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DESIGN AND OPTIMIZATION OF THE WELDING ROBOT SYSTEM FOR ALUMINIUM FRAMES USING SIMULATION SOFTWARE

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Abstract

The aim of this study was to evaluate Welding Robot Systems (WRS) for aluminium parts in terms of energy efficiency, cycle time and workspace, automation process and cost. The study also considers the reachability, accessibility and positioning accuracy requirements for automated robotic welding to ensure the ability to weld any part of the product. The most recent methods and technologies such as seam tracking, simulation software, digital twin and virtual reality are used in this work to determine compliance with the concept of intelligent manufacturing.

Using the methodical approach, different layouts of the WRS are designed to meet different industry requirements and to handle different configurations for different products. A robot simulation tool has supported all design steps, evaluating different scenarios for different system configurations. The virtual reality capabilities of the simulation tool provided the ability to check the movement of the robots through fixtures and parts in "near real" dimensions. Intelligent system software would be used to ensure the accepted quality of the parts and to automate various activities.

The study also considered intelligent welding systems, as they have shown great potential in experimental settings and there is growing interest in their application in industry.

Keywords: Robot System; Simulation; Intelligent Welding.

1. Introduction

Welding allows the components to be permanently joined together. This joining allows the components to withstand the mechanical stresses throughout their life cycle. As this process is accompanied by various side effects such as exhaust fumes, heat, etc., which would have health effects on humans, welding is carried out with the robot systems. To get an idea of how large the share of welding applications is in the industry, Figure 1 is shown. According to “World in Robotics 2022” [1], it has the second biggest installations of industrial robots.

Despite great advances in processes such as bonding, clinching, etc., welding remains the only alternative due to the mechanical properties of the welded parts. Robotic systems are therefore also being developed and optimized for a range of products. Some robot manufacturers even offer complete solutions that include welding equipment, safety components, exhaust systems, etc. This significantly reduces engineering, assembly and set-up costs, whereby the robot vendor then takes responsibility for the safety of the robot system.

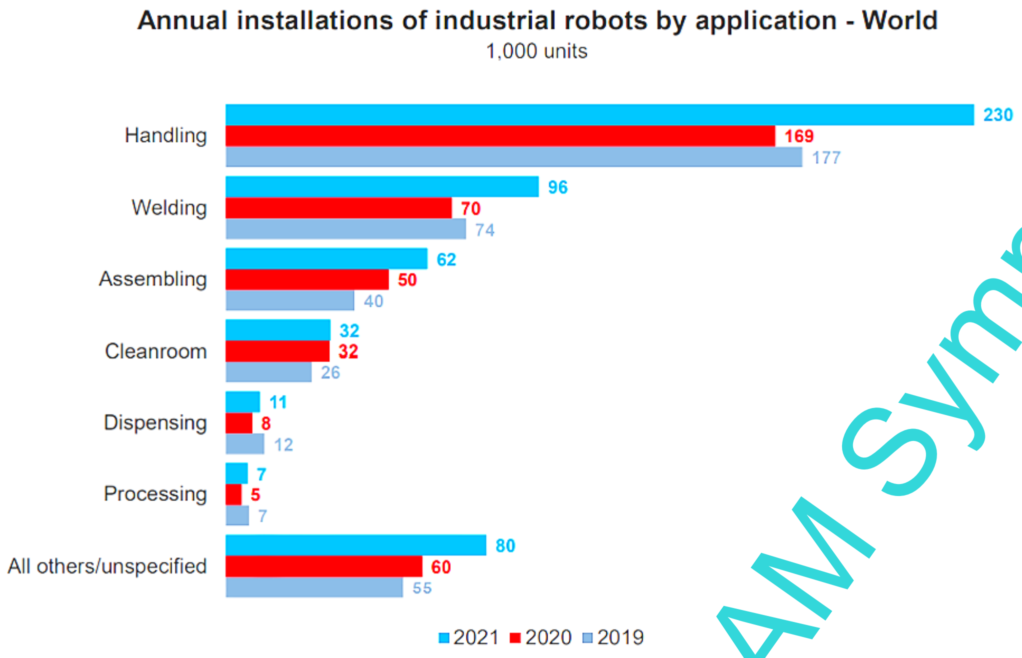

Fig. 1. Annual installations of industrial robots by application [3]

Most used technology for welding is MIG/MAG (Metal Inert Gas /Metal Active Gas). MIG/MAG welding is a widely used manufacturing process to produce components with high strength properties. This process involves permanently joining two or more components through the application of thermal energy [2]. In MIG/MAG welding, a filler metal or welding wire ignites the arc when it touches the component. To protect the arc from the reactive oxygen in the environment, a so-called shielding gas also flows through the gas nozzle [3]. This displaces the oxygen during welding and thus prevents oxidation of the arc and the weld pool [3].

