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Research Paper

Optimizing the Implementation of a Robotic Welding System

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Abstract
This paper describes the research, development, and optimization of a robotic welding system at a leading Irish AgriTech company. The project required the development of robotic welding fixtures using best design principles and the generation of associated weld programs to enable the automated welding of several products in the production system of the company. This study provides complete fixtures in line with customer requirements using Autodesk Inventor CAD software. By following an integrated methodology that links the industry standard approach to fixture design with product development tools including QFD, Pugh charts, and DFMEA, a defined structure to this process is provided, while ensuring transferability throughout the industry. It was found that the generation of an industry-ready robotic welding program using Panasonic DTPS software was aided by following a prescribed methodology. This complex process was streamlined by applying the defined coordinated approach enabling the gradual knowledge growth necessary to complete an industry-ready robotic program. The study demonstrates that moving from traditional manufacturing methods to robotization is possible for an SME. The benefits for enterprises seeking to replace mechanical manufacturing processes by adopting robotic welding systems and consequently capitalizing on the potential of this robotic technology are evident.

Keywords
Robotic Welding, Fixture Design, Industry 4.0, Internet of Things, Robotic Programming, AgriTech

1. Introduction

Rapid advancement in intelligent manufacturing systems has forced many enterprises to implement modern manufacturing systems in efforts to maintain global market expansion. Those willing to change are reaping the product and organizational benefits of this evolution and expanding their knowledge of the production system. Industries are now expected to have communication and intelligent capabilities throughout manufacturing, engineering, material usage, supply chain, and, life cycle management [1]. The benefits are reflected in increased productivity, improved quality, efficiency, and mass customization [2]. The emergence of the Internet of Things (IoT) and Industry 4.0 have revolutionized industrial capabilities. With Industry 4.0 the presence of these intelligent systems connected through the Internet of Things (IoT) can provide interaction in smart factories [2]. Production systems are evolving into cyber-physical-production-systems (CPPS) and machines are now becoming smart machining centers [3]. The physical being machines and sensors and the cyber being, data storage, and mining. For welding technology, Industry 4.0 can be characterized as the interaction of components, intelligent welding robots, and CPPS-supported welding systems with networked product quality [4]. Welding and joining have been recognized as key enabling technologies for EU manufacturing, with almost thirteen million jobs in high-tech manufacturing, enterprises need to embrace the full potential of these modern systems [5]. The implementation and optimization of a robotic welding system at this manufacturing site highlight a considerable engineering knowledge gap which may be evident throughout the Irish AgriTech industry. This knowledge gap ensures the transformation from existing manual manufacturing methods to intelligent manufacturing systems remains a major challenge. This is a challenge shared not only in the AgriTech industry but across many enterprises seeking to adopt these systems.

Ireland has a rapidly developing economy with the AgriTech sector seeing exponential growth. Maintaining a competitive advantage within this industry requires efficient production and high-quality standards due to high labor costs. Additionally, sourcing suitably qualified welders is an ongoing challenge for the industry, and therefore, a gradual transition from manual arc welding to robotic welding on this product was planned. It was envisaged that robotization of the key manufacturing steps on selected products can enable superior quality, and higher productivity, and provide a safer working environment for its employees.

The implementation of a robotic welding system is dependent on the availability of accurately designed fixtures and a high level of programming experience. These fixtures ensure the locational accuracy of the workpiece while the welding program is run. Core functionality must include the elimination of movement, and sufficient torch access to each weld seam while providing a straightforward loading and unloading system for the operator. The fixture design process can be complex, time-consuming, costly, and typically heavily dependent on system and product knowledge built over many years. When acquiring this technology, the company did not have significant robotic system knowledge, with many of the existing manual fixtures developed by skilled operators to suit their specific needs. While a limited number of fixtures have been developed using CAD onsite, none have been developed following a defined approach and therefore any proposed methodology must be easily followed from the industry partners' perspective to enable successful implementation. In addition to these challenges, the development of robotic weld programs is a highly specialized task and can be associated with a considerable proportion of the overall system implementation costs [6]. Studies have shown these costs can be as high as 63% of total costs [6]. These programs typically require a skilled programmer or extensive operator training with limited alternatives found outside of manufacturer-specific training programs, which are extremely costly. These limited training options and specific skills requirements can dilute the benefits of the robotic systems for many SMEs, highlighting the need to provide structured guidelines allowing the development of skills and process understanding through each of the individual programming stages. While novel developments in these subject areas may provide some suitable solutions, the complexities involved in implementing these solutions would broaden the knowledge deficit and not serve as a useful purpose for this enterprise or similar SMEs who remain the focus of this study.

