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DEVELOPMENT OF A ROBUST COMMUNICATION AND CONTROL PLATFORM BETWEEN A 5-AXIS CNC MACHINE AND A MOBILE TELE-OPERATED COLLABORATIVE ROBOT

Updated 4.6.2019

Examiner(s): D. Sc. (Tech.) Hamid Roozbahani
D. Sc. (Tech.) Heikki Handroos

ABSTRACT

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Development of a Robust Communication and Control Platform Between a 5-axis CNC Machine and a Mobile Tele-Operated Collaborative Robot

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This work is a contribution for development of the ongoing fourth industrial revolution. Developing of cyberphysical systems brings new challenges to industrial networks. They have to be more reliable and flexible than ever.
It is a case study of the project that integrates several machines in a mechatronic system. The main emphasis is on the system design. However, other aspects are discussed, such as mechanical design and component choice.
Components of the studied system are a machining center, a mobile manipulator and a central control unit with additional devices. They are interconnected in one system with industrial network. Topology design and used industrial protocols are discussed in detail. The general system algorithm is developed. Calculations are made to ensure proper component choice, and mechanical design is made for mobile robot frame and other components.
This work helped to acquire know-how in modular mechatronic system utilizing mobile manipulator in industrial automation.

ACKNOWLEDGEMENTS

I would like to cordially thank my supervisor, Hamid Roozbahani, for his invaluable help in managing this project.

I am grateful to BRP Rotax RIC team, in particular Josef Fuerlinger and Chloe Nativel, for providing their expertise and leadership in support of this project.

Arina Lomp

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TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC Alternating current

AGV Automated guided vehicle

CNC Computer numerical control

DC Direct current

DIS Draft international standard

GSD General Station Description

HMI Human-machine interface

HRC Human-robot collaboration

I/O Inter/Out

IoE Internet of Everything

IP Internet Protocol

IPC Industrial (personal) computer

ISO International Standardization Organization

M2M Machine to machine

MiR Mobile industrial robots

OSI Open SystemInterconnection

PoE Power over Ethernet

RFID Radio frequency identification

RIC Regionales innovation centrum

ROS Robotic Operating System

TCP Transmission Control Protocol

TIA Totally Integrated Automation

UPS Uninterruptable Power Supply

UR Universal robots (UR10 and UR10e are specific models)

USB Universal Serial Bus

WLAN Wireless Local Access Network

VPN Virtual Private Network

1 INTRODUCTION

1.1 Background

The ongoing fourth industrial revolution is the first one that is predicted and pre-described by scientific society and industry. Most attention began to be drawn to this topic since 2011 when German government introduced its Industrie 4.0 initiative. But over following years, the definition of this term became blurry and there emerged a need to clearer define the terminology of this process as well as its core principles. Such an attempt was made in 2016 (Hermann, Pentek and Otto 2016, p.1). In their extensive study, authors analyzed relevant literature in English and German and drawn unified definition and design principles to Industrie 4.0.

There are several terms commonly used to describe similar concepts. This includes, in addition to German "Industrie 4.0", English terms "Industry 4.0", "Manufacturing 4.0", "fourth industrial revolution", "industrial Internet", "integrated manufacturing", "smart industry" and others.

The four design principles crucial to development of the Industrie 4.0 were formulated as follows:

Interconnection

Information transparency

Decentralized decisions

Technical assistance

Interconnection means integration of network nodes of different nature (humans, machines, sensors, …) into one diverse network. This allow transition from separate Internet of People, Internet of Things and Internet of Services towards unified Internet of Everything (IoE). Technical prerequisites of this transition are discussed further in this work.

Information transparency principle highlights aggregation of collected physical data with digital models and making this data accessible to different IoE members to make informed decisions.

Those decisions should be made by IoE members as autonomous as possible, and this is the essence of decentralized decisions principle. However, if attention of a higher-level decision-maker is needed, the information transmitted to that level must meet certain requirements.

Technical assistance principle stands for lean, comprehensive information representation to (human) decision-maker. Lower-level tasks (physically or mentally tiring to humans) should be delegated to machines. Humans, as flexible decision-makers, receive data sets immediately. Since these data are organized in a concise manner, decision is made as fast as possible.

As of today, numerous publications continuously re-shape the meaning of this term and its key aspects as its popularity grows. In 2017, the development areas for fourth industrial revolution are re-defined and narrowed: *advanced robotics, big data/analytics, cloud computing, cognitive computing, cybersecurity, Internet of Things (IoT), Machine to machine (M2M), mobile technologies, radio frequency identification (RFID) technologies and additive manufacturing (3D printing). (*Saturno, Moura, & Deschamps, 2017)

Framework of this thesis is fourth industrial revolution and its aspects, in particular: advanced robotics, IoT, M2M and mobile technologies.

Naturally, industrial automation is one of the most involved market areas when it comes to Manufacturing 4.0. In a joint effort to make it happen, pioneer researchers and businesses utilize findings of the third industrial revolution (such as robots), as well as develop new robust systems.

One of the systems that became a common practice is automatic workpiece handling at the workshops. Until this moment, robotics is a fast-growing field. The main markets are China, Japan, the USA, Korea and Germany. Collaborative robotics in particular is also booming. However, it is not yet common practice to use a collaborative mobile manipulator. (www.robotics.org, 2015)

BRP Rotax is a part of a global concern of Canadian origin named BRP. The factory called Rotax is based in one of the most industrially developed regions of Austria. Its main business is combustion engine design and production. Regionales innovation centrum (RIC) is a daughter company of BRP Rotax, located in the same place. It provides expertise to the factory in form of development of human resources (employee training) and innovative know-how, such as project discussed in this work. Workshop of RIC is an educational and experimental field that is directly connected to real-life industrial plant, which makes it a perfect place for development of a master's thesis in engineering.

In addition to RIC, there are other participants to the project, such as LUT University and other departments and employees of BRP Rotax.

1.2 Research problem

The main aim of the automation project is development of a collaborative automation system, which consists of a CNC machine and mobile manipulator robot, that allows 24/7 operation of the workshop.

1.3 Goals

This thesis mainly concentrates on connectivity issues of this project. The key goal of this thesis is to develop the system topology of a control station and a mobile manipulator.

However, to execute the project, many other issues must be solved. Several of them are also addressed in this thesis:

- System topology design
- Mechanical design of mobile manipulator frame
- Power system design for mobile manipulator (partially addressed in this work)
- Control station choosing

1.3.1 Research question

Research question is, what is the best topology to control a system that contains collaborative mobile manipulator?

1.3.2 Hypotethis

To avoid system redundancy, topology should include as little elements as possible. So it is supposed that the machining center and the mobile manipulator should be connected directly without additional devices.

1.4 Contribution of the thesis

Further development of this automation project includes addition of industrial mobile manipulators (this thesis contains a brief overview) and other types of machining centers.

2 LITERATURE REVIEW

2.1 Industrial control networks

Collaborative robots, or cobots, are robotic systems that are designed to work in a shared workspace with humans. To meet safety requirements, cobots are equipped with sensors to detect presence of workers. The control system of the robot uses data from those sensors to make a decision to slow down or completely stop the movement.

In this work, two collaborative robots were used: automated guided vehicle (AGV), or mobile platform robot and a serial robot (robotic arm).

In a modern industrial environment, network communication is of growing importance. Open-loop systems are hardly usable in workshops nowadays, making it necessary to implement feedback networks. It starts from hard wires connected to discrete sensors and grows to centralized lifecycle management databases. The main feature of an industrial network, in contrary to commercial, is its connection (typically through a fieldbus) with a field device that is working with a physical process.

Industrial control networks are systems of connected devices that work in industry. With development of cybertechnology, however, the border between an industrial control network and a conventional commercial network disappears as both types of them merge. There are many layers of industrial networks, from field networks up to production supervisory.

	Industrial	**Conventional**
Primary Function	Control of physical equipment	Data processing and transfer
Applicable Domain	Manufacturing, processing and utility distribution	Corporate and home environments
Hierarchy	Deep, functionally separated hierarchies with many protocols and physical standards	Shallow, integrated hierarchies with uniform protocol and physical standard utilisation
Failure Severity	High	Low
Reliability Required	High	Moderate
Round Trip Times	250 μs - 10 ms	50+ ms
Determinism	High	Low
Data Composition	Small packets of periodic and aperiodic traffic	Large, aperiodic packets
Temporal Consistency	Required	Not required
Operating Environment	Hostile conditions, often featuring high levels of dust, heat and vibration	Clean environments, often specifically intended for sensitive equipment

Figure 1. Comparison of industrial and conventional networks. (Galloway, Hancke. 2013)

To allow reliable function, there are features to implement in an industrial network. The network should be inmpemented in a way that reassures discrete manufacturing for the given application. When developing an architecture of an industrial network, it is important to recognize different levels of it. One level can be instrument control in the machining centre, and another is Human Machine Interface (HMI) level to control a whole group of devices. Failure of an industrial control system can lead to more serious consequences than in a conventional network because it is connected to industrial equipment. Real time operation is required for reliability, especially in time-crucial tasks like motion control. Small response times are also important for control loops. The deterministic nature of data is needed to ensure fixed time intervals between data packets. This is the main feature of industrial protocols. Size of this data is normally minimal in industry, starting from few bytes. In conventional networks, smallest data packet is 64 bytes. However, deterministic small packets have to carry both periodic and aperiodic data. Timestamps and synchronized clocks assure temporal consistency in industrial network protocols. And finally, since the industrial networks are located in the immediate proximity to production, they must be durable to resist workshop environments, which includes dirt, moisture, vibration and other physical factors.

