ROBOTIC TILING SYSTEM

An adaptive and high-precision robotic solution for the construction industry

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ABSTRACT

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ABSTRACT

The construction industry is one of the least automated and digitalized industries globally due to the massive employment of the human workforce there. Commissioned by the Robotic Research Group-a subsidiary of the HAMK Tech Research Unit of Häme University of Applied Sciences, this robotic tiling project aimed to transform the tiling process of the construction industry. As a part of a three-stage project, the scope here was to establish an operation logic and develop a high-accuracy PLC-based measurement system for the robotic tiling concept. Besides, the development process of this thesis included the design of a user-friendly HMI and a data acquisition system for the project.

To achieve a solution, the following concepts were examined in the theoretical part: collaborative robot, programmable logic controller, human-machine interface and photoelectric sensor. Furthermore, the concept of industrial data communication protocols was examined. Extensive discussions between the supervisor of the commission party and the students engaged in the conceptual project were conducted on a weekly basis. The discussions were to ensure that the advancement of the project was right on track. The author also received considerable technical support from the manufacturers of industrial equipment used in this project.

The outcome of this thesis project was comprised of a fully developed operation logic supported by a millimetre-grade accurate Siemens PLC-based sensor measurement system. Besides, a highly configurable human-machine interface established from the new Siemens HMI template and a data acquisition system was successfully established and tested. Conclusively, the thesis project achieved all the targets set by the commissioning party; it is the initial premise for the other two parts of the robotic tiling concept.

Keywords Collaborative robot, PLC, HMI, Profinet.

Pages 33 pages including appendices 1 page.

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LIST OF ABBREVIATIONS

CPU	Central Processing Unit
FBD	Function block diagram
GSD	General Station Description
HMI	Human-Machine Interface
IL	Instruction list
KPI	Key performance indicator
LAD	Ladder logic
LED	Light-emitting diode
MES	Manufacturing Execution System
OPC UA	Open Platform Communication Unified Architecture
OSI	Open Systems Interconnection
PC	Personal computer
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
SFC	Sequential function chart
ST	Structured text

1 INTRODUCTION

This section introduces the mission of the Robotic Research Group and describes how the scope of the thesis project fit to that vision. In the last part, a clear target for the robotic tiling solution is also presented.

1.1 Overview of the Robotic Research Group of HAMK Tech

The Robotic Research Group is a division of HAMK Tech Research Unit. The research group concentrates on the application of collaborative robotics in various industries such as manufacturing, construction and horticulture. The general projects of the research group are the combination of industrial automation and robotics solution to solve practical problems of productivity, quality and safety. Since its establishment, the Robotic Research Group has continuously evolved and gained specific achievements in promoting automated robotic applications to companies in the region.

1.2 Project background

The construction industry has always faced numerous challenges associated with labour and the environment. Considered to be the industry that has the least labour productivity, the time a construction worker spends on-site is an imbalance to the output achievement. A report from the US Bureau of Labour Statistics indicates the efficiency has even been diminishing for many decades. To add more injury to one of the world’s oldest industry, the European Commission estimates that 25-30% of the total amount of material waste comes from the construction industry (Higgins, 2019). While other industries have long seized the advantages of employing various automation technologies including robotic to benefits their production, construction is still lagging. Facing the disadvantages, the industry is in desperate need of automation and digitalisation to do more with less. Constant development in robotic technology is transforming the old industry to the new age of automated production. The Hadrian X and SAM100 automated bricklaying solutions offer the reduction of operation cost, waste and safety hazard. Hadrian can construct a wall of a house in a single day; which is must faster and cost-effective than employing human worker. In transporting materials to the construction site, HX2 is the autonomous vehicles that employed vision systems to detect humans and obstacles. Doxel is a small tread-based robot that drives around the construction site with Global Positioning System and using lidar scanner to assess the site. The collected data constructs a clear picture of the process and quality of the whole project (Matthews, 2019). Mentioned above examples shown even an industry that has a notorious reputation for slow adoption of new technologies, is transforming to adaptive production and digitization age.

While a vast majority of robotic advancements has made their way to construction engineering, human work force is still mostly responsible for the tiling for flooring process in building construction. Starting with laying down the cement broad and grout; which is a dangerous chemical that can cause first-degree burn if getting into the eyes of workers. Not to mention wet cement in the process can also cause lifelong chromium sensitisation. The gap alignment requires a manual measuring with chalk lines and grout spacer. The continuous process for proper flooring is physically demanding and require highly trained professionals. The Robotic Research Group has previous experience in the development of UR5-based robot solution in the construction industry. A concept of a automate tiling process deems possible by the head engineer at the Research group. The main target is to automate the cement and tile placement for the flooring process using an existed UR5 robot platform. The conceptual project has three stages and involves tiling of a four by four floor. For this concept, the UR5 robot performs the tiling operation of a set of 20 by 20cm tiles. The three stages include logic planning and automation design, mechanical design and robot motion planning. Further development takes place when the first three stages finished. The successful development of the fully automate tiling solution has a strategic significance of increasing the competences of construction companies in the region considerably and premising the robotic development within HAMK.

1.3 Targets for the experimental process

The robotic tiling project is the involvement of three students from Häme University of Applied Sciences; each student has a specialized expertise area and in charge of different parts of the project. There are three parts in total. The first part and second part are planning and automation design in which the author and another automation student take charge. A mechanical student form Riihimäki campus handles the mechanical design and production process of the project. The students must consult and report to the commission party’s supervisor and HAMK’s thesis supervisor after completing each of the states of the project.

Three students involve in this project have agreed and divided the robotic tiling project into three main parts. Details about each of the three parts of the robotic tiling project are in the Table 1:

Part	Category	Personal	Main tasks
1	Project planning and automation	The author	• Component selection • Operational logic planning • Sensor integration

			- Data communication between the robot and the PLC - PLC Programming - HMI design - Data acquisition system design
2	Robot movement planning and project finalisation	Duong Truong	- Programming the UR5 robot movement with established signals from the PLC - Robot sequential testing - Project finalisation
3	Mechanical design and production	Nitija Thapa	- Design the scanning tool - Design the concrete dispenser - Material selection and material’s strength testing - Production of robot’s tools - Testing of robot’s tools

Table 1. The three main parts of the robotic tiling project.

2 THEORETICAL FRAMEWORK

2.1 Collaborative robots

This chapter introduces the key definitions and the main differences between collaborative robots, the more widespread industrial robots into the discussion. The purpose of this assessment is to comprehend why the commissioning party deployed cobots for the empirical part of this thesis.

2.1.1 Definition of collaborative robots

Collaborative robots or cobots are robots that are designed to safely interact or operate alongside human within proximity (Roehl, 2012). The primary duty of cobots is to assist human employees with dangerous, strenuous or tedious tasks. Corresponding to ISO 10218 part 1 and part 2, 4 factors make cobots collaborative:

- Safety monitored stop: This function allows cobots commission with a set of pre-defined safety zones or barriers. The robot will stop movement altogether when human enter the restricted area.
- Hand guiding: Operator can access this function to rapidly teach the trajectory for the robots, for example, in pick and place application.
- Speed and separation monitoring: The robot system has a laser or vision system to monitor the position of workers. If a worker breaches the specific predefined safety limit, the robot will respond consequently with designated speeds (generally slower or full stop).

- Power and force limiting: Force sensors continuously detect abnormal forces acting on the robot when carrying out work tasks. The robot comes to complete stop or dissipate forces when irregular forces are overload.

The fourth function is an essential function when it comes to the ability to deal with safety hazards of cobots. Technical specification ISO/TS 15066 specify the maximum energy (J) and force (F) that can be applied to a human being by the robot without causing any harm (Bélanger-Barrette, 2015). By employing cobots, productivity and the safety of workspace will substantially growth.

2.1.2 Collaborative robots or Industrial robots

The fundamental difference between collaborative and industrial robots is cobots are aimed to work alongside human operator (Roehl, 2017). On the flip side, factories worldwide deploy industrial robots to automate the manufacturing process entirely without any operator interaction. Industrial robots are frequently operating in safety barriers. These barriers include physical fence or presence sensing devices such as a light curtain or floor mats. The performing robot unit will shut down instantly if there is any severe safety hazard to prevent injury to human. Implementing safety elements to industrial robot cells is mandatory when commissioning industrial robot, hence, pumping up the price for many small-scaled experimental robotic projects to the point it is unprofitable. Conversely, the utilisation of collaborative robots such as the Universal robot UR5, UR10 series lower the cost of implementation drastically. Thus, cobots are generally more comfortable in programming aspect compare to industrial robots. The capability of “learning” on the job of cobots are unique since factory workers can re-program a cobot by just only moving it along the desired track. Industrial robots demand specialised programs such as Sunrise of Kuka and a well-trained engineer to program. Overall, the deployment process of industrial robots require additional time and cost compared to the collaborative robots.

One downside of cobots compare to the industrial counterpart is the payload. The industrial robot can handle heavy materials of hundred kilograms thanks to their heavy-duty drive system. While the behemoth industrial robot arm M-2000 of Fanuc can lift to 2.3 tonnages of cargo, Universal robot’s UR16 has a modest maximum payload of 16 kilograms. However, under experimental projects such as robotic tiling solution, the payload does not pay that much of a significant role compared to human safety and robotic precision. With the astonishing repeatability of +/- 0.1 mm for most of the UR cobots from Universal robot company, they are more than capable of carrying out the tasks (Universal robots, 2016). Ultimately, for laboratory projects which will gradually act as experimental and learning tools for student, collaborative robots outweigh industrial robots in cost, safety and ease of programming aspects.

2.2 Programmable Logic Controller (PLC)

This section is intended to introduce the definition, architecture and a brief comparison between programming languages of the programmable logic controller. Programmable Logic Controllers (PLCs) or programmable controller are widely used devices controlling industrial machines and processes. It is a computer that has been ruggedised to operate in harsh environment and highly adaptive to a variety of manufacturing processes. Dissimilar to a general-purpose computer system, the PLC is destinated to run a single, discrete, dedicated process, specific to the application of the factory and specialised to achieve total control over related functions. Since its first creation, PLCs have been employed in every factory all over the world to control from chemical processes, assembly lines to robotic devices (Walker 2012, 20). Based on its popularity and importance, there is no doubt that PLC technology is the heart of Industrial Automation.

With its variety of I/O configurations, the PLC is intended to abridge the connection of the factory’s floor sensors, instruments and actuators. Inputs and outputs from I/O system are detached onto input only and output only cards for a complementary and modular approach of PLC systems. The I/O cards are then inserted directly into a rack that enables the interfacing between the sensors, actuators or other PLCs that allows to the I/O cards and the central processing unit (CPU) of the PLC (Walker 2012, 45). Figure 1 demonstrates a complete PLC system with input, output cards and CPU module in the block diagram. Although the design seen in Figure 1 is from 1976, PLC manufacturers have still employed a similar design principle until today. As the design of PLC progresses, modern PLCs such as the Siemens ET200SP Distributed IO system has advanced and highly modular IO cards that allow hotfix and up-grade by swapping IO cards onsite in a matter of seconds without having maintenance staffs to rewiring I/O cards.

