GEOFENCING FOR WIRELESS HUMAN-MACHINE INTERFACES IN PACKAGING MACHINERY: FROM ANALYSIS TO IMPLEMENTATION

Lappeenranta–Lahti University of Technology LUT

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Abstract

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Keywords: geofencing, indoor positioning, BLE, Wi-Fi, UWB, wireless HMI

Traditionally, human-machine interfaces of packaging machines are physical control panels attached to the machine. With the current trend of wireless technologies, companies have started to implement wireless human-machine interfaces also in the field of packaging machinery. They offer more flexibility to the user but introduce new safety-related challenges. When an operator is actuating a machine, they must see the machine to mitigate safety risks, which wireless panels no longer guarantee.

Geofencing means setting virtual boundaries around an area of interest. This thesis explores and compares technologies for geofencing that can be used to restrict certain human-machine interface functions when the user is not in proximity to the machine. Design science research methodology is used to gather requirements and build a proof of concept of three chosen indoor positioning technologies: Bluetooth Low Energy (BLE), Wireless Fidelity (Wi-Fi) and Ultra Wide Band (UWB). The proofs of concept are evaluated against the gathered requirements in a realistic factory environment.

The results show that UWB is more accurate than BLE and Wi-Fi, making it a more reliable technology for safety-critical applications in packaging machinery. However, UWB has a higher hardware cost, and most mobile devices do not support it. In contrast, while BLE and Wi-Fi are cheaper, they are also more prone to interference and variating noise levels in the environment.

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Geoaitaaminen langattomille käyttöliittymille pakkauskoneissa: analyysistä toteutukseen

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Avainsanat: geoaitaaminen, sisätilapaikannus, BLE, Wi-Fi, UWB, langaton käyttöliittymä

Pakkauskoneiden käyttöliittymät (HMI) ovat perinteisesti olleet koneessa kiinni olevia ohjauspaneeleita. Nykyisin langattomien teknologioiden aikakaudella yritykset ovat alkaneet ottaa käyttöön langattomia HMI:tä myös pakkauskoneissa. Ne tarjoavat suurempaa joustavuutta käyttäjälleen, mutta tuovat mukanaan myös uusia turvallisuusriskejä. Kun käyttäjä ohjaa konetta, hänellä on oltava näköyhteys koneeseen turvallisuusriskien minimoimiseksi, mitä langaton HMI ei takaa.

Geoaitaaminen tarkoittaa virtuaalisten rajojen luomista alueen ympärille. Tämä diplomityö tutkii ja vertailee geoaitaamiseen käytettäviä teknologioita, joita voidaan käyttää rajoittamaan tiettyjä HMI-toiminnallisuuksia käyttäjän ollessa määritellyn alueen ulkopuolella. Tutkimuksessa käytetään Design science -menetelmää vaatimusmäärittelyyn sekä kolmen valitun paikannusmenetelmän - Bluetooth Low Energy (BLE), Wireless Fidelity (Wi-Fi) ja Ultra Wide Band (UWB) - konseptitodistusten kehittämiseen. Konseptitodistukset arvioidaan realistisessa tehdasympäristössä.

Tulokset osoittavat, että UWB on tarkempi kuin BLE ja Wi-Fi, minkä ansiosta se on luotettavampi teknologia turvallisuuskriittisiin sovelluksiin pakkauskoneissa. Toisaalta UWB:n laitteistokustannukset ovat korkeammat, ja suurin osa kaupallisista mobiililaitteista ei tue UWB-teknologiaa. BLE ja Wi-Fi sitä vastoin ovat halvempia mutta toisaalta herkempiä häiriötekijöille ja kohinan voimakkuuden vaihteluille ympäristössä.

Symbols and abbreviations

ANN	Artificial Neural Network
AoA	Angle of Arrival
BLE	Bluetooth Low Energy
CFR	Channel Frequency Response
CIR	Channel Impulse Response
CNN	Convolutional Neural Network
CSI	Channel State Information
$DS-TWR$	Double-Sided Two-Way Ranging
DSR	Design Science Research
$GDPR$	General Data Protection Regulation
GPS	Global Positioning System
HMI	Human-Machine Interface
kNN	k-Nearest Neighbor
LED	Light-Emitting Diode
PDR	Pedestrian Dead Reckoning
PoC	Proof of Concept
$RFID$	Radio Frequency Identification Device
$RSSI$	Received Signal Strength Indicator
$SS-TWR$	Single-Sided Two-Way Ranging
SVM	Support Vector Machine
ToF	Time of Flight
TWR	Two-Way Ranging
UWB	Ultra Wide Band
VLC	Visible Light Communication
VLP	Visible Light Positioning
$Wi-Fi$	Wireless Fidelity

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1 Introduction

This thesis explores the use of geofencing solutions to improve the safety of wireless human-machine interfaces (HMIs) in packaging machinery. As wireless control of machinery becomes increasingly common, it is essential to ensure that the operator is located within a safe area when actuating a machine. The focus of this research is on evaluating and comparing different technologies for geofencing in an industrial environment.

HMI refers to a device or application through which a user can interact with a machine (National Institute of Standards and Technology, 2025). Traditionally, physical control panels connected to the machine have been used for the purpose in industrial settings. However, as wireless technologies have been increasingly adapted in recent years, HMIs are also evolving. Wireless HMIs are an attractive option because they offer the user more flexibility. Nevertheless, they introduce new safety-related challenges. It is important that the operator can see the machine that they are actuating. In traditional HMIs, this is guaranteed because the device is connected to the machine. In wireless HMIs, however, new solutions need to be developed to ensure safety.

Geofencing refers to defining virtual boundaries around an area of interest (Rahimi, Nur Zincir-Heywood & Gadher, 2013). This thesis explores the use of geofencing to improve safety in packaging machinery. The idea is to define a geofence around the machine where it is safe to use the machine. If the operator steps outside the predefined safe zone, the system should restrict some of the HMI functionalities. The thesis explores and compares different technologies for the purpose.

1.1 Background

Indoor positioning systems have gained a lot of attention in research and practice in the past few years. In outdoor settings, the Global Positioning System (GPS) is the most popular localization method. However, it is not reliable in indoor environments because it requires a line of sight with the satellite infrastructure. (Rahimi, Nur Zincir-Heywood & Gadher, 2013) Different technologies have been studied for indoor localization, including systems based on communication technologies such as Bluetooth Low Energy (BLE), Wireless Fidelity (Wi-Fi), and Ultra Wide Band (UWB), as well as computer vision and inertial measurements.

Geofencing is a technique that builds on positioning data by defining a boundary around a specific area. It can be used to trigger actions or to manage access control based on whether the user is inside or outside a predefined area. There are several examples in the literature where geofencing has been used to increase safety (Zimbelman et al., 2017). In the context

of industrial machine safety, geofencing can be used to grant or remove control of certain machine functions based on where the operator is located.

This master's thesis is carried out in a case company that designs and manufactures packaging machines for industrial use. The company wants to explore geofencing as a way to support the development of wireless HMI panels. The motivation is to ensure that the panels can be used safely without the risk that the operator could use the machine from an unsafe location. This reflects broader technological trends in the packaging industry and industrial automation in general. Flexibility and remote access are becoming increasingly popular (Business Research Insights, 2024).

1.2 Objectives and Research Questions

The main objective of this thesis is to research and compare different possibilities to determine whether a user is located inside a predefined geofenced area. This objective can be divided into several smaller goals. One goal is to gain an understanding of existing technologies and techniques for indoor positioning and geofencing. Another is to identify the requirements of a geofencing system in the context of packaging machinery. Another goal is to analyze the existing technologies based on literature and the gathered requirements, and to choose three promising technologies for further testing. Additionally, the thesis aims to develop a proof of concept (PoC) for each of the selected technologies. Finally, the performance of those implementations is evaluated in a realistic factory environment.

From a scientific perspective, the goal of this research is to contribute to research in the field of indoor positioning and geofencing. In recent years, many scholars and practitioners have been increasingly interested in indoor positioning technologies (Zafari, Gkelias & Leung, 2019; Hayward et al., 2022). Although many technologies have been explored in the academic literature, studies are often conducted in a controlled laboratory environment or in an office space, such as (Obreja & Vulpe, 2020; Subhan et al., 2022). Many papers focus on optimizing the performance of certain technologies in a controlled environment, while in industry there is a need for cost-efficient and reliable solutions that are easy to set up and deploy in different locations. This thesis aims to bridge the identified gap between research and practice by identifying industrial requirements and evaluating technologies in a realistic factory setting.

From an industrial perspective, the goal is to explore viable geofencing solutions that could be used in the context of wireless HMIs in the packaging machine industry. The resulting PoCs offer an architecture and algorithms that the commissioning company can use as a basis to build upon. Furthermore, the thesis gives practitioners an overview of how different indoor

localization technologies perform in a factory, as well as an overview of the challenges and requirements particular for geofencing in the packaging industry.

Based on the research objectives, the following research questions were crafted.

Q1: What are the advantages and disadvantages of different geofencing technologies for ensuring safe operation of packaging machinery?

Q2: What requirements need to be considered when developing a geofencing solution for a factory environment?

Q3: How do selected technologies perform in a factory setting with respect to key requirements?

Q1 approaches the topic from a theoretical perspective. The aim is to find out which kinds of technologies exist for geofencing and indoor positioning, how they have been used in research and practice and what their advantages and disadvantages are. With Q2, the goal is to explore requirements that are specific for a factory environment, specifically in packaging machinery. The results give insight into the special characteristics of packaging machinery in terms of geofencing and serve as guidance for selecting technologies for proof-of-concept development. Finally, Q3 explores how well the chosen technologies meet the specific requirements.

1.3 Scope

The thesis discusses geofencing in the specific context of packaging machinery and wireless HMIs. It concentrates on challenges unique for that environment and use case. This focus means that the requirements, evaluations and findings are specific to industrial environments, particularly to packaging machinery.

The focus of the thesis is on the evaluation of relevant technologies and the development of simple PoC implementations. Integration into the existing software ecosystem of the case company is out of scope; however, the design choices aim to make the developed PoCs easily extensible and integrable into a future product.

Only three technologies are prototyped. They are chosen for the present use case based on their theoretical attributes and the requirements of the solution. Comparison of other technologies is limited to literature review and comparing the requirements with the theoretical properties of the technologies based on literature.

While this thesis frequently discusses indoor positioning, it is important to note that the only possible approach for geofencing is not an absolute localization. It is, however, the most straightforward way to classify whether the user is inside or outside a geofence. Furthermore, it simplifies the accuracy comparison. However, the thesis also explores other alternative approaches.

1.4 Structure of the Report

The thesis report consists of seven chapters. After the introduction, the chapter 2 covers related work in the field of indoor positioning. Chapter 3 describes the design science research methodology used for the thesis, along with the interview and analysis methods. Chapters 4 explains the thematic analysis process and its results, and chapter 5 explains the results of the proof of concept development and evaluation. Finally, chapter 6 critically discusses the key findings and chapter 7 summarizes the study.

2 Literature Review

Geofencing refers to setting virtual perimeters for geographical areas. Different technologies are used to track whether a device is inside the virtual boundary. Geofencing has been used for several purposes, such as targeted advertisement, transportation path control, and asset management. (Rahimi, Nur Zincir-Heywood & Gadher, 2013) Proximity-based access control means that only users in close proximity to a machine or a device are able to access its data or functionalities (Zhang et al., 2023). This thesis studies how proximity-based access control can be utilized in packaging industry, exploring different geofencing methods for localization and granting the users access to certain functionalities based on their proximity to the machine. This literature review introduces different technologies and techniques for indoor positioning systems, explaining their usage along with their advantages and disadvantages.

The first step for proximity-based services or access control systems is to locate the nearby device and determine whether it is inside the close-proximity area. For this reason, this literature review encompasses different indoor positioning systems that are all possible options for calculating proximity for the proximity-based access control system. This chapter introduces related work in the field of indoor positioning. The findings from the literature review are used in later chapters to inform the choice of suitable technologies for geofencing in a factory.

2.1 Indoor Positioning Technologies

GPS is the most popular localization method, widely used in outdoor environments. However, GPS is not reliable in indoor settings because it requires a line of sight with the satellite infrastructure to provide an accurate localization (Rahimi, Nur Zincir-Heywood & Gadher, 2013). That is why different technologies are needed for indoor positioning. There are several existing technologies, including ones based on communication technology, computer vision, and inertial measurements. This chapter gives an overview of the existing technologies and their characteristics. The technologies introduced in this chapter have been chosen based on the most frequently mentioned technologies in recent survey papers on indoor positioning systems.

2.1.1 Communication Technology -Based Systems

Communication technology -based systems leverage wireless communication infrastructure for location estimation. They have some common characteristics, such as the use of signal properties to determine the position of a device. Systems based on communication technol-

ogy also face common challenges that decrease localization accuracy, especially when there are a lot of obstacles and signal interference in the environment. Multipath fading, where signals reflect from surfaces and cause interference, and non-line-of-sight conditions, where obstacles block the direct signal path, are examples of such challenges. (F. Liu et al., 2020)

Wireless Fidelity (Wi-Fi)

Wireless Fidelity (Wi-Fi) technology is based on the IEEE 802.11 family of wireless connectivity standards. Devices within a certain local area can use Wi-Fi to communicate with each other via radio waves. (Ruth, 2023) Most of the current mobile devices can communicate through Wi-Fi, which makes it an attractive option for indoor positioning. In most indoor spaces, a Wi-Fi infrastructure already exists, and the existing access points can be used for localization purposes. However, Wi-Fi networks are typically deployed for communication instead of localization purposes, and they are optimized to maximize data throughput and network coverage. If high localization accuracy is desired in such networks, efficient algorithms for positioning are needed. Moreover, the use of the Wi-Fi infrastructure for localization can negatively affect its primary purpose, connecting users of the network. (Zafari, Gkelias & Leung, 2019; Kunhoth et al., 2020)

F. Liu et al. (2020) mention in their survey paper a few challenges that need to be considered with Wi-Fi-based localization in indoor spaces. One of them is the multipath effect. As indoor spaces are often small and full of obstacles, apart from the direct signal the receiver may receive several reflection signals, distorting the signal. Obstacles also make it challenging to accurately estimate the signal loss value if the obstacles are blocking the line of sight between the transmitter and receiver. A third challenge mentioned by F. Liu et al. (2020) is device heterogeneity, meaning that devices in the same Wi-Fi network are often different with each other. Aspects such as Wi-Fi chips, Wi-Fi antennas, hardware drives, packaging materials and operating systems affect the strength of the signal.

Wi-Fi-based indoor positioning techniques can be divided into two classes: active positioning and passive positioning. Active positioning means that the user carries a mobile device with them, which searches for signals from nearby access points, calculating the position based on positioning algorithms. Passive positioning, on the other hand, does not require the user to carry the device with them. Instead, the technique is based on how the user's change of position affects the received signals. Active positioning has a higher accuracy than passive positioning and has been researched and used more. From the practical point of view, they have the difference that active positioning tracks the location of the device and passive positioning the location of the user, thus suiting different situations. (F. Liu et al., 2020) In busy environments, it may be difficult to know if the changes in the signal strength are actually

caused by the user or other moving objects or passers-by.

Kunhoth et al. (2020) mention that the accuracy of Wi-Fi-based indoor positioning lies typically between 2 and 5 meters. The accuracy depends on the chosen techniques, and some techniques, such as CSI fingerprinting, can achieve a significantly higher accuracy. Wi-Fi operates in 2.4 GHz and 5 GHz frequency bands.(Leitch et al., 2023) Additionally, Wi-Fi 6E extends support to the 6 GHz frequency band (Wi-Fi Alliance, 2025).

Bluetooth low energy (BLE)

Bluetooth Low Energy (BLE) is a variation of Bluetooth that is designed to have a low power consumption. It is widely used in indoor positioning systems. In localization, BLE is typically used through beacons. They are small devices with low power consumption, which can be supplied by batteries or directly from different types of power outlets, such as a USB port. The beacons broadcast BLE advertising packets, and other devices can estimate their own position based on those packets. (Leitch et al., 2023; Zafari, Gkelias & Leung, 2019)

BLE operates in the 2.4 GHz band, the same one that is also used by Wi-Fi. To avoid interference, the channels need to be spread out across the band, which can lead to unequal signal attenuation and higher path losses at high frequencies. (Leitch et al., 2023) The number of channels in BLE is reduced to 40, compared to the 79 channels in Bluetooth Classic. Out of the channels, 3 are used for advertising and the remaining 37 for exchanging data between devices. (Bluetooth SIG, 2024) The 3 advertising channels of BLE are primarily used by beacons, and they are chosen in a way that minimizes the interference with Wi-Fi signals (Kriz, Maly & Kozel, 2016)

One of the advantages of BLE is its low cost. The hardware costs are low, and compared to most other wireless technologies, the power consumption is relatively small. In the present moment, most modern mobile devices include BLE capabilities, so the technology is compatible with most devices. (Leitch et al., 2023) BLE has a similar or slightly better accuracy compared to Wi-Fi (Kunhoth et al., 2020).