In recent years, various tools/systems have been developed to enable weldability when joining components made of different materials on the one hand and to increase energy efficiency on the other. Intelligent Manufacturing (IM) and Smart Manufacturing (SM) are terms that refer to the use of technologies such as Artificial Intelligence (AI), and Machine Learning (ML) in the manufacturing industry. Both terms refer to the integration of intelligent systems and technologies into Manufacturing Processes (MP) to improve efficiency and enhance product quality [4]. The main difference between IM and SM is that IM is based on the use of AI and ML to automate and optimise MP. Smart manufacturing, on the other hand, refers to the use of Internet-of-Things (IoT) technologies and other digital solutions to improve and optimise MP. In general, it can be said that IM is a subset of SM, as IM builds on SM technologies. However, there is also overlap between the two areas and the boundaries between them are not always clearly defined. Due to the digitalisation of the industry, digitalisation is also becoming increasingly important in the field of welding robots. This can be seen in Fig. 2.2, which shows the number of papers published on SM and IM over the years [5]. From 2015 onwards there has been an increase in scientific papers on these topics. For this purpose, numerous simulation tools and Power Packs such as "Arc Welding Power Pac for RobotStudio" have also been developed. In this paper, the state of the art of software for MIG/MAG welding is analyzed. The most recent software from the main robot manufacturers and software vendors is examined.

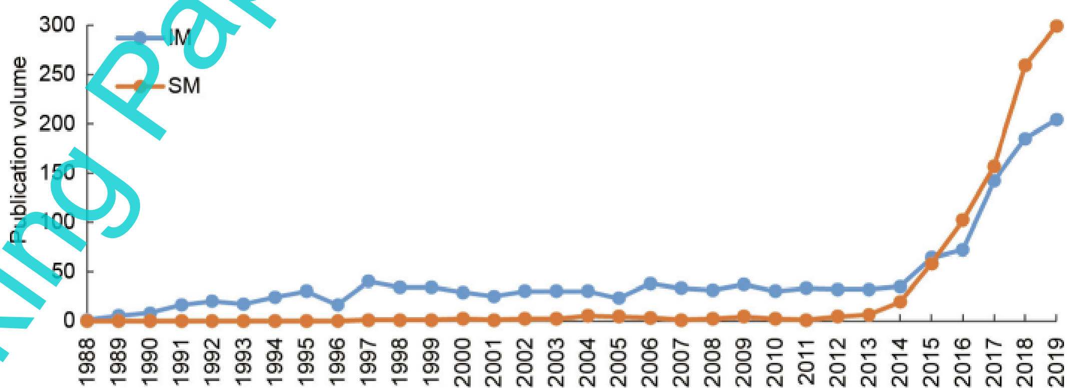

Fig. 2. Publication volume on SM and IM during 1988-2019 [5]

2. Problem description

The rapid advancement of technology has greatly impacted the efficiency and effectiveness of various industries, including the market for MIG/MAG welding robots. As a key economic sector, it is important to understand the current state of the art in terms of software and simulation software used in this market.

While the main manufacturers of these products offer similar features, there may be a lack of representation from pure software manufacturers, and it is unclear which features truly represent the current state of the art. In order to stay competitive and meet the demands of an ever-evolving industry, it is necessary to examine the latest features and assess their alignment with the concept of intelligent manufacturing.

Welding Robotic System (WRS) has been proposed based on the requirements from the industry. An industrial robot with 6 axes should work in parallel with 2 (two) working tables, so the working space of the industrial robot should cover the area of 350°-360° for each table of the WRS. Welding gun cleaner should be able to be able to match with welding robot. Manual loading and unloading of product. One time fixing of the product onto the fixture (see Figure 3).

An Industrial robot has to reach the entire working space of the structure to be welded.

Workpiece material: aluminium, wall thickness: 2,5 mm – 15 mm; Max. Frame Size: Length: 1500x750 mm, and Min. Frame Size: Length: 1200x750 mm. Product Tolerance: ±0.05 mm. No gap between welded profiles. The dimensions of the profiles are mainly for the plates for building.

The cylinders or fast clamps or other solution need to be used to fix the position of the product with the lever principle to ensure the positioning requirements of automatic welding of the robot, so as to ensure that it can be welded to each part of the product. According to the requirements of production efficiency, two sets of one axis positioner need to be designed, one for loading and unloading of the workpiece, one for welding.

In addition to robotics, the accompanied software can be used to easily program industrial robot and software usage. If possible to add the instrument Point to Point recording of the material to be welded.

The working tables should be easily rotated in order continue with welding on opposite side.

Special protective mechanism to prevent welding spatter or dust in the air which will cause bad impact of precision parts. In order to adapt to the different conditions of different requirements, be able to do different configuration for industry.

The anti-collision device needs to been considered to feedback the collision information in time and protect the key parts of the robot. Additional request from the industry is related to the robot working software for welding.

One of the main requirements regarding the robotic arm for welding is its connection with various working programs such as Autodesk Inventor, SolidWorks, etc.

Why this advantage would be more acceptable we will give the following explanation:

If this data were to be transferred to the RWS, it would not be necessary to compile a robot programming for different details each time, but any robot programming information would be obtained from the working program, and the only action that would be done would be to centre the robot on the first point of the weld and everything would be easier.

TIG welding, MIG welding can be used for Aluminium welding. Simulation software needs to be used in the MIG/MAG welding robot market, and to outline the Intelligent Welding Systems (IWS) developing process.

