University of Twente

Faculty of Engineering Technology

Master Thesis in Mechanical Engineering

A Methodology for Transitioning from Jig-Based to Jigless MIG Welding Utilizing Articulated Robots

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Abstract

This thesis presents a methodology to replace jig-based welding systems with jigless solutions utilizing articulated robots. The goal is to reduce overall cycle time and increase flexibility to handle more product variations. The methodology entails setting the requirements first, followed by designing a robotic cell layout, selecting suitable grippers, defining required components, and experimental verification via simulation. It is applied to a case study of welding steel brackets. The application successfully designs customized solutions tailored to the bracket parameters. Simulation confirms the feasibility of the proposed cell layout and 21-second cycle time with a 74% reduction. Further prototyping is needed to quantify improvements versus jig welding. This research demonstrates the methodology's potential for flexible, automated jigless welding to improve productivity.

Contents

Chapter 1

Introduction

In the field of manufacturing, welding is a crucial process used to join two or more metal parts together. Traditionally, welding has relied heavily on the use of jigs, which are fixtures that hold the components in place during the welding process. However, jig-based welding faces some key limitations in today's environment where industries seek to achieve mass customization, high mix/low volume production, and rapid changeovers.

The use of custom jigs and fixtures for each product configuration is typically required, which results in low flexibility and adaptability of the jig-based welding to the product variations. This extensive reliance on jigs leads to high changeover times and costs as new jigs must be designed and manufactured for every minor product variation.[1] For example, in automotive manufacturing where body tolerances are about 5mm, any small design change necessitates new jig designs and extensive retooling.[1] Moreover, using jigs or fixtures can be expensive. For instance, the fixture and clamping technologies of automated production lines for structural components in vehicles are the main cause of high costs. These technologies account for up to 29% of the production equipment's costs.[2]

As industries strive for increased productivity, efficiency, and customization, there is a growing need to transition from traditional jig welding to more flexible jigless welding methods that can handle more product variations.[3] One solution that addresses the limitations of traditional jig welding is the implementation of a multi-robot system for welding. A multi-robot system involves the use of multiple robots working collaboratively to perform welding tasks. This approach offers several advantages over traditional jig welding, including increased flexibility, adaptability, and efficiency.[3] However, transitioning to jigless welding systems is a complex undertaking with many technical challenges. Without a structured methodology, it is difficult to systematically address critical design factors like designing a fully functional welding cell. Therefore, to enable the transition to flexible jigless welding, this research will propose and evaluate a structured methodology for designing and implementing multi-robot welding systems. The methodology will address key considerations such as cell layout, end-effector design, simulation, and integration steps to systematically develop an automated solution.

This research is relevant to multiple industries such as the automotive and construction industries because it addresses the aforementioned limitations of traditional jig welding and offers a more flexible and adaptable approach through the use of a multi-robot system. AWL is a company that specializes in designing and building custom welding jigs and automated systems for manufacturing clients, AWL is interested in exploring the potential of jigless multi-robot welding through a case study. One such client, HALFEN, contracted AWL to design welding jigs for brackets used in facades. While fulfilling this order, AWL identified an opportunity to examine the feasibility of taking a jigless approach for the same bracket designs using multiple robots. The proposed methodology will be applied to this problem of the construction industry, as a case study, to produce the jigless design. Highlights the applicability and benefits of the proposed methodology in real-world scenarios

1.1 Problem Definition

Traditional jig-based welding processes face significant limitations in meeting the demands of modern manufacturing. The extensive use of custom fixtures and jigs leads to lengthy changeover times, inflexibility, and high costs. This outdated approach is hindering responsiveness and productivity in today's environment of high-mix, low-volume production and mass customization.

Specifically, the reliance on jigs and fixtures causes major inefficiencies. Designing and building custom jigs for each product configuration is time-consuming and expensive. The jig design must be re-done from scratch for any new part geometry. Physical jig manufacturing and re-tooling with each product change lead to production downtime, severely impacting changeover agility. Furthermore, part dimensional variances outside tight tolerances require jig adjustments or re-work, restricting product diversity. Manual loading/unloading of jigs reduces throughput and adds labour costs. Large jigs occupy significant space on the shop floor, adding storage overhead from inventorying multiple jigs per product. Moreover, dedicated jigs assigned to specific part numbers also limit flexibility in production scheduling and volumes. Therefore, the jig approach is misaligned with key manufacturing trends.

This misalignment with modern requirements results in reduced competitiveness and missed opportunities. A more agile, automated approach is needed to deliver productivity and flexibility gains.

As such, the problem this research plans to address is transitioning from jig-based welding to jigless robotic welding system. The limitations of traditional jigs necessitate alternative solutions enabling automated high-mix production, rapid changeovers, and responsiveness to market demands.

1.2 Research Questions

The research problem led to the formulation of the following research questions:

How can a high-mix, low-volume MIG welding cell be converted from jig-based to jigless multi-robot welding to reduce overall cycle time?

- **Layout Design:** What are the key considerations for designing the layout of a jigless multi-robot welding cell?
- **Fixture replacement:** What alternatives can replace traditional jigs to ensure both accuracy and efficient cycle time?

- **Robot Cooperation:** How can multi-robots cooperate to achieve the desired welding results?

The first sub-question covers a crucial step in transitioning to a jigless multi-robot welding system, as it involves designing the physical layout of the welding cell to accommodate the robots and other components.

The second sub-question on fixture replacement ties directly into the main question, as identifying the right fixture replacement strategy is crucial for the successful transition to jigless multi-robot welding. By eliminating traditional jigs and fixtures, manufacturers can significantly reduce setup times and increase flexibility in their welding processes. However, this shift requires careful consideration of alternative fixture solutions that ensure the same accuracy and repeatability level as traditional jigs.

Finally, the third sub-question addresses the overall methodology and integration process for implementing the multi-robot welding cell. This is consistent with the main question's focus on converting the system and improving its flexibility.

In summary, the design of the cell layout and the selection of an optimal fixture replacement are essential components that enable the jigless welding of parts. Furthermore, the overall integration methodology seamlessly combines these elements into a complete production system, achieving the main research goal of enhancing flexibility and performance compared to jig-based welding. These three sub-questions collectively address the main research problem, providing the necessary framework for the successful transition.

1.3 Research Method

The research method followed in this study consists of both theoretical investigation and experimental validation. On the theoretical side, an extensive literature review is conducted to examine prior work on jigless robotic welding systems and supporting technologies like machine vision. The literature review synthesizes key findings, limitations, and opportunities to inform this research. Building on the literature, a methodology is proposed for designing optimized jigless multi-robot welding cells to minimize cycle times. The methodology formalizes an approach incorporating major considerations like layout, end-effectors, components, and simulation.

The development of the structured methodology provides a systematic framework for approaching the design and implementation of jigless multi-robot welding cells. Formalizing the key steps to take in creating an optimized solution establishes a sound theoretical basis. Meanwhile, the application of this methodology to a real-world industry case study validates its feasibility and applicability for developing tailored jigless systems for specific production scenarios. By combining theoretical methodology development with practical case study implementation, this research establishes a robust foundation grounded in both rigorous engineering principles as well as demonstration of viability in an industrial context. The methodology provides a structured process, while its customization and simulation for the case study brackets prove its capability to generate feasible solutions for actual parts. This combination of theoretical formalization and practical customization for a physical application creates a robust basis for further refinement and expansion of the jigless welding methodology through future work.

1.4 Case Study

For practical implementation, the methodology is applied to an industry case study provided by AWL. The case study involves developing a jigless welding solution for specific steel bracket parts based on given specifications. By tailoring the methodology to these brackets through conceptual design and simulation, its feasibility is evaluated.

The case study focuses on three key phases aligned to the methodology:

1. Designing a robotic cell layout matching the spatial constraints and workflows of the target parts.
2. Selecting and conceptually designing a suitable robotic gripper for jigless fixturing.
3. Conducting robotic simulations to verify the proposed layouts, end-effector designs, motions, and cycle times.

The case study involves investigating jigless welding solutions for HALFEN steel brackets. The purpose of this project is to assist AWL in determining whether a jigless multi-robot approach is feasible for welding brackets that were originally intended to be welded using AWL's standard jig fixtures.

The task assigned is to research solutions for enabling jigless welding. As AWL is interested in exploring the potential of jigless welding technology but requires guidance on viable techniques and best practices. AWL's objective is to investigate the available options for automated welding without custom jigs to fix parts in place.

If jigless welding proved viable, AWL could offer this flexible automation option to future customers. The HALFEN bracket project serves as a case study for AWL to apply emerging jigless techniques in a real-world application. Positive results would validate their investment in jigless technology and expertise. AWL sees the potential to reduce the manual labour of jigs while speeding changeovers between bracket designs. This could benefit both AWL and its customers by increasing the responsiveness and scalability of automated welding solutions.

In addition to a research report, a concept design for a jigless welding test cell will be introduced. This will allow them to tangibly evaluate if jigless welding can meet their quality and productivity requirements.

Chapter 2

Literature Study

2.1 Jigless Welding

In this section, studies related to jigless welding will be examined. It will cover robotic solutions and other methods that have been used to eliminate the use of jigs.

2.1.1 Non-Robotic Solutions

Research by Kampker et al.[4] proposed a jigless laser welding concept for car body manufacturing to improve flexibility and reduce investment costs. Their approach relies on tabs and slots in the sheet metal parts for self-locating instead of jigs. Compliant parts compensate for tolerances during plug-together assembly prior to welding. Continuous welding is executed from one side by a remote laser scanner mounted on a robot. Two welding strategies were tested – rectangular high-speed welding along the joint requiring tight 0.25mm accuracy and oscillating welding allowing larger 0.5-1mm gaps but slower speed. The oscillating approach proved more robust for jigless laser welding for their car underbody demonstrator despite 3x longer process times. The research provides a valuable case study on jigless welding applied to automotive manufacturing. However, this method relies on redesigning parts to incorporate tabs and slots, which may not be feasible in some applications and it lowers the welding seam strength by 20% which adds more vulnerability.

Another non-robotic solution was developed by Zhang et al [5]. which is a reconfigurable welding fixture system for automotive manufacturing using a dowel pin modular design shown in figure (2.1). Their fixture utilizes adjustable platforms, independent locating mechanisms, repositionable clamps, and adaptive devices for error compensation. This allows the fixture to be reconfigured for different parts with similar geometries, enabling flexibility. Online sensors and controls adjust for tolerances. A pneumatic system handles clamping. Experiments with sheet metal assemblies demonstrated successful reconfigurations within 5 hours and dimensional accuracy improvements. However, their focus is on reconfigurable fixtures rather than eliminating jigs entirely. It also relies as well on the part redesign for modular fixturing. While presenting a useful modular fixture approach, their solution lacks the full flexibility of jigless welding. Their research provides valuable insights but does not fully solve the problem of transitioning to adaptable jigless systems. Further work is still needed to achieve the benefits of automated high-mix production without custom fixed tooling.

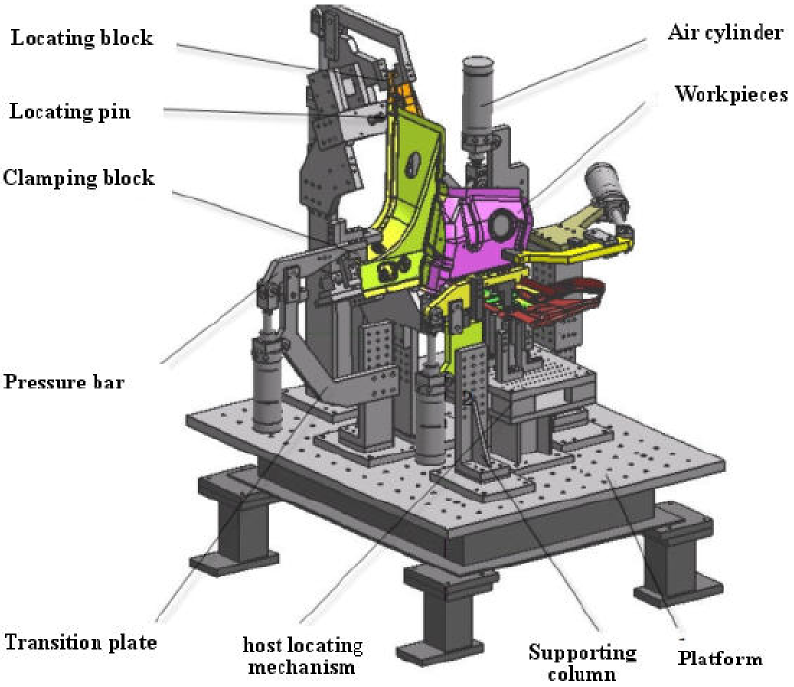


Figure 2.1: Modular mechanism[5]

2.1.2 Robotic Solutions

Ahmad et al. [6] proposed a reconfigurable robotic welding fixture using lockable arms and modular electric clamps. Their structural robot concept transitions between movable and rigid states to reconfigure and fixture parts. Four arms with 2DOF lockable joints and manual wrist rotation enable adaptation to different workpieces (figure 2.2). The frame slides to adjust for length variances. Physical testing showed successful grasping and welding of automotive assemblies. Direct fixture exchange between robots via integrated tool changers increased flexibility. However, their custom structural robot has a limited payload compared to industrial robots. It also requires part redesign for compatibility with the specific clamp end effectors. While demonstrating reconfigurable robotic welding fixtures, the proprietary hardware limits broad applicability. Their lockable joint technology is promising for reconfigurable systems if implemented on standard industrial robots and integrated with commercial grippers and sensors.

