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OVERCOMING INDUSTRIAL ROBOTICS CHALLENGES AND THE ROLE OF OFFLINE PROGRAMMING

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A b s t r a c t: Industrial robots play a pivotal role in modern industrial production, with robotic welding standing out as a crucial application. This paper analyzes the utilization of online and offline programming methods to optimize robotic welding processes, with an application of Gas Metal Arc Welding (GMAW) techniques. GMAW offers exceptional versatility, including adaptability to various plate thicknesses, high productivity rates, compatibility with diverse materials, and the ability to weld coated metals. The synchronization of robotic movements and positioners plays a crucial role in ensuring precise welding execution. This complexity is particularly evident in scenarios involving welding complex curves, where coordinated movement between the robotic arm and positioner is essential for successful outcomes. In this study, an experiment involving the welding of a pipe-pipe joint using a robot with 6 and positioner with 2 degree of freedom is presented. By applying synchronized movement, seamless welding operations are achieved, highlighting the importance of advanced programming techniques and synchronized operations in enhancing the efficiency and precision of robotic welding in industrial production.

Key words: welding robot; robot programing; OLP; GMAW; MIG/MAG

НАДМИНУВАЊЕ НА ПРЕДИЗВИЦИТЕ НА ИНДУСТРИСКАТА РОБОТИКА И УЛОГАТА НА ПРОГРАМИРАЊЕТО ОФЛАЈН

А п с т р а к т: Индустриските роботи играат клучна улога во современото индустриско производство, при што роботското заварување се издвојува како клучна примена. Овој труд го истражува користењето на методите за онлајн и офлајн програмирање за оптимизирање на процесите на роботско заварување, со примена на електролачно заварување со топлива електрода во заштитна атмосфера од инертен/активен гас. GMAW нуди исклучителна разновидност, вклучувајќи приспособливост на различни дебелини на плочи, високи стапки на продуктивност, компатибилност со различни материјали и способност за заварување обложени метали. Синхронизацијата на движењата на роботот и позиционерот игра клучна улога за обезбедување прецизно извршување на заварувањето. Оваа комплексност е особено видлива кај предмети кои вклучуваат сложени просторни криви за заварување, каде што координираното движење помеѓу роботската рака и позиционерот е од суштинско значење за добивање квалитетни резултати. Во оваа студија е претставен експеримент кој вклучува заварување на спој цевка-цевка со помош на робот со 6 и позиционер со 2 степени слобода на движење. Преку употреба на нивно синхронизирано движење се постигна квалитетно заварување, што ја истакнува важноста на напредните техники на програмирање и синхронизираните операции со цел подобрување на ефикасноста и прецизноста на роботското заварување во индустриското производство.

Клучни зборови: роботско заварување; програмирање на роботи; OLP; GMAW; MIG/MAG

1. INTRODUCTION

Welding is the process of joining two or more pieces, usually metallic, with or without the use of additional material, applying a combination of thermal and/or mechanical energy. Numerous factors, such as carbon migration from the low alloy side, microstructure gradient, and residual stress across various regions of the weld metal, influence the properties of the welded joints and the feasibility of the welding processes [1]. Welding techniques are commonly observed and analyzed from several points of view such as: structural, metallurgical, chemical, physical and electrical. Accordingly, this activity overlaps with several disciplines from technology and science, which gives it a multidisciplinary character. It enables and requires the engagement of more profiles of experts in the research and application of this activity. From a sustainability standpoint, welding has not received much attention. Instead, research on welding has been more dedicated on developing welding processes, studying applications on different metals, and improving weld performance and quality, meanwhile, society, economy, and the environment were rarely considered [2].

