

Table 5.1: Harris Profile of design scenario 1.

Design Scenario 1

Requirements	**Score** -2	-1	1	2
Max 1.5 m between antenna and surgical table			■	■
Free line-of-sight			■	■
Under an angle			■	■
2.10 m above floor		■		
At a minimal distance of 1.5 m from medical equipment			■	■
No blockage (physical)	■	■		
No shadow forming		■		

5.2. Design Scenario 2

A second possible option for placement of the RFID antenna is at the edge of the plenum ventilation area. In chapter 2 we have seen the multiple ceiling supply systems at the edge of the plenum. Figure 5.2 shows two possible options of this scenario.

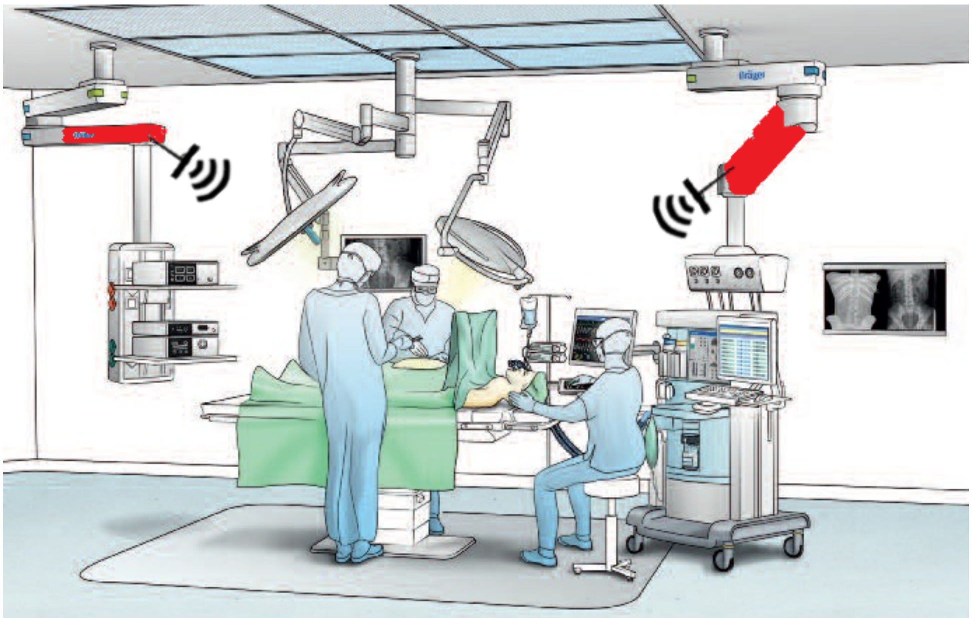


Figure 5.2: Sketch of design scenario 2.

The dimensions of the plenum ventilation area is approximately 3.4 x 3.2 m. This would mean that the horizontal distance from the side of the plenum ventilation area to the center of the plenum is 1.5 m. The distance to the surgical working zone will be the diagonal of this horizontal line and thus the distance will be more than 1.5 m. Free line-of-sight can not be ensured in this scenario. It can be positioned under an angle but this requirement

is only important in case the antenna is positioned above the surgical table. The same goes for the distance of 2.10 m.
A big disadvantage of this position is that it will be located close to the anaesthetic equipment and endoscopy tower and thus in the range of 1.5 m. The main advantage is that the antenna is in this scenarios located outside the the plenum ventilation area and thus no extra turbulence occurs. Furthermore, it would not lead to any physical obstructions in the room and no shadow can be created.

Table 5.2: Harris Profile of design scenario 2.

Design Scenario 2

Requirements	**Score** -2	-1	1	2
Max 1.5 m between antenna and surgical table	■	■		
Free line-of-sight	■	■		
Under an angle				
2.10 m above floor				
At a minimal distance of 1.5 m from medical equipment	■	■		
No blockage (physical)			■	■
No shadow forming			■	■

5.3. Design Scenario 3

A third scenario of placement of an RFID antenna above the surgical table would be at a fixed point in the center of the plenum. The antenna can be fixed to the central axis of the Polaris 600 surgical lights. Figure 5.3 shows a sketch of this design scenario where the antenna is mounted to the central axis (red).

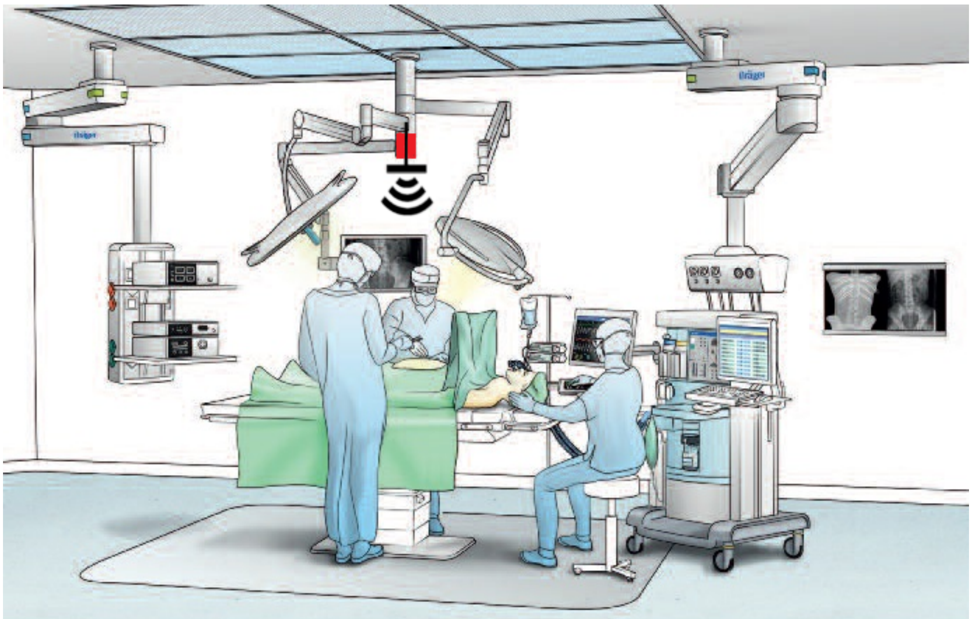


Figure 5.3: Sketch of design scenario 3.

This position brings a lot of advantages because the antenna can be positioned straight above the table. The height of this position is estimated at approximately 0.85 m from the ceiling which means a height of 2.15 m from the floor and 1.55 m from surgical table at its lowest position. At this position the antenna almost always has a free line-of-sight to the surgical working area. It can be positioned under an angle but only when a surgery is not performed straight under the central axis. In that case it is horizontally oriented. The distance between the floor and the antenna will be above 2.10 m when looking at the length of the central axes. The antenna is located outside the range of 1.5 m from medical equipment so no interference should occur. Furthermore, it can not cause obstruct the movements of the surgical lights because the first swivel arms move from the central axis and thus they circle more around the antenna. Shadow is also not formed in this scenario because the antenna is positioned at a place the surgical light can not be positioned.

Table 5.3: Harris Profile of design scenario 3.

Design Scenario 3

Requirements	**Score** -2	-1	1	2
Max 1.5 m between antenna and surgical table			■	■
Free line-of-sight			■	
Under an angle			■	
2.10 m above floor			■	■
At a minimal distance of 1.5 m from medical equipment			■	■
No blockage (physical)			■	■
No shadow forming			■	■

5.4. Design Scenario 4

The fourth design scenario is placement of the antenna to the lower swivel arm. This position can be seen in figure 5.4. In red the first swivel arm of the surgical light which is positioned at the lowest of the two to the central axis. Positioning to the highest one would cause obstruction of the movement of the lowest swivel arm.

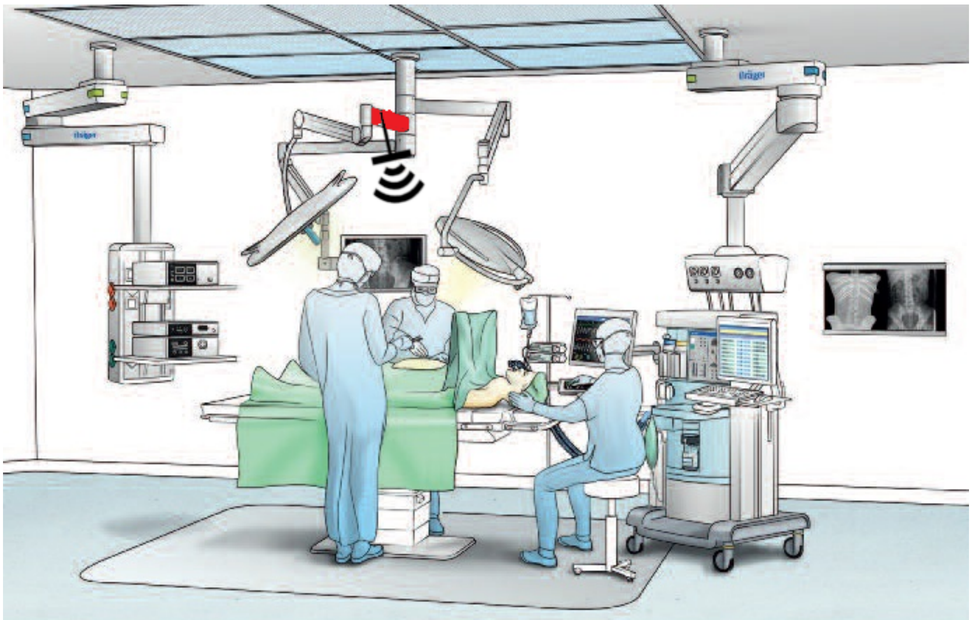


Figure 5.4: Sketch of design scenario 4.

This fourth design scenario is almost equal to design scenario 3 when looking at the height. The direction is in this scenario always dependent on the position of the surgical lights and thus this also determines if the antenna has free line-of-sight to the surgical table. It can also be positioned under an angle but that also depends on the position of the swivel arm with respect to the surgical working area. The antenna has a height of more than 2.10 meters which is a plus and is at this position outside the range of 1.5 m from medical equipment. The surgical lights be physically blocked by the antenna at this position. An advantage is that is positioned above the surgical light heads and thus no shadow can occur.

Table 5.4: Harris Profile of design scenario 4.

Design Scenario 4

Requirements	**Score** -2	-1	1	2
Max 1.5 m between antenna and surgical table			X	X
Free line-of-sight			X	
Under an angle			X	X
2.10 m above floor			X	X
At a minimal distance of 1.5 m from medical equipment			X	X
No blockage (physical)	X	X		
No shadow forming			X	X

6 Winning Scenario

The design scenarios of the previous chapter led to one winning concept. Design scenario 3 was considered as the best possible option for placement of the RFID antenna in the OR. The Harris profile showed plusses for all the requirements regarding the position. Now the optimal position of the antenna is known, further choices can be made regarding the RFID equipment. This chapter will elaborate on this and will describe the choices of the antenna, reader and tags.

6.1. RFID Antenna

The previous chapter already described the position of the antenna. The antenna will be fixed to the central axis of the surgical lights. A clinical physicist of RdGG agreed on it that this was the best possible position of the four proposed scenarios. The distance between the antenna and the surgical table will depend on the length of the central axis and on the set height of the surgical table. The length of the central axis in the two visited ORs in RdGG was 0.58 m and 0.76 m. This results in a distance from the floor to the central axis of 2.42 m and 2.24 m. As described in the requirements in chapter 4, the minimal height should be 2.10 m in order to stay out of the range of the surgeon. Some space between the antenna and the central axis is required in order to mount the antenna. Therefore, a height of 2.10 m above the floor is chosen. The surgical table can move in a range of 0.6 m and 1.06 m. This means that the distance between the antenna and the surgical table is maximal 1.5 m and minimal 1.04 m. Assuming that the surgeon uses the instruments approximately 0.1 m above the surgical table the maximal distance is 1.4 m and the minimal distance is 0.94 m. This position requires an antenna that is able to detect tags on a distance of 1.4 m and that is able to create a beam width that can to cover a large part of the surgical table. The table below shows an overview of commercial available UHF circular polarised antennas. The most important characteristics of the antenna are given in the table.

Table 6.1: Commercial available antennas with different characteristics.

	Antenna type	Gain	Beam Width	Front-to-back ratio	Axial ratio	Dimensions
A.	LAIRD S9025PL/S8655PL (LHCP) OUTDOOR [47]	5.5 dBi	100 °	8 dB	2 dB	132 x 132 x 18 mm
B.	ALIEN ALR-A0501 COMPACT [48]	6 dBi	105 °	5.6 dB	1.5 dB	128 x 128 x 20 mm
C.	RFMAX S9028PCR/S8658PCR (RHCP) INDOOR [49]	8.5 dBi	70 °	18 dB	1 dB	259 x 259 x 33 mm
D.	RFMAX R9028LPV/R8658LPV	8.5 dBi [50]	68 °	Not given	1.4 dB	250 x 250 x 14 mm
E.	Harting Ha-VIS RF-ANT-WR30-EU [51]	8.5 dBi	69 °	>18 dB	1 dB	270 x 270 x 45 mm
F.	ALIEN ALR-A1001 ULTRA SLIM [52]	8.5 dBi	68 °	20 dB	2 dB	250 x 250 x 14 mm
G.	INVENGO XC-AF26 HIGH GAIN [53]	12 dBi	45 °	Not given	Not Given	431 x 431 x 60 mm

The table shows antennas with a gain in a range of 5.5 dBi and 12 dBi. The front-to-back ratio of antenna A and B is 8 dB and 5.6 dB which is low compared to all the other antennas. When looking at the antennas with a gain of 8.5 dBi the beam width is almost equal, the front-to-back ratio of antenna F is the highest but the axial ratio of this one is 2 dB while the other antennas of 8.5 dBi have an axial ratio smaller than 2 dB. Antenna C and E shows the best results regarding the axial ratio. In case an antenna is used with a higher gain the beam width will decrease which is not desirable in creating the right interrogation zone. Figure 6.1 shows a sketch of an antenna with a beam width of 69°and an antenna with a beam width of 45°. An antenna with a small beam width would not be able to cover a large part of the surgical table. In addition, an antenna with 12 dBi is almost twice as large as the antenna of 8.5 dBi and this would be too large to place above the surgical table in the plenum ventilation area. The size of the antenna must be as small as possible.

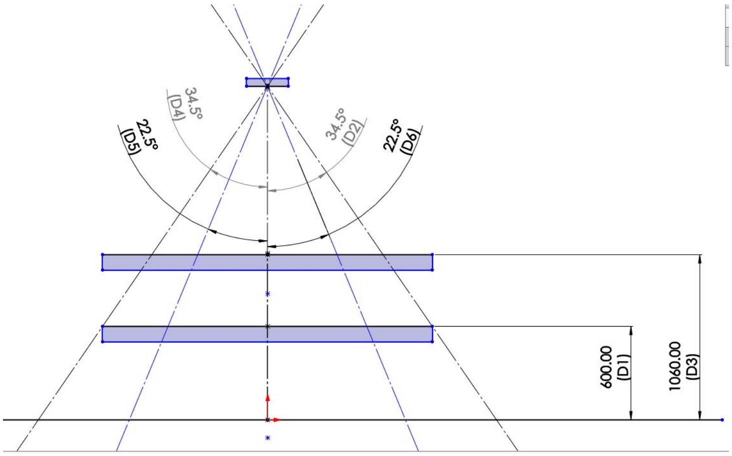


Figure 6.1: Schematic representation of the antenna facing the surgical table at its highest and lowest point (on scale).