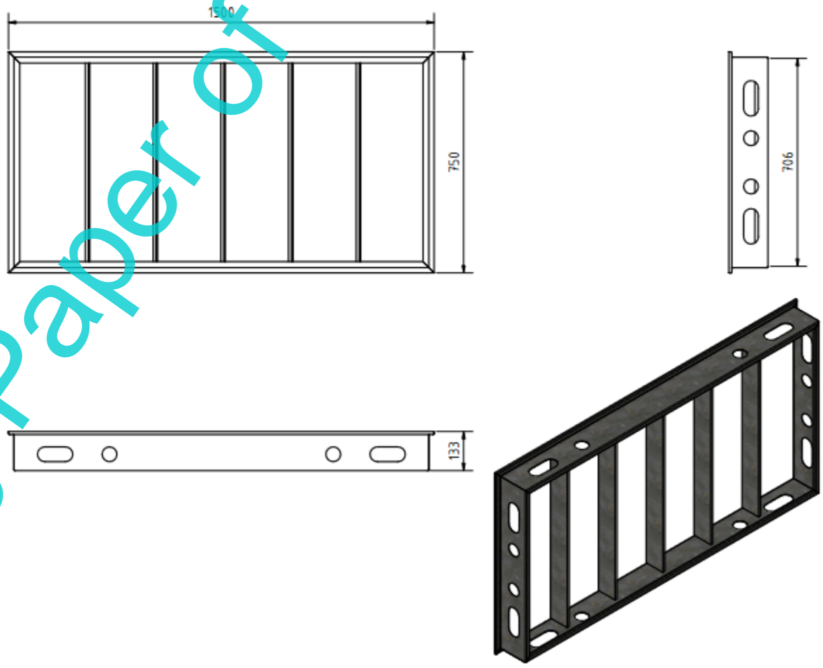

Fig. 3. Dimensions in mm of the frame to be welded

3. Materials und Methods- Design of mechanical system of the intelligent robot welding systems

As described in the problem statement above, in this study case, aluminium frames in various sizes are to be welded. The customer's list of requirements is very long and part of it is shown in Table 1. From this list, the requirements must be fulfilled, whereby there are also customer wishes and customer recommendations which are also fulfilled if possible. In other words, the designed robotic cell must fulfil multi-criteria (technical, economic, safety, environmental, etc.). On the other hand, there are many companies (such as ABB) that offer standardized solutions for welding applications. In most cases, these solutions are also configurable, which drastically reduces engineering costs. But, in most cases the customer is looking for an offer that is more cost effective (in most cases customized) than standardized solutions. In addition, there are so many component manufacturers competing for the same robot system function carrier. This makes the task very difficult to solve, especially with the limited time to solve the problem/provide the solution to the customer. In this case, students (education) and system integrators - small and medium sized companies (industry) - become uncertain and sometimes overwhelmed. To remedy this situation, this paper describes a method based on VDI-2221 (Verein Deutscher Ingenieure -2221). This method has already been explained in the papers [6], so the steps are not explained explicitly.

3.1. Customer Requirements - the first stage of the methodical approach-for welding robot system

The requirements list is the first stage of the design process. In this stage, the system integrators/students create a list of customer requirements in terms of the desired functionality of the robot applications. It is very important that all requirements are included in the table. Later, it is very easy to check that the requirements have been met. This means that checking row by row, rather than reading the whole project folder, saves a lot of time. At the same time, this provides more transparency between the customer and the system integrator.

Here are the requirements that are important in the case study:

- The parts are aluminium frames with different dimensions and geometric complexity (see Figure 3). The maximum dimensions are 1500mm long x 600mm wide x 200mm high.
- There are no customer fixtures. This means that the fixture must be designed.
- The frame is to be welded using a conventional process such as inert gas (MIG) or tungsten arc (TIG) welding. There is also no customer specification for the welding process. This means that there are a number of different processes to evaluate in order to select the best and most cost effective. This will depend on the material, material thickness and mechanical requirements.
- Loading and unloading can be done manually (by the operator), which has a direct impact on safety, but also requires cycle time analysis check- using simulation software. Cycle Time should be max: <4 Minutes/ Frames.
- In this case the material flow is not continuous. There are also interruptions while the operator loads and unloads the parts and restarts the machine.
- Safety requirements should be covered by current standards and machine guidelines.
- Safety requirements: the cost of the project must not exceed the budget. In these Case < 350.000 Euro.

Requirements			Demands	Wishes
Technical Req.				
	Workpiece	Weight	10kg	15kg
		Content	Aluminium Frames	
		Dimension	Max 1.500mm x 600mm x 200 mm	
		Cycle Time	<4 Minutes/ Frames	3
		Loading/Unloading	Manual by operator	
	Fixture	Weight	Manual Loading	Semiautomatic Loading
	Processing	Type	MIG/TIG	
		Material Workflow	Discontinuously	Continuously
Safety Req.				
	Mechanical		National guidelines/ ISO	
	Electrical		National guidelines/ ISO	
Secure Req.	**Software**	Authorization	OPC UA	
	Hardware			
Cost Req.			<350.000€	

Table 1. Short list of customer requirements for welding of aluminium Frames.

3.2. Conceptual design – searching for suitable solutions of welding robot system.

The conceptual design stage is a process of generating different proposals (Variants or Solution candidates) that can be used to build the welding robot system. Usually there are complex system with lot of components. To reduce the complexity, the whole system (based on VDI- approach) can be divided into subsystems with less complexity (see the Table 2). That is the first step in this stage. The left column of the table shows the Subsystems/subfunctions. If the subsystem is still complex, it can be divided into smaller function carriers, e.g., "device for positioning of parts" and so on.

The second step in this stage is finding solutions for each subsystem. More than one solution (sub-solution 1, 2 … n) should be found for each subsystem. For a better understanding or management of the sub-solutions, they can be placed in a box (called Zwicky "morphological box"). This approach stimulates creativity to find new solutions.