Data that is transported trough an industrial network falls into one of the three following categories: control, diagnostic or safety.

Devices exchange control information to use in control loops, so it has the highest requirements to real-time implementation and determinism.

Diagnostic, or monitoring, information is also collected constantly, but the control unit does not use this information in the control loop, so in normal operation there is no action on this data. Still it requires minimal data loss and temporal consistency.

Safety information has the highest requirements to the network qualities as it implements critical functions. While it is possible to merge monitoring and control data, safety information is sent through separate channels that are also backed up.

Any type of information can be logged and stored in memory, and then this archive can be used for analysis. This information is then referred to as historic data. (Galloway, Hancke. 2013)

In fieldbus network protocols, a piece of data (a message) is called stack. A stack can consist of up to seven layers, or types, of information. Open System interconnection model (OSI) describes the seven functions of the layers.

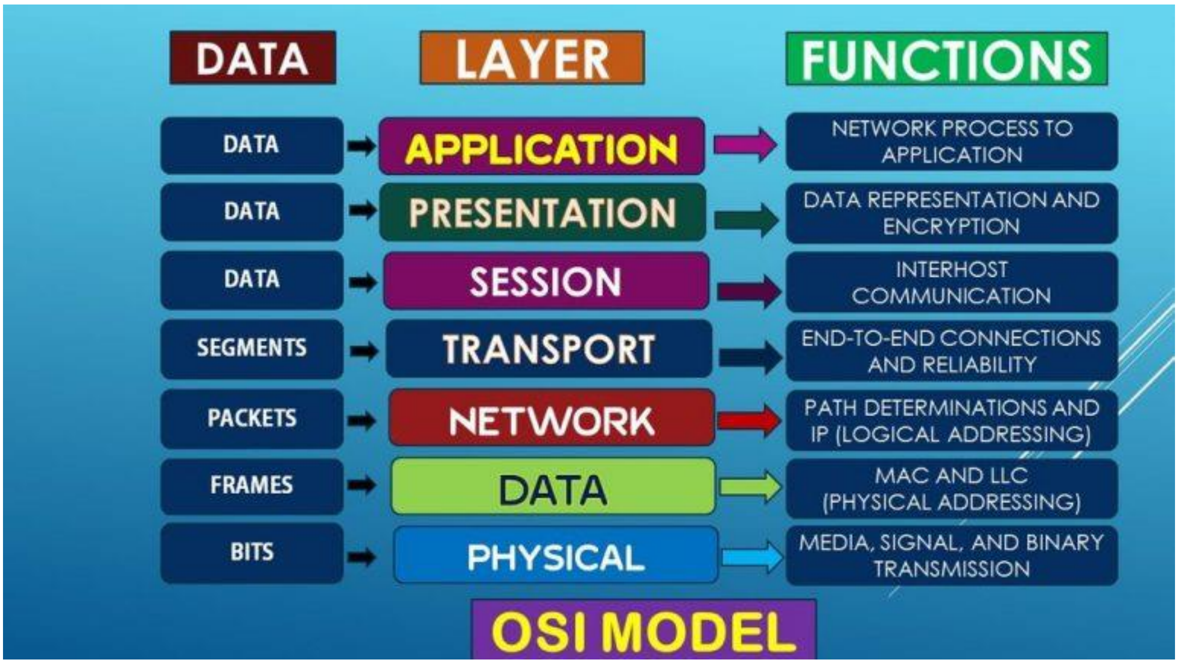


Figure 2. OSI model. (www.glossaryweb.com, 2018)

7. Application layer is directly interacting with communication software. One of the main aims of the application layer is to determine communication partners in the network.
6. Presentation layer provides context for application layer. This can include syntax and semantics. Presentation layer converts data to establish coherence between the application layer and the network format.
1. Session layer supports connections between devices in the network. It starts, supports and end sessions. Sometimes it is used for system recovery.
4. Transport layer is used to transmit variable-length data. It also controls the data flow and errors. In case of failure transport layer can re-send a broken package to the destination device.
3. Network layer also transfers variable-length data. It uses more general approach than a transport layer, mainly managing the network addresses. Network layer defines system nodes and reassures delivery of the messages. However, this layer is not error-critical and does not necessarily need to check for errors.
2. Data link layer provides communication between two directly connected network nodes. Also it monitors and if possible corrects errors in the physical layer. Data link layer starts and stops direct node-to-node connections.

1. Physical layer receives and transmits data to the outer devices. It converts bits of digital signal to signals of other physical nature: optical, radio or electrical.

2.2 Industrial protocols

The two main industrial protocols that are use in this work are PROFIBUS and PROFINET.
PROFIBUS protocol is an industrial information protocol initially announced in 1989 as a fieldbus protocol.
Its implementation is designed with compliance with OSI model.
On layer one (physical), PROFIBUS is generally copper-wired, however, it can also be used wirelessly or with optical transmission.
Data link layer of PROFIBUS defines security. Token method and master-slave method are both used in the protocol.
Layers from 3 to 6 are not used.
On application level, PROFIBUS connects the link between the application and communication.

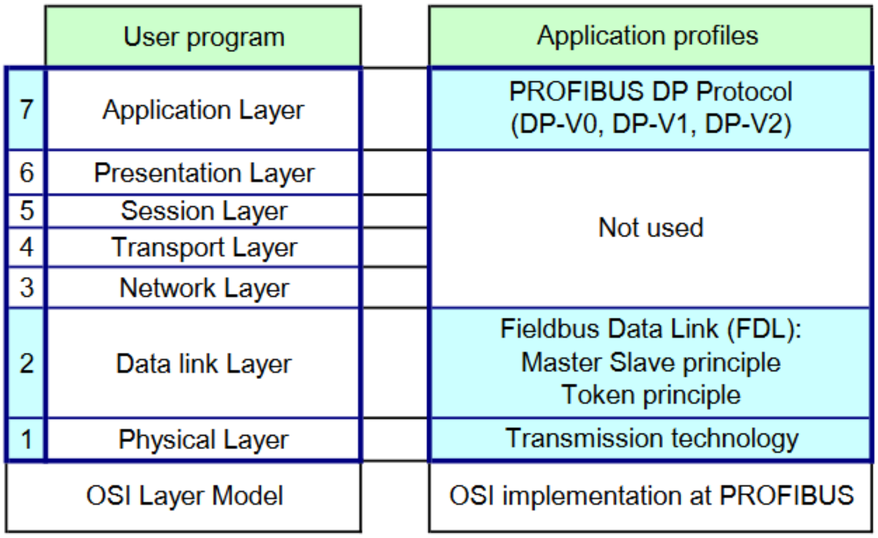


Figure 3. OSI model and PROFIBUS protocol usage of layers. (PROFIBUS, 2016)

PROFINET is a more modern, Ethernet-based industrial protocol. To some degree, it is a more complicated successor of PROFIBUS. It uses five levels that are available for Ethernet. Two of them, physical and data link, are defined by Ethernet. Application level also must be present. Transport and network level are also used. Transport level establishes links between devices, segmenting and troubleshooting, and network layer assembles data packets and routes them in the network.

