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DEVELOPMENT OF A MULTI-ROBOT WELDING CELL FOR JIGLESS WELDING

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TIIVISTELMÄ

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Monirobottiaseman kehittäminen jigittömään hitsaukseen

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Robottihitsaus on yleisin teollisuusrobottien käyttökohde, mutta yksi suurimmista ongelmista on ollut osien kiinnittäminen jigeillä ennen silloitushitsausta. Kappaleen kiinnittäminen jigeillä on aikaa vievä työvaihe ja aiheuttaa aina tuotannon pysähtymisen ollen robottihitsaustuotannon suurimpia ylimääräisiä kustannuksia. Lisäksi uudet tuotteet vaativat yleensä erittäin kalliiden varta vasten tuotteelle kehitettyjen jigien käyttöä. Edellä mainittu ongelma voidaan ratkaista kehittämällä jigitön monirobottihitsausasema. Tässä tutkimuksessa on selvitetty millä teknologisilla ratkaisuilla mahdollistetaan hitsaaminen monirobottiasemassa ilman jigejä. Millaisia vaatimuksia ja toimenpiteitä onnistunut jigitön hitsaus asettaa? Miksi jigitöntä hitsausta ei ole saatu aiemmin toimimaan ja mitkä ovat syyt ja ratkaisut tähän?

Tutkimuskysymyksiin haettiin vastausta käyttämällä menetelmien triangulaatiota, jossa kahtena laadullisena tutkimusmetodina hyödynnetään kirjallisuuskatsausta sekä systemaattista tuotekehitystä, joilla haettiin vastausta teknologisiin ratkaisuihin jigittömän monirobotti hitsausaseman kehittämiseksi. Näiden menetelmien lisäksi jigittömästä monirobottihitsausasemasta luodaan simulaatiomalli, jolla testattiin jigittömän hitsauksen vaatimia toimenpiteitä sekä selvitettiin miksei aiemmin ole onnistuttu kehittämään vastaavaa jigitöntä monirobottihitsausasemaa.

Tutkimuksen tuloksena uutta tieteellistä tietoa syntyi jigittömään hitsaukseen soveltuvien teknologisten ratkaisujen muodossa. Jigitön hitsaus on mahdollista silloin, kun kokoonpanon ensimmäinen osa tuodaan robotilla magneettiselle paikoitusasemalle ja kokoonpanon muita osia pidetään silloituksen ajan kiinni magneettitarraimella varustetulla käsittelyrobotilla. Tutkimuksen tuloksilla on suora hyödynnettävyys erityisesti levyosien robottihitsaustuotannossa, sillä jigitömän monirobottiaseman käytöllä kyetään eliminoimaan tuotevaihdoissa kuluva aika. Selvä jatkokehitystarve syntyy simuloidun liikeradan ja robotin liikeradan tarkkuuden parantamiselle, jotta robottihitsaustuotantoa voitaisiin tehostaa lisää.

ABSTRACT

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Development of a multi-robot welding cell for jigless welding

Master's thesis

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The robotic welding is the most common application of industrial robots, but the one of the main problems has been the fixturing of part with jigs before tack welding. The fixturing of part is a time-consuming task, which always causes stopping of the production, therefore being one of the major excessive costs in robotic welding production. In addition, new products usually require the use of expensive and specifically made jigs. The above-mentioned problem can be solved by developing a multi-robot jigless welding cell. In this research it is reviewed what are the technological solutions to substitute the use of jigs in robotic welding. What are the requirements and guidelines for successful multi-robot jigless welding? Why have not the functional multirobot jigless welding cells already been developed and what are the reasons for the non-existence?

To answer the research questions a triangulation of research methods were applied. Two qualitative research methods applied are literature review and systematic design process, which are used to examine the technological solutions to develop multi-robot jigless welding cell. In addition, a simulation model of the multi-robot jigless welding cell are created, which was used to test the requirements of multi-robot jigless welding and also why similar multi-robot jigless welding cell have not been developed earlier.

As a result of the research a new scientific information was generated in a form of suitable technological solutions for jigless welding. Jigless welding is possible when the first part of assembly is brought with robot to the magnetic positioning system and the other parts of assembly are held in place during tack welding with handling robot equipped with magnetic gripper. The results can be directly applied to the robotic welding production of plate-structures, as the multi-robot jigless welding cell can eliminate time consumed during product changes. A further research is required in increasing the accuracy between simulated robot path and actual robot path, so that production efficiency of robotic welding can be increased further.

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LIST OF ABBREVIATIONS

CAD	Computer Aided Design
CCD	Charge-Coupled Device
DAQ	Data Acquisition system
DOF	Degree Of Freedom
I/O	Input/Output
IoT	Internet of Things
MAG	Metal Active Gas
PLC	Programmable Logic Controller
pWPS	Pre-Welding Procedure Specification
RFID	Radio Frequency Identification
TIG	Tungsten Inert Gas
ToF	Time of Flight
WPQR	Welding Process Qualification Record
WPS	Welding Procedure Specification

1 INTRODUCTION

Recently, there has been a wide interest in developing a robotic welding system which is working with internet of things (IoT) principles. Ke & Xiaogang (2016) proposed a robotic welding monitoring system which is based on software defined networking and IoT architecture. The development steps of an IoT robot welding systems with machine vision are well known and a few case studies exists. Pasinetti et al. (2018) researched a machine vision system which monitors a laser welding process and French, Benakis and Martin-Reyes (2017) designed a robot welding cell with intelligent sensing system for re-manufacturing jet engine compressor blades.

IoT technology is widely being used in manufacturing (Lu & Cecil 2016). In welding industry, the IoT applications by the welding machine manufacturers, such as Kemppi, Fronius, EWM and Esab, has focused on providing software solutions for welding management. (Kemppi 2018a; ESAB 2019; EWM 2018 p. 54–57; Fronius 2019.) The research by Lu & Cecil (2016) states that the technological development of cloud computing systems and decreased price of sensor technology as well as machine vision systems, has generated new possibilities for manufacturing organizations. The new cloud computing technology is often called with following names: a fourth industrial revolution, smart manufacturing, industrial IoT or industry 4.0. IoT technology makes possible the decentralized decision making and manufacturing. In principle, according to Ke & Xiaogang (2016), the IoT consists of the idea that all devices, machines and manufacturing systems are connected to the digital network and therefore it is possible for human to be interactive with the data through user interaction modules, such as smartphone or computer. In practice this means that big amount of data needs to be collected throughout the manufacturing process. The developed sensor technology makes it possible to collect data and cloud computing makes it possible to analyze big amounts of data. The machine vision systems could have potential to be used to correct the robots path inaccuracies.

The known problem in robotic welding has been the fixturing of the workpiece assembly. The common way is to use jigs to hold workpieces together and/or manually make tack welds before robotic welding. Another use of jigs is in reducing the welding distortions caused by the heat. Using of jigs is time consuming, requires manual labor and the manufacturing of jigs is expensive. Not to mention, the setting up of jigs ads up a large portion to the production time. For tack welding process, the time spent for setting up jigs can be even 20 % of the whole processing time. Increasing the level of automation in welding production, has been successful in mass production, but in low volume production, in which the batch sizes are small and product variation is common, the applying of robotics has not been as widely adapted due to the reason that welded parts usually require modified welding jigs, which are rather expensive. Therefore, the solution for removing the need to use jigs during robotic welding production would have several advantages, such as increasing the automation level of welding as well as changing the welding industry environment in such a way that the manual tack welding process and the following robotic welding process can be replaced with a robotic welding process where jigs are not required to be used. (Bejlegaard, Brunoe and Nielsen 2018.)

1.1 The research problem

Only few scientific researches have been made about jigless welding and the existing researches have not been able to make a fully jigless multi-robot welding cell where metal active gas (MAG) welding is used as a welding process. Multiple robots, adaptive gripper and machine vision have been used in Paquin and Akhloufi (2012), but the system was not fully jigless, because some parts of the assembly required the use of jigs. Bejlegaard, Brunoe and Nielsen (2018) research made a concept model of multi-robot jigless welding system, but the research does not describe how part handling of the multi-robot jigless welding cell is managed.

The challenging thing in jigless robotic welding has been the actual implementation of fully functional jigless robotic welding cell and it might be a reason of invalid theoretic model, which does not describe the theory of jigless robot welding sufficiently. Therefore, the research problem in this master’s thesis is to develop a concept for fully functional multirobot jigless welding cell, which applies the IoT system principle.

1.2 The aims of the research and research questions

This research aims to solve the problem of how to develop robotic welding system, which does not require any jigs to be used during welding. Based on the research problem the following the research questions was formulated:

- Why have not the functional multi-robot jigless welding cells already been developed and what are the reasons for the non-existence?
- What are the requirements and guidelines for successful multi-robot jigless welding?
- What are the technological solutions to substitute the use of jigs in robotic welding?

The aim of the literature review is to find answers to how the multi-robot welding can be performed without jigs. Therefore, it is required to know what the recent discoveries are in multi-robot systems, robot grippers, jigless welding and machine vision. The current state in welding management softwares and recent developments in IoT in welding are also in the point of interest. The literature review also answers to what are the quality requirements of the robot welded workpieces and what is the theoretical accuracy of the machine vision and robots.Therefore, it was necessary to have an extensive literature review of this subject, so that the all the recent and possible technological solutions on how to achieve in multirobot jigless welding could be found and evaluated during systematic development process and simulation.

1.3 Research methods

To carry out this master's thesis and to answer the research questions the triangulation of research methods was utilized. Research methods were a literature review, systematic design process and simulation. Therefore, the qualitative research methods are literature review and systematic design process and quantitative methods are the simulation model. In literature review the references were required to have been published from the year 2013 onwards and to be scientific journal articles, scientific books or conference papers. The keywords used were "jigless welding", "jigless assembly", "fixtureless welding", "fixtureless assembly", "multirobot welding", "internet of things", "machine vision", "accuracy", "robot path correction", "locating", "measuring", "pose estimation", "robot gripper", "mechanical gripper", "vacuum gripper", "magnetic gripper" and "adaptive gripper". Keywords were sometimes combined with Boolean operators such as AND and OR. In systematic design process a requirements list was used for task clarification, abstracting was used to find the essential problem, morphological classification was used to find technical solutions for the problem and value analysis was used to analyze the most suitable option for the multi-robot jigless welding cell. In simulation, the model of multirobot jigless welding cell with all the components designed in the systematic design process was made with welding simulator program Delfoi arc 4.0. The simulation model was tested with two different workpieces. Based on the simulation a functioning logic for the multi-robot jigless welding cell was made and the challenges and solutions of multi-robot jigless welding were examined.

The results of literature review and systematic design process are used to analyse what are the technical solutions for multi-robot jigless welding. The results of systematic design process and simulation are used to analyse what are the requirements and guidelines for successful jigless welding. The results of literature review and simulation are used to analyse why multi-robot jigless welding have not been developed and what are the reasons for it.

1.4 Scope

The research was scoped to focus on designing and developing a multi-robot jigless welding cell, where the workpiece material are ferrous plates, meaning in practice structural steel plates. The practical applying of machine vision sensing was scoped out for future development and the welding experiments in the multi-robot jigless welding cell are left for future research. Therefore, in this master’s thesis the focus is on the design, development and simulation of the multirobot jigless welding cell.

1.5 Contribution

As a result of this master’s thesis new information is produced in the form of multi-robot jigless welding cell concept and a simulation model of the welding cell. Generalized results are in form of designed components, which are used to make multirobot cell jigless, and a functioning logic of the multirobot jigless welding cell. The general challenges of multi-robot jigless welding were examined and solutions for the challenges were given.

2 RESEARCH METHODS

To carry out this research three research methods were applied. The research methods were literature review, systematic design of jigless multi-robot welding cell and simulation of the jigless multi-robot welding cell. Therefore, the results of this research remain on theoretic level. The figure 1 presents the functional diagram of methodological steps to carry out the research. The research methods are shown in green and the steps are shown in blue.

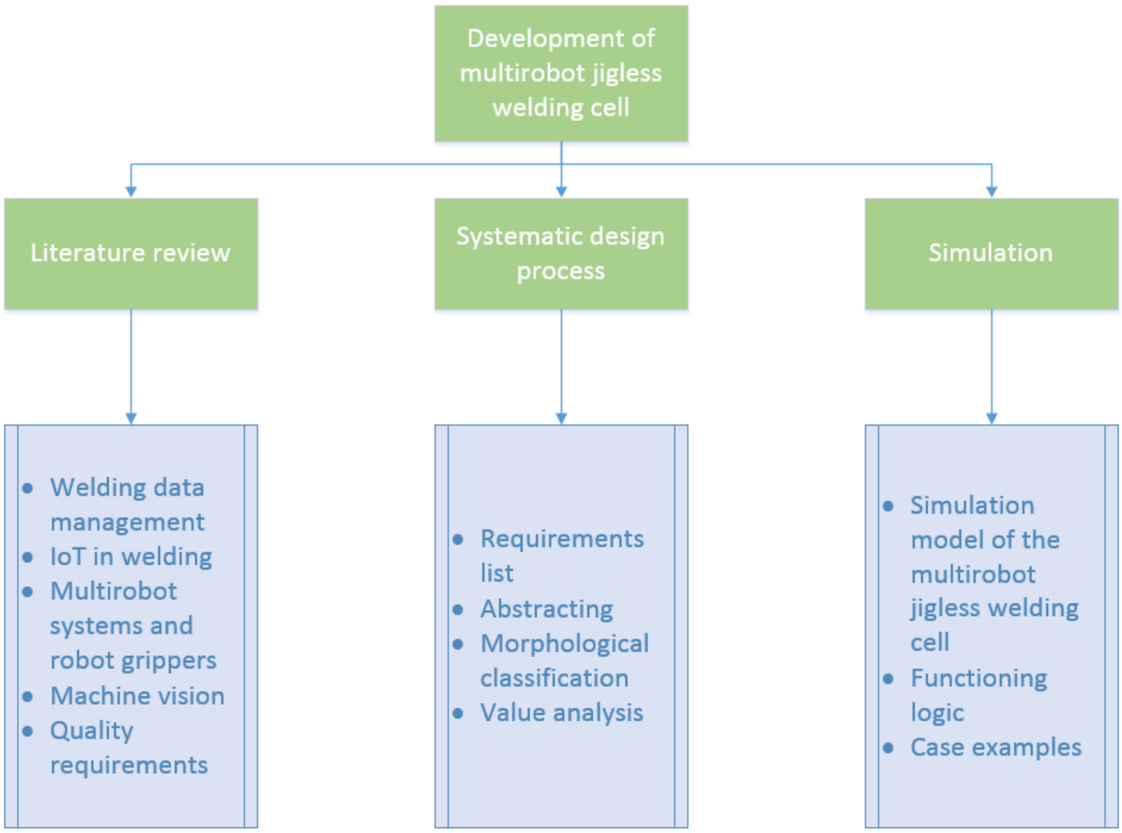


Figure 1. Research methods of the research.

2.1 Literature review

To conduct a literature review a Scopus abstract and citation database was used to find scientific articles, scientific books and conference papers to be used as a reference. Other databases used to find references were LUT-University's academic library, SFS-standards and Google scholar. The literature review was conducted as a guiding review. The scope for the references were that references must be as new as possible, so that new scientific information would be provided. Therefore, the references were required to have been published from the year 2013 onwards. The used keywords to find literature were “jigless welding”, “jigless assembly”, “fixtureless welding”, “fixtureless assembly”, “multirobot welding”, “internet of things”, “machine vision”, “accuracy”, “robot path correction”, “locating”, “measuring”, “pose estimation”, “robot gripper”, “mechanical gripper”, “vacuum gripper”, “magnetic gripper” and “adaptive gripper”. Keywords were sometimes combined with Boolean operators such as AND and OR. In literature review 42 references were used and 29 of them were scientific articles, books, standards or conference papers. The rest of the references were commercial product information data sheets or company web pages. The information found from the literature were used in comparisons and in graphical illustrations.

2.2 Systematic design process

To develop a multirobot welding cell which is capable for jigless welding, a systematic design process developed by Pahl et al. (2007) was applied. The first step in systematic design process was to gather requirements for the multirobot jigless welding cell and classify requirements to demands and wishes. The second step was to revise the requirements in an abstracting process, in order to find the essential problems. When the essential problems were known a morphological classification of different solutions for problems were presented. The third step was to make a evaluation of different design solutions and therefore value analysis was applied. The software used to make CAD-models of the components was Solidworks.

2.3 Simulation

The simulation model of multirobot jigless welding cell was made with the welding simulation software called Delfoi ARC 4.0. The simulation model was created by using the existing model layout of the current state of the welding laboratory’s multirobot welding cell. The existing model consisted of welding robot, positioner and a handling robot.

The designed CAD-models of the components and workpieces were imported to the welding cell simulation model and the components were attached to their respective places. For example, designed robot gripper was attached to handling robot, machine vision sensor was attached to its position and solution for achieving jigless welding was attached to positioner.

To test the multirobot jigless welding cell simulation model, two workpiece assemblies were tested. The first case was a simple t-joint type workpiece and the other case was more complex resembling I-beam structure welded on a top of a plate. Both workpieces are shown in figure 2.

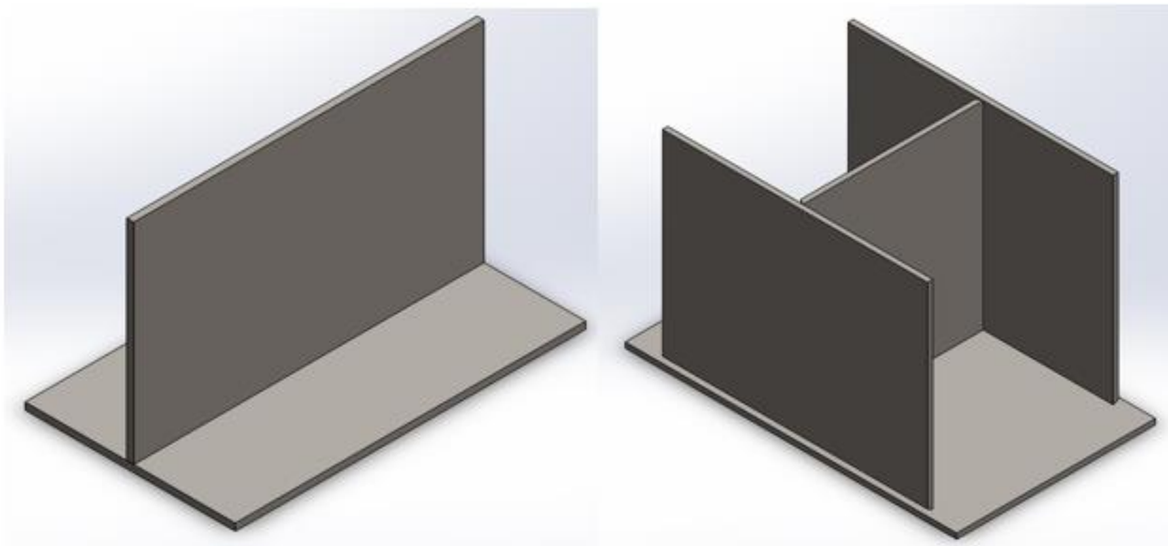


Figure 2. Workpieces to be assembled during simulation.

In the multirobot jigless welding cell simulation model robot programs for assembling the workpieces were made. The general structure of the robot program followed the following steps:

1. Handling robot picks the first plate, moves and connects it to positioner, and releases the plate.
2. Handling robot picks the second plate, moves it to positioner, and holds it during machine vision sensors joint inspection and during tack welding.
3. After tack welding handling robot releases the plate and keeps proceeding as mentioned in step 2 until the assembly is finished.

Based on the simulation, a detailed functioning logic for the multi-robot jigless welding cell was made and a classification of challenges and possible solutions in jigless welding.

2.4 Reliability, validity and sensitivity analysis

For the analysis of the results a triangulation of methods was used, in which the results of literature and systematic design process were analysed with the following question: "What are the technological solutions to substitute the use of jigs in robotic welding?" The results of systematic design process and simulation are analyzed with the following question: "What are the requirements and guidelines for successful multi-robot jigless welding?" The results of literature review and simulation are analyzed with the following question: "Why have not the functional multi-robot jigless welding cells already been developed and what are the reasons for the non-existence?" The illustration of how triangulation is applied in the research is shown in figure 3.

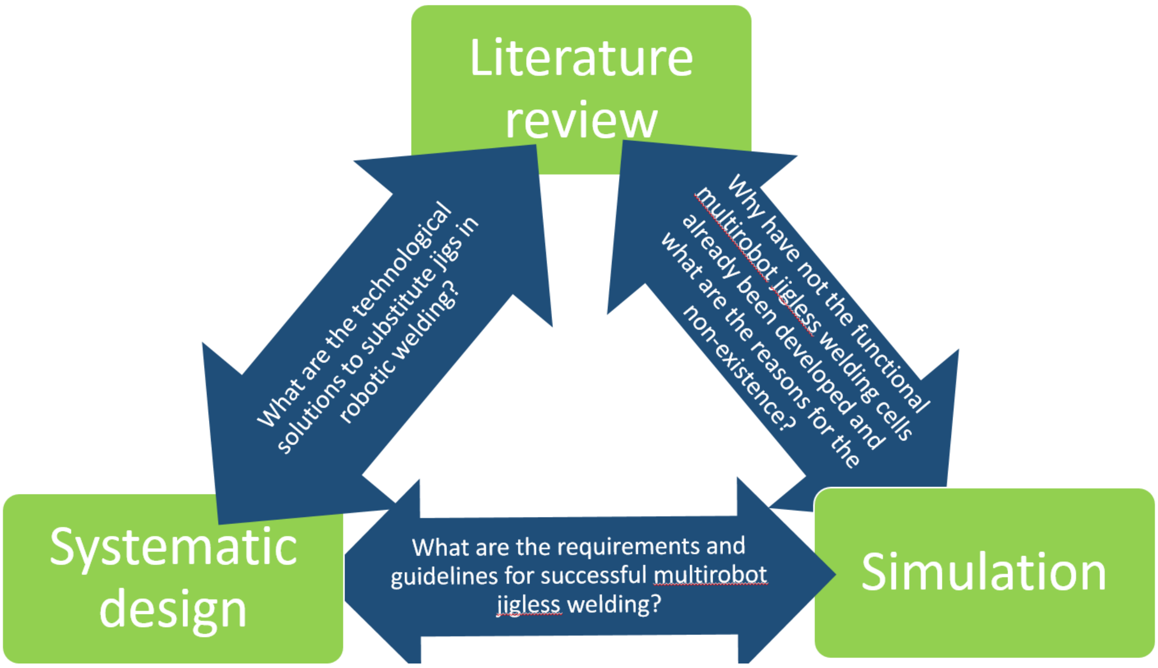


Figure 3. Illustration of how the triangulation is applied.

To ensure the reliability of the results, the results of systematic design and simulation were compared to results of a literature review to find out how the results compare to the previous researches. The reliability was also ensured by analyzing how extensively the results can be applied in other applications, what are the estimated benefits of the research and what practical benefits or solution models can be produced based on the research.

For validation of the results of systematic design process the different technical solutions found were analyzed with a value analysis, where different functions of the technical solutions are given highlighting points according to functions importance, then the technical solutions of functions are given a grade, according to how well the function performs its function. Then the grade and highlighting point are multiplied to find the highlighted grade, which is divided by the estimated proportional costs and then the values of technical solutions are known. To further validate the systematic design results the designed components are imported to the simulation and tested if they fulfill the requirements set for multirobot jigless welding cell.

To verify that the concept of multi-robot jigless welding works as intended a preliminary welding experiment was made by manufacturing a workpiece resembling the I-beam structure welded on a top of a plate as was seen on the figure 2 above. Workpiece was made from 5 mm thick S355 structural steel.

Sensitivity analysis of the qualitative research was carried in a following way. The estimation when enough data was collected from literature review and systematic design process with following question “What are the technological solutions to substitute the use of jigs in robotic welding?”. Enough data collected from systematic design process and simulation were analyzed with the following question: “What are the requirements and guidelines for successful multi-robot jigless welding?”. Finally, the results of literature review and simulation was evaluated with following question “Why have not the functional multirobot jigless welding cells already been developed and what are the reasons for the non-existence?” to justify that enough data has been collected to make conclusions for the research.