The third step in this stage of methodical approach is combining of sub-solutions to find the whole solution of the system. Another advantage of the morphological box is the creation of different solutions (solution candidates) or variants of the system by combining (mapping) different sub-solutions (if technically feasible). After combining/mapping the possible solutions, the possible candidate concepts are selected for evaluation. However, during the selection process of variants should take into account all customer requirements, compliance with security guidelines and technical/economic requirements. This requires a great deal of experience on the part of the system integrator [6].

	Sub-Solutions for the Sub-Functions			
Sub-Functions of robot system	**Sub-Solution 1**	**Sub-Solution 2**	**….**	**Sub-Solution n**
Handling/TCP Moving/ Robot	6 axis Welding Robot	6 axis universal Robot	….	Cartesian Robot, Hyper redundant robot [11]
Welding System	MIG	TIG	….	Laser Welding
Robot Moving	Stationary	Linear axis		Linear axis hanging
End-Effectors	22-degree Weld-Gun	45-degree Weldgun		Tandem Weld gun
Parts Positioning	Linear Axis	2 Axis	….	3 Axis
	Two Stations/ two Devices	Two Stations / one device		
Part inspection/scanning	Tactile sensor	Using IR Sensor	….	Vision systems
Exhaust/extractor system	Localy/partial	full		
Safety components	Safety Gates	Light Grids	….	Optical monitoring
……………………	………………..	………………..	…..	…………………
User Authorization	OPC UA	Windows embedded /IOT	….	Linux
Solution Candidate (SC) - Variants	SC1	SC2		SCn

Table 2. Simplified "morphological box" (Zwicky box) for creating of solutions -variants.

Let's look at the selection of the first candidate (SC1) in the table.

- The main component of the system is the robot (manipulator). There are different kinematics that can be used to perform the welding task, but nowadays there are special robots for special tasks. You can use a welding robot instead of a universal robot. The advantage of the welding robot is that the media (gas, filler material, etc.) go directly into the holes of the wrist. This means that there is no noise during welding. The disadvantage is that this type of robot can only be used for welding or in a water jet system. For other applications, such as palletising, this robot kinematics is unsuitable. A Cartesian robot cannot be used in this case study.
- There are also different welding processes (first column, row 2). Possible candidates are MIG, TIG, laser, etc.
- For the Robot moving subsystem (Function), the question is whether the robot is stationary or in a linear motion axis. This would make sense for long parts or when operating several stations in a row.
- The next sub-function deals with the torch. It is obvious that a torch will be used. For simple parts or good accessibility, a torch with a small bend (22 degrees) will be sufficient. For complicated parts and tight spaces, for example, 45 or 60 degrees should be used.
- Through the other partial solutions considered, different variants can ultimately be created. The following illustrations show different layouts. This means that different options can be considered. The best solution will depend on the requirements and evaluation criteria.