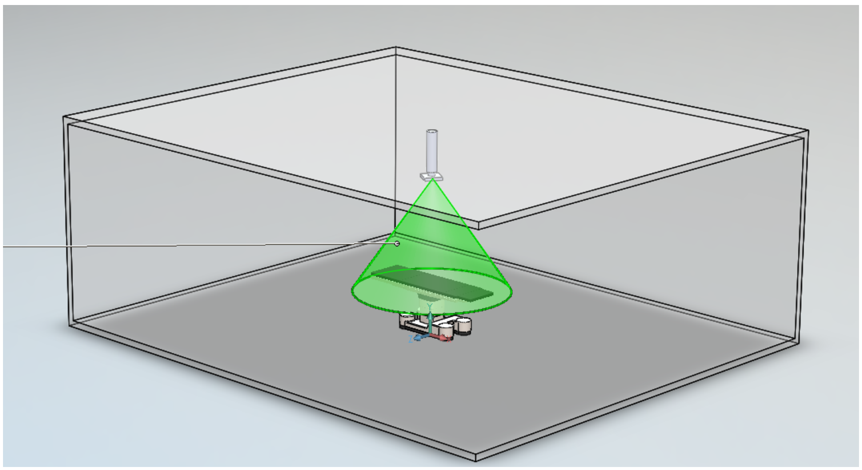


Figure 6.2: Schematic representation of the beam width of the antenna facing the surgical table.

Given the fact that antenna E is already available at the TU Delft and the performance characteristics are positive compared the lower gain and higher gain antennas and almost equal to other 8.5 dBi antenna this antenna is chosen to be used for this project. Theoretically, this antenna seems the best option because of the balance between the beam width and the gain. Figure 6.2 shows an estimation of the interrogation zone of the chosen antenna applied in the OR. The reader antenna has the following specifications [9]:

Table 6.2: Specifications of the RFID antenna [9]

Electrical properties	**Mechanical properties**
Frequency range: 865...870 MHz	Dimensions: 270X270X45 mm
Impedance: 50 Ohm	Weight: 1.7 kg
VSWR: <1.2:1	Degree of protection: IP 65
Polarisation: Circular	Antenna cover: Tough, weather-resistant polymer blend
Gain: 8.5 dBic @866 MHz	Colour: RAL 7045 (light grey)
Far field half-power beam width: 69°	Chassis: Aluminium
Front-to-back ratio: >18 dB	Installation: Four M5 drill holes 100X100
Axial ratio: typ. 1dB	Operating temperature range: -20 °C... +55°C
Max power (ETSI EN 302 208): 2W ERP	Storage temperature range: -40 °C... +85°C
Connection TNC socket	

The only criteria of chapter 4 that the chosen antenna can not comply to is criteria number 11. This criteria states that the antenna should not produce heat in order to overcome turbulence of the airflow. In the specification nothing is stated about the heat production by the antenna. Multiple tests are performed with this antenna and no extreme changes in temperature are detected. For this phase of research heat production is not taken into account. For the experiment in the next part of this project the antenna will be fixed with a Manfrotto magic arm and a clamp which is able to fit around an object of 0.010 m. The antenna can be fixed around one of the swivel arms and be positioned below the central axis to mimick design scenario 3. The antenna will be positioned above the surgical table and will be fixed to the central axis of the surgical lights. Mounting the antenna to this round object is not easy. A specific mount has to be design in order to make sure that the antenna is fixed properly to the central axis. The figure below shows the possible holes for mounting the antenna. The port for the coax-cable always has to be free. In the left sketch of this figure it can be seen that the antenna has four holes for screws in a square of 0.10 x 0.10 m. This is commonly known as VESA100x100. A standard measure for fixing commercial monitors.

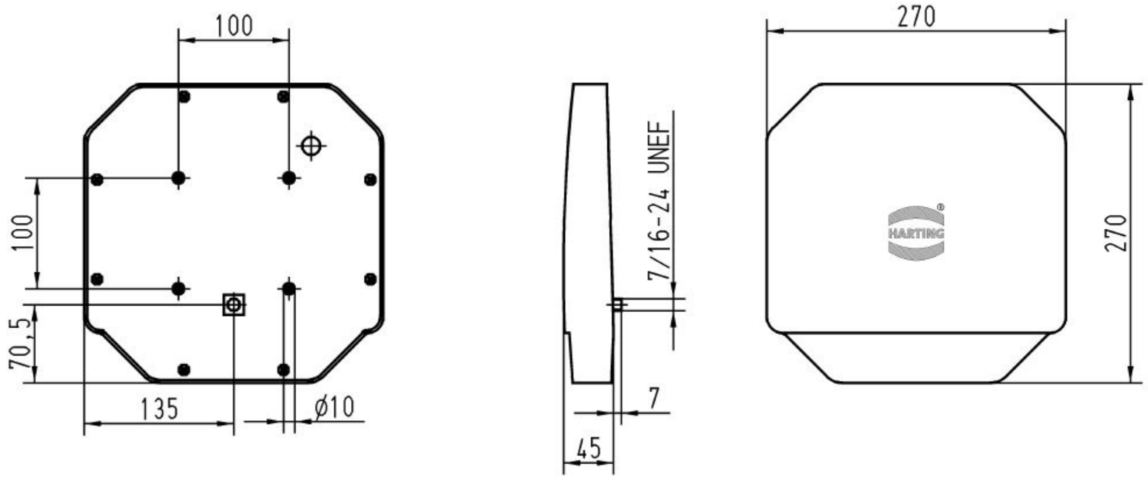


Figure 6.3: Sketches of the RFID antenna [9].

The position of the antenna is in the plenum ventilation area where turbulence should be minimised. This is not an issue for the experiment in the next phase but for implementation the design should be more smooth to minimise the turbulence. A simple model is created (figure 6.4). This shows a model of the antenna at the bottom and a more aerodynamic housing around it with fixing mechanism in it. The two swivel arms of the surgical lights originate from the central axis above the conical part. This is a model to show that it is at this position possible to minimise the turbulence caused by the antenna.

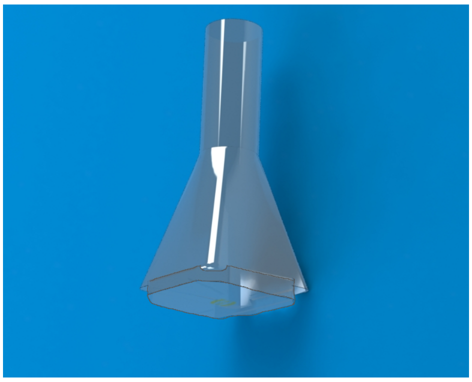


Figure 6.4: Proposed version of aerodynamic housing for the RFID antenna.

6.2. RFID Tag

Multiple tags are considered for placement on the instruments. Previous studies of Koffeman and Haring used the Xerafy Dot-On XS and the Dot-On XXS [2, 17]. These tags are round and small and are able to be read on a distance of max 1.5 m and 1 m, respectively. The Xerafy Dot-On XXS is not usable in this application because read range of 1 m is too short for the proposed scenario. Tags with a larger read range are the Xerafy Dash-On XS and the Xerafy Pico Plus tag. Together with the Xerafy Dot-On XS tag, the tags are tested in an experiment (appendix A). Tags of the brand Xerafy are chosen because they offer a large range of autoclavable and on-metal tags in different sizes. These tags are also meant for use on surgical instruments. Table 6.3 shows operating frequency, dimensions and on-metal read range of the tested tags.

Table 6.3: Autoclavable, on-metal Xerafy RFID tags[10].

Tag type	Operating frequency	Size (mm)	Read range on-metal
Xerafy Dot-on XS	UHF 866-868 MHz (EU)	⌀6 x 2.5	Up to 1.5 m
Xerafy Dash-On XS	UHF 866-868 MHz (EU)	13.3 x 3.0 x 2.2	Up to 2 m
Xerafy Pico Plus	UHF 866-868 MHz (EU)	12.8 x 7.0 x 3.0	Up to 3 m

The experiment tested the three different tags on different distances and compared the RSSI values with each other. The results were as expected. The Pico Plus tag showed the best RSSI values and the Dot-on XS showed the poorest RSSI values. The maximum distance on which the tags were tested was 1.2 mm. The average RSSI value of the Pico Plus tag was at this point -58 dBm, the average RSSI value of Dash-On XS was -60 dBm and the Dot On XS tag showed an average RSSI of -62 dBm. This was the mean of less values than for the other two tags because not much data was acquired due to poor performance of the tag. It was good to see in this experiment that the tags were able to be read at this distance because a larger distance between the tag and the antenna would mean that the RFID antenna can be positioned further away from the surgical working area. Considering tag choice, the Xerafy Pico Plus tag and the Xerafy Dash-On XS tag have the potential to be read on a distance of around 1.5 m. The Pico Plus tag would probably show better results on a larger read distance but a tag of this size would probably obstruct the surgeon in his handlings, especially when the tag will be fixed to the instrument with the use of an attachement as in the study of Koffeman [2]. The chosen tag for this application is the Xerafy Dash-On XS tag. This is a EPC Class 1 Gen 2 tag and works in the UHF operating frequency. Following documents, this tag has a read range on-metal up to 2 meters which should be enough to be detected in the surgical working area. Furthermore, the choice for this tag depended on the dimensions of the tag. Because the tag has to be fixed to surgical instruments it is desired that the tag is small in size. Figure 6.5 shows the dimensions of the tag.

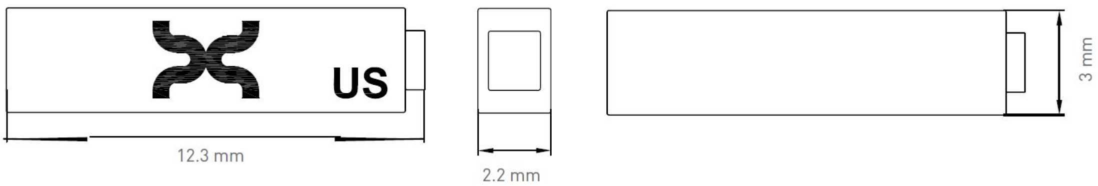


Figure 6.5: Dimensions of the Xerafy Dash-On XS tag[10].

6.3. RFID Reader

The used RFID reader is the RFID RF-R500-c-EU. This is a stationary RFID reader suitable for the chosen Harting RFID antenna. This reader is able to read on long distances and can be applied in rough environments. It fully supports the RFID antenna and with that it meets its most important criteria. Furthermore, it is able to detect maximal 150 tags per second, it is able to read out RSSI values.

III

Part 3: Testing

7
Introduction

The theoretical framework from chapter 2 and 3 led to the design requirements for an RFID system in the OR. With the requirements four design scenarios are created and analysed. This led to one concept which should be useful in the OR. This winning concept is based on theory and in this chapter the concept will be tested in the OR environment. It is common in RFID implementation projects that a system is tested in its new environment. In this experimental testing phase of the project, the RFID system will be deployed in the MISIT-lab in Delft (MISIT-lab experiment) and in an OR in RdGG (OR experiment). The first experiment in the lab is performed to see whether the RFID system is able to achieve the required detection distances and to check if some changes are required before testing in the OR. After this, the OR test should show whether the implementation of RFID is feasible.

7.1. Experimental Goals

Both two experiments have the following goals:

1. *Can tags be read in the area above the surgical table and is the interrogation zone stable?*
2. *Is there a difference in environment between the lab setting and the OR setting?*
3. *What is the behaviour of the RSSI values?*

The first goal is to see whether instruments can be detected in the area above the surgical table and if no extreme deviations in detections occur in this area. The area is based on the different heights of the surgical table and on different orientations of the table. The second goal examines what the effect of the environments is on the detection of tagged instruments. In the OR a test is performed with medical devices turned on and off to see if interference arises. The third and last goal is about the RSSI values. This test examines the behaviour of RSSI values during a measurement. With behaviour is meant the change over time and the difference between neighbouring tagged instruments. It is expected that tags can be read till a distance of approximately 1.3 m and 1.4 m. Below this distance it is expected that tags are not able to be detected by the antenna. When comparing the two environments it is expected that during the MISIT-lab experiment the environment will have a larger effect on the performance than in the OR experiment. The MISIT-lab is a more cluttered room with tables and chairs around the interrogation zone. In the OR the antenna has a free line-of-sight which should improve the performance. Lastly, it is expected that the RSSI values will vary in time and in location. A previous conducted experiment (appendix A) performed measurements for different read distances and showed fluctuations in the RSSI values of maximal 3 dBm. The boxplot below shows the RSSI variations for eighteen different measurements. Based on this, it is expected that the RSSI values show fluctuations.

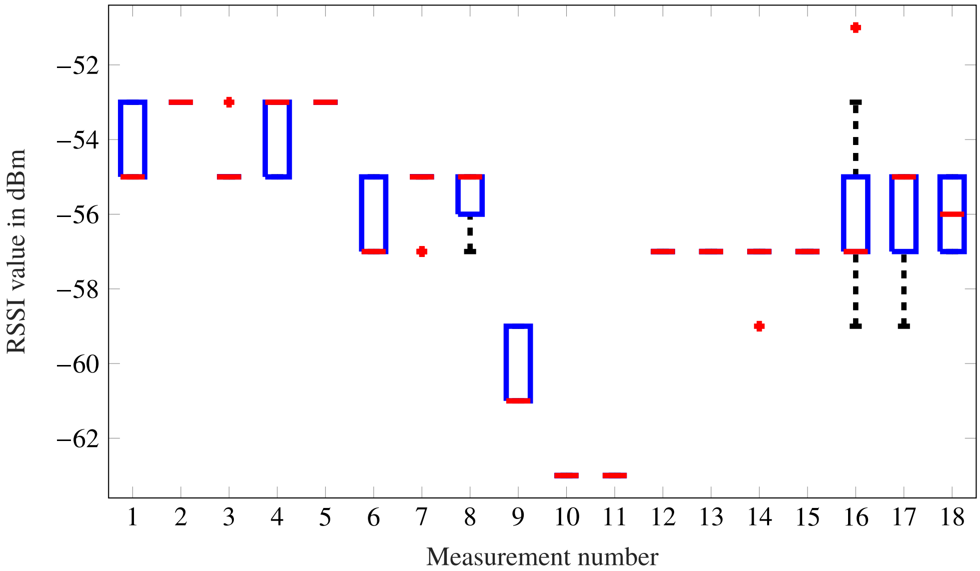


Figure 7.1: Variations in RSSI values among eighteen different measurements of each 20 seconds.

7.2. Materials

For both experiments the RFID equipment is used as described in chapter 6. Ten surgical instruments are tagged with Xerafy Dash-ON XS tags and labelled with a number from 1 to 10 (figure 7.2). Every tagged instruments matches to a UID (figure 7.3 and table 8.2). A surgical cloth is used to place the surgical instruments on during both experiments. This cloth has the same size of the surgical table and is divided in 20 blocks of approximately 0.20 x 0.20 m. In the center of each block a tagged surgical instrument is placed (figure 7.4). This is done to assure that every experiment is conducted with the same positions of the instruments. Beside the RFID system and the instruments, measuring tape is used to measure the distance between the surgical cloth and the RFID antenna, purple tape is used to highlight positions on the surgical cloth and to label the surgical instruments. Basic glue is used to fix the tags to the instruments.

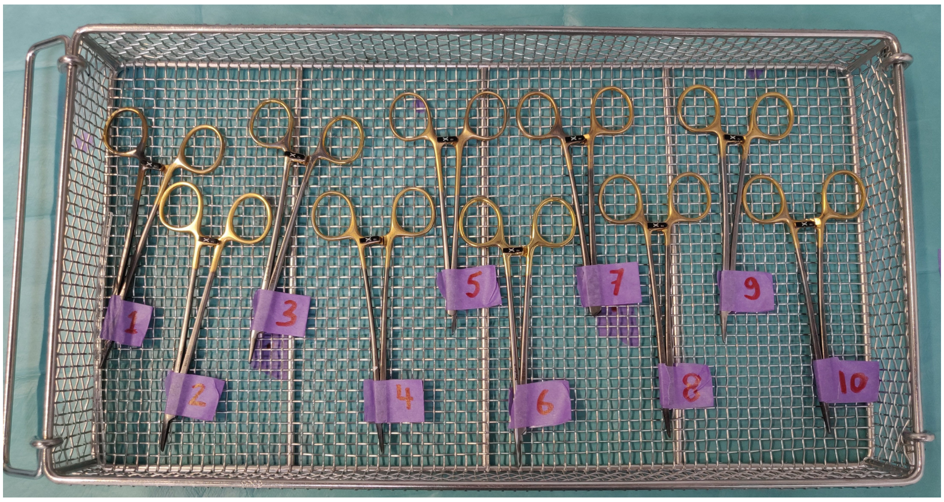


Figure 7.2: All tagged and labelled instruments in instrument tray.

