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Communication between collaborative mobile industrial robots and elevators

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Abstract

In recent years, mobile robots have become common in a wide number of applications. In multi-floor offices and factories, mobile robots are often required to use elevators. Much research has been devoted to developing their ability to do so. However, most of this research has focused on stand-alone robots that use the elevator interfaces originally developed for humans and far less research has attempted to develop direct connection methods between the robots and the elevators.

This thesis focuses on identifying and evaluating communication methods between networked mobile robots and IoT devices such as elevators in modern smart buildings and how to retain these connections while the robots enter and leave elevators.

This thesis concludes that there are three common ways to allow communication between elevators and mobile robots: PLCs, IO-cards, or APIs. Successful applications have been made with all three of these methods with the best method for each environment depending on the pre-existing infrastructure.

As a case study, a system that uses elevators to change floors with a mobile robot was designed, implemented, and tested. There were problems with the interconnectivity of the devices and the system did not work reliably in the end. Potential future improvements are discussed in this thesis.

Keywords Mobile robots, IoT, elevators

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Tiivistelmä

Mobiiliroboteista on tullut viime vuosina yleisiä monenlaisissa eri käyttötarkoituksissa. Tehtaissa ja toimistoissa, joissa on useita kerroksia, mobiilirobotit käyttävät usein hissejä kerrosten välillä liikkumiseen. Mobiilirobottien hissien käytöstä on tehty paljon tutkimusta, mutta se keskittyy usein itsestään toimiviin robotteihin, jotka pystyvät käyttämään ihmisille tehtyjä hissejä sellaisenaan. Suoraa kommunikointia hissien ja mobiilirobottien välillä on tutkittu vähemmän.

Tässä diplomityössä keskitytään tunnistamaan ja arvioimaan eri kommunikointimenetelmiä esineiden internetissä olevien toimilaitteiden välillä moderneissa älyrakennuksissa, erityisesti keskittyen mobiilirobotteihin ja hisseihin. Työssä selvitetään myös, miten nämä yhteydet saadaan säilytettyä robottien liikkuessa hisseistä sisään ja ulos.

Tässä työssä tullaan johtopäätökseen, että on olemassa kolme yleistä tapaa toteuttaa kommunikointi hissien ja mobiilirobottien välillä: PLC, IO-kortti, tai API. Kaikilla näillä kolmella tavalla on tehty toimivia järjestelmiä ja paras tapa riippuu siitä, minkälaisessa ympäristössä järjestelmää ollaan käyttämässä.

Osana työtä kehitettiin, toteutettiin ja testattiin järjestelmä, jossa mobiilirobotti käytti hissiä kerrosten välillä liikkumiseen. Eri toimilaitteiden välillä havaittiin kommunikointiongelmia ja järjestelmä ei toiminut luotettavasti. Mahdollisia tapoja parantaa järjestelmän toimivuutta käydään läpi työn lopussa.

Avainsanat Mobiilirobotti, esineiden internet, hissi

Contents

Preface

I want to thank my wife for believing in me even when my own resolution wavered. Special thanks to our cats Arvo and Ilmo for keeping me sane during remote working and trying help with the writing by sitting on the keyboard. Thanks also to my advisor Fredi and supervisor Ville for valuable feedback and support throughout the thesis process.

Espoo, 27 December 2022
Ville Välikylä

Abbreviations

5G	Fifth-generation technology standard for broadband cellular networks.
AP	Access Point.
API	Application Programming Interface.
CPU	Central Processing Unit.
dBm	Decibels in relation to milliwatt.
ERP	Enterprise Resource Planning.
IEEE	Institute of Electrical and Electronics Engineers.
MiR	Mobile Industrial Robots, a mobile robot manufacturer.
IIoT	Industrial Internet of Things.
IoT	Internet of Things.
PLC	Programmable Logic Controller.
RFID	Radio-Frequency Identification.
TK27/29	Used to refer to the two buildings of the factory in which the case study was conducted.
Wi-Fi	Commonly used wireless network standard.

1. Introduction

With recent advances in robotics, collaborative mobile robots have become increasingly common in a wide number of industrial applications. Since robots are often added to existing infrastructure, they must be able to work in the same area as people or work directly with them. In multi-floor offices and factories, this usually requires that robots use the same elevators.

The use of elevators by mobile robots can be divided into three main tasks: navigation, detection of controls and usage of controls [1]. In the present study, navigation includes finding, entering, and exiting an elevator. Controls can consist of either a physical button panel designed for human users or a network connection to the elevator control box. Thus, it is possible to have either direct communication between the robot and the elevator, or to modify the robot to enable it to use the human interface of the elevator (i.e., buttons).

In recent years, much research has been devoted to developing the ability of robots to use elevators. However, most of this research has focused on standalone robots that use the elevator interfaces originally developed for humans, and far less research has attempted to develop direct network connection methods for enabling robot use of elevators.

More recently, the Internet of Things (IoT) has received much attention due to improved connection technologies and the potential benefits from employing IoT [1]. In building automation (i.e., smart buildings), IoT refers to sensors and actuators connected to each other to improve energy efficiency and safety. IoT also enables the user to remotely access devices throughout the building. In smart buildings, elevators form part of the IoT, and the elevators also communicate with other devices, such as mobile robots. However, since smart buildings are a new concept, connection methods and protocols can vary due to a lack of standards.

Wi-Fi signals are commonly used by robots for connecting to networks. Because elevator cars are usually closed metal containers, they act as a Faraday cage, which considerably limits the Wi-Fi signal into or from the elevator car [2]. A potential solution for solving this problem is to use a Wi-Fi access point inside the elevator car for communicating with a robot. This enables communication to the inside of the car to be wired and not hindered by the metal walls.

The aim of this thesis is to identify, evaluate and adapt methods for enabling communication between elevators and mobile robots while allowing the robot to retain its connection with the network when inside the elevator car. Robot path planning, mapping of the floors, and navigation through the narrow elevator door will not be considered in this thesis, as most mobile industrial robots can already perform these tasks.

As a case study, communication between the MiR200 collaborative mobile robot and two Kone freight elevators will be implemented in the Helsinki factory of GE Healthcare Finland Oy. Thereafter, the thesis evaluates the identified methods by testing the ability of the robot to transport objects independently between floors.

For the robot to be able to change floors, it must be able to send floor calls to the elevators and receive information from them, such as position and door state. To do this, communication between the fleet management system and elevator control cabinet must be established as the robot cannot communicate directly with the elevator controls. The robot is controlled by the fleet management system running on a server that is connected to the local area network. As the elevator control cabinet is not directly connected to the local area network, an interface is required between it and the fleet management system.

The research questions of this thesis are "What are the commonly used methods of communication between networked mobile robots and IoT devices such as elevators in a modern smart building?" and "How to retain a connection with a networked robot while it enters and leaves an elevator?".

The rest of this thesis is divided into five chapters. Chapter 2 reviews the literature on mobile robots, IoT communication methods and elevator communication protocols. Chapter 3 introduces the system that was developed as a case study. Chapter 4 describes the experiments done with the system, and Chapter 5 concludes the thesis by discussing the results and proposing potential future work.

2. Literature review

This Chapter gathers data from state-of-the art research articles related to the research question “What are the commonly used methods of communication between networked mobile robots and IoT devices such as elevators in a modern smart building?” and describes the background information on collaborative industrial mobile robots, internet of things and various elevator protocols.

2.1. Collaborative industrial mobile robots

Traditionally industrial robots have been machines that operate behind safety doors and curtains. However, as technology and safety systems have improved, robots can now operate closer to humans. This has increased the significance of mobile robotics. Mobile robots are robots that can move around in their environment. They can be either wheeled, legged, tracked, amphibious or flying [3].

Currently wheeled robots are the most common type of mobile robots, because they are easiest to design and control as they are easy to balance, even if they are carrying a load [4]. Many wheeled robots are designed to only navigate flat surfaces so they must use elevators to change floors. Tracked robots are more complex and therefore not as effective as wheeled robots [3]. Legged robots offer advantages such as capability to operate non-flat surfaces.

If a robot can work directly with people or in the same area without any separate safety walls or fences, it can be said to be collaborative. Collaborative mobile robots can move freely in same space as people without being restricted to separate areas.

Currently, collaborative mobile robots are used in hospitals, warehouses and hotels [5], but they are becoming more common everywhere as industries and offices have been increasingly using mobile robots as well. Market size of collaborative robots has been increasing rapidly and the grow is expected to continue, as can be seen for example in a report by Next Move Strategy Consulting [6], illustrated in Figure 1.