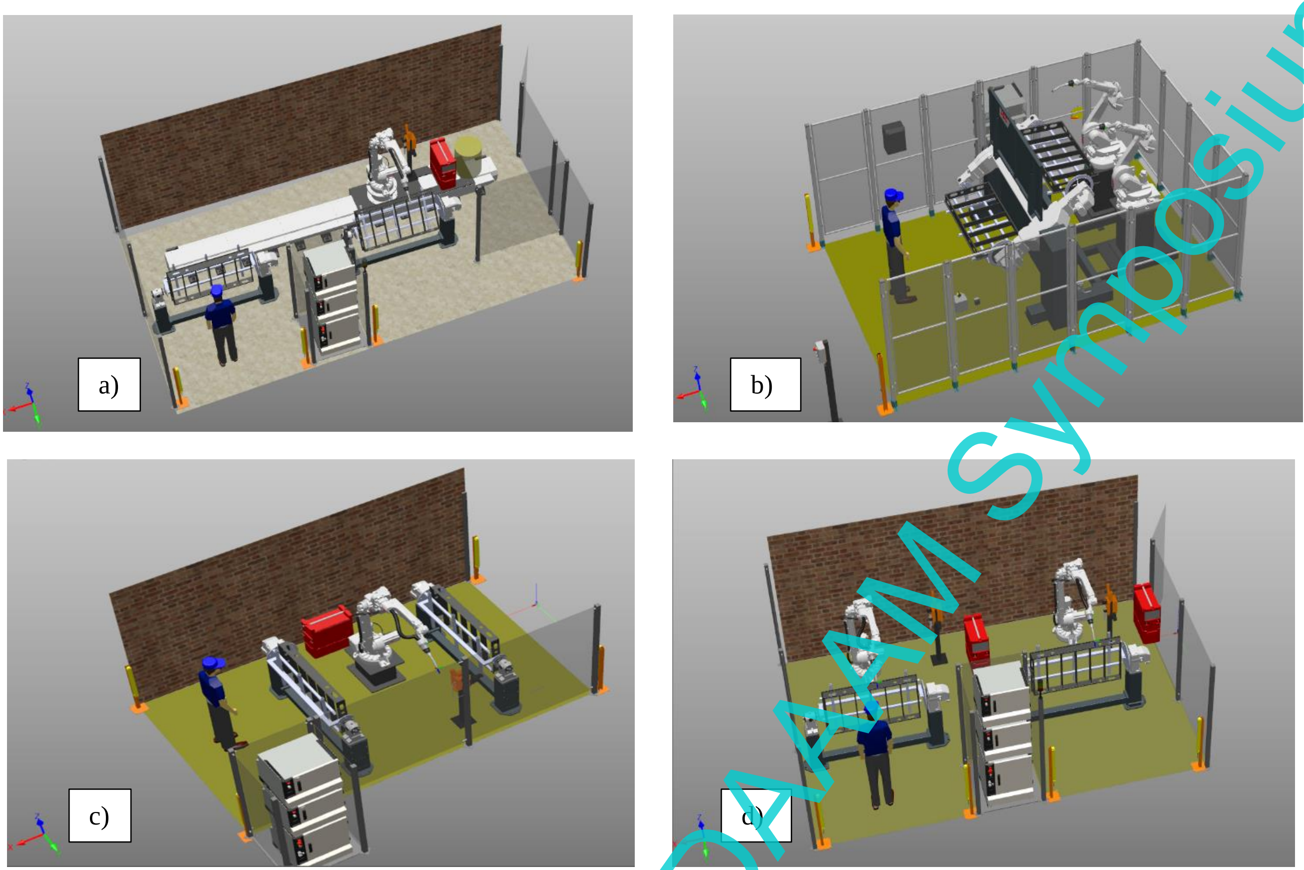

Fig. 4. Different Variants (Solution Candidates) for WRS: a) Robot in linear moving axes, b) Two Robots and K-Positioner, c) One robot and two L-Positioner and d) Two Robot/two L-Positioners

As can be seen in the Figure 4, different combinations of subsystems are possible, resulting in different solutions for the overall robotic welding system. The next step is to evaluate the generated layouts according to predefined criteria and customer requirements. The next figure shows the evaluation criteria for this case. If all the criteria have the same weighting coefficient, this looks like a regular polygon. If the criteria have different weighting coefficients, then this would be seen as a non-regular polygon.

In this case, the solutions can be scored between 0 (inappropriate solution) and 1 (ideal solution). Where 0.75 would all be favourable. Ideal solutions are very rare when multiple criteria are used (see Figure 5).

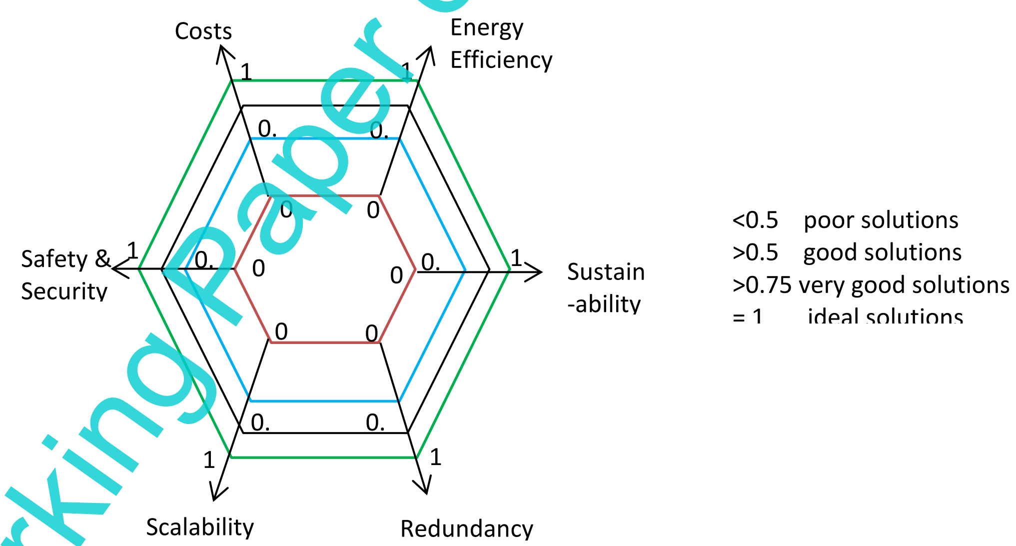

Fig. 5. Evaluation of variants using for customer important multi-criteria

3.3. Preliminary design

The third phase of the design process according to the VDI is the preliminary design. All the necessary components (parts, fixtures, etc.) must be designed in CAD. As the parts interact dynamically with the robot, it is also necessary to simulate the system. Simulation can be used, for example, to determine whether the fixture is suitable. To answer the question: is the welding process even possible without collision with the fixture ore any clamps? If cycle time analysis is also important, the robot manufacturer's simulation tools must be used more often. Simulation can also be used to answer questions about reachability, accessibility and optimisation of the overall cycle. With the help of simulation, it is possible to determine why a D-positioner (which is expensive Figure 6 below) should be preferred to a K-positioner (Figure 4 b above). The D-positioner has an extra axis and allows better positioning of the workpiece. With the K-table, in this example, you would also have to weld overhead or use an inappropriate welding torch angle.