2.5 Presentation method of results

The results are presented in the following order, the literature review is presented in the chapters 3–6, then the systematic design process of multirobot jigless welding cell is presented in chapter 7, which provides new scientific information of technological solutions for multirobot jigless welding and concrete applications for jigless welding. Then the simulation results are presented in chapter 8, which also provide new scientific information in form of simulation model of multirobot jigless welding cell and some generalised results in form of multi-robot jigless welding cells functioning logic. The results are discussed and analysed in chapter 9.

3 WELDING MANAGEMENT SOFTWARE

Welding documentation and management is a time-consuming process and therefore welding companies have developed their solutions to handle welding production management. These welding management softwares rely heavily on the cloud service technology, which makes it possible to have real-time information and data of the welding production processes. The following chapter introduces a few of the available commercial welding management software's from the companies like Kemppi, ESAB, Fronius and EWM. (Kemppi 2018a; ESAB 2017, p 1–2; ESAB 2019; EWM 2018 p. 54–57; Fronius 2019.) For the development of multi-robot jigless welding cell it is necessary to review commercial welding management softwares, in order to get information of what welding data can be collected during welding with welding management software, what properties the softwares have for quality control and in which welding power sources the software is compatible.

3.1 Kemppi Weldeye

Weldeye is a welding management software developed by Kemppi. The purpose of a Weldeye is to give universal control over the company's welding production projects. The principle of the software is to collect company's welding information into a cloud service, which makes it possible to track the welding project in one place. The information collected from the welding equipment can be accessed from anywhere, without depending where the welding work is done. The data that can be collected with Weldeye are welding current, welding voltage, arc time per machine, wire feed rate and arc on time. Weldeye can be used with any welding equipment brand. Weldeye has a digital library for the pWPS (pre-welding procedure specification), WPS (welding procedure specification) and WPQR (welding process quality record) documents and it is also possible to keep track on the welders and inspectors qualification certificates. (Kemppi 2018a, p. 1–7; Kemppi 2018b p. 1–7.) The welding management software consists of different functions, which are as follows (Kemppi 2018c):

- welding management function
- welding procedures function
- personnel and qualifications function

- quality control function
- monitoring and analytics function.

The welding management function is a tool for welding project management and it includes project planning tool, welding coordination tool and tool to create final report. The welding procedures function is a tool for creating WPS. It has built-in templates to create WPS that are following AWS, ASME, EN and ISO standards. Weldeye will automatically keep on track when the standards are updated. The welding procedures function also has a drawing tool for sketching joints. The personnel and qualifications function is a tool for keeping track on personnel qualification certificates, mainly welders and inspectors. The tool will notify if some qualifications are going to expire and the user can prolong all of them at once. The quality control function is a tool for verifying that welding quality is the same that is stated in the WPS. The tool collects welding parameter data from each weld and notifies if parameter limits are exceeded. Therefore, each weld can be tracked and quality of the welds can be assured in real-time. The monitoring and analysis function is a tool for collecting data from welding stations. The main data that it tracks and measures is the welding process data such as welding current and welding voltage, and welding production data such as arc-on time, serial productions standard times and time spent on non-welding activities. (Kemppi 2018a, p. 1–7; Kemppi 2018b, p. 1–7; Kemppi 2018c; Kemppi 2018d, p. 1–7.)

3.2 ESAB WeldCloud

According to ESAB (2017) and ESAB (2019) WeldCloud is a welding data management software and it can be used on multiple platforms such as computers, smart-phones or tablets. WeldCloud can be used to track all the welds that have been welded within the company as the software collects welding data for each seam produced. The data that can be gathered are welding process related data, such as heat input, deposition rate, filler wire and gas usage, or welding production related data such as product number and operator identification. The welding data can be analyzed from multiple welding power sources that can locate within the factory or in multiple factories. The gathering and analysis of data can be done in real-time. The software can be used to develop weld schedules for one welding machine and that schedule can be transferred to multiple other machines. The software makes it also possible to change welding parameters if necessary, and software can send notifications if parameters are changed. The WeldCloud can be used on ESAB own welding power sources and with universal connector the WeldCloud can be connected to other welding machine manufacturers machines. (ESAB 2017, p. 1–2; ESAB 2019.)

3.3 EWM XNET

According to EWM (2014) the EWM Xnet is a welding management system, which can be used on multiple platforms such as computers, tables and smart-phones. Xnet allows to control and monitor the welding process in real-time. Multiple welding machines can be connected to the Xnet system. The welding parameters can be analyzed, reported and documented in real-time with Xnets documentation and analytics tools. The data that can be collected are welding current, welding voltage, wire feed rate, the motor voltage of wire feeder, shielding gas flow, heat input, arc time and energy consumption. (EWM 2014, p. 1–12.) According to EWM (2018) Xnet consists of four modules and components, which are Starter set, WPQ-X Manager, Xnet component management and Xbutton. The Starter set is a real time welding data recording and managing tool. WPQ-X Manager is a tool for making WPS. Xnet component manager is a tool for managing the weld components and creating welding sequence plans. Xbutton is a tool for the welder to get access rights to the system so the welder can read instructions from the WPS. (EWM 2018, p. 54–57.)

3.4 Fronius WeldCube

According to Fronius (2018) The WeldCube is a browser-based welding management software developed by Fronius. WeldCube consists of six functions, which are as follows (Fronius 2018, p. 1):

- component management
- user management
- welding data documentation
- device overview and machine details
- job management
- statistics.

The component management function includes real-time monitoring, component monitoring and management, traceability of the welds, consumption analysis and welding data documentation for each component. User management function includes tools for adding users to the system and defining user’s authorization level. Welding data documentation function collects the welding parameter data for each weld seam. Device overview and machine details function allows to monitor all of the welding systems for general overview. Job-management function allows to user to manage all the welding jobs. Statistics function allows to analyze the documented data. (Fronius 2018, p. 1.) According to Fronius (2019) the welding data that can be collected in WeldCube are welding current, welding voltage, wire consumption, gas consumption, welding duration, filler wire feed, power consumption, wire and gas costs and deposition rate.

A comparison of welding management softwares properties were made and the properties can be seen in the table 1. The properties were compatibility of welding management software to different welding powers sources, what data the welding management software can collect, what standards are supported, does the software include data analysis tool and what is the cost of welding data management software.

Table 1. Comparison of welding management softwares (ESAB 2017, p. 1–2; ESAB 2019; EWM 2014, p. 1–12; EWM 2018, p. 54–57; Fronius 2019; Fronius 2018, p. 1; Kemppi 2018a, p. 1–7; Kemppi 2018c. Kemppi 2019).

Software	Compatibility	Collected data	Supported Standards	Data analysis	Cost
Weldeye	All power sources	Welding current, welding voltage, arc time per machine, wire feed rate, production standard times and arc on time	AWS-, ASME-, EN- and ISO-standards	Yes	Cloud service licence 2650 € Monthly user fee 75 €
WeldCloud	All power sources	Heat input Deposition rate Filler wire feed rate Gas feed rate	-	Yes	-

Table 1 continues. Comparison of welding management softwares (ESAB 2017, p. 1–2; ESAB 2019; EWM 2014, p. 1–12; EWM 2018, p. 54–57; Fronius 2019; Fronius 2018, p. 1; Kemppi 2018a, p. 1–7; Kemppi 2018c. Kemppi 2019)

Software	Compatibility	Collected data	Supported Standards	Data analysis	Cost
XNET	EWM welding machines and welding machines from 2002 onwards with 7-pin digital port.	Welding current, welding voltage, wire feed rate, the motor voltage of wire feeder, shielding gas flow, heat input, arc time energy consumption.	SFS-ISO 3834 SFS-EN-ISO1090	Yes	-
WeldCube	Fronius machines	Welding current, welding voltage, wire consumption, gas consumption, welding duration, filler wire feed, power consumption, wire and gas costs and deposition rate	-	Yes	-

According to this review made of commercial welding management software it can be said that welding management software can be used as a platform for analyzing welding process and production data in a multi-robot jigless welding cell. Still the welding management softwares does not have a function for locating the exact location of weld defect, although the seam where the defect is can be tracked. Also, the welding management softwares does not have function for gathering any robot related data, such as robot position or torch angle. The welding management softwares does not include image related data gathering and therefore use of machine vision sensor would require own software for image data analysis.

4 INTERNET OF THINGS IN ROBOTIC PRODUCTION

In this section the concept of the Internet of Things (IoT) is reviewed from the viewpoint of manufacturing, welding and welding data acquisition methods. The multi-robot jigless welding cell under development would ideally function without or with minimal amount of human involvement and therefore the welding cell is required to have capability to be controlled remotely and have some level of artificial intelligence. Therefore, the capabilities of IoT technology are reviewed in this section. According to Badarinath and Prabhu (2017) the IoT is commonly considered to be the 4th industrial revolution. The technology behind the IoT makes it possible to monitor or control physical objects remotely in a network, which allow the development of a totally new applications in the field of manufacturing and welding. (Badarinath and Prabhu 2017, p. 111-112.) In practice, according to Badarinath and Prabhu (2017, p. 111-112) IoT application requires “integration of sensors, actuators and tracking devices” in order to function.

4.1 Internet of things in manufacturing

According to Lu & Cecil (2016), in manufacturing engineering the use of cyber-physical systems, like software entity embedded in a thin client or smart device, is becoming more common. In these cyber-physical systems, the physical devices interact with software tools in order to perform different types of functions, such as sensing and monitoring of the process, and advanced manufacturing and assembly. The interaction of physical devices and software tools can be realized with local area networks or through the Internet, typically by using cloud services. Cloud service-based manufacturing has many benefits such as reduced costs in up-front investments, infrastructure, maintenance and upgrading. (Lu & Cecil 2016 p. 1141–1143.)

In manufacturing framework, the key components are divided in physical components and in cyber components. The physical components consist of machines used in manufacturing, assembly, testing and quality control. The cyber components consists of softwares that are used in simulation, scheduling, monitoring machines and processes, manufacturing and assembly planning and data analysis. Data is collected from the physical components with sensors and cameras, which provides feedback and monitoring of the activities. In the research by Lu & Cecil (2016, p. 1144) it is suggested that the cyber components in manufacturing organization should be able to perform the following functions:

- design interpretation tools to convert design files of the product for manufacturing and assembly
- design analyzing
- manufacturing process planning
- assembly planning
- scheduling
- simulation
- data & information interface, and integration sensors and agents, for monitoring of manufacturing processes
- user interaction modules.

The figure 1 presents the basis of IoT-based manufacturing framework. Each of the cyber and physical components seen in figure 4 can be in same location, as in a factory, or they can be distributed around in several locations. (Lu & Cecil 2016, p. 1141-1144; Badarinath and Prabhu 2017, p. 113.)

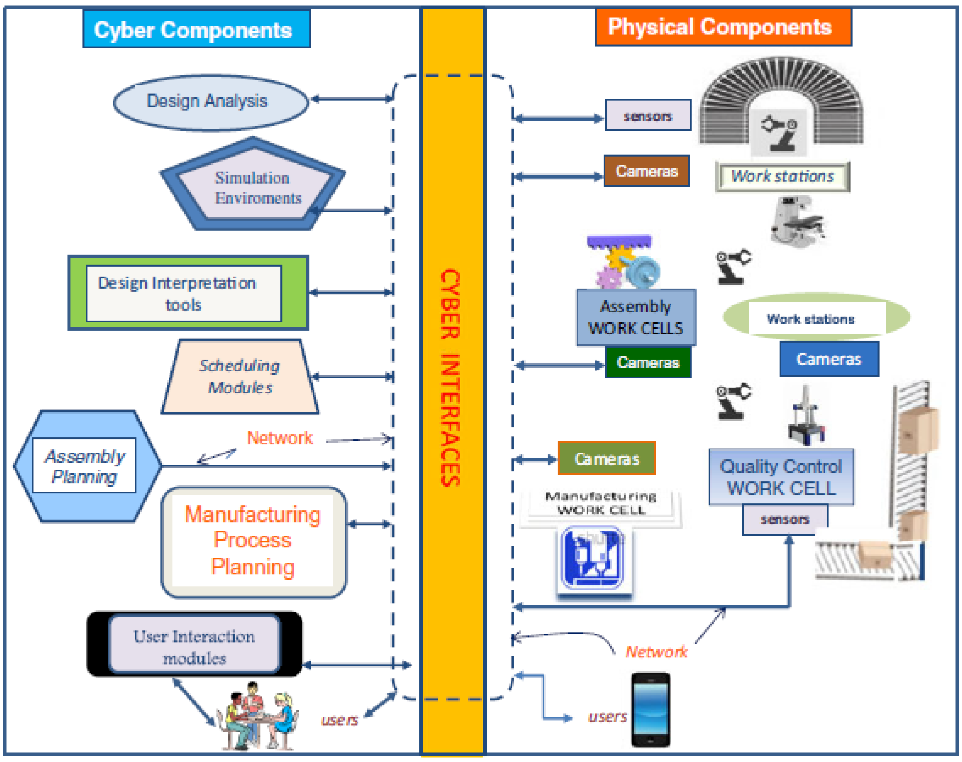


Figure 4. Schematic of IoT-components in manufacturing (Lu & Cecil 2016, p. 1144).

4.2 Internet of things in welding

IoT in welding has been under a research in past few years. The research has focused mainly on development of a robotic welding cell with a visual sensing system, which uses cloud service to analyze the weld quality and gives feedback to the welding system according to the quality. In a research by Pasinetti, Sansoni & Docchio (2018) smart vision system was used for the in-line monitoring of laser welding. The vision system consisted from a single optical head which was connected to the robot manipulator and coaxially with the welding head. The IoT technology was exploited in the research set up, as the smart vision system is embedded to the communication infrastructure and cloud-based analysis of the welding data was used. The actuators of the welding system are controlled by the vision system and not by the user. This makes it possible to monitor multiple welding units from a single central unit, which can be a remote unit. (Pasinetti, Sansoni & Docchio 2018, p. 134–138.)

In analyzing of the images captured by the vision system, two different methods were used. The first method used was seam tracking and the second method was keyhole monitoring. The seam tracking was used to track the weld joint and to keep the welding laser in optimal position. The seam tracking was done by analyzing the joint center position and the joint width, and then calculating the needed offset for moving the welding head to the direction perpendicular to the motion, in order to keep the welding head in the center of the joint. The keyhole monitoring was used to get feedback of the welding quality, by monitoring the melt pool for incomplete keyhole penetrations. (Pasinetti, Sansoni & Docchio 2018, p.134–136.)

Research by French, Benakis and Martin-Reyes (2017, p. 272–275) proposed intelligent sensing system ”for re-manufacturing jet engine compressor blades” with robotic welding. French, Benakis and Martin-Reyes designed a robot welding cell, which follows the IoT principles. The process flow of the system consists of following steps (French, Benakis and Martin-Reyes 2017, p. 272–275):

- detection of the blade
- identification and scanning of the blade
- loading of the blade for inspection
- vision system inspection, pre-weld evaluation and determination of the welding parameters
- welding process

- monitoring of the welding process
- evaluation of the weld.

During the blade detection and blade identification steps, the system recognizes possible blades coming into the system and define their location and orientation. Then the blades are characterized by reading manufacturers' code or with shape recognition and the system checks the corresponding material data and dimensions for the type of blade being processed. After identification the blade is moved for further inspection. The machine vision checks the blade for signs of damage or wear and determines if the blade can be repaired. If the blade is acceptable, the vision system determines the welding parameters, otherwise the blade is rejected. The next step is the welding process, where the robot's guidelines are defined based on the welding parameters. Welding process is monitored and data acquisition system (DAQ) collects data into database for weld evaluation. The data that is collected consists of image feed, electric measurements and operational parameters. After welding the weld data is analysed and based on the quality analysis the blade is either accepted or rejected. The figure 5 presents the IoT network between the robot and the robots' peripheral systems. (French, Benakis and Martin-Reyes 2017, p. 272-275.)

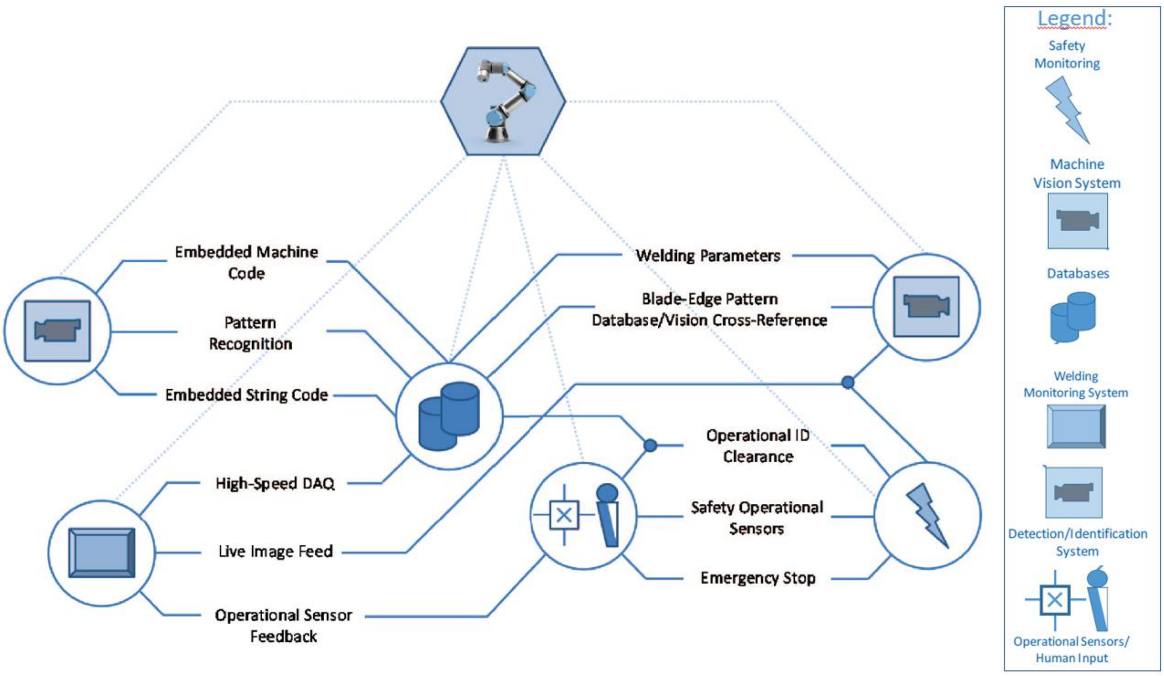


Figure 5. IoT network connections in robot's peripheral systems (Modified from French, Benakis and Martin-Reyes 2017, p. 275).

In a research by Ke & Xiaogang (2016) a robot welding monitoring system which is based on software defined networking and IoT architecture was proposed. Software defined network is a cloud service system. The real-time monitoring system can control the welding machine operations and monitor the weld pool to get feedback of the weld quality. Their IoT architecture in the monitoring system has a physical, control and application layers. The physical control layer collects welding parameter data using sensory networks. The data that it collects consists of welding speed, current and voltage, but also radio frequency identification (RFID) tags and images of molten weld pool. The control layer manages the network devices and the resources of the physical layer. The application layer processes and manages information as well as makes possible for human to operate with the system. (Ke & Xiaogang 2016, p. 113.)

According to Ke & Xiaogang (2016, p. 113–114) the monitoring system consists of function modules, which are: “monitoring information collection, remote monitor, welding parts management and visual display.” The monitoring information collection module uses sensors to collect welding current and voltage and utilizes programmable logic controller (PLC) to read welding speed. Then the collected information is sent to wireless gateway, by using ZigBee communication protocol. ZigBee protocol can be thought as a communication language between sensors and monitoring system. The module also reads welding parts RFID tags and captures images of molten weld pool, which are sent to wireless gateway. The remote monitor module analyzes the welding quality based on the data gathered from the monitoring information collection function and the welding quality data is described to the welding parts RFID tags. The welding parts module is responsible of managing the production process based on the information read from the welding parts RFID tags. After the welding process is finished, the quality data is read and the decision of acceptance is made. The visual display module displays the real-time welding process information. (Ke & Xiaogang 2016, p. 113–114.)

4.3 Data acquisition from the weld joint

During welding it is possible to gather welding process data, such as current, voltage, wire feed rate, gas flow rate, welding time and welding speed. Also, for pulse welding, parameters such as pulse frequency, background and peak voltage and currents can be measured.

Typically, a welding power source can be used for gathering most of the welding process related data, but for example measuring the temperature a thermal-couple or infrared sensor is required. Besides of a welding process related data, a welding production data can be gathered. For example, welding production data can be equipment effectiveness related data, such as arc-on time and downtime, or performance related data, such as wire usage, gas usage and deposition rate. Also welding quality related data can be gathered. (Lin & Luo 2015, p. 2437.) These welding data's can be monitored, analyzed and stored with welding management software's, which were introduced in the previous chapter.

Apart from welding process and welding production related data, also image data can be gathered from the weld joint by using a machine vision sensor. A typical use of machine vision in robot welding is seam tracking and weld quality inspection. (Ke & Xiaogang 2016, p. 113; Pasinetti, Sansoni & Docchio 2018 p.134–136.) Another use for machine vision is the part identification and measuring of part dimensions. The information of the parts can be stored to RFID tags and with the machine vision the part information can be read. (French, Benakis and Martin-Reyes 2017, p. 274-275; Ke & Xiaogang 2016, p. 113.) As the parts are identified before welding, it can be assured that the parts are the right ones. Furthermore, the RFID tag can contain information of the part dimensions, if the part has already been measured, for example by the part manufacturer. This dimension information can be used to correct robots' path (French, Benakis and Martin-Reyes 2017, p. 274-275). If the part dimensions are not already measured the measuring should be possible to do on-site with machine vision. Another possible uses of machine vision is the inspection of the joint geometry before welding, especially the root gap and the angle between two plates. The schematic illustration of how data flows in robotic welding cell is shown in figure 6. In figure 6 the data is collected from the weld joint (red) and from the workpiece (green) with welding power source, thermal sensor and machine vision sensor. The data is processed in computer and is sent to monitoring system for further inspection from the operator/management (red) and also data is sent to robot controller for adjustment of robot paths according to data collected (green).

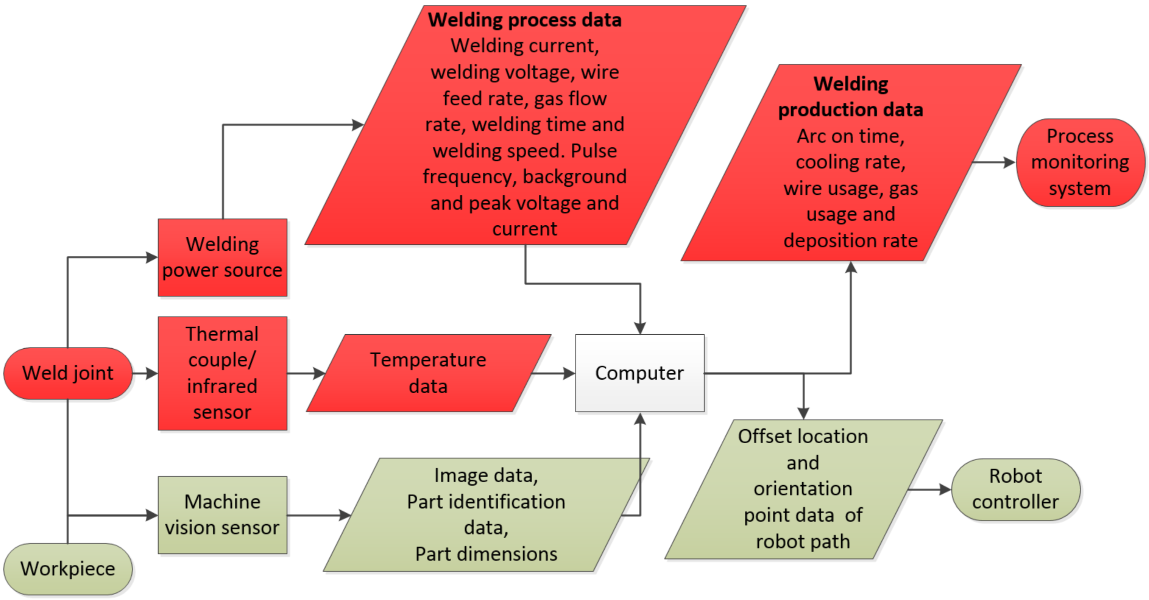


Figure 6. Data flow in robotic welding system, red resembles welding related data and green workpiece and robot related data (Lin & Luo 2015, p. 2437; Ke & Xiaogang 2016, p. 113; Pasinetti, Sansoni & Docchio 2018 p.134–136; French, Benakis and Martin-Reyes 2017, p. 274–275).