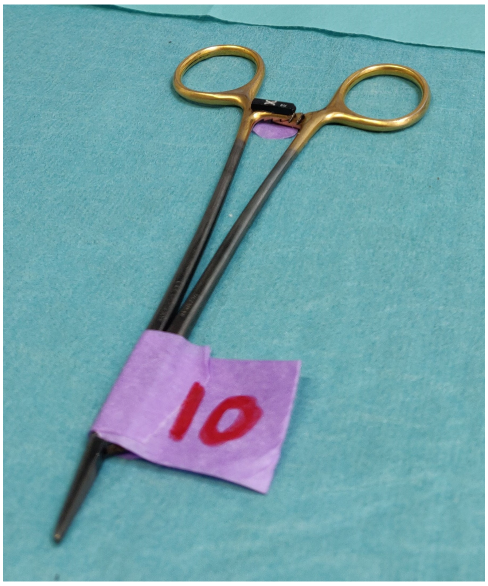


Figure 7.3: Surgical instrument with Xerafy Dash-On XS tag fixed to it.

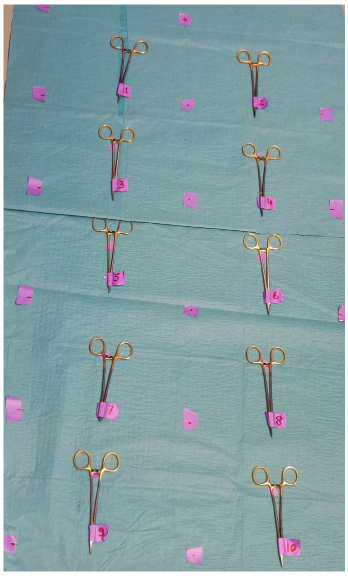


Figure 7.4: Surgical cloth as template for positioning of the ten tagged surgical instruments

8 MISIT-lab Experiment

An experiment is performed in the MISIT-lab at the TU Delft to test the performance of the RFID system in a normal room before testing it in the OR.

8.1. Experimental Set-up

The experimental set-up can be seen in figure 8.1. The RFID antenna can be positioned at different heights. The maximal distance between the antenna and the surgical cloth with the tagged instruments on it is 1.5 meters and the minimal distance is 1 meter. These heights are based on the distance between the antenna and the surgical table in the OR. The antenna is fixed with the clamp to a chair on a table so that it can reach the desirable heights. The RFID reader is positioned on the table on the right side of figure 8.1 and the laptop is positioned outside the figure due to lack of space in this room.

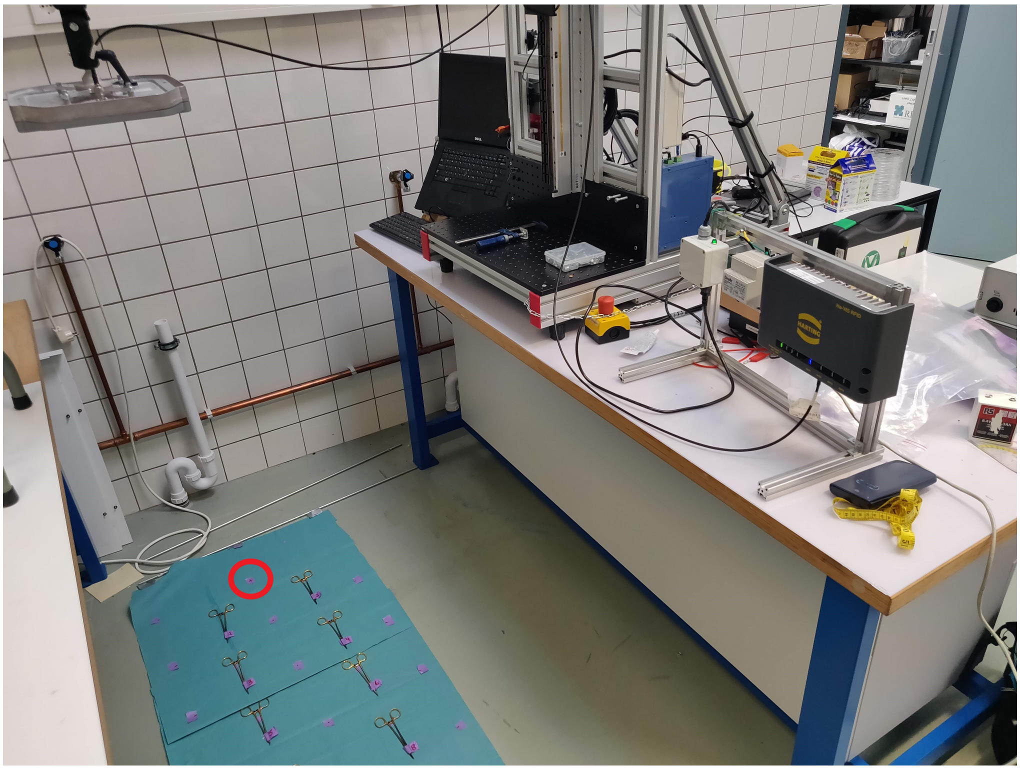


Figure 8.1: Experimental set-up in MISIT lab at TU Delft.

8.2. Experimental Protocol

After installing all the equipment and positioning the surgical cloth with the tagged surgical instruments measurements can be performed. Firstly, a test is performed to the fuctioning of the equipment. This is done by placing every tag straight under the antenna (0 mm distance) and note the UID and the RSSI of the particular tag. After this, the responsiveness is measured for the tags at the same time. The instruments are placed on a plastic plate and are positioned on a distance of approximately 1.2 m under the antenna.

Secondly, different measurements are performed to obtain data to answer the questions for this experiment. The surgical cloth has ten marked positions over a distance of approximately 1 m. This means that this surgical cloth is able to cover half of the surgical table. For the first measurements, the antenna is positioned above the red circle in figure 8.1. By doing this, the detection ability can be tested from the center to the edge of the surgical table. By mirroring these results an estimation can be made about the width of the interrogation zone.

In the second measurement the antenna is positioned above the center of the surgical cloth. By doing this, the symmetry of the the interrogation zone can be investigated. This measurement is performed in two directions. Due to a lack of space in the MISIT-lab and the fact that only ten tagged instruments were available, it was not possible to examine the symmetry over the whole length of the surgical table. Both measurements contribute to answering the question if the interrogation field is stable and if it is possible to detect tags at the different antenna heights. These heights are based on the minimal and maximal distance between the antenna and the surgical table. The distances are: 1.5 m, 1.4 m, 1.3 m, 1.2 m and 1.1 m. An additional distance of 1.0 m is added because instruments the actual position of the antenna is always higher than the surface of the surgical table. From retrieved data the number of detections and the RSSI values can be extracted and analysed. Every measurement had a duration of 30000 ms. The transponder valid time was set at 1 x 100 ms (1 detection per 100 ms). This would mean that the total number of measurements after 30000 ms is 300 per tag (detection rate of 100 percent).

8.3. Data Analysis

The data acquired from the experiments is automatically saved as a CSV-file and can be opened using Microsoft Excel. The CSV-file looks as follows:

No.	TrType	UID	Date	Time	RSSI
1	0x84	E2009A4120039AF000000757	29/10/2019	11:27:07.909	Ant.No 1 - RSSI: -55 dBm
2	0x84	E2009A4120039AF000000741	29/10/2019	11:27:07.978	Ant.No 1 - RSSI: -59 dBm
3	0x84	E2009A4120039AF000000757	29/10/2019	11:27:08.017	Ant.No 1 - RSSI: -55 dBm
...	...	...	...	...	...
504	0x84	E2009A4120039AF000000741	2019-10-29	11:27:37.852	Ant.No 1 - RSSI: -59 dBm
505	0x84	E2009A4120039AF000000757	2019-10-29	11:27:37.868	Ant.No 1 - RSSI: -55 dBm

Table 8.1: Example of retrieved data by the RFID reader.

The data is exported and analysed using MATLAB R2017a. The different CSV-files are loaded in MATLAB. After this, the 'No', 'UID' and 'RSSI' columns from the data set of table 8.1 are extracted. This three-column wide table was then filtered on UID. This resulted in 10 tables where every table represented one of the ten tagged instruments. The number of detections per tag in the 30000 ms and the RSSI value per detection was extracted from the data. Scatterplots are created where every scatterpoint represents a tagged instrument. Every mark has a color based on the number of detections or the RSSI value of that tag.

8.4. Results

The test whether the system was functioning properly yielded a positive result: each tag was detected. Table 8.2 shows the ten instruments with their UID, RSSI value straight against antenna and mean RSSI values during the two performed tests on 1.2 m. The ranges of the test straight against the antenna yielded RSSI values in the range of -45 dBm and -49 dBm (column 3 table 8.2). The results of the other two tests can be seen in column four and five of table 8.2. The mean RSSI values vary between -51 dBm and -60.5 dBm.

Table 8.2: UID of the used tags and their RSSI value at zero distance from the antenna (not fixed to instrument).

Instrument no.	UID	RSSI straight against antenna	RSSI test 1	RSSI test 2
1.	E2009A4120039AF000000757	-45 dBm	-53.0000	-53.0000
2.	E2009A4120039AF000000565	-45 dBm	-53.7059	-52.6306
3.	E2009A4120039AF000000222	-49 dBm	-60.3248	-60.4854
4.	E2009A4120039AF000000741	-45 dBm	-57.0000	-57.0769
5.	E2009A4120039AF000001741	-49 dBm	-59.5137	-59.4276
6.	E2009A4120039AF000000743	-45 dBm	-51.0755	-51.0828
7.	E2009A4120039AF000000593	-49 dBm	-55.1600	-55.1589
8.	E2009A4120039AF000000674	-47 dBm	-57.6600	-57.8355
9.	E2009A4120039AF000001628	-45 dBm	-54.0955	-54.1060
10.	E2009A4120039AF000000484	-45 dBm	-51.0000	-51.0000

Beside checking the RSSI values for all tags, the number of detections is visualised per tag of the two tests on a distance of 1.2 m (figure 8.2). The bar plot shows approximately the same number of detections for all the tagged instrument except for instrument number 3. This instrument showed for both experiments a lower number of detections and this tag also resulted in the lowest RSSI values in the previous tests (table 8.2).

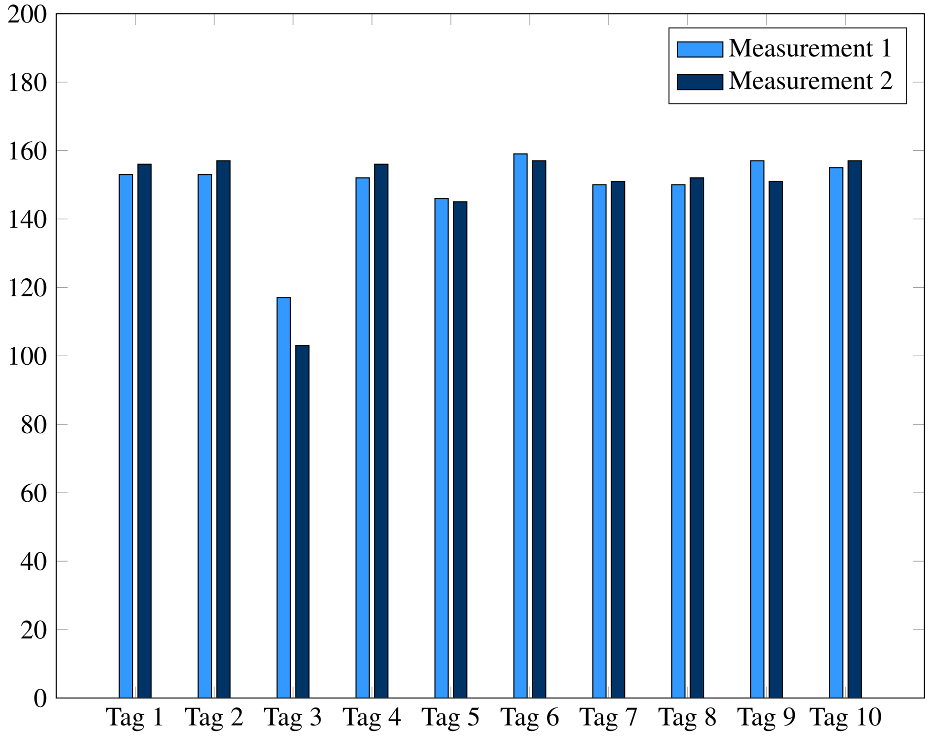


Figure 8.2: Barplot visualising the number of detections of two test measurements for ten different tags.

Now that the functioning of the equipment is tested, the tests to check the experimental goals are conducted. The first test was conducted to examine the read area over the length of the surgical table. The figure below presents the results of this experiment (figure 8.3). The red rectangle represent the surgical table dimensions and the black rectangle above the field the antenna position. The figure shows the number of detections. Every column represents a tagged instrument at different heights. Black means no detection and all other colors mean that a tag was detected at least once. Column number four and seven of the front row of the field represent the number of detections of tag number 3 which showed in previous tests a poor performance. Figure C.1 in appendix C shows the slices of the different heights of figure 8.3.

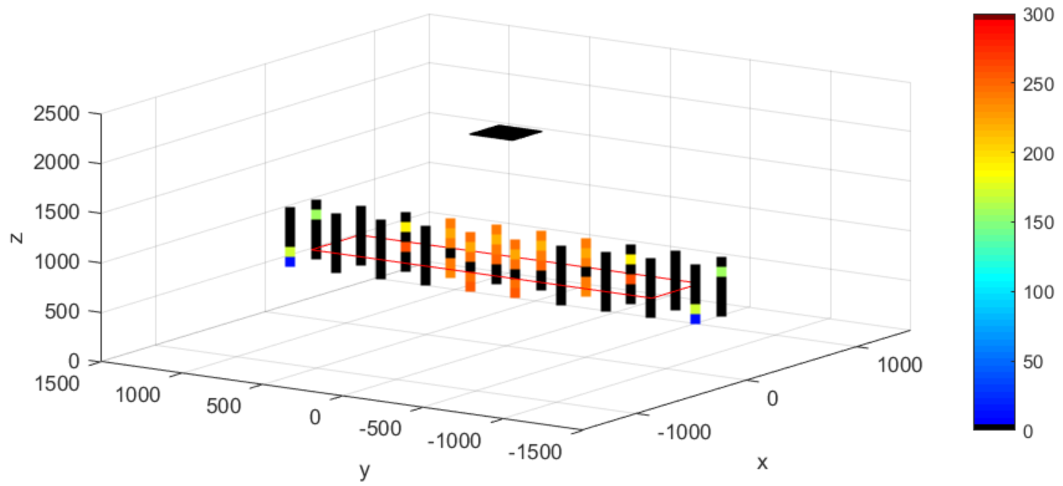


Figure 8.3: Number of detections per tag on different heights covering the whole length of the surgical table (mirrored).

Figure 8.4 below shows the results of this third experiment of this part where the antenna was positioned above the center of the 1 m long surgical cloth. The figure shows the number of detections for the ten tags. This experiment is conducted to test the performance of the RFID antenna in different directions during one test. The figure shows a lot of colors meaning that the antenna was able to detect the tagged instruments. In appendix C a figure can be seen with slices of the different heights (figure C.2).