Figure 2.2: Reconfigurable fixture prototype [6]

Regarding jigless multi-robotic welding, some initial research has been conducted. However, fully functional solutions have not yet been achieved nor have fully robotic solutions been provided. Bejlegaard et al [3] presents a concept and analysis of implementing a jigless robotic welding cell for large steel plate assemblies in low-volume, high-variety production environments. It also discusses the challenges of implementing robotic jigless welding. The transition to jigless welding places tighter demands on tolerances compared to traditional manual welding processes. Supplying processes must be reliably controlled and coordinated with the automated welding process to ensure continuous production flow. There is also a need for careful path planning and optimization to enable smooth coordination between multiple robots working in close proximity. Programming robots for new products in high variety/low volume production may be time-consuming compared to one jig design. Standardizing components can help enable the reuse of existing programs. Managing distortions from welding without the fixture support of jigs can also be challenging. Solutions may involve testing to find optimal welding parameters and heat input. While jigless welding can reduce changeover time and eliminate jig costs, the capital investment required is still significant. Determining the feasible applications where the benefits sufficiently outweigh the risks and challenges of this emerging technology will be key. Overall, achieving the seamless integration and coordination required for automated jigless welding of large steel assemblies presents significant technical hurdles compared to traditional fixed jig methods. [3]

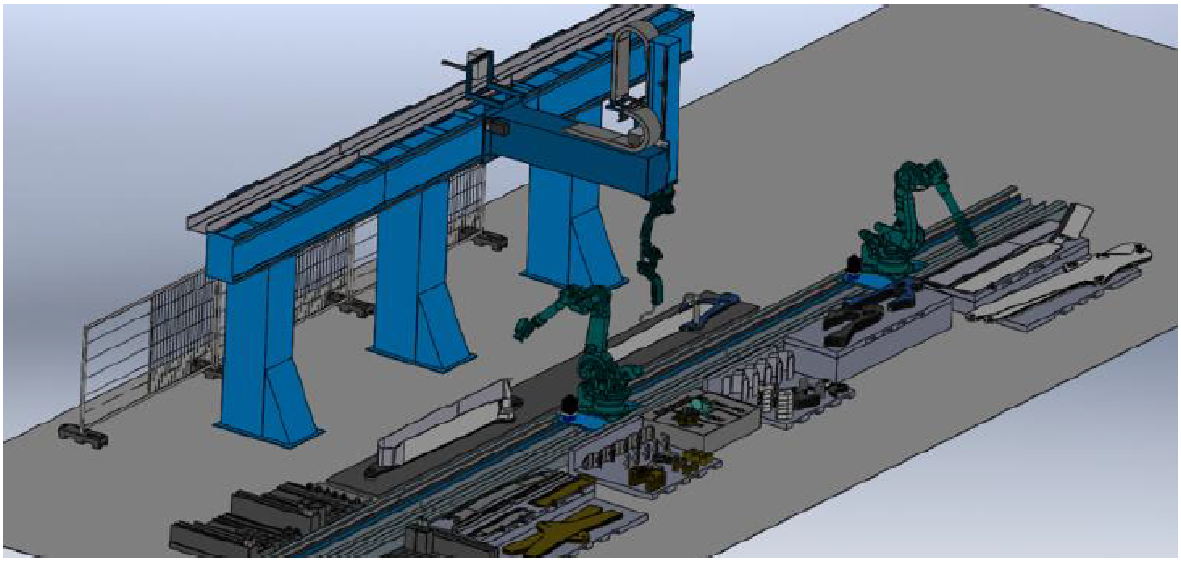


Figure 2.3: A concept for Jig-less welding cell [3]

Paquin and Akhloufi[7] introduced a multi-robot solution. Two robotics arms were used, one equipped with a gripper and the other with a welding torch. The system depended on machine vision to pick the parts from a conveyor belt or a stationary table. However, the system was not fully jigless, since the central part was still fixed on a jig as shown in figure (2.4).

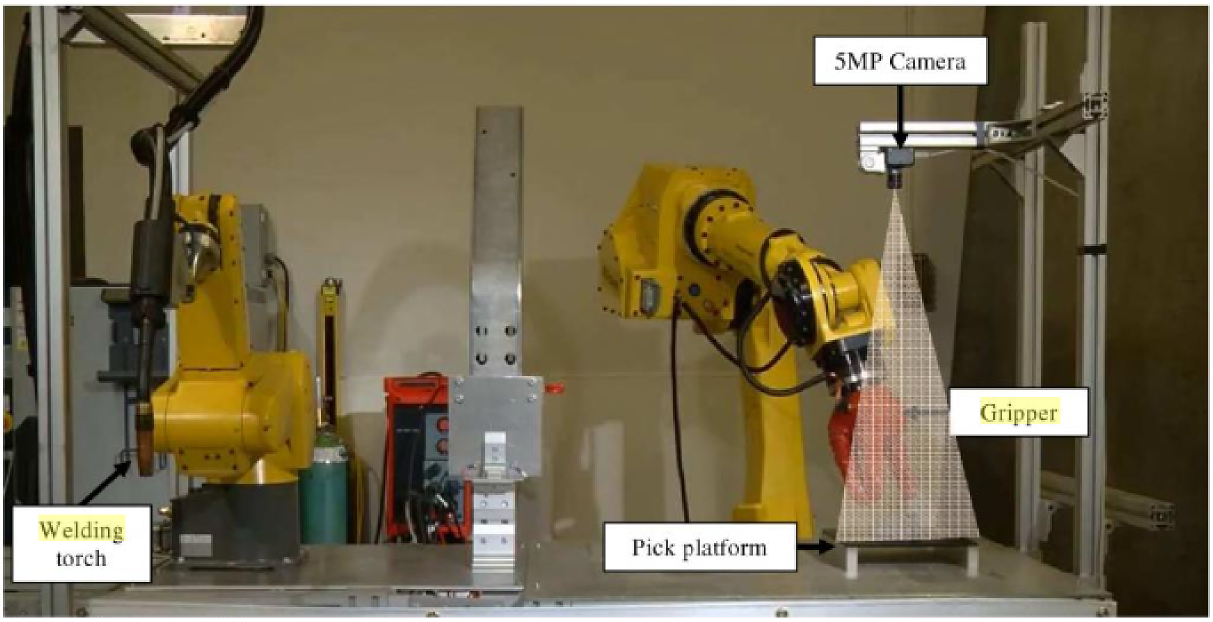


Figure 2.4: Prototype of the proposed solution[7]

The used gripper is a universal articulated gripper. The gripper has three articulated fingers and provides 9 degrees of freedom (three for each finger). The gripper is able to adapt to different types of parts such that no re-tooling is required.

Lund[8] presents a concept for a fully jigless multi-robot welding cell that can assemble and weld plate structures without requiring jigs. Two key technical solutions are proposed to achieve jigless welding:

- A magnetic positioning system to hold the first plate of the assembly in place
- A magnetic gripper on the handling robot to hold subsequent plates in place during tack welding

The paper concludes that the magnetic positioning system and magnetic gripper can enable fully jigless robotic welding of steel plate structures. It also provides a concept model and solutions to address the prior limitations around fixturing the initial component. However, the results are mainly theoretical and limited in terms of using cases because of the magnetic gripper.

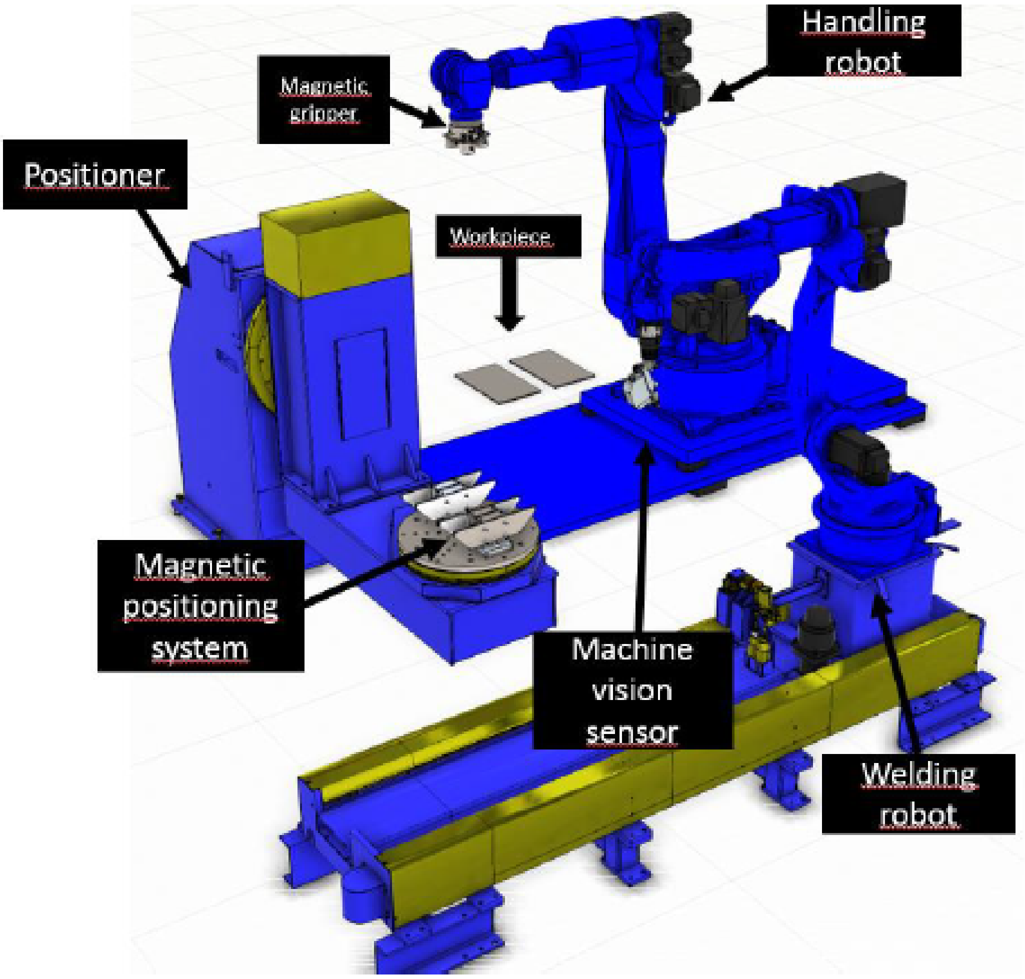


Figure 2.5: Representation of Lund's solution[8]

2.1.3 Jigless Spot Welding

A study by Bagherian analyzed process data to compare the performance of jigless spot welding versus semi-automated welding [9]. The jigless system utilized a handling robot to present parts to a welding robot. Data was gathered on operation times, defect rates, throughput, work in process, and resource utilization. The production volume analyzed was 500 water heater tanks per month.

The results showed the jigless robotic spot welding system improved the throughput time by 6.5% compared to the semi-automated method (3.096 vs 3.297 minutes). Additionally, the defect rate dropped by 50% from 0.00059% down to 0.00029% with the robots. However, the operation time varied for different steps. While the total welding time decreased from 1.03 to 0.86 minutes with the robot welders, the material handling time increased. This shows the importance of planning coordinated motions between the welding arm and part manipulation robot[9].

Overall resource utilization remained comparable at 4% for both manual and automated welding workstations. This indicates the jigless robotic solution matched the capacity needs, although future work could examine right-sizing robot numbers to optimize utilization. The author recommended future comparisons to manual welding processes and larger production volumes representing maximum throughput[9].

In summary, the case study from Bagherian provides empirical evidence of process improvements from a jigless dual-robot spot welding solution over a semi-automated system. While focusing specifically on water heater fabrication, it demonstrates viable techniques for pairing welding robots with material handling robots to eliminate static jigs[9]. As one of the few data-driven studies quantifying metrics, this work confirms some of the expected benefits around flexibility, speed, quality and adaptability that motivate further jigless welding research.

2.1.4 Fixtureless Path Welding

The research project "RAPIDS" (robot-assisted applicator with intelligent dynamic self-adaptation) marks a significant advancement in fixtureless welding, aiming to achieve a reproducible accuracy of better than 0.5 mm. This project utilizes two synchronized robots equipped with grippers and a laser scanner for precise measurements, integrated into a robot simulator for calibrated modelling [10]. The methodology involves initial scanning of the welding components, followed by the simulation of their geometric contours. The robots' synchronous movements are then generated based on this data, with further scans to refine the path accuracy for the final welding process. This approach overcomes the limitations of conventional robotic programming and individual component fixtures, especially in the context of single-part production [10].

The implementation process begins with both robots picking up parts of equivalent diameter from pickup stations. These parts are scanned by a laser scanner, with their geometric contours replicated in the simulator. This data enables the generation of motion paths and programs for welding at the components' end faces. The positioning of the components and the gap distance are dynamically adjusted using additional laser scans, enhancing the accuracy of the welding process. The study demonstrates that this dynamic scanning alone is sufficient to detect and correct all inaccuracies, potentially rendering static inspection unnecessary [10].

In terms of the robotic work cell design, the study utilized components such as pneumatic grippers, a laser scanner, and standard welding equipment, all mounted on a mobile robot table. The setup exemplifies the feasibility of implementing fixtureless welding in a versatile and mobile environment, showcasing the potential of this technology in industrial applications where flexibility and precision are paramount[10]. Importantly, the principles and techniques developed in this project can be transferred to other types of welding processes, such as arc welding, which is the focus of this thesis. This adaptability further underscores the broader applicability and significance of fixtureless welding in modern manufacturing environments.

2.2 Accuracy

Ensuring high accuracy in robotic welding operations is critical for producing quality welds and finished products. However, variances in workpiece positioning and geometry can lead to deviations from the programmed welding paths, resulting in defects or poor weld quality. Therefore multiple existing solutions will be discussed.

A system for automatic robotic welding based on offline programming using CAD data was developed[11]. The system uses a 3D vision camera (Microsoft Kinect) to capture a 3D image of the workpiece. This image is aligned with the CAD model to correct for any deviations in the actual workpiece position/orientation compared to the programmed position. The offline programmed robot welding paths are adjusted based on the corrected workpiece pose before being executed. This allows the system to account for variances in workpiece geometry and positioning. The Iterative Closest Point (ICP) algorithm aligns the CAD model with the 3D vision data and estimates the 3D transformation between them. In experiments, the system achieved a mean absolute error of around 2.4 mm and a maximum error of 5.7 mm in the corrected welding paths compared to optimized manual programming. The accuracy achieved is promising and acceptable for many welding applications. The system demonstrates the potential of using 3D vision and CAD models to improve robot welding accuracy and reduce manual programming.