The most significant advantage of welding is undoubtedly that it provides exceptional structural integrity, producing joints with very high efficiency [3]. The disadvantage is that there is a lot of heating and consequent changes in thermal-deformation cycle. Welding as a technique is often presented as a difficult discipline. Welders are part of a heterogeneous workforce employed in a variety of workplace settings. Well-ventilated indoor and outdoor locations, as well as small, inadequately ventilated interiors like ship hulls, pipelines, and basements of buildings, may be included. As a result, various exposure concentrations have been measured in welding-related workplaces [4]. Experienced welders are highly valued because they control the welding process, and it is not easy to practice. The traditional method of production uses labor, necessitates a large number of welders to ensure progress, and the welding quality varies. Additionally, labor costs have been rising annually, and the difficulty of recruiting and labor shortages in high-risk occupations like welders and grinders have grown in prominence. There is an urgent need to use automated equipment to improve quality and efficiency. Advancements in robotic automation and intelligent welding represent significant innovations [5].

The development of welding techniques has led to the fact that the worker is not able to perform the welding in which a high-quality welded joint should be obtained in a sufficiently short time and at a sufficiently low cost. Consequently, the development of the welding procedure is in automation and robots. Their accuracy, speed and repeatability of processes is beyond human ability. The bigger problem with welding robots is to be programmed for complex welded joints. Industrial robots are an essential segment of today's industrial production. The demands for high quality, low cost and flexibility simply compel the development of robots. Nevertheless, the focus of the intelligent welding manufacturing technology is mainly related to three key elements: sensing welding process for imitating welder’s sense organ function, knowledge extraction and modeling of welding process for imitating welder’s experience reasoning function, and intelligent control of welding process for imitating welder’s decision-making operation function [6].

The development of robotized welding, which is now one of the main applications for industrial robots, has been truly remarkable since the introduction of the first industrial robots in the early 1960s. Robot welding is mainly concerned with the use of mechanized programmable tools, known as robots, which completely automate a welding process by both performing the weld and handling the part [7]. For the reason that they are so adaptable, robots have been used for resistance and arc welding among other types of welding. Robotic welding has great advantages over any other method. Precision and reproducibility, consistent weld quality, welding at optimal speed, without delays results in a quick return on investment, consistent product quality, reduced predictability and duration of the operation and cost. Additionally, makes the process quite flexible and can be utilized for other modern manufacturing processes, and also adaptation of variation in production line with variation in production volume [8]. Manual welding has many sources of injury at work, it produces harmful gases that have a harmful effect on man and his health. Most of the time, labor costs make up the majority of the total cost. Robotic welding is harmless and allows to avoid injuries and other possible inconveniences. A single robot can perform a large number of welding operations, including welding different elements and shapes. The integration of welding robots brings numerous advantages to various industrial welding tasks since most of the drawbacks attributed to the human factors are eliminated as a result [9].

By combining offline programming with an 8 degree of freedom (DOF) system, manufacturers can address various challenges in industrial robotics effectively. The virtual simulation environment provided by offline programming helps in optimizing robot programs and ensuring seamless integration into the production line. Meanwhile, the enhanced capabilities of an 8 DOF system enable robots to handle intricate tasks and navigate challenging workspaces more effectively, leading to improved productivity and quality in manufacturing operations. In the following, Section 2 introduces Gas Metal Arc Welding, considering its advantages and disadvantages. Section 3 examines the programming methods essential for optimizing efficiency and precision in manufacturing. Within this section, we explore both online and offline programming approaches for robotic welding. Welding robot characteristics and workspace considerations, as crucial factors in optimizing performance within manufacturing environments are mentioned in Section 4. Furthermore, Section 5 delves into the robotic welding process and the conducted experiment of welding a pipe-pipe joint via the utilization of a 6 DOF robot and a 2 DOF positioner. Finally, Section 6 is dedicated to the conclusion that synthesizes the insights gathered from our exploration, emphasizing the significance of the presented robot-based welding system for advancing modern manufacturing practices.