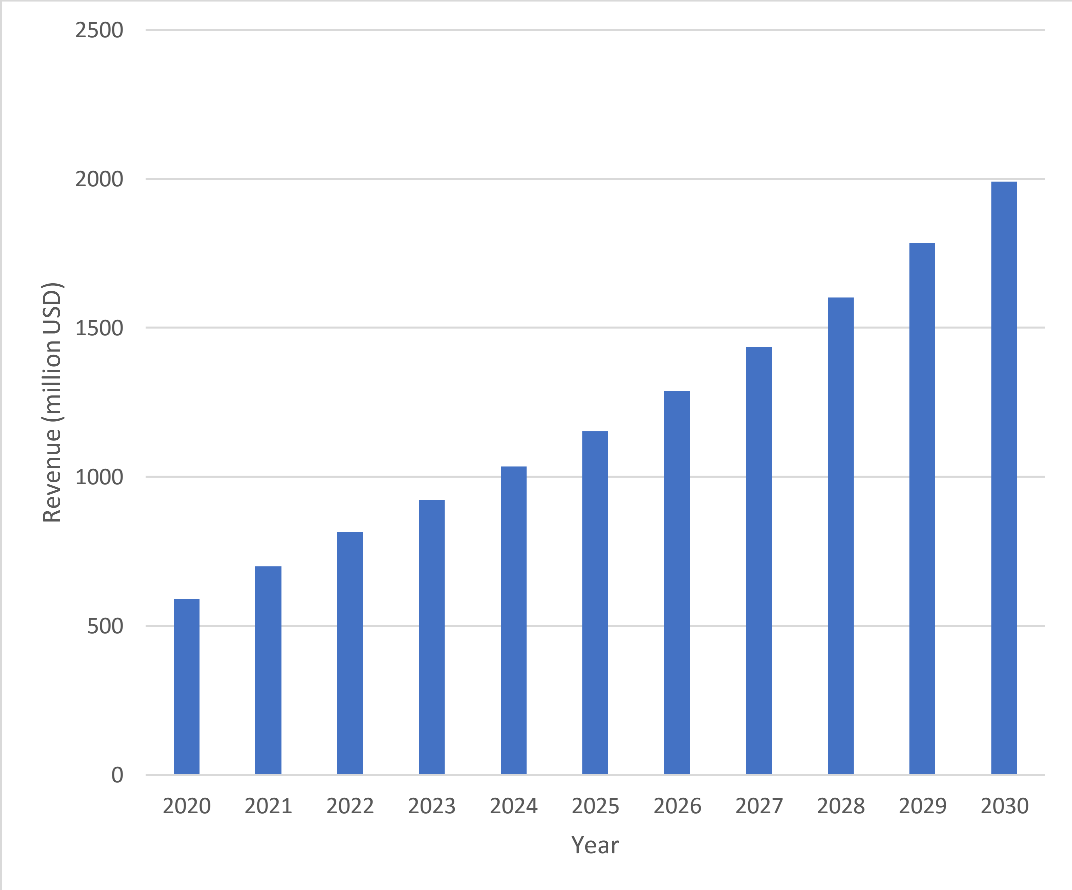

Figure 1. Estimate of collaborative robot market revenue by Next Move Strategy Consulting [6].

Many modern applications require the robots to operate in multiple working environments that are on different floors. Some wheeled robots [7] and legged robots can climb stairs, but balancing the load and the robot in stairs is challenging [8]. Therefore, elevators are often used for floor-to-floor transportation of mobile robots.

2.2. Internet of Things

Internet of Things (IoT) has gained a lot of traction in recent years as wireless communication technologies have improved [1]. The 'Things' in IoT can mean for example actuators or sensors that are connected to each other to enable cooperation to achieve common goals [9]. This can improve user experience by allowing remote access and system monitoring. IoT also potentially improves energy efficiency by controlling lighting and heating dynamically to suit user needs. IoT can be used in many different application domains as illustrated in Figure 2 [9].

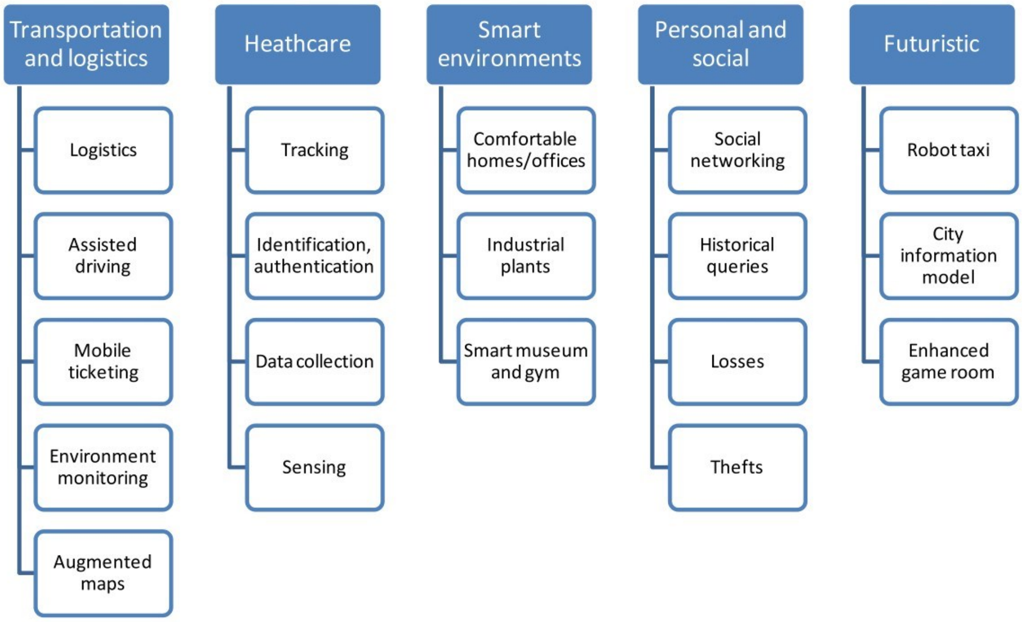

Figure 2. Some possible application domains for IoT according to a survey study by Atzori et al. [9].

A subset of IoT is Industrial Internet of Things (IIoT) which emphasises "things" that have a role in industrial business processes. IIoT potentially helps industries to collect data from their processes to help with maintenance and to improve performance [1].

IoT can be built by using standards that follow the IEEE 802 [10] standard set, which is also used by most of the local area networks today. Most sensor networks follow the IEEE 802.15.4 standard specifically because it includes lower-level definitions that are necessary for low-power and low bit rate communications [9]. For upper-level definitions of the protocol stack there are standards such as ZigBee or 6LoWPAN [10]. There are also attempts to develop new technologies and new standards will probably come with them later.

Another wireless communication protocol that can be used to communicate between devices in IoT is Bluetooth. Although it is familiar for many from smart phones it has not been a promising technology because of its high energy consumption. However, in recent years Bluetooth has also been improved to be more energy efficient and it has become a possible technology to be used for IoT applications [11] with Bluetooth Low Energy being especially promising [12].

Regardless of the technology used to create the IoT, security will also have to be considered. IoT is inherently vulnerable to security issues, because it usually consists of many components that are often in unsecure locations and unattended with minimal computing abilities, and they are connected wirelessly [13]. Therefore, a lot of research and development is focused on improving the security aspects of IoT for example with authentication methods and with ways to secure data integrity [9].

The requirements for the speed and reliability of 5G cellular networks are high and therefore they can be directly used in IoT applications [14]. Mobile broadband communications industry has been transitioning to 5G cellular networks because the user and traffic amounts of cellular networks are constantly rising rapidly. Using a cellular network to communicate between IoT applications would be convenient because it would mean there is no need to build separate networks on every site.

Elevators can also be connected to a network of other devices. Usually, the main reason to do this is to manage priority, therefore reducing the time users have to wait for the elevators [15], which is more beneficial in higher floored buildings. IoT can also be used to add recreational or informative systems to improve the elevator experience for users [16]. More recently, with mobile robots becoming common, connecting both elevators and robots to IoT networks enables them to communicate with each other. This allows robots to operate elevators to change floors without the need to physically press buttons with manipulators.

A study by Hangli et al. focused on an IoT approach to elevator handling [17]. A cyber-physical system based on Robot Operating System (ROS) and consisting of a mobile robot, an elevator, an agent server, and a vision system was developed. The elevator was enabled to be part of IoT with two I/O boards and a CPU. A python program running on a Linux server was used as an agent handling the communication between the robot and the elevator.

The vision system included a local camera, and it was used for detecting the robot. A QR code was used for robot identification.

Radio Frequency Identification (RFID) can be used as part of IoT to identify sensors and actuators [18]. RFID tags have traditionally been used mainly for inventory tracking, but possible applications have expanded for them as well. In elevator applications RFID technology can be used for example to recognise floors and thus help with navigation.

2.3. Elevator control systems

The purpose of an elevator controller is to handle all the signals it receives from the elevator system [19]. Elevator systems include the shafts and cars of the elevators, corresponding actuators, and sensors. Most elevators work in a relatively simple environment and although there are a wide variety of safety systems in place, there is often no need for complex control systems. However, when attempting to make elevators increasingly responsive to users, the technology of their controls systems have become more complicated [20].

Elevator controllers used to be relay-based, but today only the simplest ones are handled with relays. Most elevators today are computer controlled by systems of PLCs [19] or other computing systems [16].