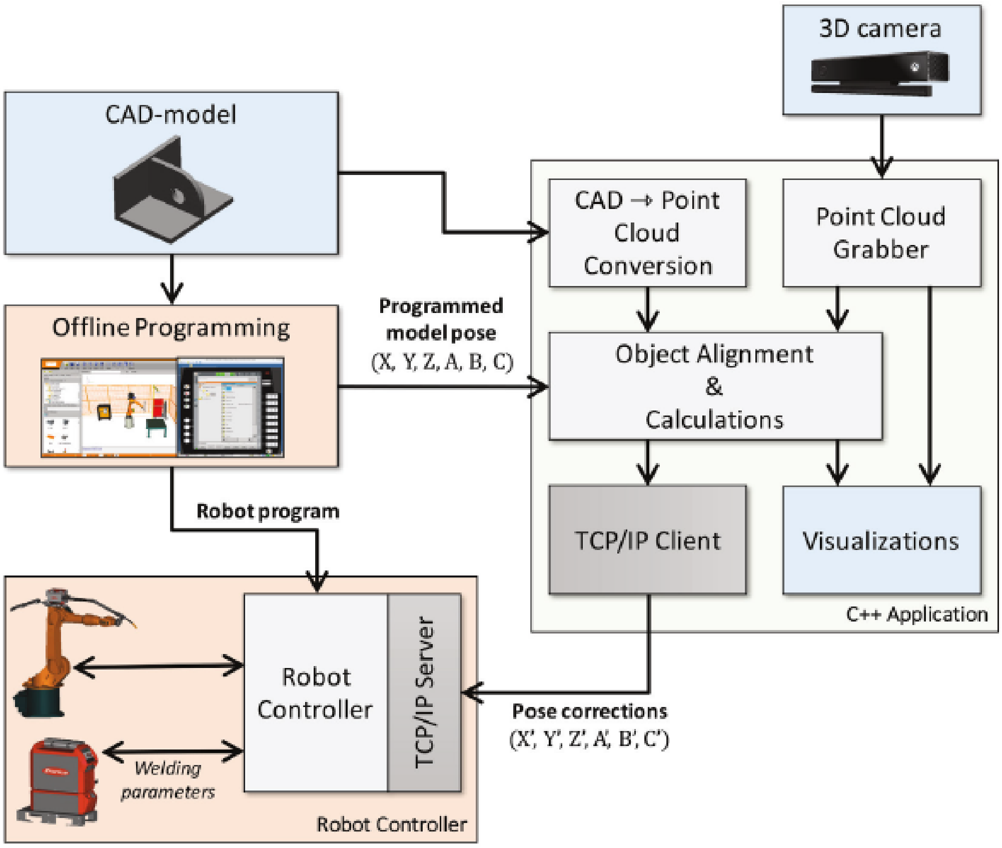


Figure 2.6: Information flow of the developed system[11]

Another paper presented a different machine vision approach for robotic assembly [12]. The goal is to enable robots to perform assembly tasks in unstructured environments using visual perception and learning techniques. The object recognition uses a neural network architecture called SIRIO. It receives a descriptive vector called CFD&POSE as input. This vector represents 3D object data in a compressed form that is invariant to scale, rotation and orientation. The CFD&POSE vector is generated from 2D images using image projections and canonical geometry grouping. It includes distance values from the object's centroid to the perimeter, centroid coordinates, orientation angle, height, and an ID code. The vector allows fast recognition and pose estimation of assembly parts in real-time. It is interfaced to a robot to provide grasping info. Experiments were conducted on an assembly cell with different peg shapes. The FuzzyARTMAP neural network achieved 100% recognition rates in milliseconds for other positions, sizes and lighting. The approach demonstrated the feasibility of providing vision guidance in robotic assembly tasks. It can enable flexible fixtureless assembly by robots without precise environment info.

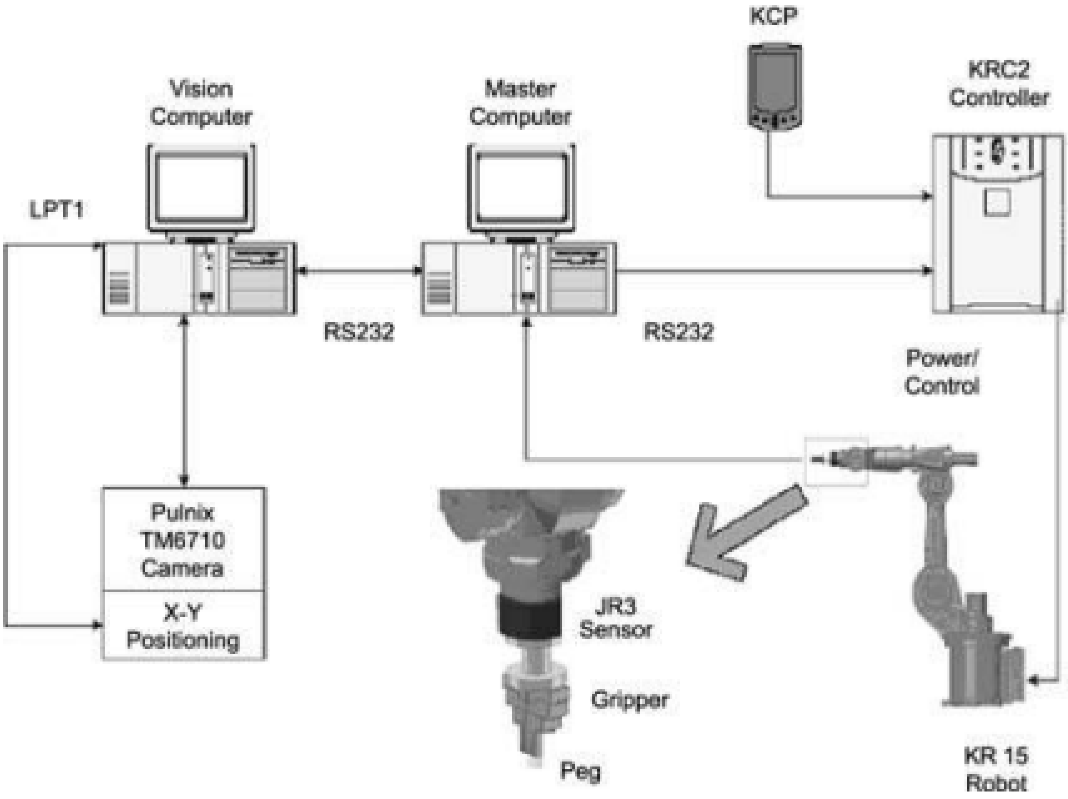


Figure 2.7: Control architecture of the developed system[12]

In short, the first system enables more flexible robotic welding that can account for workpiece variability through automatic path corrections based on 3D vision alignment. This has benefits for offline programming efficiency and reducing skill requirements. For the other system, however, the key innovation is the CFD&POSE vector that allows real-time invariant object recognition and pose estimation to guide robot assembly without fixtures. The neural network provides fast and reliable performance.

2.3 Summary

Research on developing jigless robotic welding systems has made progress, addressing key challenges and introducing concepts. However, fully functional and comprehensive solutions for MIG welding have not yet been achieved. One major limitation in current approaches is the reliance on custom fixtures or jigs to hold parts of the assembly, preventing a completely jigless automated process. Proposed alternatives like articulated grippers and magnetic grippers aim to provide a kind of flexibility but lack robust implementation and testing.

The presented vision systems offer technologies that can enhance the accuracy and flexibility of robotic welding by correcting for workpiece variances. However, these solutions are components rather than fully integrated systems. To develop a robust jigless welding methodology, these building blocks need to be combined into an orchestrated automation solution. Vision techniques show promise for adaptable locating, positioning, and quality inspection, but realizing their full potential requires systematic incorporation alongside multi-robot coordination, optimized cell layouts, suitable end-effectors, and ancillary equipment.

In conclusion, achieving fully automated jigless welding capable of handling diverse production remains a formidable challenge. The concepts explored so far represent important steps forward but lack the maturity and integration necessary for industry adoption. Additional research and development are essential to unlock the potential benefits of flexible, jigless robotic welding cells. Combining complementary technologies like machine vision, robotic motions, and specialized end-effectors is critical to improving productivity, quality, and changeover efficiency compared to traditional methods. The upcoming chapter will delve into integrating these solutions into a comprehensive methodology for flexible jigless robotic welding.

Chapter 3

A Methodology for Jigless Welding by Using Multi-Robot Cell

3.1 Proposed Four-Step Methodology

Implementing flexible, jigless welding using multiple robots is a complex undertaking with many technical challenges. Without a structured methodology, it is difficult to systematically address critical design factors like optimizing cell layout, selecting suitable end-effectors, avoiding collisions, and integrating peripheral devices. This often leads to sub-optimal solutions that fail to maximize quality, adaptability and productivity. Therefore, following a well-defined methodology is crucial to successfully design, integrate and optimize a jigless multi-robot welding system.

A robust methodology provides a framework to methodically consider the most important key elements needed for a high-performing jigless solution. It ensures that important steps like defining task requirements, studying material flows, evaluating workspace constraints, and verifying designs via simulation are not overlooked. Adhering to an established methodology significantly increases the probability of achieving the performance goals compared to an ad-hoc design approach. It provides a roadmap for developing a robust, flexible system.

In this context, clear requirements indicative of a well-designed methodology are integrated, encompassing:

- Operational Efficiency: Achieving a reduction in cycle times compared to traditional jig-based systems.
- System Flexibility: Ensuring the ability of the system to adapt to different welding tasks without extensive reconfiguration, ensuring the flexibility provided by the current setup and accommodating a wide range of part geometries and dimensions.
- Footprint Optimization: The footprint of the cell should be at least similar to or improved upon compared to the current setup, ensuring efficient use of space in the manufacturing environment.

This section outlines a comprehensive four-step methodology tailored to the needs of jigless multi-robot welding. By systematically following this methodology, users can develop optimized robotic cells aiming for maximum productivity and adaptability for their specific applications. The value of this methodology is demonstrated through its application to a real-world case study later in this thesis. The proposed methodology involves four key iterative steps:

1. Cell Layout Design - Outputs initial cell layout concepts
2. Gripper Design - Yields suitable gripper designs for fixturing
3. System Component Definition - Specifies cell components like vision systems
4. Testing, Validation, and Verification - Test and provide data to refine designs and methodology

After each step, the outputs are thoroughly evaluated to determine if previous steps need adjustment to optimize the overall methodology. This iterative approach aims to systematically address the technical and integration challenges of implementing flexible jigless welding using multiple articulated robots.

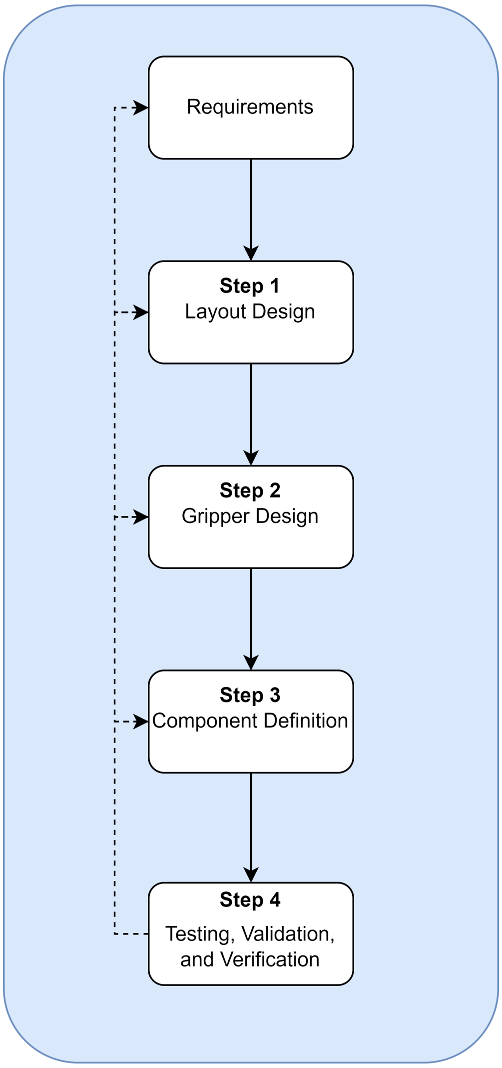


Figure 3.1: Methodology overview

The four-step methodology proposed in this thesis for transitioning to jigless multi-robot welding finds its foundation in the Generic Design Method for Reconfigurable Manufacturing Systems(RMS)[13]. This alignment is not coincidental; rather, it is a deliberate adaptation, recognizing the intrinsic value of the generic RMS design approach in addressing complex manufacturing challenges.

3.1.1 Generic Design Method for RMS

The Generic Design Method, as outlined in [13], provides a structured approach to developing manufacturing systems that are flexible and adaptable. The method is composed of several key stages, beginning with a thorough analysis of manufacturing requirements and criteria. It progresses through a synthesis phase, where provisional solutions are designed with a focus on changeability and adaptability. This is followed by rigorous simulation and evaluation, ensuring that the provisional design meets the necessary requirements. Finally, a decision is made on the approved design after evaluating its value. This comprehensive process ensures that the design is not only functional but also reconfigurable to accommodate future changes in production demands.