According to the review of IoT technologies in welding and manufacturing it can be said that IoT technology can be utilized when collecting data from the weld joint. The main sensors for IoT multi-robot jigless welding cell are welding power source and machine vision sensor, although the thermal couple or infrared sensor could be additionally used for collecting temperature data of the weld. The IoT principles to the multi-robot jigless welding cell could be applied with the following way, welding power source and machine vision sensor are used for gathering data. Welding management software is used to monitor and analyze welding process data. Image processing software is used to analyze image data and to send information to robot controller, although the development of image processing software is out of scope in this research. The most suitable welding management software for the multi-robot jigless welding cell will be evaluated with value analysis during the systematic design process.

5 ROBOTIC WELDING SYSTEMS AND ROBOT SIMULATION

This section discusses about developments in industrial robotics, multi-robot welding systems, robotic welding simulation, robotic grippers and machine vision. Also, to support the development process in this research, possible existing solutions for making the multi-robot welding cell to be jigless are reviewed.

5.1 Developments in industrial robotics

According to research by Realyvásquez-Vargas et al (2019) one of the main development areas lately in industrial robotics has been the collaborative robots. A simple definition for the collaborative robot is a robot which works collaboratively with human. Realyvásquez-Vargas et al. found in their literature review that collaborative robots have been adapted to the manufacturing industry and these robots are being used to improve the efficiency of the manufacturing process, by reducing the human workload and creating more ergonomic workspaces for humans. (Realyvásquez-Vargas et al 2019, p. 317–318.)

Another ongoing trend in industrial robotics is the development of mobile robots. According to Nielsen et al. (2017) the mobile robot integrates the movement capability with manipulation capability, therefore making mobile robots more flexible than traditional industrial robots. According to Nielsen et al. (2017, p. 1172–1173.) the typical task in which mobile robots are used are "transporting materials, machine tending, pre-assembly or quality inspection." The current state of the mobile robots is that they follow IoT principles and are capable of communicating with other manufacturing systems and also with factory workers, thus making possible the integration of mobile robots to general manufacturing network. (Nielsen et al. 2017, p. 1172–1173.)

5.1.1 Jigless robotic welding

According to the Bejlegaard, Brunoe and Nielsen (2018) literature review a few researches has attempted in creating concept of jigless assembly stations and recently the robotic jigless welding has been under research. The jigless robotic welding has a potential to increase the flexibility and productivity of welding assembly. Especially in low volume industry, the jigless robot welding can prove to be beneficial, because the technology, especially sensor technology, has developed to a point where robots flexibility can be increased without decrease in productivity. In tack welding process, the time taken for setting up jigs during product changeover can be 20 % of the whole processing time. Bejlegaard, Brunoe and Nielsen (2018) research focused on creating a concept solution for jigless welding cell and to examine potentials and challenges of jigless welding. The concept model of the jigless welding cell can be seen in figure 7. (Bejlegaard, Brunoe and Nielsen 2018, p. 307–310.)

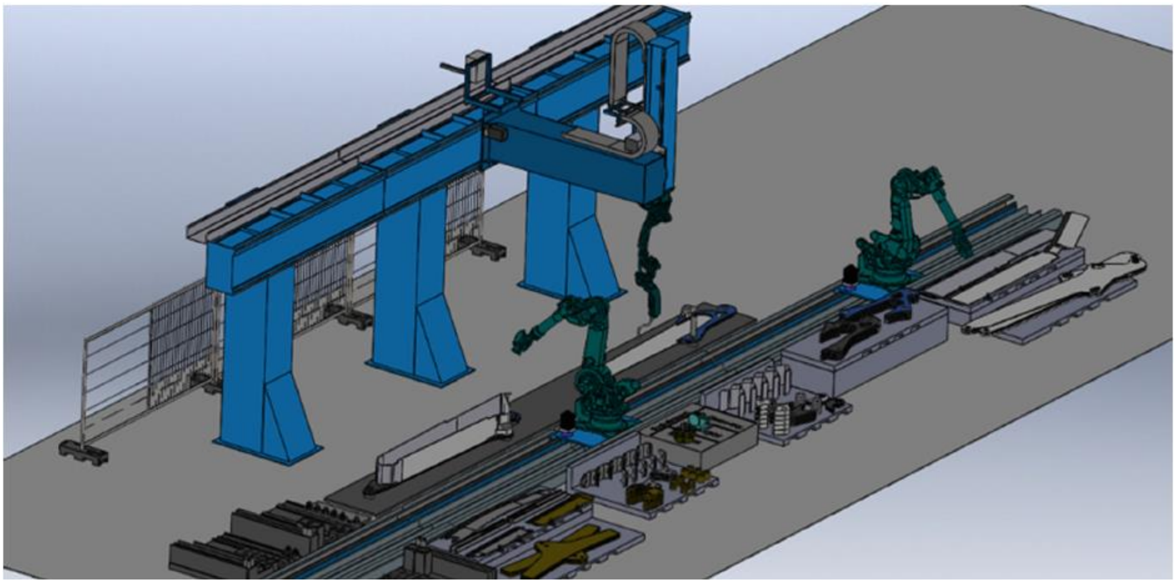


Figure 7. Concept model of jigless welding cell (Bejlegaard, Brunoe and Nielsen 2018, p. 309).

The challenges Bejlegaard, Brunoe and Nielsen found when developing a concept jigless welding cell for a case company were following (2018, p. 307–310):

- Jigless robot welding requires tighter tolerances for pre-welding tasks and for welding than tradition manual welding process.
- Amount of manual labor decreases as robots replaces most of the jobs, but robots require someone to make robot programs. Also, the designing, manufacturing and installation of jigs and fixtures is not anymore required.
- Due to high complexity of high variety and low volume production, cooperation and coordination of multiple robots is critical factor. To ensure high accuracy and proper paths, the robot controller must be able coordinate and synchronize robots.
- The programming of robots in high variety and low volume production can be a time consuming.

- A product and component standardization could benefit the hardware flexibility and make possible to reuse robot programs.
- The cost of investing in jigless welding can be quite expensive. Still, the flexible manufacturing is a sensible investment over long period of time, because the investment cost will distribute to multiple product generations and therefore will be more cost effective than traditional systems, which require customized fixturing solutions. During dimensioning of the system, it should be considered that jigless welding reduces process time and cuts out the changeover time, which may cause system to have over dimensioned capacity.
- Heat input can cause distortion on product components. Robots need to adjust for distortion and optimal heat input values should be used.

According to Bejlegaard, Brunoe and Nielsen the new product introduction design cost, fabrication and installation of new pieces production equipment will be replaced by cost of robot programming. Eventually the cost of programming will be lower than cost of equipment. (Bejlegaard, Brunoe and Nielsen 2018, p. 309.)

The research in jigless robotic welding has focused mainly on developing a gripper for robot end of arm tools as in research by Paquin and Akhloufi (2012) where adaptive gripper was used in part handling and machine vision is used to guide handling robot so it can locate the part. The Paquin and Akhloufi’s system, see figure 8, consists of welding and part handling robots, machine vision sensor and a workpiece fixed with jigs in which the welded parts will be attached. The system works as follows, first the operator teaches the picking and placing the part from pick platform to the assembly position. During the teaching, the machine vision detects parts 3D position and stores it as a reference. When the system is run, the machine vision system calculates the offset from the reference point and robot controller makes corrections to the path accordingly. The assembly position remains unchanged and therefore there is no requirement for welding robot path correction. (Paquin and Akhloufi 2012, p. 69–73.)

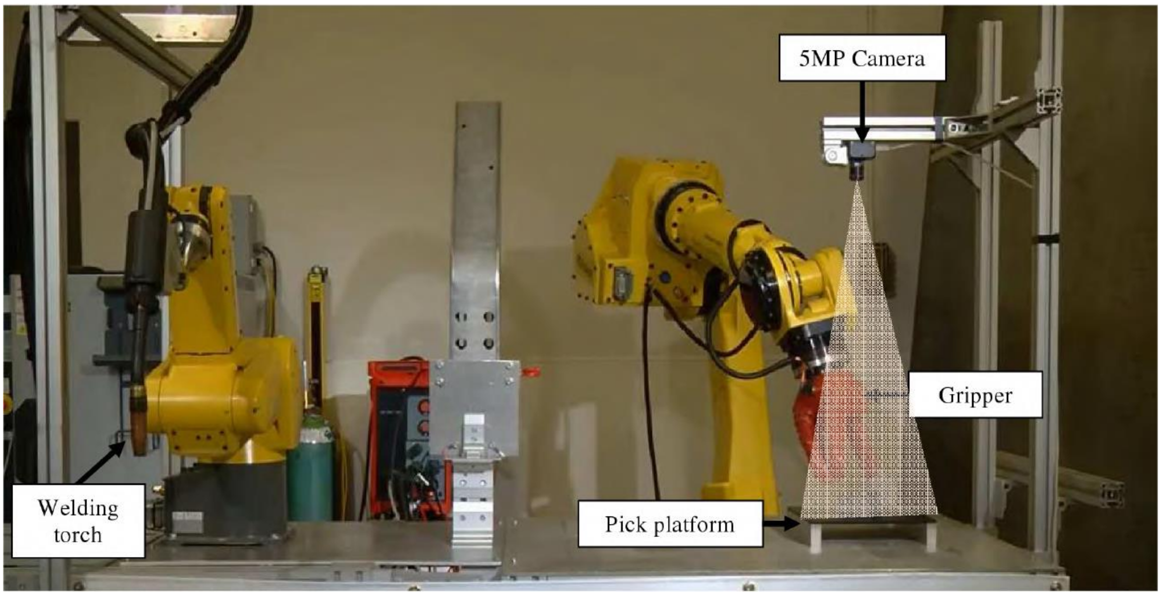


Figure 8. Jigless multirobot welding cell concept **(**Paquin and Akhloufi 2012, p. 69).

In a research by Ahmad et al. (2016) developed a concept of reconfigurable fixture, which is attached to robot arm. The reconfigurable fixture gripper was designed to grasp automotive parts with maximum length of 1.5 m during spot welding. The figure 9 presents the Ahmad et al.'s reconfigurable fixture gripper solution, as it can be seen in the left, the gripper consists of four modular lockable arms, electrical clamps in the arms, body frame, hydraulic unit and motion control unit, and on the right. (Ahmad et al. 2016, p. 1075–1081.)

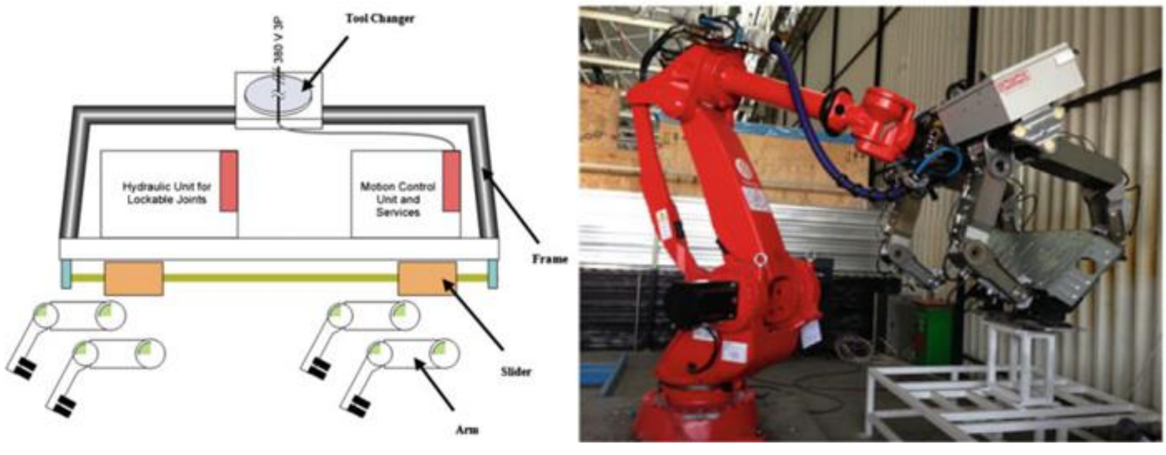


Figure 9. Schematic of reconfigurable fixture gripper (left) and in practice (right) (modified from Ahmad et al. 2016, p. 1075–1081.)

5.2 Simulation of multi-robot welding systems

According to Lin & Luo (2015, p. 2404) robot welding system usually consists of "robot manipulator, welding power source, welding torch, wire feeder, positioner, welding torch cleaning and calibration station, fume extraction, and safety fence" and seam tracking device. Robot station configuration can have both stationary or moving robot and a workpiece. The movement can be realized with a column, a gantry or a track. Multi-robot welding system is typically used when high productivity is wanted or the size of the workpiece requires multiple robots to weld. Multiple robots can be used for welding simultaneously or one of the robots can be used for handling of the workpiece. (Lin & Luo 2015, p. 2404–2406.)

According to Vuong, Lim and Yang (2015) traditional way to make robot welding programs has been the walk-through programming and lead-through programming. These programming techniques are called on-line programming and they require industrial robot to physically to move to the target locations, either by operator guiding the robot with a joystick attached near the gripper (walk-trough) or with a teach pendant (lead-trough). This means that every time a robot program is made, a downtime to the production process is evitable. (Vuong, Lim and Yang 2015, p. 2072–2073.) To avoid production downtime many robotic welding simulation software have been developed. Robotic welding simulation software have tools to make robot programs from simulations, which can be called as an off-line programming. The 3D model of the welding robot cell can be created with robot simulator software. The work cell model and computer aided design (CAD) model of the workpiece can be used to generate the geometric information needed in robot program, such as target points for robot paths. The robot program is generated by combining the geometric information and robot kinematic/dynamic model information. It is worth mentioning that even though the robot simulations try to replicate the actual working environment as accurately as possible, there will always be some differences between the real world and a simulation. These differences can cause several unwanted problems, such as a collision of a robot. (Lin & Luo 2015, p. 2437–2438; Vuong, Lim and Yang 2015, p. 2073–2075.) Generally the manufacturing task with industrial robot can be expressed as a robot programming process in following five steps (Vuong, Lim and Yang 2015, p. 2075–2076):

- dividing of the objective into sub objectives

- breaking of each sub objectives into simple instructions or commands, which can be executed by the robot controller
- gather geometric information for movement instructions
- set process parameter information for the manufacturing task
- combine geometric information and process parameters to form a robot program.

The first and second step is carried out by human as they require noticeable amount of intellectual capability, which will be problematic for current state of robot intelligence. Therefore, the scientific research to improve robot programming has mainly focused to steps 3 and 4. (Vuong, Lim and Yang 2015, p. 2075–2076.)

Robots in the welding cell must avoid collision with each other and with the workpiece. Therefore, motion planning is needed in creating of trajectories free of collision. The motion planning of multi-robot welding has been widely researched. Pellegrinelli et al. (2017) proposed an approach where cell design and motion planning problems are solved simultaneously. Chao & Sun (2017) proposed a theory of multi-robot motion planning which uses genetic algorithm.

According to Pellegrinelli et al. (2017) the common techniques in solving the motion planning problem are: “potential fields, roadmaps, cell decomposition, probabilistic potential fields, probabilistic roadmaps, probabilistic cell decomposition and simple-query sampling-based method.” Two common methods have been developed to solve the motion planning problems the first one is called decoupled planning and the second centralized motion planning. In decoupled planning the movement of every robot is defined one at the time and the existence of other robots is ignored. After the movement for each robot is defined, the paths are combined and collisions between the paths are resolved by adjusting the velocity of the robots or by changing the robot path. In centralized motion planning all of the robots in the welding cell are considered as a one operating multi-body robot. This creates higher dimensionality of the configuration space than in the decoupled planning, but according to Sanches & Latombe (2002) centralized planning has shown to be more efficient than decoupled planning. (Pellegrinelli et al. 2017, p. 99.)

In a research by Chao & Sun a genetic algorithm is used as a basis for creating an approach for collision free multirobot motion planning of spot welding robots. Genetic algorithm can be used to optimize the welding sequences and to minimize the total welding time. The algorithm functions as shown in figure 10, first the constraints are given, such as number of robots, number of welds, welding time and sequence constraint, then the initial order of welds are given for each robot and finally the genetic algorithm calculates the optimal welding sequence for the welding robots. (Chao & Sun 2017, p. 193–201.)

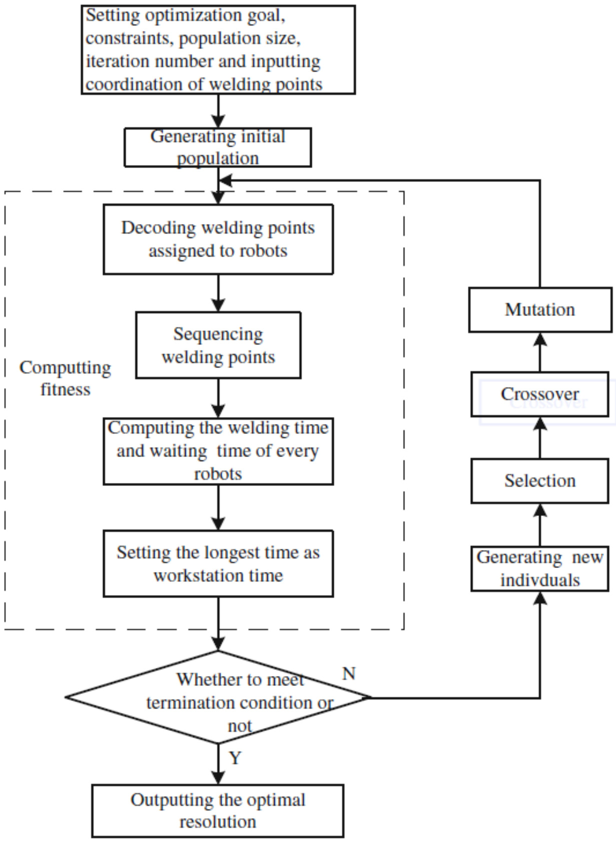


Figure 10. Illustration of how genetic algorithm can be implemented to multirobot welding (Chao & Sun 2017, p. 195).

As the genetic algorithm only produces the optimal welding order and welding path, simulation is required to ensure that no collisions occur during welding. If collision occurs, the robot position can be modified and if collision free position is still not found, the welding sequences can be changed, which also changes the robot path. Otherwise a new optimization iteration of robot paths with genetic algorithm is required to find the collision free paths. (Chao & Sun 2017, p. 193–201.)

5.3 Grippers

The use of right type of robot gripper is in key role in jigless welding, because to be able to perform robotic welding without jigs, gripper is required to perform many functions. Robot gripper is used in positioning of the workpiece and in holding the workpiece during welding. Gripper should not limit the reachability of welding robot or cause collisions with any component of the welding cell. Gripper should also have load carrying capacity for moving of heavy workpieces in horizontal and vertical directions. For above-mentioned reasons it is reasonable to have an extensive review of different types of grippers suitable for jigless welding.

According to a research by Birglen & Schlicht (2017), in robotics, the grippers serve as end-of-arm tool for robotic manipulators. The function of a robot gripper is to perform handling operations, such as grasping, holding and releasing the part. Modern mass production sets challenges to grippers as the function of the gripper, the part handling operations, does not directly add any value or increase market of the actual workpiece. Therefore, the cycle time of part handling should be as quick as possible, in order to avoid negative impact to the output rate of the production lines. The development of robotics and grippers goes hand in hand, as the kinematics of robots have high influence on the requirements of grippers. (Birglen & Schlicht 2017, p. 88.) For example, when robot's capacity for carrying a load increases the load carrying capacity of the gripper must also increase. As stated by Birglen & Schlicht the objects being handled by the robots varies so much that the gripper manufacturers have developed almost endless number of different shaped and sized grippers. Grippers are therefore available from mini to gigantic size (Birglen & Schlicht 2017, p. 88).

5.3.1 Mechanical grippers

Mechanical grippers typically have fingers which adapts the clamping force to the object being handled. Mechanical grippers can be categorized in pneumatic and electric grippers. In pneumatic grippers air is used to control the fingers and in electric grippers electric motors are used to control fingers. (Chen et al. 2015 p. 2036–2037.) According to Parlitz (2013) Pneumatic grippers produces high gripping force, are relatively cheap in prize, have high speed and are maintenance free (Parlitz 2013, p. 370). Pneumatic grippers gripping force and finger stroke cannot be controlled during operation, at least not very easily. Therefore, if the part size varies, a change for another size gripper may be needed. (Birglen & Schlicht 2017, p. 95.) Electric grippers are used in applications where speed and accurate positioning is required, such as machine tending and bin picking (Chen et al. 2015 p. 2036–2037). According to Parlitz the developments of electric grippers have increased the interest in using electric grippers. Electric grippers allow to more accurate control of stroke, closing speed, acceleration and force than pneumatic grippers. (Parlitz 2013, p. 370.) The opening and closing methods of the fingers of the gripper are same whether the gripper is pneumatic or electric driven. Typical opening or closing method is parallel or angular. The figure 11 shows seven different commercial mechanical gripper applications, which are a) two finger parallel gripper, b) three finger centric gripper, c) two finger angular gripper, d) three finger angular gripper, e) two finger radial gripper, f) four finger concentric gripper and g) special long stroke gripper. The mechanical grippers have two or more fingers with either parallel or angular opening/closing movement. (Parlitz 2013, p. 370–373.)

Figure 11. Different types of mechanical grippers, a) two finger parallel gripper, b) three finger centric gripper, c) two finger angular gripper, d) three finger angular gripper, e) two finger radial gripper, f) four finger concentric gripper and g) special long stroke gripper (Parlitz 2013, p 373–374).

In the research by Birglen & Schlicht (2017) a statistical review of commercially available pneumatic parallel two finger mechanical grippers were made and the result of the research is presented in the table 2. In the table 2 the average, median and standard deviation values, as well as min, max and count values for the common properties of gripper can be seen. The C-factor in table 2 represents the efficiency of the robot gripper and it is determined by the ratio of force produced over the weight of the gripper and the ratio is multiplied with the stroke of the gripper. It is worth noticing that there are quite large scale of grippers with varying properties available, for example force range goes from 6 N to 15400 N and stroke range goes to 1 mm to 300 mm. (Birglen & Schlicht 2017 p. 90.) To put gripper properties into perspective the gripper under development should be able to carry at least the load of 981 N and the gripper stroke should be at least in the range of 5–20 mm although wider stroke range (for example 1–100 mm) would be more desirable. In the table 2 the required values for the gripper under development are also presented, if the cell is marked with "–" no requirement for the property is set, if the value is given in brackets it means that the value would be more desirable than the required value which is given without brackets.

Table 2. Statistical values of common two finger pneumatic grippers' properties. (modified from Birglen & Schlicht 2017, p. 90).

	Average	Median	Std.dev	Gripper under development
stroke [mm]	20.78	9.55	35.10	-
force [N]	1020.44	320	1938.01	-
weight [kg]	3.41	0.59	8.43	-
C-factor [J/kg]	6.91	5.68	4.98	-
finger length [mm]	143.21	100	139.93	-
closing time [s]	0.23	0.13	0.32	-
air cons[cm^3/cyc.]	163.61	13.00	526.64	-
power [W]	239.38	82.26	355.29	-
	Min	Max	Count	
stroke [mm]	1	300	289	5 – 20 (1 – 100)
force [N]	6	15400	289	981 <

Table 2 continues. Statistical values of common two finger pneumatic grippers' properties. (modified from Birglen & Schlicht 2017, p. 90).