Usually, users operate elevators from button panels either inside the car or in halls outside the elevator shaft. In recent years as mobile technology has taken huge leaps and almost everyone has a smart phone or similar device, some elevators can also be operated remotely with them [21]. Some elevator control systems can also be accessed and controlled by other interfaces like ERPs through different communication protocols. A more detailed explanation on the possible communication methods is in Section 2.4.

All industrial control systems are subject to security risks [22]. Access control is the most important security aspect for elevator control systems. Physical access to the controls is usually restricted and if the elevator works independently without being connected to any network, then that is often enough to ensure that no unwanted parties gain access to the elevator controls.

Elevator control systems are especially vulnerable to attacks if they are part of IoT and therefore inside an industrial control network. Then unwanted parties can gain access to elevator controls through the network with a malware [23]. Adversaries can then get information from the network and give false commands or prevent the elevator from operating normally [23]. It is also possible to do so-called man-in-the-middle attacks where a message between PLCs is intercepted and changed to a false value (Figure 3) [9]. This can be mitigated with proper authorization methods.

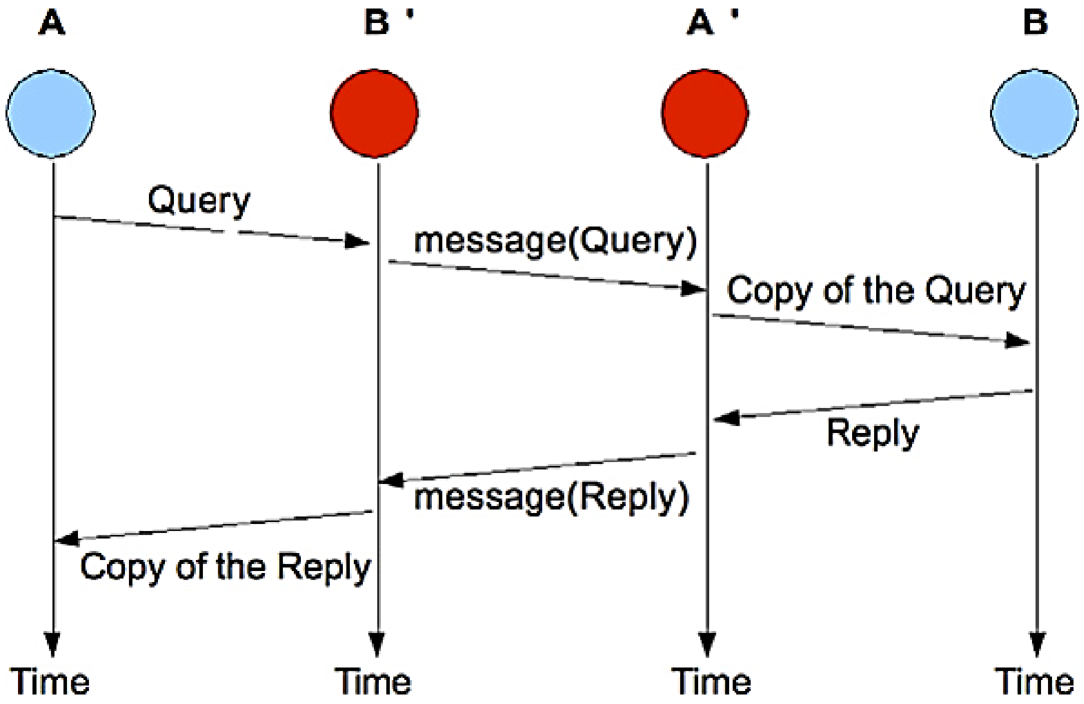

Figure 3. Man in the middle attack, where an unwanted third party intercepts and changes a message [9].

2.4. Elevator communication protocols

Modern elevator controls often have an interface built into them that allows them to communicate with other devices. This subsection identifies and evaluates elevator communication protocols and looks at the research question from the elevators point of view i.e., answers the question “what ways are there for the elevator controls to communicate with the outside world?”,

2.4.1. Application Programming Interfaces

Since IoT has become increasingly important in recent years, elevator companies have started to include a possibility to connect the elevator directly to a local area network. This gives the elevators their own IP addresses. They can then be controlled through Application Programming Interfaces (APIs) and many kinds of devices can be connected to them. Figure 4 has a high-level outline of a possible network where elevator controls are connected through API to the same local area network with mobile robots and users. Elevators can then be used and maintained through the network.

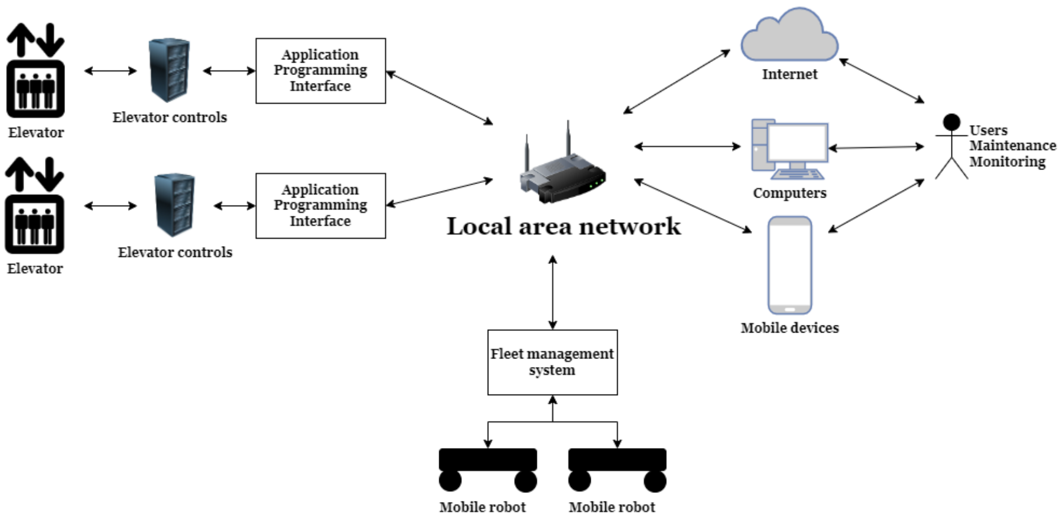

Figure 4. High level outline of a possible system where elevators, users and robots connected in the same local area network.

APIs can be seen as easier for the one implementing the elevator integration as there is no need to physically connect wires between I/O cards and PLC:s. Everything is done digitally between software running on other devices and the elevator controls. Most newly installed elevators have APIs ready or at least can easily be changed to include an API. Elevator companies tend to integrate API functionalities because it is much easier for them to use APIs to remotely monitor and partially perform maintenance.

Elevator companies use different protocols for their API systems. Some elevator companies have released their API documentation publicly to allow potential customers to familiarize themselves with them [24, 25]. For example, KONE uses WebSocket protocol to allow connection between the elevator controls and other devices in the network [24].

Elevator APIs help mobile robots, fleet management systems or some similar programs that usually control the robots, to control elevators. With API functionalities the elevator companies are also able to offer enhanced elevator experiences for users. Elevator APIs are therefore meant to make connecting devices to elevators easier. Some common advantages of APIs is the enabling of the addition of multimedia, entertainment, as well as the ease of use of mobile robots in elevators [21].

2.4.2. Input/output card or Programmable Logic Controller

If the elevator controls are not directly connected to a local area network, there needs to be a module that works as an interface between the network and the elevator controls. This can be either an input/output (IO) card or Programmable Logic Controller (PLC). This module is then connected to the local network and has an IP address.

IO-card can be used to read signals coming from other devices in the local network and then transform them to a type that is recognised by the elevator control system. Usually this means using a network cable to send data to a PLC in the elevator control system in the form of a binary digital signal. IO cards can also have simple logic built into them.

The elevator system created in the study by Hangli et al. [17] was changed in another study [15] by improving the agent server and the user interface. The later study focused on making the elevator more intelligent and time-efficient, thus increasing user-friendliness. The elevator was connected to a network to allow it to be part of the building IoT. IO-cards SN-4016-RT and SB4008-STT manufactured by Ontec were used to send and receive signals. The IO-cards were connected to a T-Engine Reference Board with a CPU that processed the input and output signals (Figure 5). Mobile robots were mentioned as potential future work in the conclusion chapter.