One challenge with BLE beacons is that the signals may be unstable, which makes distance estimation less accurate. Moreover, the received signal strength depends on several factors such as the receiver device orientation relative to the BLE beacon, whether there is a line of sight between the devices or if there are obstacles in between, and the transmission power level of the BLE beacon. (Qureshi et al., 2018)

Researchers have developed several strategies to improve the quality of the location estimates from BLE signals. Qureshi et al. (2018) conduct an experiment where several transmission

power levels are tested and the accuracies are compared. The results show that the localization accuracy tends to be higher when the transmission power level is higher. (Qureshi et al., 2018) The accuracy of location estimates can also be improved by optimizing the number of beacons. If there are not enough beacons, the fluctuations in the signal strength of an individual beacon have too large influence on the estimated accuracy. On the other hand, in a very dense BLE infrastructure with several beacons placed too close to each other, the signals from the beacons can start interfering with each other. (Jeon et al., 2018)

Ultra Wide Band (UWB)

Ultra Wide Band (UWB) is a radio frequency technology, typically used for data transmission. It utilizes techniques that spread the radio energy across a wide frequency band with a low power spectral density. In localization, the high bandwidth allows a high precision, and the low power spectral density decreases the likelihood of interference with conventional radio systems. (European Telecommunications Standards Institute, 2024) UWB localization systems generally consist of two types of nodes: anchors and tags. The location coordinates of the fixed anchor nodes need to be known beforehand in order to determine the distance between a tag node and anchor nodes. For this, calibration needs to be performed, either by manually calculating the positions of the anchors or with self-calibration. Each time that the anchor nodes are possibly moved to a new location, calibration needs to be done again. Self-calibration allows easier deployment of the anchors and updating the positions easily if they are moved. (Ridolfi et al., 2022)

Compared to Wi-Fi and BLE, UWB delivers significantly more accurate results for localization, as it is capable of centimeter-level localization accuracy (Kunhoth et al., 2020). However, the technology is more expensive due to costly infrastructure installation. It is also not very robust to situations where there is no line of sight between the anchors and the tags. (Ridolfi et al., 2022) There are several reasons behind why the UWB technology can reach such a high positioning accuracy. In narrowband systems, multipath fading is a serious problem, and receivers cannot separate the multipath components coming from different directions. In UWB, the multipath signals typically do not overlap and thus stay distinctive from each other. The system is also better at determining small time differences of the received signal. The high bandwidth of UWB also enables the realization of effective error correction techniques and packet retransmissions. Moreover, UWB is quite an energy-efficient technology. (Mazhar, M. G. Khan & Sällberg, 2017)

Radio Frequency Identification Device (RFID)

Radio Frequency Identification Device (RFID) systems consists of an RFID reader and RFID tags. The reader uses radio waves to transmit signals. When the tag receives a signal, it is activated and sends a wave back to the reader. There are two different types of RFID systems that differ from each other in terms of operating frequency and battery requirements. Low frequency systems operating at 125 kHz need almost direct physical contact between reader and tag, and cannot thus be used for localization problems. High frequency systems at 13.56 MHz have a few centimeters reading range and can be used for certain localization tasks. For typical localization tasks that require a larger reading range, ultra high frequency systems are of interest. They have frequencies between 433 MHz and 2.4 GHz, and the tags can achieve a reading range from tens of meters up to 100 meters, depending on their characteristics. (Motroni, Buffi & Nepa, 2021)

For battery requirements, RFID tags can be divided into active, semi-passive and passive. Active tags can communicate across the longest distances. They carry on a battery that feeds the transmitter. Passive tags, on the other hand, have no power supply. Instead, they communicate through the modulated backscattering principle. It means that they get their power from electromagnetic wave received from the reader and reflect the signal back by modulating it. Semi-passive tags have a battery, but it is only used for powering the microchip or sensors, not for feeding the transmitter. Thus, the method of communication between the tag and reader is similar as for passive tags. The different types of tags each have their own advantages and disadvantages. Passive RFID tags are the cheapest and easiest to install and maintain. However, the reading range is lower than for active tags. Current passive tags can reach up to 10 meters reading range. (Motroni, Buffi & Nepa, 2021)

From an accuracy perspective, the performance of RFID lies between that of UWB, and Wi-Fi or BLE. The typical accuracy is between 1 and 3 meters. The cost of hardware, deployment and use is also between those technologies. The power consumption is relatively low. (Kunhoth et al., 2020)

Over the years, a lot of research has been done on RFID technology for indoor positioning. The use of backscattered radio waves makes it possible to identify and localize an object at the same time. Several algorithms and techniques exist for both stationary object and moving object positioning. However, there are few industrial applications of the technology, as there are some challenges with real-time performance. Some further challenges of the technology include the influence of the multipath effect on accuracy in practical environments and the possible need of auxiliary equipment. That, along with the need for calibration each time the antenna location changes, means the system is not very flexible. (F. Liu et al., 2020).

ZigBee

ZigBee is a two-way wireless communication standard developed to have low cost and low power consumption. It is developed on top of the IEEE 802.15.4 protocol, an industry-standard wireless networking technology. (Connectivity Standards Alliance, 2023) Today, there are Zigbee modules on the market that promise up to a 90 meter range indoors (Digi, 2024). However, as Kuzminykh, Snihurov & Carlsson (2017) conclude in their study, factors such as multipath fading caused by reflections or non-line-of-sight situations influence performance, and the maximum range may not be reached in a real-life indoor environment with plenty of disturbances.

ZigBee has some advanced networking properties and supports multihop routing for extended range and coverage. However, one of its disadvantages is the need for dedicated hardware, as most of the current consumer devices do not include support for the protocol. It also suffers from interference. (Zafari, Gkelias & Leung, 2019)

Visible Light Positioning (VLP)

Visible light communication (VLC) utilizes light waves for communication. Visible light positioning systems (VLP), leveraging VLC, consist of light-emitting diodes (LEDs) and a camera or photodiode as receiver. The LEDs flick at a speed that is not possible for humans to detect, transmitting unique positioning identification information. Thus, the same LEDs serve a dual purpose: they are wwork as both a source of illumination in the indoor space and send signals for positioning. The receiver senses signals from one or multiple LEDs and use positioning algorithms to determine the location. (Zhu et al., 2024)

VLP is easily deployable, since most indoor spaces already include LEDs for lighting purposes. The receiver photodiode or camera can be an integrated device in a mobile device. Due to the propagation characteristics of visible light, the signals interfere very little with each other. This allows for good positioning accuracy. In other communication technology -based systems, there is a tradeoff between cost and accuracy. For example, Wi-Fi is relatively cheap, but the localization error can often be several meters. On the other hand, UWB achieves great accuracy but also has a high cost. Visible light communication makes it possible to achieve both low cost and high accuracy. (Zhu et al., 2024)

However, there are some challenges related to VLP. A lot of research has been done on the topic, but industrialization of the technology is still in the early stages. There is a lack of standards and protocols for implementation, which makes it difficult to develop a scalable and interoperable system. In different environments, the LED layouts and models usually differ from each other, which makes the portability of a VLP system more challenging.

Additionally, VLP requires special LEDs that have positioning capabilities. That means that the deployment of a VLP system often requires changing the lights in the location. The specialized LEDs have a limited individual coverage, and their cost is higher compared to normal LEDs. Factors influencing positioning accuracy include the type of LED light used and how well it fits the chosen computational model, ambient lighting, and dust. Even though visual light is less prone to interference, some interference may still occur. Corner areas often have significantly worse accuracy than the center area of a room. (Zhu et al., 2024)

2.1.2 Acoustic Systems

Acoustic systems include an emitter and a receiver of sound waves. The receiver can be placed either in the environment or attached to the object that is being localized. Acoustic systems can be divided into regular acoustic, operating in the range of human hearing (between 20 Hz and 20 kHz), and ultrasonic systems (over 20 kHz). Ultrasonic systems are typically more accurate, reaching accuracies from around a few centimeters to tens of centimeters. (Hayward et al., 2022)

Acoustic systems require ceiling-mounted nodes, which makes the integration of the system into a room more challenging and time-consuming. Ambient noise may interfere with the signal, especially in noisy environments. The systems also may have challenges in distinguishing which nodes sent pulses. The lower propagation speeds of sound waves compared to radio frequencies results in both positive and negative characteristics of acoustic systems. On the positive side, the lower velocity of the wave makes it easier to calculate the position based on time of arrival information. On the negative side, the lower velocity results in issues like the Doppler effect, where motion affects the time that a signal is detected. (Hayward et al., 2022)

2.1.3 Computer Vision -Based Systems

Computer vision -based systems aim to understand the surroundings based on information gained from images. There are several different approaches to computer vision -based localization. The systems differ from each other in regard to environmental data, cameras, detected elements and localization method. In the beginning, each method has a configuration stage, in which landmarks and sensors are placed to the environment. Environment data for the model can consist of either information about the position of markers or cameras, images in a database with position and orientation information, or a 3D model of the surroundings. The cameras can capture the scene in 2D or 3D and be static or mobile. Sometimes, other sensors are also used together with cameras to improve accuracy. The goal of computer vision algorithms is to detect elements on the scene. Those can be either real features, such as objects, or artificial markers inserted into the environment, such as QR codes.

According to the localization method, the different methods can be classified into traditional image analysis, and artificial intelligence based analysis. (Morar et al., 2020)

Computer vision -based systems require additional hardware and occasionally other adaptations in the working environment in order to function. The system requires a camera or several cameras for the photographs. If the cameras are static, they are fixed to a point in the environment and track moving objects; if they are mobile, they are attached to the moving object (Morar et al., 2020). There is a possibility to use the camera of the user's mobile device, but for it to work at all times, it would require the camera never to be covered, such as the device laying on a surface. On the other hand, static cameras will likely not track the device itself, but rather users moving in the area. Some additional difficulties for the use of computer vision -based localization in a factory setting include the constantly changing, dynamic environment where assets can be moved around, and also General Data Protection Regulation (GDPR) challenges when processing and analyzing images of the people inside (Hayward et al., 2022).

It is possible to achieve high positioning accuracy based on computer vision. Wu et al. (2022) test a computer vision solution based on the Convolutional Neural Network (CNN) with images from security cameras and achieve positioning errors typically within half a meter. However, to achieve such high accuracy, a well-designed environment with a suitable computer vision algorithm is required. The problem of indoor localization with computer vision can be divided into several smaller sub-problems. Wu et al. (2022) divide their positioning method into three phases: pretreatment, pedestrian detection, and position estimation. In pretreatment, things like camera calibration and installation are considered. In pedestrian detection, the model is trained and used for recognizing objects in the images. For position estimation, if the scene has few cameras, a new challenge is to estimate the depth information.

In their article about indoor navigation, D. Khan et al. (2022) name some further issues and challenges of computer vision -based systems that also apply for indoor positioning. Those challenges include accuracy challenges resulting from occlusion and changes in light intensity. Applying the working solution to another building can also be challenging because most methods need to be trained specifically for each space. Computer vision -based methods are also often computationally heavy, as they work with real-time pattern recognition. (D. Khan et al., 2022)

2.1.4 Inertial Positioning Systems

One group of indoor positioning systems uses inertial information in order to determine the subject's trajectory of movement. In this thesis, they are referred to as inertial positioning systems. Inertial positioning systems are often used together with different communication technologies in order to offer more accurate estimations. From the hardware perspective, inertial sensors, such as accelerometer, gyroscope or magnetometer, are needed. In recent years, low cost and small inertial measurement units have been developed. Modern smartphones typically have such sensors embedded, thus, it is possible to perform inertial positioning using only the smartphone sensors. (Wang et al., 2018)

Inertial positioning systems estimate movement of the device based on changes in acceleration and rotation. Several methods for implementing inertial positioning exist, such as Pedestrian Dead Reckoning (PDR), which is based on counting the user's steps and estimating the change in position. The systems can be mounted or handheld. Mounted systems include a sensor that is mounted to a certain part of the user's body. Handheld systems are based on a mobile device and its sensors. The accuracy of mounted systems is generally higher, whereas handheld systems are often easier for the user. (Wang et al., 2018)

Compared with localization techniques based on communication technology or vision sensors, inertial positioning systems are faster at giving an accurate estimate and have a lower power consumption. (Wang et al., 2018) However, as they do not have direct data on the surroundings, they work accurately only for a short period of time and, in reality, need to be combined with another technology to work correctly.

2.1.5 Comparison of Technologies

The table 1 provides an overview of the attributes of different indoor localization technologies based on the literature. Each technology has their own advantages and disadvantages. Common tradeoffs exist between cost and accuracy. Additionally, the ease of integration differs between the technologies.

Technology	**Accuracy**	**Range**	**Cost**	**Ease of integration**	**Energy consumption**
Wi-Fi	2-5 meters	Dozens of meters	Low-medium	Easy, infrastructure often already exists	High
BLE	2-5 meters	100 m	Low	Easy, additional hardware is cheap and easy to install	Low
UWB	Centimeter level/ sub-meter accuracy	Around 30 m	High	Requires specific hardware	Low
RFID	1-3 m	From only a few centimeters to up to 100 meters depending on the type of tags	Medium-high	Requires tag setup	Low
ZigBee	A few meters	Up to 90-100 m	Low	Many common mobile devices do not support the protocol	Low
Acoustic	Sub-meter, tens of centimeters	Up to 30 m	Low-medium	Difficult, ceiling-mounted nodes needed	Medium
Computer vision	Highly dependent on the algorithms, sub-meter accuracy possible	Range limited by line-of-sight	High	Difficult, placement of cameras is important	Medium
Inertial positioning	Drifts over time without recalibration	Not applicable	Low	Easy	Low

Table 1: Indoor localization technologies

2.2 Indoor Positioning Techniques

Several different techniques are used for determining the position of a device. This chapter covers some of the most commonly used techniques with their characteristics and suitable uses. The following techniques are used with different communication technology -based solutions.

2.2.1 Received Signal Strength Indicator (RSSI)

The method based on Received Signal Strength (RSS) is one of the most widely used techniques for indoor localization, perhaps due to its simplicity. The received signal strength describes the actual signal power strength measured at the receiver. In the RSSI method, it is used to estimate the distance between the transmitter and the receiver. Several signal propagation models exist that can be used for distance estimation. (Zafari, Gkelias & Leung, 2019)

For device-based localization, trilateration or N-point lateration is required. It means that at least three reference points are used. The distance between the user device and each reference point is calculated, and based on these measurements, the location of the user can be calculated using geometry. However, for proximity-based services, where only the distance of the user from a certain point is of interest, only one single reference node is enough. (Zafari, Gkelias & Leung, 2019)

The model is simple and cost-efficient, but it has some drawbacks regarding accuracy. Especially when there is no line-of-sight and there is additional noise and multipath fading, the localization accuracy is quite poor. (Zafari, Gkelias & Leung, 2019)

2.2.2 Time of Flight (ToF)

Time of Flight (ToF), also called Time of Arrival, measures the time it took for the signal to arrive from the transmitter to the receiver. The position is then estimated according to a calculation that exploits the speed of the wave through air. In order for the ToF method to yield accurate estimates, the transmitter and receiver need to be strictly synchronized with each other. Depending on the communication protocol, the signal is often transmitted together with a timestamp that makes it possible to measure the time of flight as accurately as possible. (Zafari, Gkelias & Leung, 2019; Ojo et al., 2022)

The ToF technique has issues in non-line-of-sight situations that are difficult to mitigate. Without a line of sight, the signal needs to travel a longer way to reach the receiver, which increases the time taken. Thus, the localization accuracy suffers. Other factors affecting the

accuracy are the signal bandwidth and the sampling rate. Low sampling rate reduces the accuracy because the signal may arrive in between the sampled intervals. A larger sampling rate and bandwidth result in a better quality of ToF estimation. (Zafari, Gkelias & Leung, 2019; Ojo et al., 2022)

2.2.3 Angle of Arrival (AoA)

In the Angle of Arrival (AoA) technique, arrays of antennae are used on the receiver side in order to estimate the angle at which the signal arrives. The time difference between the signal arrival at the different elements of the antennae array is used to estimate the angle at which the signal arrives at the receiver. (Zafari, Gkelias & Leung, 2019)

The technique works well when the distance between the transmitter and receiver is small. However, if they are far away from each other, small errors in the angle estimation can result in large errors in the actual location estimate. In indoor environments, multipath effects also make the estimation of the angle challenging. (Zafari, Gkelias & Leung, 2019)

2.2.4 Channel State Information (CSI)

Channel state information (CSI) is a more reliable representation of the wireless channel compared to RSSI. The principle of the CSI technique is that the receiver obtains an estimate of the wireless channel through channel sounding. In practice, it means that a training sequence known to both the transmitter and receiver is sent, and the channel state information is obtained from that. Once the CSI is known, it can be used to cancel out deterioration in the actual signal. (Tadayon et al., 2019)

CSI can characterize multipath fading, unlike RSSI. To characterize the individual paths, the wireless channel is modeled as a temporal linear filter called Channel Impulse Response (CIR). In the frequency domain, frequency-selective multipath fading happens. The Fourier pair of Channel Impulse Response is called Channel Frequency Response (CFR), which resolves frequency-selective fading. (Yang, Zhou & Y. Liu, 2013)

CSI can be used together with both range estimation, meaning time-or power-based estimations, or angle of arrival estimation. In research, CSI paired with AoA has achieved the best outcomes. Tadayon et al. (2019) demonstrate that using it with ToA measurements can also result in on-par accuracies.

2.2.5 Two-Way Ranging (TWR)

Two-Way Ranging (TWR) is a frequently used method for distance estimation and localization. It is based on ToF information between two tranceiver nodes. Tranceivers are devices

that can work as both signal transmitters and receivers. The advantage of TWR is that the clocks of the devices do not need to be synchronized. Two most common types of TWR are Single-Sided Two-Way Ranging (SS-TWR) and Double-Sided Two-Way Ranging (DS-TWR).

In SS-TWR, one of the nodes initiates the ranging exchange. It sends a signal to the responder, and when the responder receives it, the responder sends a signal back. When the general reply time delay of the responder hardware is known, the time of flight can be calculated. Then, the distance between the nodes is calculated based on the time of flight and the speed of the signal. (Lian Sang et al., 2019)

DS-TWR works with the same principle as SS-TWR, measuring signal round-trip time to estimate distance between devices. However, it has an additional message exchange. The initiator sends a ranging request and the responder replies with a message including timestamp information. After that, the initiator replies with a final message with its own timestamps. (Lian Sang et al., 2019) DW-TWR is more accurate than SS-TWR because it handles asymmetric delays better.

2.2.6 Fingerprinting

Fingerprinting technique for localization requires a scene analysis, which is an environmental survey to gather features of the environment where the localization system shall be used. The technique consists of an offline phase and an online phase. During the offline phase, RSSI or CSI measurements called fingerprints are collected. In the online phase, when the system is in use, the real-time measurements are compared against the fingerprints in order to estimate the user location. The signal measurements are used to map the user position on a discrete grid. Each point on the grid corresponds to one measurement in the offline phase in the beginning. (Zafari, Gkelias & Leung, 2019)

There are several possible algorithms that can be used to match the online measurements with the offline ones. Some typical methods for this include probabilistic methods Artificial Neural Networks (ANN), k-Nearest Neighbor (kNN) and Support Vector Machine (SVM). Probabilistic methods operate based on a likelihood estimation, predicting the location of the user by determining which location is the most likely given the signal measurements. They are only able to map user positions directly to the exact same points that have been used in the grid in the offline phase. This leads to some challenges, as when the grid has few points, the possible estimations are far from each other and estimation errors are unavoidable. However, if the grid has a lot of measurement points, the issue is that the difference of signal strengths between neighboring points can become smaller than the typical indoor signal variation.