2. Methods

The costs associated with fixture design can be as high as 20% of the total costs of the manufacturing systems [7]. Up to 40% of all rejected parts linked to dimensioning errors can be attributed to poor fixturing design. Significant cost savings can be achieved by reducing design costs and increasing the accuracy of fixturing [8]. These figures highlight fixtures as key components in modern manufacturing systems [7]. In automated welding, a fixture is required to rapidly, accurately, and securely, position the workpiece during the welding operation. Automated fixture design while extremely efficient is complex and often relies on the use of established fixtures to finally deliver a conceptual solution. The reliance on industrial experience is highlighted in many of the design processes studied, signifying the need for a clearly defined process that provides a pathway for inexperienced designers. Following a defined process with links to the new product development process can reduce fixture implementation costs and time by up to 75% [9].

The advantages of robotic welding systems are clear, many smaller production systems have struggled to adopt Offline programming (OLP) due to the prohibitive cost of software implementation and the requirement for either a skilled programmer or extensive operator training. Over 63% of the total costs of ownership of an industrial robot are associated with training employees or external programmers. OLP methods may vary, but the programming methodology must follow several core steps to generate a complete program [10]. Automatic path generation is novel but has not yet provided a sufficient fit for all requirements. Tag generation, trajectory planning, and process planning are highlighted as tedious steps and research indicates little if any generic guidance is offered. The efficient generation of robotic welding programs can be aided by a transparent methodology linking the specific software and system used with programming methods extensively adopted in the industry. These issues can be supplemented by the development of a structured OLP methodology guiding SMEs through the individual programming process stages.

2.1 Fixture Design

Developing a fixture in line with the methods documented in published literature can substantially reduce these costs and lead times. The four main stages of the design process are setup planning, fixture planning, fixture unit design, and design verification. Collaborative discussions with the industry partner provided a clear understanding of the design goals in terms of suitable materials, selected suppliers, and manufacturing methods and additionally provided alignment with other documented product design procedures observed in the literature. The creation of the core requirements utilizing the structured Quality Function Deployment (QFD) design tool can provide the designer with a methodical starting point while ensuring the needs of the SME remained a priority. Once concepts have been generated using the Autodesk Inventor CAD software package, the use of structured screening tools and methods including Pugh charts can enhance fixture unit design. Additionally, these can provide a clear stepping stone between the fixture planning and unit design stages. Fixture verification using the Design failure mode and effect analysis (DFMEA) enables a structured design verification throughout the process, and this broadly adopted method can be of additional support to verification methods using tools such as Autodesk Inventor and Desk Top Programming & Simulation System (DTPS). In addition to this, location accuracy and accessibility verification can be conducted on physical samples once the fixture has been manufactured.