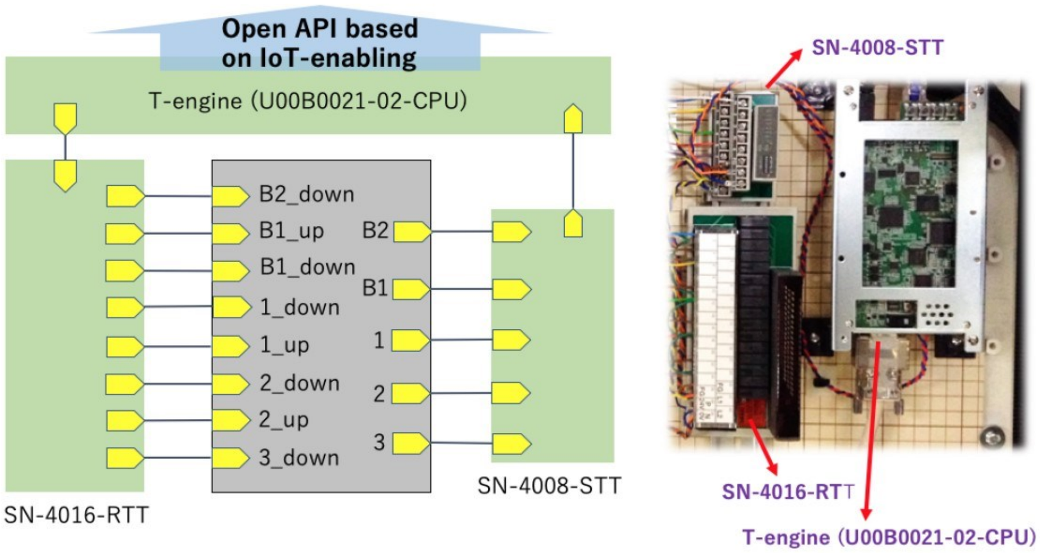

Figure 5. Components used in a study by Hangli et al. to make their elevator IoT enabled [17].

PLCs are similar to IO cards, but as the name suggests, they can be programmed to perform simple logical tasks. They can be seen as computers that are specialized to handle specific tasks. For example, the Rocon control box manufactured by RoboConnect Ltd (Figure 6) is an example of an elevator control system with PLC modules that MiR mobile robots in the Fleet Management System can use to control elevators [26].

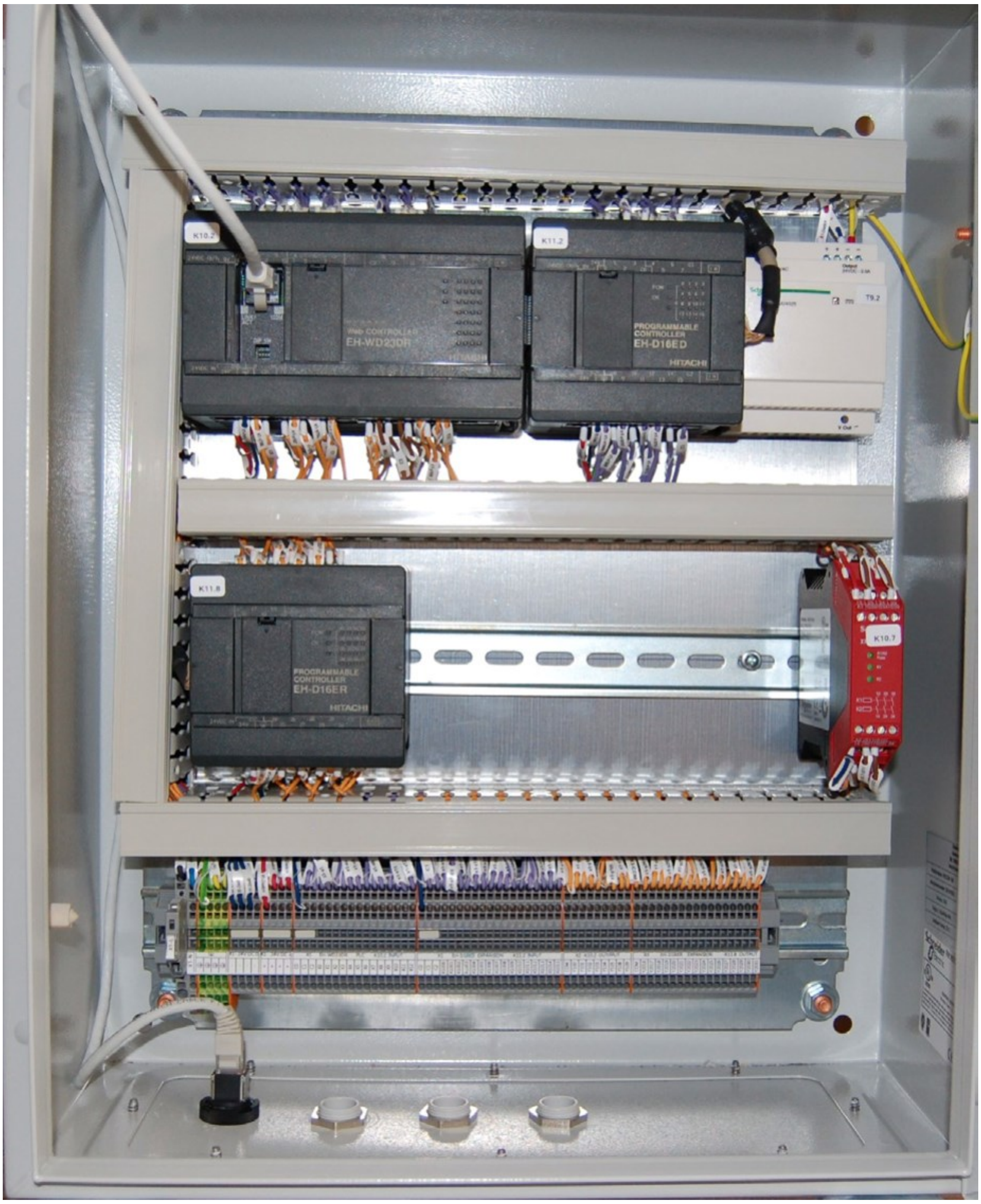

Figure 6. Rocon control box that uses four PLC modules to handle communication between MiR Fleet management system and elevators.

2.5. Literature analysis methods

A systematic data analysis of the state-of-the-art research will be conducted as part of this thesis. The analysis will focus on the communication methods between elevators and mobile robots with the specific research question being "What are the commonly used methods of communication between networked mobile robots and IoT devices such as elevators in a modern smart building?".

In Sections from 2.1 to 2.4 data was gathered from state-of-the-art research articles and then cleaned to identify the parts relevant to the research question. Data is analyzed and different methods are compared in Section 2.6. The results are interpreted and discussed in Chapter 5.

2.6. Literature analysis results

Many mobile robot studies that include floor-to-floor transition concentrate on stand-alone robots that can climb stairs or operate elevators without direct communication. However, there is plenty of research on IoT and communication between other devices that can be applied to mobile robots and elevators. IoT has gained a lot of traction in recent years, and some IoT research mentions mobile robots as possible devices to connect to the network.

There are three common ways to allow communication between elevators and mobile robots: PLCs, IO-cards, or APIs. Successful applications have been made with all three of these methods. The best method for each environment depends on the pre-existing infrastructure. If there are other devices already connected in the local area network forming an IoT the easiest solution is most likely to connect the elevators and robots to the network as well and let them communicate through it. If there are no plans to connect the elevators to anything else but mobile robots, then it is likely to be easier to implement the connection partly with physical systems such as IO cards or PLCs as most elevator controllers still require wired input and output connections.

3. Developed system

This Chapter describes the background, requirements and design of the robot-elevator integration system that was made as a case study for this thesis.

3.1. Background

GE Healthcare Finland Oy is a subsidiary of GE Healthcare which is part of multinational conglomerate General Electric. GE Healthcare is one of the largest Healthcare technology companies in the world [27]. GE Healthcare Finland Oy has a factory in Helsinki that manufactures and develops patient monitoring devices and anaesthesia equipment.

Lately the role of automation and usage of robots as part of the production in Helsinki has been increased. One of the automation projects has been to deploy a mobile robot that can be used to transfer assembly components from the receiving goods department to production lines and finished products from production lines to the shipping department. Currently this is done manually with carts pushed by workers. After trying out a few alternative mobile robots, a MiR200 robot by a Danish company Mobile Industrial Robots was acquired for the purpose of the automated transportation of production components and products. This robot was named Reetu.

The factory operates on many floors and as Reetu is a wheeled robot, it must use elevators to move between them. The factory has two Kone freight elevators for the purpose of transferring products between floors. These elevators were modernised a few years ago and are now operated by Kone KCE elevator controllers.

Mobile Industrial Robots company's fleet management system called MiR Fleet is used to control and access the robot remotely. This system runs on a Linux server that is connected to a local area network. The MiR Fleet software has built-in functionality for the robots to use elevators. Elevators and floors can be added to the system and the Fleet Management System then changes between them accordingly.

A Rocon Lift Interface Panel was installed in both elevator control rooms. It is a control box recommended by the manufacturer of MiR-robots that has been developed by a third-party supplier company called RoboConnect [28]. It is designed to work as an interface between the MiR fleet management system and most elevator controls. It is a cabinet that has two Hitachi EH-WD23DR PLC modules, two Hitachi EH-D16ED PLC modules, a

XPSAFL5130 safety relay, terminals and a power supply [29]. The PLCs handle the input and output signals.