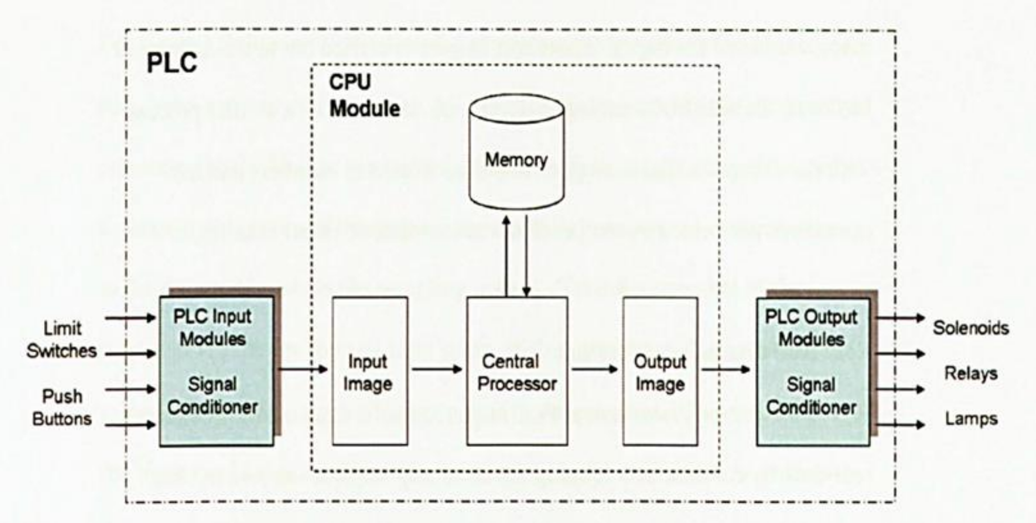


Figure 1. An early conceptual design of a complete PLC system in 1976 (Walker, 2012).

Automation designer programs modern PLCs by using application software installed on a personal computer. PLC programmers physically link the PLC to the PC via USB, RJ45, RS232, RS-485 or RS-422 cabling. Nowadays, Ethernet with RJ45 port connection is the most common way to join PC and PLC. With the networking to PC established, programmers then can utilise vendor-specific development environments such as Siemens TIA Portal, Beckhoff TwinCAT or Rockwell RSLogix to program PLCs. Generally, the development software package from PLC the manufacturer provides diversity options for troubleshooting, debugging and cross-referencing the PLC software. Additionally, the development environment permits downloading and uploading the PLC program to and from any designated PLCs that is connected to the same network by just a click. These tools ease-off the programming process and enable a programmer to modify or comprehensively overhaul PLC programs from another programmer successfully.

According to IEC 61131-3:2013 standard, programmers can program PLC using any of the standardised programming languages. There are four PLC programming languages divided into two groups: textual group and graphical group. An additional set of graphical elements is the last group to be classified for constructing the internal organisation of the PLC program (IEC 2013, 8). The textual PLC programming language which comprises of Instruction List (IL) and Structured Text (ST). In the two, ST is popular among programmers for the similarity of it and high-level programming languages such as C or C++. Contrast to ST; IL is a low-level language comparable to Assemble Language. IL is exceedingly hard to debug left alone debugging or modifying the already made programs from other programmers. Although it is believed that IL bears the benefit of fast loading and taking less space in PLC’s memory, the new PLCs with faster and spacious memory makes the language obsolete and now, can only be found in legacy systems. The graphical languages comprise of Ladder Diagram (LD), Function Block Diagram (FBD) and lastly, Sequential function chart (SFC). Ladder Logic is alleged to be the most wide-spread language of PLC programming for it representing each network as the demonstration in a circuit diagram for relay logic control. Therefore, LAD is extremely popular among those with an electrical background. In the other hand, FBD is the jack-of-all-trade in the graphical programming language selection of PLC. With the visualisation based on logic gates of FBD, it is the well-suited language for engineers with electrical or computer science background. Both graphical FBD and LAD are straightforward to debug as individual contacts or gates are highlighted to show the Results of Logic Operation (RLO), so the programmer can quickly navigate what is preventing the coil or gate from being energised. Although not specified as an official programming language by IEC 61131-3:2013, the fifth “language”, is SFC which is a graphical method of constructing the internal organisation of PLC programs based on GRAFCET. Together, all five programming languages create extreme flexibility for programmers to program PLC to specific needs.

2.3 Human-machine Interface (HMI)

This section explains the definition of a Human-machine Interface. A methodology of how to design a good HMI and the comparison between HMI and SCADA are also shown.

2.3.1 Definition of HMI

A Human-machine Interface (HMI) is an operator interface or dashboard that allows users to control or monitoring a machine. Technically, the application of the HMI term points to any screens that enable the user to interact with a device; however, Most industrial processes employ the HMI in the context of real-time control. In the industrial configuration, an HMI usually displays:

- Control screen with operation modes on control inputs
- Graphics and oversee KPIs (key performance indicator)
- Track production date and time, trends and tags
- System diagnostic, messages, warning and alarms
- Servicing screen with input and output tags

HMIs comes in a variety of formats such as PC-based application, a built-in screen on the machines and mobile tablets or monitors. The most familiar responsibilities that interact with the HMI s are operator, control engineers and system integrators. HMIs are the essential resources for professionals who work with processes in the operation site. With HMIs, process monitoring, problems diagnostic and visualised data are in the reach on the hands.

HMIs communicate with field sensors and actuator via the Programmable Logic Controller (PLC) to serve various functions. Depend on the specification of the HMI, the communication with the PLC establishes via RS232, RS 485 or industrial ethernet such as Profinet. Some unique HMIs runtime can communicate with software PLC via softbus. HMIs also can connect to higher-level control systems such as SCADA (Supervisory Control and Data Acquisition System) or MES (Manufacturing Execution System). Hinge on the implementation, HMI screens can serve from simple applications such as monitoring, switching or tracking to sophisticate applications such as increase/decrease the production speed. By leveraging HMI, operators have the ability to observe and managing industrial processes with digitising and centralising data all in one console. The HMI integration to the plant’s control system eliminates significantly the operation cost and human errors caused by the lack of real-time information.

2.3.2 Designing an efficient HMI

A good HMI design provides the operator with a strong visual understanding of the operation process with both moderate and complex applications. As HMIs are the crucial points that hold the interaction between the user and high-stress industrial processes, a well-designed and thoughtful HMI makes this interaction seamlessly. A good HMI also provides the operator with a full picture of the industrial process; hence, keeps the safety hazard at the minimal level. On the contrary, a poor designed HMI hides potential problems. By adding confusion to the operator, an inadequate-planned HMI causes a reduction to overall system performance or even injuries/fatalities for the plant’s operator. In conclusion, HMI design has significant importance in ensuring the flawless operation and reducing safety hazards of industrial processes.

A proper screen layout is the first thing to be done for a decent HMI display. As with many regular screens, the human operator scans the HMI from the top left corner to the right side and down the screen. Therefore, it is crucial to keep important KIPs at the places where the operator eyes can go smoothly. Alarms, warning, date/time and login information are on the very top of the screen. Graphical objects should locate on the centre-left with data on the centre-right. Critical control functions such as alarm reset or emergency stop button should be on the upper left side to prevent any miss presses. The navigation must be on the lower right side. The figure below indicates a well-established HMI design with a modern-looking interface:

State Production
Current Recipe R/120/200
Operator Mike

Overall OEE 81.20 %
Availability 62.80 %
Performance 76.10 %
Quality 82.40 %

Figure 2. A layout designed for smooth operation, transparency and expandability (HMI Template Suite application note 91174767, n.d).

The screen layout is the backbone of a well-designed HMI as it lays down the foundation for all HMI's objects (Hossain & Zaman, 2012).

The second most crucial aspect of designing an HMI is using the correct colour scheme. There is the universal colour code for representing certain operations:

- Red: stop, emergency, dangerous or prohibition.
- Green: start, selected or normal operation.
- Yellow: warning.
- Blue: compulsory operation.

The HMI designer must maintain the colour conventions to provide visibility clearance and avoid misinterpretation or confusion for the operator (Hossain & Zaman, 2012).

A proper representation of data values enables the operator to read and observe essential system parameters accurately. Data values scattered around a picture or graphic objects are difficult for the operator to scan. Hence, data values must be concentrating on one group of the HMI screen. If the automation process requires a comparison between the values, the designer must place the data in tables and locate them next to each other. Besides, HMI creator must take the unit of each data field into proper labelling and ordering. A graphical value is always easier to understand and respond to than alpha-numeric values. Besides the excellent presentation, the designer must take the critical level of a specific data into account when designing the data field in order to avoid the confusion of the operation process (Hossain & Zaman, 2012).

Alarms and events are the critical parts of the HMI since it supports the operator to quickly identify and prevent malfunctions that might occur during the operation. Alarms should be regards as significant changes in the system control process and require immediate actions from the operator. Therefore, the record of all alarms during operation prosses is necessary. The following characteristics are essential for alarm functions (Hossain & Zaman, 2012):

- Informative: short and informational alarm notifications help the operator realising and isolating the problems faster. For example, “Pos 21U1, Frequency converter error”.
- Preventive: the process stops immediately or slows down significantly to prevent further damages to the operation. For example, the machine shuts down automatically if there is a breach in the safety zone.
- Audio alarms: different audio is useful to grab the operator's attention or to identify the problems quickly.
- Complete elimination of safety hazard: the operation is unable to restart the process if the error is still present. In another case, if the maintenance staffs breach the safety area to clear the error, the operation is incapable of returning to the normal state. The operator

should perform unique action on the HMI following the final check to restart the operation after the error occurred.

2.4 **Data communication protocols**

This section introduces the absolute foundation of data communication- the seven layers of the OSI model. The communication protocol to be used in the empirical part of this thesis-Profinet is familiarised and stacked up against the OSI model.

2.4.1 Open Systems Interconnection model (OSI)

The absolute objective of the Open Systems Interconnection (OSI) is to enable computer systems from dissimilar vendors to share the information efficiently and transparently. The OSI structure of seven layers defines how systems from different manufacturers cooperate. The OSI layers contain all characteristics of the flow of data starting at application-related services offered at the application level to the physical connection of devices at the Physical level. Figure 2 demonstrates how different computer systems communicate with one another through seven different layers of data communication defined the OSI model.