The other three mentioned methods can also estimate the user location to be in between the offline measuring points. The challenge of choosing the number of offline measuring points, however, remains. (Zafari, Gkelias & Leung, 2019)

3 Methodology

This chapter describes the methodology used in the thesis. The overarching methodology is called design science research (DSR), which is covered in chapter 3.1. Chapter 3.2 discusses semi-structured interviews and Braun and Clarke six step method for thematic analysis that has been used for requirements gathering.

3.1 Design Science Research

This thesis follows Pfeffers et al. Peffers et al. (2006) design science research methodology. It was chosen because the goal of the thesis is to design, develop and evaluate proof of concept solutions for a real-world industrial problem. Design science research provides an iterative and structured framework to conduct such a development process scientifically.

The framework describes a process consisting of six activities. Figure 1 illustrates the process. Problem identification and motivation is the step where the problem is defined and its importance is justified. The objectives of a solution are inferred from the problem. In the design and development activity, an artifact is developed as a solution to the problem. An artifact can be any object that addresses the identified problem, such as a prototype, software system or a conceptual model. In this thesis, the proof of concept solutions are the artifacts. Demonstration means that the artifact is used to solve the problem and demonstrated, for example, through experimentation, prototyping or case study. In the evaluation activity, the effectiveness of the artifact is assessed. Finally, communication refers to the scientific or professional publications of the results. (Peffers et al., 2006)

The design science research process is inherently iterative and flexible. It does not need to follow a strict sequential order from problem identification and motivation to communication. Instead, it has four possible entry points for research. The problem-centered approach begins by identifying a real world problem and using it as a starting point for the deriving objectives and designing a solution for the problem. The objective-centered solution starts when the goals of the solution are already known, and the research focuses on building an artifact that meets those specific objectives. The design and development -centered approach is suitable when an artifact already exists and the research aims to improve or extend it. Finally, starting with observing a solution happens when the researchers analyze a practical solution that worked in order to generalize or scientifically validate the solution. (Peffers et al., 2006)

In this thesis, a problem centered approach is used. The research stems from the practical need to limit the access control of wireless HMIs in packaging machinery in order to ensure

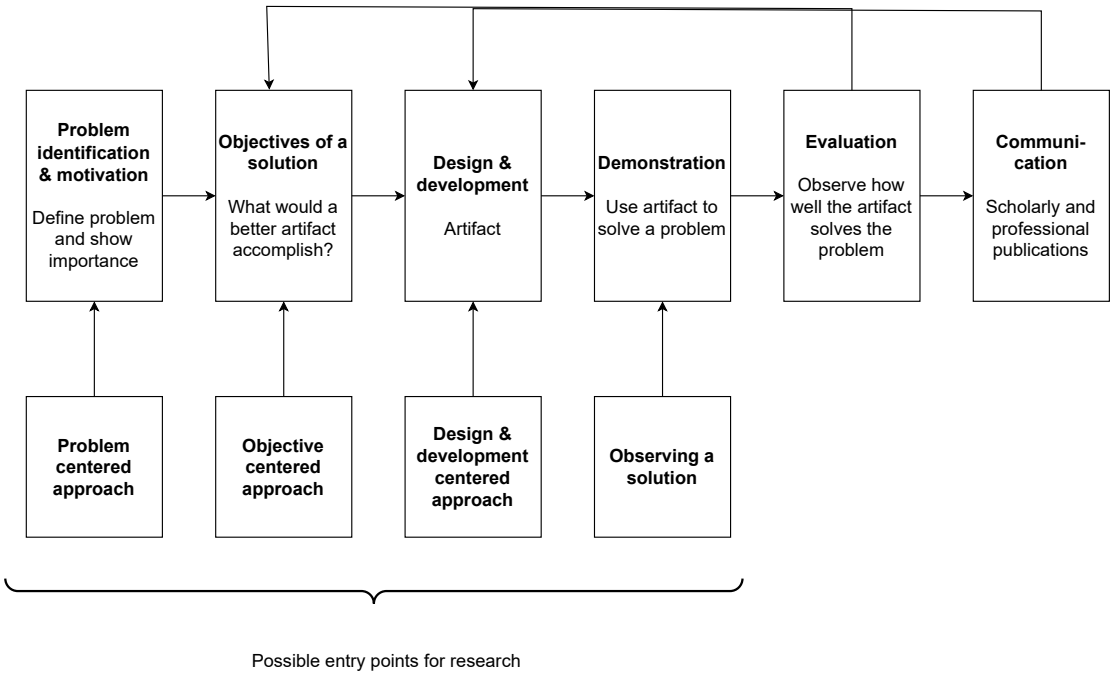

Figure 1: Design science research process (adapted from Peffers et al., 2006).

human and machine safety. This problem is described and formulated in chapter 1. To define the objectives of the solution, interviews are used to gather requirements. In the design and development phase, three promising technologies are chosen based on the requirements and a proof of concept is developed for each of them. In the demonstration phase, the PoCs are tested in a factory hall. In the evaluation phase, the solutions are compared both with each other and against the requirements. Finally, the written thesis serves as communication of the results. Table 2 summarizes which parts of the thesis process belong to each of the design science research process activities.

DSR Step	**Thesis Steps**
Problem Identification & Motivation	Background, research objectives and research question
Objectives of a Solution	Interviews, thematic analysis and deriving requirements from themes
Design & Development	Development of PoCs
Demonstration	Testing PoCs in a factory environment
Evaluation	Comparing PoCs with each other and against requirements
Communication	Written thesis

Table 2: Design Science Research steps in the thesis process.

3.2 Requirements Gathering by Semi-Structured Interviews

Requirements engineering is an important part of a software project. Studies show that more than 30 % of defects in software projects are caused by missing or faulty requirements. (Atoum et al., 2021) Understanding the requirements well is an essential part of the software engineering process. Because of this, before going into development, requirements for the solution were gathered.

In this master's thesis, semi-structured interviews are used for requirements gathering. In semi-structured interviews, the interviewer follows a predefined set of open-ended questions. However, the interviewer has the freedom to ask clarifying questions and explore emerging themes during the conversation. At the same time, the method gives some structure to the interview and also gives freedom to explore themes that arise spontaneously during the interview. (Ruslin et al., 2022)

Semi-structured interview fits this research because it allows flexibility in conversation. Each of the interview participants is an expert in the field of packaging machinery but looks at the topic of a wireless HMI from their own unique perspective. The predefined questions of a semi-structured interview make sure the participants consider all of the relevant aspects related to functional and non-functional requirements. At the same time, novel ideas and requirements that have not been anticipated in advance can be explored more in depth. The format also allows the interview to be tailored for each interviewee, to focus more on their areas of expertise.

To analyze the answers, the Braun and Clarke six-phase method for thematic analysis is used. Thematic analysis is a method for qualitative data analysis that aims to answer research questions by identifying patterns in the data set and organizing them into themes (Braun & Clarke, 2012). This method is commonly used and well-suited for exploring qualitative data, such as interviews.

Braun & Clarke (2012) divide thematic analysis into six distinct phases. In the first phase, the researcher familiarizes themselves with the data. It involves reading through the material and writing comments about it. In the second phase, initial codes for the data are generated. It is the beginning of the systematic analysis of the data. Codes provide a label for a feature in the data that can potentially be relevant to the research question. The phase ends when all potentially relevant excerpts from the material have been coded. In the third stage, the researcher searches for themes. The coded data is reviewed in order to identify similarity and overlaps between codes. Those similar codes are then clustered into themes. In phase 4, the potential themes developed in the previous step are reviewed through a recursive process.

In phase 5, the themes are defined and named. The final step is producing a report. (Braun & Clarke, 2012)

4 Interview Results and Thematic Analysis

Semi-structured interviews were conducted in order to gather requirements for the geofencing solution. This chapter explains the interview process and decisions that have been made, as well as introduces the themes that have been identified in the data. Chapter 4.1 delves into the process of thematic analysis. Chapters 4.2 and 4.3 analyze the identified themes. In the last subchapter 4.4, the requirements for the solution are then derived based on the thematic analysis.

4.1 Analysis Process

In total, four semi-structured interviews were conducted to gather requirements. In order to have different perspectives, people from different backgrounds were interviewed. When selecting the interviewees, it was important that we can cover all relevant aspects in the interviews and that the interviewees have sufficient domain knowledge of the questions they are asked. Three main focus areas were identified. As the most important reason for the geofencing solution is personal and machine safety, possible risks and ways to mitigate them were one focal point of the interviews. The second focus was on the factory environment. When operating industrial packaging machinery, the factory hall typically has many disturbances. The interviews aimed to explore the challenges of the environment from the perspectives of the user and the machine. The third focal point was technical details and restrictions. To have a good overview of each of these areas, interviewees with experience in either security, software engineering, commissioning or a combination of these were selected. The interviews were tailored for each participant, but the most fundamental questions were common to everyone.

The interviews were analyzed with the Braun and Clarke six-phase method for thematic analysis (Braun & Clarke, 2012) introduced in chapter 2 of this thesis. Each interview was recorded for the analysis. Next, the process is described more in depth.

Phase 1, familiarization: The first phase of the thematic analysis included getting familiar with the data by listening to and transcribing it. After all of the interviews had been transcribed, the transcripts were read through to form a better overview of the general topics of the interviews.

Phase 2, coding the data: In the coding phase, each transcript was gone through manually. Coding was done in an inductive manner, without predefined codes or a theoretical framework. An inductive approach was chosen so that the initial coding process could be guided by the data rather than any presumptions. Each potentially relevant point in the interviews

was marked. It was then examined to decide whether it fits into one of the previous codes, or if a new label has to be written for it. A total of 10 initial themes were identified across the interviews.

Phase 3, grouping codes into initial themes: When the codes were grouped into initial themes, the approach was switched from inductive to deductive. As stated in literature about thematic analysis, the themes should answer the research question. In this thesis, the themes answer the second research question in particular: What requirements need to be considered in developing a geofencing solution for a factory environment? Since the goal is to find requirements, a deductive approach for themes was used. First, themes were divided into so-called functional and non-functional themes, to reflect the distinction between functional and non-functional requirements. The Volere template (S. Robertson & J. Robertson, 2006) was used in order to further categorize non-functional themes. For functional requirements, few classifications, such as (Sharma & Biswas, 2015) and (Ghazarian, 2012), exist in the literature. They are not as established as classifications of non-functional requirements, and oftentimes they only fit certain types of applications. Because of this, the functional themes do not follow a predefined framework as the non-functional themes.

Phases 4 and 5, reviewing and defining themes: In the fourth phase of thematic analysis, the themes were reviewed. Two initial themes were discarded because they felt too vague or did not have enough content. One of them was called “Make machine connectivity easy for user”. While it is an important aspect of a user-friendly wireless application, it was not an important enough part of the interviews to constitute a separate requirement. Instead, the topics are more implicitly discussed under other themes. The other discarded theme was related to maintainability and support, and it was called “Easy to Integrate at Customer Site”. The theme was merged with another one and discussed under “Always Ready and Reliable”.

Phase 6, writing the report: Writing each theme further clarified which themes were important and which did not include enough content. From this stage, the process went iteratively back to phases 4 and 5 when a theme with not enough data to support it was identified in the writing process.

The following subchapters introduce the functional and non-functional themes. The themes explain which ideas and concerns the interviewees have about the geofencing solution, and which common topics emerged across the interviews. However, they do not yet contain properly defined requirements. Therefore, in the last subchapter, the main requirements based on the thematic analysis are defined and prioritized. The requirements are used at the end of the thesis to compare the PoCs of different technologies against the requirements for the solution.

The interviews were conducted in German. The quotes used in the analysis have been translated into English based on the transcripts, and the original quotes can be found in the appendix 2.

4.2 Functional Themes

This section introduces the themes that have been crafted by concentrating on the functional requirements of the solution and common functional themes in the interviews. Even though the thematic analysis process starts from the division into functional and non-functional themes, this does not mean that everything discussed inside this section finally belongs to functional requirements.

4.2.1 Restrict Functions only when Needed

This theme covers the core functionality expected from the geofencing solution. The main purpose of the solution is to restrict certain functionalities when the user cannot see and have an overview of the whole machine. The ideas of the interviewees were very uniform on this theme. All interviewees agreed on which functionalities should be restricted and when.

The most important requirement for the geofencing solution appeared to be preventing the user from actuating the machine when they are not in proximity. The interviewees emphasized the importance of a line of sight between the user and the machine.

> *"This needs to be followed as the basic principle: when you start actions, set actuators into motion, you must always be in front of the machine, and that needs to be ensured. [...] As soon as it [the machine] is no longer in the field of vision, the function is immediately restricted."* (respondent 3)

The idea behind this is to restrict all functions in the HMI that can potentially be harmful to people or the environment in the factory when the user is not able to supervise the machine. Another interviewee delved deeper into what is included under the term actuation. The most obvious case is starting the machine operation. However, machines not only have moving functions, but there could be, for example, lasers, suction systems or heating. The operation of all of these should be forbidden when the user is away from the machine. Some interviewees were talking about the need of having the machine in the field of sight from a practical user-centric perspective, while others reasoned for that requirement with laws and regulations. In practice, the user needs to be able to clearly see and check the whole machine before actuating it, which requires the user to be positioned in a way that they can have an overview of the whole machine.

As described by several people, the area where the user is able to see the whole machine may be different around different machines, ranging up to approximately 10 meters from the machine. Thus, the geofence should not be a hardcoded boundary but rather be configurable for various machines and layouts in a factory. When asked about the largest permissible error in positioning, the answers ranged from the stricter half a meter to the more generous two meters. Two respondents talked about the idea of having a security margin where it is not safe to use the machine anymore because the user may or may not actually be inside the geofence, depending on the current circumstances and possible disturbances around the machine. In this thesis, 2 meters is considered the desired maximum error tolerance. In case of a higher accuracy, the security margin can be smaller, allowing for a larger geofence.

After explaining what needs to be restricted, most of the interviewees proceeded to express their opinions about the functionalities that can be safely used from afar. There was a consensus that visualization and reading information does not need to be restricted.

> *"We can read information, some kind of statistical information about the machine. Nothing speaks against it."* (respondent 2)

As Interviewee 2 stated, there is no risk in accessing data about the machine even outside the geofence. Some interviewees even saw it as beneficial, as it would offer even greater flexibility.

Another topic in the interviews was whether the machine should stop if the user leaves the geofenced area or if it should continue to run. Again, the answers reflected the theme "Restrict functions only when needed".

> *"The machine should continue to run exactly the same, and on the control panel you should see clearly that you cannot perform the action anymore, that you are outside of this area."* (respondent 4)

Often, packaging machines are built so that there is no need for constant supervision. This applies regardless of whether the HMI is wireless or fixed to the machine. In such situations, the operator can leave the machine in proximity without concern. In order to ensure smooth operation, the interviewees leaned towards letting the machine run when the HMI panel leaves the geofenced area. As stopping is not necessary, it could both disturb the production flow in the factory and require special focus on safe stopping mechanisms.

4.2.2 Connect to and Control the Correct Machine

The theme "Connect to and control the correct machine" deals with the fact that there are often several packaging machines in one packaging line, and they may be close to each other. This is a factor that needs to be considered when developing a geofencing solution. It was one of the most important concerns that the interviewees had about the wireless HMI and geofencing.

> *"So a security risk is [...] the misinterpretation that one says you are at the wrong machine, so it has assigned you incorrectly. I am now at station 4 and not 5, or machine 4 and 5, and something moves on the other side where someone might be currently working."* (respondent 1)

The theme was mentioned in interviews in relation to both safety and operational aspects. The safety viewpoint is concerned with if the operator thinks the machine is safe to use but is in fact looking at a different machine. The operational aspects include, for example, changing the parameters of the wrong machine. That can lead to confusion, and wasted products and time. Thus, it is necessary that the user can be sure of which machine they are connected to.

Regarding this topic, different ideas of how to ensure that the operator know exactly which machine they are operating, came up. Visual or technological solutions were recommended, allowing the user to make sure which machine they are facing.

> *"So in my opinion, what geofencing should also do is offer the possibility to say that the device is also facing the machine. So in my opinion, if two machines are facing each other and the operator is unsure which machine they are now setting up, it is either visible somewhere by a color, but also by a double check."* (respondent 3)

Depending on the decision on how the problem will be solved, it may be a hardware or software solution. For example, HMI panels and machines could have a visual indication of pairing, or there could be a software solution that ensures that the user is turned in the correct direction.

The theme also covers the access control of multiple users. Sometimes, several operators may try to use the machine at the same time. This can happen if there are multiple working stations at the same machine, or with a wireless HMI several panels that can control the same machine. Several interviewees voiced their concern about this. When developing a solution with wireless HMIs, this needs to be considered if multiple HMIs can connect to the same

machine.

> *"What do you do if there are two operators? Who then has the rights? [...] You should not be allowed to operate on both [operating stations], you always have to switch. You should not be able to operate on both because otherwise it can be that one person wants one thing and the other one something else, and they contradict each other."* (respondent 1)

The European Union Directive 2006/42/EC (European Union, 2006) also states that if machinery has several starting control devices and two operators could put each other in danger, the devices must be fitted to rule out such situations. In practice in packaging machinery, this means that only one operating station is allowed to be active at a time.

4.3 Non-Functional Themes

This section discusses the themes that arose in the interviews about non-functional requirements and wishes. The Volere template (S. Robertson & J. Robertson, 2006) cathegories for non-functional requirements have been used to guide the process of grouping the codes into themes.

4.3.1 Safe and Secure for User and Machine

Safety is the main reason for developing the geofencing solution in the case company. Based on the interviews, safety can be divided into two parts: personal safety and machine safety. As a related concept, security is also an important one, as most geofencing technologies rely on communication technology.

Personal safety is related to everything that could be dangerous to the user while operating the machine. An interviewee described how personal safety is present in the discussions with customers as follows.

> *"We have a lot of discussions with our customers about safety, about hypothetical things. [For example,] somewhere, you could get your finger or hand caught there."* (respondent 1)

The topic of personal safety includes all types of injuries that could happen in the factory. In the interviews, further examples of personal safety hazards were named, such as burns from heating or injuries caused by machine parts falling on a user after releasing the brakes. The second aspect of safety, machine safety, is about ensuring that the machines are built and installed in a way that does not cause safety risks to the machinery or its users. Thus, it is

important for machine safety that the equipment itself is also safe from breaking. Two of the interviewees explicitly mentioned this distinction between personal and machine safety. There is a certain overlap between personal and machine safety. Machine design and safety features also play a key role in personal safety and preventing hazardous situations.