2. GAS METAL ARC WELDING

Gas Metal Arc Welding (GMAW) is one of the most widely used welding techniques and is also known as MIG/MAG welding. GMAW is valued for its versatility, making it a widely used welding process in industries ranging from automotive manufacturing to construction. Belongs to the fusion welding processes that utilizes a consumable wire electrode and a shielding gas to create an arc between the electrode and the workpiece. The wire electrode is fed continuously from a spool, and the arc created melts the wire and the base metals, forming a weld pool that solidifies to create the weld joint. The shielding gas protects the weld from atmospheric contamination. Figure 1 depicts this process, providing a visual representation of the GMAW [10]. The density of the shielding gas used in welding is critical for ensuring proper protection of the welding area from atmospheric contamination. Gases like argon and carbon dioxide, due to their high density, provide excellent shielding, while gases like hydrogen and helium, with lower densities, are less efficient in shielding and can lead to turbulent flow issues. The presence of metal vapors in the gas plasma, combined with the characteristics of the shielding gas, affects the stability and ignitability of the welding arc in MIG/MAG welding. Argon typically forms a soft and stable arc, while helium forms a less stable arc that is also harder to ignite [11].

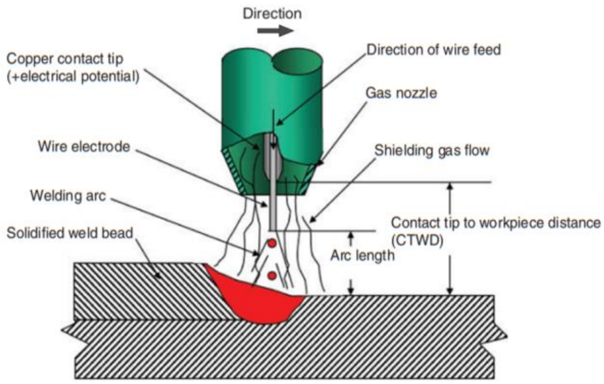


Fig. 1. Gas metal arc welding process

During welding, harmful gases are emitted, affecting human health. Greater consumption of shielding gas correlates with higher impacts on human health indicators. However, these harmful gases can be controlled and removed, minimizing their impact on workers. Measures such as mandatory gas filter masks and designated welding areas with extractors help mitigate health risks in welding workshops [12].

MIG and MAG welding methods are highly flexible and widely applicable, offering benefits such as suitability for various plate thicknesses, high productivity, compatibility with a wide range of materials, capability to weld coated metals, and versatility in welding positions. While MIG/MAG welding offers numerous advantages, it also has limitations compared to Manual Metal Arc (MMA) welding, including more complex equipment and a more restricted application outdoors due to the need to protect the shielding gas from draughts [13]. In conventional MIG/MAG welding, the productive capacity is constrained by the maximum current that can be used. This limitation arises because when the current reaches a certain level, the metal transfer process shifts to a mode known as rotating-spray transfer. Despite its advantages in terms of productive capacity, high strength and ductility with low hydrogen and nitrogen contents [14], submerged-arc welding is not always a suitable replacement for MIG/MAG welding in various applications. This is because submerged-arc welding may lack the versatility or practicality needed for certain welding tasks. Double-wire MIG/MAG welding offers a solution to enhance the productivity of the welding process while preserving its versatility. By utilizing two wires and maintaining operational flexibility, this method overcomes the limitations of conventional MIG/MAG welding, resulting in higher deposition rates, increased travel speeds, and stable metal transfer [15].

3. PROGRAMMING METHODS

The robotic welding process to be of high quality which is essential, and the robot can adapt to certain changes in the welding conditions or environment through making an appropriate response to the movement correction or other process parameters, can be achieved by adaptive process control. The structure of adaptive control is made up of modules that have specific tasks and that interact with each other. Industrial robots can be programmed in different ways, i.e., offline, online, and hybrid programming [16].