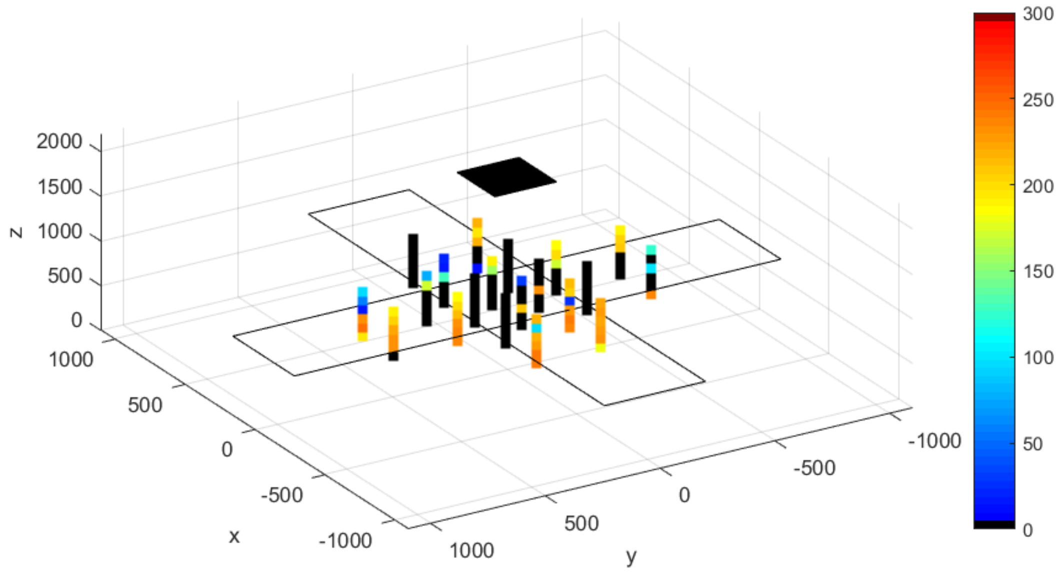


Figure 8.4: Number of detections per tagged instrument in two directions.

It was expected to see variations in the RSSI values among tags and positions. Figure 8.5 shows the results of a measurements. The RSSI values vary in a range of -55 dBm (red) and -63 dBm (yellow). Different neighbouring tagged instruments show different RSSI values. For most columns the RSSI decreases while increasing the read range. Towards the positive side of the y-axis the antenna detected more tags than on the negative side of the y-axis. The total black column represents tag number three.

The slices of the different heights of figure 8.5 can be seen in appendix C figure C.3.

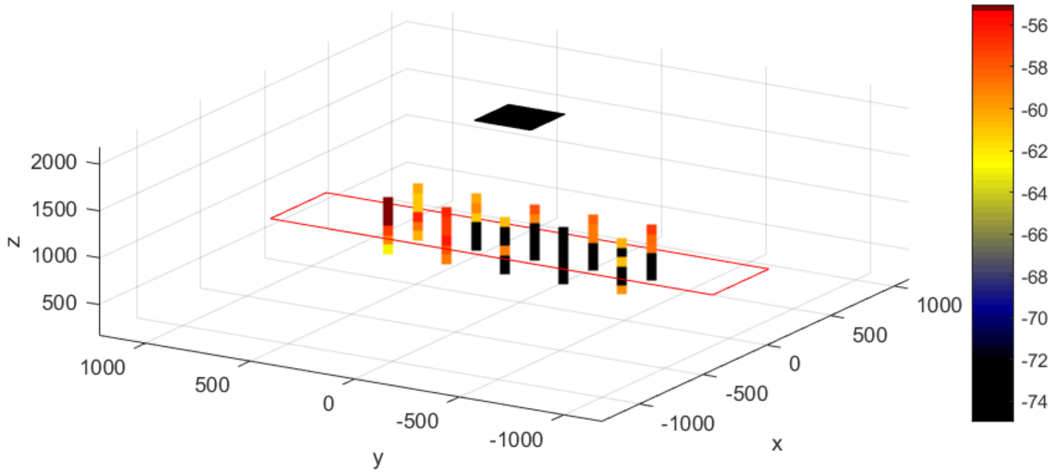


Figure 8.5: RSSI values per tag on different heights in two directions

8.5. Discussion and Conclusion

This first experiment is conducted in the MISIT-lab at TU Delft. Basic functioning of the RFID system is tested. This test showed that the system was working properly. Only tag number 3 deviated from the other tags. The number of detections for this tag during the first test was around 110 detections while the other nine tags achieved more than 150 detections. The RSSI values during two tests at 1.2 m resulted in the poorest RSSI value among all ten tags. Interference is not plausible because the deviation for tag three appeared in all tests. In case of tag-to-tag interference other tags also should be affected. The most likely cause for the poor performance of tag number 3 is a defect. Despite the bad results for one tag, the other tags resulted in good performance. It was not possible to replace the tag because only ten tags were available.

The results from figure 8.3 show that the antenna is able to detect tags at different heights. The orange zone represents the interrogation zone. In case tag number 3 was working properly this zone should probably have been larger. At the end of the zone some tags are detected (green and blue marks) while other tags closer to the antenna were not detected. This can be the effect of constructive interference.

The results in figure 8.3 are mirrored around the y=0 and thus this is an estimation of the interrogation zone. To examine the symmetry of the interrogation zone another test was conducted. This resulted in figure 8.4. A lot of tags are detected during this test. At every height of the surgical table the antenna was able to detect tags.

Looking at stability of the field it can be concluded that the tags are consistent in their performance for different heights. The north and east side of the figures of C.1 show more black marks than south and west side. This is probably caused by the fact that on one side of the room the environment affected the performance more than on the other side.

The RSSI values of the tags varied in between -55 dBm and -63 dBm. For most tags the RSSI was decreasing when the distance was increasing. This would mean that the behaviour of the RSSI values is more predictable than expected.

The main conclusion from this first experiment is that the antenna was able to detect tags at different predetermined heights. Null spots also appeared in the results (black marks). These spots are probably caused by the environment the experiment was conducted in. A pattern among the different measurements was observed. During different measurements tags were not detected on one side of the antenna while the other side yielded many detections. Based on the test where the performance of all the tags was examined it is not plausible that this different is caused by difference in tag performance. Therefore, the third test was performed to see whether the antenna was able to achieve as symmetric interrogation zone. In the third test the antenna is also shifted in angle to see if it is able to achieve the same results in a different orientation. The data of this third experiment resulted in figure 8.4. These figures show that it is possible to read in multiple angles from the antenna and that the antenna is able to read enough tags up to a distance of 1.3 m. But also for 1.4 m and 1.5 m the antenna detected different tags. Not every tag could be read at the different distances. This was also not the expectation. Detection of tags at different positions at different heights is a positive finding and creates supports for the test in the OR.

When looking back at the experimental goal formulated at the beginning of this chapter we can say that, following this experiment, the tags can be read on distances equal to that in the OR. In this setting the interrogation zone was not really stable. It is expected that in the OR the performance will be better because the environment is less cluttered.

9

Operating Room Experiment

The results of the experiment in the lab setting created enough support for the tests in the OR in RdGG. The antenna was able to detect tags at different distances and even at 1.5 m some tags were detected. This was the main goal of the test in the MISIT-lab. It is expected that the experiment in the OR will yield better performance due to less environmental objects in proximity of the antenna.

9.1. Experimental Set-up

The experimental set-up during the OR experiment can be seen in figure 9.1. The RFID antenna is fixed with a Manfrotto magic arm and clamp to the first swivel arm of one of the surgical lights. This is done for this experiment because it is not yet possible to fix the antenna to the central axis. The antenna will be positioned under the central axis and is horizontal oriented and directed towards the surgical table. The laptop and RFID reader are placed at a mobile table in the OR. The height and orientation of the surgical table will be changed after each measurement. The initial height of the surgical table is 0.6 m above the floor. The antenna is positioned at a height of 2.10 m above the floor. The surgical cloth used in the MISIT-lab experiment is also used in this experiment and is placed at the surgical table with ten tagged instruments on it.

Figure 9.1: Experimental set-up during the test in the OR.

9.2. Experimental Protocol

Multiple tests had to be performed with different heights and orientations of the surgical table. Due to a lack of tagged instruments at surgical table setting the tags has to be changed from one side of the table to the other side of the table. As said before the table is shifted in height between 0.6 and 1.06 m with steps of 0.1 m. These heights are used for different positions of the table in the plenum area. The table is moved from position to left and right in figure 9.1. By this a large part of the plenum ventilation area is covered. Figure D.1 in appendix D shows the testing procedure. The six blocks seperated by the red line are six different runs. All these six measurements are performed at the six different heights. A total of 36 measurements of each 30 seconds will be performed. Every measurement of 30 seconds will be saved in a separate CSV-file.

9.3. Data Analysis

Data analysis is performed the same way as for the lab experiment.

9.4. Results

The results of the experiment can be seen in figure 9.2. Every datapoint is black which means zero detections through the whole experiment.

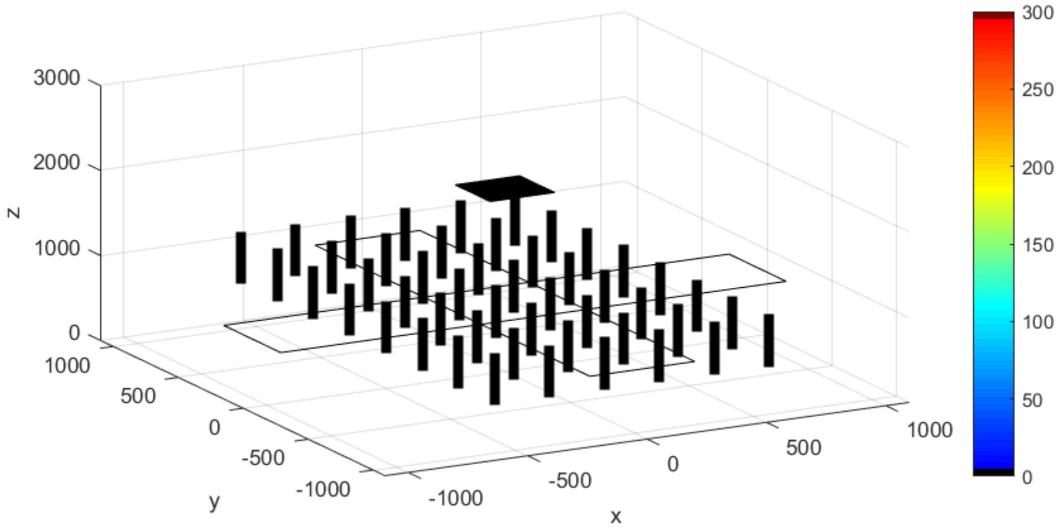


Figure 9.2: Overview of detections during OR tests.

9.5. Discussion and Conclusion

The antenna was not able to detect tags on the minimal distance of 1.0 m. At 0.8 m from the antenna the first tag was detected. This is not a realistic position of the surgical working area. The results were in contrast with the MISIT-lab experiment. It was expected that the experiment in the OR would result in better performance because of the open field the antenna was deployed in. When comparing figure 8.1 and figure 9.1, it can be seen that there is more furniture around the set-up in the MISIT-lab than in the set-up in the OR. It was expected that this cluttered environment would have a detrimental effect on the performance of RFID. Looking at the goals of the experiment, the antenna is not able to detect tags in the field above the surgical table. There is a significant difference between the two environments which has to be analysed. The last part of this thesis will evaluate the steps toward the experiments and will evaluate the poor performance of the RFID.

IV

Evaluation

10 Discussion

This thesis presented a systematic approach to test the feasibility of implementation of RFID in the OR in RdGG for the use of surgical phase recognition. This part will evaluate the performed study.

An RFID antenna was positioned in the center of the plenum ventilation area above the surgical table. This was considered as the best suitable position because it does not disturb the surgical personnel in their movements and it has a free line-of-sight to the area instruments are used in. A maximal read range of 1.5 m from the antenna perpendicular to the surgical table was defined. The minimal read range was set at 1 meter. These ranges were based on the height of the surgical table. Furthermore, the position of the surgical table is in most procedures approximately in the center of the plenum ventilation area (based on appendix B). Based on the desired read ranges, RFID equipment was selected. The equipment is tested in the experimental phase. First, an experiment in the MISIT-lab in Delft was performed and after this an experiment was performed in an OR in RdGG. The experiments had multiple subgoals: examining the detection ability and stability of the interrogation zone above the surgical table, compare the performance of the RFID system in the two environments and examine the behaviour of RSSI values during different tests. These goals should contribute to the main goal of this thesis:

> *Investigate the feasibility of implementation of RFID technology in the Operating Room in Reinier de Graaf Gasthuis in Delft for the purpose of surgical phase recognition.*

With the chosen RFID equipment detection in a range of around 1.3 m was achieved. In the OR a range of 0.85 m was achieved which is too low because an antenna can not be positioned on such a close distance.

In case of no detections, an easy and obvious thought is to choose another, better RFID antenna and better tags. Tag and antenna can both have a large effect on the performance. However, the two choices are constrained in dimensions and power due to the complex environment. The dimensions of the tag are constrained because of the size of surgical instruments and the dimensions of the antenna due to the vertical airflow pattern above the surgical table. For example, tag that is able to be detected on a larger range is the Xerafy Pico Plus. This tag is almost twice as large as the proposed tag (Xerafy Dash-On tag) and including an attachment which is required for safe placement on instruments, the size would become too large and can bother surgeons in their handlings. A stronger RFID antenna (in terms of read range) is presented in table 6.1. The antenna of 12 dBi is almost twice as large as the antenna of 8.5 dBi (figure 10.1). A larger surface in the airflow causes more turbulence in the plenum ventilation area. This increases the risk on infections. Furthermore, the beam width of a high gain antenna is smaller meaning a smaller interrogation zone and thus less coverage.

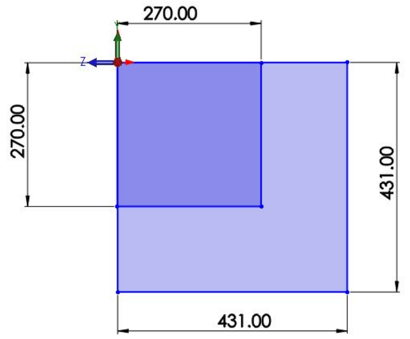


Figure 10.1: Sketch of the surfaces of antenna with 8.5 dBi (inner) and 12 dBi (outer

Both experiments used the same equipment meaning that the cause of signal attenuation will not be due to poor equipment. The origin of the attenuation must be found in the environment in the OR. In chapter 3 a short overview is given about the effect of electromagnetic interference and possible sources (electromagnetic noise). Multipath propagation due to reflective objects or other electrical equipment can cause constructive or destructive interference. As aforementioned, multipath propagation can cause destructive interference and can result in null spots. The results of the experiment in the OR did not just resulted in null spots. The area where no detection was possible varied over multiple spots meaning a total decrease in read range. It is possible that different electrical equipment (while turned off) cause a high level of electromagnetic noise in the OR. This is a possible cause of the signal attenuation. The study of Poulin et al. referred to wires in the floor or ceiling or lights as a source of electromagnetic noise [44]. This is different in the two environments. While it is not known what exactly is hidden in the floor or ceiling it is known that floors and ceilings in and OR are more complex due to the electrostatic discharge floor and the plenum ventilation system installed in the ceiling.
Summarizing, it is difficult to track down the actual cause of the signal attenuation during the tests in the OR. Based on the two performed experiments and the big difference between the two, it is not likely that the RFID equipment is the cause of the poor detection rate. Furthermore, a reflective environment causing interference is also not likely. Reflective metal instruments are used during both experiments and no other large (visible) reflective surface was in proximity present in the OR. The most plausible source of the disturbance of the signal is a high-level of electromagnetic noise throughout the room. This can be caused by medical devices and wires in the floor and ceiling. Finding the exact cause of the noise would probably not contribute to making the system work. The RFID antenna was positioned in the center of the room while most equipment was positioned outside the plenum area. In addition, the equipment was not in use and thus turned-off. It is likely that the noise will increase in case equipment is be turned on. In future research that incorporates RFID in the OR it is important to first perform on site tests with the equipment.
Future research should focus on new RFID technologies which makes it possible to be integrated in the complex environment. For example, the Ha-Vis LOCFIELD RFID antenna. This is a coax cable which serves as the antenna. When tags come in proximity of this cable, it is able to detect tags. The advantage of this antenna is that the cable defines the read zone and thus is very flexible. In the OR it could be possible to integrate it in OR tables or place it around the wound area of the patient. The read range depends on the used tags and can vary between a few centimeters and 2 meter. It is expected that when using the small tags as proposed in this study, the read range would be a few centimeters. In case it can be positioned around the wound area this can be useful. Positioning on the surgical table would probably not lead to detections in the surgical working area due to a read distance of around 30 cm and the obstruction by the patient. This option is not considered in this study because it requires a complete different approach. It is recommended for next studies to investigate the possibilities of the Ha-Vis LOCFIELD RFID antenna.