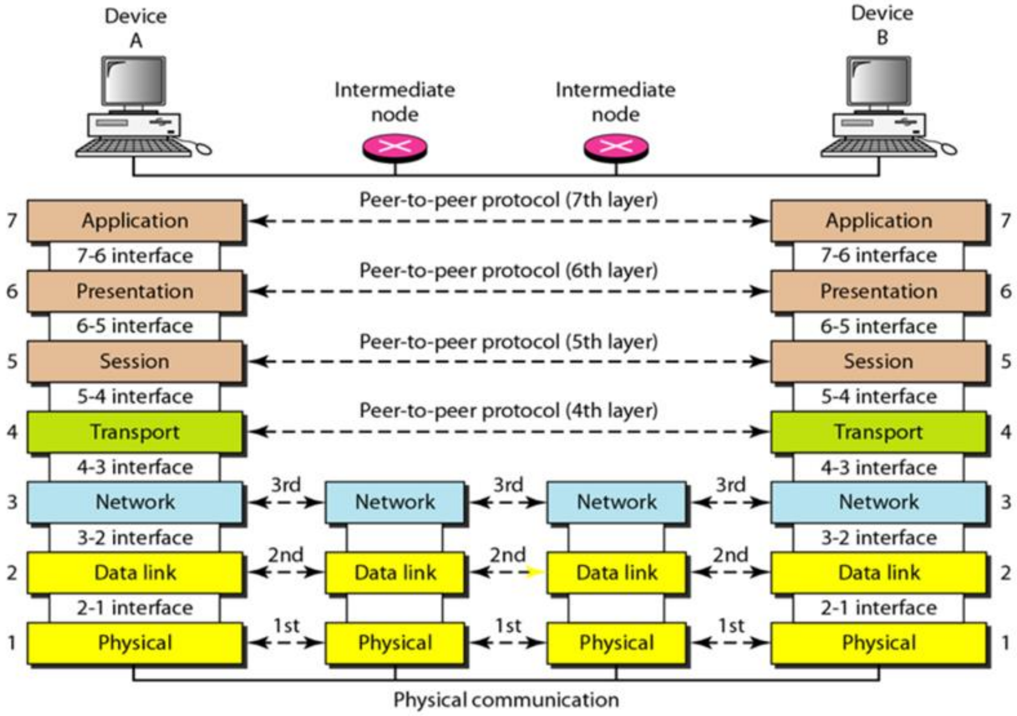


Figure 3. The interaction between seven OSI layers enables data communication between two computer systems (Mhatra, 2017).

Each of seven layers of the OSI Model hands a different functionality. Table 2 shows a complete summary of the functionalities of each OSI layers:

Layer	Name	Function
7	Application	The application layer is the single layer that allows the direct interaction between the data and the user. Software applications such as web browsers or email clients request from the application layer to initiate communications. These applications are dependable on the application layer to transfer data that human can comprehend.
6	Presentation	Presentation layer main's responsibility is pre-processing data for the application layer. Pre-processing of this layer means anything from translation, encryption to compression of data.
5	Session	Session layer permits opening and closing communication between two devices. The session time is the time measured between the opening and closing of the communicating interface. The session layer guarantees the duration of the session time in an appropriate time when data is being exchanged and then closing the session to avoid wasting resources.
4	Transport	The transport layer is the handler of the end-to-end communication of two devices. This layer obtains data from the session layer and convert it into smaller pieces called segments and then send it to the network layer. The transport layer of the receiving end additionally reconstructs each portion of data to readable data for the session layer.
3	Network	The network layer is accountable for facilitating data transfer between two different systems. On the sending end, network layer breaks up segments from the transport layer into a smaller processable unit called packets, and then reconstruct these packets on the receiving end. The network layer is also responsible for routing, which means finding the best physical path for data to reach the destination.
2	Datalink	Except facilitating the data transfer process on the same network between two devices, the data link layer is quite comparable to the network layer. This layer receives packages from the network layer and smashes them into smaller fragments called "frames". The data link layer held responsible for error contraption and flow control in intra-network communication.

1	Physical	Physical layer incorporates all physical equipment for data transfer, for instance, switches or cable. This layer transforms data into a bitstream of 1s and 0s. The physical layer of each device must decide on a signal convention for 1s can be differentiated from 0s on both devices.

Table 2. The functionalities of each OIS layer (Smith, 1997).

Communication protocols can use some or all OSI layers to establish data communication. The concept of splitting up a communication system into seven general levels, each one stacked upon the last, has become the universal language for computer networking since International Organization for Standardization published the OSI Model from more than 30 years ago.

2.4.2 Profinet

Profinet is a communication protocol most commonly used in industrial automation that allows robust and deterministic data exchange between controllers and devices. Defined by IEEE802.3, Ethernet network with open standards is the build platform for Industrial Ethernet such as Profinet. Having well over 25 million operating nodes as of 2018, Profinet is believed to be one of the most commonly used Industrial Ethernet standard in the world (Henning, 2015). Not to mentioned Profinet is backed by the Industrial giant-Siemens, it certainly is the reliable and future-proof solution when it comes to selecting the Industrial Ethernet protocol.

Main advantages of Profinet compares to an older industrial communication protocol such as Profibus comprises of three categories: efficiency, performance and flexibility. One of the decisive factors in Profinet's advantage is its higher efficiency than older industrial data communication protocols, mainly related to the number of nodes, baud rate, and diagnostic capability. The size of the networks is almost unlimited. The transmission speed of 100 Mbit/s in the full-duplex mode of Profinet with parallel communication through Profinet switches is much quicker than the older Profibus at which performs the maximum speed of 12 Mbit/s. Alongside with superior speed compared the Profibus, Profinet has the astonishing maximum data volume per telegram of 1440 bytes versus the moderate 244 bytes of Profibus. A sides from similar specs such as the functional model and topology variants, exceeding specs of the new Profinet compared to the pevious Profibus DP can be found in the Table 3:

	Industrial Ethernet Profinet IO	**Fieldbus Profibus DP**
Maximum transmission speed	100 Mbit/sec	12 Mb/sec
Maximum data volume per telegram	1440 bytes	244 bytes
Maximum participants per network	Practically unlimited	126
Combination IO and IT on one cable	Yes	No
Dynamic Frame Packing (with PN IRT)	Yes	No
Functional model	Similar	
Topology variants	Similar	
Secure data transmission (PROFIsafe)	Identical	
Timestamping and redundancy	Similar	
Usable in explosive/hazardous area	Not currently	Yes
Auxiliary power supply via bus	Not currently	Yes
Connection cost for small devices	Reasonable (Identical)	

Table 3. Scope of Profinet compared to the Profibus Fieldbus technology (Fuchs & Hecker, 2018).

Profinet supports the real-time transmission with RT (real-time) and IRT (Isochronous real-time) modes allowing the deployment in very dynamic applications including isometric motion control applications with short and rapid cycle times. This is only possible when employing Profinet and it easily meets the practicality requirements of every industrial and experimental application in use at present. With the cycle times of as low as 31.25ms, the Profinet standard provides a significant reserve performance for expansion with higher requirements for data communication structure (Fuchs & Hecker, 2018). The result of increased control accuracy is more consistent product quality and quantity. Extended diagnostic capabilities enable the optimisation in a localised network. One way to perform network diagnostic on the Profinet network is to use Siemen’s Proneta network analyser. Proneta supports a variety of functions such as scanning network topology in online mode, topology comparison between online and offline mode and forcing/monitoring IO values of the SIMATIC distributed IO ET200 series. Simplify operation and implementation makes a significant contribution to maintain the operational readiness of machines, systems, and in the bigger picture-factories to the maximum. That means a significant increase in productivity, quality and profit. Therefore, it proves to be useful for automation designers that comparing the specific requirements of each automation project before deciding on the most suitable data communication protocol can indeed bring long-term benefits. In most cases, the advantages of the new Profinet technology over an older protocol such as Profibus DP/PA will prevail even for small-scale projects.

To enable the integration of open features from the floor level to the SCADA (Supervisory Control and Data Acquisition) level requires serious security measures to guard data communication system against unauthorised access. Some of these distinctive security measures include:

- Profinet equips with protection against incorrect functions, errors and incidents with pre-established procedures.
- Profinet provides deterrence versus unauthorised access that occurs from manipulations within the network or espionage.
- Profinet utilises of well-established and verified standards and devices such as Firewalls, VPN (Virtual Private Network), IDS/IPS (Intrusion Detection System and Intrusion Prevention System).
- Profinet implements security protection at end devices. By selectively disabling services, modifying default passwords and uninstalling excessive applications, Profinet protocol enables the protection of devices present in an industrial network and minimising shortcomings and breaches of security.

These security measures are some of the critical keys that require correct implementation in order to maintain the integrity of a PROFINET network without applying restrictions to personals who need to access the network (INCIBE, 2017).

Profinet reduces the seven layers OSI model to four layers by using a basket full of protocols to fill up the OSI model with each of these protocols has some data transmission between communication partners. The Figure 4 demonstrates how data flow through layers of Profinet:

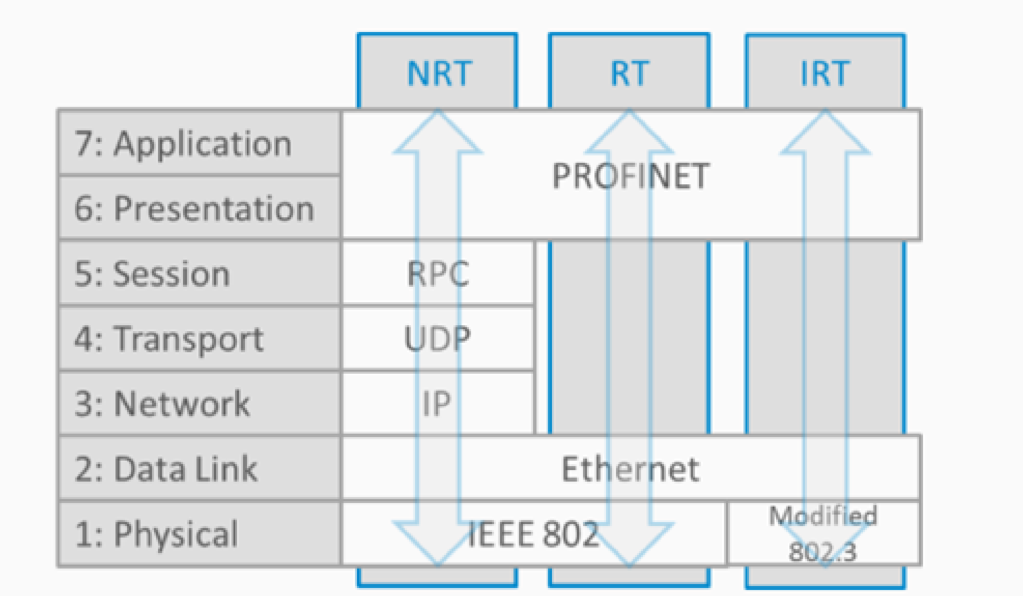


Figure 4. The data stream of Profinet (Profinet University, n.d).