3.1. *Online programming*

The online programming method is performed at the robot's workplace and therefore they should be excluded from production. Conventional online programming is a completely manual process [17]. Direct and indirect teach-in programming are the two primary types of online programming. Direct teach-in takes place in a way that the operator guides the robot manually along the path. Physically along the path, where key points or positions are stored in memory, allowing the robot to repeat the movement later. As lead-through programming [18] is the simplest of all robot teaching methods. This programming method is outdated and therefore rarely used in welding programming.

The indirect way of programming as pendant programming [19] is when the operator, with the help of the control panel, follows the desired path by saving the positions in the memory as well as other process parameters such as voltage, current, welding speed, and so on. After the teach-in, the program is tested, in order to see if the robot will interpret well and whether it will execute the assigned program. The advantage of this programming method is that it does not require additional purchases of hardware and software. Moreover, the teaching can be done by an operator who has no competencies in robotics easily and intuitively [20]. The robot cannot perform a production function during programming, which is one of its disadvantages.

3.2. *Offline programing*

Programming according to offline method is performed on a computer and does not require physical movement of the robot, therefore it is not excluded in the production process, which is economically feasible and is the main advantage over teach-in programming. Offline programming may be considered as the process by which robot programs are developed, partially or completely, without requiring the use of the robot itself [21]. Due to deviations in machining tolerances in the robot linkages, robot arm compliance and elasticity, encoder resolution, and the lack of repeatability during calibration, significant errors can occur in an offline generated tool path. The meaning of offline programming is to project as many technological processes as possible at a separate workplace, independently of the robot and in the shortest possible time. In some instances, the programming time during which the facility is ineffective may last for days or even weeks. Therefore, reducing set-up time is the primary benefit of using an offline programming system [22]. The programming time in which the facility cannot be used productively may in some cases last days or even weeks. Hence, the primary motivation for utilizing an offline programming system is to minimize the set-up time. Offline programming method systematically combining CAD-based, vision-based, and vision & CAD interactive activities can overcome the limitations of current automatic program generation methods for robotic welding systems [23]. Through programmatic use of CAD, i.e., knowledge-based engineering system (KBE) as a phase in the evolution of CAD leads to possibility of automating the engineering task of marking a weld path, by logically defining weld locations in code. The paths may be extracted and exported for generating robot code for a welding robot [24].

The high cost of the offline programming package and the programming overhead required for software customization for specific applications make it uneconomical to justify offline programming implementation, especially for smaller product values. Furthermore, the development of customized software for offline programming is a time-consuming process that demands high-level programming skills that are often not available from process engineers and operators who typically perform robot programming [25]. Additionally, the hybrid programming method offers efficiency in robotic welding by combining online and offline processes. During the online phase, the method controls the welding path in real-time, memorizing key position points. In the subsequent offline stage, a welding program is generated based on these memorized points, incorporating parameters like welding current and other necessary characteristics. This dual-phase approach significantly reduces programming time and minimizes production losses.

Synchronized programming in robotic welding involves the meticulous coordination of the welding process through the integration of positioners. A typical welding positioner consists of a rotating platform or fixture on which the workpiece is securely mounted. This platform can be rotated, tilted, or both, allowing for precise control over the orientation of the workpiece during welding. In this method, the programming ensures a harmonized movement of both the robotic arm and the positioner, optimizing the welding position for efficiency and quality. Non-synchronized programming, on the other hand, deviates from the use of positioners and relies solely on the robotic arm to execute the welding motion along a predetermined trajectory. The programming involves defining a set path for the robotic arm without the added coordination with a positioner. While non-synchronized programming may be simpler in setup, it may not optimize the welding position to the same extent as synchronized programming.

Different robot manufacturers use different programming languages for their controllers. This lack of standardization means that there is no universal language that all robots use for programming. Due to the diversity in programming languages, achieving standardization across the robotics industry becomes challenging. Many robot programming languages are in use across the industry, making it complex for operators and programmers who need to work with different robots. A procedure that utilizes forward and inverse kinematics, applies to different types of robots and is STEP-NC-compliant, can significantly cut down the time needed for setting up and integrating robots in manufacturing operations [26]. The focus is on improving the efficiency and standardization of the programming and control processes for robotic systems.