11

Conclusion

This research presented a systematic approach to the optimal position of the RFID antenna and the optimal RFID equipment in order to acquire accurate data of used instruments during surgery. This data can be useful for surgical phase recognition. The study showed that the RFID system was able to acquire data in a laboratory environment but not during experiments in the OR. This difference measn that that there is a difference in environment. The most probable cause for the signal attenuation is electromagnetic noise originating from electrical medical equipment and wires in the ceiling and floor.

In conclusion, it is not possible to implement an RFID system in the OR for phase recognition purposes. RFID technology is fast evolving and new technologies as described in the chapter 10 (Ha-Vis LOCFIELD antenna) can offer a solution. It is certainly possible that RFID can be implemented in the future when tags and antennas are more powerful while retaining small dimensions. For future research about RFID in the OR, it is recommended to perform on site tests of RFID in the OR before developing the application of RFID.

Bibliography

[1] FC Meeuwsen. *Safe Surgical Signatures*. PhD thesis, Delft University of Technology, 2019.

[2] Jeroen Koffeman. Instrument identification to improve OR scheduling: Evaluating an RFID-based approach. Master's thesis, Delft University of Technology, the Netherlands, 2019.

[3] Reinier de Graaf Gasthuis. Als eerste af en als laatste klaar. URL `reinierdegraaf.nl/algemeen/nieuws/als-eerste-af-en-als-laatste-klaar/`.

[4] Drägerwerk AG & Co. Dräger Polaris 600 Operatielampen. URL `https://www.draeger.com/Products/Content/polaris-600-pi-9072987-nl-nl.pdf`.

[5] P J Sweeney. *RFID For Dummies*. Wiley, 2010. ISBN 9781118054475.

[6] Daniel M. Dobkin. *The RF in RFID*. Newnes, Burlington, 2008. ISBN 978-0-7506-8209-1. doi: https://doi.org/10.1016/B978-075068209-1.50015-2. URL `http://www.sciencedirect.com/science/article/pii/B9780750682091500152`.

[7] AtlasRFIDstore. 9 tactics for choosing an rfid antenna. URL `https://www.atlasrfidstore.com/9-tactics-for-choosing-an-rfid-antenna/`.

[8] D C Giancoli. *Physics for Scientists & Engineers, Vol. 1 (Chs 1-20): Pearson New International Edition*. Pearson Education Limited, 2013. ISBN 9781292037295.

[9] Harting BV. Harting BV. Reader Antenna Charachteristics. URL `http://www.harting-rfid.com/en/products/ha-vis-rfid-antennas/ha-vis-rf-ant-wr30/`.

[10] Xerafy. RFID Enabling Healhcare. URL `https://www.xerafy.com/rfid-tags-and-labels`.

[11] A. de Vries R. Mikkers, A. van Poucke. KPMG Healthcheck: Ontwikkelingen binnen de ziekenhuiszorg, 2018. URL `https://home.kpmg/nl/nl/home/insights/2018/08/healthcheck.html`.

[12] Brecht Cardoen, Erik Demeulemeester, and Jeroen Beliën. Operating room planning and scheduling: A literature review. *European Journal of Operational Research*, 201:921–932, 03 2010. doi: 10.1016/j.ejor.2009.04.011.

[13] Antti Peltokorpi. How do strategic decisions and operative practices affect operating room productivity? *Health care management science*, 14(4):370–382, dec 2011. ISSN 1386-9620 (Print). doi: 10.1007/s10729-011-9173-8.

[14] Afroza Sultana and Abdus Sobhan. RFID in Healthcare Systems: Applications and Implications. 06 2008.

[15] N. Rivera, Rosemary Mountain, Lia Assumpcao, Allen Williams, A.B. Cooper, Douglas Lewis, Richard Benson, Joseph Miragliotta, Michael Marohn, and Russell Taylor. ASSIST - Automated System for Surgical Instrument and Sponge Tracking. pages 297 – 302, 05 2008. ISBN 978-1-4244-1711-7. doi: 10.1109/RFID.2008.4519358.

[16] Michael Kranzfelder, Armin Schneider, Adam Fiolka, Elena Schwan, Sonja Gillen, Dirk Wilhelm, Rebecca Schirren, Silvano Reiser, Brian Jensen, and Hubertus Feussner. Real-time instrument detection in minimally invasive surgery using radiofrequency identification technology. *The Journal of surgical research*, 185(2):704–710, dec 2013. ISSN 1095-8673 (Electronic). doi: 10.1016/j.jss.2013.06.022.

[17] Mariëlle Haring. Instrument Tracking in the Operating Room. Master's thesis, Delft University of Technology, the Netherlands, 2018.

[18] Remko van der Togt, Piet J M Bakker, and Monique W M Jaspers. A framework for performance and data quality assessment of Radio Frequency IDentification (RFID) systems in health care settings. *Journal of biomedical informatics*, 44(2):372–383, apr 2011. ISSN 1532-0480 (Electronic). doi: 10.1016/j.jbi.2010.12.004.

[19] Reinier de Graaf Gasthuis. Veranderde parkeersituatie door bouw OK-complex. URL `https://www.reinierdegraaf.nl/algemeen/nieuws/veranderde-parkeersituatie-door-bouw-ok-complex/`.

[20] MAQUET Getinge Group. Mobile Universal Operating Table AlphaMaxx 1133.12 and 1133.22. URL `http://www.fastus.is/library/Birgar-D3/Maquet/alphamaxx.pdf`.

[21] Interflow BV. Reinier de Graaf. URL `https://www.interflow.nl/projecten/reinier-de-graaf`.

[22] Werkgroep Infectie Preventie (WIP). Luchtbehandeling in operatiekamer en opdekruimte in operatieafdeling klasse 1, 2014.

[23] Sameer Jain and Mike Reed. Laminar Air Flow Handling Systems in the Operating Room. *Surgical infections*, 20(2):151–158, 2019. ISSN 1557-8674 (Electronic). doi: 10.1089/sur.2018.258.

[24] WAC Zoon, SAM Heijkant, JLM Hensen, and MGLC Loomans. Assessment of the performance of the airflow in an operating theatre. In *Proceedings of the SCANVAC Roomvent 2007 Conference*, page 8, 2007.

[25] Sasan Sadrizadeh and Sture Holmberg. Surgical clothing systems in laminar airflow operating room: a numerical assessment. *Journal of Infection and Public Health*, 7(6):508–516, 2014. ISSN 1876-0341. doi: https://doi.org/10.1016/j.jiph.2014.07.011. URL `http://www.sciencedirect.com/science/article/pii/S1876034114001117`.

[26] Pete Sorrells. Passive RFID basics. *Microchip Technology Inc*, pages 40–49, 1998.

[27] Nemai Chandra Karmakar. *Handbook of Smart Antennas for RFID Systems*. John Wiley & Sons, 2011.

[28] GS1 EPCglobal. Regulatory status for using rfid in the epc gen 2 band (860 to 960 mhz) of the uhf spectrum. *GS1 RFID Standards (Updated)*, 2018. URL `https://www.gs1.org/docs/epc/uhf_regulations.pdf`.

[29] Stephen A Weis. RFID (radio frequency identification): Principles and applications. *System*, 2(3):1–23, 2007.

[30] M Bolic, D Simplot-Ryl, and I Stojmenovic. *RFID Systems: Research Trends and Challenges*. Wiley, 2010. ISBN 9780470975664.

[31] V Daiya, J Ebenezer, S A V S Murty, and B Raj. Experimental analysis of RSSI for distance and position estimation. In *2011 International Conference on Recent Trends in Information Technology (ICRTIT)*, pages 1093–1098, 2011. ISBN null VO -. doi: 10.1109/ICRTIT.2011.5972367.

[32] David Munoz, Frantz Bouchereau Lara, Cesar Vargas, and Rogerio Enriquez-Caldera. *Position Location Techniques and Applications*. Academic Press, Inc., Orlando, FL, USA, 2009. ISBN 0123743532, 9780123743534.

[33] Staffan Hengst. Improving the Performance of the RFID Reader Antenna for Operating Room Implementation: A Literature Study., 2019.

[34] H Lehpamer. *RFID Design Principles*. EngineeringPro collection. Artech House, 2012. ISBN 9781608074716.

[35] Paul Sanghera. *RFID+ Study Guide and Practice Exams: Study Guide and Practice Exams*. Elsevier, 2011.

[36] E Zeisel and R Sabella. *RFID+*. Exam cram. Que Certification, 2006. ISBN 9780789735041.

[37] Reuven Drori. Selecting RFID antennas. *White Paper, MTI Wireless Edge Ltd*, 2005.

[38] Giovanni Calcagnini, Federica Censi, and Pietro Bartolini. Electromagnetic immunity of medical devices: The european regulatory framework. *Annali dell'Istituto superiore di sanità*, 43:268–76, 02 2007.

[39] US Food and Drug Administration. Radio Frequency Wireless Technology in Medical Devices; Guidance for Industry and Food and Drug Administration Staff, 2014.

[40] INTERNATIONAL ELECTROTECHNICAL COMMISSION. MEDICAL ELECTRICAL EQUIPMENT–Part 1-2: General requirements for basic safety and essential performance–Collateral standard: Electromagnetic compatibility–Requirements and tests. URL https://webstore.iec.ch/preview/info_iec60601-1-2%7Bed3.0%7Db.pdf.

[41] Remko van der Togt, Erik Jan van Lieshout, Reinout Hensbroek, E Beinat, J M Binnekade, and P J M Bakker. Electromagnetic interference from radio frequency identification inducing potentially hazardous incidents in critical care medical equipment. *JAMA*, 299(24):2884–2890, jun 2008. ISSN 1538-3598 (Electronic). doi: 10.1001/jama.299.24.2884.

[42] Seth J Seidman, Randall Brockman, Brian Marc Lewis, Joshua Guag, Mitchell J Shein, Wesley J Clement, James Kippola, Dennis Digby, Catherine Barber, and Dan Huntwork. In vitro tests reveal sample radiofrequency identification readers inducing clinically significant electromagnetic interference to implantable pacemakers and implantable cardioverter-defibrillators. *Heart rhythm*, 7(1):99–107, jan 2010. ISSN 1556-3871 (Electronic). doi: 10.1016/j.hrthm.2009.09.071.

[43] Bryan Houliston, David Parry, Craig S Webster, and Alan F Merry. Interference with the operation of medical devices resulting from the use of radio frequency identification technology. *The New Zealand medical journal*, 122(1297):9–16, jun 2009. ISSN 1175-8716 (Electronic).

[44] Francois Poulin and L-P Amiot. Interference during the use of an electromagnetic tracking system under OR conditions. *Journal of biomechanics*, 35(6):733–737, jun 2002. ISSN 0021-9290 (Print). doi: 10.1016/s0021-9290(02)00036-2.

[45] S M Norzeli, I Ismail, and M F M Busu. Designing an UHF RFID reader antenna. In *2012 IEEE Symposium on Humanities, Science and Engineering Research*, pages 599–602, 2012. ISBN 2378-9816 VO -. doi: 10.1109/SHUSER.2012.6268894.

[46] A van Boeijen, J Daalhuizen, R van der Schoor, and J Zijlstra. *Delft Design Guide: Design Strategies and Methods*. Bis B.V., Uitgeverij (BIS Publishers), 2014. ISBN 9789063693275.

[47] atlasRFIDstore. Laird S9025PL/S8655PL (LHCP) Outdoor RFID Antenna (FCC/ETSI), . URL https://www.atlasrfidstore.com/laird-s9025pl-s8655pl-lhcp-outdoor-rfid-antenna-fcc-etsi/.

[48] atlasRFIDstore. Alien ALR-A0501 Compact RFID Antenna (FCC/ETSI), . URL https://www.atlasrfidstore.com/alien-alr-a0501-compact-rfid-antenna-fcc-etsi/.

[49] atlasRFIDstore. RFMAX S9028PCR/S8658PCR (RHCP) Indoor RFID Antenna (FCC/ETSI), . URL https://www.atlasrfidstore.com/rfmax-s9028pcr-s8658pcr-rhcp-indoor-rfid-antenna-fcc-etsi/.

[50] atlasRFIDstore. RFMAX R9028LPV/R8658LPV Circular Polarized Antenna (FCC/ETSI) - VESA Mount, . URL https://www.atlasrfidstore.com/rfmax-r9028lpv-r8658lpv-circular-polarized-antenna-fcc-etsi-vesa-mount/.

[51] HARTING technology group. HA-VIS-RF-ANT-WR30. URL http://www.harting-rfid.com/en/products/ha-vis-rfid-antennas/ha-vis-rf-ant-wr30/.

[52] atlasRFIDstore. Alien ALR-A1001 Ultra Slim RFID Antenna (FCC/ETSI), . URL https://www.atlasrfidstore.com/alien-alr-a1001-ultra-slim-rfid-antenna-fcc-etsi/.

[53] atlasRFIDstore. Alien ALR-A0501 Compact RFID Antenna (FCC/ETSI), . URL https://www.atlasrfidstore.com/alien-alr-a0501-compact-rfid-antenna-fcc-etsi/.

[54] Hengameh Hosseini. Aging and the Rising Costs of Healthcare in the United States: Can There be a Solution? *Ageing International*, 40(3):229–247, sep 2015. ISSN 1936-606X. doi: 10.1007/s12126-014-9209-8. URL https://doi.org/10.1007/s12126-014-9209-8.

[55] Christopher P Childers and Melinda Maggard-Gibbons. Understanding Costs of Care in the Operating Room. *JAMA surgery*, 153(4):e176233–e176233, apr 2018. ISSN 2168-6262. doi: 10.1001/jamasurg.2017.6233.

[56] Daniel Dobkin and S.M. Weigand. Environmental Effects on RFID Tag Antennas. page 4 pp., 07 2005. doi: 10.1109/MWSYM.2005.1516541.

A

Experimental Study

A.1. Introduction

A.1.1. Background

Healthcare costs are rising due to the ageing population, a higher demand of patients for better quality and increased complexity of technology [54]. In addition, the operating room (OR) is the most expensive area of a hospital [55]. Efficiency of the OR is clearly needed to reduce costs and to increase patient satisfaction. Radio frequency identification (RFID) technology can be used in the OR to detect instruments in order to gain data for phase recognition of the procedure. This information can be used to improve the planning and scheduling of the OR. It may be clear that the identification of the surgical instruments has to be very accurate. Without high accuracy of the RFID system the planning cannot be improved. In-vivo tests in previous research with the RFID system resulted in some problems considering the reader antenna. The antenna was fixed to an IV-pole and was positioned beside the surgical table. This resulted in not reading the tags due to blockage of the RF signal by surgical personnel, by the patient or other objects. In addition, the surgical table was changed in height during the procedure while the reader antenna was fixed at a certain height [2]. Placement of the reader antenna above the surgical table would be desirable in order to overcome these problems. A previous literature study showed that horizontal orientation with respect to the ceiling compared to vertical orientation gave different results concerning the performance. It was concluded that more tests has to be performed in order to prove that a horizontally oriented reader antenna yields better results compared to a vertically orieted antenna [33], This experiment will not compare a horizontal positioned antenna with a vertical one because this also changes the environment which affects the performance of the reader antenna and will definitely result in different measurements. Therefore, we only focus on horizontal placement of the antenna. The purpose is to measure the Received Signal Strength Indication (RSSI) values of the horizontally oriented reader antenna. The RSSI value is a measure of the strength of the signal received by the reader antenna from the tag. A high RSSI value means a strong signal and a the lower this value the weaker the signal. A distance measurement will be performed to see how the RSSI values change when increasing the distance between the reader antenna and the tag. In practice the tags will often be positioned not straight under the reader antenna and therefore a measurement is performed under an angle. Furthermore, a measurement is performed while placing multiple surgical instruments in the interrogation zone in order to see whether this changes the RSSI values at different distances. Lastly, every measurement is performed with a different tag in order to see which tag is best suitable for this application. These four different circumstances will be tested because these are important in an OR environment.