For implementing the first layer-the physical layer, Profinet is using a decades-old couple of proven physical layer protocols: the wired ethernet IEEE 802.3 and the wireless ethernet IEEE802.11. Up next, the IEEE 802.3 ethernet standard integrated with the data link layer means that each device in the Profinet network has MAC (Media Access Control) address.

Profinet sometimes utilises protocols such as IP (Internet Protocol), RPC (Remote Procedure Call) and UDP (User Datagram Protocol) for communication. However, mentioned protocols come with increased overhead, so, Profinet solved this problem by only calling those three protocols when it has no other option. They have the benefit of packing the address information of MAC addresses, IP addresses and UDP port into a single UDP/IP packet to be used to help switch, route and process Profinet data. There are, however, have two main issues when using the entire OSI stack for all communication. The first one is that each layer of the stack has extra work of pack and unpack Profinet data at the source and destination. The second drawback is employing the network layer means adding a delay between the sender and receiver. Both of those drawbacks introduce latency and jitter to the network. Profinet is a well-establish industrial communication protocol over the OSI model; however, it is not immune to some drawbacks of latency and jitter.

Profinet moves data through three main channels: RT, IRT and Non-Real-Time Channel (NRT). The analyses of each channel below show how Profinet utilises communication channels to move data efficiently:

- RT Channel: Latency and jitter are a burden for any industrial communication protocol, so, Profinet has the Real-time to reduce both of those values. By skipping the encapsulation steps in Session, Transport and Network layers, frames exchange over this channel has low latency and jitter. However, frames from this channel cannot route between LANs (Local Area Network) since there is no IP address. The Figure 5 demonstrates the structure of the RT packet:

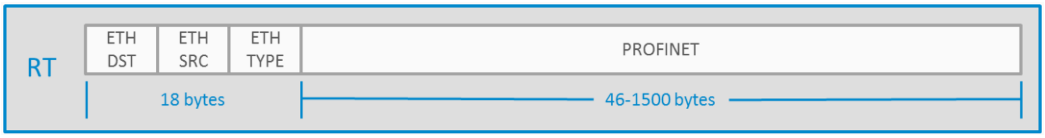


Figure 5. Structure of a data packet in Profinet's RT channel (Profinet University, n.d).

- NRT Channel: In the enterprise network, routing restrictions are a real dilemma. This is because diagnostic tools require access to devices of Profinet to maintain tabs on the operating state of the network. NRT channel operates all layers of the OSI model and has IP address. Therefore, with NRT, Profinet supervisors can gain access to devices across routing boundaries or even over the Internet. However, the trade-off compared to RT is the latency and jitter are skyrocketed. Profinet uses NRT for communications that require less time-sensitivity, such as accessing diagnostic data from an external source or setting up the connection between controllers and devices. The Figure 6 shows the structure of an NRT packet, notice the 108 bytes of extra data.:

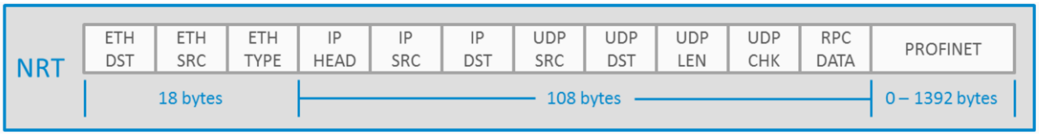


Figure 6. Structure of a data packet in Profinet's NRT channel (Profinet University, n.d).

- IRT Channel: IRT is a stripped-down variation of the RT channel. Although jitter from the transmission over standard ethernet switches is unavoidable. The reduction of jitter is possible by using industrial switch such as Siemen's Scalance series. Switches funnels multiple streams of data down to one transmission line. This can cause unexpected delay in data traffic. IRT disregards those delays by applying a set of special Profinet traffic regulations to ethernet switch. It adds some expansions of regular IEEE 802.3 Ethernet to execute something like an "HOV Lane" for IRT traffic.

Different channels configuration of Profinet makes communication easier. By using a specific channel according to the context of the communication, Profinet executes the data transmission brief and efficiently.

2.5 **Photoelectric sensor**

This section discusses the fundamentals of Photoelectric sensors. The explanation includes the definition, types and sensing modes of photoelectric sensors. Photoelectric sensor primary function is detecting objects or any changes in the surface conditions by detecting a change in light intensity. Typically, this implies the absence or present of the photocell's emitted light source. In rarer cases, photoelectric sensors can also detect light intensity to measure distances. A photoelectric sensor comprises primarily of the emitting element such as LED (Light-emitted diode) for rejecting light beam, the photodiode/phototransistor receiver element for receiving light beam and supporting electronics for amplifying the signal transmitted from the receiver unit. There are three types of commonly used photoelectric sensor as listed (Frigyes, Myers, & Allison, n.d):

- Laser photoelectric sensor: Using laser as a sensor light source, this is the most popular type of photoelectric sensor. Laser photoelectric sensors are available at a variety of versions. These are thru-beam, diffuse scan and diffuse scan with background suppression configurations. Utilising laser as a light source provides high intensity and concentrate beam which facilitates simple adjustment and assembly. By detecting the presence or the strength of the light beam, photoelectric sensors can reliably detect an object or measure the distance between the sensor and the object. Photoelectric sensor with laser technology can detect a tiny object or distance of up to micrometre precision.
- Fibber optics photoelectric sensor: These sensors use an emitter, receiver, and a flexible cable that is full of microscopic optical fibres designed to transmit light. In the application of plastic fibres, the emitter source is usually visible light such as red or green/blue for identifying colours. On the flip side, the emitted source light is

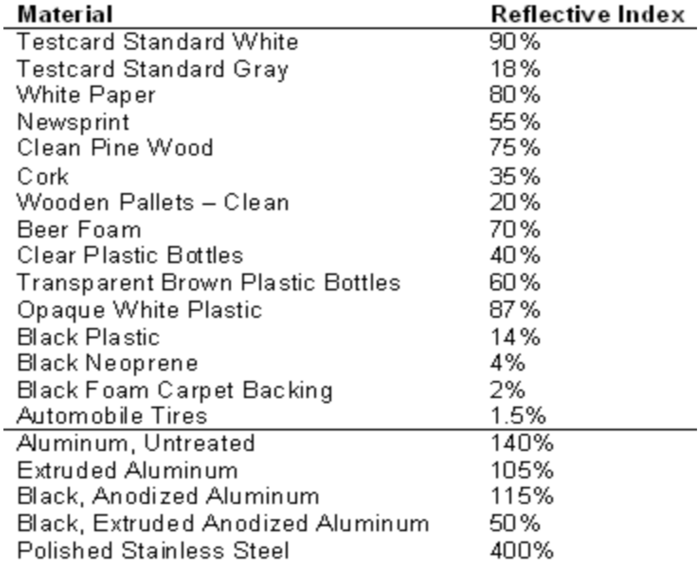
infrared light when glass fibres are in place. Fibber optics are available to thru-beam, retro-reflective scan, or diffuse-scan sensor configurations. Fibber optic photoelectric sensors have the best of usage for small sensing areas or tiny objects.

- Remote photoelectric sensor: Remote photoelectric sensors has the main functionality of remote sensing and comprise only the optical components of a standard photoelectric sensor.

Advantages of photoelectric sensors have long surpassed other sensor technologies such as inductive, capacitive, ultrasonic and magnetic. Sensing range, the compact housing and cost of the photoelectric sensor units make them an ideal fit for any applications or industries.

Photoelectric sensor configuration offers three sensing methods of target detection: diffused, retro-reflective and thru beam with each sensing method has even more variations. Below is each of the three methods in details:

- Diffused mode: The diffused model sometimes referred to as proximity mode, the emitter and receiver are in the same sensor housing for compact and fast deployment. The reflection of light from the target reflects at arbitrary angles returns to the receiver. This means the objective is in detection if the receiver detects return the light beam. One disadvantage of this configuration is most of the transmitted energy is dissipate due to the angle and the ability to reflect the light of the target; diffused mode has significantly lower sensing range compares to two other methods. The Figure 7 rejects the effect of the target’s size, colour and finish into the ability to reflect light to the sensor’s receiver:



Material	Reflective Index
Testcard Standard White	90%
Testcard Standard Gray	18%
White Paper	80%
Newsprint	55%
Clean Pine Wood	75%
Cork	35%
Wooden Pallets – Clean	20%
Beer Foam	70%
Clear Plastic Bottles	40%
Transparent Brown Plastic Bottles	60%
Opaque White Plastic	87%
Black Plastic	14%
Black Neoprene	4%
Black Foam Carpet Backing	2%
Automobile Tires	1.5%
Aluminum, Untreated	140%
Extruded Aluminum	105%
Black, Anodized Aluminum	115%
Black, Extruded Anodized Aluminum	50%
Polished Stainless Steel	400%

Figure 7. Reflective index of some reference materials for diffused-mode photoelectric sensors (Frigyes, Myers, & Allision, n.d).

There are more refined versions of diffused mode to mitigate some of the downsides such as diffused convergent beam mode, diffused mode with background suppression and diffused mode with mechanical background suppression. The most advanced diffused mode is the diffused mode with electronic background suppression which employs a Position-Sensitive Device inside the sensor housing. With diffused mode, the is almost no need to a secondary device to be deployed such as a reflector or a separate sensing device. This allows photoelectric sensors of this configuration usable in compact spaces.

- Retro-reflective mode: Retro-reflective mode has higher efficiency compared to the diffused mode. The emitter and receiver are in the same sensor housing, but, an additional reflector is rejecting light from the emitter back to the receiver when in operation. The trigger for the output signal engages when the target blocks the beam from the sensor to the reflector. Sensors in this configuration are available with or without polarization filters. A polarisation filter permits light at a particular phase angle back to the receiver, which allows the sensor to identify a shiny object as a target and not mistakenly as a reflector. This is because the light bounced back from the reflectors shifts its phase, whereas light reflected from a shiny target does not. The Figure 8 demonstrates the retro-reflective photoelectric sensors in action with polarising filter:

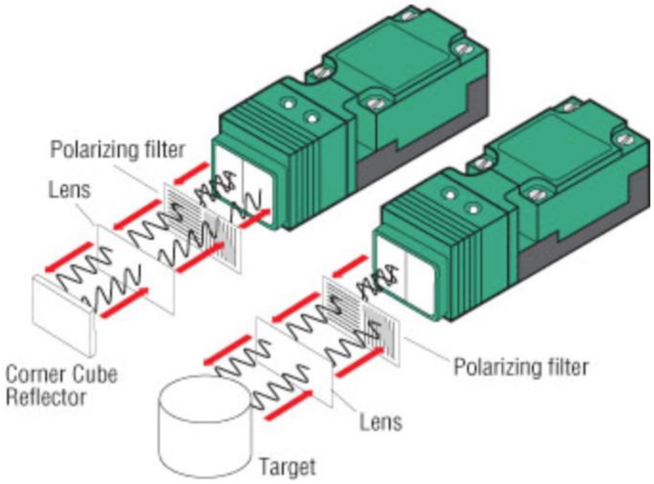


Figure 8. Photoelectric sensors in retro-reflective mode with polarising filters (Frigyes, Myers, & Allision, n.d).