4. ROBOTIC WELDING SYSTEM

Since there are many parameters and a limited knowledge of how the process works, today's welding techniques are sophisticated. Users and customers have specific weldment requirements and dynamic work environments. Therefore, welding is moving towards more customized production by leveraging next-generation welding systems capable of intelligently adapting to evolving welding requirements while maintaining high quality [27]. The robotic welding system integrates several key components essential for efficient welding operations. The welding torch serves as the primary tool for generating the welding arc and directing the flow of shielding gas. Supported by a wire feeding mechanism and tray, it ensures a continuous supply of welding wire for seamless operation. Fixtures and positioners provide stability and adjustability to secure and orient the workpiece for precise welding from various angles. The gas cylinder contains shielding gas, crucial for protecting the weld from atmospheric contamination. A water chiller system maintains optimal temperatures, particularly for the welding torch, to prevent overheating during prolonged usage. The power supply provides the necessary electrical energy to sustain the welding arc, while the control unit manages parameters such as arc voltage, wire feed speed, and travel speed to ensure consistent weld quality. Additionally, the teach pendant offers a handheld interface for operators to program and control the robotic welding system with desired accuracy. These components, shown in Figure 2, collectively contribute to the functionality and effectiveness of the robotic welding system.

4.1. *Welding robot characteristics*

In this study 6 DOF industrial robot Panasonic YA-1 TA-1400 was utilized for performing welds. With a repeatable precision of 0.1 mm, the robotic arm ensures accurate and consistent weld placements. Its payload capacity of 6.0 kg and an arm reach of 1374 mm highlight its versatility in handling various welding requirements. The main control unit serves as the system's core, processing data for seamless coordination of the positioner and robotic manipulator. A 2 DOF positioner supports the robotic arm, with a maximum load capacity of 500 kg, along with torque specifications of 1470 Nm and a rotation speed of 16 r/min. The welding torch attached to the end of the robotic arm serves as both a wire transmitter and gas conductor, ensuring stable arcs for producing high-quality welding joints. Furthermore, it is equipped with water cooling to avoid overheating during operation. In Figure 3 detailed dimensions of the 6 DOF manipulator are shown, outlining its physical extents including height, width, and depth, crucial for spatial planning and integration within a given welding station. Additionally, it delineates the manipulator's range of movement, showing its DOF, essential for task feasibility assessment and workspace design. Points P and O within the work envelope denote critical locations where the manipulator can effectively execute tasks important for trajectory planning and operational analysis.