The RoCon Lift Interface Panel is connected to the local area network with an ethernet cable and to the elevator control cabinet with signal wires. MiR Fleet management communicates with Rocon Lift Interface Panel through the network using drivers made by Hitachi [30]. Binary digital signals (24V) are used for communication between the Rocon Lift Interface Panel and the elevator control box. Both control boxes have PLCs that handle the incoming and outgoing signals. The connection infrastructure is illustrated in Figure 7. Although the robot is physically inside the elevator, the communication signals do not go directly between the elevator and the robot, but through the local area network.

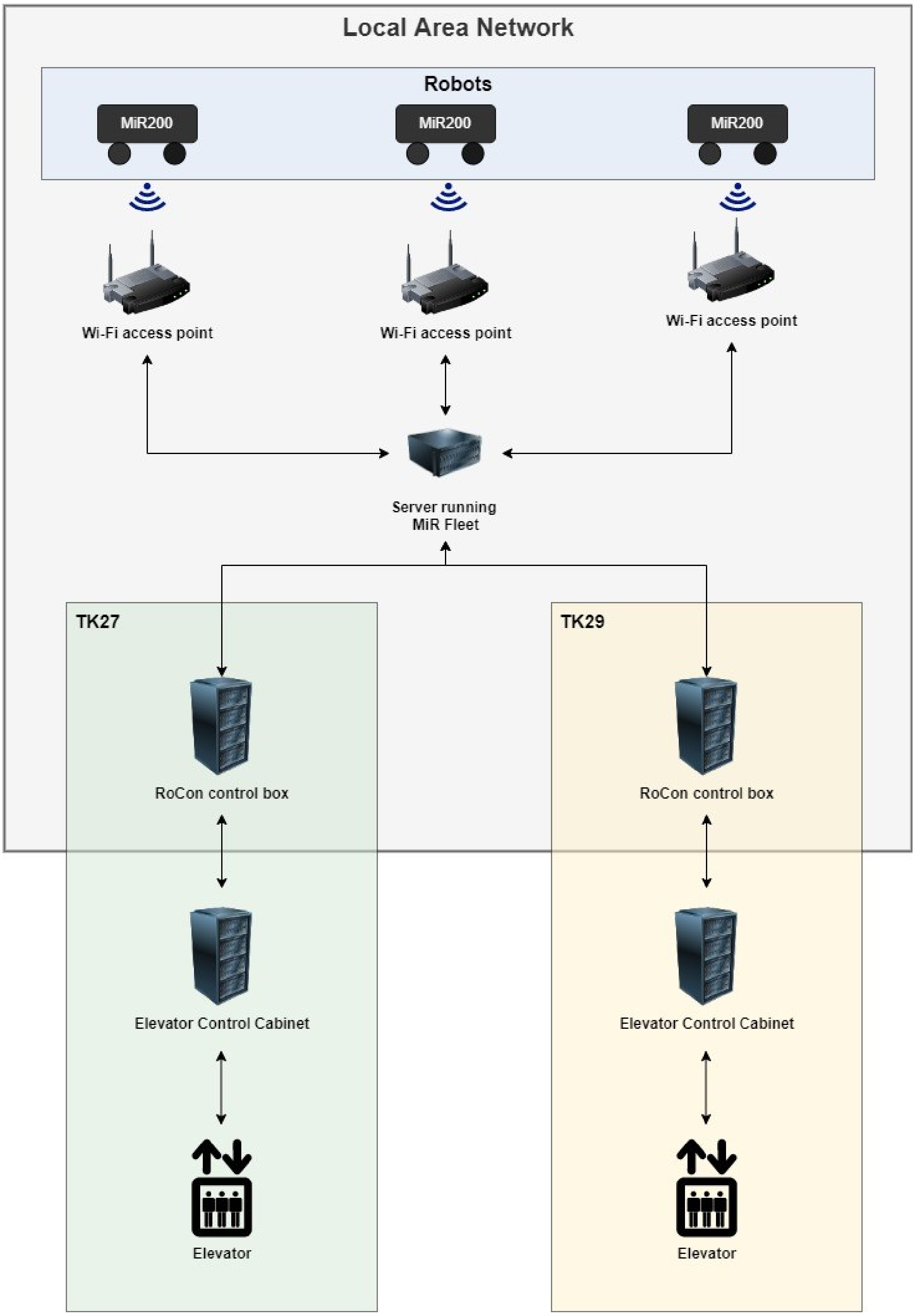

Figure 7. Connection infrastructure. The two freight elevators are in different buildings that are commonly abbreviated as TK27 and TK29.

Although the robots are physically inside the elevators, they do not communicate directly. Instead, the signals go through the local area network. The robots cannot reliably connect wirelessly to the local area network from inside the elevators as the metallic walls block the Wi-Fi signal (Figure 8).

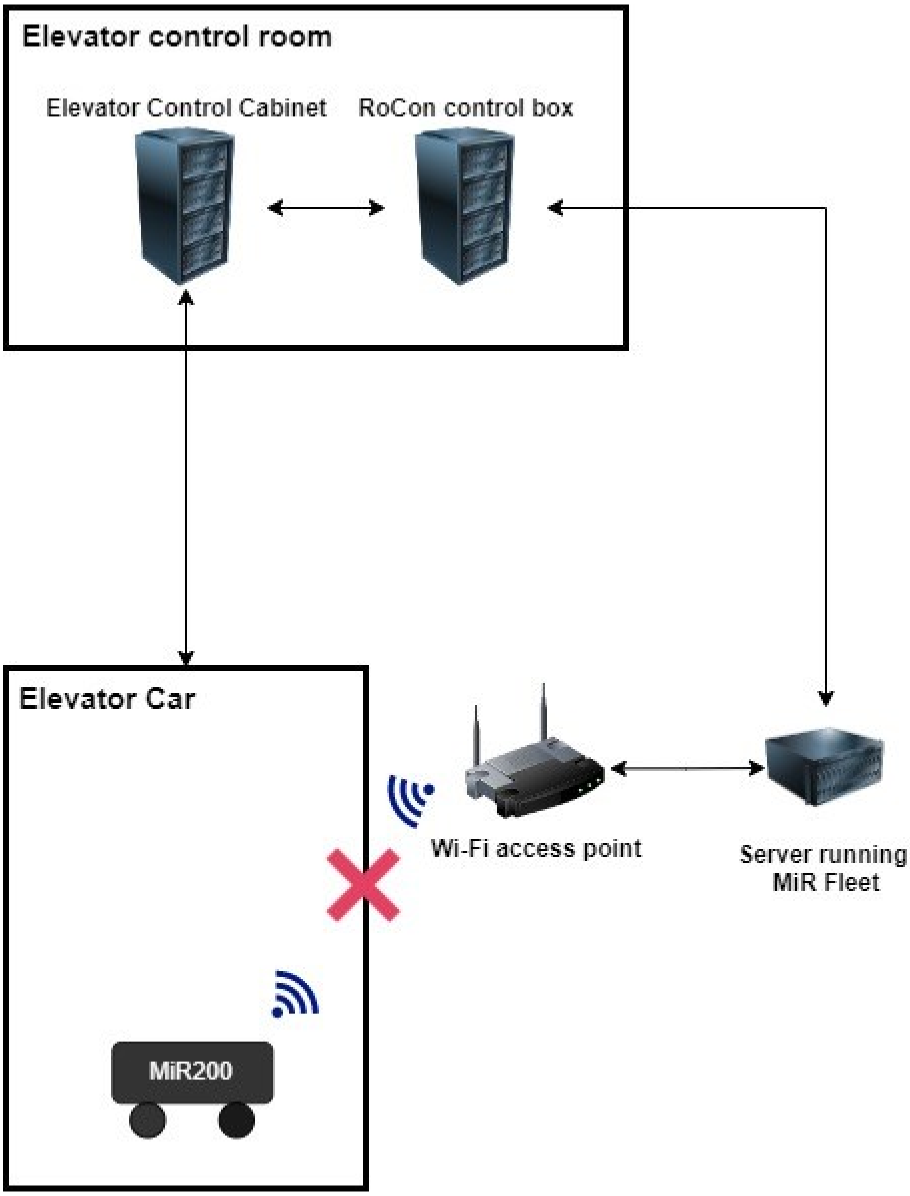

Figure 8. The freight elevators cars have metallic walls, which block the Wi-Fi signal used by the robot to connect to the local network.

The goal of the elevator integration project is that Reetu should be able to operate the freight elevators independently. This should be possible after communication has been established as the movement and navigation of the robot already worked previously. The MiR mobile robot, the RoCon control box and the server running MiR Fleet were all acquired before the work done on this thesis. Consequently, the goal of the case study is to design, implement and test the communication between these devices and the freight elevators of the factory.

3.2. Requirements

Minimum signals needed between the Rocon control box and elevator controller for the robot to operate the elevator independently are listed in tables Table 1 and Table 2. The robot must get information about the current elevator floor and the state of the doors, and it must also be able to send floor calls as well as open the elevator doors. In addition, maintenance and emergency information from the elevator is needed to prevent the robot to take control of the elevator in those situations for safety reasons.