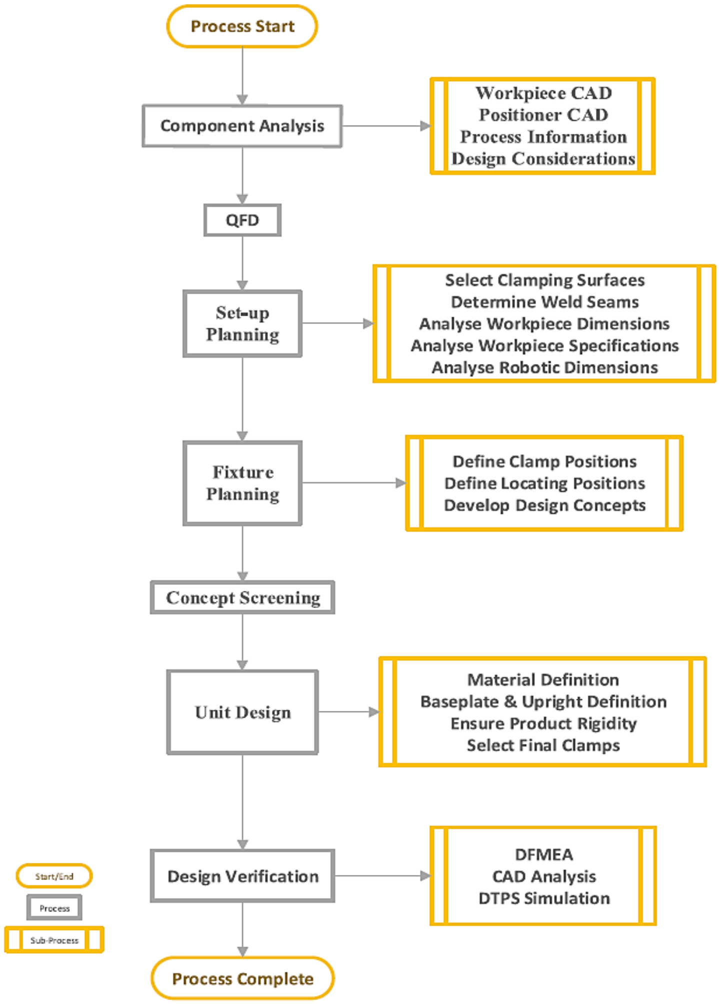


Figure 1. Fixture Design Methodology

2.2 Robotic Programming

The methodology highlighted in **Error! Reference source not found.** provides a structure that can enable SMEs to efficiently develop a robotic weld program in line with accepted industry methods and published literature. The main programming steps are transferred into specific tasks which remain aligned with guidelines provided by the welding system supplier through each of the online training sessions and programming manuals. Positional and procedural tags are universally recognized in robotic programming and the addition of numerical weld points identifying each weld seam during the trajectory planning stage is an accepted robotic welding process step. These were developed in conjunction with the SME through the many review meetings and are an adaption of the existing manual welding steps. Collision avoidance is an iterative process and can be run completely once the program has been developed to a sufficient level. However, the touch sense functionality which is handled in the process planning and calibration section is only relevant to robotic welding systems utilizing this type of calibration method. The complexity involved in programming a robotic welding system can be significantly reduced by closely following the high-level steps as outlined in the proposed methodology. These headings provide defined start points for the unskilled programmer and provide a structured pathway to develop the welding program. This methodology provides a combination of extensively used industry methods while remaining focused on the knowledge deficit amongst many SMEs.

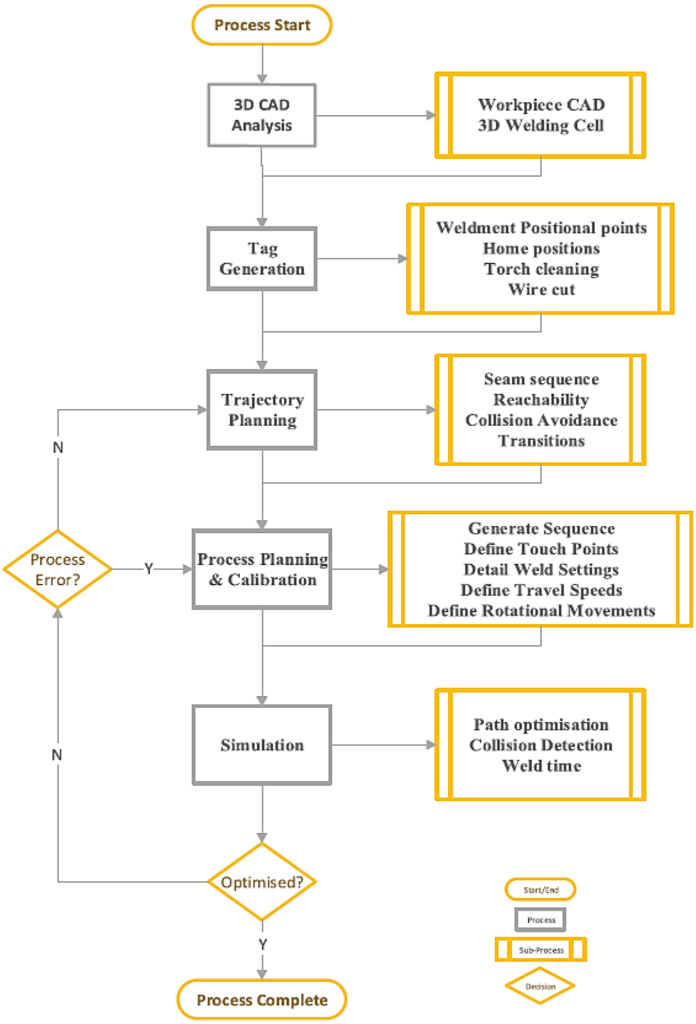


Figure 2. Robotic Programming Methodology

3. Results and analysis

3.1 Fixture Design

By using the methodology outlined, it was possible to develop a deep and structured understanding of each critical component of the robotic welding system. Once the QFD was complete the system requirements were identified, and several individual concepts were then developed. These concepts were then analyzed, assessed, and ranked using Pugh charts with a final version detailed and developed in line with manufacturing requirements. The final fixtures were then validated remotely using a DFMEA, Autodesk Inventor, and DTPS simulations to ensure robotic access for all identified weld seams was possible before final assembly.