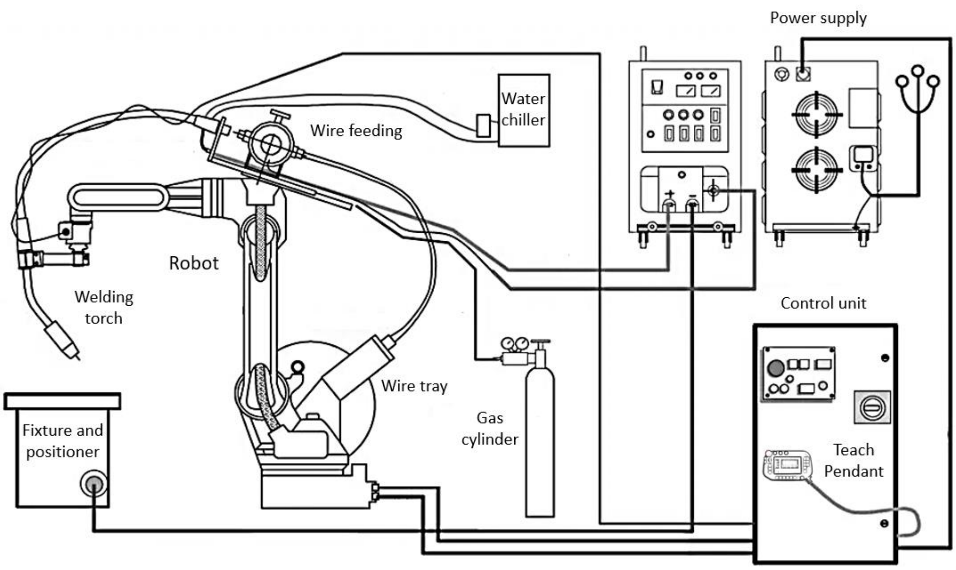
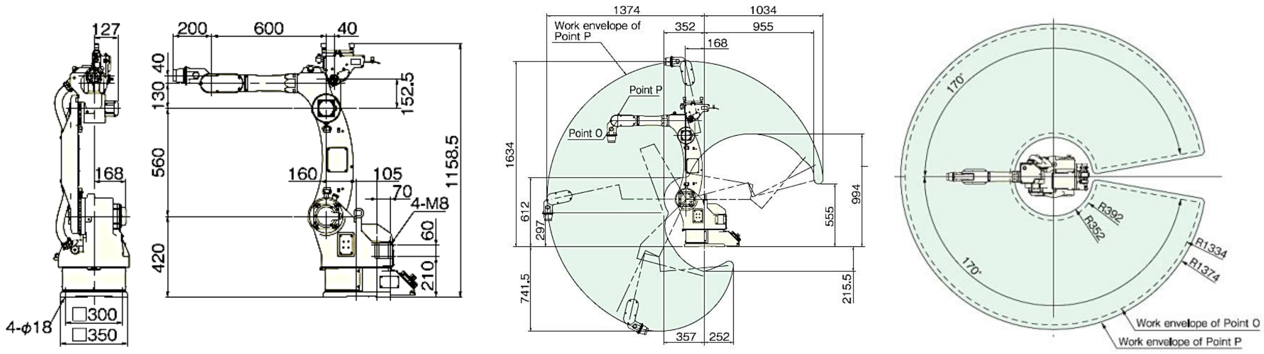


Fig. 2. Scheme of the robot-based welding system



a) b) c)

Fig. 3. 6 DOF manipulator: a) dimensions, b) range of movement, c) work envelope points P and O

4.2. *Robot workspace*

The workspace is determined by the geometry of the manipulator and the limits of the joint motions. It is more specific to define the reachable workspace as the total locus of points at which the end-effector can be placed and the dexterous workspace as the subset of those points at which the end-effector can be placed while having an arbitrary orientation. Dexterous workspaces exist only for certain idealized geometries, so real industrial manipulators with joint motion limit almost never possess dexterous workspaces [28]. As well as reaching the weld, the robot must be able to achieve the torch postures necessary for a quality weld, which means that the sets of joint angles determined by inverse kinematics must be within the robot's range [29].

Depicted as a point cloud, the robot's operational workspace utilized in our study is shown in Figure 4. The method for determining the reachable workspace of a robot includes four steps. It starts by randomly selecting combinations of joint angles for the robot within specified limits, considering physical constraints from welding cell. Each joint angle determines a unique configuration of the robot's arm. Once the joint angles are chosen, forward kinematics is used to calculate the position and orientation of the robot's end-effector in space for each configuration. In the third step, the positions and orientations of the end-effector obtained from forward kinematics are extracted and recorded. These positions represent points in space that the end-effector can reach. Lastly, by repeating this process for a large number of randomly sampled joint angles, the entire reachable workspace of the robot can be comprehensively delineated. To facilitate better visualization, i.e., to clearly observe the robot and positioner with the workpiece, the number of points in this specific view is not maximized. The limitations that arise from both the physical characteristics of the robot itself and the constraints imposed by the fencing in the work cell are noticeable.