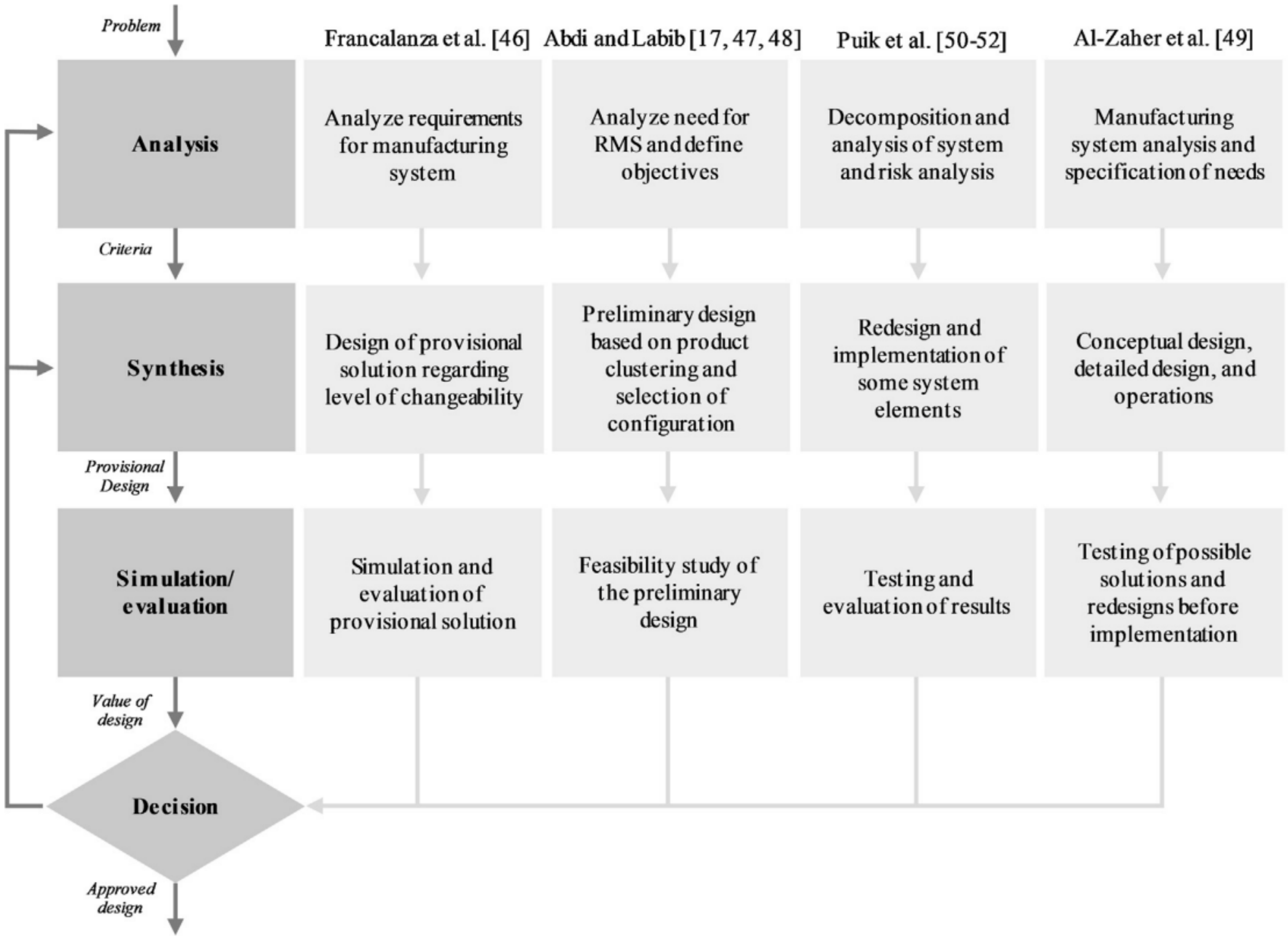


Figure 3.2: Generic RMS Design Method stages [13].

3.1.2 Similarities with the Generic RMS Design Method

This method is particularly pertinent to the design of jigless welding systems with multiple robots, as it emphasizes the importance of adaptability and the ability to reconfigure for various tasks. Each step of our methodology aligns with these stages, ensuring a robust and flexible welding system design.

- **Step 1: Cell Layout Design** mirrors the initial phases of the RMS method, focusing on conceptualizing layouts that are flexible and adaptable to different welding tasks.
- **Step 2: Gripper Design** resonates with the RMS approach towards modular tooling and end-effectors, allowing for rapid reconfiguration based on task requirements.
- **Step 3: System Component Definition** is akin to selecting system components in RMS, emphasizing the importance of choosing elements that enhance system flexibility and efficiency.
- **Step 4: Experimental Verification** aligns with the RMS methodology's emphasis on testing and refining the system, ensuring that the final configuration meets the desired performance criteria.

3.1.3 Adaptation Justification

The rationale for adapting the Generic RMS Design Method in our methodology is rooted in its proven effectiveness in creating systems that are not only adaptable to changing manufacturing requirements but also efficient and scalable. By leveraging this method, our approach to jigless welding with articulated robots becomes more systematic, robust, and aligned with the principles of modern, adaptable manufacturing practices.

The upcoming sections will provide further details on the process, considerations, and goals of each methodology step. By following this systematic methodology, an optimized robotic cell achieving flexible, automated multi-robot welding can be designed.

3.2 Cell Layout

The first step in the methodology is designing the overall cell layout. This involves planning the arrangement of robots, defining workspace requirements, material flows, and component pick/place locations. To develop an optimized layout, the structured approach proposed by Zhang and Fang [14] is followed. This structured layout design approach provides a systematic framework for developing optimized robotic cell layouts. This method is well-adapted for designing the multi-robot jigless welding cell because it incorporates several key considerations relevant to this application:

- It analyzes the process requirements and breaks down tasks, which is important for coordinating multiple robots and workstations.
- The focus on task relationships and material flows matches the need to orchestrate

interactions between the handling robots, welding robots, vision systems, and other cell components.

- Evaluating workspace requirements and reach ensures the cell layout provides the necessary access and collisions are avoided with multiple robots.
- Developing and comparing alternative layouts allows the exploration of different arrangements to find the optimal configuration.

In summary, the structured approach accounts for critical factors in a multi-robot cell like task coordination, material handling, workspace constraints, and flexibility through alternative evaluations. By systematically addressing these aspects, following Zhang and Fang's methodology helps develop an optimized cell layout for the defined jigless welding application that integrates the robots, peripherals, and workflows. This method involves:

- Process study - Analyze the traditional manual or semi-automated processes and configure them for automation.
- Task breakdown - Break down the overall process into individual sub-tasks that can be assigned to robot workstations.
- Task relation and flow diagram - Determine the sequence relationships between tasks and the material flows between stations.
- Space requirement - Determine the space needs and layout requirements for each workstation.
- Alternative layouts evaluation - Develop alternative cell layouts based on criteria like efficiency, collision avoidance, etc.
- Layout optimization - Evaluate the alternative layouts through methods like simulation to select the optimal layout.

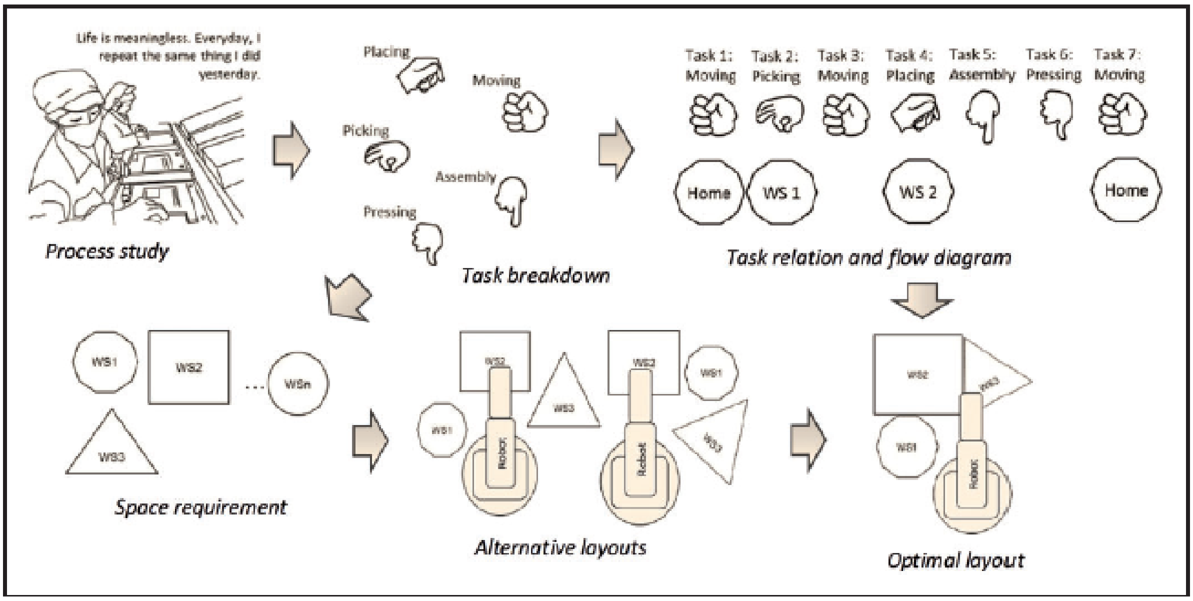


Figure 3.3: Systematic robotic cell layout design.[14]

3.2.1 Requirements

In addition to the layout design steps already outlined, it is also important to define the general requirements for the robotic cell. These requirements are aimed at achieving maximum flexibility and enabling full automation. Based on these goals, the following key requirements have been established within the context of this paper's methodology for the multi-robot welding cell:

- At least two robotic manipulators for handling parts are essential for a jigless process, as each robot can hold a different part. This eliminates the need for fixed jigs during welding.
- At least one welding robot. The number of welding robots can be varied depending on cycle time and cost constraints, with additional robots decreasing welding time.
- Machine vision is likewise a core requirement, with one system for process monitoring to ensure weld quality per ISO standards, and another for verifying part locations relative to each other before welding. The latter requires camera resolution, the field of view, and algorithms suited for precise part alignment inspection.
- For flexible robotic handling, suitable grippers are necessary for each manipulator to grasp and locate the various part configurations. The grippers must provide sufficient payload capacity for the maximum expected part weight based on the specifications of the application. High accuracy and repeatability are also critical for precision locating during welding.
- The maximum dimensions of the workpieces should be suitable for the designed cell.
- Safety devices and fencing that comply with robotic safety standards are essential.

- A programmable logic controller (PLC) will coordinate the various robots, I/O devices, and motions through appropriate communication interfaces.

3.3 Gripper Design

The gripper is a critical component enabling flexible, jigless welding in the multi-robot cell. To perform welding without jigs, the gripper must be able to securely hold parts in position, serving as a replaceable 'fixturing' solution Therefore, careful gripper selection and design are essential for achieving the goals of precise part locating, rapid cycle times, and overall welding quality.

In approaching the gripper design, it is insightful to study the key functions and requirements of a traditional welding jig that the gripper must fulfil. While a jig relies on fixed physical fixturing, the gripper must play a similar role but in a flexible, adaptable manner using robotic technology. By understanding the considerations for an effective welding jig, those criteria can guide the development of a gripper that can accurately locate parts without rigid jigs.

3.3.1 Jig Requirements

Some of the main design objectives for the robotic gripper based on typical welding jig requirements are[15]:

- **Rigidity** - The fixture must hold parts completely rigid and stationary to prevent any movement or distortion during welding. This requires sufficient clamping forces and stiffness.
- **Accessibility** - The fixture design must allow the welding torch full access to all required weld joints.
- **Fit-up** - Fixtures must locate parts precisely to ensure proper alignment and gap tolerance at weld joints.
- **Thermal management** - Welding generates localized intense heating. The fixture must withstand this and allow sufficient cooling after welds to minimize residual stresses and distortion.
- **Low thermal expansion** - Materials with low coefficients of thermal expansion are preferred to minimize distortion from welding heat.
- **Ease of loading/unloading** - The fixture should allow quick and easy loading/unloading of parts.
- **Adjustability** - The ability to adjust and fine-tune locations of parts may be required to control fit-up.
- **Cost** - Fixture cost should be reasonable. Simple designs with standard components are preferred.

- **Safety** - The fixture must secure parts against accidental movement and allow no unintended contact between the welder and fixture during the welding process.

With these goals in mind, the gripper can be designed to fulfil the key functions of a jig in a flexible robotic solution. The following section will elaborate on the proposed gripper design and how it aims to meet these technical criteria for successful jigless robotic welding.

3.3.2 Gripper Design

Starting by reviewing common classifications of grippers based on their configuration, actuation method, type of mechanism, and stiffness. The following table summarizes the main types of grippers according to these categorizations based on reviews of existing literature on robotic grippers [16, 17]. This categorization provides a helpful background for selecting a suitable gripper design for the welding application.

CONFIGURATION-BASED	**ACTUATION-BASED**	**STIFFNESS-BASED**	**MECHANISM-BASED**
Robot Grippers with 2 Fingers	Cable-Driven Grippers	Rigid Grippers	Screw driven mechanism
Robot Grippers with 3 Fingers	Vacuum Grippers	Soft Grippers	Pack and pinion mechanism
Robot Grippers with Flexible Fingers	Pneumatic Grippers		Cam and follower mechanism
Multi-Finger and Adaptive Grippers	Hydraulic Grippers		Rope and pulley mechanism
Grain-Filled Flexible Ball Grippers	Servo-Electric Grippers		Worm gear mechanism
Bellows Grippers			
O-ring Grippers			

Table 3.1: Types of Grippers Based on Classifications[16, 17]

For example, if a finger gripper is chosen, the design will follow a systematic process proposed by Honarparda et al.[18] for finger gripper design as outlined in 3.4. The steps are as follows:

1. Define the task type - For this welding application, the task is the assembly of welded components.
2. Determine the working knowledge - The 3D models of the parts provide known geometry to design for. (IF not known to use vision system)
3. Select an appropriate contact model either Force-Closure or Form-Closure - As welding requires securing parts firmly, a force-closure approach with friction contacts is chosen.
4. Perform grasp synthesis and analysis - Suitable contact points are identified on the models that allow force closure.
5. Design the gripper finger structures - Fingers will be designed to match the welded parts geometry at the planned contact locations.

6. Check for collisions - The gripper design is verified to avoid collisions with the parts during grasping motions.
7. Experimental verification - Prototypes of the gripper and parts could be tested to validate the design before final implementation.

By following this systematic procedure matched gripper fingers can be designed to successfully locate the parts for jigless robotic welding. The gripper aims to provide the accuracy and rigidity needed while avoiding costly custom jigs. This methodical finger design process aims to fulfil the requirements outlined based on traditional welding fixtures. While these steps focus on automating this entire process, the general framework provides a logical sequence that can be applied even for manual gripper design.