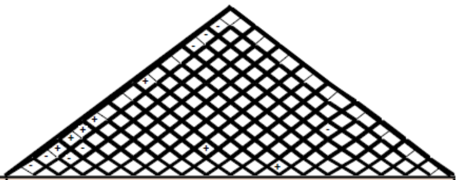
3.2 Component analyses

The first step in the design process requires the team to analyze the core aspects of the required work package. The workpiece CAD geometry provides a starting point where detailed information on the size and shapes can be reviewed. High-level design considerations such as existing fixtures and concepts as well as customer requests are all a fundamental part of this step. Additional considerations here include the process type, weld locations, and any forces or movements that may be encountered during the welding process

3.3 QFD

These rankings can guide the design process and can be kept in alignment with the DFMEA process. From the completed QFD, the rankings highlight the following specifications as essential for the successful design of the robotic welding fixtures:

1 Ease of location and accuracy (Six Degrees Of Freedom)
2 Torch/robotic clearance
3 Low material cost (Raw Material)
4 Fixture size (HxWxD)
5 Manufacturing Complexity/cost
6 Fixture rigidity



Quality Function Deployment
Project: Robotic Welding Fixtures

Correlation		
+		-
Postitve	None	Negative

Relationships			
9	3	1	
Strong	Moderate	Weak	None

Physical requirement (PR)
Collision Prevention (CP)
Usability Requirements (UR)
Affordability requirements (AR)
Design Constraints (DC)
Tolerance Requirements (TR)

Customer Requirements - (What's)		Customer - AgriTech	Fixture size (HxWxD)	Robotic positioner geometry (Location)	Robotic positioner dimensions (W)	Torch/robotic clearance	Remains within Torch/robotic reach	Within positioner rotation pathway	Clear error proofing (Poke Yoke)	Loading Time	Fixture safety features	Steps to load workpiece	Low material cost (Raw Material)	Number of parts	Manufacturing Complexity/cost	Ease of location & accuracy (Six DOF)	Robust clamping mechanism (Kg)	Fixture rigidity	Workpiece Tolerancing	Manufacturing Tolerancing	AgriTech Fixture	Modular Fixtures	Automated Fixture
		Who	How - Functional Requirements: PR			CP			UR				AR			DC			TR		Now		
		1:Low 5: High	↓	↑	↓	↑	↓	↓	↑	↓	↑	↓	↓	↓	↑	↑	↑	↑	↓	↓			
Fitment of workpiece and weld sation's must be ensured	Workpiece must fit on fixture	5	9									3				3			3	1	5	4	4
	Fixture must fit on positioner	5	3	9	9																5	3	4
Must allow welder to access all desired weld points	Robot must reach all welds freely	5				9	9														5	3	4
	Torch must have clear access	5	1			9	3	3													4	4	4
	Unobstructed positioner rotation	3		1	3	3	1	9													5	3	4
Loading and unloading must be straightforward and fool proof	Must be easy to load and correctly locate the workpiece	2	1						9	9		9				9	3	3			4	3	3
	Can be placed and removed from the positioner	1		9						9		9				9	3		3		4	2	3
	Must be safe to handle	4								1	9	3					1				5	4	5
Jigs needs to use affordable material and be easy to	Reasonable material costs	4	3		1				3		1		9	9	9			3			4	1	3
	Easy to manufacture	3							3				9	9	9						5	1	1
	Easy to replace parts if damaged	3							3	3			9	3	3						5	3	3
Secure the position of workpiece	Workpiece must be fully constrained when in jig	5												1	1	9	9	9			4	4	4
	Must not flex or move during operation	2	1									1		1	3	9	9	9			4	4	4
Must allow for production variability	Must fit all produced workpieces	4	1																9	9	4	5	4
	Importance		85	57	58	99	63	42	48	40	40	56	90	79	83	105	76	81	54	41	Total Score		
	Importance Weight %		7.1	4.8	4.8	8.3	5.3	3.5	4.0	3.3	3.3	4.7	7.5	6.6	6.9	8.8	6.3	6.8	4.5	3.4	63	44	50
	Rank		4	11	10	2	9	15	14	17	17	12	3	7	5	1	8	6	13	16			

Figure 3. Fixture Design QFD

3.4 Setup Planning

During this phase, it is essential to analyse the workpiece dimensions and properties, highlight potential clamping surfaces, and understand the relevant robotic dimensions. Many of these dimensions link directly to the QFD specifications which provides design guidance for the team which in turn significantly reduces the time spent analysing each area once again.