	Min	Max	Count	Gripper under development
weight [kg]	0.01	70	289	< 20 (1–3)
C-factor [J/kg]	0.36	28.57	289	-
finger length [mm]	9	900	197	(50–200)
closing time [s]	0.01	2.30	270	-
air cons[cm^3/cyc.]	0.09	4600	170	-
power [W]	0.77	1840	170	-

5.3.2 Vacuum grippers

Vacuum grippers utilize force created by vacuum to grab objects. Vacuum grippers require that the object being handled have clean, flat and smooth surface. The vacuum is created between the surface of the object and round shaped vacuum cups made of elastomeric material. Typical applications are in automobile assembly lines and in packaging industry. (Chen et al. 2015 p. 2038–2039.) According to Tai et al. (2016) the vacuum grippers have restriction in speed and acceleration when moving workpiece, because too high speed or quick acceleration may cause vacuum gripper to lose suction. Another problem with vacuum grippers is the maintaining the vacuum in suction cups when the vacuum system has long tubes and multiple suction cups, as there might be some pressure differences between suction cups. (Tai et al. 2016 p. 4.)

5.3.3 Magnetic grippers

Magnetic gripper is a typical solution for grasping ferromagnetic materials, such as all ferrous steels. Magnetic grippers are classified to two categories, electromagnets and permanent magnets. Electromagnetic grippers' movement is controlled by the controller unit which is powered with DC power source. The advantages of electromagnetic grippers are easy control and release of the object. Electromagnetic gripper may cause residual magnetism on the object and to prevent residual magnetism, the controller minimizes the level of polarity before the release of the object. With permanent magnet grippers, any external power is not required for handling of the object. The permanent magnet gripper consists of magnet and a release device named as stripper push-off pin. Permanent magnet grippers are suitable to be used in hazardous and explosive environments. (Chen et al. 2015 p. 2039–2040.)

According to research by Roy (2015) magnetic grippers can be integrated with sensors such as proximity, infrared, laser and force/torque sensors. Roy also states that recently a lot of research interest has been concentrated on magnetic gripping due to the suitability for unstructured robotic environments. (Roy 2015, p. 16–17.) This could indicate that magnetic grippers could be used as a universal gripping method for ferromagnetic materials. In the research by Roy a comparison of commercial magnets was made, and the result was that commercial magnets were capable for producing a lifting force of 395 N and were more or less designed for lifting of thin sheet metals and were not suitable for heavier lifting (Roy 2015, p. 18). The commercial magnets lifting capacity seems to been developed a lot in recent years as commercial magnet manufacturer Ixtur has developed a magnets capable to lift loads up to 1,7 kN with a safety factor of 3. Ixtur magnets are also suitable for lifting thicker plates, at least 25 mm thick. (Ixtur 2018, p. 1.)

5.3.4 Adaptive grippers

The adaptive grippers or underactuated grippers have been under attention in recent years, because these grippers have possibility to grasp and adapt to a different sized and shaped objects due to their mechanism. Therefore, adaptive grippers are suitable for unknown and oddly shaped objects. In adaptive gripper a single actuator is designed to envelop the part being grasped mechanically and therefore avoiding need for sensors or control. Another type of adaptive gripper is a multi-fingered gripper where the finger movement is controlled with electric control. Feedback sensors can be integrated to fingers to ensure that the object is grasped with required force. The typical multi-fingered gripper consists of at least three fingers, which are mounted on the “palm of the hand” which acts as an additional revolute joint. The adaptive gripper hand can have 10 degrees of freedom (DOF), when each finger have 3 DOFs and the rotating of hand adds the one DOF, which makes total of 10 DOF. The 10 DOF can be achieved with just two actuators, one for closing/opening the fingers and on for rotating the hand. The principle of adaptive gripper is shown in figure 12, where the examples of parallel gripping and power gripping are presented. (Birglen & Schlicht 2017 p. 95; Tai et al. 2016, p. 10–11; Chen et al. 2015 p. 2046–2053.)

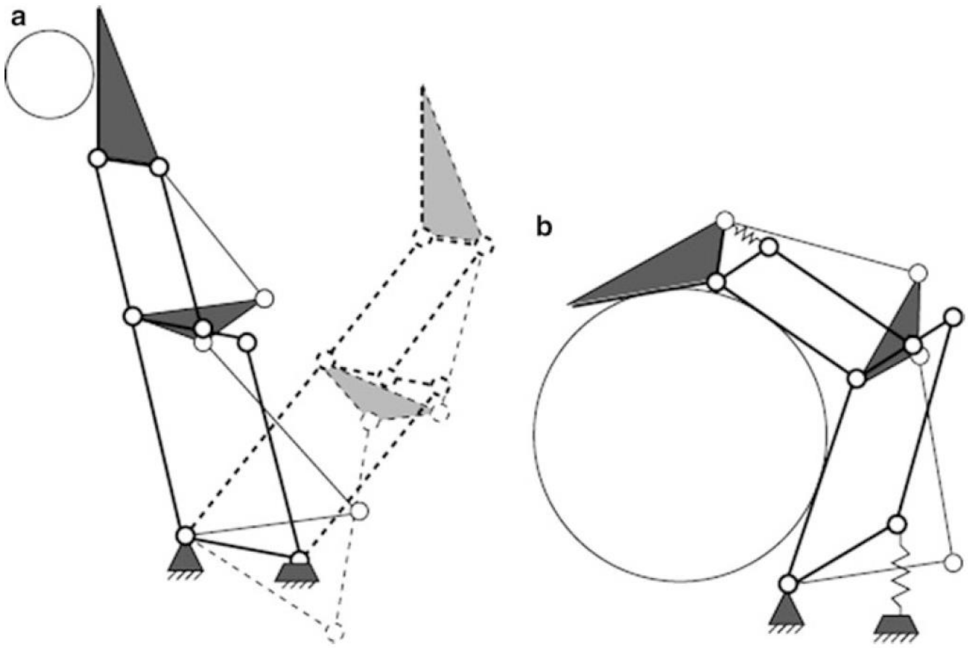


Figure 12. Parallel grasping a) and power grasping b) of adaptive finger gripper (Chen et al. 2015 p. 2053).

5.3.5 Comparison of grippers

According to review made of different types of grippers a comparison of grippers were made in table 3. In table 3 the comparison is made between the grasping point, object shapes that gripper can grasp, lifting capacity, advantages and disadvantage. As grippers can be highly customized for particular solutions the table 3 presents only overall comparison between mechanical, vacuum, magnetic and adaptive grippers.

Table 3. Comparison of properties and suitability of grippers. (Birglen & Schlicht 2017, p. 88–95; Chen et al. 2015 p. 2036–2053; Parlitz 2013, p. 370– 373; Roy 2015, p. 16–17; Tai et al. 2016 p. 4; Ixtur 2018, p. 1).

Function	**Type of gripper**			
	Mechanical	**Vacuum**	**Magnetic**	**Adaptive**
Grasping point	Object edge Around the object	Flat surface	Flat surface Round surface	Object edge

Table 3. Comparison of properties and suitability of grippers. (Birglen & Schlicht 2017, p. 88–95; Chen et al. 2015 p. 2036–2053; Parlitz 2013, p. 370– 373; Roy 2015, p. 16–17; Tai et al. 2016 p. 4; Ixtur 2018, p. 1).

Function	**Type of gripper**			
	Mechanical	**Vacuum**	**Magnetic**	**Adaptive**
Suitable object shape	Plates Tubes Round	Plates	Plates Tubes	Universal
Lifting capacity	Light – Heavy	Light – Medium	Light – Heavy	Light – Medium
Advantages	High variety of commercial grippers available	Suitable for flat surfaces	High lifting capacity	Adaptivity for different shape and size objects
Disadvantages	Reachability and limited options for gripping	Customized solutions required	Suitable to only ferrous and magnetic materials, Customized solutions required	High cost, Limited lifting capacity

The jigless welding will require universal gripping method for part handling. The parts of the workpiece in the jigless welding cell will be mostly different size of steel plates, but the workpieces itself may have many shapes. Based on the review made of grippers it can be said that promising solutions seems to be magnetic, mechanical and adaptive grippers. Magnetic and mechanical grippers are capable to lift heavier workpieces, but with vacuum and adaptive gripper the lifting capacity may become a limiting factor. Mechanical gripper needs to grasp workpiece by some plate edge or around the workpiece, which may cause limitations with the stroke length, if part sizes vary. Magnetic gripper has limitation with the workpiece material, as it must be magnetic. Magnetic grippers also require development of some sort of adapter plate for connecting magnets to the robot manipulator.

Further comparison of grippers is required to be made when developing the multi-robot jigless welding cell. Still, a gripper itself will not be enough to achieve jigless welding and a solution for positioning the workpiece is required.

5.4 Machine vision in robotic welding

According to Muhammad, Altun & Abo-Serie (2016) typical use of machine vision in robotic welding is seam tracking. With optical sensing it is possible to track and profile both weld seam and weld pool. The machine vision can be either passive or active. Passive vision uses two cameras, but not any light source. Active vision uses one camera and a light source. The image processing is more complex in passive vision system than in active vision system, due to the reason that passive vision systems image processing algorithm needs to process the information of two images during welding. Passive vision can obtain information about the seam profile and welding pool profile. The welding pool profile cannot be obtained with active vision. The seam path can be obtained holistically with passive vision, which is not possible with active vision as it only captures one point at a time. There are multiple ways in passive vision system to manage pre-processing of image and profiling of weld seam and weld pool. (Muhammad, Altun & Abo-Serie 2016, p. 127–131.)

Active vision system is presented in figure 13, the system consist of charge-coupled device (CCD) camera, light source, optical lenses and filters. Active vision utilizes triangulation technique to have geometrical data of the welding joint. The light is projected on the joint, then the camera captures the pattern on joint and finally the image is processed to get the geometric data of the joint. The properties of the pattern produced by the light depend on five factors: i) type of the welding joint, ii) pattern produced by the light source, the pattern can be line shape or a 2D shape, such as circle or triangle, iii) welding part surfaces optical properties, iv) the lights location relative to the torch and v) quality of camera and laser. (Muhammad, Altun & Abo-Serie 2016, p. 127–131.)

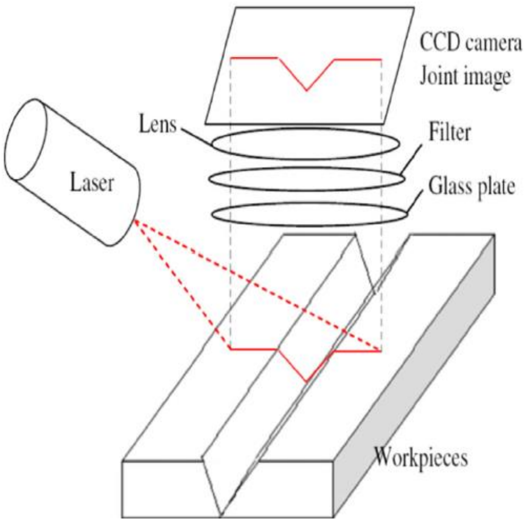


Figure 13. Representation of the active vision system and its components (Muhammad, Altun & Abo-Serie 2016, p. 129).

Surface reflections and metal spatter along the joint may cause a few discontinuities and deviations in the width of the light pattern captured by the sensor. Therefore, for receiving accurate data of the weld joint geometry, complex image processing and pattern recognition algorithms are needed. According to Muhammad, Altun & Abo-Serie (2016) the algorithms can be categorized as follows: “image pre-processing”, “extraction or segmenting of the laser stripe pattern from the captured image“ and “welding joint feature extraction and profiling”. The typical steps and techniques in image processing of active vision system are presented in the figure 14. A more detailed summary of the image processing and pattern recognition algorithms for active vision system is presented in appendix 1. (Muhammad, Altun & Abo-Serie 2016, p. 140-142.)

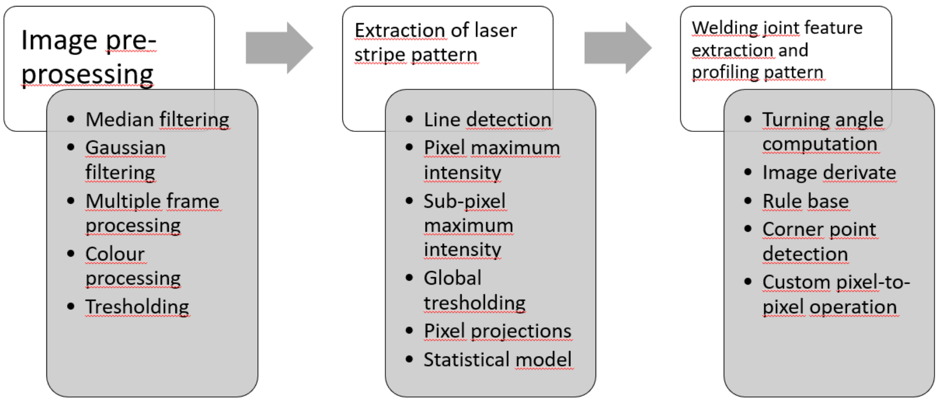


Figure 14. The image processing process and processing techniques (Muhammad, Altun & Abo-Serie 2016, p. 140–141.)

5.4.1 Machine vision techniques for object pose estimation

The locating and measuring of the workpiece in robotic welding and other robotic applications has been under a research a lot in the recent years. Njastaad and Egeland 2016 researched 3D vision and CAD model data combining system for correcting robot welding path trajectories created in simulation. Perez et al. (2016) have made a review where different machine vision techniques, which are suitable for guiding robot, are compared.

Perez et al. (2016) reviewed 3D vision techniques suitable for guiding robot. The techniques were i) passive: stereo vision and photogrammetry and ii) active: time of flight (ToF), structured light, light coding and laser triangulation. Passive techniques function by searching for same point or target in various images and then calculating the intersection of the projection lines. Active vision techniques function by projecting light pattern against the object and estimating the depth data. In ToF the depth estimation is calculated from returning time of light, in light coding the depth estimation is calculated from the deformation of the light pattern and in laser triangulation and in structured light techniques the depth estimation is calculated by using trigonometry. (Perez et al. 2016, p. 4–5.)

5.4.2 Robot path correction with machine vision

According to Njastaad and Egeland 2016 the tolerances in the workpiece geometry as well as inaccurasies in of information of workpiece location and position will cause robots programmed welding paths to have variance between the workpieces (p. 73). This will be a problem when trying to fit robot simulation model in real world robotic welding, because the programmed path created in simulation will vary a bit when compared to the actual robot path needed for the welding. To overcome the problem Njastaad and Egeland developed a 3D computer vision system, which utilizes geometrical information from CAD model of the workpiece and 3D image data of the time-of-flight camera from the workpiece. The location and orientation data of welded component was presented in terms of (X; Y; Z; Rx, Ry, Rz) values. The acquired data from the camera was processed by using point cloud processing method and the aligning of image data as well as geometry data of simulation model was done with a local optimization method, called iterative closest point algorithm. If offset between the simulated and programmed paths or components pose was discovered by the system, the new location and orientation points were calculated and transferred by the system. The new pose of component was presented as (X´, Y´,Z´, Rx´, Ry´, Rz´) values. The figure 15 presents the information flow in the Njastaad and Egeland research. (Njastaad and Egeland 2016, p. 73–76.)

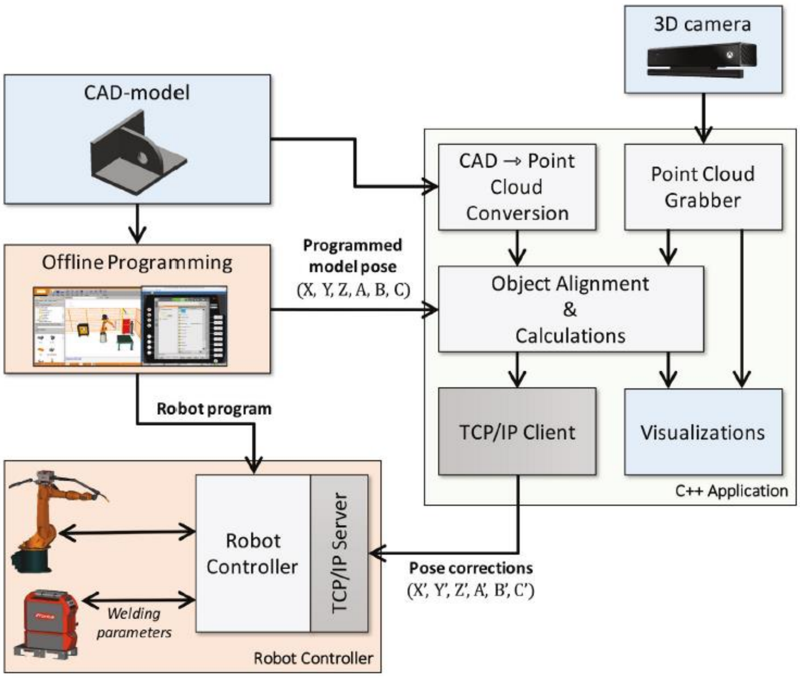


Figure 15. Information flow (Njastaad and Egeland 2016, p. 76).

The results of the Njastaad and Egeland research shows that their system was capable to make object pose estimation with a mean absolute error of 2.4 mm while maximum error being 5.7 mm. (Njastaad and Egeland 2016, p. 73–76.) From the viewpoint of the multi-robot jigless welding cell the maximum error value of 5.7 mm is quite high. Njastaad and Egeland does not mention what is the latency in their system.

Cubillos et al. (2016) have developed a method for correcting welding robots' path in real-time by using a structured light machine vision technique and image processing. Cubillos et al. used CCD camera and laser for image processing and for path correction the robot controller was connected to a computer, which calculated the error between programmed path and data acquired from the camera. In their set up Cubillos et al. welded a butt joint between two plates. Therefore, the possible errors in robot paths are caused by the misalignment of the plates. According to Cubillos et al. for correcting the robot path the misalignment needs to be measured with image processing tools and when the misalignment is known, the data can be sent to robot controller, which makes the corrections to robot path.

The misalignment can be measured from the discontinuous line, which is captured by the camera, when laser is projected onto the plates. Typically, the image requires some pre-processing before the misalignment can be determined. (Cubillos et al. 2016, p. 265–266.)

For correction movement Cubillos et al. designed a Fuzzy algorithm-based controller. The controller functions as follows: the robot’s program is modified in real-time, if offset in robot path is detected. The modification of the path occurs after the misalignment of the path is measured and then path is reviewed to the original path, therefore the industrial robot can know which way to move and how much to move. The result Cubillos et al. research was that the system developed was able to perform with a maximum error of 1.6 mm in Y axis. (Cubillos et al. 2016, p. 267–269.) The maximum error of 1.6 mm seems accurate enough to be an acceptable result for multi-robot jigless welding cell. Cubillos et al. states that their system makes the corrections to robot path on-line before and during welding, but they do not mention how much latency their machine vision system has.

Based on the review made of machine vision techniques a comparison of machine vision properties was made. The comparison is presented in the table 4 and it can be seen that the comparable items are how the machine vision technique handles depth estimation, accuracy when sensor is connected to robot, processing time and is the technique affected by the lighting conditions. For some techniques and properties quantitative values were not available and therefore a qualitative evaluation is given. In case of accuracy when the sensor is connected to robot the term “high” can be interpret as in the range of 0–1.5 mm. In case of processing time the term “high” can be interpret as that the image processing would cause noticeable pauses during robots’ operation and the term “low” can be interpret as the image processing would be executed in real-time without pauses in robots’ operation. For the development of multi-robot jigless welding cell in this research in this research the scope must be set for comparing the suitable machine vision techniques for the welding cell, but the development of software which corrects the robots’ path or measures the part/joint dimensions will be left for future development and research. Passive vision techniques require the camera sensor to stay still, which means that passive vision techniques are not considered to be suitable for the jigless welding cell under development.

Table 4. Comparison of different machine vision techniques properties (Cubillos et al. 2016, p. 264–269; Njastaad and Egeland 2016, p. 73–76; Perez et al. 2016, p. 1–20).

Vision technology	**Depth estimation**	**Accuracy with robot [mm]**	**Processing time**	**Disturbed by light**
Passive				
Stereo vision	Point estimation	High	High	Yes
Photogrammetry	Point estimation	0.2–0.5	High	Yes
Active				
ToF	Returning time of light	2.4	Low	No
Structured light	Trigonometry	1.6–3	High	Yes
Light coding	Deformation of light pattern	10	Low	Yes
Laser triangulation	Trigonometry	High	Low	Yes

Based on this chapter the key aspects for the development of multi–robot jigless welding cell are that the previous researches have not presented a system which would have made the robotic welding cell fully jigless, therefore such a technical solution must be developed to ensure that the welding cell is capable of jigless welding. Robot gripper have also crucial role in making the multi-robot welding cell jigless. The gripper can be used to hold the workpiece in position during tack welding. Robot gripper will be used to grasp different size and shapes plates and plate structures. The active machine vision sensors can be used when the robots or targets are moving and therefore the machine vision sensor in the multi-robot welding cell should use active vision.

6 QUALITY REQUIREMENTS OF ROBOT WELDED STRUCTURES

In this chapter the relevant quality requirements given in welding standards are presented, mainly focusing on quality requirements which are thought to be suitable for jigless robotic welding and also a review of the accuracies of industrial robots and machine vision was made. The standards SFS-ISO 3834 can be used as a tool to ensure that the manufacturing of welded structures is efficient and proper quality control is executed throughout whole operation. The quality of the welded product is made by manufacturing and therefore the quality control in design, material selection, manufacturing and inspection are in key role to ensure high quality manufacturing. (SFS-ISO 3834-1 2006, p. 6.) The quality requirements for the welds are presented in the welding standards. As it is stated in the standard SFS-ISO 3834-2 the quality level of the weld is determined by the customer during contracting with the manufacturer and manufacturers duty is to establish and maintain the welding quality requirements. (SFS-ISO 3834-2 2006, p. 6.)

The standard SFS-EN ISO 5817 sets guidelines for the assessment of weld imperfections and categorizes weld imperfections into three quality levels B, C and D. (SFS-EN ISO 5817 2014, p. 20–47). In case of jigless robotic welding the point of interest is in geometrical imperfections, because the geometrical imperfections set the limits for the accuracy in locating the parts. By selecting the wanted quality level for the welds in robotic welding it is possible to determine the requirements for accuracy. Generally according to SFS-EN ISO 5817 for quality level of B the linear misalignment between plates in longitudinal welds can be at maximum of 3 mm and the incorrect root gap for fillet welds can be at maximum of 2 mm. (SFS-EN ISO 5817 2014, p. 20–47.) The tolerances for welded structures are given in the standards SFS-EN ISO1090-2 and SFS-EN ISO 13920 (SFS-EN ISO1090-2 2018 p. 78; SFS-EN ISO 13920 1996 p. 5–7). More detailed instructions from the standards SFS-EN ISO 5817 and SFS-EN ISO1090-2 are presented in appendix III.

6.1 Accuracy of machine vision and industrial robot

In Njastaad and Egeland (2016) research the accuracy of ToF machine vision system was tested in 2D and in 3D object alignment cases and also in horizontal and vertical positions. The accuracy of the system was measured by comparing the manually optimized welding path and the machine vision system corrected off-line programmed path to each other and calculating the errors in target points P1 to P6, the results of measured absolute error values are can be seen in figure 16. The figure 16 also presents the measured absolute error values in horizontal and vertical welding position without object alignment, with 2D object alignment and with 3D object alignment. In 3D object alignment case the mean absolute error value was 2.4 mm and maximum error value was 5.7 mm. (Njastaad and Egeland 2016, p. 75–78.) The maximum error value of 5.7 mm is quite high and would cause concerns of possible collisions within the multi-robot jigless welding cell.