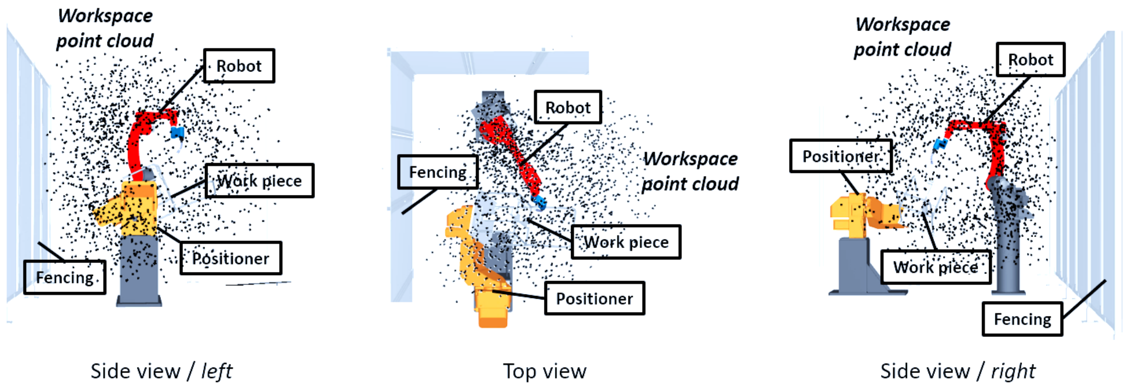


Fig. 4. Workspace point cloud and welding cell

5. ROBOTIC WELDING PROCESS

The robotic welding process can be divided into a few procedures. It begins with preparation which involves determining the welding parameters such as voltage, current, wire feed speed, and shielding gas. Additionally, to program the robotic welding system with the appropriate welding path and parameters. This involves defining the weld joint geometry, specifying the welding sequence, and setting the sensors for vision-based seam tracking. The setup follows, involving the positioning of the workpiece and calibration of the robotic arm for ensuring accurate positioning and alignment with the clamped workpiece. Touch sensing and seam tracking play a crucial role in ensuring accurate alignment of the welding torch before the actual welding process begins. Initiation marks the start of welding as the robotic arm moves to the starting position. During execution, the arm follows the programmed path, depositing filler material and applying heat. Monitoring occurs throughout, ensuring key parameters are maintained and the weld quality is high. Upon completion, the arm returns to its home position, and the finished workpiece can be removed. Post-welding operations may be performed, and maintenance is crucial for optimal system performance. Throughout this process, safety measures are paramount to protect both the robot operator and the equipment. The welding task in our case was welding pipe-pipe joint, and the time key frames are presented in Figure 5. The welding parameters consist of a welding current of 80-85 A, a welding voltage of 14.5–14.8 V, and a welding speed of 10 m/min.