As stated by an interviewee, the base requirements for the machine should be the same with or without a wireless HMI. Most safety functions are implemented in other parts of machinery and software, but the possibility for the user to move away from the machine brings new safety concerns that need to be considered. Actuating and stopping a machine were described as the most critical points for safety. In the case of packaging machinery, actuating refers to initiating movement, starting the machine or enabling other functions such as heating.

> *"So I just want to briefly address the two main focal points of personal safety. One is actuating the machine. [Explains what actuating includes.] And the second point is exactly the opposite of actuating, namely stopping the machine in case of emergency, that is an emergency stop."* (Respondent 2)

The European Union Directive 2006/42/EC defines certain boundary conditions for starting and stopping a machine. The machinery directive, for example, requires that each workstation needs to have a stop button and that the machinery must include additional emergency stop devices. (European Union, 2006) In a machine with wireless HMI, the same level of safety and compliance with the safety regulations needs to be achieved even when the operator is not directly at the machine. This came up in the interviews, for example, when participants pondered the placement of emergency stops and the size of the geofenced area.

> *"And so there will be a guarantee that you can keep an eye on the machine, that you are also close enough to an emergency stop or have the possibility to press an emergency stop if something happens. How you would have that if you were at the machine."* (respondent 4)

Security is another concern that appeared in the interviews. The participants expressed their thoughts on the possibility of tampering with the system or unauthorized connections to the machine. These concerns were especially raised while talking about the idea that customers could use their existing mobile devices to control the machines.

> *"The devices need to also fill the relevant security standards, so that an attack can't break the connection or attack the machine in any way. And as soon as you are connected to the Internet, it is a different situation than now."*(respondent 4)

In addition to external attacks, manipulation by the user was a source of concern. For example, the possibility for the user to manipulate the system and easily detach the geofencing component from the HMI or machine was seen as a potential issue.

> *"In any case, it should be ensured that the geofencing cannot be manipulated, that somehow, let's say, another device is paired, and you leave it there and walk away with the HMI. So if it [the geofencing device] is just stuck on and the counterpart goes to the wireless HMI, then you can unscrew it and leave it on the machine, and then you can move away with the HMI."* (respondent 3)

Regarding user manipulation, the main worry was the machinery and hardware, and if their connections can be somehow falsified. For example, as in the previous quote, some interviewees expressed concern about geofencing solutions where the communication component is easily detachable from the machine or the wireless HMI. Those types of solutions make it easy for the user to bypass safety regulations, and depending on the implementation, the parts could even disattach by accident. This raises questions about liability in case of accidents and compliance to safety regulations.

4.3.2 Designed for Human Intuition

This theme is about the intuitiveness and user-friendliness of the geofencing component. It is related to the "usability and humanity" category of non-functional requirements. Several interviewees brought up intuitiveness as an important quality of the system. Training in form of guides was recommended in order to improve the learnability of the new features.

Apart from generic HMI usability themes, clear user feedback of remote functions came up in several interviews. Some interviewees proposed different ways of giving multimodal feedback to the user. For example, an interviewee gave an example of how some cars make noises when the doors are opened remotely, and how the packaging machines could work in a similar way.

> *"And that could be similar with the machine, that the machine can be started from 3 or 5 meters distance, but then it beeps, to be sure."* (respondent 2)

Several interviewees think that these types of suggestions about noise confirmations or alternatively visual cues from the machines, such as blinking lights, would make it easier for the user to understand the remote functionalities. In the previous example, the extra confirmation from the machine would ensure the user that they are operating the correct machine. Another interviewee suggested a multimodal feedback from the HMI when the user leaves the geofenced area, in case that they are not actively looking at the HMI screen.

> *"I would also prefer if the thing would vibrate or so, so that when he [operator] walks away with it under the arm, then it carries out such a vibration like a cell phone."* (respondent 3)

While sound feedback was discussed positively, it was also mentioned that factories can be quite noisy environments and tones may not be heard by the operator. For that reason, interviewee 3 suggested vibration of the device instead of, for example, a notification tone. Thus, the human-machine interaction between the user and the HMI panel, as well as between the user and the packaging machine need to be well thought out with the characteristics of the environment in mind.

4.3.3 Built for the Factory Environment

This theme takes a deeper look into the characteristics of the factory environment, mainly from the system perspective. As discovered in the literature review, most technologies for indoor positioning systems work the best in line-of-sight conditions. Many of them use electromagnetic signals and are thus prone to interference. A typical factory has a lot of different obstacles and interferences that can decrease the accuracy of indoor positioning. Some technologies are more and some less affected by such disturbances. However, no matter the chosen technology, obstacles and interference need to be considered in the geofencing solution.

One thing that needs to be considered are physical obstacles. In the factory, they can be anything from walls to moving people and vehicles like forklifts. The packaging machines themselves are often large and can break the line of sight between a signal sender and receiver. Normally, there are also other machinery in the same space.

> *"It should be made sure it works if there is something in between. So what it looks like if there is some privacy wall in between, for example. Or a metal grid as protective fencing."* (respondent 2)

When talking about physical obstacles, there is also the question whether the person can see through the obstacle and or if their overview of the machine is compromised. For example, a brick wall between should prevent the person from using the machine, but a metal grid or another worker passing by is not an issue.

Electromagnetic interference is another important theme that is possibly even trickier than physical obstacles. In general, the topic of obstacles and interference was seen as one of the most important themes in geofencing. It came up in each interview, also in ones where it was not explicitly asked about. It is likely to be one of the most challenging parts about making

geofencing work in a factory.

> *"Yeah, I think that probably the most difficult theme with geofencing is that one can actually set limits that are then still secure despite interferences."* (respondent 4)

Most technologies for indoor localization are based on electrical signals. Thus, electromagnetic interference creates difficulties. When determining the distances between the HMI panel and signal senders, interference easily decreases the quality of the position estimate. The sources of those interferences are often other communication technologies used in the factory. Reflections and multipath effects also deteriorate the quality of position estimates from received signals. One interviewee named an important requirement as follows.

> *"And if there are electromagnetic reflections in some form, that this system is also not misled."* (respondent 2)

As it is an important requirement for the system that it should work reliably despite interference and obstacles, this means that the software needs to take these factors into account. It needs to have mechanisms in place that detect outliers in signals and compensate for interference. The same machine can also be used in several different environments, where the sources and strengths of interference are not exactly the same. Apart from the previously mentioned types of interference, the materials of the machines and packaging materials can create static electricity when they are moving.

> *"So you see, actually everything is made of metal. Metal causes interferences. Then we have foil here, our plastic foil. Then all the plastic bands that move."* (respondent 1)

4.3.4 Always Ready and Reliable

The theme "Always ready and reliable" is concerned with the continuity of work in the factory. With a fixed panel on the machine, it is easier to ensure continuous availability than with a wireless HMI. With a wireless solution, there might be issues such as lost connection or incorrect geofencing results that prevent the operator from using the machine even when they are inside the geofence.

> *"It should be offline, so that means, for example, GPS or something like that doesn't work there when you are in the hall, and sometimes there is no GSM reception, so no cell phone network and nothing."* (respondent 1)

As seen in the quote, there are some expectations for the geofencing component in order for it to fulfill the requirement of continuous production. The technology should be reliable enough so that it does not cause interruptions in the work. The initial connection and start of geofencing, for example, after a pause in production, should be quick and seamless.

For the same reason, many interviewees did not like the idea of a battery-based solution where some kind of signal senders are powered by batteries. Recharging or replacing a battery takes time and can stop production if it has been forgotten. In general, the interviewees wished for a solution that is effortless for the customer and does not require special maintenance efforts. However, in case something needs to be maintained or exchanged, it should be made easy for the customer.

> *"However, the spare part must make it possible for the customer to be able to replace it if it is defect and to be able to teach it again themselves and then integrate again. Not that they're stuck with production just because they're missing a certain tool to pair it with the HMI or something like that."* (respondent 3)

To ensure that the system with geofencing succeeds at providing the same level of reliability and continuity as a traditional HMI, all of these topics need to be considered. It may affect the choices of technology, as well as software design.

4.3.5 Compliant with Laws Around the World

Compliance with laws and regulations is essential in the production of packaging machinery. Remote control and technologies that enable geofencing add their own considerations from the compliance perspective. In the interviews, several different laws and regulations were mentioned. Many of them were related to machine design rules that need to be followed even with a wireless HMI and that pose restrictions to its design. Another regulatory topic that was often mentioned was laws around the possible positioning and geofencing technologies.

Most interviewees mentioned the European Union Machinery Directive 2006/42/EC and its impacts on things related to personal and machine safety, or design of the machine and HMI. As mentioned in earlier sections, the directive regulates things such as the design of start and stop buttons, the placement of emergency stops, and situations where a machine has several operating stations or HMIs. (European Union, 2006) The directive has to be considered when producing machinery for sale in the EU, but it is also often used as a benchmark for safety standards globally.

> *"In essence, it [the law(s) that need to be considered] is the machinery directive."* (respondent 2)

Other important laws mentioned were the laws about radio technology and electromagnetism. The allowed frequency bands for certain technologies vary from one country to another. For example, the used UWB channels are different in Europe, the USA, China, Japan, and Korea, with a couple of channels allowed in each of the mentioned countries and regions (Qorvo, 2021). Similar laws also exist for other radio technologies. Apart from that, the radiation that devices are allowed to emit is regulated in order to protect people (European Union, 2014).

> *"The radio frequencies are the decisive factor. Each country has approval for certain frequencies and radio standards. And here, you first need an overview, and the most broadly used standard should always be chosen."* (respondent 3)

The interviewees did not see data protection as an issue, since no personal data needs to be processed on the HMI. However, any solution involving personal data would be difficult from the perspective of data protection laws such as GDPR. For example, in a computer vision -based system, collecting video footage of the workers could conflict with GDPR requirements (reference). This highlights the importance of evaluating the technological scope of a planned solution and to consider the possible complications it might have.

The interviews revealed that the laws related to packaging machinery and possible geofencing technologies are diverse. Manufacturers who target a global market need to consider the different local legislations around the world. For example, the laws in Europe and the USA often differ from each other. For the geofencing project, machine design safety legislation and laws related to specific indoor localization technologies are important to consider.

4.3.6 Adds Value to the Customer

The most important part of any product is that it provides value to the user. In the interviews, it was also mentioned that the wireless HMI should provide the user with added value compared to a machine with a fixed HMI panel. This theme encompasses why the interviewees think that a wireless HMI with geofencing could bring added value to the customer, and what it needs to do to create value.

Important keywords that were mentioned in the interviews regarding added value were comfort, flexibility, and mobility. The HMI should be able to perform all of its usual functions as well as previously and additionally offer flexibility to the user.

> *"And that's why we need to fulfill the requirements as so far but with other conditions, for example with usability. [...] and then to offer a certain comfort."* (respondent 4)

The need for flexibility was reasoned with the fact that it can improve the visibility of the whole machine. Also, if the operator needs to work on a large machine in a certain position, for example working on a possible issue, they do not need to go back and forth between there and the HMI working station. Also, rotating the wireless HMI is easier than with a fixed work station, even though some have rotational arms.

> *"You can't always see everything from one point of view and it should offer him [the user] added value to be able to operate the machine from anywhere."* (respondent 3)

While designing and developing the geofencing component, the added value perspective should be kept in mind. This theme has two key points. One is that geofencing should not negatively impact the core functionality of the system and thus decrease its usefulness in other areas. The other one is that the system should be designed so that it offers mobility to the user, and the user can use it from different positions and angles, offering better visibility to machine parts or enabling the actuation of the machine directly from where the operator needs to be working.

4.4 Deriving Requirements from Themes

The interviews and themes identified in them were used as a source of initial requirements for the geofencing solution. Different types of requirements were identified, some of which are technological requirements relevant in the PoC phase and others are relevant only when developing a commercial product. The requirements gathered from the interviews are initial requirements that shall be refined later in the development process.

For the purposes of the thesis and the PoC development, the requirements are divided into four categories. First, a distinction is made between functional and non-functional requirements. Both of those categories are further divided into requirements relevant for the PoC stage, and requirements that are relevant only for the commercial product. As the scope of the thesis only covers the PoC stage and the comparison of technological solutions, this categorization allows us to concentrate on the correct requirements at this stage and to evaluate the finished PoCs to see how well they fulfill the requirements.

The requirements are prioritized with the MoSCoW method. The principle of the technique is that the requirements are classified into four priority categories: **Must have**, **Should have**, **Could have** and **Won't have**. The **Must have** category has all the requirements that are essential for the success of the project. **Should have** includes other high-priority features that are, however, not completely mandatory. **Could have** includes requirements that would

bring added value to the user but are not a high priority. Finally, the **Won't have** category has requirements that shall not be implemented at least in the current development stage. (Hudaib et al., 2018)

In table 3, the functional requirements that need to be considered in the development of PoC are specified. In terms of functional requirements, the main focus of that stage is in comparing the chosen technologies and how accurately they can locate whether the user is inside or outside the geofence. As found out in the interviews, a positioning error of less than 2 meters is desired. The geofencing problem is binary in its core: the user is either inside or outside the geofence. Thus, accurate localization inside or outside the geofence is not necessary. However, the boundaries of the geofence are the most critical areas where it is important that the classification boundary accurately describes the actual geofence. The system needs to be able to work offline. This is because there is often no cellular network or GPS signal inside a factory hall. Thus, it should be possible to accurately place the user inside or outside the geofence even if their end device does not have access to external networks.

Requirement ID	Description	Prioritization
F-01	Indicate to the user if they are outside of the geofenced area.	MUST
F-02	The decision boundary of the geofence must be defined with less than 2 meters error.	MUST
F-03	Enable configuring the geofence and positions of system components	SHOULD
F-04	Function offline, i.e. without GPS or cellular networks.	MUST

Table 3: Functional requirements to be considered in PoC stage

Table 4 specifies the functional requirements that must be considered in future product development. The main purpose of the geofencing solution is to disable the actuation functions when the operator is outside the geofenced area. This functionality is not considered in the PoC phase because the PoC concentrates on the technologies and what their possibilities, limitations and challenges are. Integration to the HMI with disabling and enabling correct functionalities is seen as a more trivial task that shall be performed once the technology has been chosen.

Table 5 includes the non-functional requirements that shall be considered while developing the PoC. Different interferences and obstacles in the factory environment were one of the most important topics in the interviews. A factory hall can potentially have a lot of disturbances. As the geofencing application is designed to be used in factories, it should be

Requirement ID	Description	Prioritization
F-05	Disable all actuation functions when the operator is not within the geofenced area.	MUST
F-06	Allow non-hazardous functions regardless of the location.	SHOULD
F-07	Prevent several people from controlling the same machine at the same time.	MUST
F-08	Ensure continuation of operation if the user steps outside the geofence.	SHOULD
F-09	Verify that the operator is turned towards the correct machine.	COULD
F-10	Provide multimodal feedback to user.	COULD

Table 4: Functional requirements to be considered in the product stage

robust against such disturbances. In the PoC development, this shall be taken into account by testing the technologies in a setting that resembles the real use case.

Requirement ID	Description	Prioritization
NF-01	The system shall be robust against electromagnetic interference.	MUST
NF-02	The system shall operate reliably despite physical obstacles.	MUST

Table 5: Non-functional requirements to be considered in PoC stage

Table 6 introduces the non-functional requirements that have been derived from the interviews but are not relevant in the PoC phase yet. We have decided that the main focus of the PoC should be on evaluating the technologies, and thus, the requirements related to legal aspects and intergation at customer site shall not be included yet.

Requirement ID	Description	Prioritization
NF-03	Adhere to EU machinery directive.	MUST
NF-04	Adhere to laws about radio frequency communication around the world.	MUST
NF-05	Integration at customer site should be possible in maximum 2 days.	SHOULD
NF-06	Provide the customer with necessary tools and knowledge to maintain the system if needed.	SHOULD

Table 6: Non-functional requirements to be considered in product stage

4.5 Technology Selection

All technologies covered in the literature review in chapter 2.1 were evaluated against the requirements based on findings from the literature. Based on their theoretical characteristics and alignment with the requirements, three promising technologies were chosen for the development of a PoC.

Several technologies were excluded from further development based on their limitations. First, computer vision was discarded as an unrealistic choice for this use case. A computer vision -based solution would likely suffer from portability issues. The integration at a customer site would require a lot of planning and engineering in advance, as well as on site, which is likely to conflict with the requirement NF-05. A computer vision -based system would require careful planning with the camera positions in order to maintain a line of sight condition as needed. The maintenance and equipment costs are high, and there seems to be no clear benefit for the specific use case. Furthermore, the use of personal data in form of images is problematic and against GDPR without a justified reason.

Inertial positioning systems are independent of external signals and obstacles, but they are not a suitable localization method on their own. As an inertial positioning system only gives the relative location of the user, the accuracy decreases over time without calibration. Thus, they do not fulfill the requirement of a certain accuracy F-02. However, inertial positioning systems could be used together with another type of technology to improve positioning accuracy. Several researchers have used them, for example, to enhance a BLE indoor positioning system.

Visual light communications would experience issues adhering to the accuracy and integrability requirements because the light distribution in different factories may differ significantly. Acoustic solutions were also discarded, as there are a lot of potential sources of noise in a factory setting, and they are partially unpredictable and may vary from one factory building to another. ZigBee was excluded due to a combination of limited mobile device compatibility and a lack of performance advantages over other technologies.

RFID was briefly considered as a candidate technology. However, a search for commercially available RFID devices and solutions for indoor localization revealed that the selection of viable options is limited. As supported by literature, RFID is not widely adopted for indoor localization purposes. Moreover, the available systems tend to be relatively expensive and primarily optimized for identification and asset tracking, which often has different requirements than our use case.

The chosen technologies for PoC development are BLE, Wi-Fi and UWB. BLE was chosen because it has native support on mobile devices and is fairly easy to integrate at a customer site. In research, errors around 2 meters or less have been achieved, suggesting that it might be possible to reach the required accuracy. Wi-Fi was chosen because it would be the cheapest option, as the existing Wi-Fi infrastructure in a factory can be utilized. While lower accuracy than with BLE was expected, if Wi-Fi could still meet the minimum requirement, it would become an attractive alternative due to the low cost. UWB was chosen as the third technology to compare. It is significantly more accurate than BLE and Wi-Fi, working on a different frequency band and typically with a different method.