3.5 Fixture Planning

Fixture planning involves the development of conceptual fixtures based on the requirements highlighted through both the QFD and setup planning. Once the initial system analysis has taken place it is possible for the designer to develop simple conceptual sketches or if sufficiently skilled the designer can choose to create basic CAD models. Suitable workpiece surfaces are studied, and specific points are selected as potential clamping solutions. Details of numerous clamps are analyzed and imported into a 3D format for ease of manipulation and interpretation. These models provide a clear graphical overview of the workpiece, and they can be used to guide a design team through each concept. While fasteners may be intended in the final design, details of these items are not specified or refined at this point. Additionally, material definition can take place, while ensuring individual and customer requirements during this step. Once several solutions are generated it is then possible to use concept screening charts to select a preferred solution while observing the functional requirements as developed and prioritized in the QFD.

3.6 Concept Screening

Each fixture concept outlined in the fixture planning stage was input into this matrix where the pros and cons were itemized and allocated to each of the concepts. The mechanical criteria ratings follow the key functionality as outlined in the published literature and compiled in the QFD in Figure 3. All concepts were rated against each other in their ability to meet the design criteria.

Robotic Fixture Concept Pugh Chart

Design Criteria	A: Concept V01	B: Concept V02	C: Concept V03	D: Concept V04	E: Concept V05	F: Concept V06
Fixture size (HxWxD)	+1	+1	0	0	0	0
Robotic positioner geometry (Location)	-1	0	+1	+1	+1	+1
Robotic positioner dimensions (W)	-1	-1	+1	+1	+1	+1
Torch/robotic clearance	-1	-1	0	0	+1	+1
Within Torch/robotic reach	0	0	0	0	0	0
Within positioner rotation pathway	0	0	0	0	0	0
Clear placement error proofing (Poke Yoke)	0	0	0	0	0	+1
Loading Time	-1	-1	-1	-1	+1	+1
Fixture safety features	-1	-1	-1	-1	+1	+1
Steps to load workpiece (4)	0	0	0	0	+1	+1
Low material cost (Raw Material 41 Kg)	+1	+1	-1	-1	-1	+1
Number of parts (17)	0	0	-1	-1	-1	+1
Manufacturing Complexity	-1	-1	-1	-1	+1	+1
Ease of location (Six DOF)	-1	-1	-1	-1	+1	+1
Robust clamping mechanism (550Kg)	0	0	0	0	+1	+1
Fixture rigitidy	+1	-1	-1	-1	+1	+1
Workpiece Tolerancing	-1	0	0	0	+1	+1
Manufacturing Tolerancing	-1	0	-1	-1	+1	+1
Sum +	3	2	2	2	12	15
Sum 0	6	9	8	8	4	3
Sum -	-10	-8	-9	-9	-2	0
Net Score	-7	-6	-7	-7	10	15
Rank	4	3	4	4	2	1

Figure 4. Concept Screening Method

3.7 Detailed Unit Design

With a final concept selected, it is then possible to refine each component and generate a final assembly. The main components including the baseplate, sides, supports and clamps must be fully defined. This design must ensure the assembly can achieve sufficient clamping forces, and rigidity and absorb any workpiece tolerance. While the SME does not perform final dimensional checks on the manufactured components or assemblies it was advised through design review to ensure all fixture tolerances are kept to less than 1mm. The completely detailed 2D engineering drawings for each component were presented to the SME, here only the main design considerations are listed.

Fixture Design Considerations		
Overall Assembly	**Headstock Legs Fixture**	**Hinge Fixture**
Rigid base part	Yes (6mm & 30° bend)	Yes (8mm & 30° bend)
Base part with fixturing features	Yes (8.5 x 20.5mm slots)	Yes (8.5 x 20.5mm slots)
Absorb workpiece functional tolerance	Yes >1mm throughout	Yes >1mm throughout
Overall part count minimized	Yes	Yes
Minimum use of separate fastners	All M10 x 35	All M10 x 35
Weld access	Yes (1.5mm recess for plug weld)	Yes (1.5mm recess for plug weld)
Parts with end-to-end symmetry	All main uprights	All main uprights
Straight-line motions of assembly	Yes (90° angles only)	Yes (90° angles only)
Chamfers to facilitate insertion and self-alignment	Yes (2x2mm chamfer)	Yes (2x2mm chamfer)

Figure 5. Final fixture design considerations

3.8 DFMEA

The DFMEA is utilized here to identify the main failure modes associated with the Fixtures. As highlighted in the literature it considers the effects of each failure, the potential causes of the failure, and the estimated frequency of the occurrence of those failures. Finally, the DFMEA provides a risk priority number that enables the indexing of each identified failure and guides the required corrective action to ensure the issues are not present in advance of final production. The top ten items from this DFMEA are highlighted below. With each identification number linking the requirements captured in the QFD. The applied methodology analyses each requirement and the associated component or feature to develop a systematic analysis of the fixture designs and build a comprehensive DFMEA.