Signal	Description
Floor Level Signals.	Indicate the current car position.
Front Door open.	Indicates the front door is fully open.
All Doors closed.	Indicates all doors are closed.
Rear Door open.	Indicates the rear door is fully open.
Inspection/out of order.	MiR Robots will not attempt to use an elevator that is in inspection mode.
Emergency mode.	MiR Robots will not attempt to use an elevator that is in Fire/Emergency Mode; if Robots is inside when the car enters Fire Mode, it will immediately release all control and remain passive.
Elevator is moving.	Indicates that lift is driving up/down.
Elevator gives access to robot transport.	Elevator controller gives access to the robot, so that it can use the elevator.

Table 1. Signals from Elevator Controller to Rocon input.

Signal	Description
Car calls.	MiR Robots send the car to the indicated floor.
Hold front door open.	Keep front door open.
Hold rear door open.	Keep rear door open.
Disable hall call.	The elevator should not respond to hall calls; car calls and door operation should not be affected.

Table 2. Signals from Rocon output to Elevator Controller

Working Wi-Fi inside the elevator car is essential because the robot needs to be able to communicate with the fleet management system to send the floor calls and receive the current floor information from the elevator even when the elevator doors are closed. Therefore, Wi-Fi access points were planned to be installed inside the elevator car to mitigate the problems caused by the metal walls. There would have then been a cable connection from the elevator control room through the shaft to the elevator car (Figure 9). This way the connection would have been wired and therefore not hindered by the walls.

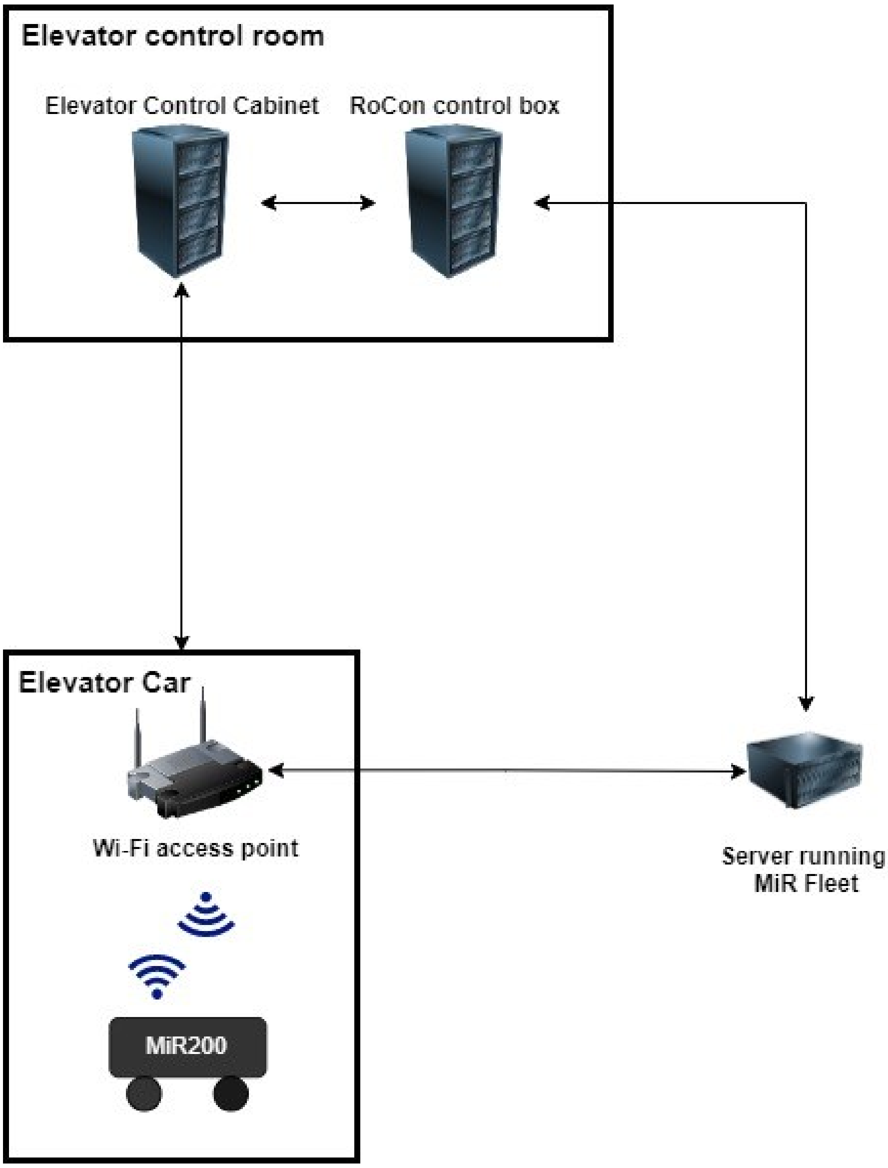

Figure 9. With the Wi-Fi access point inside the elevator, communication signals are sent wirelessly only inside the elevator car itself and not through the outer walls of the elevator.

The GE factory at Helsinki has two freight elevators in different buildings. These buildings are commonly abbreviated as TK27 and TK29. At the TK27 the robot is required to move between the receiving goods department on floor 1 and production on floor 3. For the TK29 elevator the third floor is split to two levels by a small ramp, because it used to be two separate buildings that have since been combined. The robot was tested between floors 3A and 3B because it cannot drive up or down the ramp with a load.

3.3. Design

Moving the APs inside the elevator cars proved to be more challenging than initially thought. The network cords going to the APs in the elevator cars are so long that extenders are needed to make sure the signal stays strong enough. These could not be acquired in time to be tested as part of this thesis. An AP was moved close to the elevator shaft to have as good a signal as possible inside the elevator. Although not ideal, this proved to be enough to be able to conduct other tests, as can be seen in the results in Section 4.2.

The fleet management system has a navigation map of each area the robots can move in, and consecutive areas have transition points where the robots can change maps (Figure 10 and Figure 11). Elevators are mapped as their own areas (Figure 12). When a robot enters or exits an elevator, it first moves to the transition point and then changes from a floor map to the elevator map and vice versa.

Figure 10. Transition points on the map in MiR Fleet management system.

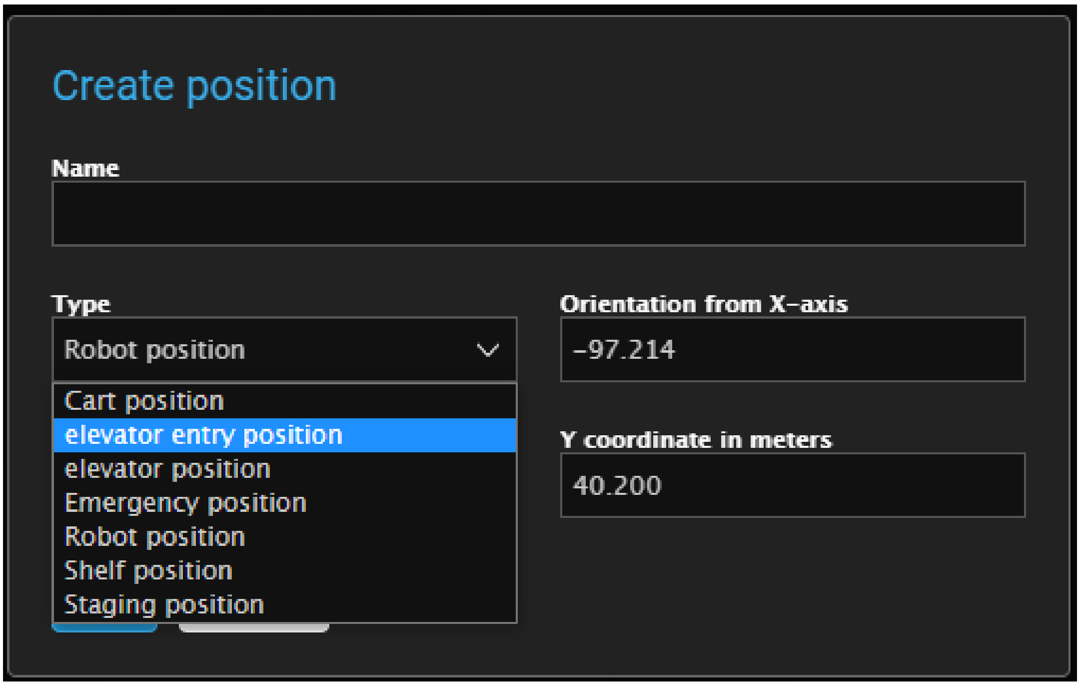

Figure 11. MiR Fleet management system has built-in elevator functionality. It is possible to add elevator related transition points to the navigational maps.