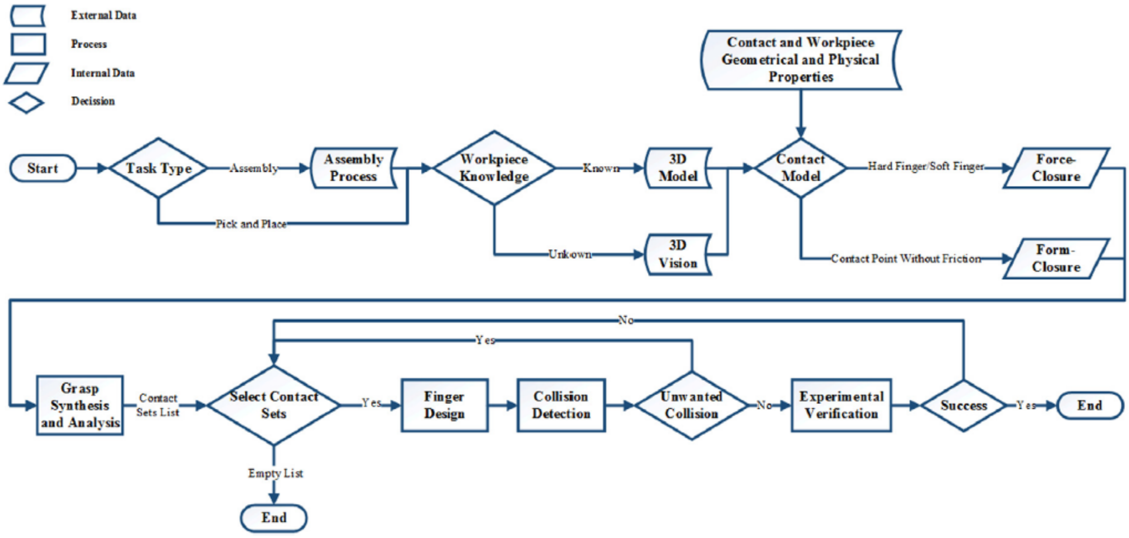


Figure 3.4: Flowchart of an example of the design process for a gripper.[18]

3.4 Component Definition

In addition to the core elements of the robotic cell layout and gripper design, a variety of supporting components must be specified to enable full automation, process control, and safe operation. This stage of the methodology involves identifying and defining the necessary complementary technologies and equipment needed for implementing the flexible jigless welding cell using multiple articulated robots. Key considerations include machine vision systems, safety measures, part positioning fixtures, the control system architecture, and integration software. A thorough definition of all required cell components is essential for transforming the conceptual layout and grippers into an integrated, automated multi-robot welding solution. The upcoming sections will elaborate on the function, selection criteria, and integration of the vital ancillary components that complete the robotic welding cell. These include:

- Robotic Arms

  - The robotic manipulators should have 6 degrees of freedom or more to access all required poses.
  - The arms must provide adequate payload capacity, reach and accuracy for handling the parts and welding torch.
  - The number of robots can be scaled based on production volume needs.
- Machine Vision Systems
  - An initial vision system is needed to locate parts at the pickup station for the robots. This allows flexible, jigless part loading by precisely identifying part positions rather than relying on fixed jigs.
  - A second vision system should be positioned to inspect the fit-up and alignment of parts held by the robots prior to welding. Feedback from this vision system helps the robots adjust part locations for high precision.
  - Vision systems require suitable cameras, optics, lighting, and software for robust object detection and localization under varying conditions. Some example vision systems are discussed in the Literature Review section.
- Safety Equipment
  - Light curtains, proximity sensors, and safety scanners are necessary around the cell perimeter to detect human entry and trigger safe robot stops.
  - Weld curtains made of arc-resistant material should surround the welding area to protect operators from sparks and arc flashes.
- MIG Welding Equipment
  - MIG welding power source, wire feeder, torch, and interfacing cables.
  - Shielding gas supply and hoses.
  - Fume extraction equipment.
- Control System
  - A programmable automation controller (PAC) or Programmable Logic Controller (PLC) integrates the robots, I/O devices, conveyors, and safety systems via digital and network connections.
  - The PAC/PLC coordinates the sequence of operations and motion trajectories based on pre-programmed routines and sensor feedback.
- Integration Software
  - Software platforms like RobotStodio from ABB or Visual Components are beneficial for simulating, programming, and verifying device integration before physical commissioning.
  - Software assists with cycle planning, robot programming, vision integration, simulation, and offline debugging of sequences.

By thoroughly defining these additional equipment needs and functions, the complete jigless multi-robot MIG welding cell system can be specified. The integration of the robots, grippers, sensors, safety measures, fixtures, controllers, software, and welding equipment transforms the individual components into an automated, flexible welding solution.

3.5 Testing, Validation, and Verification

Simulation plays a vital role in verifying and validating the robotic cell design before physical implementation. It provides a virtual environment to test and refine the proposed concepts from the previous methodology steps at low risk and cost.[19].

For this methodology, the simulation will be used to:

- Evaluate the workspace requirements and motions of the robots based on the defined cell layout. This verifies that the layout provides adequate reach and access for the required tasks. Collision checking ensures no conflicts between robots.
- Test the effectiveness of the gripper designs for securing and locating parts, either by simulating the designed gripper or a similar one. The gripper motions and clamping forces can be simulated with various part configurations. This validates the gripper's ability to handle part variation as needed.
- Analyze the vision system placement and field of view to ensure full coverage of the welding area and pick-up locations. Camera models can be tested in the simulation to verify the configured resolution, focal length, and frame rate are sufficient for the determined coverage areas and inspection tasks.
- Optimize the positions of widgets, fixtures, and stations for efficient material flow based on simulated cycle times.
- Program and visualize the coordinated motions of the robots working collaboratively. This tests the feasibility of the conceptual workflow.
- Estimate overall process cycle times under ideal conditions to set expectations before physical commissioning.
- Identify any missing components or required adjustments to the cell layout, gripper, or other elements that may be needed for successful automation.

Essentially, the simulation will test the complete robotic cell design, gripper concepts, vision integration, safety measures, cycle planning, and workflow coordination developed through the methodology steps. It provides an opportunity to verify the proposed designs and uncover areas for improvement prior to investing in physical prototypes and testing. This upfront analysis and optimization via simulation aim to accelerate implementation while maximizing the probability of achieving the desired flexible, automated multi-robot welding solution.

Assumptions

At the outset of developing the methodology, certain foundational assumptions were established to guide the design and evaluation process. These assumptions are critical as they set the boundaries within which the methodology operates and the conditions it is expected to meet. They include, but are not limited to, the stability of input material characteristics by assuming that the materials used for welding (e.g., metal sheets, rods) are consistent in quality and dimensions, ensuring predictable welding conditions, and the reliability of robotic equipment which assumes that the robotic systems and associated machinery operate without frequent breakdowns or deviations from expected performance levels, ensuring steady production flow.

Chapter 4

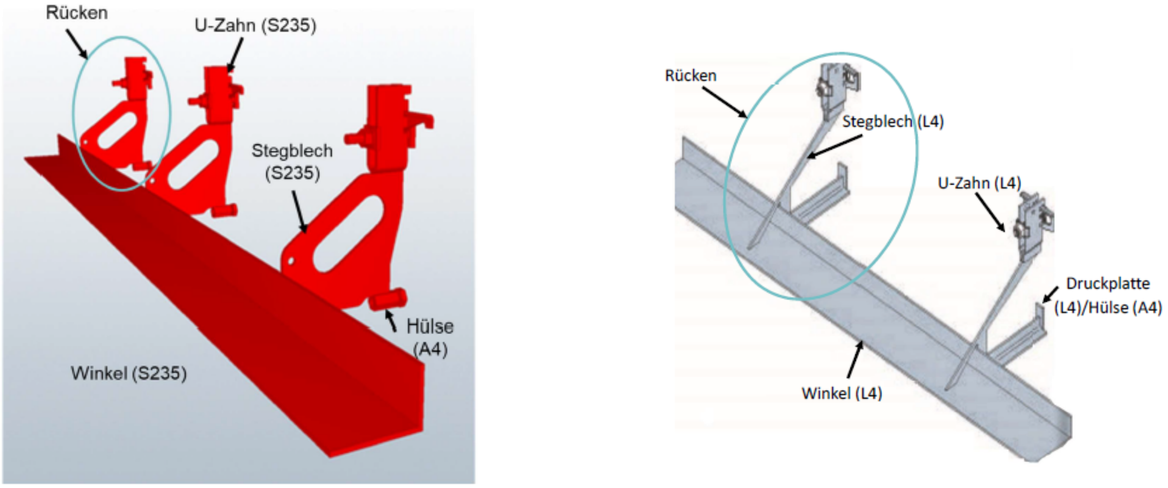
Testing and Results

In this chapter, the proposed methodology for designing a jigless multi-robot welding cell will be applied to a defined case study. The case study provides a basis for implementing each step of the methodology and evaluating the feasibility of the jigless approach through simulation. The following sections will walk through conducting the four key steps of cell layout design, gripper design, system component definition, and experimental verification via simulation for the specific case study parts and requirements. This application of the methodology to a case study through simulation is an initial phase in assessing the robotic concepts. By progressing through each design step tailored to the case study parameters in simulation, the viability of the solutions can be evaluated. The simulation results will identify areas for refinement while validating the overall direction. Following the structured methodology provides a lower-risk approach for developing an optimized jigless multi-robot welding cell for the target application. This methodology-driven case study assessment builds confidence that the jigless welding system can be a practical automated manufacturing solution before proceeding to physical implementation.

4.1 Technical Information On The Study Case

The case study involves the development of an automated, robotic welding cell for the production of facade brackets at HALFEN. Based on the technical requirements specification provided, the target brackets are types FK5 and HK5 consisting of laser-cut steel plate components up to 10 mm thick. The welding cell must join the bracket parts made of structural and stainless steel using arc welding processes.

The designed welding cell incorporates a rotary table to mount modular welding fixtures and two industrial robots with welding torches. Key performance requirements include quick changeover times of under 15 minutes between bracket designs and minimization of manual material handling.



(a) FK5 (b) HK5

Figure 4.1: Facade brackets

Flexibility is necessary for the project because the result may vary in terms of:

- The brackets used (HK5 or FK5)
- The number of welded brackets (1 up to 5 see figure 4.2)
- The distance between the brackets on the bar
- The bar length (max 2500 mm)

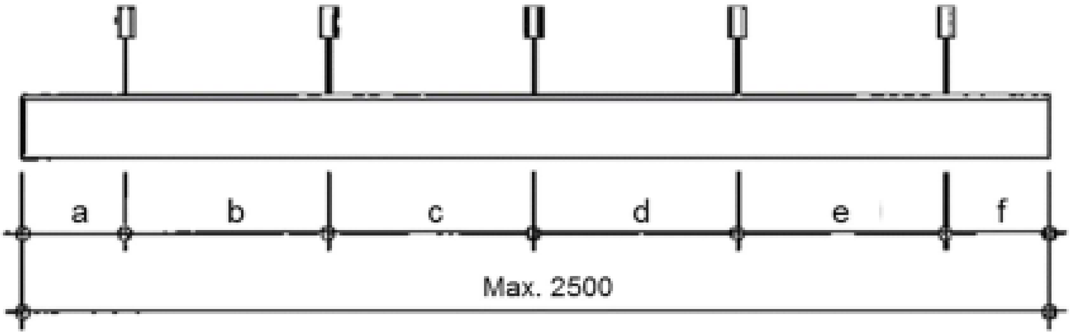


Figure 4.2: possible configurations

4.2 Methodology Implementation

4.2.1 Cell Layout

The first step in applying the methodology to the case study is designing the overall cell layout. As the case study involves welding HK5 and FK5 steel brackets using multiple robots, the layout must be optimized for this specific application. By following the structured layout design process, an initial cell configuration can be developed to meet the needs of this bracket welding application. This section will go through the key steps like analyzing the process requirements, identifying tasks, studying task relations, and defining space needs while considering the specifics of the HK5 and FK5 parts and welding operations. The output is an initial cell layout tailored to the case study parameters as a starting point for refinement. Applying the layout methodology provides a systematic approach for developing a cell optimized for flexible, jigless multi-robot welding of the target bracket designs.

By following this structured layout development method from Zhang and Fang, an initial robotic cell layout can be designed to enable flexible, automated jigless welding using multiple articulated robots in a general sense. The following section will elaborate on each step in this structured layout development approach.

- **Process study:** The current process (using a jig) was analyzed to identify limitations and improvement opportunities. Key observations:
  - Operator manually loads and unloads parts onto a welding jig
  - Jig holds parts rigidly in position for welding
  - Operator repositions parts in a jig for each weld seam
  - Cycle time impacted by manual handling and jig limitations
- **Task breakdown:**The main sub-tasks identified are:
  - Robot 1 picks parts from a defined pick-up point
  - Robot 1 positions part 1 for access by Robot 2
  - Robot 2 picks part 2
  - Robot 2 brings part 2 to the right position w.r.t part 1
  - Vision system 1 confirms parts are aligned properly
  - Welding robot executes all welds on aligned parts
  - Vision system 2 monitors weld quality during the process
  - *In case more of part 2 are welded to part 1 the last 5 steps will be repeated(optional)*
  - Robot 1 unloads the completed assembly to the deposit area
- **Task relations:** The key task dependencies and sequences are:
  - Robot 1 picks before positioning for Robot 2
  - Robot 2 picks after Robot 1 positions
  - Assembly by robot 2 must precede vision check 1
  - Vision check 1 before welding begins

  - Vision 2 is concurrent with welding
  - Unloading after welding finished
- **Space requirements:**
  - Each robot needs sufficient work space for motions
  - Vision systems positioned for a proper view of parts/welds
  - Pick-up, position, and deposit zones based on material flow
  - Welding robot access to all sides of parts

Based on the method defined previously, an initial layout of the cell has been designed, as shown in figure 4.3.