5 Proof of Concept Implementation and Technical Results

For this thesis, three proofs of concept were developed, one for each of the chosen technologies: BLE, Wi-Fi, and UWB. The PoCs serve two purposes. Most importantly, they offer insights into how reliable each technology is and how realistic it would be to use it for geofencing for the case company's needs and use case. Apart from that, a simple architecture is built that can be expanded in the future for more experimentation and possibly product development purposes. This chapter explains the architecture, methods and test results of each PoC. First, the common software architecture is introduced. After that, the choices made for each individual technology, along with findings and test results, are discussed in separate subchapters.

5.1 Architecture

The first step in the PoC development was architecture design. The goal was to design an architecture that is modular and that can be used to evaluate all three technologies with minimal changes. Another goal of the architecture was that it should be easy to integrate into existing HMI and packaging machine lines. This would enable using the PoC as a basis for product development later and build on top of it.

BLE and Wi-Fi solutions share the same architecture, while the UWB architectural design differs from the other two technologies. BLE and Wi-Fi solution was built for an Android device, as the current HMI panels use Android as their operating system. However, the used test devices do not have UWB functionalities. Thus, dedicated UWB devices were used as both the tag and anchors.

5.1.1 BLE and Wi-Fi Architecture

The BLE and Wi-Fi PoC was developed for an Android device. In the PoC stage, only one end device was used, but in a finished product, it should be possible to integrate a whole line of packaging machines into the same architecture. It should also be possible to configure the placement of signal transmitters in the system, and each HMI device should be aware of them. Because of this, a web server architecture was designed. The server could communicate with several HMI devices if needed, and the API can be used as an interface with the existing system, to retrieve position information and decide which functionalities on the HMI stay available for the user.

Figure 2 shows the architecture diagram. The main building blocks of the PoC architecture are an Android application, web server, database, and a frontend where the user can see positioning results and configure transmitter information.

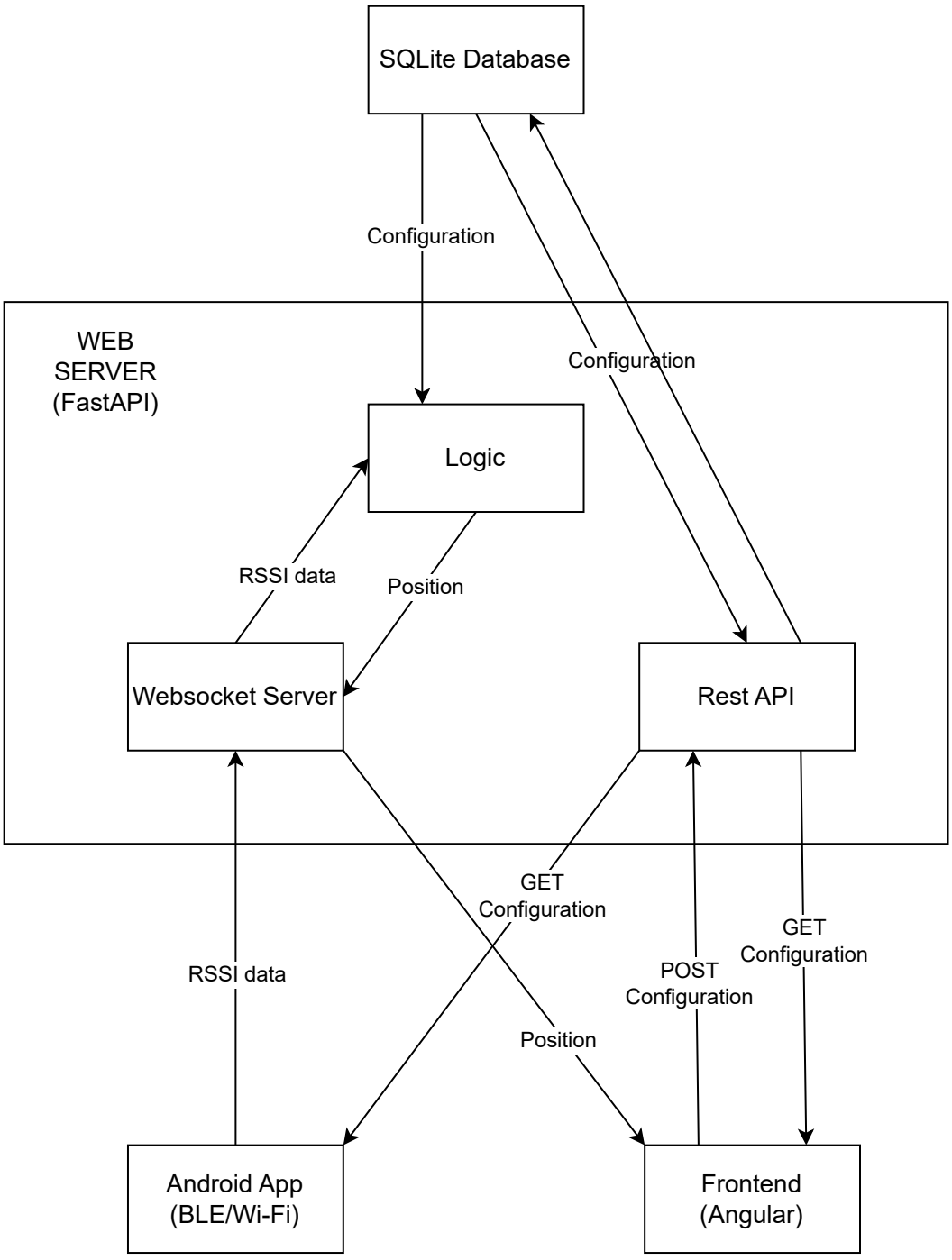

Figure 2: BLE and Wi-Fi architecture.

The Android application was kept as simple as possible, only performing essential activities, such as BLE or Wi-Fi scanning. It reads the RSSI data and sends it with a timestamp to the server for further processing. This fosters modularity, as only a minimal portion of the system

needs to be modified for each technology. The websocket client in the Android application always sends the received signal data to the server via websockets, along with a technology flag that specifies which technology the data has been captured with. On the server side, the Websocket server handles the messages differently depending on the technology.

The most important part of the system is the "Logic" block on the web server. It receives RSSI data from the Android application via web socket server, and the configurations including addresses and locations of transmitters from the database. Logic calculates the distances of each transmitter to the Android device. Based on the estimated distances, it then estimates the position of the user. The position is sent to the frontend where it is displayed.

Fast communication is needed between the end device and web server, so that position calculation can happen in a timely manner. Hard real-time functionality is not required, but a quick response to received signals is necessary to accurately track the user's position. Signal readings may be received several times a second. Due to this and the requirement for fast communication between the server and the end device, websockets are used for this communication. With web sockets, the client can maintain an open connection with the server and send the new received data with low overhead.

On the other hand, the system also includes information that needs to be sent from the server to a client only when the connection is initiated or when the web page is refreshed. This includes, for instance, sending the transmitter configurations to the clients so that the Android application knows the addresses of the transmitters and the frontend can display their information. For this, a REST API is more suitable than websockets, as it is a more efficient, simpler and less resource-intensive way for infrequent requests.

A frontend was developed with Typescript and Angular. In the frontend, it is possible to see the position estimates and change the configurations of the transmitters, including the addresses of the transmitters and their positions along x and y axes.

A database stores the configurations. When a websocket connection is initiated between the client in the Android application and the websocket server on the webserver, the server queries the configuration information in the database and sends it to the client.

To keep the architecture diagram 2 clear and easy to read, it includes only the connections that are significant for functionality. For analysis purposes, the RSSI data and estimated positions are also saved in the database. Old measurements are cleaned from the database when the web server is restarted.

5.1.2 UWB Architecture

As the test mobile devices do not include UWB, four DWM1001-DEV UWB tranceiver development boards were used, three as anchors and one as a tag. Figure 3 illustrates the UWB architecture.

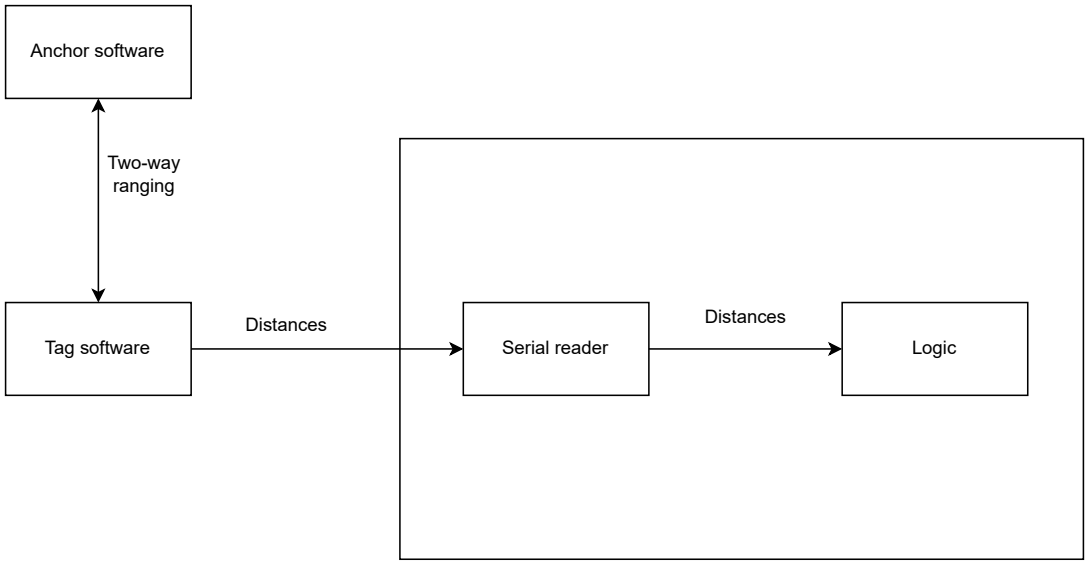

Figure 3: UWB architecture diagram.

Logic includes the same functions for positioning that are also used with BLE nd Wi-Fi. The difference is that the distance is already calculated in the user device. As the main logic is exactly the same for all technologies, it is possible to later integrate the UWB solution into the web server architecture described in the previous subchapter.

As the tag and anchor devices have distinct roles, two different pieces of embedded software were written for them. In figure 3, they are called tag and anchor software. The tag and anchors communicate with each other using two-way ranging. The tag initiates the ranging exchange and gets a response from the anchor. The tag calculates the distance based on how long time the ranging exchange took.

Currently, serial communication is used to transfer the distances from the embedded devices to a PC where the logic is executed. For this purpose, UART communication is set up in the tag software, and it inputs each distance with the corresponding anchor ID to the serial. The serial reader program on the PC listens to the correct serial port that the tag is connected to via USB cable and reads the information from there, calling the logic functions. Reading and logic happen in two separate threads so that they do not block each other. This simple architecture was used for the purposes of the thesis, as it allowed more time to be invested in verifying and testing the UWB technology. However, the solution can be integrated into the

web server in the future if needed.

5.2 Mathematical Basis

This subchapter describes the equations and calculations that have been used for positioning.

5.2.1 Distance Calculation Given RSSI

BLE and Wi-Fi PoCs are both based on the received signal strength. In literature, there are several examples of calculating the distance between a transmitter and receiver node based on RSSI. Sakphrom et al. (2021) and Li et al. (2018), among others, use the following formula for solving the problem.

$$d = 10^{\frac{A-\text{RSSI}}{10n}} \tag{1}$$

where d is the distance between the transmitter and receiver, A is the RSSI one meter away from the transmitter, $RSSI$ is the measured signal strength, and n is signal attenuation factor that captures how strongly the signal strength deteriorates with distance. The signal attenuation factor depends on the environment and should be estimated separately for each environment. In open air, the value of n is around 2, and in closed spaces a typical value is between 3 and 6, depending on how many disturbances and objects there are.

In this thesis, the localization is done in 2D because users always walk on the same plane, and it can be assumed that the HMI device is usually close to the same plane as well. The equation 1 works when the transmitters are also at the same height with the user's hands. However, if they are placed at a different height, such as high above the head, height needs to be considered in the formula. In the geofencing use cases on a packaging line, we can make the assumption that all transmitters are mounted at the same height.

When the transmitters are not at the same height with the receiver, Pythagorean theorem is used to find the distance on the floor. Figure 4 illustrates the geometrical problem. Tx refers to transmitter and Rx to receiver. h is the height difference between the transmitter and receiver, d the direct distance between them and x the horizontal distance.

For solving the horizontal distance d_{xy}, Pythagorean theorem is used as follows. It is assumed that the height d_z is known and the same for each transmitter.

$$d_{xy} = \sqrt{d^2 - d_z^2} \tag{2}$$

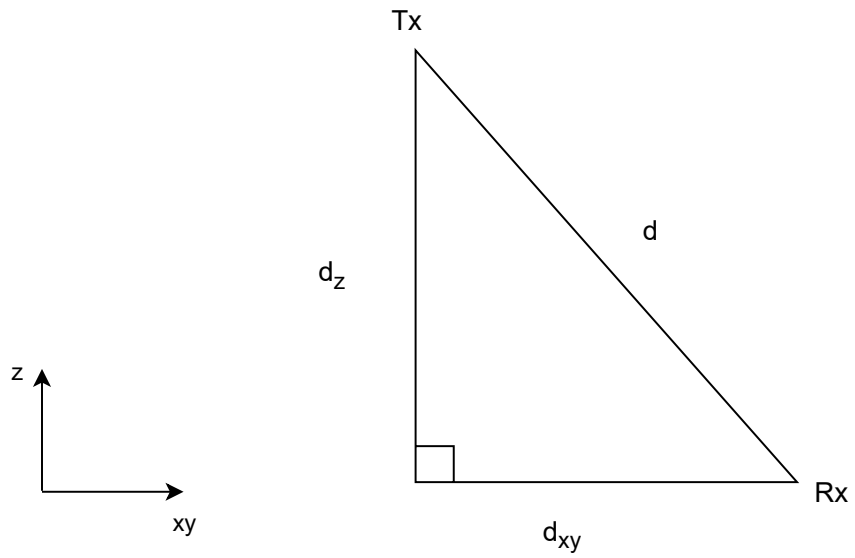

Figure 4: Pythagorean theorem is used when transmitter and receiver heights are different.

When we substitute d in the formula 2 with the right side of formula 1, we get the complete formula to calculate the horizontal distance.

$$d_{xy} = \sqrt{\left(10^{\frac{A-\text{RSSI}}{10n}}\right)^2 - d_z^2} \tag{3}$$

The first step in BLE and Wi-Fi solutions is to fit a model to find the most optimal value of n. The model used for optimization is based on equation 1. Different optimization methods exist, and the choise of a method depends, for example, on the distance at which we want the most optimal results. In this thesis, RSSI is measured at several reference points with equal spacings, and the optimization error aims to minimize the average error as shown in equation 4.

$$n = \arg\min_n \frac{1}{N} \sum_{i=1}^{N} \left| d_{i,\text{estimated}}(n) - d_{i,\text{actual}} \right| \tag{4}$$

where $d_{i,\text{estimated}}(n)$ is the estimated distance at the i-th reference point, computed using the signal attenuation factor n, and $d_{i,\text{actual}}$ is the corresponding real distance. The goal is to find the n that minimizes the mean error between the estimated and actual distances across all N reference points.

In several parts of the thesis, an average of several RSSI values is taken for model fitting or distance calculation. RSSI is expressed in dBm (decibel-milliwatts), which is an intrinsically logarithmic unit. Thus, to compute a more representative average, it is better to do the calculation in a linear scale. For this reason, RSSI is expressed in milliwatts (mW) using the equation 5. After that, the average is computed in the linear power units scale. Finally, the average is transformed back to dBm using the relationship in equation 6.

$$P = 10^{\frac{RSSI}{10}} \tag{5}$$

$$RSSI = 10\log_{10}(P) \tag{6}$$

5.2.2 Non-linear Least Squares for Positioning

Once the distances between the user device and each transmitter have been calculated, the next step is to calculate the position of the user. We are looking for a point in a 2D plane that best corresponds to the estimated distances to each transmitter. As the distance estimations usually have some error compared to the real distance between nodes, it is likely that there is no single solution that exactly matches each distance.

There are several algorithms for approximating solutions of overdetermined systems, with the least squares method being selected for this thesis. Li et al. (2018) describe it as a standard approach for such approximations and use it for indoor positioning with BLE. Whiles Li et al. (2018) among others linearize the problem, this thesis uses a non-linear least squares algorithm from Python SciPy library (SciPy, 2025). Both of the approaches were tested in the early stages of PoC development, and the non-linear least squares performed better with the type of noisy data captured in the factory hall. It is slower in terms of execution time, but still several orders of magnitude faster than the rate at which measurements are received.

On a high level, the least squares method can be formulated as follows. The goal is to minimize a residual function r so that the sum of the error is as small as possible.

$$[x,y]_{\text{estimated}} = \arg\min_{x,y} \sum_{i=1}^{n} (d_i - h)^2 \tag{7}$$

where

$$h_i(x,y) = \sqrt{(x-x_i)^2 + (y-y_i)^2} \tag{8}$$

In equations 7 and 8, the variables have the following meanings. $[x,y]_{\text{estimated}}$ is the estimated position of the user device. d_i is the measured distance between the user device and the transmitter i in the known position $[x_i,y_i]$. $h_i(x,y)$ is the predicted distance between the estimated position and the known transmitter position $[x_i,y_i]$. n is the number of transmitters.

5.2.3 Position Uncertainty Calculation

The previous step gives the estimated position of the user based on the estimated distances to each transmitter. Those distance measurements are subject to uncertainty resulting from noisy measurements, and it is interesting to understand how this uncertainty in the distance measurements affects the uncertainty in the position estimate. When geofencing, this information can give an insight into the confidence level that the user is inside the geofence. As distance errors have been calculated in several different distances and a model has been fitted to be able to get the standard error at any distance, this information can be used to propagate the uncertainty in each distance measurement into uncertainty in the position estimate.