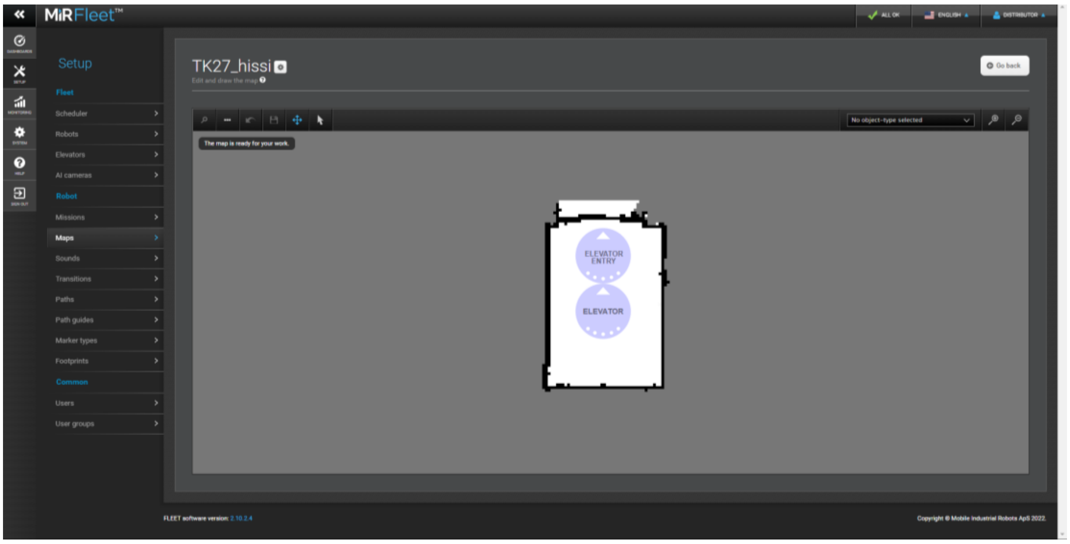

Figure 12. Map of the elevator car with transition points in MiR Fleet management system.

To use an elevator the robot must first move into the elevator entry point on the floor map and then request control of the elevator. This is done by sending a signal to the elevator controls to disable hall calls and thus make the elevator unavailable for humans [31]. The robot then waits for the elevator to be free, immobile, and the doors to be closed for set duration. This is done to ensure that the elevator is empty before the robot starts to operate it. Even after the robot has taken control of the elevator, it can be operated from the panel inside the elevator car but not from the panels outside. This way in case there is a person still in the elevator car, they can still use the elevator control panel.

After the robot receives a signal that it has control of the elevator, it will call the elevator to the robot's current floor and wait for it to arrive. The robot receives floor level signals from the elevator and thus it will know when the elevator has arrived at the requested floor. At arrival the elevator opens its doors, and the robot sends a signal to enable a loading-mode for the elevator that keeps the doors open. This allows for the robot to enter the elevator without the doors closing on it.

When the robot reaches the elevator transition point inside the elevator car it sends a signal to disable the loading-mode and let the doors close. Then the robot sends a floor call signal to the elevator and waits for the floor level signals to indicate that the requested floor has been reached. The robot will then again send a signal to enable the loading-mode and exit the elevator by moving to the elevator entry transition point outside the elevator on the floor map. Then the robot releases all signals to return the control back to the elevator and then it can continue with its mission on the new floor.

4. Experiments

This Chapter describes the experiments made with the mobile robot at the factory. The goal of the experiments was to determine whether the robot can operate the freight elevators independently and reliably and whether the signal strength stays strong enough inside the elevator to retain a connection to the robot. The communication signals include taking and releasing control of the elevator, sending floor calls, receiving floor level signals, and information on the door state. As navigation is not part of this thesis, it will not be evaluated in the experiments. The robot was able to move around and enter and exit the elevators even before the work done on this thesis.

4.1. Design

Figure 13 shows the steps involved in a robot operating an elevator. The eight steps that require communication between a robot and elevator controls have green backgrounds.

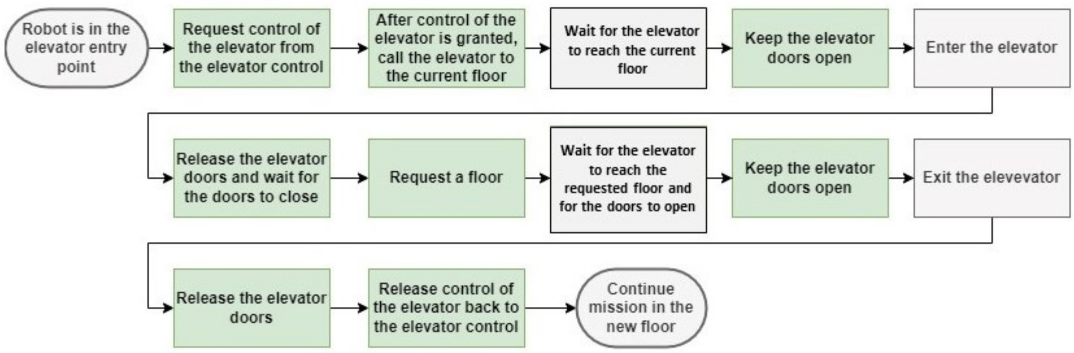

Figure 13. Flow chart of the steps the robot must take to change floors with an elevator.

To test the robot operation with the TK27 elevator, a mission was made with a testing point in the navigation map of the robots in both floor one and floor three. Reetu was then ordered to move between these points. The TK29 floor 3 is divided into two navigational maps, because it is effectively split into two floors from the robot's point of view. Testing points were made to both, and Reetu was then ordered to move between them.

There are eight phases in the communication between the elevator and the robot that will be evaluated in this thesis (Table 3Table 3. Phases/steps that are evaluated). First the robot must take control of the elevator. If this succeeds, the elevator floor screen indicates that the elevator is in service mode. Then the robot must call the elevator to the current floor. This can be easily evaluated by determining whether the elevator arrives. Next assessed behaviour is the door state. The door must stay open until the robot has fully entered the elevator car. Both freight elevators have loading-modes that enable the doors to stay open. Then the robot must send the elevator to the desired floor and there keep the doors open again. After the robot has exited the elevator car it must release the control of the elevator.

Phase#	Action	Effect	Evaluation method
1	Take control.	Elevator enters service mode.	Visual check from floor screen text.
2	Call elevator.	Elevator comes to the desired floor.	Elevator arrives.
3	Keep door open.	Doors stay open.	Doors stay open.
4	Release doors.	Doors close.	Doors close.
5	Send elevator.	Elevator moves to the desired floor.	Elevator moves to the desired floor.
6	Keep door open.	Doors stay open.	Doors stay open.
7	Release doors.	Doors close.	Doors close.
8	Release control.	Elevator exits service mode.	Visual check from floor screen text.

Table 3. Phases/steps that are evaluated.

The robot will be ordered to change floors 10 times with each elevator. The eight phases involved in the robot using the elevators (Table 3) will be observed. All the phases must be successful for the robot to operate the elevator. Repeated tests are done to test the reliability of the robot and to evaluate whether it can operate the elevator independently. Data from the tests will be presented in Section 4.2 and discussed in Section 4.3.

4.2. Results

Figure 14 shows that the signal strength diminishes from around -55 dBm to -80 dBm inside the elevator car when the elevator door closes. dBm scale is logarithmic with -30 dBm being the maximum achievable signal strength and -90 dBm being practically unusable. For the signal to be reliable for package delivery it would have to be at least –70 dBm strong [32]. MiR mobile robots require a signal strength of at least -75 dBm [33]. Wi-Fi signal strength was measured using a laptop with a free software called inSSIDer [34]. The accuracy of this measurement is enough to observe the drop in signal strength as the elevator doors close.

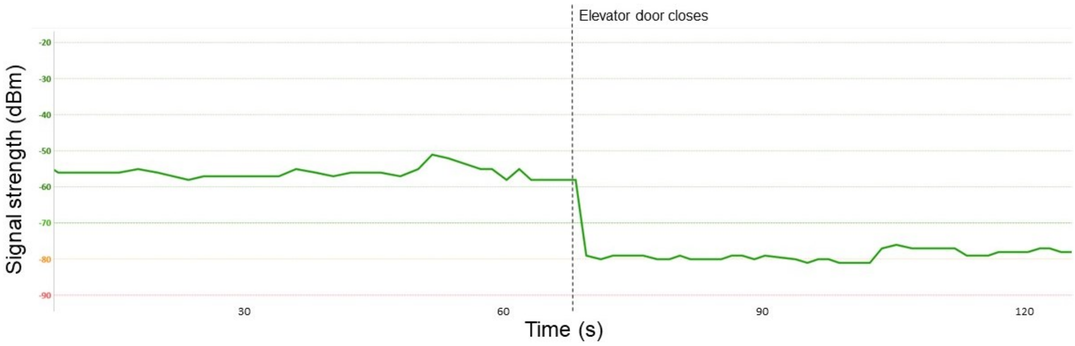

Figure 14. Wi-Fi signal strength inside the elevator car in decibels in relation to milliwatt (dBm).

Figure 15 illustrates that the signal strength still diminishes significantly even when the AP was moved close to the elevator shaft. However, the signal stayed strong enough to maintain a connection and conduct the other experiments of the case study.