Due to the ability to distinguish shiny objects, this model is suitable for any application with reflective targets such as glass or metal. Two other variations of the retro-reflective method are also available. One of them is the retro-reflective mode for precise object detection with a low hysteresis circuit to detect small changes in light to detect transparent objects. The last variation is the retro-reflective mode with foreground suppression suited for detection object with glossy covering such as shrink-wrapped pallets. Throughout variations of retro-reflective mode, the target colour and finish do not affect the sensing range or the ability to detect an object in this mode. However, additional elements such as the reflector make mounting these sensors not an ideal in some situation involves compact spaces. Overall, when the mounting space permits this configuration, retro-reflective mode proofed to be more precise and reliable than standard photoelectric sensors in diffused mode.

- Thru-beam mode: Thru-beam mode, often known as opposed mode, is the final primary detection method for photoelectric sensors. Sensors in this configuration have two different housing, one for the emitter and one for the receiver. The light beam projects from the emitter aim straight for the receiver. The event of an object breaking the light beam results in the activation of the output signal from the sensor. Similarly to two other modes, thru-beam sensor available in a variety of types. The most familiar one comprises one emitter housing, one receiver housing and one light beam rejecting between the two sensor shells. An alternative model is “slot” or “fork” photoelectric sensors that combine both the emitter and the receiver into one housing, with no pre-alignment required. Light grids are arrays of many distinct transmitters in one sensor shell and many different receivers in additional housing, which, when targeted at each other, create a virtual “sheet” of light beams. This mode has the most extended potential sensing radius and the most efficient of the three working methods of the photoelectric sensor (Frigyes, Myers, & Allision, n.d).

With three main operating modes, photoelectric sensors offer a massive selection of configurations suitable for almost every industrial application. Moreover, the cost for deployment and maintenance of the photoelectric sensor is relatively low. Those two combines have made photoelectric sensor one of the most popular industrial sensor.

3 PROJECT IMPLEMENTATION

3.1 Operation logic based on tiling pattern

This section discusses in great details about the operation sequence of the alignment process of each set of tiles. The operation logic has three primary states according to the tiling pattern. The division of the tiling pattern appears on the HMI for the user to control the system step-by-step. The HMI only allows the operator to jump to another state when the operator thoughtfully inspects the previous tile pattern. The operation logic is the backbone of the entire operation; it’s the coordination between the sensor measurements, the logic control of the PLC and movement of the UR5 robot.

The first state of the operation is scanning and laying down the first tile. The first tile is the tile surrounded by two sides of the wall. The Figure 9 validates the position of the first tile:

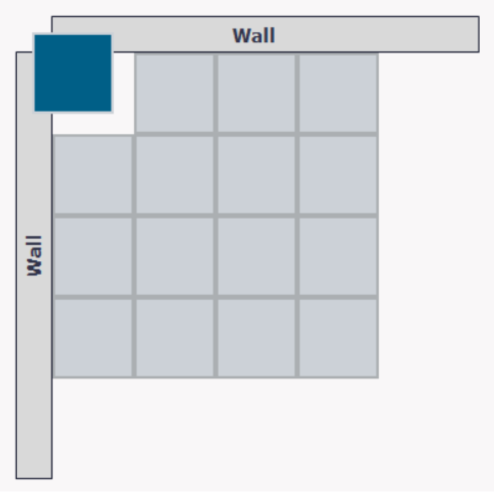


Figure 9. The location of the first tile of the first state.

The alignment of the first tile has strategic importance when it comes to the orientation accuracy of the whole floor. Due to this significant aspect, the operator must physically inspect and confirm the correct placement of the first tile on the HMI after the robot has finished the arrangement process. The execution of the alignment bases on three measurement references: the reading from the first and second horizontal sensors and the elevation reading from the first vertical sensor. The operation logic is the following:

- Step 1: The robot moves to the horizontal scanning position. The scanning process completed only when the reading of both horizontal sensors is equal in a given tolerant. The scanning process continues with vertical scanning.
- Step 2: The robot moves to the vertical scanning position. The scanning process achieved if the reading from the vertical sensor 1 reaches a pre-determined elevation. The scanning process for the first tile finishes with this step.

After realising the proper distance to the walls and the elevation from the wet concrete ground, the robot starts setting down the tile. To move the first tile into the position, the UR5 must pick up the tile with its suction cups and rotate the tool 180 degrees. The reason for the rotation is the vertical sensors are poking out on the scanning tool preventing the tile from being put close to the walls. Without this rotation movement, the set of four vertical sensors would have scratch up against two sides of the wall. Following the accomplishment of the first tile laying process, the operator confirms the alignment on the HMI and the second state begins.

The second state of the operation contains the scanning process and the placement of the vertical and horizontal sets of tiles that are close to the walls. The position of the tiles of the second state is as demonstrated in Figure 10:

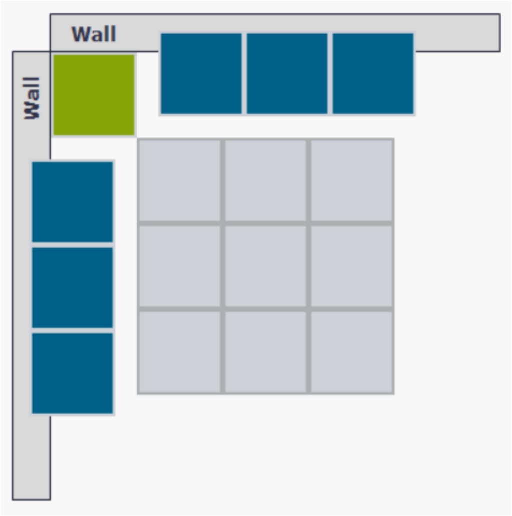


Figure 10. The location of the second set of tiles close to the walls.

The alignment for the set of tiles in the second state bases on three references. The references are the switching output from two in-lines vertical sensors and the measured distance from the horizontal sensor on the corresponding side of the scanning tool. There are two steps for the scanning process of each tile in this state:

- Step 1: The robot moves to the vertical scanning location and gradually pulls the scanning tool to pass the first tile. The two in-line vertical sensors send output signals at the same time to the PLC confirming the edge detection of the first tile. The correct realisation of the position of the first tile is now complete. The robot is ready for the second step.
- Step 2: The robot sets for the horizontal scanning location and mobilises the scanning tool to the direction of the wall. The horizontal sensor on the corresponding side sends the trigger signal when the distance from the scanning tool and the wall reaches a set limit. The scanning process for the gap between the tiles and the wall is complete.

The scanning process for each tile in the second state ends after the correct realisation of the edge of the previous tile’s location and the distance to the wall. The robot rotates the scanning tool 90 degrees, facing the blank side of the scanning tool to the wall to avoid the collision between the vertical sensors and the wall. The robot then moves to lay down the tile after the tool rotation. Following, the scanning procedure for the next tile of the second state reinitialises and the process repeats. The HMI switches to the third state when the operator confirms the alignments of the tiles in the second state.

The third stage of the process initialises after the confirmation of the second state and centres on two reference measurements. Placement of the set of tiles in the third state is demonstrated in Figure 11:

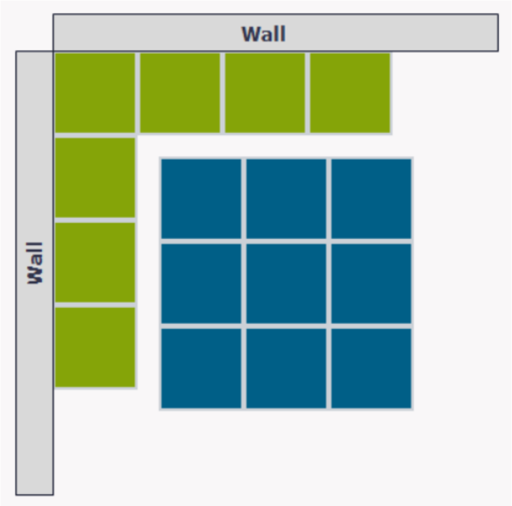


Figure 11. The location of the tiles of the third state.

The correct alignment of each of the tile in the third set relies on two references: the edge detections of the first and second adjacent tiles to the target tile. There are two similar steps for the scanning process of the tiles in the third state. The scanning launches when the robot adjusts its placement on top of the first adjoining tile to the target tile. The robot mobilises the scanning tool passes the edge of the first adjacent tile. The edge detection of the neighbouring tiles deems to be correct if the PLC registers the two-switching output from the set of parallel vertical sensors to the adjacent tile at the same time. The scanning procedure repeats to detect the edge of the other adjoining tile to the target tile. After the correct location detection of the two adjacent tiles, the robot begins the placement process for the target tile. The scanning and placement procedures repeat for each tile of the first state. The entire tile alignment process ends with the placement of the last tile in the third set of tiles.

3.2 Component selection

This section discusses the selection of components of the robotic tiling project. The component selection for this thesis based on requirements of precision, expendability and cost-saving for robot tiling platform. The Table 4 contains hardware components for this thesis:

Name	Part number	Brand	Amount
Short-range distance sensor OD Mini Prime	6050512	Sick	4
3m extension cable (M12, 5-pin)	2104367		6
Mid-range distance sensor DT35	1057651		2
ET200SP Open Controller	6ES7677-2AA40-0AA0	Siemens	1
S7 1505S Software PLC + HMI RT	6ES7672-5AC00-0YA0		1
ET200SP IO-Link Master	6ES7137-6BD00-0BA1		1
ET200SP Light Base Unit	6ES7193-6BP00-0DA0		3

Profinet cable			1
ET200SP Digital Output card	6ES7132-6BD20-0BA0		1
ET200SP Analog Input card	6ES7134-6HD00-0BA1		2
24VDC and N+PE terminal			
Universal Robot UR5 CB3 series. Maximum capacity: 5kg.		Universal Robot	

Table 4. The hardware list of the robotic tiling project.