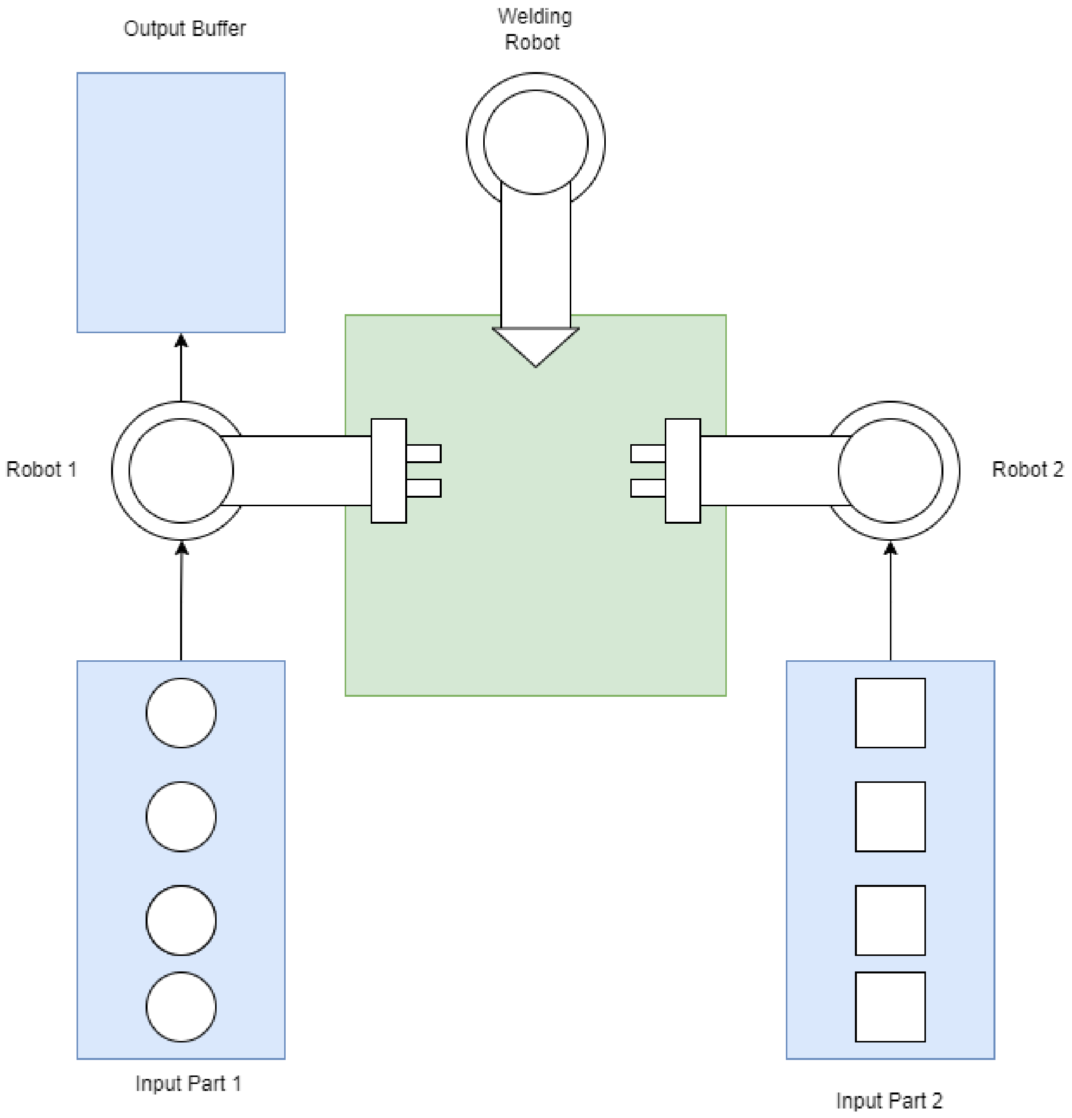


Figure 4.3: Initial cell layout

4.2.2 Gripper

Based on the jig requirements and the presented methodology, a servo-electric gripper with three articulated fingers is selected as the ideal configuration. Servo-electric grippers provide highly controllable and precise clamping forces needed for accurate locating without jig support. The three-finger design improves grip stability and adaptability to complex part geometries.

The gripper configuration consists of two fixed opposing fingers and a moving centre finger. The fixed outer fingers provide rigid locating points on each side of the bracket part. The moving centre finger actuates in and out via a screw-driven mechanism to grip and locate the part against the fixed fingers. When closed, the three fingers clamp and precisely position the part for welding. The fixed outer fingers offer stability while the actuated center finger allows flexibility to adapt to different part geometries.

This arrangement combines the advantages of two-finger parallel jaw grippers and three-finger adaptability. The dual-sided locating by the fixed fingers increases accuracy and rigidity for jigless positioning. Meanwhile, the servo-actuated centre finger enables programmable adaptability to different designs without retooling.

By integrating active force-controlled clamping and multi-finger locators, this gripper aims to satisfy the requirements of strength, precision, flexibility and control needed for repeatable jigless welding.

Additionally, the gripper design must account for the high temperatures generated during welding operations[20]. The operating temperature range of the selected servo-electric gripper model is -10°C to 50°C[21]. This is likely insufficient for the intense localized heating from welding, which can reach over 3000°C. Therefore, several design precautions may be necessary for a servo-electric gripper near the weld joint, including:

- Lengthening the gripper fingers to keep the gripper body safely distant from the heat zone.
- Adding insulating covers or heat shields to protect temperature-sensitive gripper components.
- Using suitable feedback force sensors.
- Selecting gripper materials that withstand high temperatures.

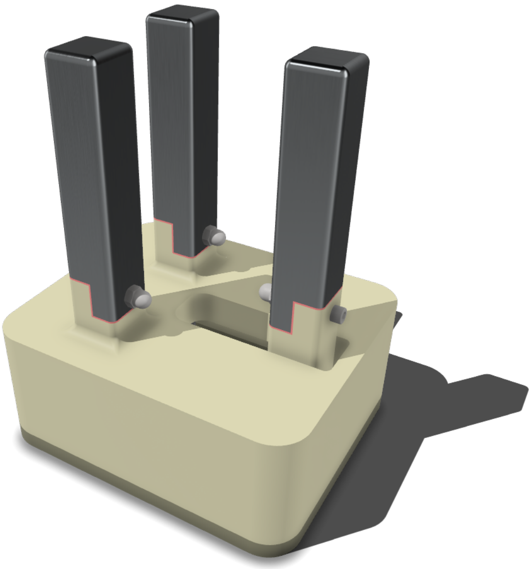
Based on a literature review of materials for jigs and fixtures[22], mild steel emerges as a suitable material choice for the gripper fingers in the proposed robotic welding solution. Mild steel provides good machinability, weldability, strength, and rigidity at a low cost. It can withstand repeated heating/cooling cycles and resists wear in sliding gripper components. Mild steel has a high heat capacity to absorb welding heat without distortion. While the gripper body should be kept away from the intense welding heat, mild steel possesses properties that make it an ideal material for the replaceable gripper fingers that will contact the hot welded parts. The high hardness of mild steel will resist wear from clamping forces. Based on its relevant material properties and widespread use in traditional welding jigs, mild steel is recommended as a promising material choice for robotic gripper fingers.

Additionally, the mild steel fingers will be thermally isolated from the gripper housing to protect the temperature-sensitive servo motor and other electrical components in the gripper body. A high heat resistance material will separate the fingers from the body, preventing heat conduction during welding. Potential options include ceramic inserts and high-temperature thermoplastics like Hard ceramics. The isolating material must withstand temperatures over 300°C without melting, burning, or degrading. By combining mild steel gripper fingers for durability and rigidity with a thermally resistant separating material, the gripper can withstand welding heat loads without overheating or degrading the enclosed actuators and components. This dual-material approach aims to satisfy both the thermal management and structural rigidity requirements for successful jigless robotic welding.

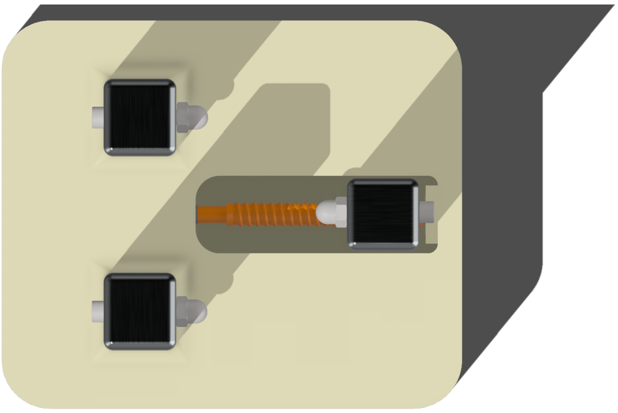
Based on the analysis of gripper requirements, a three-finger gripper design has been proposed, as shown in Figure 4.4. The gripper consists of two fixed outer fingers made of mild steel and a central servo-actuated finger. A summary of the key features of the gripper design are:

- The fixed outer fingers provide rigid locating points on each side of the picked part.
- A servo motor actuates the central finger to grip and clamp the part against the fixed fingers. It can move in and out to adapt to different part thicknesses.
- The servo motor supports torque control to replace the force sensor.
- The fingers are thermally isolated from the gripper body housing using ceramic inserts(shown in figure 4.4c). This protects temperature-sensitive components from welding heat.
- The gripper fingers are modular, allowing for the installation of smaller or larger fingers to adapt to different part sizes.
- The gripper is designed for strength, rigidity and precision locating similar to a welding jig while enabling programmable flexibility and automation.

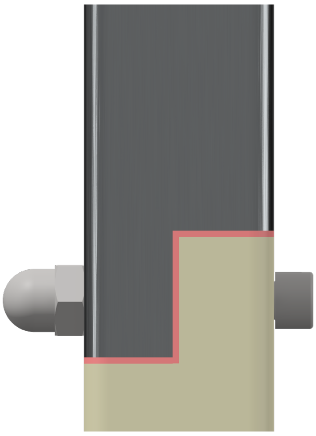
Eventually, the proposed 3-finger gripper shown in figure 4.4, aims to satisfy the requirements of jigless robotic welding, including rigidity, fit-up accuracy, thermal management, safety, and adaptability. By combining multi-finger locating with servo-electric actuation and modular fingers, the gripper provides a flexible yet robust jigless fixturing solution.



(a) Prospective view



(b) Top view



(c) Zoomed

Figure 4.4: CAD model of the proposed gripper

4.2.3 Component

In addition to the core elements of the robotic cell layout and gripper design, a variety of supporting components must be specified to enable full automation, process control, and safe operation for the HK5 and FK5 bracket welding cell. This section will identify and define the complementary technologies and equipment needed for implementing the flexible jigless welding cell using multiple articulated robots for the case study application.

Key components include:

- **Robotic Arms:** The cell will utilize 3 articulated robots - 2 for material handling equipped with grippers, and 1 dedicated welding robot. The ABB IRB 2600ID is selected, providing a 6 kg payload and 2 meter reach suited for the bracket dimensions.
- **Machine Vision Systems:** A vision system is needed at the part pick-up station for localization. A second vision system inspects part fit-up alignment before welding. The vision systems will utilize suitable cameras, optics, lighting and software for robust object detection and localization under varying conditions.
- **Safety Equipment:** Light curtains, safety scanners, and weld curtains made of flame-retardant material will surround the cell perimeter and welding area.
- **MIG Welding Equipment:** A MIG welding power source, wire feeder, torch, and interfacing cables suitable for the steel bracket welding application will be utilized. Appropriately rated fume extraction equipment is included.
- **Conveyor belt:** delivers parts to the defined pick-up location accessible by the handling robots.
- **Control System:** A suitable programmable logic controller (PLC) system will coordinate the devices via digital and network connections.
- **Software:** Visual Components is utilized for simulation, offline programming, and cycle planning.

While some components like the robotic arms and gripper are defined in detail based on the case study requirements, other complementary equipment is left generic at this conceptual design stage. For example, the appropriate vision systems, welding equipment, fixtures, controllers and software can be selected by AWL or other users. Different choices of these supporting components will not fundamentally alter the feasibility of the flexible jigless welding solution. By defining the key robotic elements like the layout, gripper and motions, the conceptual cell design establishes a framework for an integrated, automated bracket welding system using the presented jigless welding methodology. The remaining complementary equipment simply needs to meet the functionality requirements within the overall architecture. Therefore, the core technologies enabling flexible multi-robot jigless welding are assembled into a manufacturing system, while allowing leeway in choosing suitable secondary components.

4.2.4 Simulation

A simulation of the complete robotic cell design was created using Visual Components(VC) software. The cell uses three ABB IRB 2600ID robots with an average position accuracy of 0.35mm.

Figure 4.5 shows a screenshot from the VC simulation depicting the multi-robot welding cell. The arrangement utilizes the working envelopes of the IRB 2600ID robots to provide adequate space for the required motions of each robot and workstation.

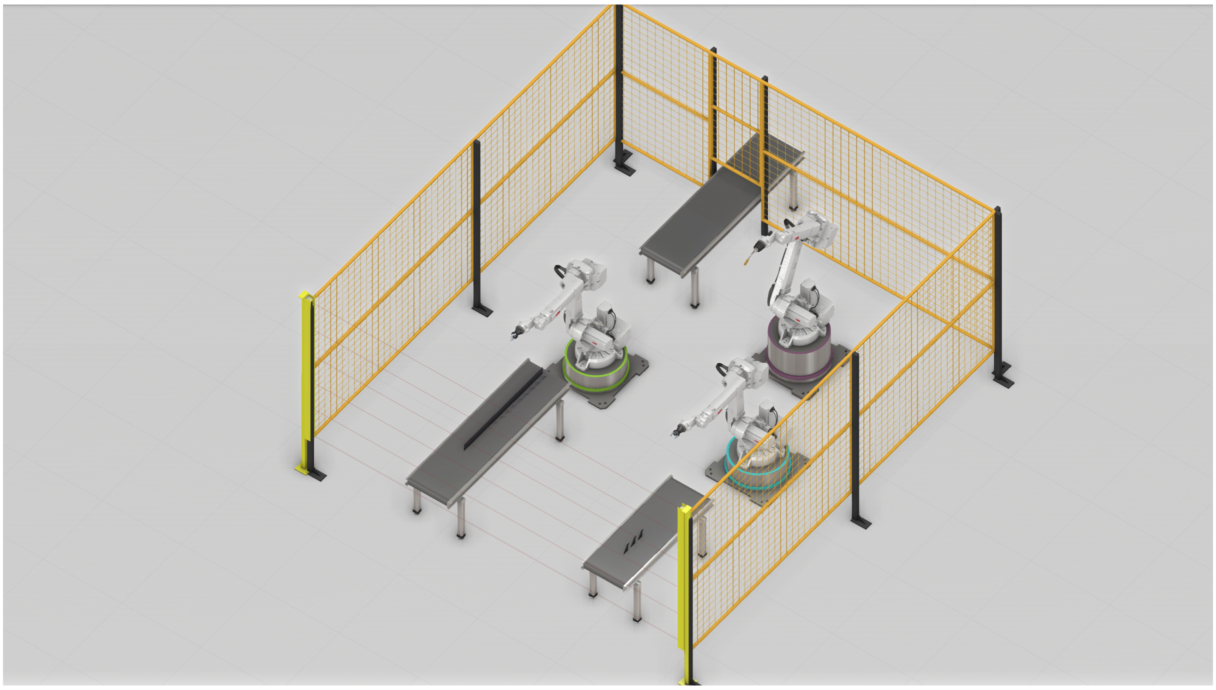


Figure 4.5: Robotic cell simulation in VC

A proposed high-level workflow for the jigless multi-robot welding cell is shown in figure 4.6. This conceptual workflow illustrates one approach for how the system could operate:

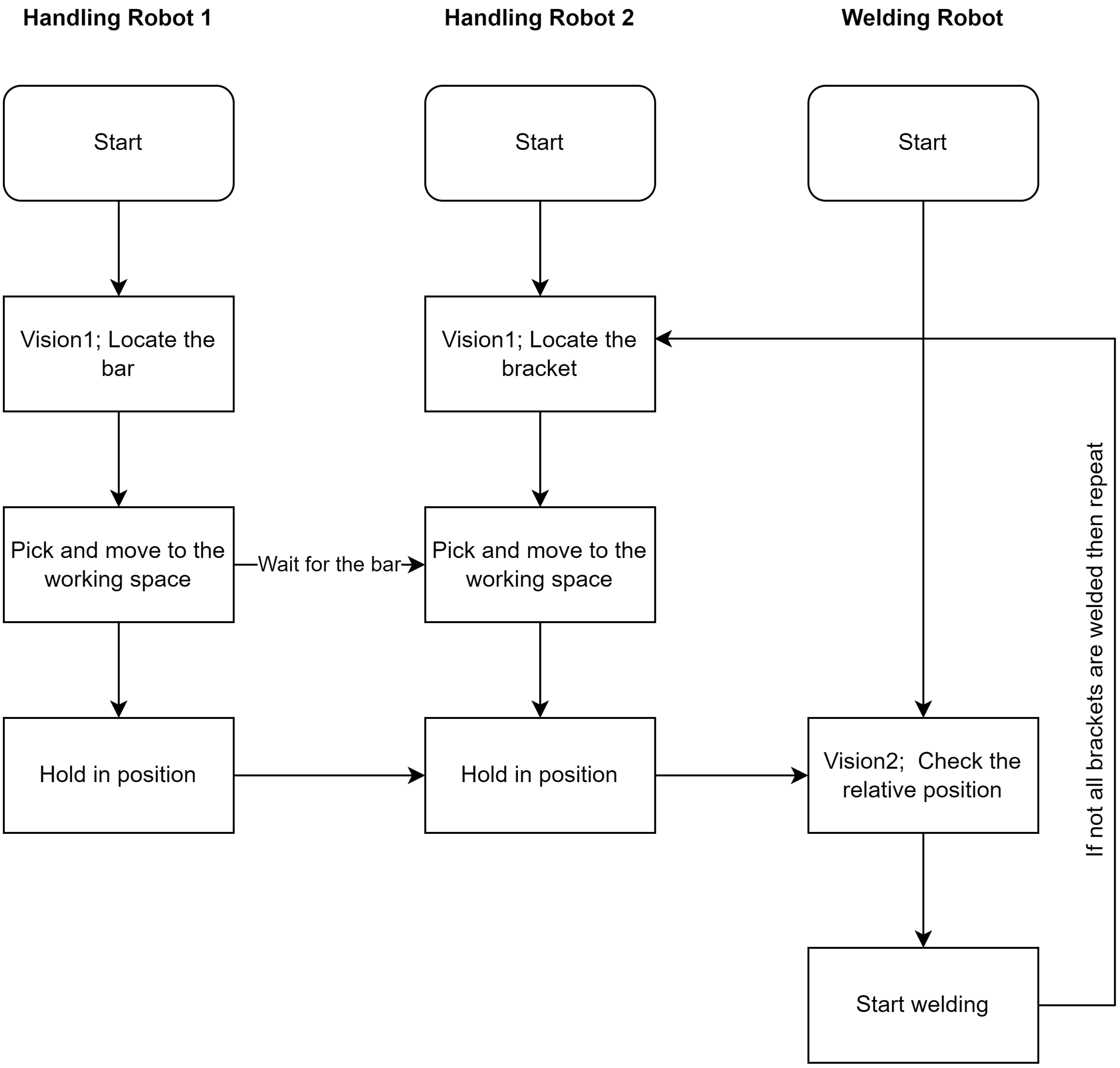
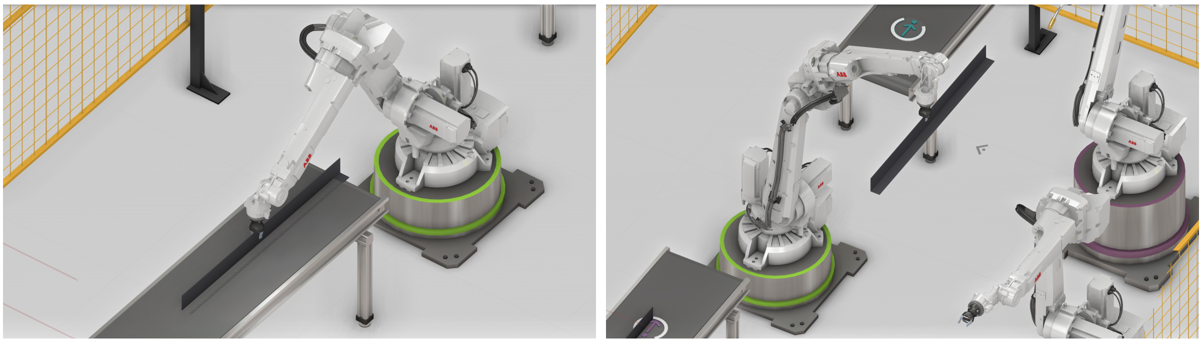


Figure 4.6: Flowchart of the process

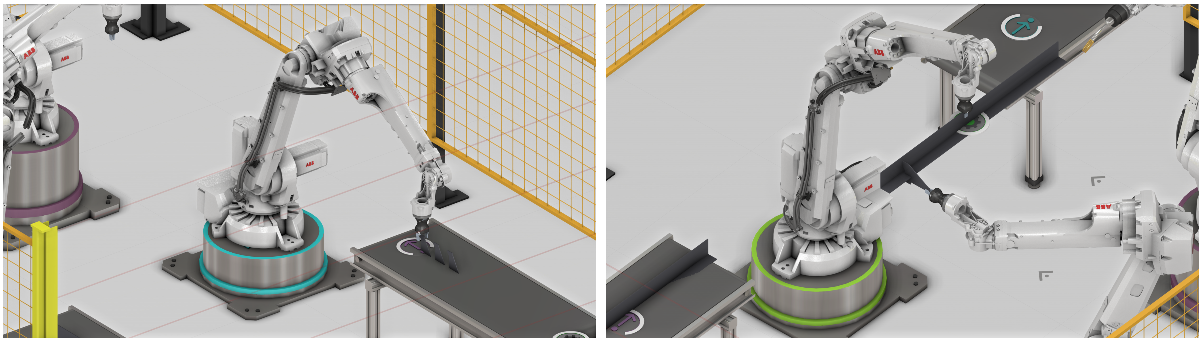
The process would begin with the first vision system locating the base part pick-up position. Robot 1 would then pick up the base part from this defined pick-up point. Robot 1 would position the base part for access by Robot 2 as shown in figure 4.7.



(a) Picking (b) Placing

Figure 4.7: Pick and place the base part

Robot 2 would then locate and pick up the second part to be welded. The second vision system could be used to check the relative positions of the two parts held by the robots. Using robotic motions and gripper adjustments, Robot 2 would align the second part precisely with the base part held by Robot 1 (as shown in figure 4.8), based on feedback from the vision system.



(a) Picking (b) Placing

Figure 4.8: Pick and place the secondary part

With the parts accurately located, the welding robot would execute the required welds to join the two components as illustrated in figure 4.9. The last two steps will be repeated depending on the number of brackets, which in this case is three times. Additionally, the sequence of welding the brackets was optimized to minimize the number of obstacles for the welding robot. Therefore, it was chosen to start with the furthest part from the welding robot.

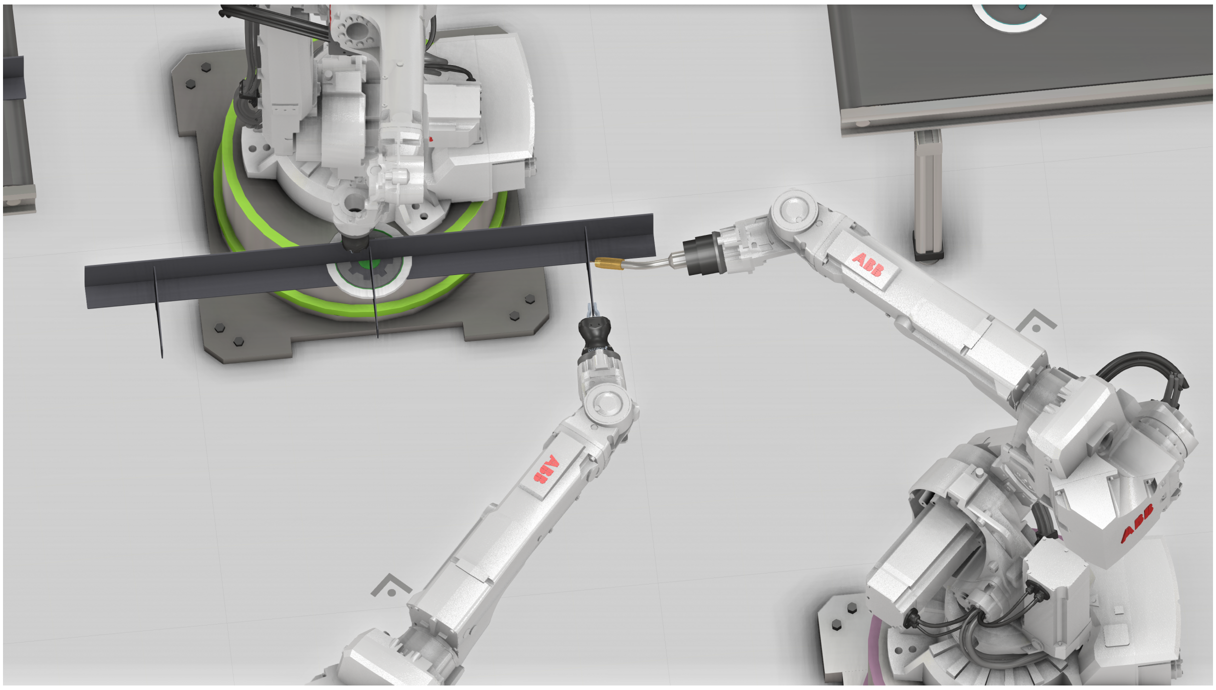


Figure 4.9: Welding process

Note that while vision systems are not included in the simulation model, they could be utilized in a real-world implementation for accurate part localization and positioning. This proposed workflow illustrates how the core functions could be coordinated across multiple robots to enable flexible jigless welding with efficiency and quality. However, physical testing is needed to validate the methodology.

The simulation was used to check the validity of the designed cell and to verify the cycle time for welding three HK5 bracket parts to the bar. The simulated time to complete the welding process was approximately 21 seconds. This time includes only the robotic motions and excludes the time needed for welding as they should be similar in both cases.

Additionally, The simulation results confirmed the feasibility of the cell design and welding cycle times before proceeding to physical prototyping and testing. No collisions, conflicts or unreachable locations were found during the extensive simulations using the defined IRB 2600ID robots.

4.2.5 Results Comparison

Operational Efficiency:

The existing process utilizing AWL's modular welding fixtures involves approximately 82 seconds. That includes the time for the manual steps of opening the jig, such as: turning the jig table, unclamping parts, loading, and unloading (3 sec jig opening, 8 sec turning table, 15 sec x 2 clamps, 34 sec part load, 15 sec part unload). In contrast, the proposed jigless methodology achieved a 21-second cycle in simulation. This implies the jigless approach could reduce the cycle time by 74% compared to the current 82-second jig-based process.

System Flexibility:

The proposed multi-robot welding confirmed through simulation the ability to achieve the same level of flexibility as the jig-based system. This was evidenced by the ability of the new system to handle different numbers of brackets at different locations on the bar(as shown in Figure 4.9, where the robot can adjust the bracket position by simply moving the second arm). However, the new multi-robot cell surpassed the jig-based system in terms of flexibility, as it was not limited by the shape of the bar and the brackets, the maximum length of the bar, or the maximum number of brackets, which was only 5 using the jig. This increased flexibility is a significant advantage of the new multi-robot cell, as it allows for greater adaptability and versatility in handling a wider range of part geometries and dimensions.

Footprint Optimization:

The results of the Footprint Optimization are illustrated in Figure 4.10, which provides a top-view comparison of both the jig-based cell(top) and the new multi-robot welding cell(bottom). The jig-based cell has a footprint of approximately 5.7 by 4.6 meters, while the new cell has a footprint of 5.1 by 4 meters. This means that we have a reduction of 22% in space compared to the jig-based footprint.

These results provide initial validation of the jigless methodology's feasibility. However, physical prototyping is needed to quantify true benefits.