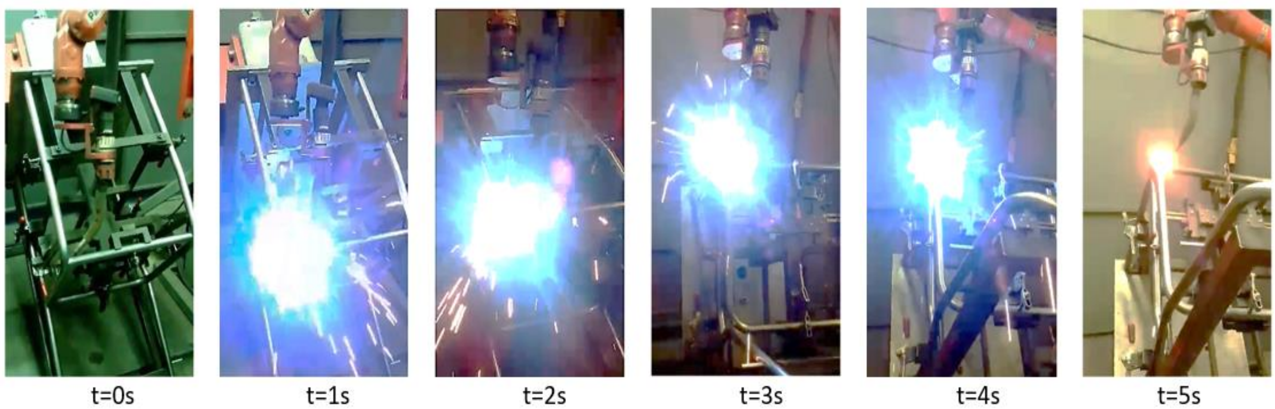


Fig. 5. Welding task key frames

Since this joint is a complex curve, within the frame of the constructive concept of the chair as a workpiece, a synchronized movement of the robotic arm and the positioner was applied. By applying synchronized movement, successful welding was achieved. In Figure 6 the touch sensing and seam tracking, as part of the procedure related to the preparation step, as well as a display of the finished weld, are presented.

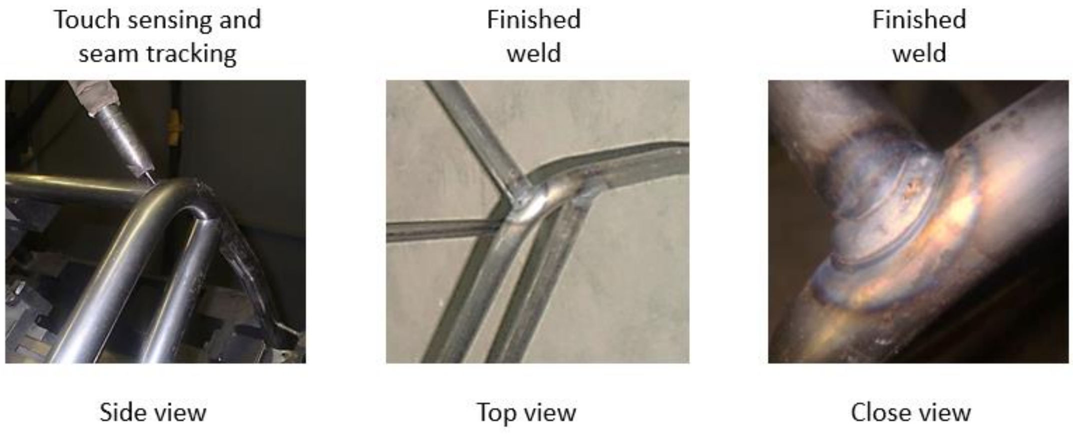


Fig. 6. Touch sensing and finished weld

6. CONCLUSION

The innovation of robot welding has been impressive since the introduction of the first industrial robots, making it a major application for industrial robots. Creating an automated robotic welding system is difficult because of its adaptable nature and requires preparation, welding, and assessment. Developing such a system requires a combination of mechanical and software engineering expertise to ensure the reliable production of high-quality welds in a variety of situations.

The robot must move along the programmed path precisely, maintain proper torch angles, and adjust welding parameters as needed to achieve the desired results. To increase productivity, offline programming is essential as it combines programming and regular robot operation and reducing the setup time for the robotics system. Offline programming allows for better production anticipation, estimation, and minimization of robot cycle times, resulting in more repeatable and compliant welding procedure qualification records. Offline programming also enhances safety by taking place in a comfortable environment away from hazardous workshop conditions.

The presented approach and simulation model are based on a real case of industrial welding process. To complete welding tasks along a space-curved path, a robot and a positioner as an 8-DOF system were used and analyzed. The virtual experiments were used to analyze the robot welding path planning, collision analysis, and reachability of the industrial robot before welding. The simulation environment offered by offline programming aids in refining robot programs and ensuring smooth integration into the production line. Our approach offers to save time and to increase productivity in the welding process, leading to a quick return on investment. Additionally, allows for rapid reconfiguration of robotic welding systems to adapt to changing production requirements, further increasing flexibility and competitiveness.

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