The measurement model from equation 8 is used. Using Taylor approximation, the problem can be linearized around the estimated position. In particular, the Jacobian matrix of the measurement model with respect to the position is calculated.

$$H = \begin{bmatrix} H_1 \\ H_2 \\ \dots \\ H_n \end{bmatrix} \tag{9}$$

Each row of H_i of the Jacobian matrix H corresponds to the partial derivatives of the i-th distance measurement, between the user device and the transmitter i.

$$H_i = \begin{bmatrix} \frac{\partial d_i}{\partial x} & \frac{\partial d_i}{\partial y} \end{bmatrix} = \begin{bmatrix} \frac{x-x_i}{\sqrt{(x-x_i)^2+(y-y_i)^2}} & \frac{x-x_i}{\sqrt{(y-y_i)^2+(y-y_i)^2}} \end{bmatrix} \tag{10}$$

Finally, the uncertainty in distance estimations is propagated into uncertainty in the position estimate using a standard formula for uncertainty propagation estimation theory, as described by Simon (2006) This can be expressed as follows.

$$P_{xy} = \begin{bmatrix} \sigma_x & \sigma_{xy} \\ \sigma_{xy} & \sigma_y \end{bmatrix} = \begin{bmatrix} H^T & R^{-1} & H \end{bmatrix}^{-1} \tag{11}$$

where P_{xy} is the covariance matrix of the position estimate and R is the covariance matrix of the distance measurements.

$$R = \begin{bmatrix} \sigma_{d,1}^2 & & 0 \\ & \ddots & \\ 0 & & \sigma_{d,n}^2 \end{bmatrix} \tag{12}$$

where $\sigma_{d,i}^2$ is the variance of distance to beacon i given the estimated distance.

We are interested in the variance in x direction σ_x and y direction σ_x in the diagonal of the matrix P_{xy}.

5.3 BLE

BLE is typically used in localization either with RSSI or AoA information. As the goal is to develop an Android application, using AoA is not feasible, as mobile devices do not typically have the multiple antennae required to determine the angle of signal arrival. Thus, RSSI is used for this PoC. The hardware used for BLE are BlueUp USB beacons (BlueUp, 2025). The beacons were configured to send signals in the most frequent interval that they are capable of, which is every 100 milliseconds. The final PoC has been tested in a factory hall that resembles a real environment where the product would be used.

This chapter is further divided into sections “Absolute Positioning” and “Relative Positioning”. They each describe a different approach to geofencing with the mentioned BLE beacons. Both of them were tested in the factory, and their results are discussed in the respective chapters.

5.3.1 Absolute Positioning

The first approach for BLE positioning was based on absolute positioning, meaning that the algorithm attempts to localize the user to a specific point. 3 beacons were used for the tests.

First, signal strength at one meter (A) was obtained in the factory hall by continuously measuring the RSSI 1 meter from a BLE beacon, facing the beacon, and averaging the results. The approach described in formulas 5 and 6 for averaging RSSI was used, meaning that the

signal strength is first transformed into linear power scale, then averaged, and then transformed back into the logarithmic RSSI scale. A model was fitted to find the optimal signal attenuation factor n based on formula 4. For BLE, RSSI measurements were performed at distances of 1 to 9 meters from the beacon, at 1 meter intervals. The average RSSI at each distance was used to find the optimal n.

On the web frontend, the MAC addresses and positions of the beacons in the system can be configured. The Android application constantly scans for BLE signals from the specified MAC addresses, reads the RSSI and MAC address of the sending device. As soon as a signal has been received, the information is sent to the server.

The signal strength data is very noisy, and one measurement is not a very good indicator of how far the transmitter is. Because of this, various techniques for data pre-processing and weighting were tested. The worst outliers have been filtered out. However, when there are a maximum of 10 signals per second, only minimal outlier filtering is possible. Several methods for outlier detection were tested. The final choice was modified z-score with MAD scale estimator for its optimal balance between filtering out clear outliers and retaining the majority of the data, which suited the noisy test environment. Yaro et al. (2024) mention that the z-score with MAD scale estimator is less sensitive to extreme values in RSSI data.

Because the signal strengths vary a lot and there is a lot of noise in the measurements, a strategy of averaging the measurements from a certain time period has been developed. Different time windows were tested. There is a tradeoff between the higher accuracy of longer time windows and the closer to real-time tracking of the user with shorter time windows. Finally, a time window of 5 seconds was used in the tests. It was determined to be the longest still reasonable time, considering the typically slow movement when working on a machine. If signals from a longer time are averaged, the user can move too much during the time. Figure 5 demonstrates the positioning results over half a minute of standing still in the marked position, with a 5 second positioning time window.

Another tested strategy was to instead of the average RSSI work with the strongest RSSI from within a certain time frame. When the environment was especially noisy, this approach often led to better results. Otherwise, the averaging approach performed better. A higher number and density of beacons was also tested, but it did not lead to the desired improvement in accuracy.

The positions were calculated from the estimated distances between nodes by triangulation with non-linear least squares, as described in chapter 5.2.2. A weighted version of the least squares optimization was also tested because the shorter the estimated distance is, the more

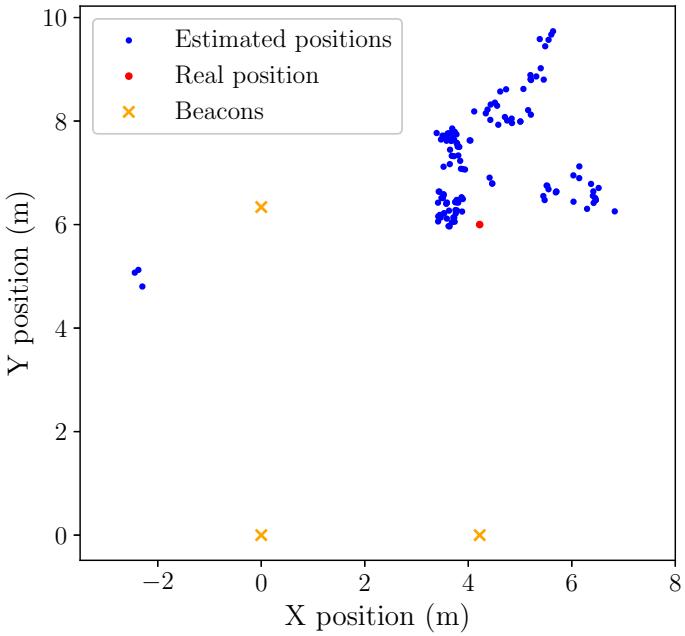

Figure 5: BLE positioning.

reliable it tends to be. Thus, higher weights were assigned to the beacons that were estimated to be the closest. This was tested with different magnitudes for the weights. However, weighting the results did not offer a clear advantage over the unweighted version.

As mentioned in the previous chapter, the values of the parameters A and n depend on the environment and the strength of the signals the beacons transmit. For example, in an open space, the signal attenuation factor is much smaller than in a tight space with obstacles and electromagnetic interferences. In the experiments in the factory hall, it was discovered that the amount of interferences changes from one moment to another. Figures 6 and 7 illustrate this. They show the same measurements performed on two different days, showing vastly different RSSI levels and variances. Some of those changes could be attributed to a specific change in the environment. For example, turning on a nearby machine increases disturbances and weakens the RSSI, which was also observed in the tests. The varying number of other devices with Bluetooth or Wi-Fi enabled, such as smart phones and wireless earphones, may also influence this. However, also a lot of unexpected signal deviation occurs, and many differences in measurements cannot be explained with known distractions.

Because of these kinds of changes in signal strength and amount of noise, it is not possible to fit one model that would always deliver quality results. When the parameters are fitted and used immediately for the current environment, an error of 2-3 meters has been achieved in the factory tests. However, the same parameters may result in up to 20 meters error on another day. Without a way to constantly calculate the noise level of the environment and

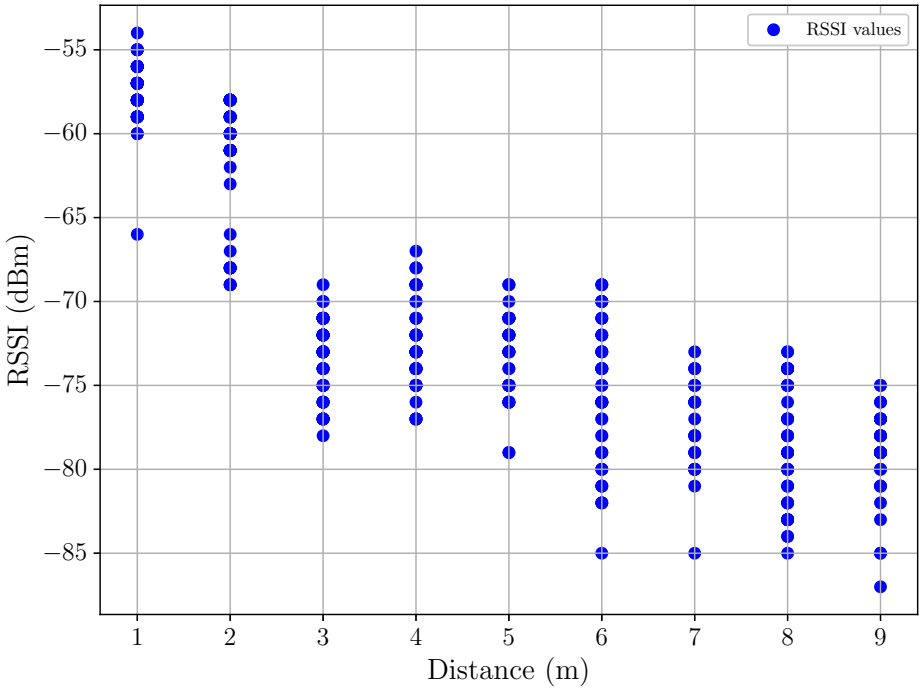

Figure 6: RSSI measurements in the factory on day 1.

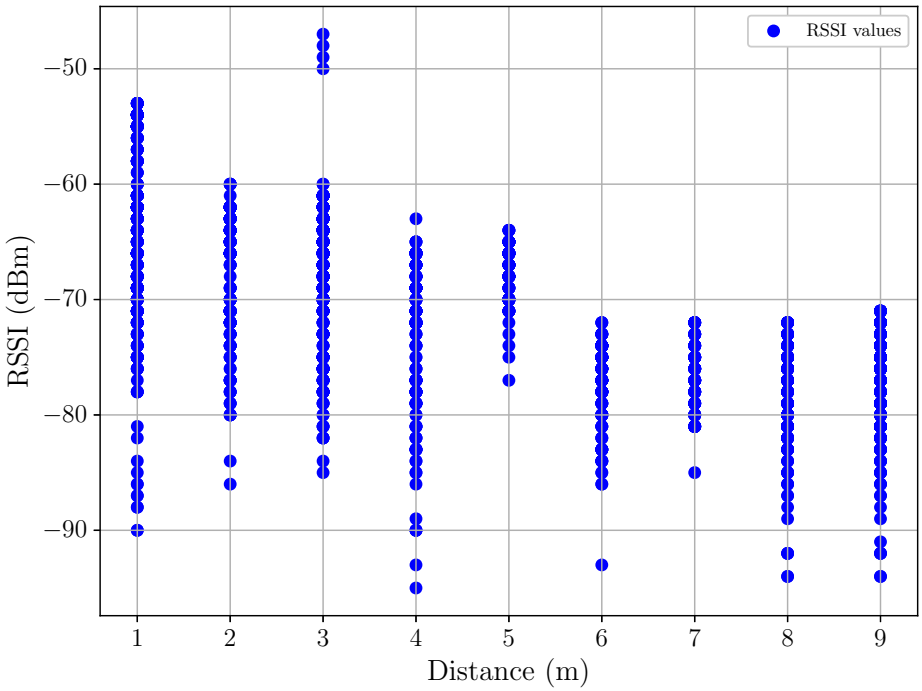

Figure 7: RSSI measurements in the factory on day 2.

update the model parameters, the solution is not safe to be used in a changing environment.

Mobile devices do not always receive each signal, and there are also differences between receiver devices. The differences can depend on operating system limitations and hardware attributes. In the testing, two mobile phones were used: Zebra Technologies TC27, and Samsung Galaxy A52s. The devices had significant differences in the received RSSI data. When the beacons had been configured to transmit 10 times per second, Samsung Galaxy A52s received approximately 5.8 signals per second on average in the factory, while Zebra Technologies TC27 received only 1.5 signals per second.

Another important issue is that signal strengths are affected a lot by whether there is a line of sight between the transmitter and receiver. Any obstacles between them significantly decrease the RSSI. This is especially tricky when the user is facing away from the BLE beacon and the line-of-sight is blocked by the user's body. The effect of user orientation was tested by standing 2 meters from a beacon and measuring the RSSI, first directly facing the beacon and then with the back turned towards the beacon. On average, the RSSI was 10.38 dBm stronger when facing the beacon. In an environment like in figure 6, this would roughly correspond to a 2 meter difference in the distance estimation.

5.3.2 Relative Positioning

Since absolute positioning was found to be extremely unreliable due to changes in the environment, another option for BLE geofencing was tested. In the second alternative, instead of the absolute signal strengths, the relative signal strengths were used. In practice, this means that the program compares the signal strengths of the transmitters with each other and based on that determines where it is located. The goal is not to get exact x and z coordinates. Instead, the area is first divided into quadrilateral bins. In each corner of the bins, there is one BLE beacon. The program compares the average signal strength of the beacons in each bin and determines the area where the user is based on which bin has the strongest average signal strength. Figure 8 illustrates the setup of the beacons and definition of bins in the test environment. The orange dots mark the beacon positions, and the numbered areas are bins.

This solution is more robust to external disturbances. When there are overall more disturbances in the environment, all signals tend to become weaker. When standing close to the middle of a bin and facing away from the other bins, the program was able to correctly classify the area 97.24 % of the time. However, when the user was directly facing another bin, the accuracy was only 66.01 %. It varied significantly depending on the bin, which suggests that the shape, size and obstacles inside bins have an important effect on the localization.

Furthermore, some of the same issues persist that were already noticed with absolute posi-

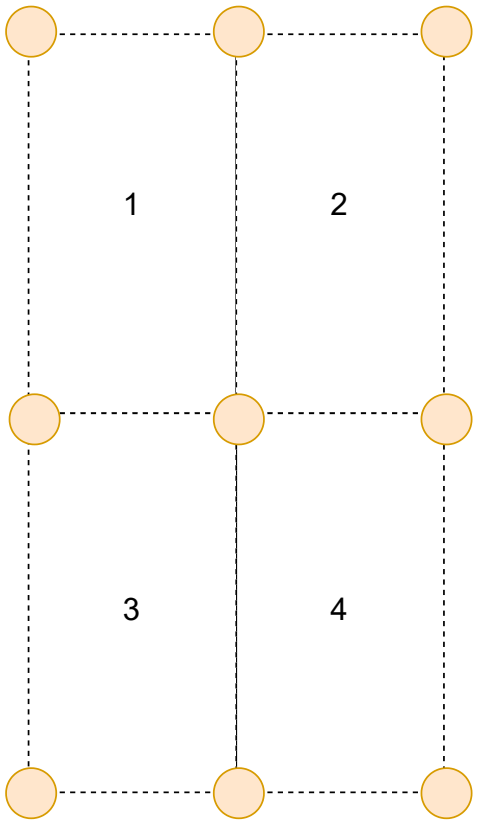

Figure 8: Relative positioning using bins.

tioning. For example, the orientation of the user influences the bin assignment. At equal distances, transmitters located in front of the user exhibit stronger RSSIs than those located behind. This sometimes influences the bin assignment, and the user may be falsely classified in the bin in front of them. Signal deviations also affect the results even when working with relative signal strengths.

Furthermore, the design of the setup is a critical step in this solution, and it needs to be done separately for each new factory environment. The positions of the BLE beacons greatly affect the accuracy. The more regularly the beacons are placed, the higher the accuracy is. If some bin areas are significantly smaller than others, it will negatively impact the solution. The shape of the bins also influences the localization. Another aspect that needs to be taken into account is that any physical obstacles affect which one of the signals is heard the strongest. In a large packaging line, the sizes of the machines and their distances from each other may vary, and there may be walls and other obstacles between them.

Something else that needs to be considered is that the last beacons need to be placed outside of the geofence, unless there are walls that limit the area. This way, there would also be a possibility to determine that the user is outside the geofence. To achieve this, beacons would also need to be set up outside of the machines.

Because of the challenges mentioned, it seems difficult to develop the solution to a stage where it could easily be integrated into any customer factory. Despite having some advantages, relative positioning did not yield to overall better results compared to absolute positioning in the tests.

5.4 Wi-Fi

The already existing Wi-Fi infrastructure in the factory was used for the Wi-Fi geofencing PoC. Compared to BLE, the distance between the transmitters was much longer. The Wi-Fi access points were located about 40 meters from each other. Using this setup had practical reasons related to integrability at the customer site. Customers typically already have an existing Wi-Fi infrastructure that the packaging machine manufacturer does not have control over. Realistically, the distance between the access points is going to be much longer than the BLE beacon setup used earlier, and the access point positions depend on the customer.

The Wi-Fi access points were mounted around 6 meters above the floor level. Thus, formula 3 was used for distance calculation. A total of 5 access points were used.

All of the architectural components were the same for Wi-Fi as for BLE, but small additions were made to both the Android application and web server. In the Android application, a new tab for Wi-Fi was developed. On the web server, small modifications were made to accommodate to the different data. When the Android app sends a websocket, it includes a technology flag that signals to the web server how the message should be processed. The most important difference is that the Wi-Fi position is calculated with an algorithm that takes the height of the transmitters into account.

Even before the tests, it was clear that even if the solution worked well enough in testing, there could still be problems at integration since each customer has their own Wi-Fi infrastructure that the packaging machine manufacturer has no control over. The distances between access points, together with the quality of the network, may vary significantly from one customer to another. In the tests, it was quickly discovered that Wi-Fi would not be a sufficient method for geofencing. An absolute positioning solution, analogous to the BLE one, was used. The error in distance estimation could go up to 20 m even though the model was fitted for the current environment. Figure 9 shows the positioning results of Wi-Fi in the factory.