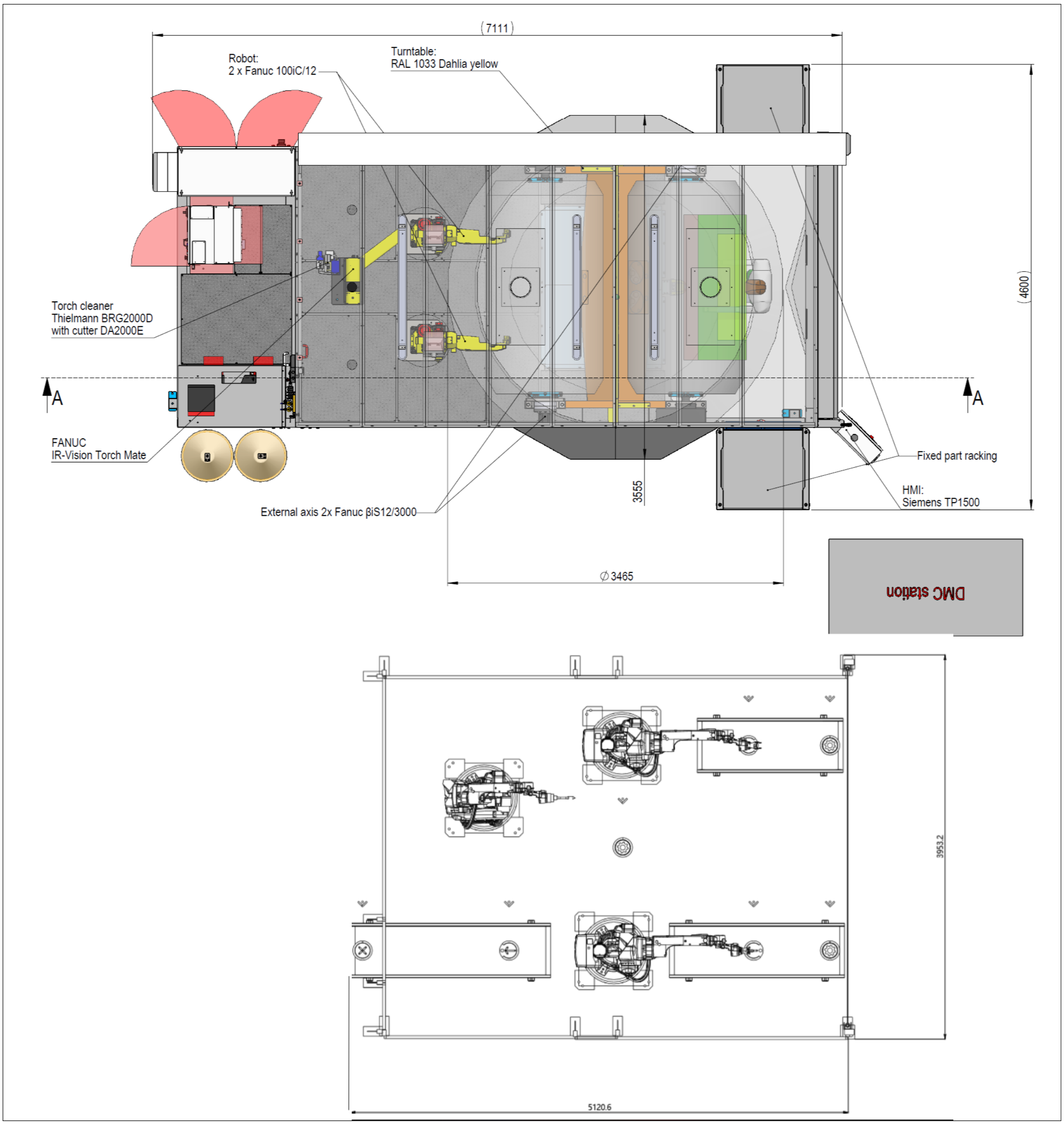


Figure 4.10: Footprint Comparison

Chapter 5

Discussion

In the preceding chapters, we have explored the intricacies of transitioning from traditional jig-based welding processes to jigless multi-robot welding systems. Through a comprehensive investigation, we have addressed the key considerations for designing the layout of a jigless multi-robot welding cell, identified the most appropriate robotic gripper design, and examined how multi-robots can cooperate to achieve desired welding results. Now, we delve into the key findings and interpretations derived from the application of our methodology, shedding light on the feasibility, potential, and implications of this innovative approach in the realm of manufacturing.

5.1 Key Findings and Interpretation

The application of the methodology successfully designed a robotic cell and gripper customized to the specific bracket parameters. This indicates its capability to systematically develop tailored jigless solutions across a range of parts. The simulated 21-second cycle time suggests significant productivity improvements may be achievable versus manual welding with a potential 74% cycle time reduction versus the 82-second jig-based process.

Relating the findings to the original research questions:

Main question: How can a high-mix, low-volume MIG welding cell be converted from jig-based to jigless multi-robot welding to reduce overall cycle time?

- The application of the methodology successfully designed a robotic cell and gripper customized to the specific bracket parameters. This indicates its capability to systematically develop tailored jigless solutions across a range of parts. The simulated 21-second cycle time suggests significant productivity improvements may be achievable compared to manual welding. However, further physical prototyping is needed to quantify true benefits in terms of cycle time reduction and welding accuracy versus traditional jig-based methods.

Sub-question 1: What are the key considerations for designing the layout of a jigless multi-robot welding cell?

- The key considerations for designing the layout of a jigless multi-robot welding cell include generating initial cell layout concepts, yielding suitable gripper designs for fixturing, specifying cell components like vision systems, and providing data to refine designs and methodology. Safety features, such as barriers and sensors, are also considered to protect workers and equipment. Flexibility is crucial, allowing for easy reconfiguration to accommodate different part geometries and dimensions.

Balancing these considerations with the constraints of the manufacturing environment, such as available floor space and existing infrastructure, is essential for a successful jigless multi-robot welding cell design.

Sub-question 2: What alternatives can replace traditional jigs to ensure both accuracy and efficient cycle time?

- The 3-finger servo-electric gripper with modular steel fingers was proposed as an optimal design for replacing the jig after analysis of gripper classifications and requirements.

Sub-question 3: How can multi-robots cooperate to achieve the desired welding results?

- The jigless methodology utilized three collaborative robots - two robotic arms equipped with customized grippers for flexible part fixturing, and a third robot dedicated to executing the welds. The handling robots worked cooperatively to accurately locate and align the parts using the grippers. This multi-robot cooperation eliminated the need for fixed jigs during automated welding. The simulation results validated the feasibility of this coordinated approach to enable flexible jigless welding by distributing roles across the robotic system.

In summary, the application of the methodology to a real-world case study demonstrated its feasibility for developing customized jigless welding solutions and indicated significant productivity potential based on simulation. Further physical testing is needed to quantify accuracy and compare performance metrics to jig-based welding.

5.2 Implications

This research has several important theoretical and practical implications. On the theoretical side, it makes a contribution by formalizing an integrated 4-step methodology for designing jigless robotic welding cells. This provides a structured framework that can be built upon and refined through future work. The quantification of performance metrics like cycle time reductions also adds useful data points to help optimize jigless methodologies.

On the practical side, this research demonstrates the feasibility of implementing jigless solutions in real manufacturing settings through the industry case study. This provides guidance to companies like AWL seeking to offer flexible automated welding to clients. The ability to rapidly adapt processes to new part designs without custom jigs addresses key needs for mass customization and high-mix/low-volume production.

As demands grow for agile, customizable manufacturing, the flexible automation enabled by jigless welding will become increasingly relevant across sectors like automotive, aerospace, appliances, and construction. This research could assist manufacturers in cost-effectively adopting jigless techniques, allowing accessible implementation at small to mid-size companies. This is significant as automated welding has traditionally required major investments in engineering and capital equipment.

By reducing changeover time and costs, jigless welding can help manufacturers improve responsiveness to market changes and new product variants. This research contributes both the theoretical groundwork and initial practical guidance needed to unlock these benefits. As more companies realize the value potential, jigless welding systems could see greater real-world adoption leading to gains in efficiency, quality, and flexibility across manufacturing industries.

In summary, this work makes both scholarly contributions in formalizing an integrated jigless methodology, as well as practical impacts in demonstrating feasibility for industrial applications. This combination of theoretical and applied insights can help drive further refinement and broader adoption of jigless solutions to meet key emerging manufacturing needs.

5.3 Limitations and Future Work

While conceptual feasibility is demonstrated, hands-on testing will be essential to validate capabilities. Therefore, future work should emphasize physical implementations and bench-marking assessments.

One potential opportunity for future work could be the development of a physical prototype based on the methodology and designs proposed in this research. This would involve constructing a jigless multi-robot welding cell by following the proposed methodology. The physical prototype could then be tested in a real-world manufacturing environment to validate the methodology and assess its performance in terms of cycle time reduction, welding accuracy, and overall productivity. Additionally, further research could explore the integration of digital twin technology to enhance the design and optimization process by enabling real-time data exchange between simulations and physical systems. This would allow for more efficient development and testing of jigless welding solutions, ultimately leading to improved flexibility, quality, and cost-effectiveness in manufacturing processes.

Chapter 6

Conclusion

This research investigated the feasibility of implementing a flexible, jigless multi-robot welding system as an alternative to traditional jig-based welding processes. A structured four-step methodology was proposed for designing optimized robotic cells for jigless welding. The methodology encompasses cell layout design, gripper selection, system component definition, and experimental verification via simulation.

The methodology was applied to a case study involving the welding of HK5 and FK5 steel brackets. Following the methodology, a robotic cell layout, gripper design, and simulation model were developed and customized to the parameters of the target brackets. The application demonstrated the methodology's capability to systematically generate tailored jigless solutions for a range of parts.

The simulation results confirmed the feasibility of the proposed cell layout, gripper, workflow, and approximately 21-second cycle time. This indicates significant productivity benefits may be achievable compared to manual jig welding. However, physical prototyping and benchmarking will be essential to quantify the true improvements versus traditional methods.

This research makes both theoretical and practical contributions. Theoretically, it formalizes an integrated methodology for jigless welding system design. Practically, it provides guidance for industrial adoption by demonstrating a customized solution for a real-world case study. As demands grow for flexible automation, this methodology could assist manufacturers across sectors in implementing accessible jigless welding systems.

in closing, this research presents a promising methodology for flexible jigless welding and validates its potential through the conceptual application. With further refinement and real-world testing, the methodology can be a valuable tool for cost-effectively automating high-mix, low-volume production. By enabling automated welding solutions without custom jigs, this research aims to bring greater efficiency and responsiveness to manufacturers.

Bibliography

[1] W. Nguyen and J. Mills, "Multi-robot control for flexible fixtureless assembly of flexible sheet metal auto body parts," in *Proceedings of IEEE International Conference on Robotics and Automation*, vol. 3, 1996, pp. 2340–2345 vol.3.

[2] G. Schuh, G. Bergweiler, F. Fiedler, and M. Koltermann, "Flexible production concept of a low-cost battery pack housing for electric vehicles," *Procedia CIRP*, vol. 93, pp. 137–142, 2020, 53rd CIRP Conference on Manufacturing Systems 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827120305990

[3] M. Bejlegaard, T. D. Brunoe, and K. Nielsen, "A changeable jig-less welding cell for subassembly of construction machinery," in *Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing: IFIP WG 5.7 International Conference, APMS 2018, Seoul, Korea, August 26-30, 2018, Proceedings, Part I.* Springer, 2018, pp. 305–311.

[4] A. Kampker, G. Bergweiler, J. O. Hansen, and W. J. Borbola, "Jigless laser welding in the car body production," *ATZ worldwide*, vol. 119, no. 2, pp. 72–75, 2017.

[5] J. Zhang, J. Yang, and B. Li, "Development of a reconfigurable welding fixture system for automotive body," in *2009 ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots*, 2009, pp. 736–742.

[6] Z. Ahmad, S. Lu, M. Zoppi, D. Zlatanov, and R. Molfino, "Reconfigurability and flexibility in a robotic fixture for automotive assembly welding," in *Advances in Reconfigurable Mechanisms and Robots II.* Springer, 2016, pp. 1073–1081.

[7] V. Paquin1a and M. Akhloufi2b, "Vision-guided universal articulated gripper for jigless robot welding," in *Applied Vision and Robotics Workshop 2012.* Moulay Akhloufi, 2012, p. 68.

[8] H. Lund, "Development of a multi-robot welding cell for jigless welding," 2019.

[9] E.-R. Bagherian, "analysis of jigless spot welding process parameters," 11 2020.

[10] D. Rokossa, "Automatic path and program generation for fixtureless welding with two synchronized robots," in *2022 IEEE 1st Industrial Electronics Society Annual On-Line Conference (ONCON)*, 2022, pp. 1–6.

[11] E. B. Njaastad and O. Egeland, "Automatic touch-up of welding paths using 3d vision," *IFAC-PapersOnLine*, vol. 49, no. 31, pp. 73–78, 2016.

[12] M. Peña-Cabrera, I. Lopez-Juarez, R. Rios-Cabrera, and J. Corona-Castuera, "Machine vision approach for robotic assembly," *Assembly Automation*, vol. 25, no. 3, pp. 204–216, 2005.

[13] A.-L. Andersen, T. D. Brunoe, K. Nielsen, and C. Rösiö, "Towards a generic design method for reconfigurable manufacturing systems: Analysis and synthesis of cur-

rent design methods and evaluation of supportive tools," *Journal of Manufacturing Systems*, vol. 42, pp. 179–195, 2017.

[14] J. Zhang and X. Fang, "Challenges and key technologies in robotic cell layout design and optimization," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 231, no. 15, pp. 2912–2924, 2017.

[15] H. Wang, Y. K. Rong, H. Li, and P. Shaun, "Computer aided fixture design: Recent research and trends," *Computer-Aided Design*, vol. 42, no. 12, pp. 1085–1094, 2010.

[16] Z. Samadikhoshkho, K. Zareinia, and F. Janabi-Sharifi, "A brief review on robotic grippers classifications," in *2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE).* IEEE, 2019, pp. 1–4.

[17] S. Raval and B. Patel, "A review on grasping principle and robotic grippers," *Int. J. Eng. Dev. Res*, vol. 4, no. 1, pp. 483–490, 2016.

[18] M. Honarpardaz, M. Tarkian, J. Ölvander, and X. Feng, "Finger design automation for industrial robot grippers: A review," *Robotics and Autonomous Systems*, vol. 87, pp. 104–119, 2017.

[19] A. Vatankhah Barenji, X. Liu, H. Guo, and Z. Li, "A digital twin-driven approach towards smart manufacturing: reduced energy consumption for a robotic cell," *International Journal of Computer Integrated Manufacturing*, vol. 34, no. 7-8, pp. 844–859, 2021.

[20] D. Pham and S. Yeo, "A knowledge-based system for robot gripper selection: criteria for choosing grippers and surfaces for gripping," *International Journal of Machine Tools and Manufacture*, vol. 28, no. 4, pp. 301–313, 1988.

[21] "Servo motor design considerations for hazardous environments," 2021. [Online]. Available: https://www.kollmorgen.com/en-us/blogs/servo-motor-design-considerations-hazardous-environments

[22] C. C. Okpala and E. Okechukwu, "The design and need for jigs and fixtures in manufacturing," *Science Research*, vol. 3, no. 4, pp. 213–219, 2015.