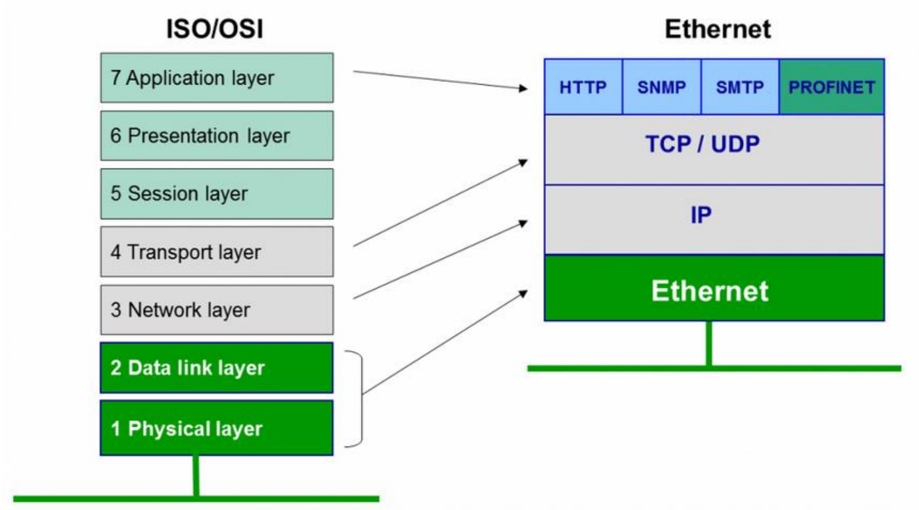


Figure 4. PROFINET usage of OSI model layers. (profinet.com, 2015)

2.3 Mobile robots

There are numerous mobile manipulators in various fields, such as domestic care robots (Yamamoto et al., 2019), or teleoperated rescue robots. However, using a serial manipulator with a mobile platform, unlike stand-alone, is not yet a common practice in automation industry, but many market players experiment in this field. Mainly, those, who have both AGV production and manipulator production. Manufacturers especially design this type of mobile robots in accordance with principles of the fourth industrial revolution. The main advantage of such system in production is its significant flexibility. If workflow or the floorplan of the workshop changes, only minor changes to mobile manipulator are needed (such as re-programming or gripper change).

Installation of any of these robots only requires minimal changes to the workshop environment:

- installation of suitable charging stations
- removing obstacles for safety

Charging is discussed with specific models. Removing obstacles for safety means that any element of the environment must not prevent the robot from detecting a human. For example, material supply shelfs must have console-supported design because laser scanner sensors are located at the bottom (approx. 15cm from the ground), and shelf legs are an obvious problem for such a sensor.

In academia, research in the field of mobile automation is wide, and one of the commonly used platforms is a combination of MiR100 and UR robots.

2.3.1 Industrial robots

Figure 5. KUKA KMR iiwa industrial mobile manipulator. (kuka.com. 2019)

KMR iiwa is a mobile manipulator created by a German company KUKA. Its base is an AGV with omni-directional wheels that help to navigate in narrow spaces and make maneuvers that are impossible for other types of wheels. Autonomous mobile platform navigates with two laser scanner type sensors. Both AGV and manipulator are collaborative. Manipulator is a lightweight type, payload can be different depending on the specific model. According to different sources from the manufacturer, positioning accuracy is up to 1 or 5 millimeters. Gripper flange can be chosen from variety of standards.

Charging interface for the whole system is floor-built contacts. To some fast-changing workshops installing charging stations in the floor is inappropriate.

Data interface can be chosen in accordance to intended application. All common industrial interfaces are supported. The AGV has a relatively big top surface that can be used as a mobile storage.

Figure 6. Stäubli HelMo industrial mobile manipulator. (staubli.com. 2019)

HelMo system by Stäubli originates from Switzerland, however, it is mainly being developed in Germany. The base is a cylindrical AGV (“drive unit”) with three laser scanners. Top half (“rotating unit”) is rotating for ±180°. On the rotating unit, collaborative robot manipulator is located. Two types of charging sockets are available. One has to be located on a vertical surface and robot plugs in by driving in it. Another type is flexible in installation and functions similarly to a consumer electric outlet. HelMo robot can plug itself to such a socket with its flexible cable. Both charging sockets are supplied not only with electricity, but also with pressurized air and can charge robot’s pneumatic tank. The tank is located inside the AGV and its capacity is used to attach and remove grippers as well as to perform small pneumatic-driven tasks. End effector positioning accuracy is up to 0.03 millimeter. Such a great accuracy is achieved with a calibration system.

Table 1. Comparison of the key characteristics of KMR iiwa and HelMo robots (options with similar manipulators).

Feature	**KMR iiwa**	**HelMo**
Weight, kg	420	710
Platform dimensions w*d*h, mm	630*1080*700	890*100*1120
Manipulator length, mm	1306	1000
Payload, kg	14	14
Accuracy, mm	5 or 1	0.03 after calibration
In-built pneumatic system	no	yes
Gripper flange	flexible	MPS 032
Interface standard	customizable	customizable
Charging interface	floor contacts	socket connector

2.3.2 MiR100

The platform is MiR100. This robot has two driving motors and four free-rotating revolving wheels. The user can mount a load of up to 100 kg on the top of it or equip it with automatic clamps to use with external trolleys. It is also possible to install another robot on MiR100 (MiR, 2017). For this purpose, a special platform has to be designed. At the electrical side, MiR100 allows to connect to its power source, which for this purpose can be extended with additional battery. Control systems of the robots can be integrated.

Disadvantage of MiR100 is its low positioning accuracy (in the range of +- 5cm). While this is tolerable in many applications, such as material supply or warehouse trolley transportation, robot position has to be calibrated if it is used for more precise operation, in our case, CNC machine automatic loading. One way to lower positioning inaccuracies is to install the charging station in the critical point. When the robot connects to the charger, its accuracy increases up to +-1cm.

This id due to the fact that the charger has a special v- or L- shape which is recognized by th MiR100 laser scanners. It is also possible to build those shapes independently and use them as reference for MiR100.

2.3.3 UR10e

UR10e is a new variation of UR10, the popular collaborative serial manipulator with payload of 10 kg. Robot has six rotating joints that allow positioning and orientating of the end effector.

Collaborativity of the robot is ensured through force sensors in robot joints, so it only stops once it mechanically contacts the obstacle.

UR10e consists of the manipulator itself and control box. Power consumption from the industrial network is estimated at 400 Watt. The manipulator can be controlled and programmed with the teach pedant. It uses a specific software called PolyScope. When an external device is connected to the robot, it can use URCap functions to seamlessly integrate in PolyScope.

Programming the robot with teach pedant is used with a specific programming language. To set a waypoint, the user can either move the manipulator using teach pedant, or release the brakes and move the robot manually (Universal Robots. 2018).

2.3.4 Workpiece description

The part that is being produced at the first stage of the project is fixed. It is a small cylindrical part with the greatest dimension of 50 mm. It is produced from a rectangle or cylindrical block of steel.

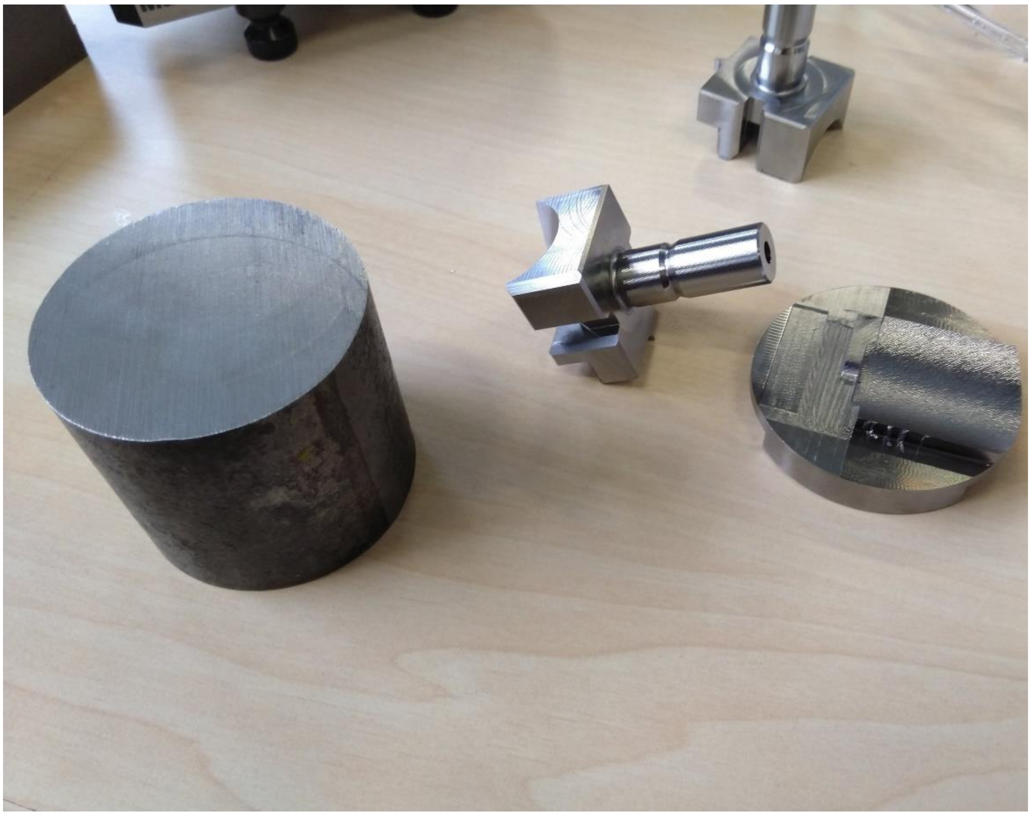


Figure 7. Cylindrical workpiece and final part.

Some of the clamping systems that are used in the workshop with the machining centre have clamping surfaces with dents that help to keep the workpiece in place. The dents are needed in manual clamping systems when the force is not sufficient to hold the part in place.