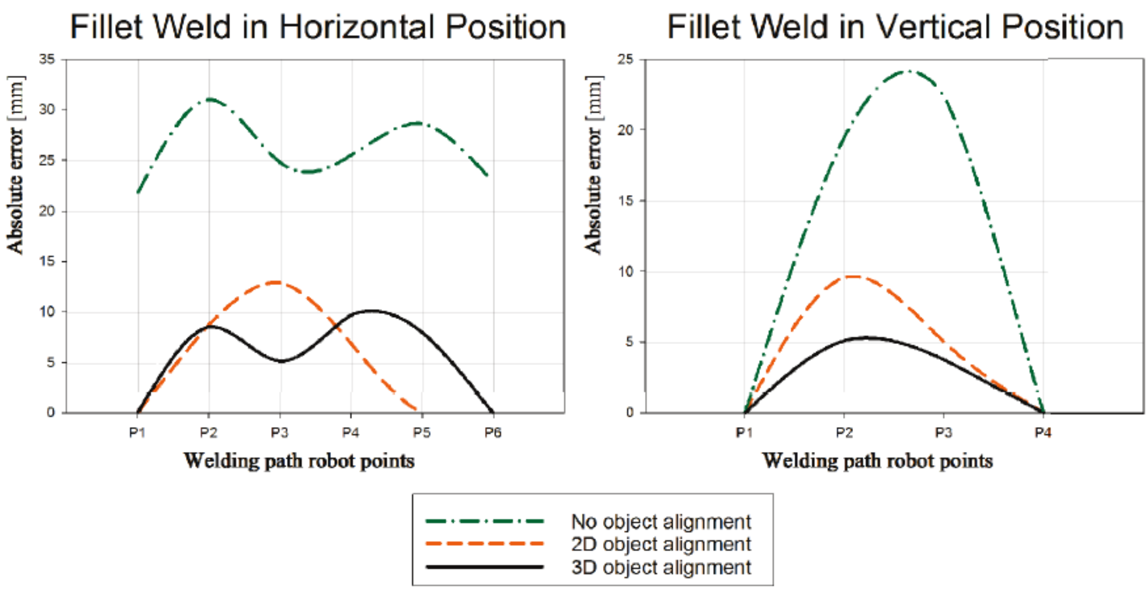


Figure 16. Absolute error values of machine vision system without object alignment, with 2D object alignment and with 3D object alignment (Njastaad and Egeland 2016, p. 78).

In the Perez et al (2016) literature review accuracies of different machine vision systems were reviewed. The off-line photogrammetry systems accuracy was found to be quite precise 0.05 mm for 2 m object and the on-line photogrammetry systems accuracy was found to be 0.2–0.5 mm in a range of 2 m. The off-line system can be used for measuring and quality control and the on-line system can be used for real-time robot path correction. For structured light machine vision technique an accuracy of 3 mm was found. Perez et al. made also a comparative review of accuracies of machine vision systems based on the literature review, the comparative review is shown in table 5. (Perez et al 2016, p. 11–18.)

Table 5. Comparison of accuracies of machine vision techniques (modified from Perez et al. 2016, p. 18).

Machine vision technique	Accuracy [mm]
Stereo vision and photogrammetry	0.05
Projected texture stereo vision	0.1
Time of flight	10
Structured white light	0.127
Structured blue LED light	0.034
Light coding	10

In the Cubillos et al. (2016) research the structured light machine vision techniques accuracy was tested on a welding robot. The maximum error value was found to be 1.6 mm. (Cubillos et al. 2016, p. 269.)

In a research by Nguyen, Zhou and Kang (2013) an effort to increase robot accuracy by a calibration method that uses kalman filter algorithm and artificial neural network was made. In their approach robots' geometric variables are first modeled and then recognized with the extended kalman filter algorithm, which is then combined with the artificial neural network to moderate the robots' non-geometric errors. After the calibration process the robot's accuracy improved from 4.07 mm to 0.3368 mm. (Nguyen, Zhou and Kang 2013, p. 1003.)

Based on the review made in this chapter, following conclusion can made. Given in the standards the maximum misalignment in longitudinal weld were 3 mm and the maximum inaccuracy in fillet welds were 2 mm. Based on the review made of machine visions and industrial robots accuracy it seems that ToF and light coding techniques are struggling to meet limitations of standard, but structured light and passive vision techniques are able to function within the limits of standard. This is an aspect that must be considered when developing multi-robot jigless welding cell.

7 SYSTEMATIC DESIGN OF MULTIROBOT JIGLESS WELDING CELL

Current state of the multirobot welding cell is following. Cell consist of welding robot MOTOMAN MA1900, handling robot MOTOMAN-ES165N and positioner robot. Currently the system requires use of jigs during welding to hold the workpieces in position. The handling robot is equipped with a mechanical gripper, which causes reachability problems when handling plates, as the gripper may cause collisions with the positioner. Currently the handling robot does not have a real purpose in the system, because welding robot operator is required to place the workpiece in correct location and set up jigs.

7.1 Task clarification and requirements for the multirobot jigless welding cell

The requirements for the multirobot jigless welding cell were gathered based on the welding laboratory's staff's demands and wishes and the welding cells robots' capacities. A list of requirements was gathered and is presented in table 6. From the table 6 it can be seen that the requirements are categorized to demands and wishes.

Table 6. Requirements list for jigless multirobot welding cell.

LUT-University		Requirements list for multirobot jigless welding cell	Date 30.10.2018
Changes	Demand = D Wish = W	Requirements	
		Welding cell **Geometry and components:**	
	D	Robot cell consists of welding robot, handling robot and positioner robot.	
	D	Robot positions remains as they currently are.	
		Gripper:	
	D	Size: Suitable to carry workpiece	
	D	Connection: Gripper is connected to the handling robot.	

Table 6 continues. Requirements list for jigless multirobot welding cell.

LUT-University		Requirements list for multirobot jigless welding cell	Date 30.10.2018
Changes	Demand = D Wish = W	Requirements	
		Workpiece:	
	W	Size: From 100 x 100 - 100 to 1000 x 1000 -1000	
		Machine vision sensor:	
	W	Connection: To welding robot	
	W	Weight: ≤ 1 kg	
		Workpiece positioner system:	
	W	Size: Must fit to positioner	
	W	Connection: Connects to positioner M16 threaded holes.	
		Kinematics:	
	D	Handling robot and gripper pick, hold, move and release workpiece.	
	D	Handling robot connects workpieces to positioner.	
	W	Welding robot inspects workpiece position and dimensions, tack weld and weld workpiece.	
		Forces:	
	D	Forces in the welding cell are caused by the workpiece. Forces affect to handling robot, gripper and workpiece positioner system.	
	W	Maximum force: 981 N	
	D	Direction of forces: 	

Table 6 continues. Requirements list for jigless multirobot welding cell.

LUT-University		Requirements list for multirobot jigless welding cell	Date 30.10.2018
Changes	Demand = D Wish = W	Requirements	
		Energy:	
	D	Pneumatic energy from handling robot to gripper.	
	W	Pneumatic energy from positioner to workpiece connecting system.	
	W	Pressure: 6 MPa	
		Material:	
	D	Flow and transport: Workpiece feeding station to positioner to finished product station, movement by handling robot.	
		Workpiece properties:	
	D	Material: Steel	
	W	Other metals	
	D	Type: Plate	
	W	Tube	
		Sensors:	
	W	Control equipment: Machine vision system	
	W	Input: Image data.	
	W	Output: Sensor measures the joint geometry and makes adjustments to robot paths.	
	D	Collection of welding data	

Table 6 continues. Requirements list for jigless multirobot welding cell.

LUT-University		Requirements list for multirobot jigless welding cell	Date 30.10.2018
Changes	Demand = D Wish = W	Requirements	
		Safety:	
	D	Neither robots, robots' components nor workpieces must not cause collisions.	
		Ergonomics:	
	W	No need for human to work inside the cell, except for material loading.	
		Production:	
	D	Production method: Welding assembly without jigs	
	W	Quality and tolerances: According to standard SFS-EN ISO-5817 and SFS-EN ISO1090-2 weld class B	
		Assembly:	
	D	Welding robot, handling robot and positioner works in synchronous motions to assemble workpiece without using jigs.	

7.2 Abstracting and morphological classification

To find the relevant problems from the requirements list, presented above, an abstraction process was implemented. The abstraction process consists of 5 steps (Pahl et al. 2007, p. 165). The results of abstraction are shown in table 7. From the table 7 it can be seen that after five abstraction steps the relevant problem was found to be designing a robotic welding cell with machine vision sensor, a gripper in handling robot and a workpiece positioning system for the positioner.

Table 7. The abstracting process to find the relevant design problem

Steps	Results
1. & 2.	- Welding robot must be equipped with machine vision sensor - Handling robot must be equipped with gripper. - Gripper must withstand forces of 981 N in X, Y, Z directions. - Gripper functions pick, hold, move and release workpiece. - Gripper functioning pressure 6 MPa. - Workpiece consists of steel plates. - Workpiece is assembled, tack welded and welded without jigs. - Positioner must have system to position workpiece - Data is collected during welding and with machine vision sensor
3.	- Welding robot must be equipped with machine vision sensor - Handling robot must be equipped with gripper. - Gripper must withstand various forces in various directions. - Gripper functions pick, hold, move and release workpiece. - Gripper is pneumatic. - Workpiece consists of steel plates. - Workpiece is assembled, tack welded and welded without jigs. - Positioner must have system to position workpiece - Data is collected from the weld
4.	- Machine vision sensor must be used. - Handling robot must be equipped with gripper. - Pneumatic gripper is used to move the steel plates/workpiece - Workpiece must be positioned - Data is collected from the weld
5.	-Design a robotic welding cell with machine vision sensor, a gripper in handling robot and a workpiece positioning system for the positioner.

Based on the result of abstraction steps, the relevant problem states that the welding robot system should be equipped with machine vision sensor. Handling robot should be equipped with a gripper and positioner should have system for positioning the workpiece. A five sub-functions were identified from the relevant problem, which were the grasping workpiece, workpiece positioning, machine vision sensing, sensor location and IoT welding data collection. For each sub-function four technical options, which perform the sub-function, was made. Therefore, a morphological classification of different options for each sub-function were made, which can be seen in table 8. From the table 8 each sub-function of the multirobot jigless welding cell can be seen in the first column of the table and options for performing the sub-functions can be seen columns 2 to 5.

Table 8. The morphological classification of different options to perform the functions.

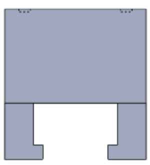
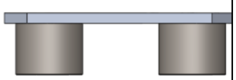
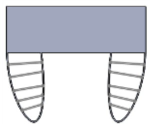
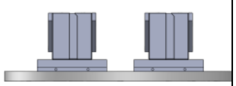
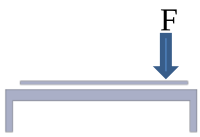
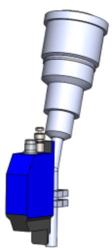
Options –> Sub-functions	**Option 1 a)**	**Option 2 b)**	**Option 3 c)**	**Option 4 d)**
Grasping workpiece	Mechanical gripper 	Magnetic gripper 	Vacuum gripper 	Adaptive gripper 
Workpiece positioning	Self-positioning 	Magnets on the positioner 	Robot usable fixture 	Operator uses fixture on the first part 
Machine vision sensing	Time of flight	Laser triangulation	Structured light	Light coding
Sensor location	Weld torch 	Weld torch adapter plate 	Robot arm	On table/positioner

Table 8 contiues. The morphological classification of different options to perform the functions.

Options –> Sub-functions	**Option 1 a)**	**Option 2 b)**	**Option 3 c)**	**Option 4 d)**
IoT welding data collection	Kemppi WeldEye	ESAB WeldCloud	EWM XNET	Fronius WeldCube

7.3 Value analysis

The functional requirements for the welding cell was that the welding cell must be capable of handling workpieces and the workpiece needs to be positioned without using jigs. Also, the system must have machine vision sensor and IoT welding data collection system. The reviewed main functions for the value analysis of the multi-robot jigless welding cell are as follows:

- grasp workpiece
- position workpiece
- machine vision sensing
- machine vision sensor location
- welding data collection.

For each main function of the multirobot jigless welding cell, four sub-functions were identified. In the table 9 the sub-functions for each main function were presented. The table 9 also presents the possible options that perform the main function and the sub-functions.

Table 9. Functions, sub-functions and options for value analysis.

Functions	Sub-functions	Options
Grasp workpiece	• Carry load (CL) • Grasp/hold/release workpiece (GP) • Avoids interferences (AI) • Suitable to plates (SP)	a) Mechanical gripper b) Vacuum gripper c) Magnetic gripper d) Adaptive gripper
Position workpiece	• Carry load (CL) • Hold workpiece (HW) • Allows rotation (AW) • Easy to operate (EO)	a) Self-positioning b) Magnets on the positioner c) Robot usable fixture d) Operator uses fixture on the first part
Machine vision sensing	• Detection distance (DD) • Measure position (MP) • Simple to use (SU) • Processes quickly (PQ)	a) Time of flight b) Laser triangulation c) Structured light d) Light coding
Machine vision sensor location	• Is movable (IM) • Does not vibrate (DV) • Reachability (R) • Avoids collision (AC)	a) Weld torch b) Weld torch adapter plate c) Robot arm d) On table
Welding data collection	• Collects welding data (CW) • Connects to multiple welding power sources (CM) • Works in real-time (WR) • Tracks quality (TQ)	a) Weldeye b) WeldCloud c) XNET d) WeldCube

The sub-functions require to be highlighted, therefore, each main functions sub-functions were highlighted and the highlighting can be seen in the appendix II. In highlighting each sub-function is compared to other sub-functions and when the sub-function is considered to be more important than the compared sub-function two points are given from the "win". When the sub-function is compared to itself a point is given. The results of highlighting can be seen from appendix II.

The next step to carry on with the value analysis was to compare the options in each sub-function category. The evaluation was performed by giving a grade to each option based on how well the option performs the sub-function. The grading was from 1 to 4. The results of grading can be seen from appendix II. The grades were multiplied with highlighting numbers and the results of multiplying can be seen from appendix II.

To calculate the value of different options in value analysis an estimation of proportional costs for each option are needed. The cost estimations for each solution are given in table 10. The final value for each option is got by dividing total sum of the highlighted grade by the estimated proportional cost. The values of each option are also shown in the table 10. The "winning" option is highlighted with green colour in table 10.

Table 10. Values of each option.

Values	**Option a**	**Option b**	**Option c**	**Option d**
Grasp workpiece	0.42	0.59	0.76	0.16
Position workpiece	0.24	0.47	0.39	0.14
Machine vision sensing	0.43	1.16	0.08	0.38
Machine vision sensor location	0.51	0.34	0.36	0.27
Welding data collection	0.64	0.48	0.48	0.48

Therefore, the results of value analysis show that the most suitable technological options for the multirobot jigless welding cell are as follows:

- magnetic gripper
- magnetic positioning system
- triangulation machine vision sensor
- machine vision sensor is connected to welding torch
- weldeye is used for collecting welding data.

7.4 Designed components

As a result of a systematic design process came magnetic gripper for grasping the workpiece parts, adapter for machine vision sensor and magnetic positioning system for attaching the workpiece to positioner robot. A CAD-model of the magnetic gripper, with a robot tool changer attached to it, can be seen from figure 17. The width of the gripper is 190 mm and the height is 70 mm or 117 mm with the tool changer attached. In multi-robot jigless welding cell the magnetic gripper is connected to the part handling robot.

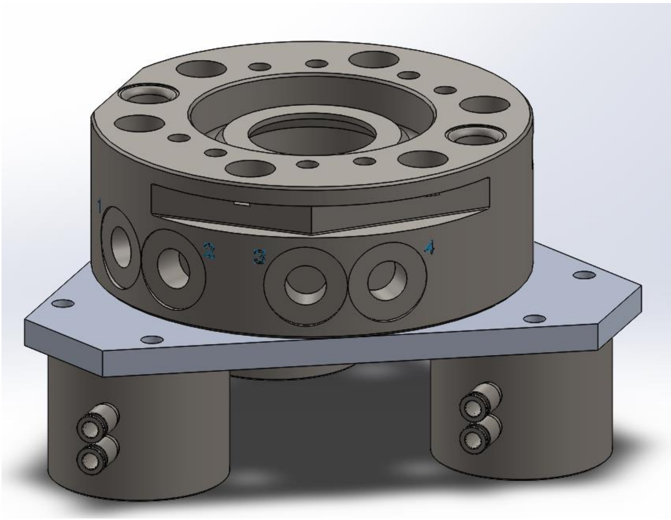


Figure 17. CAD-model of magnetic gripper, the width of the gripper is 190 mm and height is 70 mm.

A CAD-model of machine vision adapter, with machine vision sensor attached to it, can be seen from figure 18. The machine vision sensor can be seen as blue and black shaped part and the machine vision adapter can be seen as white part. The height of the machine vision sensor adapter is 135 mm, the width of the adapter is 50 mm and the depth of the adapter is 70 mm. In the multi-robot jigless welding cell the adapter is connected to the welding torch.

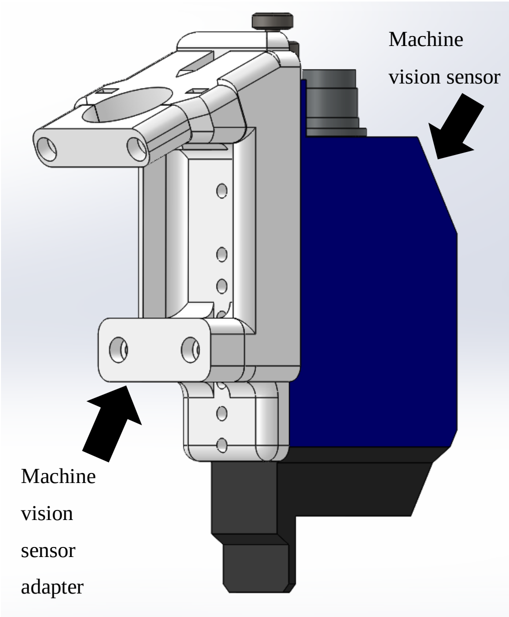


Figure 18. CAD-model of machine vision adapter and machine vision sensor, height 135 mm, width 50 mm and depth 70mm.

The CAD-model of the magnetic positioning system can be seen in figure 19. The width of the magnetic positioning system is 400 mm, the height is 150 mm and the depth is 180 mm.

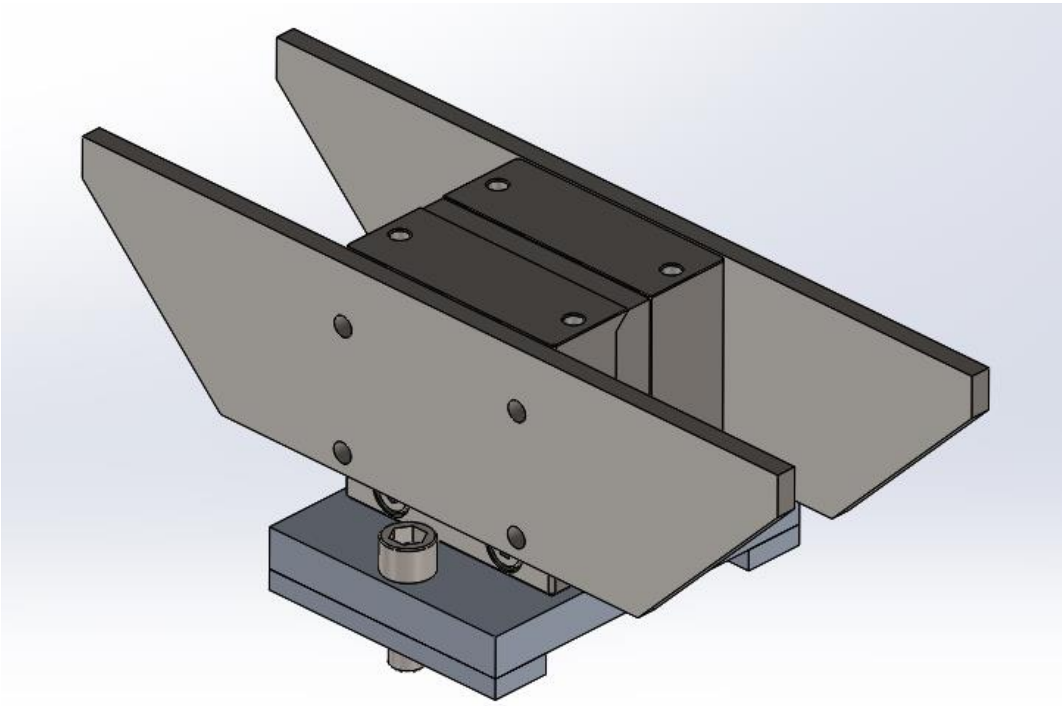


Figure 19. CAD-model of magnetic positioning system, the width is 400 mm, the height is 150 mm and the depth is 180 mm.

8 SIMULATION OF THE MULTI-ROBOT JIGLESS WELDING CELL

To simulate the multirobot jigless welding cell, a layout of the welding laboratory's multirobot jigless welding cell was made. The existing robots were equipped with the components designed in the previous chapter, to test the concept of the multirobot cell on how to perform jigless welding operation. The handling robot was equipped with the magnetic gripper, welding robot was equipped with machine vision sensor and the positioner was equipped with the magnetic positioning system. The layout of the multi-robot jigless welding cell can be seen in the figure 20 and the dimensions of the cell are following length is 4836 mm and the width is 3788 mm.

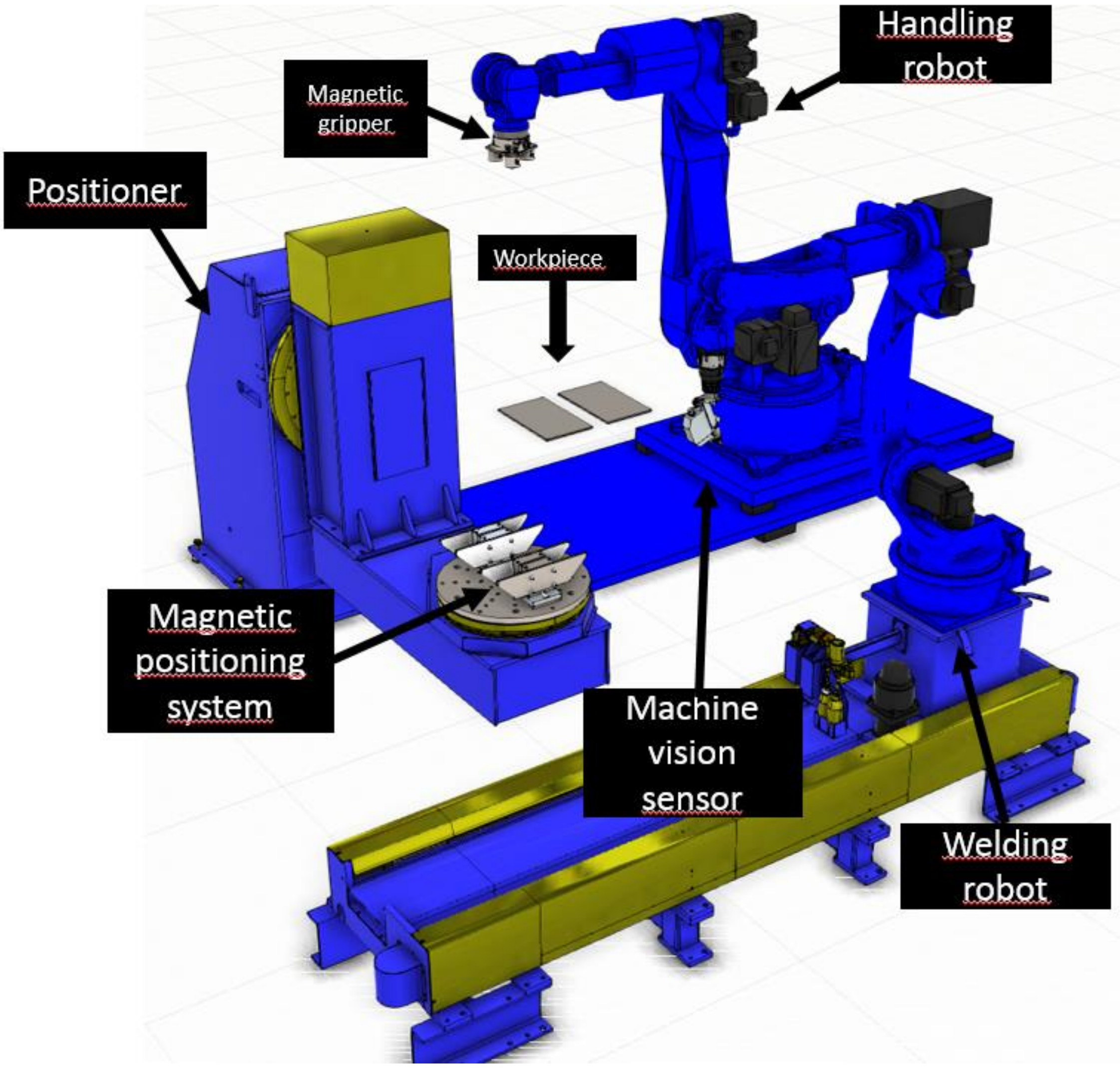


Figure 20. The simulation layout of multirobot jigless welding cell, the length of the cell is 4836 mm and the width is 3788 mm.