A.1.2. Research Question and Hypotheses

In this study the following research question will be answered: *What is the effect of tag type, read distance, angle and proximity of multiple metal instruments on the RSSI values received by the RFID reader antenna?* The distance measurements are also used as a reference measurement to compare the results with the angle and multiple instruments measurements. The hypothesis of this experiment is that the RSSI values will show significant differences between different distances straight under the antenna, under an angle and when using multiple instruments. It is expected that the RSSI values will decrease as the distance straight under the antenna increases until the tag is outside the interrogation zone and cannot be read anymore. Furthermore, it is expected that, when comparing the measurements straight under the antenna with the measurements under an angle, the

RSSI values will be worse. It is known that tag performance decreases when in proximity of metal so it is expected that the RSSI value will be lower when multiple metal instruments are placed around the tagged instrument [56]. At last, it is expected that there is a significant difference between the three tags. Following documents of Xerafy, the three tags differ in read range (3 meter, 1.5 meter and 1 meter) [10]. This implies that there should be a different in RSSI values between these tags when comparing them under the same circumstances (angle, distance). It is expected that the tags with a higher read range will have a higher RSSI value than tags with lower read range. The results of this experimental study will be used in the next step of implementation of an RFID system in the OR in order to collect data and use that data to improve the planning and scheduling of the OR.

A.2. Methods

A.2.1. Experimental set-up and Materials

The hypotheses as described in the introduction will be tested with an experiment. An RFID system is used which complies of an RFID reader, an RFID reader antenna, a laptop with software, a mounting arm and clamp to attach the reader antenna to the table, RFID tags and surgical instruments. An overview of the experimental set-up can be seen in figure A.1.

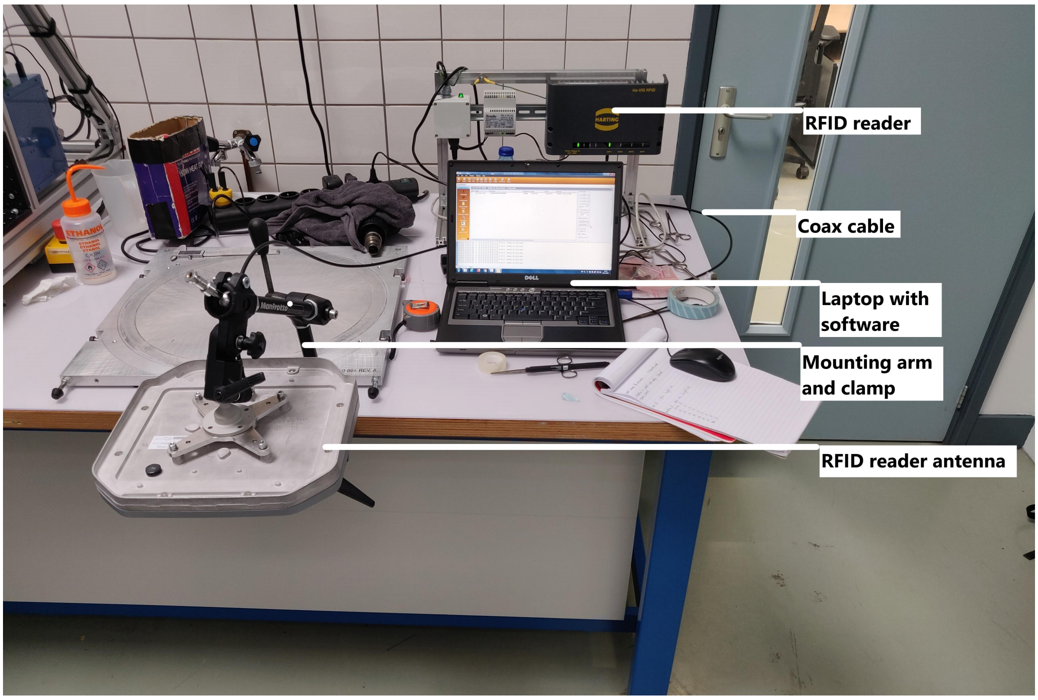


Figure A.1: Experimental set-up RFID equipment

The used software on the laptop is the Ha-VIS RFID Config V2.09.05 software. With this software the reader and the reader antenna can be controlled. The RF-R500-c-EU RFID reader and the Ha-Vis RF-ANT-WR30-EU reader antenna from Harting BV. are used to read the tagged instruments. The reader antenna is fixed horizontally to the table with a mounting arm and a clamp which are normally meant for camera use. The equipment is used to detect different tags in different situations. The Xerafy Pico-On Plus (large brick; figure A.2), Xerafy Dot-On XS (round; figure A.2) and the Xerafy Dash-On XS (small brick; figure A.2) tags were placed with glue on three identical surgical grasping instruments. The Xerafy Pico-On Plus tag is placed at a different position compared to the other two tags because of the different geometry of the tag. The three tags differ from each other in size and read range (table A.1). Other materials used to conduct the experiment are measuring tape, rope, black tape, two extra surgical instruments, a pen and glue.

Table A.1: Specifications of the used RFID tags. [10]

Tag	Read Range	Dimensions
Xerafy Pico-On Plus	3 m	12.8 x 7.08 x 3.08 mm
Xerafy Dash-On XS	2 m	12.3 x 3 x 2.2 mm
Xerafy Dot-On XS	1.5 m	ø 6 x 2.5 mm

Figure A.2: Tagged surgical instruments. From left to right: Xerafy Pico-On Plus, Xerafy Dot-On XS and Xerafy Dash-On XS.

A.2.2. Variables and Constants

The dependent variable of this experiment is the RSSI which means Received Signal Strength Indicator. This is a measure for the strength of the signal received by the reader from the tag. This metric can be read out by the software which is part of the RFID system. The independent variables are the three different tags, different distances straight under the reader antenna, different distance under an angle of 34.5 °with respect to the reader antenna and different distance straight under the reader antenna while using multiple metal instruments. Constants during the experiment are reader and reader antenna characteristics. The gain of the reader antenna is 8.5 dBic, the output power is set at 2 W, the number of reads per second is 1, far field half-power beam width is 69 °and the reader antenna is fixed horizontally with respect to the ceiling.

A.2.3. Experimental Protocol

To test the hypothesis and answer the research question as described in the introduction three different tests are performed with three different tags. In the first test the RSSI values are measured for the three tags at 50, 60, 70, 80, 90 and 100 cm straight under the reader antenna. This procedure is also used for the measurements under an angle and the measurement with multiple instruments straight under the antenna. The measurements straight under the antenna at different distances are also used as reference measurements for the angle and multiple instruments measurements. Previous research stated that the distance between the RFID reader antenna and the tagged instruments during a surgery is around 50 cm [17]. This was in a situation where the antenna was positioned vertically on an IV-pole beside the operating table. Now the antenna will be placed horizontally above the operating table and therefore the tests are performed in a range between 50 cm and 100 cm. Besides testing straight under the reader antenna the tagged instruments are placed under an angle which is half the beam width (34.5°). Figure A.4 shows the set-up for the measurements under an angle at the six distances. These results can be compared with the results of the measurements straight under the antenna to see whether the angle will affect the RSSI. The third measurement is done while placing two extra surgical instruments under the reader antenna (figure A.3). The results of these measurements can also be compared to that of the reference measurements in order to see if multiple instruments affect the RSSI values.

Figure A.3: Multiple instruments.

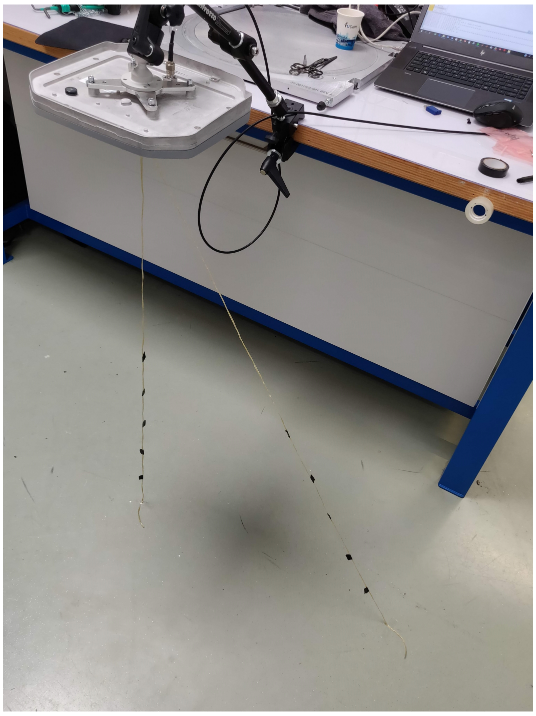


Figure A.4: Experimental set-up with rope with tape as an indication line for the different distances.

To determine the right distance and angle under the reader antenna and perform every measurement under the same circumstances a rope is placed under the reader antenna with black tape on it indicating the distances 50, 60, 70, 80, 90 and 100 cm (figure A.4). Every tagged instrument is placed at the 6 locations for 20 seconds. These 20 seconds can be set in the software on the laptop to make sure every measurement has the same length. The number of reads per seconds is set at 1 one measurement per second. Every measurement is done 3 times in order to gain enough data. The three run tables below show the procedures for three experimental conditions (distance, angle and multiple instruments). For all the three different tagged instruments the run table is used once. This results in 54 measurements per tag of all 20 seconds. Every measurements is conducted with the three different tags. This should result in data which can be used to see which tag performs the best under the different influences.

Table A.2: Run table of distance measurement. ECD stands for experimental condition distance.

	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm
Measurement 1	ECD_{11}	ECD_{12}	ECD_{13}	ECD_{14}	ECD_{15}	ECD_{16}
Measurement 2	ECD_{21}	ECD_{22}	ECD_{23}	ECD_{24}	ECD_{25}	ECD_{26}
Measurement 3	ECD_{31}	ECD_{32}	ECD_{33}	ECD_{34}	ECD_{35}	ECD_{36}

Table A.3: Run table of angle measurement. ECA stands for experimental condition angle.

	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm
Measurement 1	ECA_{11}	ECA_{12}	ECA_{13}	ECA_{14}	ECA_{15}	ECA_{16}
Measurement 2	ECA_{21}	ECA_{22}	ECA_{23}	ECA_{24}	ECA_{25}	ECA_{26}
Measurement 3	ECA_{31}	ECA_{32}	ECA_{33}	ECA_{34}	ECA_{35}	ECA_{36}

Table A.4: Run table of measurements with multiple instruments. ECM stands for experimental condition multiple instruments.

	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm
Measurement 1	ECM_{11}	ECM_{12}	ECM_{13}	ECM_{14}	ECM_{15}	ECM_{16}
Measurement 2	ECM_{21}	ECM_{22}	ECM_{23}	ECM_{24}	ECM_{25}	ECM_{26}
Measurement 3	ECM_{31}	ECM_{32}	ECM_{33}	ECM_{34}	ECM_{35}	ECM_{36}

A.2.4. Data Processing

After performing the 54 tests the data has to be analyzed. Data is saved per test in a separate CSV file giving different variables of the RFID tag as the number of measurement, Unique Identifier (UID), date, time and the RSSI value. The only variable that matters for this experiment is the RSSI value. The RSSI values are extracted from the CSV files and grouped per distance per tag. This means that for every distance for every experimental condition 60 RSSI values should be grouped in one vector. When the number of values was less than 60 this meant that certain measurements are missing. Therefore every vector is filled with NaNs till 60. A barplot is created to visualize the differences in missing values between the experimental conditions. To show the variation in RSSI values for all the experimental conditions nine boxplots are created. Furthermore, the results of the distance measurements are compared to that of the angle measurement and the measurement with multiple instruments. This is visualized in line plots. The results are presented in section A.3.

A.2.5. Data analysis

The boxplots present an overview of all the results. For every hypothesis a one-way ANOVA test has been performed in order to test whether the differences are significant. This statistical test is chosen because this experiment has one dependent variable (RSSI value) and multiple independent variables. The one-way ANOVA is used to test whether there is a difference between the three different tags (Xerafy Pico-On , Dash-On XS and Dot-On XS), between the different distances for the measurement straight under the antenna, under an angle and while using multiple instruments. Furthermore, ANOVA is used to compare the results of the reference measurement with that of the angle and the multiple instruments. The significance level used in this experiment is p ∭ 0.05. The results of the ANOVA test are presented in multiple tables in the next section. The $Prob$ ∭ F value will be given in the last column. When this value is lower than the significance level the difference can be considered as significant.

A.3. Results

A.3.1. Processed data

Figure A.5 shows the boxplots for every experimental condition. The title of each of the nine plots gives the experimental condition. Every box in the plots represents 60 RSSI values at a certain distance. The red line in every box shows the median. Overall, it can be seen that there is a downward trend of RSSI values from 50 cm to 100 cm. In the boxplots with the Xerafy Dot-on tags it can be seen that a lot of data is missing. Not every measurements resulted in the same number of measurements and therefore a bar plot is made which presents the number of missing values per experimental condition (figure A.6). The Xerafy Dot-On tag shows the most missing values compared to the Xerafy Dash-On and the Xerafy Pico-On tag. These results also show that at a distance of 80 cm RSSI values are missing for the Dash-On tag while the measurements at 90 and 100 cm does show RSSI values.

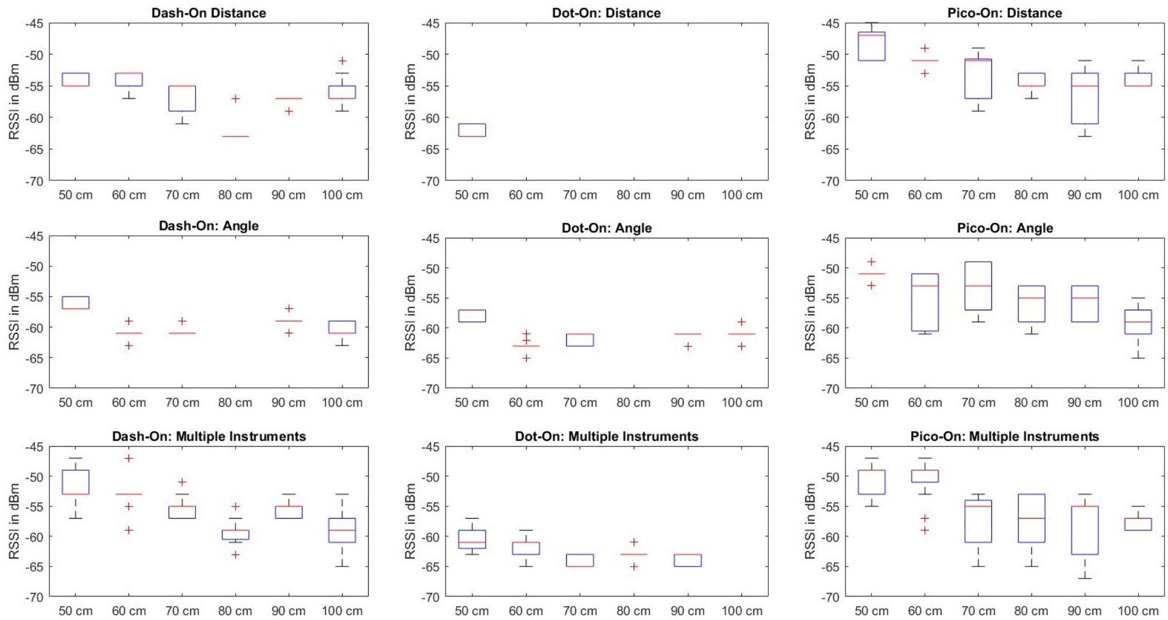


Figure A.5: Boxplots of the measurements for every experimental condition.