3.4. Final design-layout

The final stage of the design process is to finalise and optimise the best solution that is the result of the previous stage. While CAD is used to optimise the size and arrangement of the components in the robot cell, simulation is used to check and optimise the various movements of the robot and the dynamics of the components in the robot cell. In addition, activities related to the overall material flow and process need to be optimised. It is important to understand that simulation is only an off-line method for optimisation, whereas process monitoring is an on-line tool for process monitoring and optimisation. But the advantage of simulation is that the robot's movements can be incorporated into the robot's programming and in that way the structure of the robot program can be created. The figure below shows the final design. All the components of the systems can be accommodated in a compact area of 6000 mm by 3000 mm. Here are the main subsystems:

- The manipulator is an ABB welding robot 2600ID (integrated dress pack), payload 8kg, reach 200cm.
- The workpiece positioner is an ABB IRBP type D (with five axes (Station A- 2 axes, Station B- 2 axes and Interchange Station 1 axis, only for changing the station (A or B), i.e., not for synchronised movement with the manipulator).
- Binzel ID 45-degree welding torch for better access to narrow parts to be welded.
- Torq nozzle cleaner, welding wire cutter and automatic tool centre measurement.
- Robot and welding controller.
- All safety fences and light curtains (for fast part change, door safety and all safety components according to the risk analysis [7]. On entering the warning zone, the manipulator/positioner moves at a reduced speed of max: 250 mm/second.
- Workpiece Fixtures.
- Operator panel.

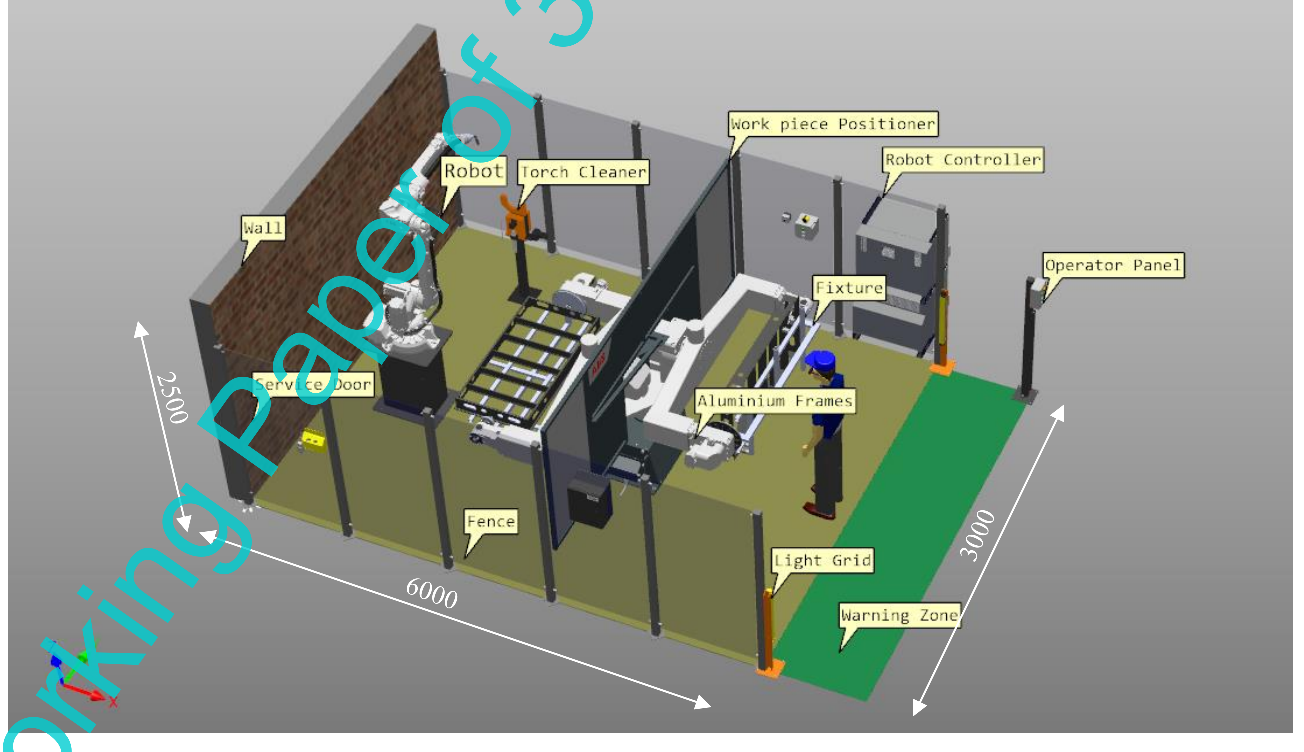

Fig. 6. Layout and simple safety concept for WRS

4. Intelligent welding system for control of the weld process -design of the information system

The IWS uses advanced computer algorithms and sensors to provide automated welding control. This technology improves welding accuracy and efficiency. It can be used in a wide range of industries, including construction, automotive and shipbuilding. A comparison between traditional welding systems and intelligent welding systems is shown in Figure 7. Key technologies such as powerful computers, IoT, big data and AI are required to enable intelligent welding systems. These will help reduce welding defects and improve the quality of welded parts. At the same time, these systems can also reduce the need for skilled human resources. This enables higher levels of automation and cost savings.

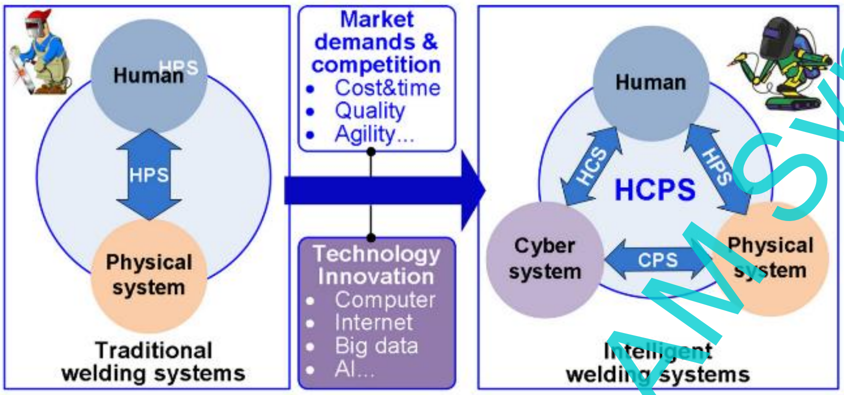

Fig. 7. Welding systems: the evolution from HPS to HCPS [4]

4.1. Seam Tracking

The general purpose of seam tracking is to automate the welding process without having to manually adjust the welding path beforehand. There are several possible approaches for tracking the seam, which are listed in Table 3.