ROBOTIC WELDING FIXTURE DFMEA

Number	Item Id Number	Function Description	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Prevention Method (prevention of cause of failue)	Occurrence	Detection Method (D) (detection of potential failure mode)	Detection	RPN	Recommended Actions	Responsible Person(s)	Corrective Actions Taken
1	9	Must not flex or move during operation	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Fixture Flex - baseplate riidity not sufficient	P: Material & Dimensions selected based on datasheets, experience and testing.	7	D: Assembly trials	3	147	Add 30° bend to increase baseplate rigidity	Fionn Foley	Bend added
2	8	Workpiece must be fully constrained when in fixture	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Fixture Dowel - locating slot incorrect location and/or incorrect dimension	P: Material & Dimensions selected based on datasheets, experience and testing. P: Review of workpiece &dowel interface via 3D model	6	D: Verification of Cad data for fit D: Assembly trials	2	84			None Required to Date
3	8	Workpiece must be fully constrained when in fixture	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Clamp force - insufficient	P: Clamp selected based on datasheets, experience and testing.	4	D: Clamping trials	3	84			None Required to Date
4	9	Must not flex or move during operation	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Fixture Flex - upright supports not sufficient	P: Material & Dimensions selected based on datasheets, experience and testing.	6	D: Clamping trials	2	84	Upright support dimensions to be increased	Fionn Foley	Redesign Complete
5	10	Must fit all produced workpieces	Tolerance requirements are not fulfilled	Installation in fixture not possible/difficult	8	fixture tolerance not aligned with workpiece tolerance	P: Design based on workpiece and customer requirements P: Open tolerances >1mm	5	D: Verification of Cad data for fit D: Assembly trials	2	80			None Required to Date
6	7	Must be safe to handle	Operator safety requirements are not fulfilled	Installation in fixture not possible/difficult	9	Fixture fillets - not sufficient	P: Design based on safety requirements P: Review of fixture safety features via 3D model	4	D: Verification of Cad data for safety	2	72	Increase Fixture fillets to 10 mm	Fionn Foley	JFixture fillets increased to 10 mm
7	7	Must be safe to handle	Operator safety requirements are not fulfilled	Installation in fixture not possible/difficult	9	Clamping method - not safe	P: Design based on safety requirements P: Review of fixture safety features via 3D model	4	D: Verification of Cad data for safety D: Assembly trials	2	72			None Required to Date
8	8	Workpiece must be fully constrained when in fixture	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Clamp position - incorrect location and/or incorrect dimension	P: Design based on workpiece requirements P: Review of workpiece &dowel interface via 3D model	4	D: Verification of Cad data of clamp D: Assembly trials	2	56			None Required to Date
9	8	Workpiece must be fully constrained when in fixture	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Clamp supports - incorrect location and/or incorrect dimension	P: Material & Dimensions selected based on datasheets, experience and testing.	4	D: Verification of Cad data for fit D: Assembly trials	2	56			None Required to Date
10	8	Workpiece must be fully constrained when in fixture	Constraint requirements are not fulfilled	Workpiece not secure in fixture	7	Clamp supports - insufficient strength	P: Clamp selected based on datasheets, experience and testing.	4	D: Clamping trials	2	56			None Required to Date

Figure 6. Robotic Fixture DFMEA Top 10

3.9 DTPS Simulation

The final verification steps outlined in the methodology required the analysis of the fixtures and the loaded workpiece within the DTPS environment. Further details of this software and its significance are detailed at length in section 4.2. The use of this software provides a link between the designer and programmer and emphasizes the importance of cross-functional collaboration between the many teams operating in a modern engineering environment. The accessibility of each seam must be analyzed and if any restrictions are evident a design update will be required. Similarly, collision avoidance must be ensured, and the complete fixture design can be carefully analyzed with each clamp in its closed position. This provides a clear representation of the physical outline of the complete fixture and enables a thorough assessment of the suitability of the final fixture design. This step is tightly bound to the unit design phase and indeed many of the functional requirements should have already been clearly understood by the designer before reaching this ultimate step. However, design errors are certainly a reality, and this study is linked to inexperienced design teams, therefore the simulations are imperative.