When such clamp is used, a pattern must be carved in the workpiece before it can be clamped in the machine. The pattern is applied to the workpiece on the manual machine, the tolerances relative to the workpiece center are very high. This makes it unreasonable to use the mobile manipulator because there is no obvious way to tell the exact pattern position on the workpiece. So if the robot picks up this part, it cannot place the part in the clamping system with enough accuracy.

However, these manual clamps are not used in automation systems, but rather installed in the machine for initial system testing.

In pneumatic clamps, the clamping surfaces are straight. Then the task of the robot is not to align the workpiece with dents, but just fit two surfaces, cylindrical or flat, together.

2.3.5 gripper

As the shapes of the workpiece and part may differ, it is important to choose and check if the gripper is compatible with both shapes. In this work, we are using Robotiq Adaptive 3-finger gripper. this device is fully compatible with UR10 robot.

It has three underactuated fingers which allow it to grip a variety of different shapes. Two fingers in a row are located opposite to the third finger. The fingers surface is a rubber with high friction coefficient.

This gripper has four gripping modes. In the basic mode, two fingers are parallel to each other. This mode allows to grip various average-sized objects. In the wide mode, two fingers are pushed away from each other. This operational mode allows to grip larger or longer objects. In the pinch mode, two fingers are touching with the tips. This mode ensures reliable grip of small objects. In scissor mode, only two fingers that are in a row are used. Gripping surface is different in this case. This mode is meant to handle extremely small objects.

For wide and basic operational modes, two types of grip are possible: fingertip grip and encompassing grip. In fingertip grip, only the fingertip falangs’ surfaces are in contact with the object. In encompassing grip, the whole finger surface and the palm surface touch the object (Fig. 8, basic mode).

Figure 8. The four operational modes of the gripper. (robotiq.com, 2019)

For our application, pinch mode of gripping is good. Testing with the real workpiece has proven this grip to be reliable.

2.3.6 MiR100 and UR10e interface.

MiR100 robot is capable of establishing a communication with one UR robotic arm. MiR100 program has set points on the map, and there is a possibility to run UR programs at selected points while the platform is still.

To connect MiR100 and the UR robotic arm, rewiring must be done in the control panel of the mobile platform. In addition to this, safe operation must be ensured. In particular, the manipulator must stop every time MiR100 emergency stop is triggered. Physically, this is done by merging the safety wirings of the both robots together.

Data connection is through Ethernet cable that is directly connected to the MiR100 on the one end, and plugged to UR control box on the other. It is recommended to set the IP address manually and then enter it in the MiR100 web interface.

To control the robot, both the regular web interface of MiR100 or ROS can be used. To utilize the web interface, the UR-related features must be enabled.

Then the web interface programming is done similarly to the usual standalone operation way.

2.3.7 Vision system

Camera installation on the mobile manipulator is beneficial from several points of view: firstly, it allows to calibrate the positioning of the whole system at the stopping points, se3condly, it helps to recognize, pick and place workpieces and parts to the storage area or to the clamping system of the machining centre. There are two camera systems available for use with UR10e.

Robotiq Wrist Camera is a standard camera recommended by universal robots. It is a compact 5 MP colour camera with electrically adjustable focus and boult-in lighting. Power supply is directly from the UR10e 24 volts, cameras mass is 160g. The main advantage of this camera is its software that is equipped with URCaps which are small programs that can be run on UR robots. (robotiq.com. 2019)

Another camera is SensoPart VISOR Robotic family. The resolution is up to 1440x1080p, different lenses are available to work with different field of view angles. Electrical communication with UR10 is similar to this of the Robotiq analogue. (sensopar.com. 2019)

When these cameras are used for the cases similar to this, image processing and pattern recognition are done 5autonomously in the camera. Data sent to the UR10 robot are coordinates of recognized parts or elements. This way, it is possible to program UR10 robot to correct its trajectory or end effect coordinates.

2.4 Robotic Operating System

Another way of controlling and programming UR10e is with Robotic Operating System, or ROS. ROS is an open-source set of frameworks designed specially to control robots.

There are two operational levels to ROS. First one is filesystem, which consists of packages and their derivatives and supporting files. Packages are cohesive software sets that contain ROS runtime processes, or nodes, libraries, configurations and datasets.

Architecture of ROS is based on computational graphs with nodes, which are separate program modules responsible for specified tasks. Nodes are connected into graphs and can exchange information through established connections called services. In the graphs, there are also topics, in which nodes can publish their messages. Nodes that are subscribed to those topics receive that data. Master process must be started to form a computational graph as it contains names of nodes and other crucial graph topology information.

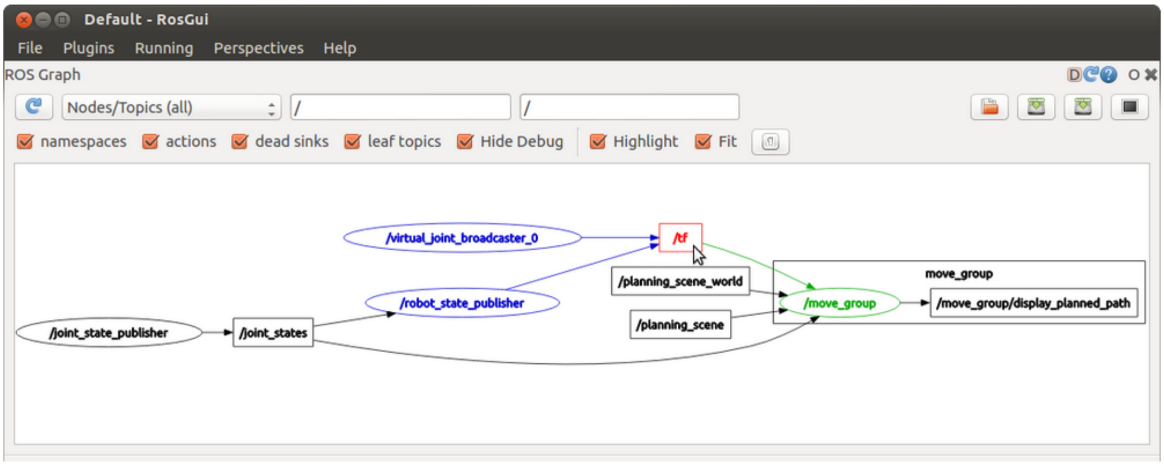


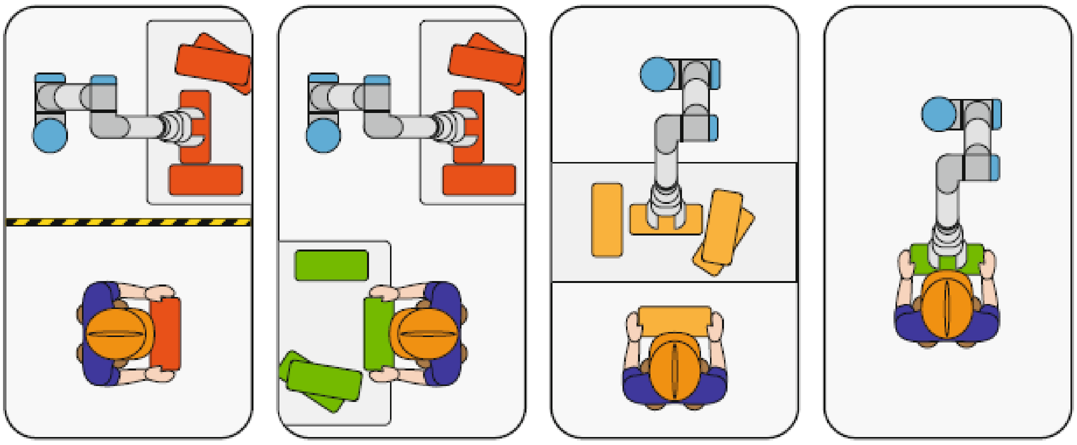
Figure 9. An example of plotted ROS graph. (ros.org. 2018)

ROS is not the advised way of controlling UR10e robot, however, it allows user to have more flexibility, so it is quite a common way to control it. There are two packages for controlling UR robots, universal_robot and ur_modern_driver that is replacing the old one and corrects its mistakes. Both packages are underdeveloped and are not yet advised to use in industry.

Controlling UR10e in ROS gives opportunities to fine-tune robot's behavior. User can program separate joints, model the robot in 3D-environment, collect extensive data logs and observe the computational graphs, edit movement planning.

2.5 Collaborativity of the whole system

Growing attention is brought to Human-Robot Collaboration (HRC). By definition, collaborative operation is "state in which purposely designed robots [...] work in direct cooperation with a human within a defined workspace" (ISO: 8373:2012–03). Many different types of "direct cooperation" are known, and L. Kaiser et al. proposed a graphical "4 Cs" classification of four degrees of cooperation in systems that involve both humans and robots.