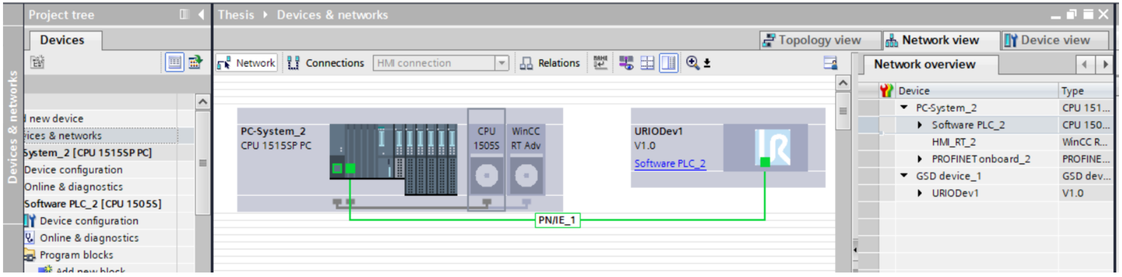
Four analogue photoelectric Sick sensors except for the UR5 Robot, which is already available at the Robotic lab, are the most expensive components of this thesis. The decision to purchase an analogue sensor instead of the cheaper digital sensors were made by a careful selection and consultant with a product manager from Sick company. The four OD Mini with the designated model number OD1-B100H50I25 photoelectric sensor handles the vertical scanning process. The sensor has 4…20mA analogue output signal. This set of sensors can reach the astonishing accuracy of one micrometre.

To trade for the high precision, OD Mini has a rather unimpressive working range of 50-100mm in an ideal situation and 50-150mm extended range. However, since the UR5 is programmable to perform the scanning process at a low height, the short working range posts no impact to the adaptivity and performance of the experiment. Thus, the analogue output function of this type of sensor is necessary to create the tolerant of switching on the output to the UR5 robot when sensors detect the edge of the previous tile in the scanning process. For example, with the tile that has the thickness of 8mm, and the robot is performing the scanning movement 100mm above the ground, the “edge-detected” signal engages if the measured distance of the sensor change drastically from 90mm to 100mm. This means the sensors pass the edge of the tile. The setpoints are entirely scalable in the PLC program with the analog output-type photoelectric sensor. The requirement of this tolerant comes from the fact that the UR5 must perform scanning while it is on the move; therefore, shaking is unavoidable.

Another point of adding tolerant is the inconsistency of the layer of concrete below the finished tiles. The concrete filling makes the elevation of the aligned tiles inconsistent. In the other hand, DT35 sensors of horizontal scanning operation have moderate repeatability of over 0.5mm and extremely high working range of 50mm-12000mm in 90% emission. The explanation for this is DT35 sensors bare the responsibility of measuring the distance to the walls; therefore, the moderate accuracy is acceptable. However, with the usage of DT35, scanning of the dimension of the entire working space is possible in future expansion. The decision for the hardware configuration of this thesis has taken the financial, development, performance and reliability aspects of the tiling solution into careful consideration.

3.3 Data exchange between robot and PLC

This section demonstrates the setup and enabling the data communication between the UR5 robot and the PLC via Profinet. The setup for data communication between the UR5 robot and the ET200SP Open Controller is straight forward. A GSD file (General Station Description), which is available from Universal Robot resources, contains a description of the Profibus DP/PA or Profinet devices. GSD files offer a way for an open configuration tool to get the device attributes automatically. The Universal robot’s GSD file after being imported to TIA Portal allows finishing the configuration process of the Profinet network. A set of available IO modules are available for adding into the URIODev1 devices. After adding the desired IO modules, the configuration is free to download to the devices. Figure 12 is the network configuration view of the TIA portal after the arrangement is done:

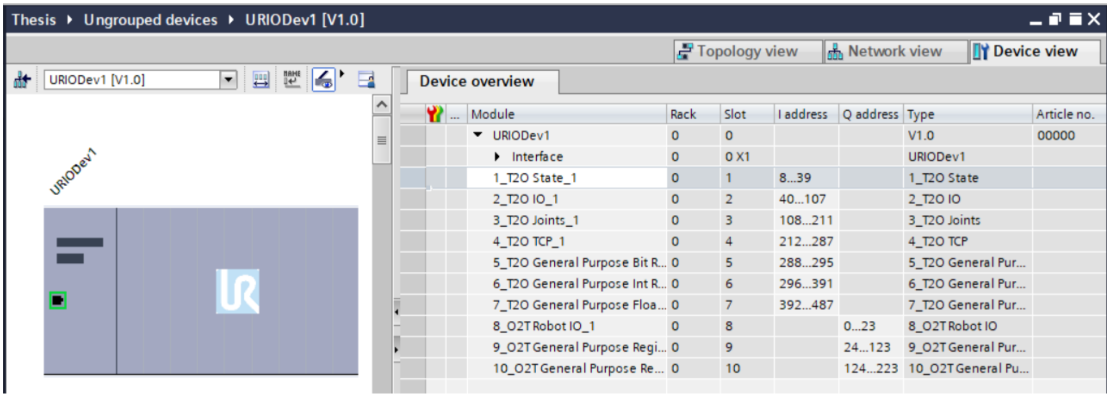


Device	Type
PC-System_2	CPU 151...
Software PLC_2	CPU 150...
HMI_RT_2	WinCC R...
PROFINET onboard_2	PROFINE...
GSD device_1	GSD dev...
URIODev1	V1.0

Figure 12. The network configuration of the robot tiling solution.

The last step of configuring the data communication between the PLC and the robot is to go online in TIA Portal and navigate to Online & Diagnostic section of URIODev1 to assign a device name to the robot.

A set of communicational data between the robot and the PLC has ten pluggable modules. In the ten modules, seven modes contain the data that is comprehensible from the robot by the PLC. In contrast, the last three modules include the data that can be set to the robot by commands from the PLC. The usage of each module is optional; however, each plugin module has a specific slot according to the modules’ order. The Figure 13 demonstrated the correct order of ten modules when all plugged in:

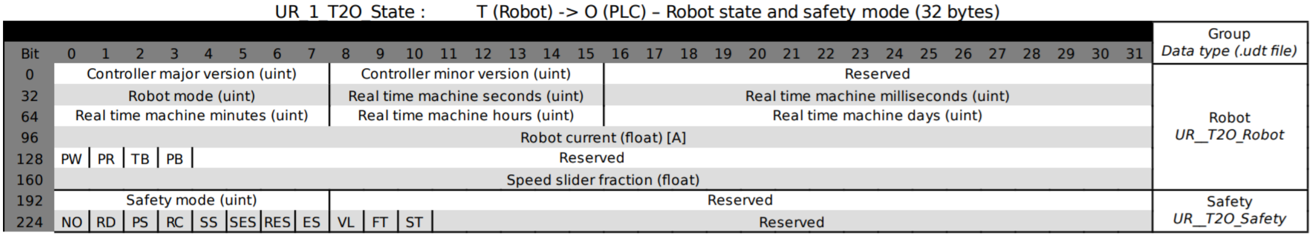


	Module	Rack	Slot	I address	Q address	Type	Article no.
	▾ URIODev1	0	0			V1.0	00000
	▸ Interface	0	0 X1			URIODev1	
	1_T2O State_1	0	1	8...39		1_T2O State	
	2_T2O IO_1	0	2	40...107		2_T2O IO	
	3_T2O Joints_1	0	3	108...211		3_T2O Joints	
	4_T2O TCP_1	0	4	212...287		4_T2O TCP	
	5_T2O General Purpose Bit R...	0	5	288...295		5_T2O General Pur...	
	6_T2O General Purpose Int R...	0	6	296...391		6_T2O General Pur...	
	7_T2O General Purpose Floa...	0	7	392...487		7_T2O General Pur...	
	8_O2T Robot IO_1	0	8		0...23	8_O2T Robot IO	
	9_O2T General Purpose Regi...	0	9		24...123	9_O2T General Pur...	
	10_O2T General Purpose Re...	0	10		124...223	10_O2T General Pu...	

Figure 13. The exact position of the robot’s IO modules corresponding from slot 1 to slot 10.

The IO modules offer not only just general-purpose IOs but a vast amount of usable data from and to the robot. For example, the UR_1_T20_State has an enormous selection of safety inputs from the robot that is necessary to integrate to alarm functions of the HMI. Besides, the UR_3_T2_Joints contains data of joints from the robot such as positioning, velocity, current, temperature and modes. The Figure 14 show the components of UR1_T20_State input module:

UR_1_T2O_State : T (Robot) -> O (PLC) – Robot state and safety mode (32 bytes)



<table>
<tr><th>Bit</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th>31</th><th>Group
<i>Data type (.udt file)</i></th></tr>
<tr><td>0</td><td colspan="8">Controller major version (uint)</td><td colspan="8">Controller minor version (uint)</td><td colspan="16">Reserved</td><td rowspan="6">Robot
<i>UR_T2O_Robot</i></td></tr>
<tr><td>32</td><td colspan="8">Robot mode (uint)</td><td colspan="8">Real time machine seconds (uint)</td><td colspan="16">Real time machine milliseconds (uint)</td></tr>
<tr><td>64</td><td colspan="8">Real time machine minutes (uint)</td><td colspan="8">Real time machine hours (uint)</td><td colspan="16">Real time machine days (uint)</td></tr>
<tr><td>96</td><td colspan="32">Robot current (float) [A]</td></tr>
<tr><td>128</td><td>PW</td><td>PR</td><td>TB</td><td>PB</td><td colspan="28">Reserved</td></tr>
<tr><td>160</td><td colspan="32">Speed slider fraction (float)</td></tr>
<tr><td>192</td><td colspan="8">Safety mode (uint)</td><td colspan="24">Reserved</td><td rowspan="2">Safety
<i>UR_T2O_Safety</i></td></tr>
<tr><td>224</td><td>NO</td><td>RD</td><td>PS</td><td>RC</td><td>SS</td><td>SES</td><td>RES</td><td>ES</td><td>VL</td><td>FT</td><td>ST</td><td colspan="21">Reserved</td></tr>
</table>

Figure 14. UR1_T20_State input module (Universal Robot, n.d).

With the support of the various data types from the robots input modules, users could completely integrate the robot into any Siemens based PLC automation system.

3.4 PLC programming

The PLC program has three main functions according to the operation logic. A sequence tag is present in each sequence to monitor sub-stages in each sequence. The HMI demonstrates stages of each sequence for the monitoring of the operator. The sequences functions are accordingly:

- First tile alignment function.
- First horizontal and vertical lines alignment.
- The rest of the tiles.

The trigger output to the robot for horizontal scanning positions proceeds only when the set point for the switching output is correct. The trigger output set point for the vertical scanning positions is a subtraction of the elevation of the sensor from the ground and the tile thickness. The trigger is true if both measured distance from the vertical sensors while the robot is performing the scanning move, are larger than the subtraction of the mentioned above units. This trigger means that the scanning tool has moved passe and detected the edge of the previous tile. This calculation proofs to be reliable since the cement below the previous tile makes the elevation oh the tile a bit higher than the actual thickness of the tile. Hence, the trigger can't activate while the scanning tool is still moving on top of the previous tile. The sequences complete when the last sequence deploys successfully and the operator confirm the alignment on the HMI.