Sensors	Advantages
Arc sensor	Cheap compared to vision-based sensors
Vision sensor	Can detect weld seam position and weld groove dimensions
Laser vision sensor	Error values in seam process is minimum
Ultrasonic sensor	Weld quality can also be inspected
Electromagnetic sensor	Not affected by arc light, fumes
Composite sensor	Advantages of both arc sensor and vision sensor can be obtained
Tactile sensor	Low cost compared to other
Touch sensing	The offset of workpiece can be recognized
Weld pool feature observation	Weld pool characteristics and geometry can be observed on the spot

Table 3: Listing of sensors with their Advantage [8]

Laser vision and optical sensors are most used for seam tracking. These intelligent sensors are very accurate and can send data corrections to the robot and welding controller in real time. Each robot target is declared as a persistent variable in the robot program. The data received from the sensors is used by the robot controller to modify the persistent variables in the program being executed. At the same time, the welding parameters are adjusted using an intelligent neural network or similar algorithm. Most of these algorithms are already part of the Fronius or Lincoln welding system. Based on the paper from Amruta Et al. [8], neural networks and the fuzzy approach are used for the welding parameter controller.

4.2. Digital Twin- virtual reality

Virtual reality is an ever more rapidly advancing technology. In the software "RobotStudio" supplied by ABB [9], a function for virtual reality is offered directly. For the practical test, the Meta Quest 2 is used with a link cable [10]. A welding cell is here the simulation model. This example is intended to highlight the advantage of virtual reality. While in the real process it is not possible to stand directly next to the welding process, this is possible with virtual reality. The VR headset was connected to the computer and the "Virtual Reality" button was pressed. Because Steam and Steam VR were installed on the computer, the emulation was automatically started via Steam VR. In the simulation, the controls were explained right away; they are intuitive and feel very natural. The simulation can be started via a play button. However, due to version differences, the entire simulation could not be run.

4.3. Interaction of the subsystems

Virtual Reality (VR), problems such as collisions and reachability can be easily identified in parallel simulations. Without this virtual verification, these problems would only be discovered directly on the robot, resulting in an extended production stop. After the program is loaded onto the robot, final adjustments are made, in the sense of online programming, to create a high-quality weld seam. Production can then be restarted. Throughout the entire product processing process, all features of the IWS are running in the background. This means that if there are deviations during production, they automatically generate a correction. Therefore, there is a continuous and permanent exchange and comparison of data throughout the entire production process. These are represented in real time in the simulation program. This allows for on-the-fly corrections to be made. By using VR during offline programming and using IWS features such as seam tracking or digital twin, the line between offline and online programming is becoming increasingly blurred (see Figure 8) [5].

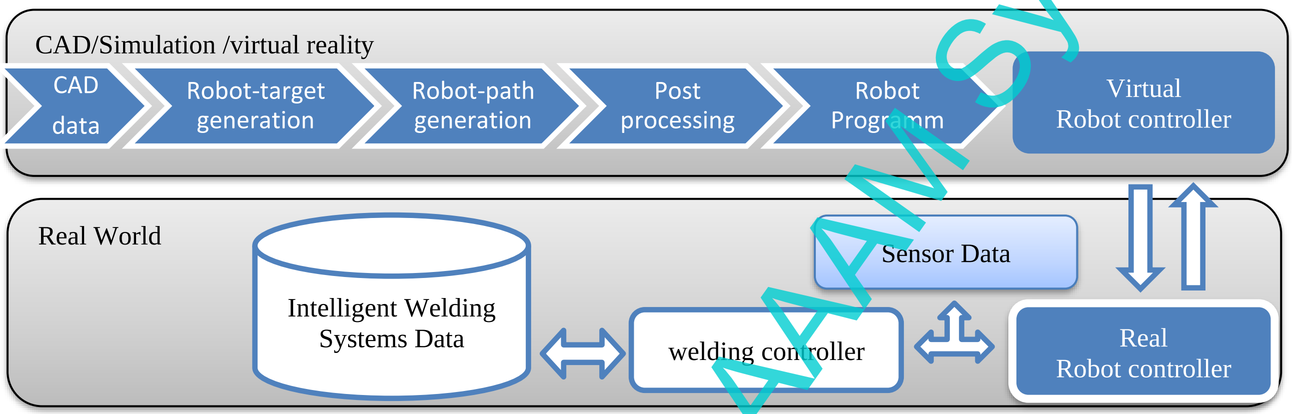

Fig. 8. Offline-Programing with IWS combined

5. Results and discussion

The design of technical systems according to the VDI 2221 guideline not only helps to solve complex tasks, but also to find the best solution to the problem. This means that the robot welding system is already optimally designed. The next step is to develop a material flow strategy that utilises the synergies to ensure the energy efficiency of the system. Although most of the energy is consumed by the welding process itself to melt the materials, the robot's movements should also be optimised for energy efficiency – ISO 50001:2018 [11]. The simulation tool RobotStudio offers the possibility to record energy measurements of the virtual robot (only the robot's movements) in the digital twin [12]. An example is shown in the figure below.