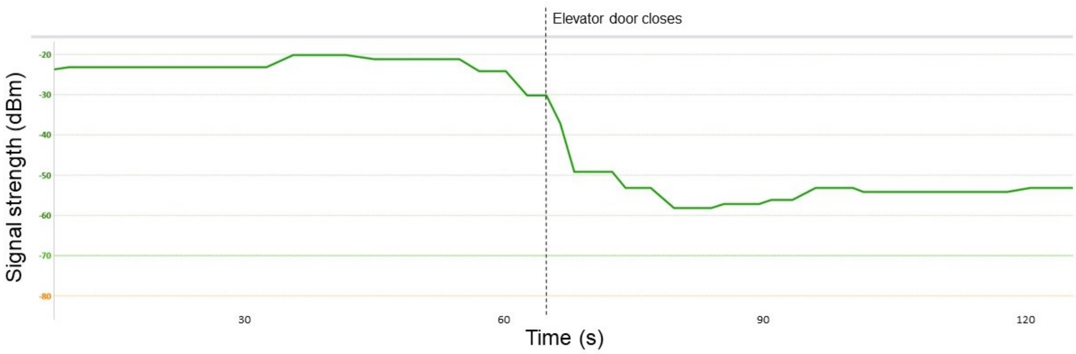

Figure 15. Wi-Fi signal strength inside the elevator car with the AP close to the elevator shaft. Signal strength is better than in Figure 14, but still it diminishes significantly when the elevator car doors are closed.

Table 4 presents the success of the phases in the 10 experiments conducted with the robot in building TK27. The elevator call signal did not go through when testing the robot. This is due to a bug that appeared in the elevator access control system after it was updated which allows only one floor call through per boot. This bug could not be fixed during the making of this thesis as only Kone approved professionals are allowed to adjust or modify the elevator controls and they were not available soon enough.

The bug cripples the robot operation in TK27, and it could not be tested properly. Only the first phase was successful i.e., the elevator entered service mode. The elevator control system did not process the floor call of phase 2. Unfortunately, this single test does not give any meaningful information as the bug that prevents the floor calls from being processed is not related to any of the parts configured in this thesis and technically the communication between the robot and the elevator could not be tested almost at all.

		Phase #							
		1	2	3	4	5	6	7	8
Test #	1	Pass	Fail	N/A	N/A	N/A	N/A	N/A	N/A
	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	10	N/A	Fail	N/A	N/A	N/A	N/A	N/A	N/A

Table 4. Results of test conducted in TK27. The software bug in the elevator controls effectively prevented the testing of the communication between the robot and the elevator. Phases are explained in Table 3.

Table 5 shows the results of the tests conducted in building TK29. Fortunately, the bug that crippled the communication in TK27 does not appear in the other elevator at TK29, as the elevator control systems are slightly different, so the robot could be tested as planned. In TK29 the robot was tested 10 times by sending it between floor levels 3A and 3B.

		Phase #							
		1	2	3	4	5	6	7	8
Test #	1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	3	Pass	Fail	N/A	N/A	N/A	N/A	N/A	N/A
	4	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	5	Pass	Fail	N/A	N/A	N/A	N/A	N/A	N/A
	6	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	7	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	8	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	9	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	10	Pass	Fail	N/A	N/A	N/A	N/A	N/A	N/A

Table 5. Results of the tests conducted in TK29. Phases are explained in Table 3.

Of the 10 times Reetu attempted to operate the elevator itself, it was successful 7 times. In three of the tests the elevator did not arrive at the floor the robot was waiting on. In addition, after test #7 the fleet management system MiR Fleet was no longer able to give missions to robots and Reetu had to be given missions directly through her own interface.

An additional new issue that emerged during testing is that an emergency stop is triggered every time the robot detects obstacles that are next to it. This happens if the robot drives to a wall or if someone walks too close. This is usually not a problem as the robot clears the emergency stop itself and continues its mission independently. However, the emergency stop also terminates all signal calls. This is a problem if the emergency stop is triggered while the robot is entering an elevator and keeping the door open with a signal to the elevator controls. This signal is then also cancelled, and the elevator doors are no longer kept open. When the emergency stop is cleared and the robot tries to continue, it will not open the doors again, it will only try to enter the elevator. If the doors were closed during the emergency stop, the robot cannot enter the elevator as the doors are now blocking the way.

This event will likely happen occasionally as people are going to enter the elevator at the same time as the robot and walk close to it which will trigger the emergency stop. To mitigate this problem, the robot would have to change the way it returns to normal operation after an emergency stop. This would require changes in the fleet management system which are not possible to do when using the ready-made MiR Fleet software.

Another problem that emerged after Reetu managed to communicate with the elevator was that her sensors saw extra obstacles inside the elevator. This is because the elevator car walls are slightly reflective, and the scanner signals used to monitor the environment bounces off them. A simple solution to this would be to cover parts of the wall surfaces with non-reflective coatings.

4.3. Discussion

For a system that is supposed to be independent, working seven times out of ten is not sufficient. There was no need to test more than ten times as the robot had not seemed to work any better during previous unofficial testing. Ten tests are enough to determine that in the present state the communication between the robot and the elevator does not work reliably.

When operating elevators, the MiR interface only indicates that the robot is completing its mission, but if nothing happens there is no way to determine if the robot is trying to do something or waiting for something to happen. This makes debugging problems related to the MiR mobile robots difficult, as there is no way to see what the robots are doing specifically. The robot that was used in this thesis also did not handle the errors that it encountered well. Every time there was a problem, the robot just stopped and waited for an operator to fix the situation. This is not acceptable behavior for a system that should be able to operate independently. To mitigate these problems, better and more specific access to the robot operation is needed by either getting it from the manufacturer or inviting someone from the manufacturer to troubleshoot the robot on site.

When testing the robot there were several occasions when the floor calls did not go through from the robot to the elevator. This problem would then not occur again after rebooting the MiR Fleet software. This would indicate that the software itself is unreliable which makes it difficult to have the system operate independently in the future.

Another difficulty when troubleshooting the process of a robot using the elevators was that access to the elevator control rooms is restricted and only certified Kone mechanics are allowed to modify the elevator controls. This is a normal procedure to ensure that the elevators stay functional and are safe to use.

The local office local area network that was used for the communication between the elevators and the robots is highly monitored and has firewalls to keep the site secure from digital threats. The connections were checked with the IT department and there should not have been anything that interfered with the connections that were being used, but the system is complex and difficult to troubleshoot so there is a possibility that something is interfering with the signals.

In the system used in this thesis the signals between the elevators and the robots went through four devices that handled the data. With every device the possibility for errors is increased. With API the number of devices could be dropped to three or even two. Therefore, a system with separate PLC control box that communicates with the elevator controls seems unnecessarily heavy and unreliable as the main issue seemed to be interconnectivity problems with these devices.

5. Conclusions

Recently elevator companies have brought API solutions to the market. API allows the manufacturer to monitor the elevators and even perform some of the maintenance remotely. It is not only easiest for them but seems also to be easiest for the user.

Current widely used Wi-Fi technology does not penetrate building walls well enough for the signal to be reliable inside elevators. The MiR Robots used in this thesis use a 2.4 G Wi-Fi signal and it seemed like an access point was necessary inside the elevator car. Newer protocols and more advanced communication technologies such as 5G penetrate walls better and make enabling IoT in buildings possible with fewer access points and could reach the moving elevator car wirelessly [1].

In the future if IoT becomes common [9], elevators are likely going to be more frequently connected to local networks as well. Even if the connection is originally made to allow maintenance and remote monitoring, it will make it considerably easier to implement connectivity to mobile robots as well. Elevator companies are pushing their API functionalities to the market as it is more efficient for them to be able to monitor elevators remotely through a cloud network rather than doing everything on-site.

PLC controllers have been used for decades to control elevators, but they are steadily being replaced by more robust computers that allow more complex software [21]. Directly connecting elevators to local area networks is a recent advancement, so most buildings still have more traditional elevators that operate just by themselves.

At GE, the mobile robot used in the case study was not able to change floors continuously without errors. For it to be able to that, the reliability of the system needs to be drastically improved. This requires better error handling from the robot in cases where communication is lost somewhere between the robot and the elevator controls.

The problem with the Wi-Fi signal being blocked by the elevator car walls could not be mitigated completely in time for this thesis. However, in all the failure cases the problem turned out to be something else than the communication between the robot and the fleet management system as the signal seemed to work between these two. It would still be recommended to move the APs inside the elevators to make sure the signal strength is stronger, and the connection is more secure.

One possibility at GE would be to continue with the modernization of the elevators to enable API functionalities and abandon the RoCon control box altogether. This could require more initial work to make the connection functionable, but it could also reduce the work needed to maintain the connection and make it more reliable as there would be less devices included.

Another way to increase the reliability would be to update or change the fleet management system as the MiR Fleet software seemed unreliable. Many companies have made their own solutions to control mobile robots and enable them to communicate with other devices. There are few readily available and working solutions in the market as the field is still new.

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