There are support functions besides the main sequential functions. The I/O function handle the data conversion of the sensors data into scalable data of the PLC. The NORM_X and SCALE_X function blocks are Siemens standards blocks to convert data from analogue sensors to scalable data. Figure 15 demonstrates the data conversion of the Vertical sensor 1-an analogue sensor with the typical feeding scale from 0 to 27648:

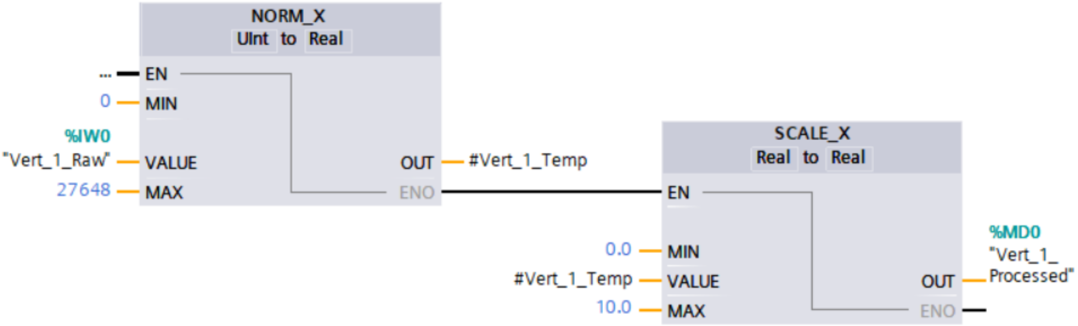
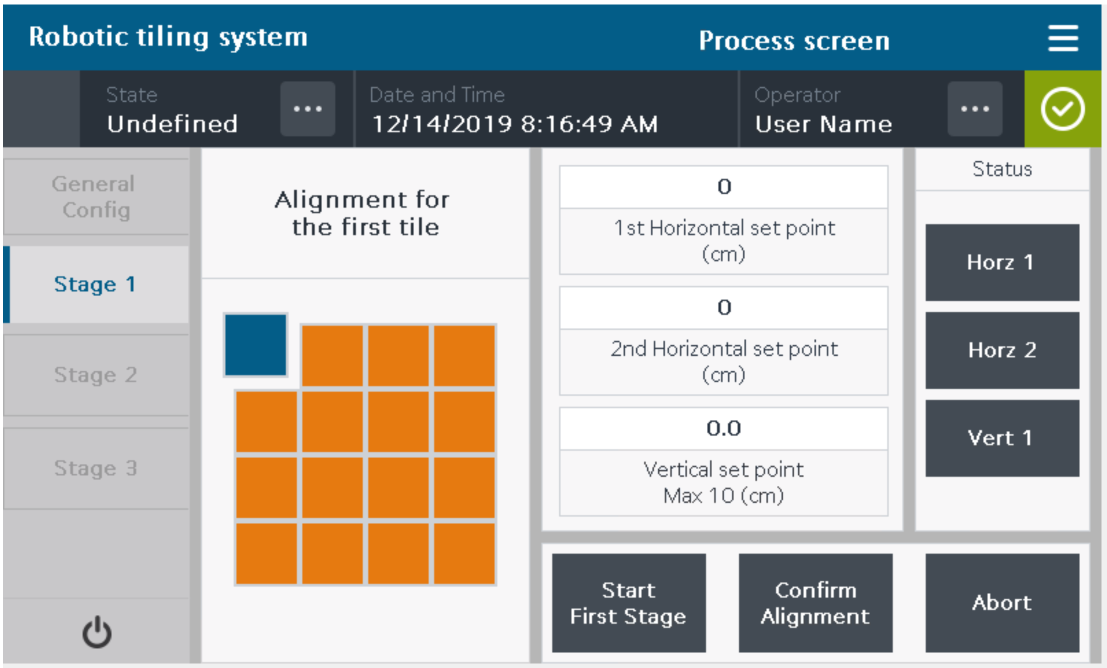


Figure 15. The standard data conversion operation for analogue sensors in the TIA Portal.

The rest of the support functions are the Global and Alarms functions. The alarms function handles alarms such as robot emergency stop, robot protective stop or reduced mode. The global function has to monitor the running state of the robot program and the power state of the robot.

3.5 HMI Design

The HMI has five main screens created using the newest V15.1 HMI Template Suite library from Siemens. The design language of the HMI is neat and unify. The screens include: Start screen, Process, Alarms, Diagnostics and Setting screen. There is a sub-navigation in the Process screen according to the operation logic. The first sub-navigation in the Process screen is the General configuration that allows the operator to set up essential parameters such as the floor sizes and the tile thickness. Three or the sub-navigation screen enable the operator to configure and monitor the tiling process of each of the three stages according to the operation logic. Figure 16 is the demonstration of the first tiling stage in the Process screen:



State: Undefined

Date and Time: 12/14/2019 8:16:49 AM

Operator: User Name

1st Horizontal set point (cm): 0

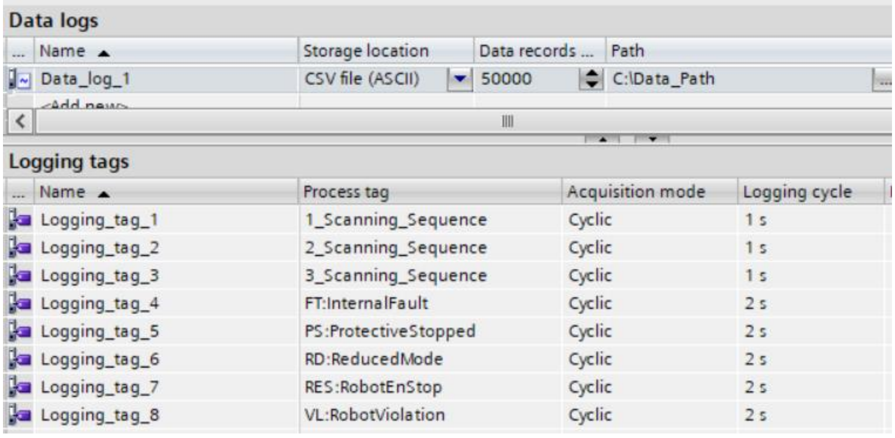
2nd Horizontal set point (cm): 0

Vertical set point Max 10 (cm): 0.0

Figure 16. Stage 1 of the Process screen.

3.6 Data acquisition system establishment

The establishment of a data logger system is performed via historical data function of Siemens HMI. Important tags such as the scanning sequences and alarms are recorded to a CSV file. The operator has control of starting, stopping and resetting the data recorder via control functions in the HMI. Figure 17 shows the process tags that are in the data recorder:



Data logs

Name	Storage location	Data records ...	Path
Data_log_1	CSV file (ASCII)	50000	C:\Data_Path

Logging tags

Name	Process tag	Acquisition mode	Logging cycle
Logging_tag_1	1_Scanning_Sequence	Cyclic	1 s
Logging_tag_2	2_Scanning_Sequence	Cyclic	1 s
Logging_tag_3	3_Scanning_Sequence	Cyclic	1 s
Logging_tag_4	FT:InternalFault	Cyclic	2 s
Logging_tag_5	PS:ProtectiveStopped	Cyclic	2 s
Logging_tag_6	RD:ReducedMode	Cyclic	2 s
Logging_tag_7	RES:RobotEnStop	Cyclic	2 s
Logging_tag_8	VL:RobotViolation	Cyclic	2 s

Figure 17. Process tags of the data recorder.

4 OBSTACLES AND RESULTS

4.1 Major obstacles

This chapter discusses the significant difficulties that raised during the commission process of this project. Some of the problems encountered during the development of this thesis and how they were overcome is described below:

- A set of digital output type photoelectric sensor in 1-point switching digital output configuration was initially chosen as vertical sensors in the planning state to save cost. However, throughout the operation logic planning, the author discovered the usage of this set of sensors is not possible in this project. The inconsistency of the concrete below the tile makes the elevation of each tile different from one another. A pre-set switching distance, which is required for digital output photoelectric sensor, is lacking the essential tolerant adjustment for the various elevation of the tiles. The solution for this challenge is to employ a more expensive set of analogue photoelectric sensors in which switching distance can be adjusted by coding in the PLC.
- The 6ES7677-2AA40-0AA0 ET200SP Open Controller-version 1.8 configuration with the Software PLC 6ES7 672-5AC00-0YA0 (1505S) has password protection set by an unknown user. Several failed attempts were made to bypass the administration password of the 6ES7677-2AA40-0AA0 to gain access to the 1505S PLC. As the last resource, the PLC was put back to the factory configuration by using Siemens recovery disk and data stored in the PLC at the moment were lost. A new Window 7 Embedded was installed in the ET200SP. A new license key was transferred to activate the software PLC and WinCC RT Advanced result in a fully functional PLC+HMI RT.
- The author initially designed the system to run with an OPC UA server. This proofed to be suitable for future upgrades. Almost all new S7 1500 series PLCs from Siemens comes with the pre-installed OPC server. OPC client runs on PLC is also a possibility by upgrading the PLC firmware to 2.6 and coding on the latest V15.1 TIA Portal. However, the 6ES7 672-5AC00-0YA0 CPU was sealed with its stock 1.7 firmware and can only be upgraded to 1.8. This results in all OPC functions are unavailable on this model of PLC. There are two possibilities of using OPC server, first, update and activate OPC server on WinCC RT V15 and the second is running an external OPC server. However, acquiring a license for the external server was impossible financially while upgrading to V15 RT might affect the integrity of PLC’s functions. The author decided not to run the OPC server and went with the integrated HMI data acquisition from Siemens.
- The author discovered the unavoidable placing of four vertical sensors on the scanning tool is going to prevent the movement of the robot when placing the first tile and the first lines of tiles. The vertical sensors obstruct the robot to place the first tiles, and the lines close to the walls due to the vertical sensors are in the way of placing movement. The solution for this matter is that the robot must rotate

the scanning tool 180 degrees after the scanning movement to place the unobstructed side of the scanning tool to go in the placing position first.

4.2 Implementation results

This section summarises the results of the thesis process, as of December 2019. All targets set for this thesis is achieved. The PLC sequence has been tested in a simulation environment without the actual robot scanning tool. The output triggers to the robot are received accordingly to the sequence logic. HMI function including the alarms, diagnostics and data recording function work flawlessly. The robot movement planning will have proceeded shortly after this thesis while the mechanical design is well on its way.