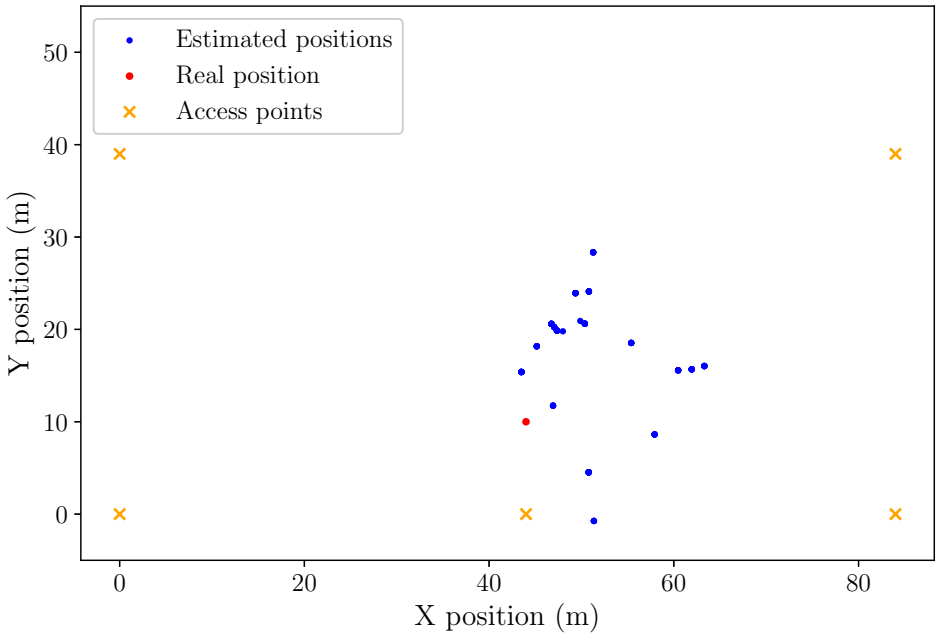

Figure 9: Wi-Fi positioning in factory.

In literature, Wi-Fi is typically said to have similar or slightly lower accuracy compared to BLE. As the transmitters in the Wi-Fi test were further apart than in the BLE tests, a worse performance was expected. Apart from the differences between Wi-Fi and BLE technologies and the long distance between the Wi-Fi access points in the test setup, there are also other aspects that further worsen the positioning accuracy. There are machines in the hall that limit the visibility between the access points and the user's mobile device. The closest access points usually had a clear line of sight with the device. However, when it comes to the furthest access points dozens of meters from the user, there were often physical obstacles between preventing a direct line of sight.

Another issue with Wi-Fi localization of Android devices is related to operating system limitations for Wi-Fi scanning. The official documentation for Android development states that for Android 9 and higher versions, each application running in the foreground can scan only four times in a two-minute period. For background applications, there are even stricter limitations. Starting from Android 10, Wi-Fi scan throttling can be turned off in the Developer Options settings. (Android Developers, 2025) For testing the PoC, Wi-Fi scan throttling has been turned off. Even when it was turned off, new scan results were received only around 3 times per second. If the PoC was developed into a product, this would also raise questions on whether changing the developer options for all customer devices would be a reasonable solution.

5.5 UWB

UWB positioning was performed with DWM1001-DEV boards. They are development boards that include a DWM1001 UWB tranceiver module. The boards can be used to evaluate the performance of the DWM1001 module, and they can be configured to function as both transmitters and receivers. The boards support two-way ranging (TWR). The boards use the UWB channel number 5, operating at 6.5 GHz frequency. (Qorvo, 2017a; Qorvo, 2017b)

Four DWM1001-DEV boards were used for the experiments. One of them was configured as a tag and three of them as anchors with fixed positions. The code was built on top of an example of simple two-way ranging with one initiator and one responder (Decawave, 2020), and it was extended for our use case with a tag and three anchor nodes. The tag initiates ranging exchanges with each of the anchors one after another.

Distance calculation was performed on the DWM1001-DEV boards and the results were transferred to a personal computer via a UART connection exposed as a COM port over USB. The positioning was performed on the computer with a Python program, using the same least squares function as for the other technologies. The distances were calculated with the following formula.

$$d = ToF \times c \times RB \tag{13}$$

where d is distance, ToF the time of flight between the transmitter and receiver, c the speed of light and RB range bias. Range bias refers to the bias in the distance estimation that results from hardware-specific delays and disturbances in the environment (Preter et al., 2019).

The UWB boards were set up in the factory hall tests in the same positions as the BLE beacons to better compare the accuracy of the technologies. Experiments were conducted in the same points with both technologies. Figure 10 shows the results of UWB positioning in the factory. The positioning error between the anchors was approximately 20 cm.

In the current solution, default range correction tables for DW1000 have been used. However, these tables give default values for the DW1000 hardware, and in order to get the most accurate measurements, range correction should be calibrated separately for the specific pieces of hardware that are being used. In the tests, it was discovered that the distance calculations are always tendencially slightly larger from reality. However, for this thesis, the explicit calibration has not been done because the results have already shown the clear ad-

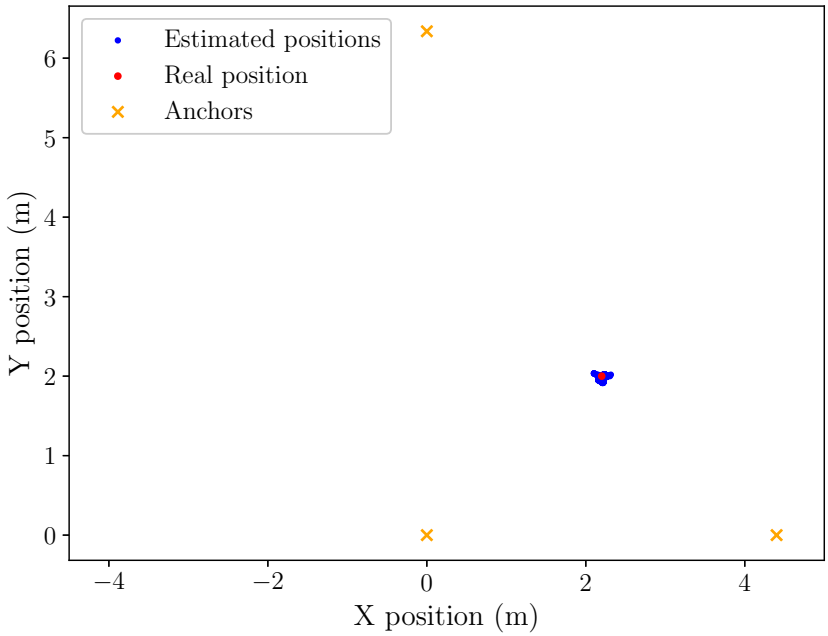

Figure 10: UWB positioning in factory.

vantages of UWB positioning and that it is an appropriate technology for the use case. If the technology is chosen for further development, this remains a task for product development. The small bias that is in each distance calculation can be seen in the results especially when the user is outside the convex hull of the anchors, such as in figure 11.

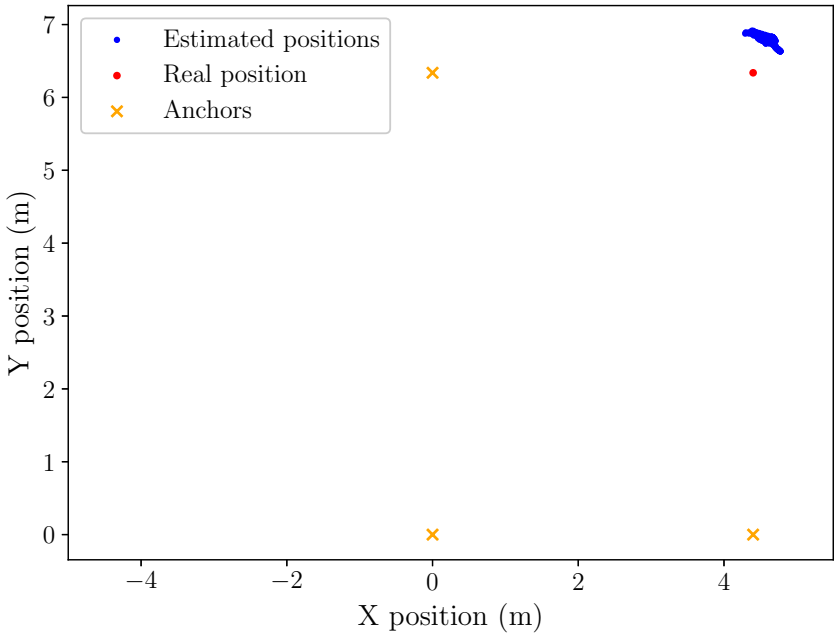

Figure 11: UWB positioning further from the anchors.

With UWB, the results were much more consistent than with BLE and Wi-Fi. Even one ranging measurement with each anchor gives a higher accuracy than any of the previous

tests. However, a slight averaging between the 10 last measurements has been used to make the results even more stable.

The clear drawback of UWB is that, at present, most of the mobile devices do not have UWB functionality. Some of the new high-end mobile phones do have UWB, but in tablets it is even less common. The only option to position those devices with UWB is to attach an external UWB tag to the mobile device, which poses several design challenges from perspectives such as usability, robustness, battery life, and safety.

The orientation of the user influences the distance calculation less than with the RSSI based methods tested. There was approximately 28.4 cm difference in the distance calculation depending on whether the user was facing the anchor or back turned to the anchor. UWB also performed better in other non-line-of-sight conditions, such as when there is a packaging machine between the user and the anchors.

Figure 12 illustrates a test result where the user walked a straight line between (2.2, -4) and (2.2, 8). For the most part, the positioning error is between 10-20 cm. As the trajectory gets to the area with less anchors nearby, the error grows. One of the reasons for this is the range bias. Apart from that, it is generally more difficult for the system to work reliably the further away it is from the anchors.

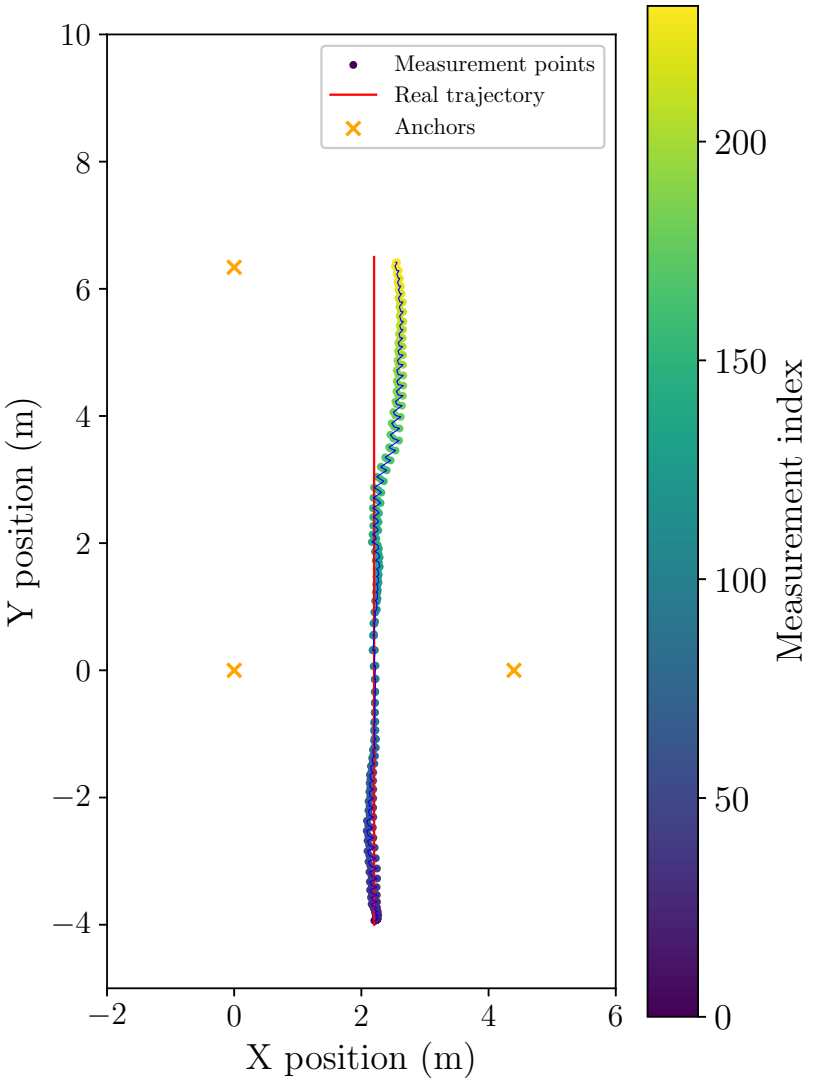

Figure 12: UWB positioning following a straight line.

6 Discussion

The results of this thesis offer insights into how geofencing can be used as a safety measure for wireless HMIs in industrial packaging machinery. This chapter discusses how these findings align with the objectives of the research, compares the results with previous research and analyzes them with a focus on their applicability in real world industrial scenarios.

The motivation of this thesis was to research and compare different options for geofencing for wireless HMIs in packaging machinery. The goal was to discover realistic, safe and cost-efficient methods and technologies for industrial use. The thesis effectively demonstrates advantages and disadvantages of different technologies in a factory environment. Next, the results and their implications are discussed in the light of the research questions.

RQ1: What are the advantages and disadvantages of different geofencing technologies for ensuring safe operation of packaging machinery?

The first research question was mainly addressed through literature review of existing indoor positioning technologies. The goal was to understand how suitable these technologies are for industrial and safety-critical systems. While each of the explored technologies has both advantages and disadvantages, with some technologies it was clear already in the literature research stage that they would not be the best fit for the present use case. Next, the most important pros and cons of each investigated technology are described.

One of the advantages of Wi-Fi in a factory setting is that there is often an existing infrastructure, which would make a solution very cheap. However, the infrastructure is typically not optimized for localization. The technology is also prone to noise. BLE has a low cost and energy consumption, and it is easy to integrate. There are beacons that are powered either by battery or via USB port, and modern mobile devices typically have native support for the protocol. UWB has high accuracy but also higher cost and does not have wide mobile support.

RFID has better accuracy compared to, for example, Wi-Fi and BLE. However, there are not a lot of commercially available products that are suitable for positioning purposes. Overall, most RFID products utilize passive tags and are developed for barcode readers, access keys and similar applications. ZigBee is a low-energy, low-cost technology that has advantages, for example, in smart home settings. However, many common mobile devices do not support the protocol, and the literature does not introduce clear advantages compared to, for example, BLE. Acoustic systems can process Time of Flight information easily and accurately due to the lower propagation speed of the signal. However, ambient sound causes interference.

This is likely to be an issue in a noisy factory environment. Computer vision algorithms can reach high accuracy, but development and hardware costs are high. For the use case in packaging machinery, computer vision is not the ideal solution, as it would introduce unnecessary complexity and GDPR issues.

It is clear in the literature that there are several tradeoffs between different metrics. One of the most important tradeoff is between accuracy and cost-efficiency. Additionally, some systems have more specific infrastructure requirements while others are more flexible. When considering a factory environment, these were considered as some of the most important aspects to consider.

RQ2: What requirements need to be considered when developing a geofencing solution for a factory environment?

The interviews gave a broad overview of the most important requirements of a geofencing system for packaging machinery. The requirements reflect the technical constraints of the system, as well as safety, usability and integrability.

The interview participants emphasized that the main motivation for implementing a geofencing system is to prevent risky situations where an operator could actuate a machine without fully seeing it. This underlying motivation can be clearly seen in most of the elicited requirements. When the interviewees were discussing the accuracy needs of the system, the starting point was always the question of what level of error could be tolerated without compromising this line of sight principle. The interviewees considered an error of more than 2 meters in the localization too large, some having even stricter expectations. Although there is no absolute threshold for acceptable accuracy, larger errors make a significant buffer zone near the geofence boundary necessary. This means that the user may be classified as outside the geofence even if they are still physically inside the area.

While accuracy is an important requirement, there are many other requirements that need to be considered. For example, the ease of integration into the customer's packaging line is a practical concern that is important if the same geofencing solution is sold to many customers. While most of the previous literature concentrates purely on the performance of technologies, such as accuracy and robustness against interferences and obstacles, in a practical use case the performance requirements need to be balanced with integrability, cost, and other considerations.

A factory has specific challenges regarding geofencing. The most important ones that arose during the interviews were interferences and obstacles. Although these themes are widely

discussed in the indoor localization literature, they become even more critical in a factory environment where there are many disturbances and moving parts.

An important further observation is that packaging machinery has specific challenges and requirements that do not necessarily apply to all types of industrial machinery. Geofencing needs in industry depend on the types of risks the machine presents during operation. With some machines, the needed geofencing functionality may also be related to restricting the user from certain high-risk zones. Some machines may pose a physical risk by movement and risk of falling objects from above. Physical safety measurements and how the machine is intended to run also differ. In this thesis, the focus is on packaging machines, where it is often acceptable for the machine to run unattended, but any new actuation should happen with the operator present. The requirements cannot be generalized to all industrial machinery as is, even though many challenges are present in other types of machinery as well.

The requirements were collected in one specific company specializing in packaging machinery. Thus, they cater to the needs of the case company and its customers. While the broad themes can be applied to other companies in the same field to an extent, each company and environment always has its unique emphasis and challenges. Furthermore, the requirements in the thesis are a first iteration of requirements. If the company decides to further develop one of the PoCs, more refined requirements shall be gathered from different internal and external stakeholders.

RQ3: How do selected technologies perform in a factory setting with respect to key requirements?

The usability of the three developed PoCs - BLE, Wi-Fi and UWB - differ a lot from each other. Based on earlier literature in the field of indoor localization, it was expected that BLE and Wi-Fi based solutions could be developed to fill the minimum requirement of less than 2 meter error in localization. However, when the PoCs were tested in the factory, it was discovered that the environment changed too much and that RSSI data was not stable enough to determine distances between nodes. The worse performance compared to literature can be partially explained by the changing interference levels in the factory that made fitting a universal model impossible.

With BLE, an accuracy of 2-3 m was achieved when the tests were performed immediately after parameter fitting. However, in another moment, the same parameters result in bad estimations with up to 20 m error. This suggests that it is very difficult to develop a BLE solution with RSSI information that is reliable enough in a rapidly changing factory environment. If the BLE solution from this thesis were to be further developed, a method for measuring the

current noise level in the environment would need to be implemented. This could be, for example, a ground-truth device in the environment whose location is known and that constantly measures the signal strengths of senders. Overall, the tested BLE solution has difficulties to meet the requirements of accuracy and robustness against interference. Distance estimation between nodes is also greatly influenced by obstacles and user orientation.