8.1 Testing of simulation model of multi-robot jigless welding cell

To test how the designed components function in multirobot jigless welding cell and what would be the functioning procedure, a two simulations where the workpieces shown in figure 15 above were made. The workpiece which consist only T-joint type workpiece was simulated first and then the more complex workpiece, which consist of I-beam looking structure on top of plate was simulated.

8.1.1 Testing of simulation model with T-joint workpiece

The phases of the simulation are shown in figures 21, 22 and 23. In the figure 21 the first part of the workpiece is picked (a) and brought to positioner in the magnetic positioning system (b). Then the second part of the workpiece is picked (c) and brought to positioner in the magnetic positioning system (d) for the joint geometry inspection and tack welding.

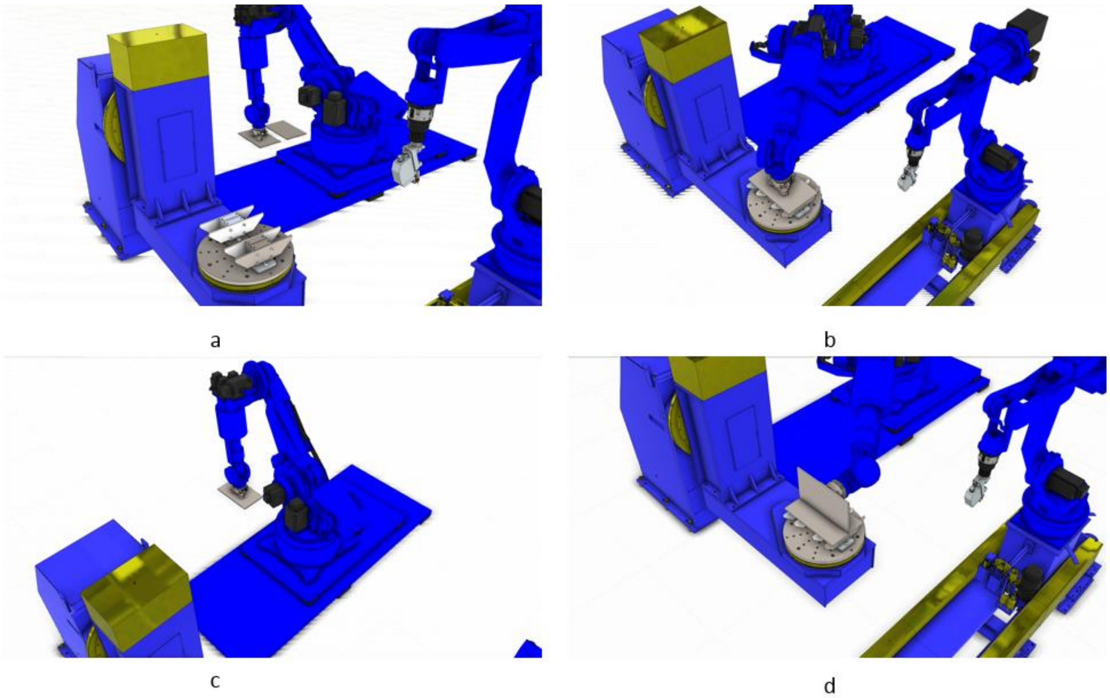


Figure 21. Phases of simulation. A) picking the first part of workpiece, b) releasing the part to the positioner, c) picking the second part of workpiece and d) locating the part to the positioner.

In the figure 22 the joint geometry is inspected (e) and then tack welded from both sides of the plate (f, g). Finally, the joint geometry is inspected again (h).

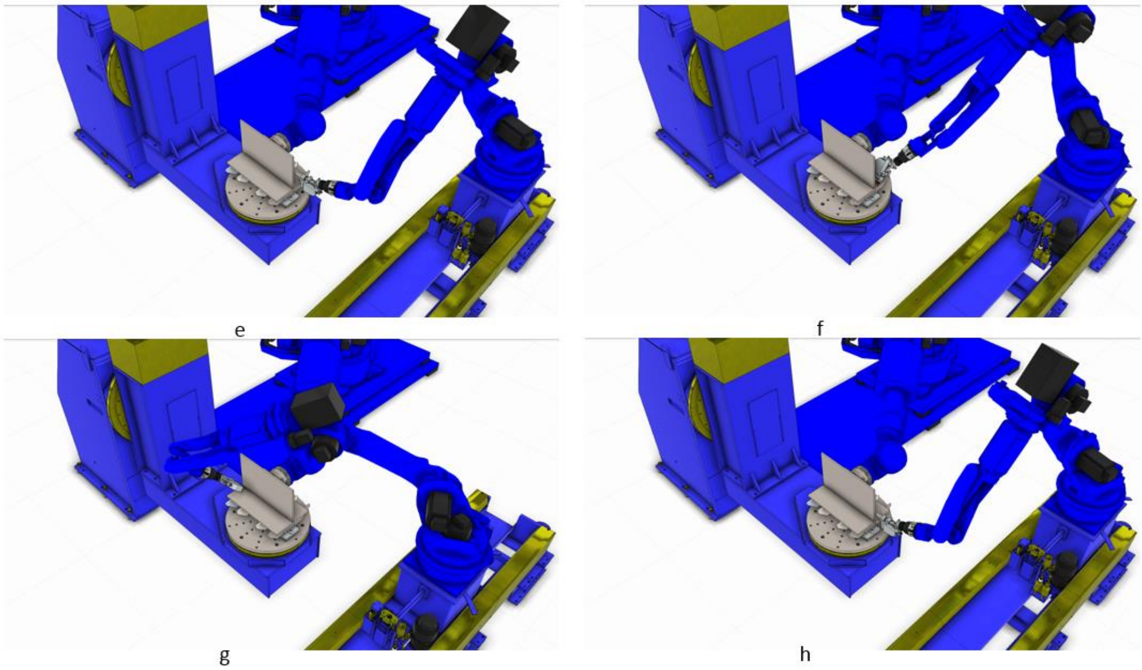


Figure 22. Phases of simulation continues. E) joint geometry inspection, f) tack welding, g) tack welding from other side and h) inspection of joint geometry again.

In figure 23 the workpiece is welded from both sides in flat position, where the positioner is rotated to 45° angle (i, j). After welding the joint geometry is inspected (k) and the finished workpiece is taken away (l).

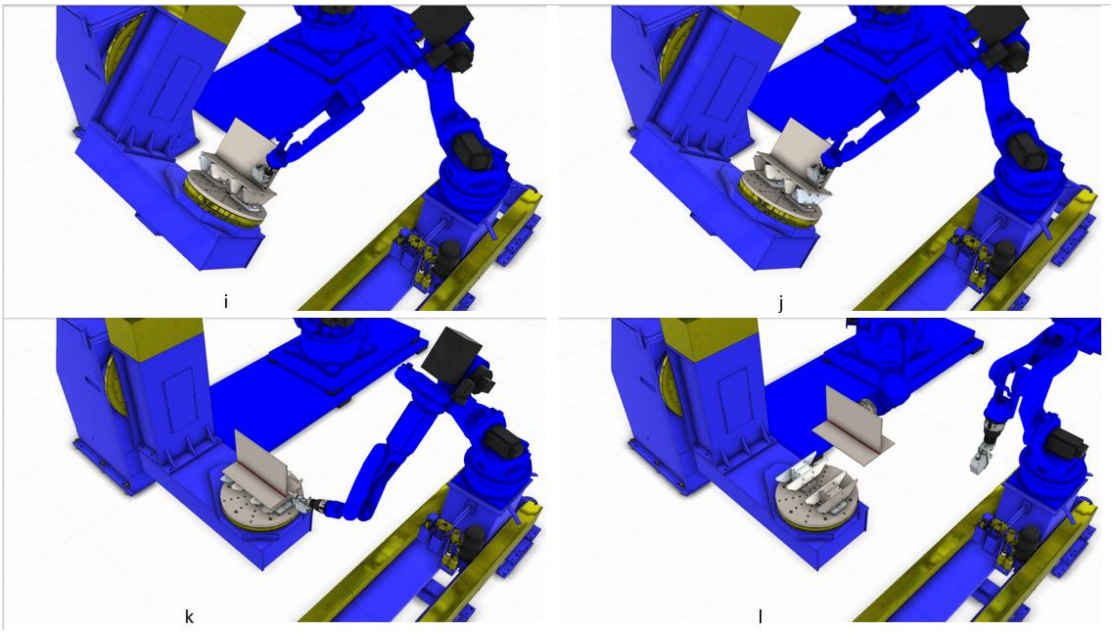


Figure 23. Phases of simulation continues. I) welding of workpiece, j) welding of workpiece from other side, k) inspection of the joint geometry and l) removal of the finished workpiece.

The created robot programs in the first simulation are shown in the figure 24. On the left in figure 24 are the main program structure for the handling robot and on the right is the main program structure for the welding robot. The main program calls for the subprograms. In the subprograms the command for robot movements and tool input and output statements are given. Synchronisation command is used to communicate between robots, as otherwise the robots would perform their programs independently during simulation.

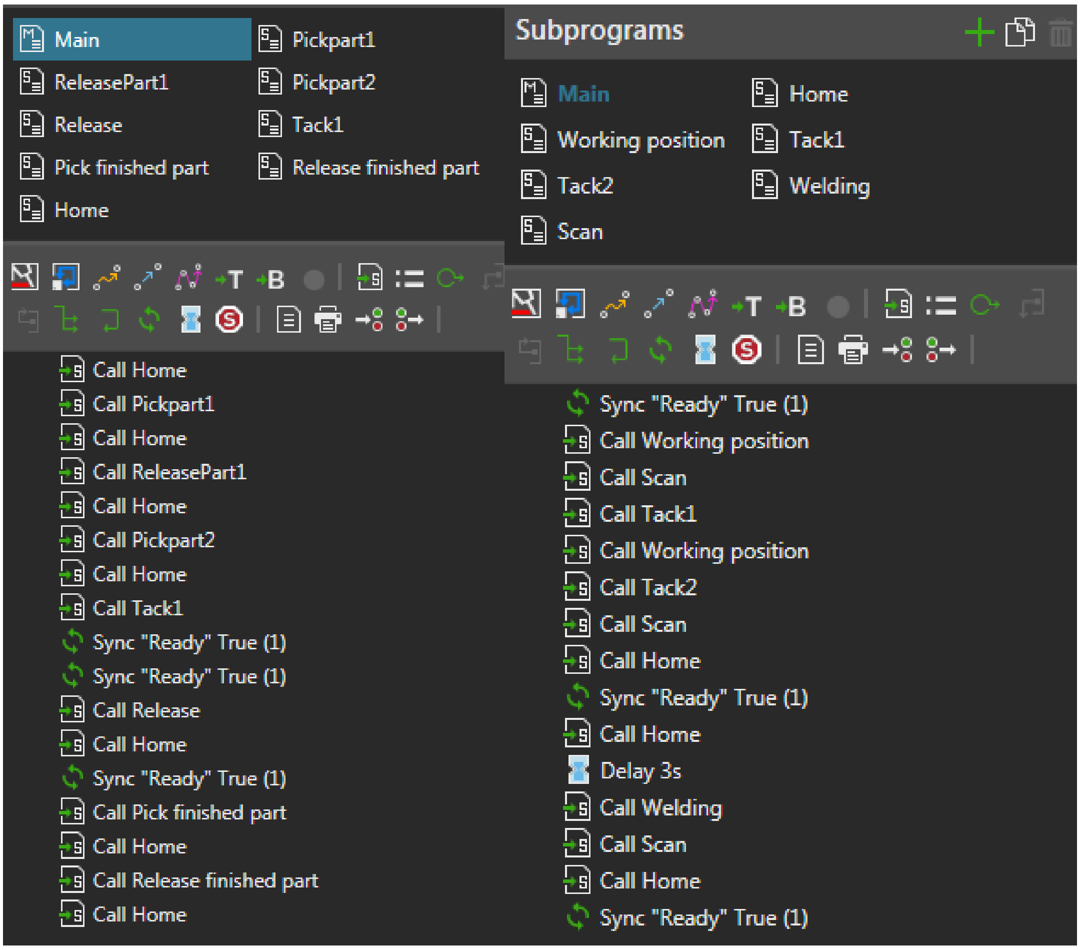


Figure 24. Robot programs for handling robot (left) and for welding robot (right).

8.1.2 Testing of simulation model with I-beam structure workpiece

In the second testing of the multi-robot jigless welding cell model, a simulation of jigless welding of more complex workpiece was made. The phases of simulation are shown in figures 25 and 26 and this time the grasping of part, inspection, some of the tack welds and welding are not presented in figures, because the principle does not change from the first simulation presented above and presenting them would make presenting of the second simulation more unclear. In figure 25 the first part is brought to magnetic positioning system (a) and then the second part is brought on to positioning system (b). Parts are tack welded (c) and then the third part is brought to the positioning system (d).

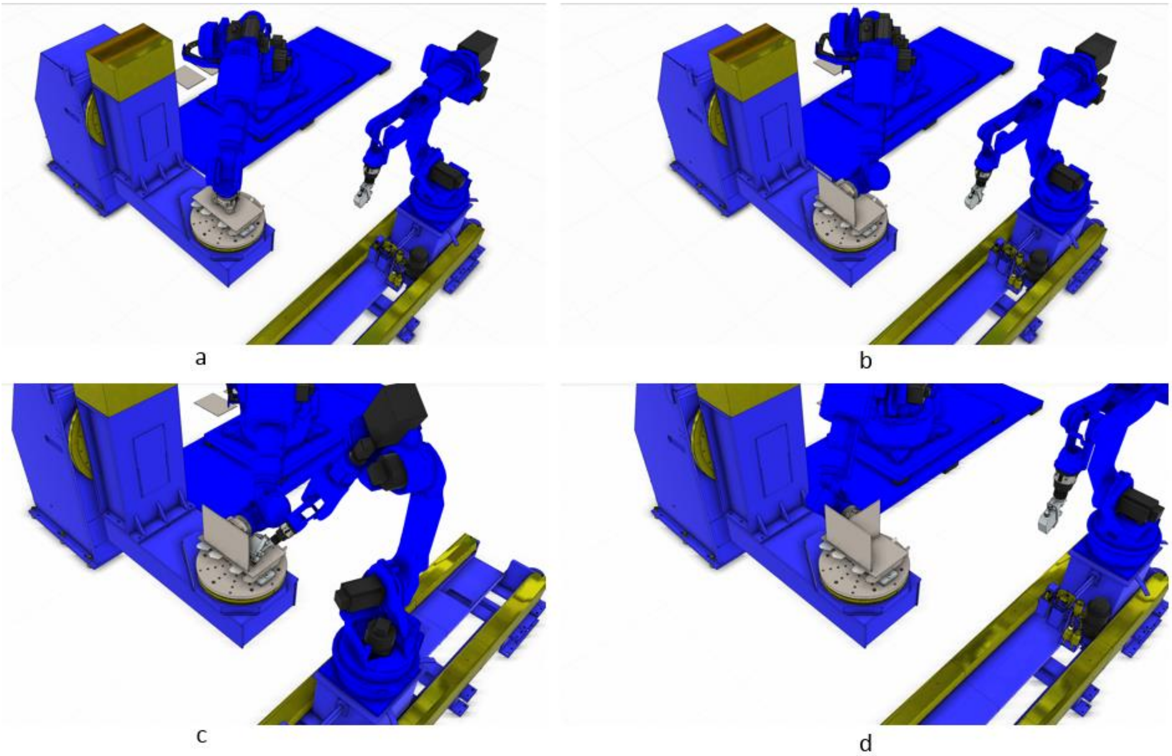


Figure 25. Phases of simulation. A) the first part is brought to positioner, b) the second part is brought to positioner, c) parts are tack welded and d) the third part is brought to positioner.

In figure 26 the third part is tack welded to the existing parts (e) and then the fouth part is brought to the positioning system (f) and tack welded (g). Finally the finished workpiece assembly is taken away from the positioning system.

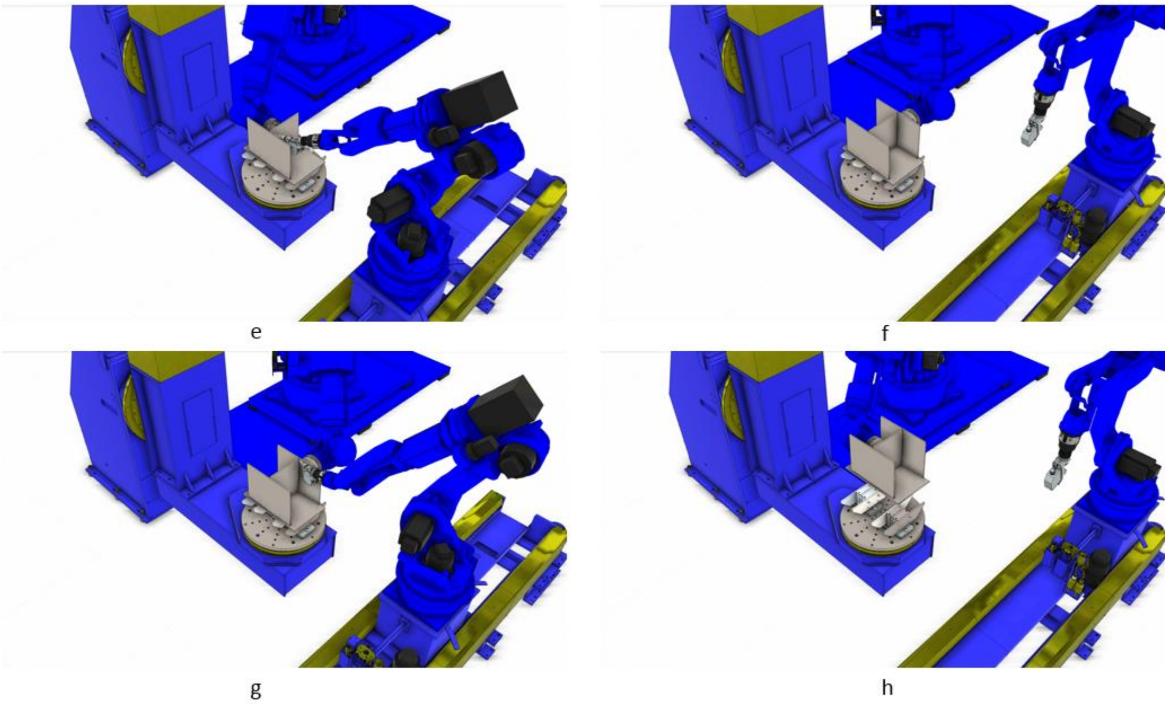


Figure 26. Phases of simulation continues. E) tack welding of the third part, f) the fourth part is brought to the assembly, g) the fourth part is tack welded and h) the finished workpiece is taken away from the positioner.

The created robot program in the second simulation are shown in the figure 27. On the left in figure 27 are the main program structure for the handling robot and on the right is the main program structure for the welding robot. The subprograms are called by the main program. The commands for robot movements and tool input and output statements are given in the subprograms. The robot communication is handled with synchronisation command to prevent robots from performing programs individually.

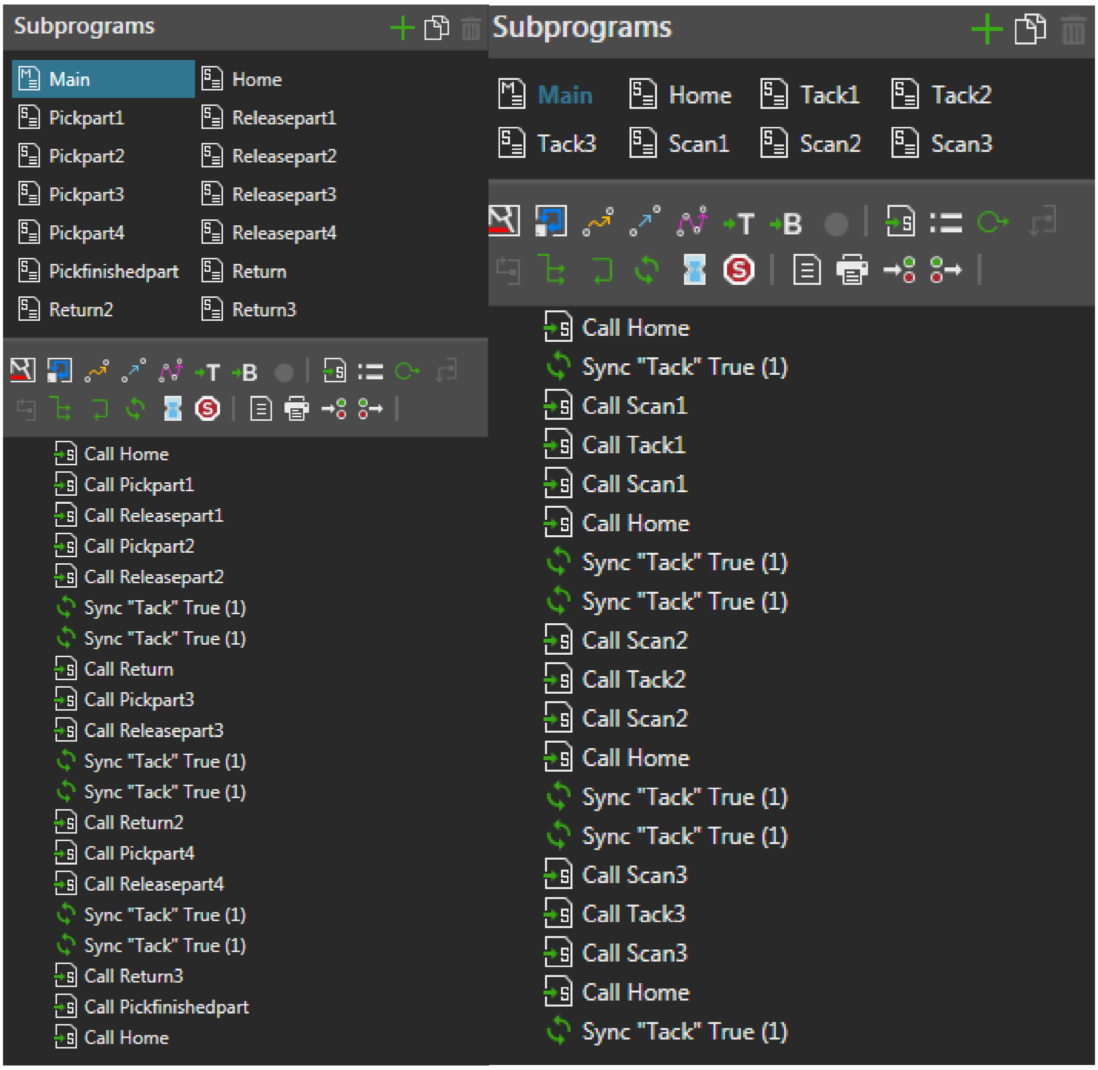


Figure 27. Robot programs for handling robot (left) and for welding robot (right).

8.2 Functioning graph of multi-robot jigless welding cell

Based on the simulation the optimal functioning logic for the multi-robot jigless welding cell was made. It shows each phase of the robot program and it can be seen in figure 28. In figure 28 the start of the program/process is marked on the green, main processes are marked with light blue, decisions are marked with yellow, data importations are marked with orange, sub-processes are marked with blue and the end of program is marked with red.