There are limitations emerge from the implementation phase of this thesis project as follows:

- The vertical sensor temperature problem: The vertical sensors are heating to high temperature while working. The initial plan to create a 3D-print scanning tool, therefore, is not possible due to the low melting temperature of plastic fibre. A metallic scanning tool housing is designed and acts as a heat sink for the vertical sensors. However, this design increases weight and reduce the capacity of the robot to lift heavy tiles.
- Tile limitation: Due to the technical aspect of the four vertical sensors, the system is incapable of working with extreme-reflective surfaces. The ideal tiles for this solution are matt surfaces.
- Unable to establish OPC UA Server & Client: This limitation will greatly reduce the expandability of the system in the future.
- Require human interaction: The robot tiling project is not completely automated. Human interaction is still in demand to manually confirm the alignment of the tiles. Thus, the robot solution is unable to cut tiles to specific needs when performing the tiling process.

5 DEVELOPMENT POSSIBILITIES

5.1 Mobile platform

A complete and commercialized-ready robotic tiling solution requires mounting on an automated platform. Such a platform allows the tiling assembly to relocate to a different position to complete the tiling process of the floor. In the future development, the robot with the mobile platform can automatically measure the dimension of the room by moving around and using the horizontal sensors. The mobile platforms are available in different configurations and are fully customisation according to the requirements of the solution. Figure 18 shows the RB-KAIROS mobile platform from Robotnik:

Figure 18. RB-KAIROS mobile platform series for Universal Robot (Robotnik, n.d).

6 CONCLUSION

In summary, the Siemens PLC system was developed for high-accuracy measurement using photoelectric sensors, as well as for the control and data communication with the UR5 collaborative robot. Besides, a configurable, modern looking and easy-to-use HMI with data recording and alarm function was deployed for the PLC-based measurement system. The operation logic is well-organized and suited for the implementation of robot movement and the mechanical design of the robot's tools.

The targets for this thesis were achieved, as the PLC was able to communicate with the UR5 robot via Profinet. The switching output behaviour of the photoelectric sensors were configured and tested according to the parameters of the tiles used in the robotic tiling project. The alarms and data recording functions were comfirmed to be an excellent addition to the HMI. Finally, the PLC program based on the operation logic is ready for implementation once the mechanical design and the production process have been completed.

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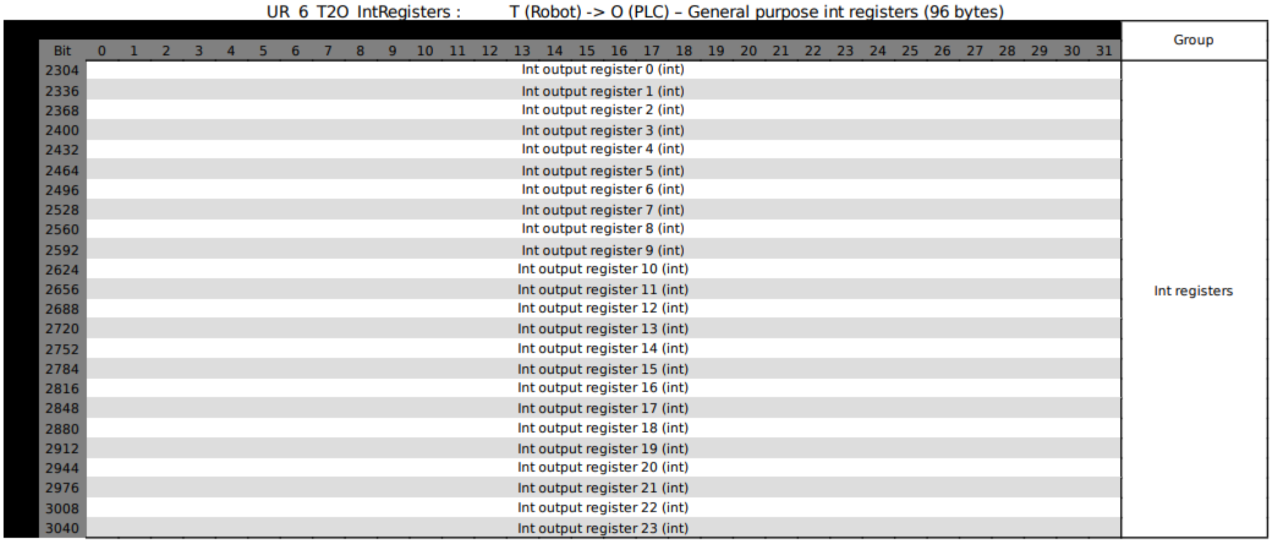
Appendix 1

PROFINET I/O MESSAGE FOR UNIVERSAL ROBOT

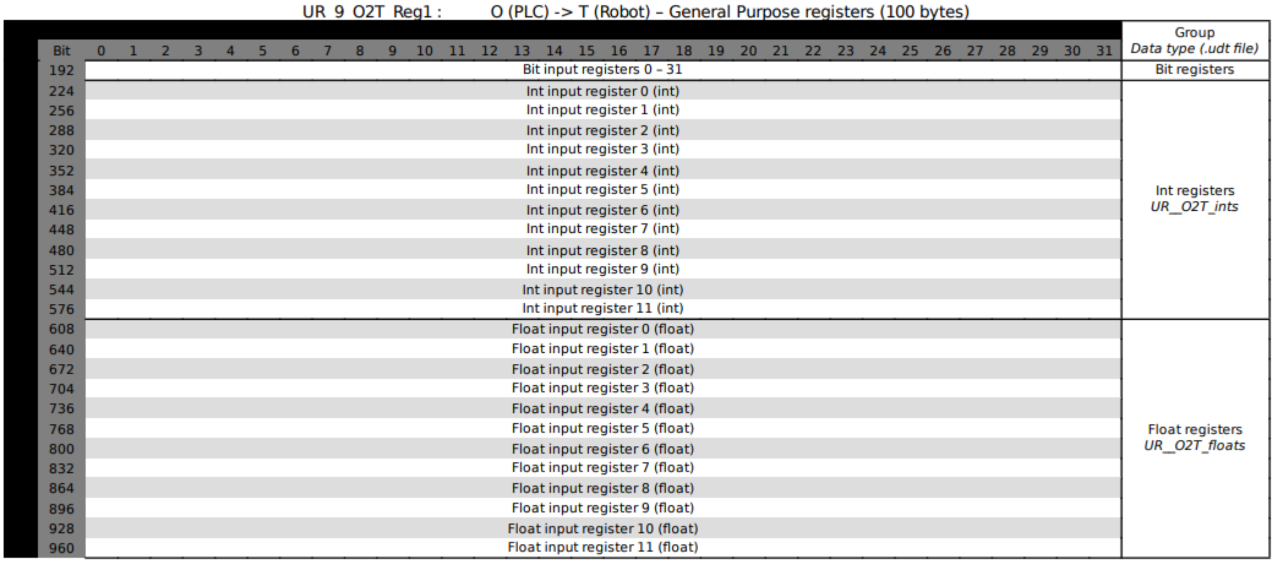
The I/O messages used in this thesis project are as follow pictures:



UR_6_T2O_IntRegisters : T (Robot) -> O (PLC) – General purpose int registers (96 bytes)

Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Group
2304	Int output register 0 (int)																															Int registers
2336	Int output register 1 (int)																															
2368	Int output register 2 (int)																															
2400	Int output register 3 (int)																															
2432	Int output register 4 (int)																															
2464	Int output register 5 (int)																															
2496	Int output register 6 (int)																															
2528	Int output register 7 (int)																															
2560	Int output register 8 (int)																															
2592	Int output register 9 (int)																															
2624	Int output register 10 (int)																															
2656	Int output register 11 (int)																															
2688	Int output register 12 (int)																															
2720	Int output register 13 (int)																															
2752	Int output register 14 (int)																															
2784	Int output register 15 (int)																															
2816	Int output register 16 (int)																															
2848	Int output register 17 (int)																															
2880	Int output register 18 (int)																															
2912	Int output register 19 (int)																															
2944	Int output register 20 (int)																															
2976	Int output register 21 (int)																															
3008	Int output register 22 (int)																															
3040	Int output register 23 (int)																															

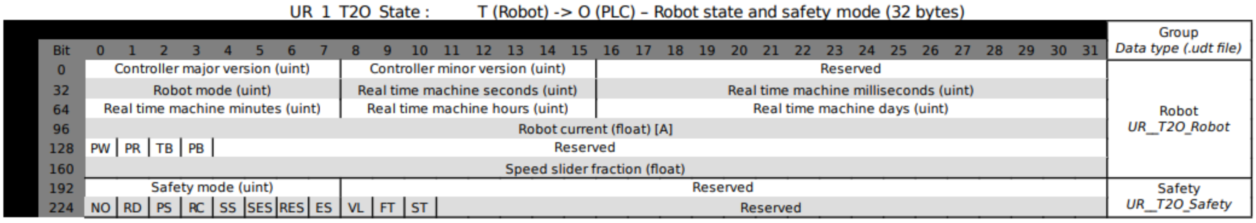
Image: Robot to PLC I/O registers (Universal Robot, n.d).



UR_9_O2T_Reg1 : O (PLC) -> T (Robot) – General Purpose registers (100 bytes)

Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Group *Data type (.udt file)*
192	Bit input registers 0 – 31																															Bit registers
224	Int input register 0 (int)																															Int registers *UR__O2T_ints*
256	Int input register 1 (int)																															
288	Int input register 2 (int)																															
320	Int input register 3 (int)																															
352	Int input register 4 (int)																															
384	Int input register 5 (int)																															
416	Int input register 6 (int)																															
448	Int input register 7 (int)																															
480	Int input register 8 (int)																															
512	Int input register 9 (int)																															
544	Int input register 10 (int)																															
576	Int input register 11 (int)																															
608	Float input register 0 (float)																															Float registers *UR__O2T_floats*
640	Float input register 1 (float)																															
672	Float input register 2 (float)																															
704	Float input register 3 (float)																															
736	Float input register 4 (float)																															
768	Float input register 5 (float)																															
800	Float input register 6 (float)																															
832	Float input register 7 (float)																															
864	Float input register 8 (float)																															
896	Float input register 9 (float)																															
928	Float input register 10 (float)																															
960	Float input register 11 (float)																															

Image: PLC to Robot I/O registers (Universal Robot, n.d).



UR_1_T2O_State : T (Robot) -> O (PLC) – Robot state and safety mode (32 bytes)

Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Group *Data type (.udt file)*
0	Controller major version (uint)								Controller minor version (uint)								Reserved																Robot *UR__T2O_Robot*
32	Robot mode (uint)								Real time machine seconds (uint)								Real time machine milliseconds (uint)																
64	Real time machine minutes (uint)								Real time machine hours (uint)								Real time machine days (uint)																
96	Robot current (float) [A]																															
128	PW	PR	TB	PB	Reserved																											
160	Speed slider fraction (float)																															
192	Safety mode (uint)								Reserved																								Safety *UR__T2O_Safety*
224	NO	RD	PS	RC	SS	SES	RES	ES	VL	FT	ST	Reserved																				

Image: Robot to PLC Stage and Safety registers (Universal Robot, n.d).