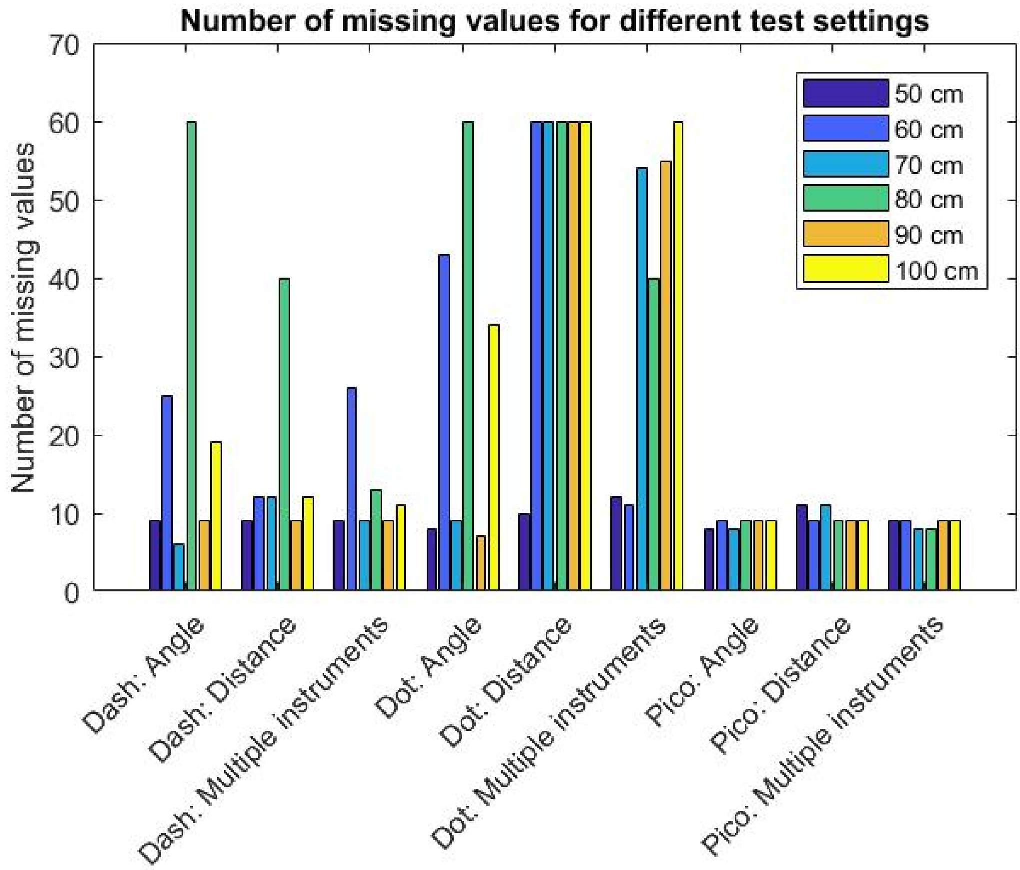


Figure A.6: Barplot visualizing the number of missing values per experimental condition for th three different tags.

Figure A.7 shows the results of the measurements under an angle of 34.5°compared to the reference measurement straight under the antenna. A downward trend can be seen in all the lines meaning that the RSSI values decrease when increasing the distance. The solid lines show the angle measurements and the dashed lines show the reference lines. For the Xerafy Pico-On and the Xerafy Dash-on XS tags the dashed lines show a higher RSSI value. For the Xerafy Dot-On XS tag no good comparison can be made because a lot of data is missing for this tag. The reference measurements show for most points better RSSI values than the angle measurements.

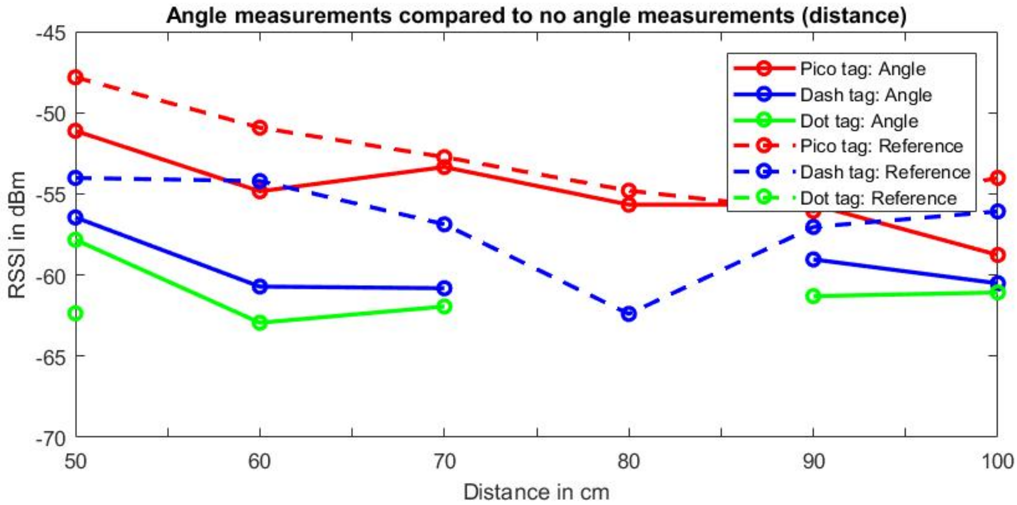


Figure A.7: Tagged instruments under an angle of 34.5°compared to tagged instruments straight under the antenna.

Figure A.8 compares the measurements with multiple instruments with the reference measurements (single instrument on different distances). The solid lines show the measurements with multiple instruments and the dashed lines are the reference measurements. The Pico-On tag (red) shows better RSSI values when using a single instrument while the Dash-On tag shows better results while using multiple instruments. For the Dot-On tag no comparison can be made because a lot of data is missing.

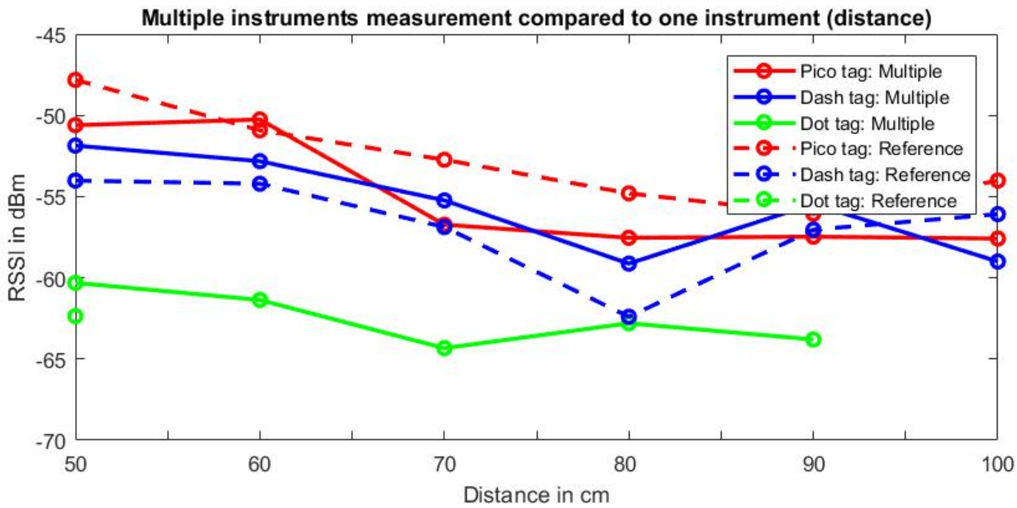


Figure A.8: RSSI values of tag with multiple instruments compared to that of a single instrument.

Figure A.9 shows the differences between the three tags. Is is clear that the Xerafy Pico-On tag (red) shows the best RSSI values and that the Xerafy Dot-On tag (green) shows the worst results. A lot of values are missing for the Xerafy Dot-On tag. The Xerafy Dash-On tag only has a gap in the data at the a distance of 80 cm.

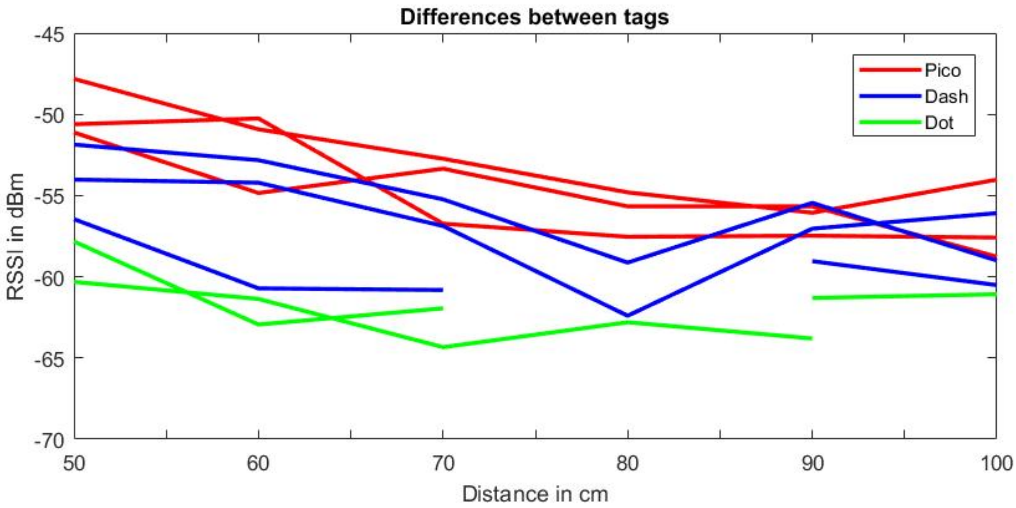


Figure A.9: Differences between the three different tags

A.3.2. Statistical Analysis

Table A.5 shows the results of the on-way ANOVA of the differences between distances for the three experimental conditions and the different tags. The analyses made a comparison of the means of the six different distances (50, 60, 70, 80, 90 and 100 cm). The orange cell for the distance condition and the Dot-On XS tag means that there are not enough data points and that a comparison between distances cannot be made. The eight other analyses show a significant difference between the different distances.

Table A.5: One-Way ANOVA between the different distances for the Distance, Angle and Multiple Instruments measuremnets.

Source		df	F	Prob>F
Distance				
	Dash-On XS	5	106.22	$9.36*10^{-61}$
	Pico-On	5	67.28	$8.59*10^{-47}$
	Dot-On XS	0	NaN	NaN
Angle				
	Dash-On XS	4	208.64	$8.30*10^{-75}$
	Pico-On	5	40.56	$7.43*10^{-32}$
	Dot-On XS	4	165.74	$2.00*10^{-61}$
Multiple Instruments				
	Dash-On XS	5	95.25	$4.21*10^{-58}$
	Pico-On	5	64.06	$2.03*10^{-45}$
	Dot-On XS	4	16.48	$7.76*10^{-11}$

Table A.6 shows results of the one-way ANOVA analyses between the means of the reference measurements and the angle measurements for every distance and tag. It can be seen that there are a lot of orange cells. This means that there are no measurements and no comparison can be made. Three red cells for the Pico-On tag means that the difference between the reference and the angle measurements for this tag at these three distances are not significant. Nine other measurements show a significant difference.

Table A.6: One-Way ANOVA between the reference and angle measurements.

Source		df	F	Prob>F
Reference * Angle				
	Dash 50	1	164.55	$7.51*10^{-23}$
	Dash 60	1	513.82	$8.10*10^{-37}$
	Dash 70	1	138.21	$1.47*10^{-20}$
	Dash 80	0	NaN	NaN
	Dash 90	1	320.32	$6.03*10^{-33}$
	Dash 100	1	198.7	$3.51*10^{-24}$
	Dot 50	1	563.45	$7.00*10^{-43}$
	Dot 60	0	NaN	NaN
	Dot 70	0	NaN	NaN
	Dot 80	0	NaN	NaN
	Dot 90	0	NaN	NaN
	Dot 100	0	NaN	NaN
	Pico 50	1	91.02	$1.10*10^{-15}$
	Pico 60	1	48.15	3.99^{-10}
	Pico 70	1	0.68	0.41
	Pico 80	1	44.24	0.042
	Pico 90	1	0.35	0.56
	Pico 100	1	137.97	$1.55*10^{-20}$

The results of the one-way ANOVA test between the reference measurement and the multiple instruments measurement are shown in table A.7. A significant difference between these two measurements can be seen for the measurements with the Dash-On tag. The Dot-On tag shows again a lot of orange cells meaning a lot of data is missing and no comparison can be made. The Dot-On tag at a distance of 50 cm shows a significant difference between the reference measurement and the multiple instruments measurement. For the Pico-On tag two comparisons show a difference which is not significant (red cells) while four others do show a significant difference.

Table A.7: One-Way ANOVA between the Reference and Multiple Instruments measurements.

Source		df	F	Prob>F
Reference * Multiple instruments				
	Dash 50	1	31.8	$1.59*10^{-7}$
	Dash 60	1	11.53	0.0011
	Dash 70	1	15.49	0.0002
	Dash 80	1	49.81	1.37^{-9}
	Dash 90	1	102.84	4.86^{-17}
	Dash 100	1	36.04	$3.51*10^{-8}$
	Dot 50	1	42.88	$2.87*10^{-9}$
	Dot 60	0	NaN	NaN
	Dot 70	0	NaN	NaN
	Dot 80	0	NaN	NaN
	Dot 90	0	NaN	NaN
	Dot 100	0	NaN	NaN
	Pico 50	1	35.11	$4.64*10^{-8}$
	Pico 60	1	2.84	0.095
	Pico 70	1	30.54	$2.65*10^{-7}$
	Pico 80	1	22.85	$5.96*10^{-6}$
	Pico 90	1	2.88	0.093
	Pico 100	1	187.35	$1.18*10^{-24}$

The last comparison is between the three different tags. The Pico-On tag, Dash-On tag and Dot-On tag are compared under the same circumstances. The results of this one-way ANOVA analysis can be seen in table A.8.

The number of degrees of freedom (df) is only 2 for the measurement at 50 cm. The other measurements only have one degree of freedom which means that the comparison is made between two tags. As explained before the measurements with the Dot-On tag did not resulted in enough data points. The one-way ANOVA for "Distance 50" does compare the three tags and give a significant difference. The other five tests only used two tags and four of them show a significant difference.

Table A.8: One-Way ANOVA between the three different tags at different distances straight under the antenna.

Source	df	F	Prob>F
Pico * Dash *Dot			
Distance 50	2	1060.46	$4.56*10^{-88}$
Distance 60	1	206.29	$9.49*10^{-26}$
Distance 70	1	43.45	$2.43*10^{-9}$
Distance 80	1	334.8	$3.53*10^{-28}$
Distance 90	1	2.89	0.092
Distance 100	1	52.48	$1.04*10^{-10}$

A.4. Discussion

A.4.1. Interpretation of the results

The processed data shows differences between tags, distances, angle and multiple instruments. The data analysis shows if these differences are significant and not based on coincidence. It was expected that the RSSI values differ significantly per distance when placing them straight under the antenna, under an angle of 34.5°and when using multiple instruments. The experiments show that for most of the measurements the RSSI value decreases when the distance increases and the ANOVA tests showed the significance of these differences. Following the graph from figure A.7 the results from the reference measurements (straight under antenna) showed better results than under an angle. The results of the one-way ANOVA for this comparison showed that this difference is significant for the Dash-On tag and also for most measurements for the Pico-On tag. The Dot-On tag only had results for the measurements at 50 cm which was significant. Using this information we can say that there is a significant difference between the placing the tag straight under the antenna and placing it under an angle. Under an angle the RSSI values are worse than straight under the antenna. This would mean that the field is stronger in the center of the interrogation zone compared to the edge of the zone.

The expectation for using multiple instruments was that the RSSI values would be worse due to the fact that tag performance decreases in proximity of metal. When looking at the graph (figure A.3 and the results from the one-way ANOVA (table A.7 it is not clear if the extra instruments improve or deteriorate the RSSI values. For the measurements with the Dash-On tag, the measurements with multiple instruments are better at every distance except at the distance of 100 cm. These differences are also all significant so it can be said that for this tag multiple instruments improve the RSSI values. For the Pico-On tag most reference measurements showed better RSSI values than for the multiple instruments measurements. The only distance where the multiple instruments measurements show better results compared to the reference measurement is at 60 cm. This difference is not significant following the one-way ANOVA. In conclusion it can be said that using multiple instruments does not improve the RSSI values. This is in line with the hypothesis.

The hypothesis for the comparison between the three tags stated that the Pico-On tag would have the best RSSI values followed by the Dash-On tag and the worst RSSI values would be for the Dot-On tag. This is in line with the results in the graph in figure A.9. For all distances the difference is significant except for the measurement at 90 cm. This is the point where the Dash-0n tag has a better result than the Pico-On tag. Overall it can be said that the results do confirm the hypothesis.