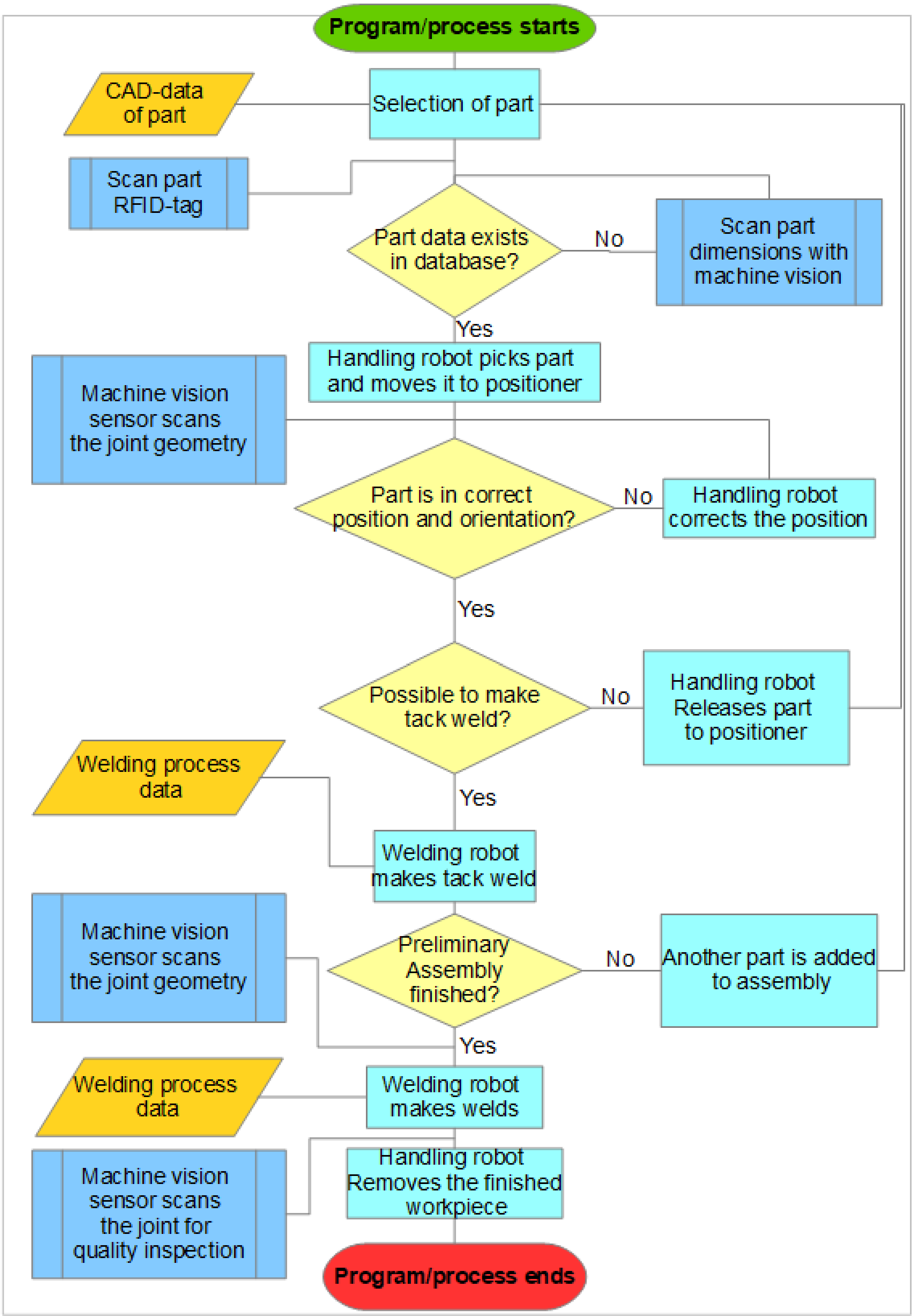


Figure 28. The functioning logic of the multirobot jigless welding cell.

9 DISCUSSION

The following chapter present the comparison of result of this research to the results found in literature review, critical evaluation of the results, key findings and suggestions for future research.

9.1 Discussion about literature and results

As a result of this research came solutions for multi-robot jigless welding and solution to add artificial intelligence to the multi-robot jigless welding cell in form of IoT data accusation methods and machine vision sensing.

9.1.1 Multi-robot jigless welding

Jigless robotic welding seems to be an emerging research area, because search engine Scopus finds only 8 documents with following keywords: “"jigless" OR "fixtureless" OR "jig-less" AND "welding" OR "robotic welding" OR "robot welding"”. When a keyword “assembly” is added to the previous mentioned keywords the Scopus search engine find 64 documents. From the figure 29 it can be seen that jigless welding or jigless assembly has been active research subject in the 90’ century but the trend has been descending until the 2010 when amount of research has started increasing again. (Scopus 2019.)

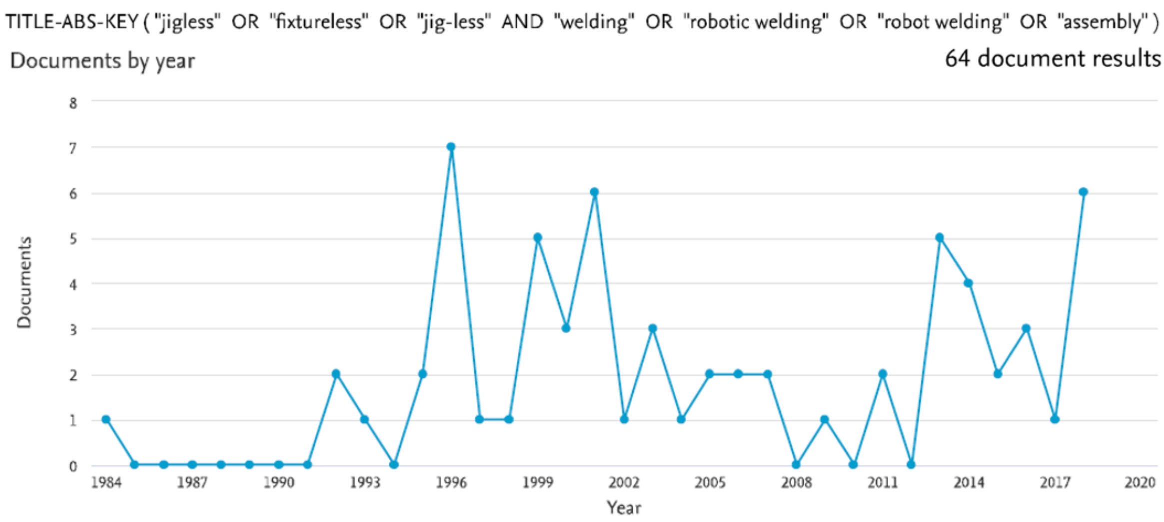


Figure 29. Research trend in jigless welding and jigless assembly (Scopus 2019).

In the literature review it was found that the jigless robot welding has been under a research, but no universal solution has been found for the jigless robotic welding. The solutions found in the literature did not either present how the jigless welding was actually achieved, as in Bejlegaard, Brunoe and Nielsen (2018), or the solution was not fully jigless as in Paquin and Akhloufi (2012). In Ahmad et al. (2016) research the flexible gripper was used to hold automotive parts during spot welding, as the system is suitable for jigless robotic spot welding, but it is not suitable for arc welding at all. In this master's thesis the presented concept of multirobot jigless welding cell is capable for fully assemble and weld workpiece made of plates without requiring any jigs or fixturing.

According to literature review made, fully robotic jigless welding has not been achieved before and this is probably because other researches have failed to develop a system in which the first part of the workpiece assembly is attached without jigs. Paquin and Akhloufi (2012) stated that such a system would be possible with a second part handling robot. Integrating a third industrial robot in the current multi-robot layout, would not be possible as the room space is limited and therefore there is not enough room for another robot, but as a concept third robot could be possible solution for holding the first part of the assembly. Although the third robot would add more uncertainties in the system in form of inaccuracies in position and collision free robot paths. Adding another robot would also be quite capital requiring investment and therefore, amongst the other reason mentioned, a third robot was not considered to be a possible solution in this research. Instead a magnetic positioning system was suggested as a solution for holding the first part of the assembly.

The magnetic positioning system uses pneumatic control to switch the magnets on and off and therefore it can be simply connected to robots I/O (input/output) system to be controlled during the welding process. The magnet itself is extended with extension poles so that a plate can be attached to it without plate being bend by its own weight. During the actual manufacturing of magnetic positioner prototype, a concern of welding causing too much heat to the magnet was taken care of with covering the magnet with heat resisting cloth and rising the magnets pole extensions so that the heat will not cause damage to the magnets. Still another concern of magnets causing magnetic blow during welding exists and further research is required to test if magnetic blow occurs during welding.

The multi-robot welding without using jigs was the main challenge of the research and developed solution was tested in simulation. The solution for jigless welding consists of magnetic positioning system, which is integrated on the positioner, and handling robot integrated with a magnetic gripper for holding the workpiece during tack welding. During assembly the first plate/part of the workpiece is put on to magnetic positioning system, which holds the plate in fixed position, and the rest of the plates/parts of a workpiece are brought on to the first plate or to the assembly and are hold in position by the handling robot during tack welding.

The part handling in the developed multi-robot jigless welding cell was achieved with magnetic gripper. In researches found in literature the part handling was achieved with adaptive gripper and reconfigurable fixture gripper, which resembles adaptive gripper. Magnetic gripper was found to be most suitable option for multirobot welding cell concerned, but in other jigless robot welding cell configurations the adaptive gripper could be a viable solution. Although the load carrying capacity of adaptive gripper is limited, unless an adaptive gripper is designed for heavy load, which then might increase the weight of the adaptive gripper and cause restrictions to workpiece weight as robots have limited load carrying capacity also.

9.1.2 Challenges and solutions of multi-robot jigless welding

A review of challenges observed during the simulation of multirobot jigless welding was made and possible solutions to challenges were given. The challenges of multirobot jigless welding and solution for the challenges are shown in table 11.

Table 11. Challenges of multirobot jigless welding and possible solutions.

Challenges	Solutions
Fixturing plates without using jigs.	Magnetic positioning system which holds the first plate of the assembly and handling robot holds the other plate during tack welding.

Table 11 continues. Challenges of multirobot jigless welding and possible solutions.

Challenges	**Solutions**
Avoiding collisions between robots during tack welding.	Assembly order. Path planning of robots. Planning of handling robots grasping location.
Tight tolerances during positioning the plates perpendicularly to each other or in correct angle between each other.	Machine vision can be used to scan the joint geometry and feedback can be used to correct the position.
Distortions caused by tack welding and welding.	Knowledge from traditional methods or from testing. WPS.

From the welding cell simulation, it was noticed that the most critical phase, during the jigless welding of the workpiece, is when two plates of the workpiece needs to be tack welded, see figure 22 f) above. As then both robots work close to each other, because the second plate of the workpiece is held perpendicularly against the surface of the first plate of the workpiece by the handling robot and the welding robot needs to make the tack welding. Solutions to avoid collisions between robots are i) planning in which order the workpiece is assembled, ii) planning of robot paths so that collisions are avoided and iii) planning of handling robots grasping location. Another critical challenge during tack welding and welding is getting the plates perpendicularly to each other, as even though the handling robot can locate plates in correct position and machine vision sensor can be used to assure the position is correct, the tack welds and welds may cause distortions. Therefore, the solution is to position the plates in position which eliminates the unwanted distortions caused by welding. The correct position can be estimated from previous knowledge of traditional welding/robot welding method or from preliminary testing. In either situation the angle between plates should be mentioned in WPS. This also means that the tolerances for positioning and for workpieces are very tight, and therefore the joint geometry and the dimensions of the workpiece should be scanned with machine vision. From the scanned data feedback to the robot controller could be provides so the controller can make adjustments to the robot position according to the data.

9.1.3 IoT and machine vision

In the literature review it was found that in the other researches the IoT technologies have been implemented to the robotic welding stations. Mainly the existing IoT systems are used to data analyzing and quality inspection as in French, Benakis and Martin-Reyes (2017). The results in literature review are similar to the IoT system implemented to the current multirobot jigless welding cell. The cyber components of IoT system are currently capable to collect welding data, present welding production data, analyze welding data and keep on track with WPS with the implementation of Weldeye software. The physical component in IoT system in which the data is currently collected is the welding power source. The IoT welding systems found in the literature were also capable to collect and analyze welding data, but the systems were implemented with the machine vision sensors.

The main uses of machine vision according to literature review were in quality inspection, seam tracking, pose estimation and robot path correction. The machine vision was not applied in practice in the current multi-robot jigless welding cell, because the existing sensor had software only for seam tracking and therefore a development of software which is capable to estimate workpiece position and send corrective coordinates to robot controller would have been required. Therefore, the integration of machine vision sensor was scoped out for future research. Instead a connection for the machine vision sensor was included in development of multirobot jigless welding cell and the use of machine vision was taken into account when the functioning logic for the robot welding cell was made.

9.2 Preliminary testing of multi-robot jigless welding cell

To test the basic functioning of the multirobot jigless welding cell, a test specimen was made. The specimen was made out of 5 mm thick S355 steel plates and it can be seen in figure 30. At first the robot program for positioning the steel plates was made and then a robot program for tack welding each plate was added to the original program. The test results were as follows: no collisions with either robot, tack welding was successful, tack welding did not cause heat damage to neither magnetic positioning system nor magnetic gripper and the distortions were minimal. The test did not include machine vision or IOT systems as the experiment was for testing and verification of the principles of multi-robot jigless welding cell in practice.

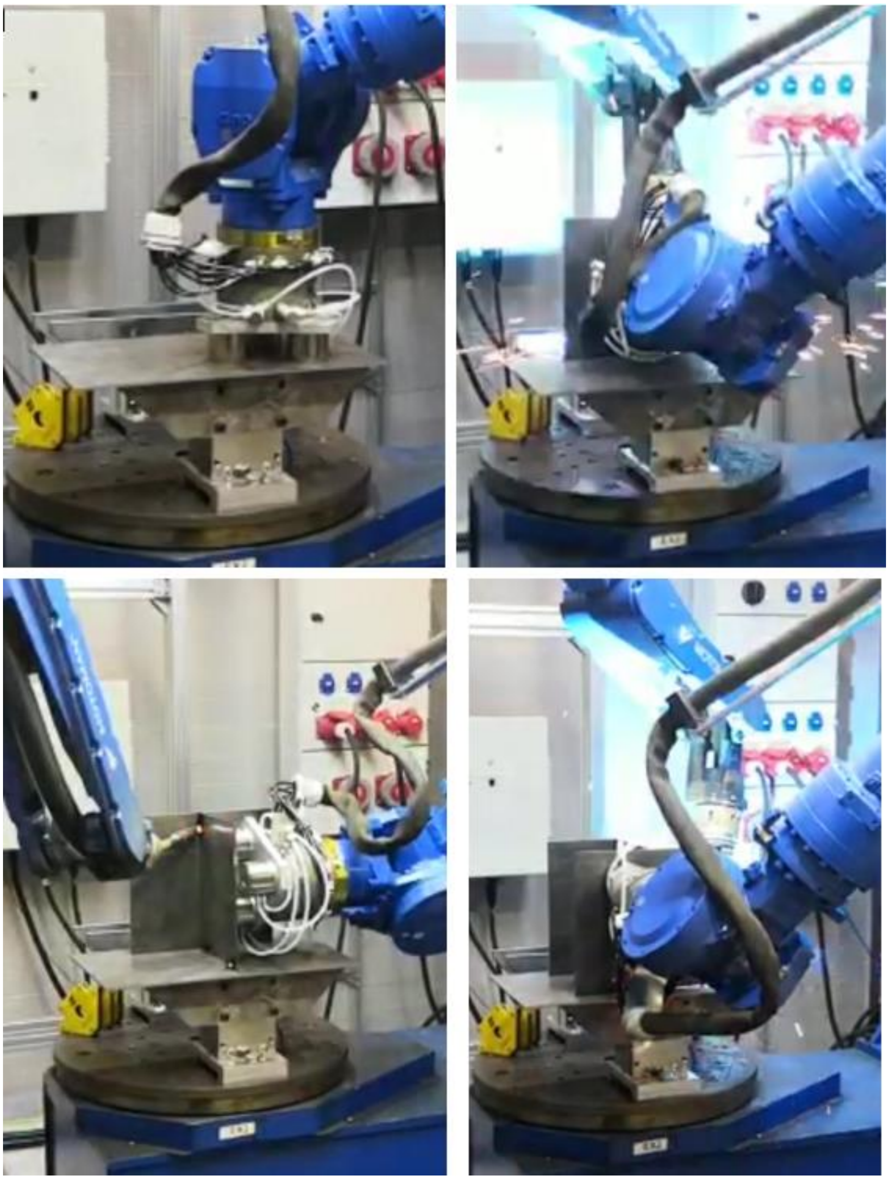


Figure 30. Preliminary testing of multi-robot jigless welding cell concept.

9.3 Critical review of the research

The validity of systematic design processes results was evaluated in the value analysis in chapter 7.3. In value analysis the different functions of the technical solutions were given highlighting points according to functions importance. The next step was to give a grade to each technical solutions function, according to how well the function performs its function. The grade and highlighting point were multiplied to get the highlighted grade, which was divided by the estimated proportional costs and then the values of technical solutions are known.

The requirements list for the multirobot jigless welding cell is a tool to find the relevant design objectives. Therefore, the requirements list provided in this research may include some aspects which were not implemented during this research. The requirements list made is built for specific application and therefore it may not be fully applicable directly to other multi-robot jigless welding cell development projects, but it can be used as a basis when developing a multi-robot jigless welding cell.

In morphological classification different options to perform the wanted functions of the multi-robot jigless welding cell were sketched and the value analysis was applied to evaluate the options. The results of value analysis are highly subjective, because it shows what are the best options for the current multi-robot jigless welding cell and also the highlighting of different options and proportional cost estimation rely heavily on the designer’s own expertise. Therefore, the results are valid and applicable only if similar multirobot cell with similar requirements is under a development. Still the results of value analysis can be used as a guideline when developing jigless welding cell with multiple robots.

In this research the found technical results for jigless welding were the magnetic positioning system and holding of workpiece with magnetic gripper during tack welding. Similar system was not found in literature, although similar attempts with adaptive gripper was found in literature Paquin and Akhloufi (2012). The concept of functioning logic made for the multi-robot jigless welding cell resembles the functioning logics found for IoT welding systems in the literature review such as in French, Benakis and Martin-Reyes (2017) research. The challenges and solutions of jigless welding found during the simulation of multirobot jigless welding cell have similarities with the challenges that Bejlegaard, Brunoe and Nielsen (2018) research found. The solutions for the challenges found in the research had also similarities with Bejlegaard, Brunoe and Nielsen (2018) research.

The result of this research can see direct application in robotic welding production, where the use of jigs can now be eliminated during tack welding and during welding. Although some limitations in part geometry and part materials exist. The multi-robot jigless welding principle is currently applicable to structural steel or other magnetic material plates, but using different magnets in the magnetic gripper also parts with round geometries could be handled. For non-magnetic materials different type of gripper would be required, such as mechanical or adaptive gripper. The non-magnetic materials would also require development of another type part positioning solution.

The results of this research are also applicable with other welding processes which are used with robots such as TIG (tungsten inert gas) or laser welding. Other applications where the results can be indirectly applied are in other robotic assembly fields such as mechanical joining with fasteners. The welding robots' tool could be replaced with a riveting tool for example.

The benefits of the research can be seen as that now multi-robot jigless welding it is possible to eliminate the time consuming and expensive use of jigs during tack welding and welding, which can have decreases in production time, increases in efficiency of welding production and decreases in manufacturing costs. The results of this research take a step towards to full automatization of welding production as the functioning logic presented in the results show how IoT technology could be used alongside with multi-robot jigless welding cell to create welding cell with some artificial intelligence.

9.4 Sensitivity analysis

In this research triangulation of research methods was applied to analyse the results. The results of literature and systematic design process were analysed with the following question: "What are the technological solutions to substitute the use of jigs in robotic welding?" Therefore, suitable options for jigless welding were searched from literature and systematic design were used to make the found options suitable for the multi-robot jigless welding cell. The specific technical solutions found for jigless welding were the magnetic positioning system and magnetic robot gripper. The results of systematic design process and simulation were analyzed with the following question: "What are the requirements and guidelines for successful multi-robot jigless welding?" The designed components were tested in the simulation and based on the results it could be verified that magnetic gripper and magnetic positioning system makes the multi-robot welding cell suitable for jigless welding and no further development is required. The results of literature review and simulation were analyzed with the following question: "Why have not the functional multirobot jigless welding cells already been developed and what are the reasons for the non-existence?" The main reason found was that the existing researches have not managed to develop a system where the first part of the assembly could be attached without using jigs. As the problem for attaching the first part of the assembly was solved with magnetic positioning system it was clear that no further data collection was required.

9.5 Conclusions

In this master's thesis a concept model for an intelligent IoT multirobot jigless welding cell was developed. Systematic design process was applied to find the technical solutions, which makes possible the multirobot welding cell to be suitable for jigless welding. The welding cell was made jigless with the following technical solutions:

- Magnetic robot gripper for ferrous materials
- Magnetic workpiece positioning system for holding the parts stationary during tack welding

Additionally, the results of systematic design process indicate that the welding data collection with IoT welding management software could be provided with the Weldeye software and the most suitable machine vision sensor for the multirobot jigless welding cell would be the sensor that uses laser triangulation for scanning of the joint geometry.

As a results of multi-robot jigless welding cell simulation it was noticed that the critical thing is to avoid collisions between robots especially during tack welding. The collisions can be avoided with planning of assembly order, planning of robot paths and planning of workpiece grasping location of the handling robot. Another critical point noticed during simulation was that the positioning of the plates and the plates itself require tight tolerances. The machine vision can be used as a solution for more precise positioning. Still the tack welding and welding may cause distortions, which may cause more challenges for jigless welding. The effect of distortions can be minimized, if the amount of distortions are tested before welding and instructions for correct position and welding parameters are given in the WPS.

Another result of the simulation was the functioning logic for the multi-robot jigless cell, where the concept how IoT technology can be utilized during the jigless welding process was presented. The IoT technology can be used for data collection and for data analysis during the welding process.

The reason for why robotic welding without using jigs have not been successfully managed to perform has been the reason, that previous attempts has not been able to develop a system which holds the first part of the assembly in place during tack welding. In this research such a system is realised with magnetic positioning system.

9.6 Generalization and utilization of results

As a result of this research came a simulation model of jigless multirobot welding cell, prototype of jigless multirobot welding cell, with components: magnetic gripper for universal gripping, machine vision sensor and adapter, and positioning magnets. Another practical application of the results of this research was a solution method for jigless multirobot welding. Meaning of assembly sequence where handling robot brings workpieces to the positioner and, if needed, holds the workpiece while welding robot makes tack welds. Additionally, the machine vision sensor can be used for measuring the parts dimensions and joint geometry before the positioning/tack welding/welding is done and corrections to robot path and position can be done according the data acquired.

The results of this research are directly applicable to the robotic welding production where the multirobot jigless welding cell could eliminate the time required for product changes. During tack welding, the time spent on fixturing takes a large proportion of the production time and every moment spent on something else than welding is considered to be unproductive and does not add any value to the product. The multi-robot jigless welding eliminates the time spent on fixturing, therefore increasing the productivity of robotic welding remarkably. The multi-robot jigless welding cell concept could be also applied to other welding processes used in robotic welding, such as TIG welding and laser welding.

The concept of multirobot jigless welding can be extended to other manufacturing methods as well and therefore other scientific fields also. An example could be in robotic assembly where mechanical joining of assemblies could be done without jigs. The concept works in other manufacturing industries the way that the welding robot is replaced with some other manufacturing robot, such as assembly robot which is equipped with a riveting tool for example.

This research aimed to answer three research questions. The first question were why have not the functional multirobot jigless welding cells already been developed and what are the reasons for the non-existence and the answer is simply that previously other researches have not been able to develop a system which holds the first part of the assembly in place. The second question was what the requirements and guidelines for successful multi-robot jigless welding are. The answer is that system for positioning the parts is required and successful jigless welding can be achieved when the already assembled parts of the assembly are held by the positioning system and new parts of the assembly are held by the handling robot during tack welding. The last research question was what the technological solutions to substitute the use of jigs in robotic welding are. The technological solutions to substitute jigs were the magnetic positioning system and magnetic robot gripper.