(a) enCapsulation (b) Coexistence (c) Cooperation (d) Collaboration

Figure 10. Four degrees of collaboration. (Kaiser, Schlotzhauer , and Brandstoetter. 2018)

enCapsulation stands for physical encagement of robots.

Coexistence is operation in the same workspace, where robot and human work with separate workpieces at the same time.

Cooperation is sharing workpieces at different times.

Collaboration is common work with the same workpiece at the same time.

Safety of collaborative robotic systems is addressed in the following standards:

- ISO 10218 Robots and robotic devices — Safety requirements for industrial robots
- ISO 12100 Safety of machinery -- General principles for design -- Risk assessment and risk reduction
- ISO/DIS 3691-4 Industrial trucks -- Safety requirements and verification -- Part 4: Driverless industrial trucks and their systems

Mobile robotic systems standardization is under development, which complicates safety evaluation as in every case it has to be individual.

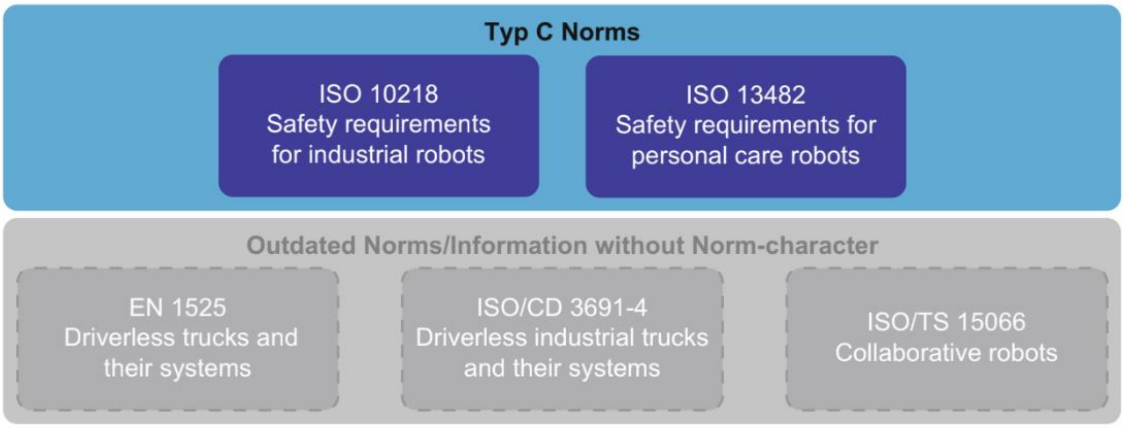


Figure 11. Norm regulating safety in collaborative robotics. (Kaiser, Schlotzhauer , and Brandstoetter. 2018)

Moreover, when it comes to risk assessment, current safety analysis approaches are not compatible with international standards, and with robotic community (Askarpour. 2016)

To sum up, it is challenging to assess risk in collaborative applications of both robotic arms and AGVs due to underdeveloped standard base. Installing a robotic arm on the top of the AGV requires even more complex risk assessment strategies. However, there are companies on the market that were able to overcome those complications and received CE certification for a mobile serial robot. Examples of such systems are KMR iiwa by KUKAand HelMo by Stäuble that are consumer-ready and can be installed in workshops after purchasing. But despite CE conformity of these robots, their usage in practice still requires extensive risk assessment as commonly additional elements are needed for function. Those elements can include grippers, calibration and vision systems, pneumatic equipment, and workpieces. Naturally, the robot manufacturer cannot assess influence of those factors on the overall automation solution safety.

Modular robotic systems consisting of HRC-compatible elements still need extensive safety study and, possibly, additional safety and monitoring devices.

Safety concept of this project includes, in addition to in-built safety systems of the separate system elements, sensitive floors or laser sensors in the zone of manipulator operation to preclude physical contact of human and manipulator. While this measure is not necessary because system components are collaborative and can share workspace with humans after proper safety assessment, it was decided to install additional safety equipment because the workshop is used primarily for trainings, and CNC machines are commonly accessed by trainees.

3 RESULTS

3.1 System components protocols

To better understand topology choice of the system, it is necessary to know exactly what kind of protocols do elements have.

3.1.1 Machining station protocols

From connectivity point of view, the type of the machine used in the automatization system is insignificant as long as the interface protocol is readable by the control station. In this project, two machines will be used.

One of them is Hermle C250, a 5-axis machining centre. This machine has three linear and two rotational axes and allows to machine complex designs in one operation. The control station of the machine is HEIDENHEIM T640. It allows to control the main operation of the machine, such as milling and door opening. To connect to it externally, a VPN connection can be used, but its functionality in this case is still limited to the same. This kind of interface does not allow automation interaction with the machine as it is expected to be used by a human. Automation of Hermle C250 is possible by installing a custom interface module discussed in “system topology”.

The other machine that is planned to be used for this project is Index turning machine. This machine allows for communication via PROFIBUS protocol without any additional modifications.

3.1.2 UR10e protocols

By default, UR10e manipulator is not equipped with any kind of wireless interface. However, it is possible to employ PROFINET interface using a gateway to Wireless Local Access Network (WLAN). Anybus Wireless Bolt is a compact solution. This gateway is specifically designed to be used with industrial cabinets (which in our case is a UR10e control box). On the wired side, it allows to connect various Ethernet and Industrial Ethernet protocols, including PROFINET and Ethernet IP/TCP. On the wireless side, this device can work with WLAN 802.11 a, b, g, n, d networks. The Wireless Bolt is powered either through Power over Ethernet (PoE) or just two contact 19-36V DC.

UR10e only has one Ethernet connector. At the first stages of the project, when the goal is to establish a connection between UR10e and the central control station, we can directly connect Anybus Wireless Bolt to this connector. However, in the future it is necessary to connect other devices to UR10e: camera system and MiR100 also use Ethernet based protocols. To allow connection of several devices to one connector, we will need to use a switch. There are no special requirements for this device, so any Ethernet switch can work.

3.2 System topology

Topology of the whole system is one of the most important challenges of this work. Many factors had to be taken into consideration and several different topologies were discussed before building. First group of factors are available communication interfaces.

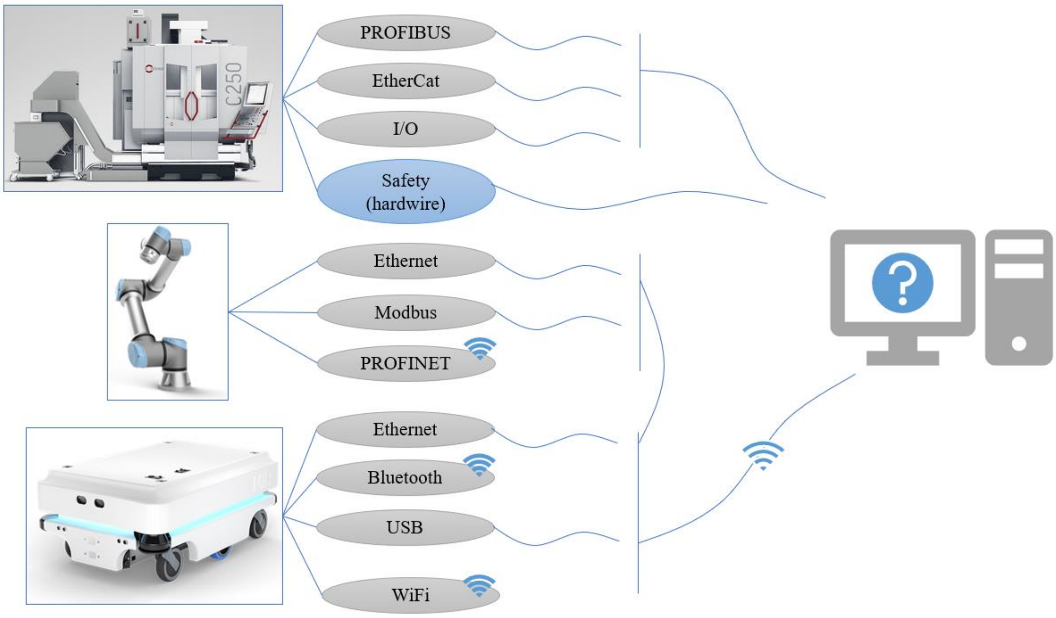


Figure 12. Available interfaces of the equipment. Computer station is unknown, because it is not clear weather this component is needed and, if yes, what are its features.

For the Hermle CNC machine, a communication interface is not a standard machine option and has to be ordered separately. But even in this case options are limited to PROFIBUS, EtherCat or simple I/O. All of those protocols might, but are not meant to be used wirelessly, thus making it impossible to use for direct communication with a mobile robot. To convert protocols, a simple gateway can be used.

UR10e comes with several TCP/IP protocols onboards: the user can plug it using Modbus, Ethernet or PROFINET.