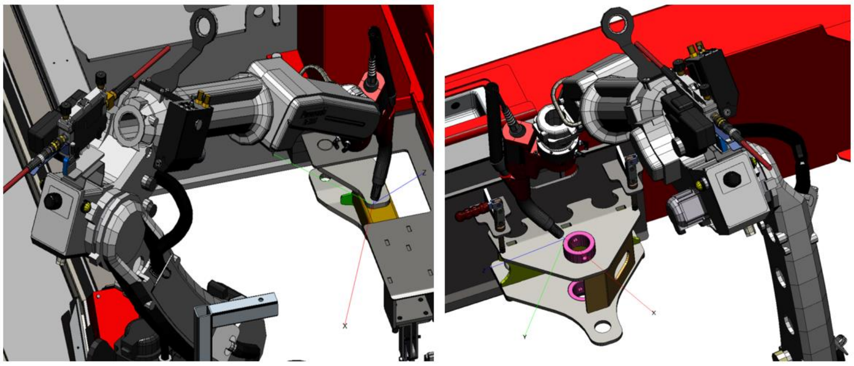


Figure 7. Validation of fixtures within the DTPS environment

3.10 Robotic Programming

DTPS software was used in conjunction with Panasonic robotic manipulators and Panasonic Tawers weld controllers for offline path generation and simulation [3]. The gradual development of the required knowledge was possible following the programming methodology developed. Tag generation ensures the positional data of the workpiece is accurate within DTPS and provides the opportunity to generate assistant tags such as home positions, approach points, and retreat points. The structured identification of each weld seam was handled in trajectory planning with a numerical seam sequence generated and revised. The process planning and calibration stages define the weld poses and transitions in combination with outlining the preliminary weld settings and travel speeds. The calibration points used to ensure accuracy were also programmed here as the specific system utilized Touch Sensing. The results obtained by following this methodology were of the industry-required standard and once the programs were transferred to the SME they were immediately utilised for onsite testing.

3.11 DTPS 3D Environment

An overview of the robotic cell, as it appears in the DTPS environment, is depicted in Figure 8. Major components within this cell are highlighted in the diagram including the Tawers Global Controller G3, Panasonic TM-2000WGH3 robot, VWP-R500 FE welding torch, Thielmann BRG 2000 mechanical cleaning unit with inbuilt wire cutter, VWK 7/1 water cooling unit, Panasonic AUR01060 teach pendant, BICORE BINZEL xFUME fume extraction system and Leuze light screen enabling emergency stop functionality.

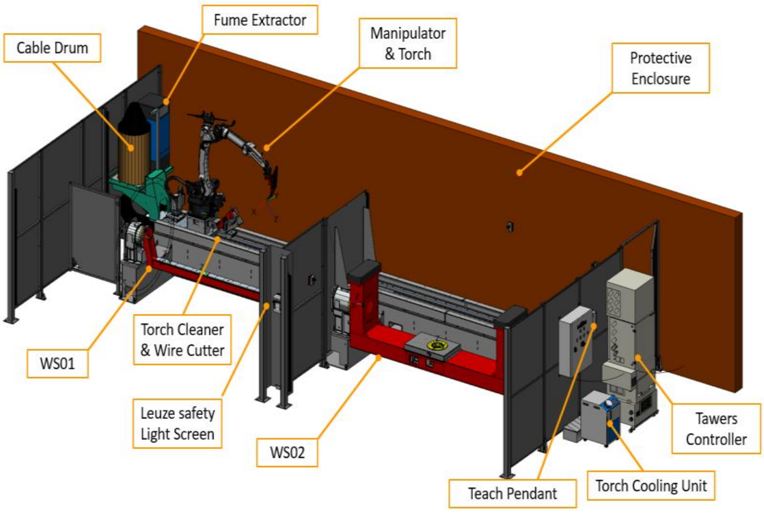


Figure 8. Robotic welding cell within the DTPS environment

3.12 Tag Generation

Tag generation is the process of extracting the positional data and reference planes of the workpiece and aligning them within the software. This ensures the workpiece geometry is aligned with the intended position during the welding process, enabling the required accuracy to be met. Assistant tag points can also be programmed here, including cleaning, and cutting procedures, home positions, approach points, and retreat points. These procedures and points can be called at any time throughout the specific weld program. Once the workpiece assembly has been imported into the DTPS environment, the axis center point requires a transfer to align it with the selected robotic axis position.