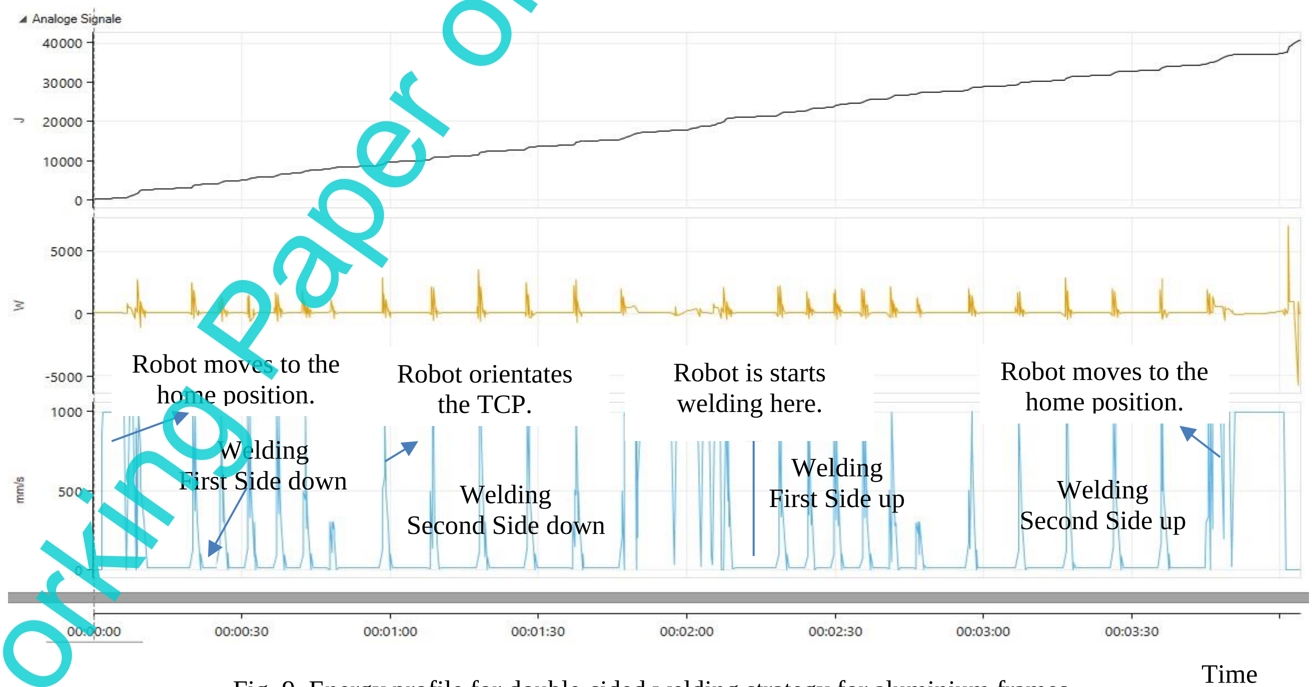

Fig. 9. Energy profile for double-sided welding strategy for aluminium frames

For each scenario it is possible to generate these profiles and thus select the best sequence scenario. For example, in the Figure 9, data are collected for the Tool Centre Point (TCP) movement in mm/sec relative to the work object coordinate systems, the work done for the manipulator only in watts and the energy consumption of the manipulator in joule (J).

All this is done offline in the virtual environment before the plant is brought online. From here, the intelligent welding process takes over, correcting the robot's movements and monitoring and controlling the welding process parameters. For a good weld, it is important to know how the parameters relate to the weld [13]. An artificial neural network has to be developed and then used to predict the hardness and tensile strength of the weld. The prediction is based on the input parameters of gas pressure, welding current and speed. Furthermore, for defect detection a fuzzy logic interference system can be used.

6. Summary, Conclusion and outlook

In conclusion, the current state of the art in welding technology does not prominently feature advanced algorithms for parameter optimization and defect detection, as evidenced by the limited availability of public information. However, recent advancements have shown promising initial steps towards the automation of these processes through the utilization of neural networks. The application of machine learning techniques in welding is still in its early stages, and it is evident that further research and development are required before these approaches can be effectively deployed in industrial applications.

The ongoing efforts to incorporate machine learning into welding systems present a significant opportunity for advancing the field. By leveraging the capabilities of neural networks and other advanced algorithms, it becomes possible to optimize welding parameters and enhance defect detection with greater precision and efficiency. The potential benefits of such automation include increased productivity, improved weld quality, and reduced reliance on manual adjustments and human inspection. However, it is essential to acknowledge that the integration of advanced algorithms into industrial welding applications will not happen overnight. The race for machine learning in welding has just begun, and substantial time and resources will be required to overcome the existing challenges and refine these techniques. Factors such as data availability, algorithm robustness, and computational requirements need to be carefully addressed to ensure reliable and practical implementation.

Looking ahead, the future of intelligent welding systems lies in the continued exploration and advancement of machine learning approaches. As research progresses and knowledge deepens, we can anticipate the development of more sophisticated algorithms tailored specifically to welding processes. These algorithms will not only automate parameter optimization and defect detection but also enable real-time decision-making, adaptive control, and seamless integration within existing welding infrastructure.

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