MiR100 is meant to be primarily controlled with the web interface through WiFi connection. It also provides Ethernet connection and special communication features to UR10. Additionally, Bluetooth and USB connections are available. Bluetooth is a short-range protocol, thus it’s out of our scope, and USB is wired.

Two topologies are hereby discussed.

In the first one, the machining center is the master of the whole system, robots are its slaves, and programming has to be done on the CNC machine side. This enables direct communication between the two machines, and a separate control module is not needed. This topology is fit for specific pieces of equipment that we have in the workshop. The direct communication in this case is realized through PROFIBUS protocol with help of PROFINET/PROFIBUS gate as the intermediate point between the machining station and the robot. On the robot side, MiR100 receives a wireless signal. Exchange between UR10 and MiR100 is programmed in the special ROS-based interface. This topology is shown at fig. XX. As can be seen, gateway and, naturally, machining center are stationary. Converting PROFIBUS connection to wireless is an option in some cases, but is not advised because of reliability problems of such conversion. Also, initially this protocol was meant to be used as a fieldbus, and it is not compliant with modern security standards.

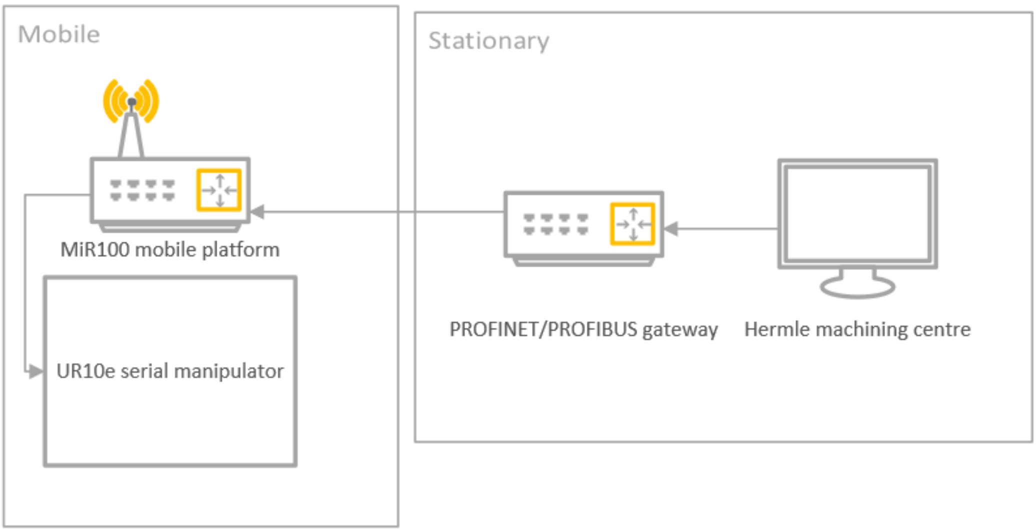


Figure 13. Topology without the central control station.

Modularity is one of the main directions of developing of the modern mechatronics. By definition, modular design is an approach which promotes usage of modules, sometimes referred to as skids, to enable faster maintenance, scalability, mobility, adaptiveness of the mechatronic system. This approach emerged as a response to growing complexity of mechatronic systems. Indeed, maintenance process can be time consuming, and failure of a small part can lead to shutdown of the whole system. However, if the system has distinctly separated groups of parts, modules, then this module can be replaced as a whole faster without lengthy shutdowns even in case of failure. In the modern robotic system, especially in the field of industrial automation, it is crucial that the systems are easy to adapt to new conditions (for example, new types of products). Automated systems were mainly made for mass-production, but the world moves towards smaller series industries being automated and one of the objectives of the fourth industrial revolution is made-to-order automation solutions. Modular design is undoubtedly the approach that helps adaptivity, be it same-level restructurization or scaling.

In the case of using a gateway approach, the system does not provide modular features. In other words, it is utterly dependent on specific hardware used in this project. As long as UR10+MiR100 robotic assembly has limited capabilities in industrial workshop, and Hermle C 250 is an “entry-level” machine, the whole system is mainly fit for the experimental workshop. However, future development of this project is to be carried out in another workshop with real-life production, and it is reasonable to introduce a separate physical module for communication interface between the mobile and the stationary parts of the system. This way, the interface is hardware-independent and can be implemented in a similar system with another hardware, such as a turning machine from another manufacturer or an industrial mobile robot. Then the system is in compliance with the modular design principles.

This topology is depicted at fig, XX. There, the machining centre is connected to the control unit via wired PROFIBUS. Stationary control station is the wirelessly connected to the mobile robot. Connection between the UR10 robot and the MiR100 mobile platform are the same as in the previous topology.

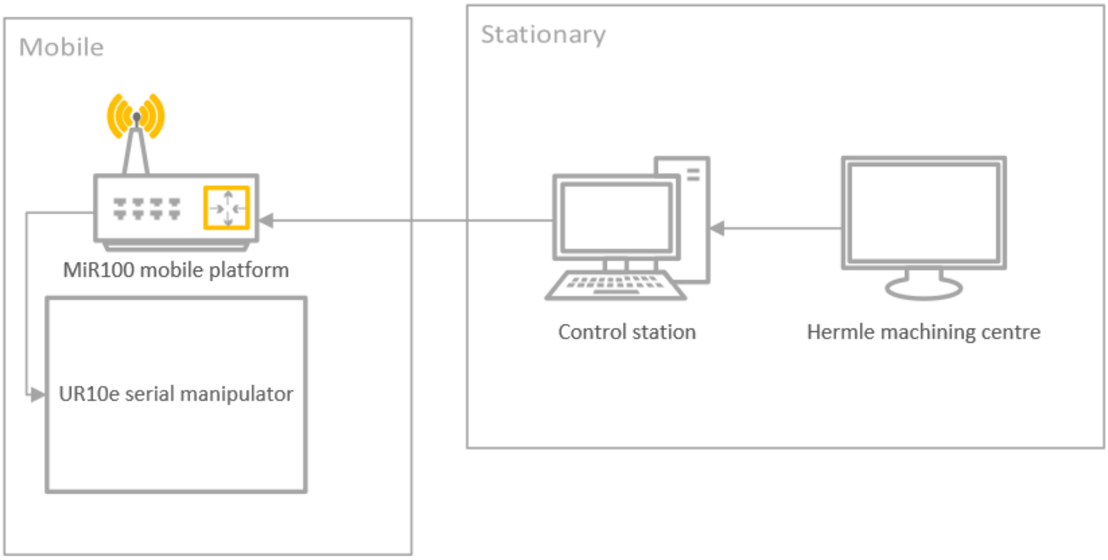


Figure 14. The system topology with control unit.

3.3 Frame design

Since it is a common practice to combine MIR100 and UR robots, many frame designs are developed, and commercial designs are available. But in the case of using this system with a CNC machine it is important to consider height of the worktable. For the Hermle C 250 the height is 900mm. The robot position is at least 800mm from the table, and length of the robotic arm is 1300mm. To achieve the best flexibility, it is important to install the UR10e on the same height as the worktable. Typically, UR10 robots are installed on lower frames when used with MiR100 because position of the center of gravity is limited by MiR100 loading capacity. However, higher frame designs are known to be used in cases when they are stationary, or a smaller version of the UR robotic arm is used (UR3 or UR5).

When lifting the center of gravity to such (untypically big) height, a counterweight must be installed to compensate possible instabilities. In our design, we use a UPS (Uninterruptible Power Supply) to power up the robotic arm. This component has significant weight (more than 20 kg), and can be used as a counterweight. But location of the center of gravity is impossible to estimate correctly since positions of centers of gravity of electromechanical components are unknown.

Thus, the frame should be designed the way that it can be easily rebuilt to a lower height in case if the counterweight does not provide enough stability.

Other design limitations are coupling surfaces for MiR100 and UR10e. Lower part must have holes to be attached to the mobile platform. Upper plain must comply with UR10e installation requirements listed in the robot’s manual.

One of the most important features of the frame design is weight limitation. Since the payload of MiR100 is 100 kg, calculations were made to ensure that the whole design is lighter.

Table 2. Weight of mobile robot components.

Component	Weight (kg)
UR10e manipulator (incl. cable)	33.5
UR10e control box, max	13.6
UR10e teach pedant (incl. 1m of cable)	1.6
UR10e payload, max	10
WiFi module	0.08
Other cables and switch, estimation	3
UPS	21
Total	82.78

Total weight of all the components installed on the robot is 82.78 kilograms, which accounts for 17.22 kilograms left for frame.

Considering all of the above discussed design requirements, the aluminum profile design was developed. Lower frame's function is coupling with the mobile platform, middle frame is used to hang the control box and to fix the UPS position. On the upper frame, UR10e coupling plate is installed.