3.13 Trajectory Planning

This step requires the programmer to analyze and identify each weld seam on the workpiece and create a high-level plan which can then provide the required steps to create a detailed weld program. Each potential configuration of the workpiece must be carefully considered to prevent collisions and minimize transitions [9]. A commonly adopted practice is to assign the weld seams and touchpoints a numerical value for ease of identification during post-processing analysis and validation [10]. These numerical values are assigned in sequential order providing a structured workflow from one seam to the next. This enables the programmer to easily arrange the most suitable transitions and pathways between each seam. Seam identification was also highlighted as an essential step in the fixture design process. This step must be reconsidered as the workpieces are now constrained within the finished fixtures and therefore, the process must carefully identify any seams with a low clearance or challenging access.

3.14 Process Planning and Calibration

Process planning involves the development and detailing of each sequence step required to generate an optimized weld program. These steps include the approach and touchpoints, weld settings, travel speeds, and the final trajectory plot. Once the weld sequence and poses are plotted, the calibration data which in the SMEs system are touch points, can be added to the program following the selected sequence. Process planning can be time-consuming and challenging, requiring a general understanding of the many commands and calls available within the DTPS system. While the provided methodology certainly delivers a high-level guide to the requirements of the process planning step, it is not designed to enable the programmer to develop a complete weld program without specific DTPS system training

3.15 Simulation
The last step involved in generating a robotic program is simulation. Here the program can be verified using the DTPS software, which significantly reduces the downtime of a robotic system while ensuring collision and limits are avoided. Within the DTPS environment, this task is straightforward as it provides the ability to simulate each step or the entire program. Using the specific collision detection application within DTPS it is possible to check for any collisions within the entire weld cell. If the collision detection simulation passes, the programmer can then move on to analysing each axis while the program is running. This provides a clear overview of the joint angles throughout the program and can highlight any areas where the desired limits are breached. The last step in the simulation environment provides a clear overview of the cycle time including, Arc ON time, Arc ON rate, welding length, number of seams, and wire length. This can provide a clear understanding of the impact each variable may have on the finalized cycle time

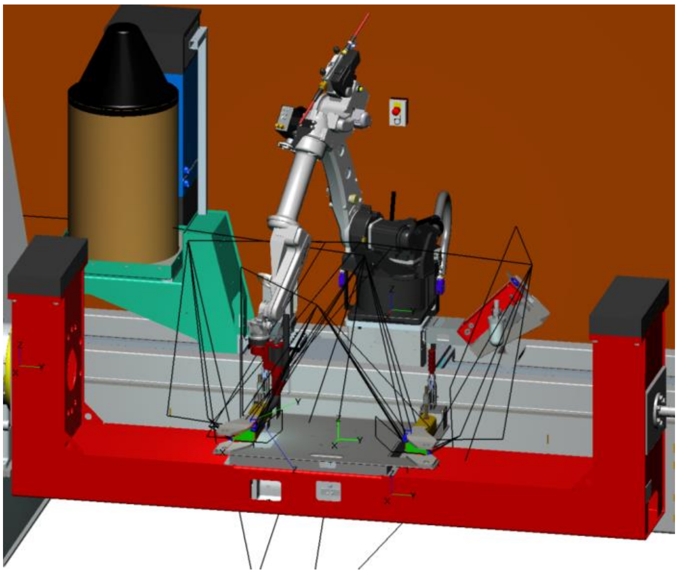


Figure 9. The final weld path as shown by the various trajectory lines

4. Conclusion
The implementation and optimization of a robotic welding system have been successful using the integrated methodologies developed throughout this study. The structured design and optimization of two robotic welding fixtures and the generation of associated robotic welding programs have been completed.

1. It was shown that the development of robotic welding fixtures was significantly enhanced following the outlined methodology which links an industry-standard approach to fixture design with product development tools that provide a defined structure to the design process. The

application of these tools including QFD Pugh charts and DFMEA provides a link between many phases in the design process and as they are universally accepted tools, the transferability of this methodology throughout the industry was ensured.

2. The generation of industry-ready robotic welding programs was developed in line with the methodology detailed. This coordinated approach ensured this process was streamlined and the development of the required programs was structured to enable the gradual knowledge growth necessary to complete this complex process.

In previous studies, the methodologies used to develop fixtures displayed several significant gaps with many of these providing little guidance on knowledge development or general structure. Here, the integration of industry-recognized product development tools removed the reliance on extensive prior knowledge and provides structure, enabling the designer to make informed decisions on key requirements, material screening, and design changes throughout the development process. Similarly, by following the proposed programming methodology a gradual development of the required skillset is possible. This methodology has effectively guided the development of two industry-ready robotic welding programs which are currently undergoing online tests to ensure optimisation of each step.

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