9.7 Future research topics

By the basis of this master's thesis the following research subjects are suggested for future research.

- Research of increasing the accuracy between simulated robot path and actual robot path to reduce the time spent in the beginning of robot welding production.
- Developing a IoT multi-robot jigless welding cell with artificial intelligence. The cell identifies the product being manufactured and chooses the welding parameters and robot programs according to the pre-made welding simulation program.
- Developing a virtual reality/augmented reality simulation model of multi-robot jigless welding cell.
- Research about what is the optimal welding sequence, in order to avoid distortions caused by the heat input and to achieve high quality welds. The research would provide information on how to minimize the effect of distortion and how to take advantage of the welding distortions.
- The multi-robot jigless welding cell performance versus traditional robot welding cell performance. The research would provide quantitative information on how much the productivity of robot welding can be increased with jigless welding.
- Research where other gripper types are used in multi-robot jigless welding cell, for example adaptive gripper and mechanical grippers. Research could provide information on what are the most suitable grippers for different shaped parts.

10 SUMMARY

Technological development in industrial robotics has reduced the costs of sensor technology, created new IoT data collecting, monitoring and analyzing systems and changed the way how robot programs can be made in simulated environment. One of the main problems in robotic welding has been the fixturing of parts with jigs before tack welding. The fixturing of parts takes a lot of time, which always causes stopping of the production during product changes. Therefore, fixturing and using jigs is one of the major excessive costs in robotic welding production. In addition, when new products are being produced, it is usually required that specifically made jigs are manufactured, which are also expensive to make. This problem has been under a research for two decades, but only some concept models of jigless welding cells have been made. Recent technological developments have showed that the above-mentioned problem could be solved by developing a multi-robot welding cell where the use of jigs have been fully eliminated. In this research the research questions focus on what are the technological solutions to substitute the use of jigs in robotic welding, what are the requirements and guidelines for successful multi-robot jigless welding and why have not the functional multirobot jigless welding cells already been developed and what are the reasons for the non-existence.

In this research a triangulation of research methods was applied in order to answer the research questions. Two qualitative research methods were applied, which are literature review and systematic design process, which are used to analyze what are the technological solutions to develop multi-robot jigless welding cell. The systematic design process was applied according to VDI 2221 and value analysis was applied to analyze the most suitable solutions for the multi-robot jigless welding cell. In addition, the third research method used was a simulation model of the multi-robot jigless welding cell. The simulation model and the systematic design process was used to analyze the requirements of multi-robot jigless welding. Literature review and simulation were used to analyze why similar multi-robot jigless welding cell have not been developed earlier.

The research provides a new scientific information in a form of technological solutions suitable for multi-robot jigless welding cell. The technological solution, which makes multi-robot jigless welding possible are the magnetic positioning system and magnetic gripper. The multirobot-jigless welding cell functions in the following way: the first part of assembly is brought with robot to the magnetic positioning system, which holds the first part in place, and the other parts of assembly are held in place perpendicularly against the first plate during tack welding with handling robot, which is equipped with a magnetic gripper. Challenges found for jigless welding were the avoiding of collision during tack welding, tight tolerances of positioning the workpiece and distortions caused by tack welding and welding. Possible solutions for the challenges were path planning of robots so that collisions are avoided and use of machine vision for confirming that the plates are in correct position. Distortions can be taken into account if there exist previous knowledge or by testing of how much distortions welding causes and making a WPS where the information is given.

The results of this research can be directly applied to the robotic welding production of plate-structures, as the multi-robot jigless welding cell can eliminate time required during product changes. The time spent on attaching the jigs during tack welding process does not add any value to the product itself and therefore multi-robot jigless welding increase productivity remarkably. The principle of jigless welding can be applied to other robotic welding processes, such as laser welding and TIG welding. A further research is required in increasing the accuracy between simulated robot path and actual robot path, so that production costs can be decreased further, because the time spent on testing the robot paths could be reduced.

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Method	Comments and relative advantages
Image pre-processing	
Median filtering	This method is used by most researches, because it can keep the detail information such as edge pieces and sharp angles of seam. Also, it is the most effective in filtering typical welding image noise (predominantly salt-and pepper noise).
Gaussian filtering	Although among the most common and fundamental noise filters used in industrial applications, very few authors used this method. This is because it is not suitable for filtering laser images, as it can suppress the high frequency component in the laser line image resulting in loss of useful positional information.
Multiple frame processing	This method is mostly useful as an intermediary pre-processing step that can be followed by an additional filtering step. This is because it does not consider the spatial relationships of the local texture in the image that defines the laser pattern but rather considers the relative temporal texture information of multiple images.
Colour processing	Although this method is ignored by most researches, this could be a potential pre-processing step to localise the laser pattern region in the image as it filters all colours except the characteristic red colour. However, this method may be somehow redundant when a narrow band optical filter is installed on the camera. This is because they are both useful in producing segmented red coloured image.
Thresholding	This method may be effective when a suitable setup of optical devices is used that produces an image with an enhanced laser pattern. Such that, the laser pattern will have a relatively higher intensity that can be easily thresholded. However, optical devices are usually very expensive and very difficult to adjust to perfection.
Extraction of laser stripe pattern	
Line detection	This method is useful in detecting 2D laser pattern with multiple lines in an image. It can be recommended for a fillet welding seam joint because the deformations of fillet joint usually are made of crossing lines. However, this method is computationally expensive and can easily fail when the structural lines have multiple discontinuities. It can also falsely detect longitudinally shaped coherent noise due to arc light spatter in an image as a line.
Pixel maximum intensity	This is the most widely used laser stripe extraction method due to its simplicity and effectiveness. It is effective because it exploits the obvious characteristic of a laser stripe image which is high-intensity values (higher brightness). When combined with some custom pixel operations that employ pixel spatial and temporal relationships, it can produce a promising result.

Sub-pixel maximum intensity	This is suitable for systems that need higher measurement accuracy. It provides an additional layer of processing and accuracy over the pixel maximum intensity method. However, with a very high-resolution cameras or wider welding seams, this method may give results that are almost similar to traditional pixel maximum intensity. This is because the laser pattern contains lesser position information.
Global thresholding	As with any thresholding technique, this method lacks universality and strongly depends on the quality and nature of the image under processing. In all the researches that fall in this category, the thresholding is performed with a value that is systematically computed. Although it was successful to some few researches, the distinct characteristics of the thresholding prevent this approach from being the commonly accepted practice in the segmentation of laser stripe in active vision systems.
Pixel projections	This method is similar to pixel intensity approach as both detect pixels with higher brightness. The method could be more accurate due its additional edge detection step after the maximum pixel selection. However, the nature of the laser stripe uniform intensity distribution makes operations like edge detection unnecessary.
Statistical model	With this method, the laser is extracted based on the notion that the laser can be modelled as series of states in space that can be analysed statistically. This method could be robust to noises that appear at an unusual location outside the laser region. However, it strongly relies on the state modelling step. As proposed by some of the authors, the states can be generated from the image pixel edges. Edge detection sometimes can produce broken edges which may lead to many false states that may affect the result of the final extracted laser.
Welding joint feature extraction and profiling pattern	
Turning angle computation	The turning angle is one of the unique characteristics that identify the feature points due to their strategic location along the laser stripe. Hence, this method can be effective in detecting the feature points. However, it is too localised, as it considers only two neighbours around a profile point. This algorithm performance can be affected when there are locally organised noisy points in the laser stripe. The performance may be improved if the turning angles for group of pixel neighbours are also considered.
Image derivative	This method shows a more appealing approach of detecting the feature points. This is because the extracted profile is treated as one-dimensional signal that can be analysed with some 1-D signal processing techniques such as the image derivatives with the feature points treated as noise. This method presents the possibilities of using some other similar 1-D signal processing techniques that could be much more effective in detecting the feature points.

Rule base	This is one of the oldest and relatively robust approaches for the feature point extraction. It is effective because it employs prior knowledge in determining the location of the feature points. It also considers both the local and global information of points before extracting the feature points. However, it is computationally expensive and strongly depends on the set of rules provided to it. The generation of the rules is also a challenging task as the rules are manually generated. It is not flexible to implement because any new noise challenge must be addressed by the rules. This method could be made flexible and much more effective when incorporated with some artificial intelligence algorithms such as artificial neural network and support vector machines that can automatically identify the rules.
Corner point detection	This approach is closely similar to the turning point approach, as they both involve searching for the corner points. However, unlike in the turning point approach, the turning angle is not considered; rather general corner detection algorithms are used. This approach could be better than turning point because it does not involve primitive thresholding of turning angle to filter out points. However, as with the turning angle approach, this method is highly localised and can lead to noisy corners that may be due to the stripe profile orientation especially in wider laser stripe.
Custom pixel-to-pixel operation	This method is too sensitive to noise due to the pixel-to-pixel operation. It also lacks universality as the pixel local distribution might vary across different laser stripe profiles. This method could be much more effective when incorporated with any of the other methods discussed previously.

Table 1a. Highlighting sub-functions for grasp workpiece function

Grasp workpiece	**CL**	**GW**	**AI**	**SP**	**Highlight Points**
CL	CL	GW	AI	SP	1
GW	GW	GW	GW	GW	7
AI	AI	GW	AI	SP	3
SP	SP	GW	SP	SP	5
Total					16

Table 1b. Highlighting sub-functions for position workpiece function

Position workpiece	**CL**	**HW**	**AW**	**EO**	**Highlight Points**
CL	CL	HW	CL	EO	3
HW	HW	HW	HW	HW	7
AW	CL	HW	AW	EO	1
EO	EO	HW	EO	EO	5
Total					16

Table 1c. Highlighting sub-functions for machine vision sensing function

Machine vision sensing	**DD**	**MP**	**SU**	**PQ**	**Highlight Points**
DD	DD	MP	DD	PQ	3
MP	MP	MP	MP	MP	7
SU	DD	MP	SU	PQ	1
PQ	PQ	MP	PQ	PQ	5
Total					16

Table 1d. Highlighting sub-functions for machine vision sensor function

Machine vision sensor location	**IM**	**DV**	**R**	**AC**	**Highlight Points**
IM	IM	IM	R	AC	3
DV	IM	DV	R	AC	1
R	R	R	R	AC	5
AC	AC	AC	AC	AC	7
Total					16

Table 1e. Highlighting sub-functions for welding data collection function

Welding data collection	**CW**	**CM**	**WR**	**TQ**	**Highlight Points**
CW	CW	CW	CW	CW	7
CM	CW	CM	WR	CM	3
WR	CW	WR	WR	WR	5
TQ	CW	CM	WR	TQ	1
Total					16

Table 2. Results of highlighting sub-functions.

Grasp workpiece	**CL**	**GW**	**AI**	**SP**
Highlight points	1	7	3	5
Position workpiece	**CL**	**HW**	**AW**	**EO**
Highlight points	3	7	1	5
Machine vision sensing	**DD**	**MP**	**SU**	**PQ**
Highlight points	3	7	1	5
Machine vision sensor location	**IM**	**DV**	**R**	**AC**
Highlight points	3	1	5	7
Welding data collection	**CW**	**CM**	**WR**	**TQ**
Highlight points	7	3	5	1

Table 3. Grading for each option that performs the sub-function.

Grasp workpiece	Option a	Option b	Option c	Option d
Carry load	3	1	4	2
Grasp/hold/release workpiece	3	2	3	3
Avoids interferences	1	3	4	2
Suitable to plates	3	4	4	2
Position workpiece				
Carry load	2	4	3	2
Hold workpiece	1	4	3	2
Allows rotation	1	4	4	2
Easy to operate	2	3	1	1
Machine vision sensing				
Detection distance	4	2	1	2
Measure position	2	4	1	1
Simple to use	2	4	1	1
Processes quickly	3	4	1	1
Machine vision sensor location				
Is movable	4	3	3	1
Does not vibrate	3	2	3	4
Reachability	3	2	1	1
Avoids collision	3	3	4	4
Welding data collection				
Collects welding data	4	3	3	3
Connects to multiple welding power sources	4	1	1	1
Works in real-time	4	4	4	4
Tracks quality	4	4	4	4

Table 4. Highlighted grades.

Grasp workpiece	Option a	Option b	Option c	Option d
Carry load	3	1	4	2
Grasp/hold/release workpiece	21	14	21	21
Avoids interferences	3	9	12	6
Suitable to plates	15	20	20	10
Total	42	44	57	39
Position workpiece				
Carry load	6	12	9	6
Hold workpiece	7	28	21	14
Allows rotation	1	4	4	2
Easy to operate	10	15	5	5
Total	24	59	39	27
Machine vision sensing				
Detection distance	12	6	3	6
Measure position	14	28	7	7
Simple to use	2	4	1	1
Processes quickly	15	20	5	5
Total	48	58	16	19
Machine vision sensor location				
Is movable	12	9	9	3
Does not vibrate	3	2	3	4
Reachability	15	10	5	5
Avoids collision	21	21	28	28
Total	51	42	45	40
Welding data collection				
Collects welding data	28	21	21	21
Connects to multiple welding power sources	12	3	3	3
Works in real-time	20	20	20	20
Tracks quality	4	4	4	4
Total	64	48	48	48

Table 5. Estimated proportional costs

Estimated proportional costs	Option a	Option b	Option c	Option d
Grasp workpiece	100	75	75	250
Position workpiece	100	125	100	200
Machine vision sensing	100	50	200	50
Machine vision sensor location	100	125	125	150
Welding data collection	100	100	100	100

Quality requirements for the welds

The standard SFS-EN ISO 5817 sets guidelines for the assessment of weld imperfections. SFS-EN ISO-5817 categorizes weld imperfections into three quality levels B, C and D. The weld imperfections are categorized into four different type of imperfections i) surface imperfections, ii) internal imperfections iii) imperfections in joint geometry and iv) multiple imperfections. (SFS-EN ISO 5817 2014, p. 20–47.) In case of jigless robotic welding the point of interest is in geometrical imperfections, because they set the limits for the accuracy in locating the parts. By selecting the wanted quality level for the welds in robotic welding it is possible to determine the requirements for accuracy. The table 1 presents the limitations for joint geometry as stated in the standard. From the table 1 it is possible to see the limits for imperfections for linear misalignment of plates and size of root gap in fillet welds. (SFS-EN ISO 5817 2014. p 43.)

Table 1. Imperfections in joint geometry (modified from: SFS-EN ISO 5817 2014, p. 20–47).

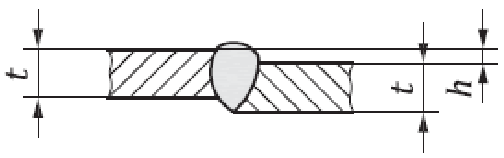
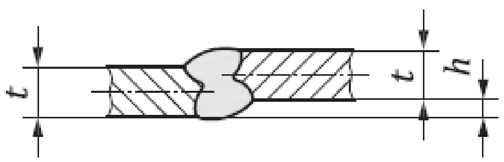
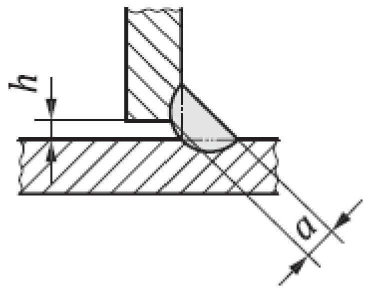
Imperfections in joint geometry	
Reference to ISO 6520-1, imperfection designation and remarks	**Limits for imperfections for quality levels**
507, Linear misalignment	
5071, Linear misalignment between plates   Plates and longitudinal welds	**0,5 ≤ t ≤ 3** **D**: $h \leq 0{,}2$ mm + $0{,}25t$ **C**: $h \leq 0{,}2$ mm + $0{,}15t$ **B**: $h \leq 0{,}2$ mm + $0{,}1t$ **> 3** **D:** $h \leq 0{,}25t$, but max. 5 mm **C:** $h \leq 0{,}15t$, but max. 4 mm **B:** $h \leq 0{,}1t$, but max. 3 mm

Table 1 continues. Imperfections in joint geometry (modified from: SFS-EN ISO 5817 2014, p. 20–47).

617, Incorrect root gap for fillet welds  Gap between the parts to be joined. Gaps exceeding the appropriate limit may, in certain cases, be compensated for by a corresponding increase in the throat thickness.	**$0{,}5 \leq t \leq 3$** **D:** h ≤ 0,5 mm + 0,1*a* **C:** h ≤ 0,3 mm + 0,1*a* **B:** h ≤ 0,2 mm + 0,1*a* **> 3** **D:** h ≤ 1 mm + 0,3*a*, but max. 4 mm **C:** h ≤ 0,5 mm + 0,2*a*, but max. 3 mm **B:** h ≤ 0,5 mm + 0,1*a*, but max. 2 mm

Dimensional accuracy

The tolerances for welded structures are given in the standards SFS-EN ISO1090-2 and SFS-EN ISO 13920. The standard SFS-EN ISO1090-2 defines geometrical tolerances into two groups' functional and essential tolerances. Essential tolerances include criteria for mechanical resistance and stability of the welded structure and functional tolerances include other criteria's that are required, such as fit-up and appearance. (SFS-EN ISO1090-2 2018 p. 78.) The standard SFS-EN ISO 13920 defines the basic tolerances for welded structures in terms of linear dimensions, angular dimensions, straightness, flatness and parallelism (SFS-EN ISO 13920 1996 p. 5–7). The most relevant geometrical tolerances regarding to jigless robot welding are shown in table 2. (SFS-EN ISO1090-2 2018, p. 111–123).

Table 2. Geometrical tolerances according to SFS-EN ISO1090-2 (modified from: SFS-EN ISO1090-2 2018, p. 111–123).

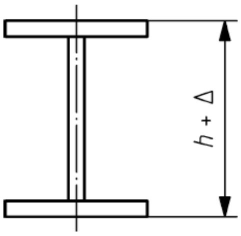
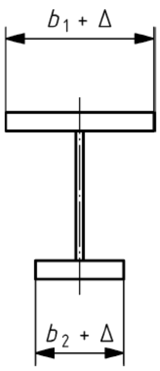
Criterion	Parameter	Essential tolerances Permitted deviation Δ	Functional tolerances Permitted deviation Δ	
		Class 1 and 2	Class 1	Class 2
Depth: 	Overall depth *h*: $h \leq 900$ mm $900 < h \leq 1800$ mm $h > 1800$ mm	-Δ = h/ 50 (note negative sign)	Δ = ± 3 mm Δ = ± *h* / 300 Δ = ± 6 mm	Δ = ± 2 mm Δ = ± *h* / 450 Δ = ± 4 mm
Flange width: 	Width $b = b_1$ or b_2:	-Δ = *b* /100	+ Δ = *b* /100 but |Δ| ≥ 3 mm	+ Δ = *b* /100 but |Δ| ≥ 2 mm

Table 2 contiues. Geometrical tolerances according to SFS-EN ISO1090-2 (modified from: SFS-EN ISO1090-2 2018, p. 111–123).

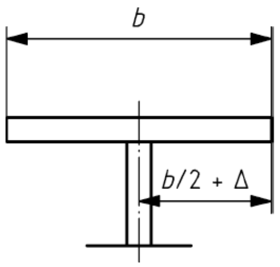
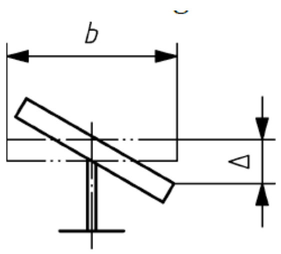
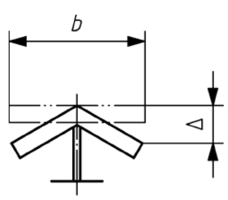
Criterion	Parameter	Essential tolerances Permitted deviation Δ	Functional tolerances Permitted deviation Δ	
		Class 1 and 2	Class 1	Class 2
Web eccentricity:  	Position of web: -general case -flange parts in contact with structural bearings:	No requirement	Δ = ± 5 mm Δ = ± 3 mm	Δ = ± 4 mm Δ = ± 2 mm
Squareness of flanges:  	Out of squareness: -general case -flange parts in contact with structural bearings:	No requirement	Δ = ± *b* /100 but |Δ| ≥ 5 mm Δ = ± *b* /400	Δ = ± *b* /100 but |Δ| ≥ 3 mm Δ = ± *b* /400
Flatness of flanges:  	Out of flatness: -general case -flange parts in contact with structural bearings:	No requirement	Δ = ± *b* /150 but |Δ| ≥ 3 mm Δ = ± *b* /400	Δ = ± *b* /150 but |Δ| ≥ 2 mm Δ = ± *b* /400

Table 2 contiues. Geometrical tolerances according to SFS-EN ISO1090-2 (modified from: SFS-EN ISO1090-2 2018, p. 111–123).

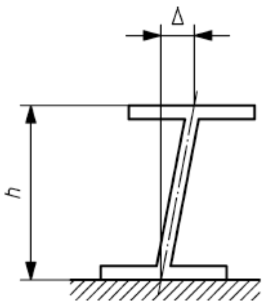
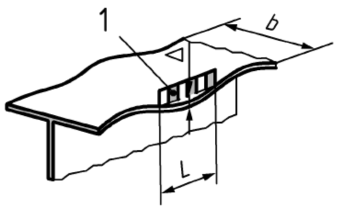
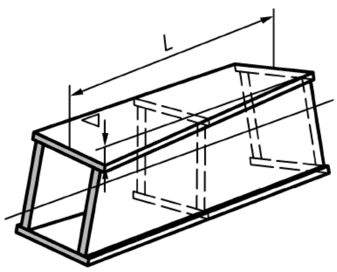
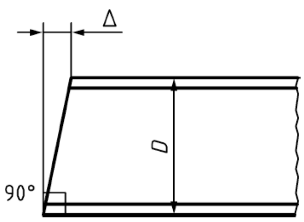
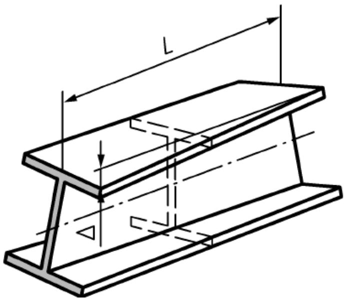
Squareness at bearings: 	Verticality of web at supports, for components without bearing stiffeners:	$\Delta = \pm h/200$ but $\|\Delta\| \geq t_w$ (t_w = web thickness)	$\Delta = \pm h/300$ but $\|\Delta\| \geq 3$ mm	$\Delta = \pm h/500$ but $\|\Delta\| \geq 2$ mm
Flange undulation of I section:  Key 1 gauge length	Deviation Δ on gauge length *L* where *L* = flange width *b:*	$\Delta = \pm b/150$ if $b/t \leq 20$ $\Delta = \pm b2/(3000\ t)$ if $b/t > 20$ t = flange thickness	$\Delta = \pm b/100$	$\Delta = \pm b/150$
Twist: 	Overall deviation Δ in a piece of length *L:*	No requirement	$\Delta = \pm L/700$ but $\|\Delta\| \geq 4$ mm and $\|\Delta\| \leq 10$ mm	$\Delta = \pm L/1000$ but $\|\Delta\| \geq 3$ mm and $\|\Delta\| \leq 8$ mm
Squareness of ends: 	Squareness to longitudinal axis: - ends intended for full contact bearing: - ends not intended for full contact bearing:		$\Delta = \pm D/1000$ $\Delta = \pm D/100$	$\Delta = \pm D/1000$ $\Delta = \pm D/300$ but $\|\Delta\| \leq 10$ mm

Table 2 contiues. Geometrical tolerances according to SFS-EN ISO1090-2 (modified from: SFS-EN ISO1090-2 2018, p. 111–123).

Twist: 	Overall deviation Δ in a piece of length *L*:		Δ = ± *L*/700 but |Δ| ≥ 4 mm and |Δ| ≤ 20 mm	Δ = ± *L*/1000 but |Δ| ≥ 3 mm and |Δ| ≤ 15 mm