Weight of the chosen aluminum profile per meter is 0.9 kg. Weight of the whole profile frame is then, according to the design:

$$0.9\frac{kg}{m}\cdot(0.59m\cdot 6+0.44m\cdot 4+0.5m\cdot 2+0.45m\cdot 4)=7.29\ kg$$

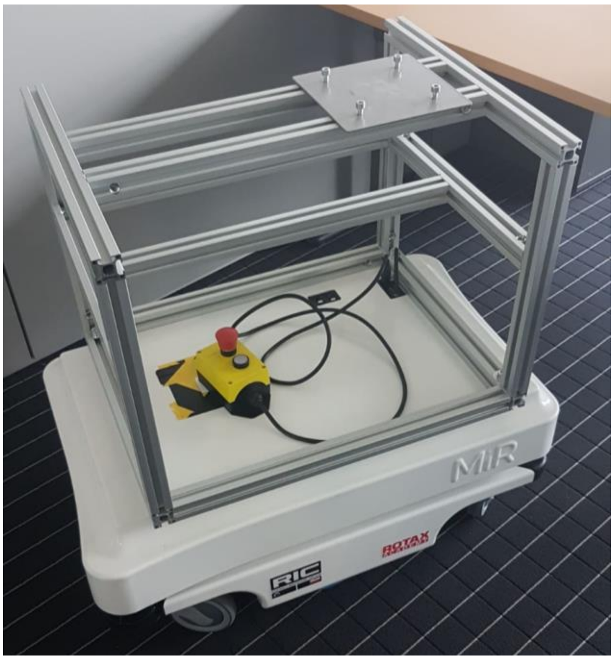


Figure 15. Frame installed on MiR100 robot.

3.3.1 UR on a table

For initial testing, UR10e was installed on a stationary table beside the machine, while MiR100 was used separately as material supplying platform. At this stage, UR10e was programmed using teach pedant, machine's clamp and MiR100 were operated manually.

This phase allowed to test geometrical and other mechanical properties of the system in practice. At this stage, no quantitative analysis was made as the aim was to check the model in practice. Only qualitative testing was made.

First, it was proved that ROBOTIQ 3-finger gripper clamping is reliable enough to handle the given workpiece. Second, the position of UR10e manipulator in relation to the machine was tested. Positioning was sufficient to allow flexible workpiece handling. Third, positioning accuracies of MiR100 and UR10e in relation to the machine, as well as in relation to each other, were tested. MiR100 positioning and repetitiveness were proved to satisfy the needs of the project. These inaccuracies did not affect the ability of the system to place the workpiece in the clamping system and clamp it. Performance of UR10e manipulator was also in accordance with expectations. However, table position on the workshop floor was unstable. Friction between the steel legs of the table and concrete floor was not enough to keep it in place while the manipulator performed its movements.

Figure 16. UR10 on a table test setup.

3.3.2 Battery issues of MiR100 and UR10 assembly

This is a common practice to use the two devices together in an assembly because there is a developed control interface. But when it comes to the mechanical connection and electrical one, it is responsibility of the user.

Original battery of MiR100 has a capacity of . MiR100 is designed to fit the second same battery inside its body.

However, there is no ready solution for powering up the UR robot directly from the resources of MiR100 because of different current specification. UR is powered from the conventional 230V alternating current, whereas the MiR100 batteries supply it with 24V direct current. This requires additional conversion and safety devices, but it is still unsafe because the system is not certified once the changes are made to MiR100 inner wiring.

To avoid that, it was decided to install an uninterruptable power supply (UPS) on the mobile robot, so it charges the MiR100 battery at all times. This solution complies with the principles of modular design as UPS is an independent module. Output of the UPS is 230V alternating current, so it can supply both robots. Calculations were made in order to ensure operational time of the mobile system.

The planned operational times:

- driving time from the machining centre to the storage area is up to 5 minutes
- pick up time at the storage area is 5 minutes for one part
- time back from the storage area to the machining centre is up to 5 minutes
- the robot extracts a part form the machine and put a new part in. It will take about 5 minutes.

After this the robot drive back to the charging station and recharge.

In total, one run needs 20 minutes. This is the time of autonomous operation of the mobile robot.

Then it is necessary to calculate the power consumption of the mobile robot elements.

Total power consumption is estimated thus at 423W. Based on this, UPS capacity can be calculated. To supply the robot with 423W for 20 minutes, the battery capacity should be at least 141Wh.

Charging time is also 20 minutes. One program at the machining centre works for longer period of time, approximately 30 minutes.

Table 3. Power consumption of the mobile robot system elements.

	W	V	A
UR10e	400	230	1.73
AC/DC converter	23	230	10
Gripper	26	24	1.1
Camera	7.2	24	0.3
WLAN router	1.7	24	0.07
Camera lights	1	24	0.390

Now we evaluate the specific models of UPS and choose the one that is suitable for our needs.

The OPTI Durable 3000VA UPS Uninterruptible Power Supply, 220 → 240V ac Output, 2.7kW. This is a universal UPS that converts 220V 40 to 70Hz input power to 240V 50 or 60 Hz.

According to the data sheet, its charging time to 90% of 56 Ah (or 50Ah) in 4 hours.

At 96V It means 4800 Wh in 4 hours, or 360 Wh in 20 minutes. Discharge in 20 minutes 141 Wh.

At 72V It means 3600 Wh in 4 hours, or 270 Wh in 20 minutes. Discharge in 20 minutes 141 Wh.

This device is suitable to support the autonomous operation of the robot.

Charging station is located at the machining center, and when the mobile robot is docked to it, it can charge. There is a standard charger for standalone MiR100, and it has to be modified to charge the UPS, too. Mechanically, however, no changes are made to the existing equipment. An additional charging panel is installed on the top of the MiR100 charging station.

3.4 The central station computer

3.4.1 Hardware

The central station computer has a control function in the studied system. Its aim is to ensure collaboration of all machines on both operational and safety levels. To choose a specific model of a control module, the following factors were considered: functionality on both levels, protocol compatibility, company standards, certain degree of flexibility, ambient conditions.

Control function of the computer station is to receive real-time and data information from other devices, store and process it, make decisions based on it and then send the respective data to controlled devices in the compatible form

Protocol compatibility issues are discussed in detail when planning the system topology in chapter X.

Normally, to simplify factory maintenance and technical support, companies limit their choice of control devices. Those limitations can be as wide as several different manufacturers, or, in some cases, as narrow as only specific models from one manufacturer. As this project lies primarily in research field, there is no strict obligation to follow the company standard, but it was chosen to consider the standard to simplify integration of the developed system in the factory infrastructure in the future.

In addition to these properties, the control station device should allow a certain degree of flexibility in protocol availability and programmability as the interface is intended to be modular, or easily changeable to work with other types of external hardware.

The control station is to be installed in a metalwork workshop in the immediate proximity of machining center. Operating under these conditions require durability.

SIMATIC IPC677D by Siemens offers functionality that is required by the above discussed limitations. There are many variations of this IPC that have different processors, operating systems, interfaces and display options. The particular model specifications are listed in table 4.

Table 4. SIMATIC IPC677D (6AV7260-2HP62-1FC0) main technical specifications.

Feature	Details
Processor	XEON E3-1268LV3 (4C/8T, 2,3 (3,3) GHz, 8 MB Cache VT-D, Amt)
Hard drive	320 GB HDD SATA (2,5")
RAM	16 GB DDR3
Display	22" Touch (1920x 1080)
PROFIBUS/MPI	CP 5622 compatible
Ethernet	2x10/100/1000 MBit/s
Operating system	Windows 10 Enterprise LTSB 2016, 64 Bit, MUI for Xeon

SIMATIC STEP 7 (TIA portal) is a controller software. It is a complex that allows a user to configure, program, simulate behavior of various PLC and IPC controllers

3.4.2 Establishing a connection

Establishing a connection with Siemens IPC via PROFINET in TIA portal.

To connect the control station to the controlled device, the following procedure should be followed. Firstly, the PROFINET protocol description file (GSD, general station description) is needed. Normally it is supplied with a PROFINET device. It is to be added to the TIA portal library of devices. Once in the library, the device is recognized by TIA portal and can be used for configuring. The library already contains GSD files of SIEMENS devices.

The next step is configuring the system elements and topology. At this stage, system elements are added to the workspace and formatted. The user should define the names and IP addresses of the elements in the Device view. Then after switching to Topology view it is possible to connect devices into networks and subnetworks into the wholistic system. At this point, the configuration is complete and there is a model of the system in the computer's memory.

Then it is recommended to check the modelled topology by auto-check function. The control station checks if the real physical network contains the same devices (PROFINET device names and IP addresses are the same) as the model. After this, the TIA portal is set up to program the system's behavior. (SIEMENS, 2018)

3.4.3 Programming

Inside TIA portal, several tools and programming languages are available.

One of those tools is SIMATIC WinAC RTX. This is a software controller designed for PC-based automation. It allows control functions to be carried out in real-time with determinism. Normally, this software is used in demanding time-sensitive applications.

Figure 17. Siemens IPC.