The tests showcase that Wi-Fi is not a viable option as an indoor localization technology for this use case. As another RSSI based solution working in the same frequency band as BLE, the changing interference levels also affect Wi-Fi geofencing a lot. In literature, Wi-Fi is often said to have a slightly lower positioning accuracy than BLE. It is not feasible to have the Wi-Fi access points as close to each other as BLE beacons, further decreasing the accuracy. The ease of integration of Wi-Fi is the best out of the three technologies. However, it fails to meet the minimum precision requirement to an extent that it is not a valid option for further development. Wi-Fi may work for localization in different indoor environments or for more coarse location estimation, but it does not work in the use case of packaging machinery.

Literature shows that UWB is the most accurate indoor localization technology. This was also proved in the factory tests of this thesis. Several sources state that UWB can reach 10 cm accuracy. In the factory tests, the accuracy varied between 10 cm and 50 cm depending on the position of the user relative to the UWB anchors. This aligned with the earlier research because several aspects make the setup non-optimal and likely to produce slightly worse results. One reason is that the distance measurement between the modules was not calibrated to the specific pieces of hardware. This caused all of the distance measurements to be consistently biased and always slightly larger than the reality. Because of this, the implemented least squares algorithm tends to make some localization error especially when the user is outside the convex hull between the anchors. For the thesis, the uncalibrated results already showed the superior accuracy of UWB for the use case, but if the PoC is developed further, calibration should be done for increased accuracy. Additonally, the anchor positioning was not optimal, as the best is when the anchors have even distances to each other. The positioning, however, was due to the locations of machines, and would likely be similar in a commercialized system.

From the perspective of the case company, the main goal is to ensure machine and personal safety when the machines are actuated. Among the three technologies tested, UWB stood out as the most promising candidate for a reliable geofencing solution. Additionally, it is likely faster to deploy a UWB solution at a customer site because it is much less sensitive to the changes in the environment. This is likely because BLE and Wi-Fi work on the same frequency, and there are a lot of devices using the frequency band, whereas UWB uses less

common frequency bands. Additionally, TWR is much more reliable than RSSI. If the company decides to further develop one of the solutions, it is responsible for meeting the legal safety requirements. With one of the RSSI based options researched in this thesis, there would be a significant liability risk in case the solution does not offer the promised safety and an accident happens under such conditions.

The problem of UWB for industrial use is that most mobile devices do not have native support for UWB. This means that separate UWB tranceivers would need to be used with those mobile devices and connected to them. From a design perspective, this is not the most elegant solution. Another disadvantage often named in the literature is the higher cost. However, it needs to also be considered that a less reliable technology most likely has higher development costs because it needs more sophisticated algorithms to make it good enough.

7 Conclusions

The goal of the master's thesis was to research and compare geofencing technologies for wireless HMIs in packaging machinery. When a user is using a machine via wireless HMI, it is important to assure that they can have an overview of the machine. If the user cannot see the machine, they should not be allowed to actuate it. By using the design science research methodology, the work progressed from problem identification and requirement elicitation to the design, development and evaluation of three proofs of concept. The evaluated technologies were BLE, Wi-Fi and UWB. This chapter offers an overview of the results and contributions of this thesis.

The first research question - "*What are the advantages and disadvantages of different geofencing technologies for ensuring safe operation of packaging machinery?*" - was addressed through a literature review. This provided an understanding of different indoor localization technologies and techniques. There is a typical tradeoff between accuracy and cost. Most of the cheaper options, such as BLE or Wi-Fi, tend to have a lower accuracy. However, the most accurate options such as UWB have a higher hardware cost. Additionally, the ease of integration, which is an important aspect for commercial solutions, differs between technologies. Some technologies, such as computer vision, require high development and hardware costs. When talking about radio frequency technologies, most modern mobile devices include Wi-Fi and BLE support, which helps with their integration into an HMI system. Many other radio frequency technologies, such as UWB, ZigBee and RFID, are only supported by specific mobile devices.

The insights from the literature were then used to craft an interview to answer the second research question - "*What requirements need to be considered when developing a geofencing solution for a factory environment?*". Four semi-structured interviews were conducted in the case company to elicit requirements. The key requirements discovered are related to the accuracy and integrability of a solution. Based on the interviews, the geofencing system should have a maximum of 2 meters error. In a factory environment, there are also many types of interferences and obstacles that need to be considered. The solution should be easy to integrate at different customer sites with different factory layouts.

Based on the requirements, three potential technologies were chosen: BLE, Wi-Fi and UWB. A PoC for each of them was developed and tested in a factory to answer the last research question - "*RQ3: How do selected technologies perform in a factory setting with respect to key requirements?*". The focus was on evaluating the technologies in a realistic environment, and additionally a web-based architecture was developed for the PoC. In the factory tests, it was discovered that Wi-Fi is not a viable option as a geofencing solution for wireless HMIs

in packaging machinery because it does not reach the 2 meter accuracy requirement in a realistic environment. BLE also had problems with the accuracy requirements. When tests were performed directly after fitting a model, the accuracy was close to the desired 2 meters. However, large differences in the noise level were observed in the environment, which made the solution extremely unreliable. UWB had a superior performance in the factory. However, the challenge with UWB is that it is more difficult to integrate to an HMI system. The main issue is the limited number of mobile devices with UWB support.

Contributions of the thesis

This thesis evaluates geofencing approaches for industrial environments, with a particular focus on packaging machinery. It contributes to the research of indoor positioning systems and geofencing by investigating low-cost, realistic indoor positioning technologies for industry.

Although geofencing and indoor positioning have been studied a lot, few studies have been conducted in industrial environments. This thesis points out several aspects in factory environments that demand special attention when designing and implementing geofencing systems. In practice, geofencing is an established practice in fields such as logistics and asset tracking. However, its application in industrial safety is not yet quite as wide-spread.

The work was commissioned by a company, and the resulting artifact can be used as a basis for future product development. The design and implementation were guided by real-world requirements, ensuring the practical relevance of the work.

Limitations of the research

This master's thesis concentrated on researching geofencing technologies in the context of packaging machinery. The challenges and tradeoffs described cannot be generalized to all indoor positioning and geofencing. A factory floor is a difficult environment with a lot of interference, which means that the challenges and accuracy of each technology may differ in other types of indoor spaces. Furthermore, packaging machinery is a distinct field with its unique characteristics, even compared to other kinds of industrial machinery.

The requirements for a geofencing technology have been gathered in one company, for the specific company's needs. Even though some generic requirements, such as following the EU machinery directive, or need of robustness against electromagnetic interference, would also constrain any other company in the same field, there are also requirements in the thesis that are specific to the case company.

The tests were performed in a factory environment in order to resemble the real use case

as much as possible. However, the test factory is a hall where packaging machines are assembled and tested, as opposed to a customer production factory.

Furthermore, choices between fair comparison between the methods and real life applicability have been made. The purpose of this research is not to provide the best comparison between the accuracies of the technologies. Instead, it aims to compare technologies from several viewpoints in a realistic setting and study real-life challenges of geofencing in packaging machinery. Because of this, for example, the setup of Wi-Fi access points was not the same as the one of BLE beacons and UWB anchors. In a real factory, it is not realistic to mount Wi-Fi access points only a few meters from each other, so a more realistic setup was used in the testing.

Future research could explore perform in other industrial environments apart from packaging machinery, to evaluate how generalizable the findings are to other industries. Additionally, combining several technologies, such as UWB with inertial measurements, could be used for developing more accurate systems.

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Appendix 1 Interview Questions

1) Can you start by telling me a bit about your role and how you interact with the packaging machines?

2) How do you see the purpose of the geofencing project? How can the geofencing / proximity-based access control solution be useful to the customer? Which problems could it solve or improve?

3) Describe with your own words the key functionality of the geofencing solution.

4) The solution will restrict some functionalities of the HMI when the user is not close to the machine. Which functionalities should be restricted based on proximity?

5) When should the functionalities be restricted?

6) When the user goes away from the machine and the area of the geofence, how should the system react? Please consider both the machine and the GUI on the mobile device.

7) What kinds of log messages or warnings should the system output?

8) Which concerns, if any, do you have about the learnability of the new system with proximity-based access control?

9) In order to restrict the certain functionalities, the system needs to localize the user. How accurate and precise should the localization be? What is the largest acceptable error?

10) What types of interference and coverage do you expect in the factory environment? How and to which extent is the system expected to deal with that?

11) What challenges are there in the factory environment regarding mobile device use?

12) What level of security is required? What are possible security threats?

13) To which extent are relevant security measures already implemented and what needs to be considered in the new geofencing component?

14) What happens when the user goes away from the machine but the machine is running?

15) Are there relevant laws and regulations related to proximity-based access control that need to be followed? What about safety-related legislation and data protection requirements?

16) How might legislation in different countries affect this project?

17) There may be customer-specific requirements to use the existing mobile devices. What requirements can you think about related to that?

18) Do you have any further points in mind that you think can be important for the proximity-based access control solution?

Appendix 2 Original and Translated Quotes

“Das muss man das Grundprinzip einhalten: wenn man Aktionen startet, Aktoren in Bewegung setzt, muss man immer sich vor der Maschine befinden, und das muss sichergestellt werden. [...] Sobald er nicht mehr in der Sichtfeld ist, ist die Funktion unmittelbar eingeschränkt.”

“This needs to be followed as the basic principle: when you start actions, set actuators into motion, you must always be in front of the machine, and that needs to be ensured. [...] As soon as it [the machine] is no longer in the field of vision, the function is immediately restricted.”

“Wir können Informationen auslesen, in irgendeiner Form statistische Informationen über die Maschine, dagegen spricht gar nichts.”

“We can read information, some kind of statistical information about the machine. Nothing speaks against it.”

“Die Ansicht, die Maschine sollte genau gleich weiterlaufen. Und am Bedienteil sollte man klar sehen, dass man die Aktion nicht mehr betätigen kann, dass man außerhalb dieses Bereiches ist.”

“The machine should continue to run exactly the same, and on the control panel you should see clearly that you cannot perform the action anymore, that you are outside of this area.”

“Also [eine] Sicherheit[srisiko] ist [...] die Fehlinterpretation, dass man sagt, man ist dann auf der falschen Maschine, also es hat einem falsch zugeordnet. Ich bin jetzt Station 4 und nicht Station 5 oder was auch immer, oder Maschine 4 und 5, und etwas bewegt aber auf der anderen Seite etwas, wo vielleicht jemand am Arbeiten ist.”

“So a security risk is [...] the misinterpretation that one says you are at the wrong machine, so it has assigned you incorrectly. I am now at station 4 and not 5, or machine 4 and 5, and something moves on the other side where someone might be currently working.”

“Also in meinen Augen, was das Geofencing auch [haben soll, ist] die Möglichkeit bieten zu sagen, das Gerät ist auch gegenüber der Maschine gerichtet. Also meiner Meinung nach, dass der Operator, wenn 2 Maschinen gegenüberstehen und sich unsicher ist, welche Maschine ich jetzt einstelle, entweder irgendwo sichtbar ist eben durch eine Farbe, aber auch durch ein Doppelcheck sozusagen.”

“So in my opinion, what geofencing should also do is offer the possibility to say that the device is also facing the machine. So in my opinion, if two machines are facing each other and the operator is unsure which machine they are now setting up, it is either visible somewhere by a color, but also by a double check.”

“Was machst du, wenn 2 [Operatoren] sind? Wer hat dann die Rechte? [...] Du solltest dann nicht an beiden [Bedienstationen] bedienen können, weil sonst kann es sein, dass der eine das will und der andere will was anderes.”

“What do you do if there are two operators? Who then has the rights? [...] You should not be allowed to operate on both [operating stations], you always have to switch. You should not be able to operate on both because otherwise it can be that one person wants one thing and the other one something else, and they contradict each other.”

“Gerade mit unserer Kundschaft haben wir viele Diskussionen über Sicherheit, über hypothetischen. [Zum Beispiel,] irgendwo, man könnte sich noch den Finger reinklemmen, die Hand.”

“We have a lot of discussions with our customers about safety, about hypothetical things. [For example,] somewhere, you could get your finger or hand caught there.”

“Also ich will einfach kurz die 2 Hauptbrennpunkte bei der Personensicherheit ansprechen. Das eine ist das Ingangsetzen der Maschine. [...] Und ein zweiter Punkt ist genau das Gegenteil von Ingangsetzen, nämlich die Maschine im Gefahrfall stoppen, also einen Notaus.”

“So I just want to briefly address the two main focal points of personal safety. One is actuating the machine. [Explains what actuating includes.] And the second point is exactly the opposite of actuating, namely stopping the machine in case of emergency, that is an emergency stop.”

“Und daher wird es eine Sicherstellung geben, dass man die Maschine im Auge behalten kann, dass man genug nahe auch einen Notaus ist oder die Möglichkeit hat, einen Notaus zu drücken, wenn was passiert. Wie man das hätte, wie man an der Maschine wäre.”

“And so there will be a guarantee that you can keep an eye on the machine, that you are also close enough to an emergency stop or have the possibility to press an emergency stop if something happens. How you would have that if you were at the machine.”

“Die Geräte müssen halt entsprechend auch Security Standards erfüllen. Damit eben nicht ein Angriff, irgendwas, kann dann die Verbindung trennen oder wie auch immer, ein Angriff auf die Maschine machen. Und sobald man halt mit dem Internet verbunden ist, haben wir eigentlich eine andere Situation als jetzt.”

“The devices need to also fill the relevant security standards, so that an attack can’t break the connection or attack the machine in any way. And as soon as you are connected to the Internet, it is a different situation than now.”

“Auf jeden Fall sollte sichergestellt werden, dass das Geofencing nicht manipuliert werden kann, dass irgendwie, sag ich mal, ein anderes Gerät gepaired wird und das belässt man dort und dann mit dem HMI geht man dann weg. Also quasi wenn es nur angeklebt ist, geht das Gegenstück am Wireless HMI und dann kann man so abschrauben und lässt es an der Maschine und dann kann man sich mit dem HMI dann weiter bewegen.”

“In any case, it should be ensured that the geofencing cannot be manipulated, that somehow, let’s say, another device is paired, and you leave it there and walk away with the HMI. So if it [the geofencing device] is just stuck on and the counterpart goes to the wireless HMI, then you can unscrew it and leave it on the machine, and then you can move away with the HMI.”

“Und das könnte bei der Maschine ja ähnlich sein. Dass die Maschine durchaus in einer Entfernung von 3 Metern oder 5 Metern gestartet werden kann, dass sie dann aber hupt, Sicher zu haben.”

“And that could be similar with the machine, that the machine can be started from 3 or 5 meters distance, but then it beeps, to be sure.”

“Am liebsten hätte ich noch, wenn das Ding sich, wenn es vibrieren würde oder so, dass wenn er unter seinem Arm das so quasi mit dem im Arm wegläuft und da noch so eine Vibration ausführt wie beim Handy.”

“I would also prefer if the thing would vibrate or so, so that when he [operator] walks away with it under the arm, then it carries out such a vibration like a cell phone.”

“Und es müsste halt auch sichergestellt sein, dass es funktioniert, wenn irgendwas dazwischen ist. Also wie es dann aussieht, also wenn da irgendeine Sichtschutzwand zum Beispiel dazwischen steht, oder? Ein Metallgitter als Schutzumzäunung.”

“It should be made sure it works if there is something in between. So what it looks like if

there is some privacy wall in between, for example. Or a metal grid as protective fencing."

"Ja, stell ich mir als wahrscheinlich das schwierigste Thema beim Geofencing, dass man wirklich Limiten setzen kann, die dann trotz Interferenzen noch sicher sind."

"Yeah, I think that probably the most difficult theme with geofencing is that one can actually set limits that are then still secure despite interferences."

"Wenn das dazu elektromagnetischen Reflektionen kommt in irgendeiner Form, dass dieses System auch nicht irregeführt wird."

"And if there are electromagnetic reflections in some form, that this system is also not misled."

"Also du siehst, es ist eigentlich alles aus Metall. Metall gibt Interferenzen. Dann ziehen wir hier Folie ab, unsere Plastikfolie. Das gibt es auch elektrische Ladungen. Dann die ganzen Bänder, Kunststoffbänder, die da sich bewegen"

"So you see, actually everything is made of metal. Metal causes interferences. Then we have foil here, our plastic foil. Then all the plastic bands that move."

"Es sollte offline sein, also es heißt gerade so zum Beispiel GPS oder so geht ja da nicht, wenn man sowieso in der Halle ist und manchmal gibt es auch kein GSM-Empfang also dann kein Handynetz und nichts."

"It should be offline, so that means, for example, GPS or something like that doesn't work there when you are in the hall, and sometimes there is no GSM reception, so no cell phone network and nothing."

"Es muss aber das Ersatzteil ermöglichen quasi, dass der Kunde in der Lage ist, das auszutauschen, wenn es defekt ist, selbst wieder zu teachen zu können und dann wieder zu integrieren. Das muss der Kunde in der Lage sein. Nicht dass er die Produktion stecken bleibt, nur weil ihm ein gewisses Tool fehlt um das mit dem HMI zu pairen oder so."

"However, the spare part must make it possible for the customer to be able to replace it if it is defect and to be able to teach it again themselves and then integrate again. Not that they're stuck with production just because they're missing a certain tool to pair it with the HMI or something like that."

“Also im Wesentlichen ist es die Maschinenrichtlinie.” (as an answer to “Und kennst du irgendwelche Gesetze oder Vorschriften zur Sicherheit und zu Datenschutz, die Im Bereich von Geofencing betrachtet werden müssen?”)

“In essence, it [the law(s) that need to be considered] is the machinery directive.”

“Also eben wie vorhin erwähnt, die Funkfrequenzen sind das Entscheidende. Jedes Land hat Zulassung für gewisse Frequenzen und Funkstandards. Und da, da braucht es erstmal ne Übersicht und den verbreitetsten Standard sollte man immer nehmen.”

“The radio frequencies are the decisive factor. Each country has approval for certain frequencies and radio standards. And here, you first need an overview, and the most broadly used standard should always be chosen.”

“Und deshalb müssen wir die Anforderungen wie bisher erfüllen, aber mit anderen Bedingungen, eben mit der Bedienbarkeit. [...] Und dann einen gewissen Komfort bieten”

“And that’s why we need to fulfill the requirements as so far but with other conditions, for example with usability. [...] and then to offer a certain comfort.”

“Vor einem Standpunkt kann man nicht immer alles überschauen und es sollte ihm einfach einen Mehrwert bieten, die Maschine von überall bedienen zu können”

“You can’t always see everything from one point of view and it should offer him [the user] added value to be able to operate the machine from anywhere.”