A.4.2. Limitations of experiment

Three tagged surgical instruments are used in this experiment. These instruments can be seen in figure A.2. Due to the size of the Xerafy Pico-On Plus tag the location of placement differs from that of the two smaller tags. This can cause different results. But to overcome this different the place of the tag is used as center and the location of the tag with respect to the antenna was the same for every measurement. The number of values detected per second was set at 1 detection per second. This means that every measurement should have 20 RSSI values and by repeating these measurements three times every experimental condition should have 60 data points. Figure A.6 shows that for every measurement minimal six RSSI values are missing. This is not caused by the fact that the the antenna was not able to read the tag but due the fact that there was a small delay between starting the measurement and placing the tagged instrument under the antenna. The figure with the missing values shows that for every measurement the first measurements are missing. Therefore it is still clear when data is missing due to the reader antenna which was not able to read the tags because this resulted in more than 6 missing values. The figure of the missing values also shows that at 80 cm a lot of values are missing for the Dash-On and the Dot-On tag. At a distance of 90 cm the reader antenna does receive a signal from the tag. An explanation for this can be that there is a null spot or hole in the interrogation zone at this distance. A hole or a null-spot are places in the interrogation zone where tags cannot be detected and can be the cause of interference. In every measurement the instruments are in the hands of the researcher and this can result in interference by the human body. It can also cause small differences between the measurements because it is not possible to keep your hand at the exact same position for every measurement. On the other hand, all measurements are performed the same way and every measurement will have this limitation.

To use the results from this experiments in the next phase of implementation in the OR care should be taken to the attachment method of the tags. In this experiment the three different tags are attached to the surgical instruments with glue. It is not possible to use this method on instruments which will be used in the OR due to the fact that glue can not withstand the cleaning process. An attachment should be designed for the tags which allows it to attach en detach the tag from the instrument. It should also be autoclavable. An attachment which fulfils these requirements should be designed in the next steps of this research.

A.5. Conclusion

To answer the research question: *What is the effect of distance, angle, proximity of multiple metal instruments and different tags on the RSSI values received by the reader antenna?* an experiment is conducted. It became clear that when increasing the distance between the tagged instrument and the reader antenna, the RSSI value decreases. Comparing the angle with the reference measurement we can conclude that the angle shows lower RSSI values than the measurements straight under the antenna. Using multiple instruments compared to one instrument does not show a clear difference and it cannot be said that it really increases or decreases the RSSI values. As expected the Xerafy Pico-On tag showed the best results and the Xerafy Dot-On xs the worst results. When it comes to implementation this does not mean that the Pico-On tag is the best suitable tag since the geometry of the tag is quite large. In most cases the Dash-On will be better for some instruments. The Dot-On tag resulted in a lot of missing values and is not suitable to use for tracking instruments in the OR.

B
Sketches of Surgical Layouts

The images of this part are confidential and can not be made public.

C

Slices of Experimental Results

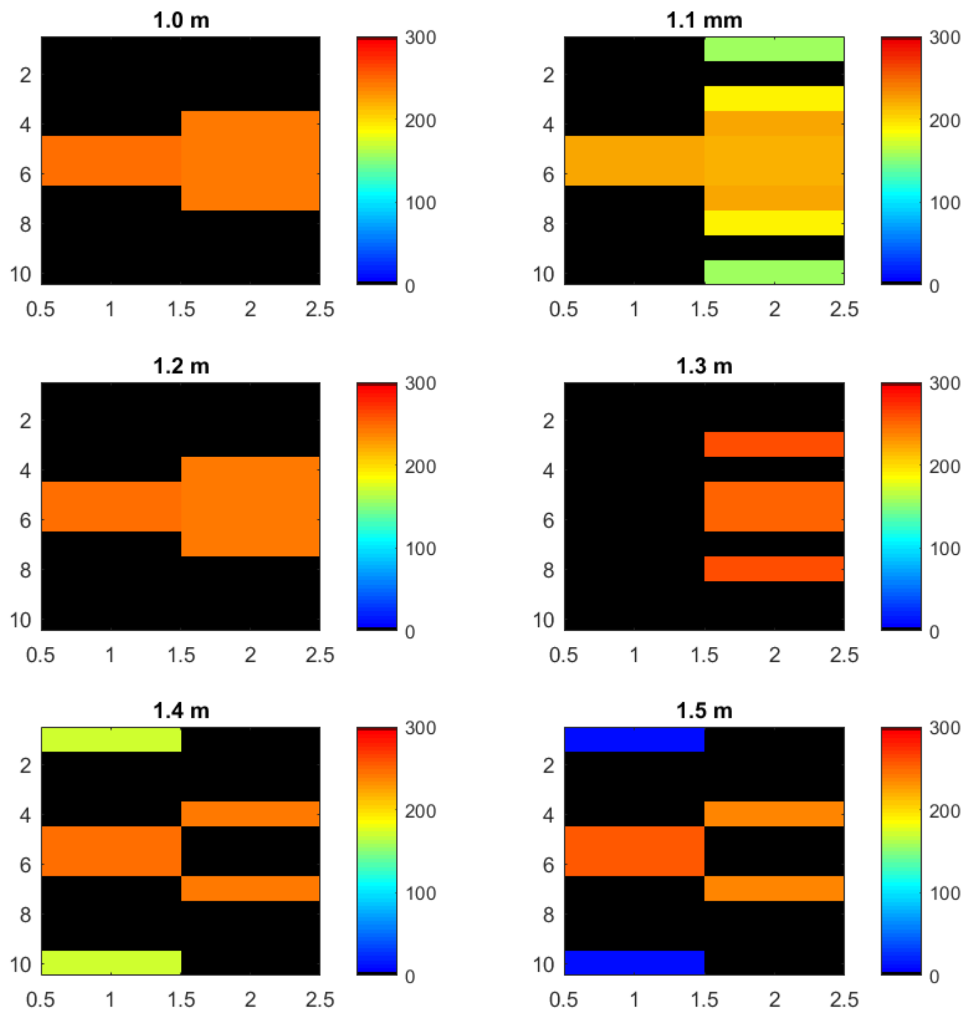


Figure C.1: Slices of the mirror 3D per read range

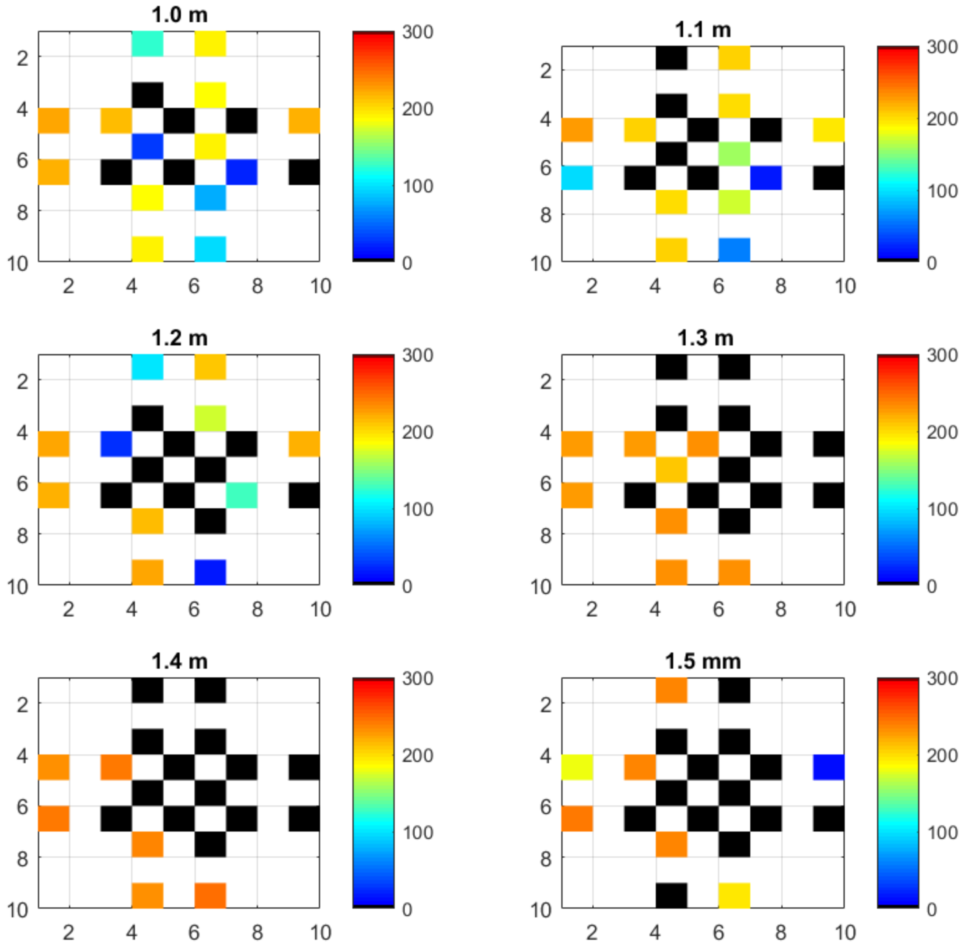


Figure C.2: Slices of the different distances between antenna and tags

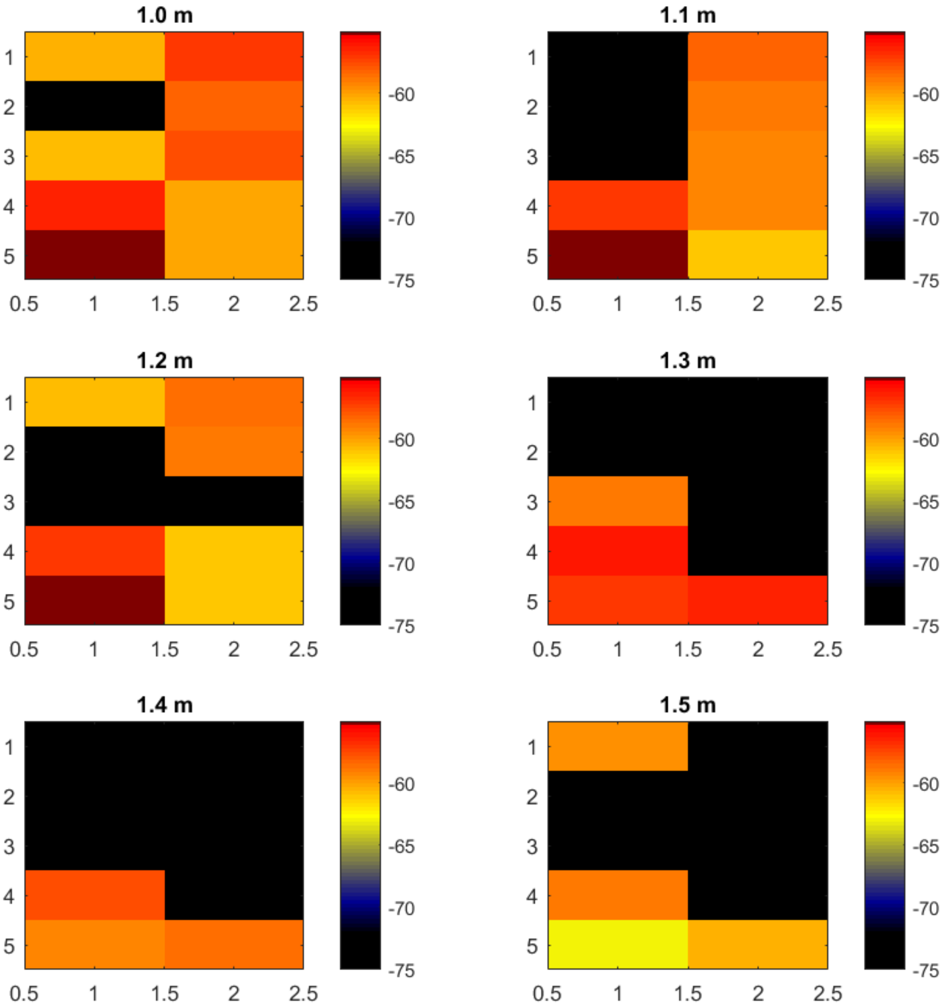


Figure C.3: Slices of the RSSI 3D model

D

Run Template for Operating Room Experiment

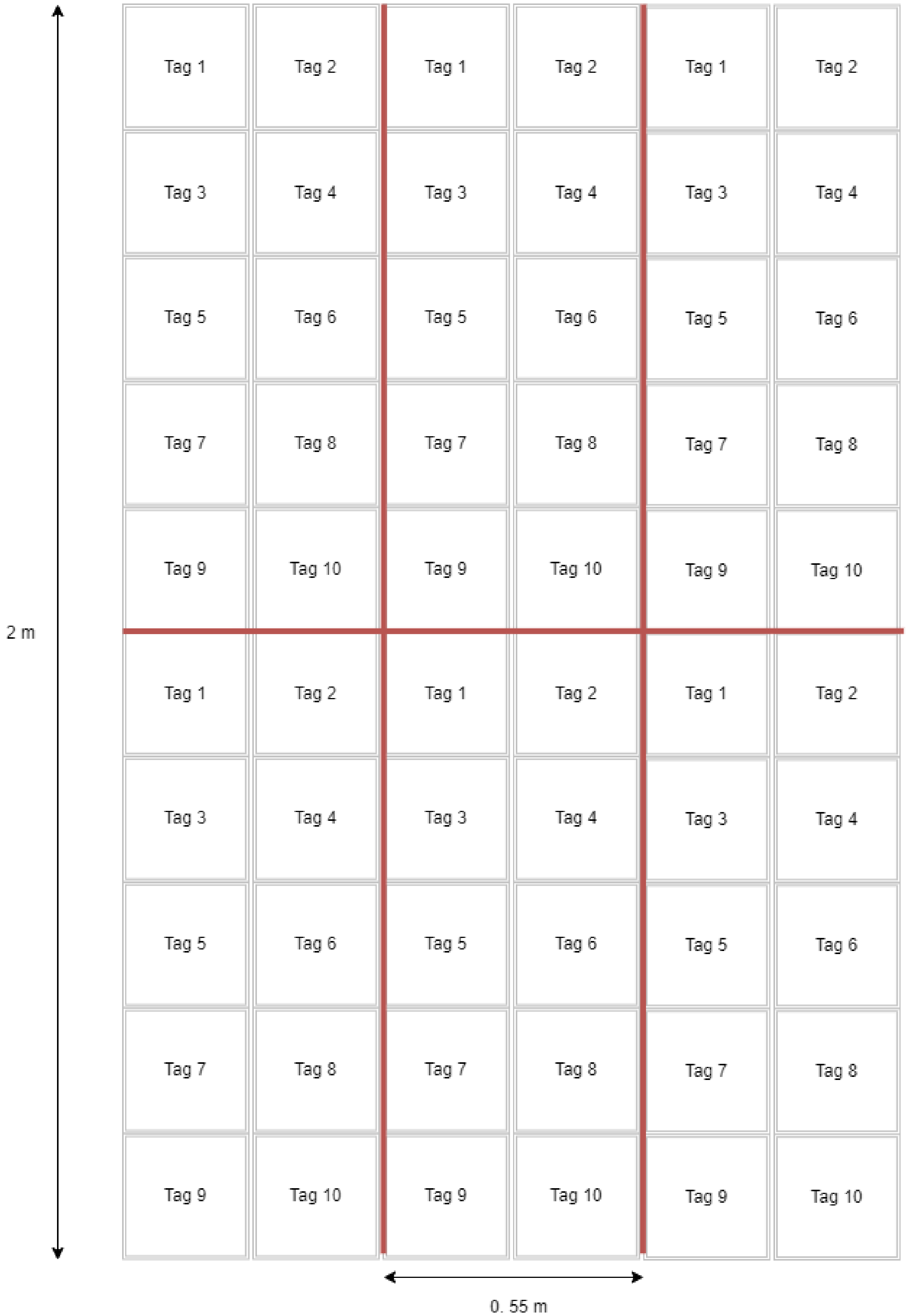


Figure D.1: Template of the measurements. Six blocks all represents half of the surgical table. The six blocks are each measured at 6 different heights.