3.5 Algorithm

The whole system algorithm is represented in appendices. Signals that are sent through the network are shown. Both machine and mobile robot "report" to the control station, and the control station gives orders to the devices to make physical processes. The algorithm starts with the machining station and the mobile robot reporting "ready" statuses to the control unit. This step is necessary to reassure that there are no errors in the devices. Based obn these signals the control station makes a conclusion that the whole system is ready to operate normally.

If at this moment machining centre sends a signal that the program is completed, then the control station is requesting if there is a need to load the machine. System can wait in the ready state for as long as needed until there is a production request.

In case there is (machining station sends a signal that it is ready to be loaded), the control station commands it to open the door. Once it is reported that the door is open, clamp opening is commanded to the machining station, and it reports if it is opened successfully.

The next step is changing the workpiece function that consists of signal exchange between the control station and the mobile robot. The separate function is needed, because this operation is different from placing and picking at the storage because of the clamp. The robot gripper can only be released once the clamp is closed. Similarly, when picking the part, clamp only releases after the gripper is closed. This is to avoid a situation when the workpiesce is not fixed by any of the clamps. At the storage, however, Parts are placed freely on the specifically designed shelf independently by the mobile robot.

Once the new part is paced at the worktable, the machining station is commanded to close the clamp and should report to successfully do so. Control station sends a command to the mobile robot to release the gripper. Mobile robot reports when this is finished.

At this point the workpiece is fixed inside the machine, so control station calls the mobile robot to retract its manipulator to the safe home position. This arm position is specifically designed to minimize risk of injury while the mobile platform is moving. There is no simultaneous movement of the mobile platform and the robotic arm. Once the robot is in this state, it sends a message to the control station. Control station makes decision on the further movement of the mobile robot as it is now safe.

At the same time, There is a message exchange undergoing between the machining centre and the control station because the machining program number should be checked. If it returns no errors, the control station makes a decision to close the door of the machine and receive a report. So it is making a request to start the program. Machining is done autonomously by the machine once the program number is confirmed.

Finally, once the program is finished, this signal is similar to “ready” from the machining centre side. If at the same time the mobile robot reported that it is docked to parking, the cycle is complete.

The change workpiece function is a two-way exchange between the control station and the robot. Docking to machine means that the robot is placed near the machine, the connector is plugged for charging electrical and, possibly, pneumatic systems, and the calibration is finished. The robot is now positioned and can pick the part. Now the arm with the workpiece gripped in it is retracted to the home position and is safe to move.

The mobile robot is moving to the storage area. It is docked there in the same way as at the machining centre. The part is placed at the shelf in storage. The arm then collects the next workpiece, and returns to home position.

The mobile robot travels with the workpiece to the machining centre and docks there in the same way. After docking, the manipulator moves inside the machine and places the part there.

3.6 Storage tray design

Special shelf tray should be designed to handle the workpieces. requirements to the tray include ability to store both workpieces and parts in the same tray, form compatibility and special design features that allow geometric positioning of the workpieces.

The prototype design was developed. It is designed for cylindrical workpieces. The tray has dimensions of 210x320mm and has eight storage cells compatible with both initial workpiece and the final part.

To support pattern recognition with a camera, a cross-shaped reference is located near each cell. It may be problematic to recognize light-reflecting steel workpieces in the environment with changing light conditions. Even considering that the camera has an in-built lighting system, experiments showed that workshop conditions are too unstable to ensure repeatability of pattern recognition. Factors affecting light conditions include windows, where light changes due to weather and time of the day, and moving objects, including humans, that can block the light unexpectedly.

The tray has eight 9 mm holes to keep the processed parts in place. Around those holes, 45 mm diameter sinking with conical surfaces around are manufactured. Unprocessed workpieces can be placed there. Conical surface allows to improve workpiece positioning even considering the mobile platform positioning tolerance of 10 mm.

4 RESULTS

4.1 Generated new technical information

Since usage of industrial mobile manipulators is still under development, this work contributed to development of this area of industrial automation. Topology development method that we used in this work broadens the view on the similar mechatronic systems design.

4.2 Applications

It is clear from literature review that safety issues are not yet solved when it comes to collaborative robots and systems. In this work, we elaborated on specific safety measures in a training workshop with access of undertrained personnel.

The main result of this work is a developed system topology and algorithm.

Both findings will be used in future as base for further development of the automation project.

4.3 Generalized results

Modular topology design allows flexibility and scalability to the system, that are important features of the fourth industrial revolution.

5 CONCLUSION

This work is the beginning of the automation project and a contribution to development of cyberphysical systems.

The research question was, what is the optimal topology to control a system that contains collaborative mobile manipulator?

We assumed in hypothesis, that the machining center and the mobile manipulator should be connected directly without additional devices. However, our research showed that including additional element (control unit) to the system is more reasonable because it is better fit with modern design principles.

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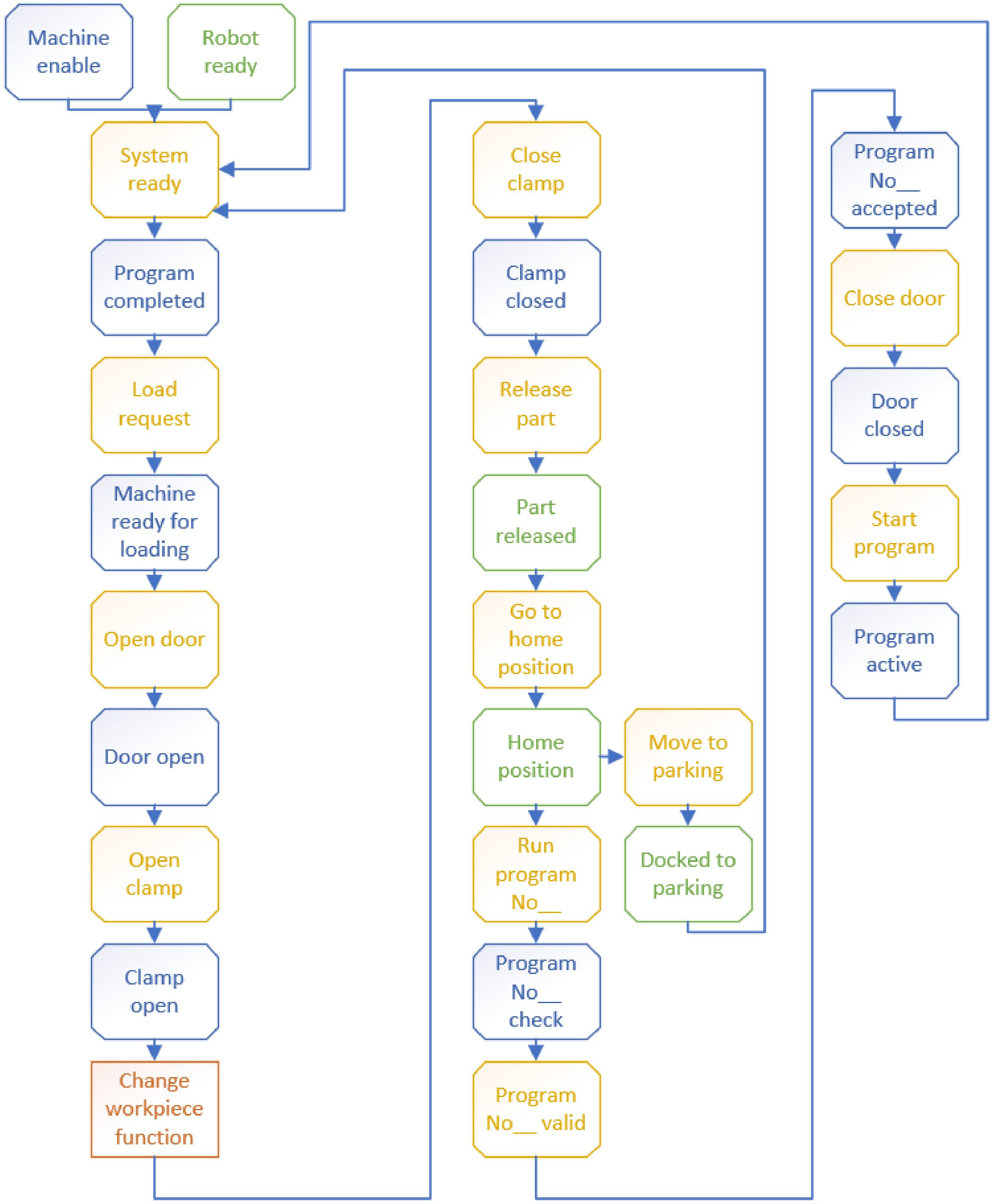
System algorithm flowchart, general. The signal sent through network are shown in the boxes. Blue is machine station, green is the mobile robot, yellow is the control module. Change workpiece is a separate function.



Algorithm of change workpiece function. The signal sent through network are shown in the boxes. Green is the mobile robot, yellow is the control module.