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Trajectory Tracking Control of KUKA KR 6 R900-2 Robotic Arm for Welding Applications

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ABSTRACT

This study presents an analysis of precision control for the KUKA KR R900-2 robotic arm during welding operations along predefined circular and square paths, emphasizing the use of image processing for navigation. The research compares the performance of Proportional-Integral-Derivative (PID) and Model Reference Adaptive Control (MRAC) systems in maintaining welding accuracy, especially with complex geometries. By integrating SOLIDWORKS for design and MATLAB for image processing, the study demonstrates how combining computer-aided design with advanced image processing enhances the precision of robotic welding. Results indicate that the adaptive controller outperforms the PID controller, achieving a reduction in mean squared error by up to 75% and improving response times. This underscores the adaptive controller's potential to significantly enhance automated welding processes. The findings contribute valuable insights into utilizing sophisticated control systems to improve the efficiency and quality of robotic welding in advanced industrial applications.

Keywords:
Adaptive; PID; image processing; welding

1. Introduction

Welding has evolved significantly from ancient techniques to modern automated methods, marked by milestones such as the discovery of arc production and the introduction of gas welding in the 19th century. The incorporation of robotics in the latter half of the 20th century, exemplified by the UNIMATE robot, revolutionized welding by enhancing precision and safety despite initial challenges related to costs and technology integration [1,2]. In the 21st century, advancements have accelerated with the integration of robotics, artificial intelligence (AI) and computer vision, optimizing efficiency and promoting sustainability in welding processes [3].

Previous research has explored various control strategies for robotic arms in welding applications. For instance, the AUTAREP project focused on mathematical modelling and developed robust control strategies, introduced a Sliding Mode Controller (SMC) and contrasting it with Computed Torque Control (CTC) across various trajectories [4].While these studies advanced understanding, they often

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concentrated on simple trajectories and did not extensively explore adaptive control methods in complex welding paths.

Other studies have applied optimization techniques like Genetic Algorithms (GA) combined with Finite Element Analysis (FEA) to minimize distortion in welded structures [5] and developed GA-based design methodologies for optimizing robotic arm trajectories [6]. Additionally, efforts have been made in dynamic modelling and parameter estimation for multi-degree-of-freedom manipulators [7] and in simulating robots for accurate trajectory prediction [8]. In terms of sensing and guidance, advanced image processing methods have been developed for automatic tracking of weld lines, enhancing precision in plasma robotic welding [9,10].

Several studies have highlighted the effectiveness of SOLIDWORKS in various engineering and industrial design applications. For instance, one study used SOLIDWORKS to develop a compound die for manufacturing an L-shaped metal bracket, enabling detailed simulations to optimize cutting forces and material properties [11]. Another investigation employed SOLIDWORKS to design and analyse shell-and-tube heat exchangers, focusing on enhancing thermal efficiency using nanofluids [12]. In addition, SOLIDWORKS played a key role in designing a solar still with optimized glass cover angles, thereby improving water desalination performance through precise modelling and simulation [13]. Collectively, these studies underscore the versatility of SOLIDWORKS as a powerful tool across diverse engineering domains, contributing to greater efficiency and accuracy in industrial projects.

Despite these advancements, gaps remain in the application of advanced control methods such as adaptive control for precision welding using industrial robots, particularly along complex geometries encountered in real-world applications. Furthermore, the integration of advanced sensing technologies with control strategies has not been extensively studied, limiting the adaptability and flexibility of current welding systems. The influence of various welding parameters on the performance of different control strategies also requires systematic investigation.

This research aims to address these gaps by comparing the performance of Proportional-Integral-Derivative (PID) control and Model Reference Adaptive Control (MRAC) in robotic welding applications using the 6-axis KUKA KR 6 R900-2 robotic arm. The study evaluates the trajectory tracking performance of both control algorithms along predefined circular and square welding paths through MATLAB simulations. By conducting this comparative analysis, the research seeks to enhance precision, accuracy and repeatability in robotic welding operations, ultimately contributing to the optimization of automated welding processes in industrial applications.

2. Methodology

This section outlines the methodological framework of the study, detailing the integration of robotics and control systems pertinent to precision welding applications. The primary focus is on analysing the performance of the KUKA KR 6 R900-2 robotic arm using two distinct control strategies—Proportional-Integral-Derivative (PID) control and Model Reference Adaptive Control (MRAC)—across two welding scenarios: circular and square paths. The methodology encompasses the design and simulation processes, the implementation of image processing techniques and the evaluation metrics used to assess the controllers' performance.

2.1 Robotics Overview

Robotics is a multidisciplinary field integrating cybernetics, mechanics and computer science. Since its inception in Čapek's 1920 play, it has evolved significantly, becoming central to various

industries where precision tasks are required. Robotics studies can be divided into several key areas [14]:

i. Kinematics: The study of motion without considering the forces causing it.
ii. Dynamics: The analysis of forces and their effects on motion.
iii. Trajectory Planning: Essential for determining the optimal path for robotic arms or mobile robots.
iv. Actuators and Sensors: Responsible for robot movement and environmental interaction.
v. Control Systems: Fundamental for efficient operations, ensuring robots achieve the desired tasks.

The KUKA KR 6 R900-2 robotic arm, used in this study, is widely recognized for its flexibility and precision in industrial applications. The robotic arm's motion is governed by sophisticated control algorithms that ensure accurate execution of tasks, such as welding. This study focuses on the comparative performance of two control strategies: PID and adaptive control systems.

2.2 Control Systems in Robotics

Control systems are essential for robotics, ensuring specific objectives are met based on feedback loops. These systems span various applications, from household appliances to advanced industrial and military technologies. With the advancement of sensors, actuators and computing power, control systems have become highly sophisticated and capable of handling complex tasks precisely.

In robotics, control systems enable accurate task execution, as seen in applications like Honda's ASIMO humanoid robot or robotic welding systems, where precise arm positioning is critical. These systems rely heavily on feedback principles to adjust robot movements in real-time, ensuring accuracy, adaptability and safety in complex environments [15].

The flexibility of control systems becomes particularly relevant in unpredictable settings. For instance, in healthcare, robots perform intricate surgeries with a high degree of precision, relying on real-time feedback to adjust their actions according to changes in the environment [16].

2.2.1 Proportional-Integral-Derivative (PID) controllers

Proportional-Integral-Derivative (PID) controllers are the most widely used control algorithms in industrial feedback systems. These controllers work by minimizing the error between the system's setpoint and the process variable. The PID controller's output is the combination of three components: proportional, integral and derivative, as shown in the equations below [17].

Equations and Parameters:

i. Error Calculation:

$$e(t) = SP - PV \tag{1}$$

ii. Output Determination:

$$u(t) = K_P \times e(t) + K_I \times \int e(t)dt + K_D \times \frac{de(t)}{dt} \tag{2}$$

iii. Proportional Component (P):

$$\mathrm{P} = K_P \times e(t) \tag{3}$$

iv. Integral Component (I):

$$\mathrm{I} = K_I \times \int e(t)dt \tag{4}$$

v. Derivative Component (D):

$$\mathrm{D} = K_D \times \frac{de(t)}{dt} \tag{5}$$

vi. Dependent Formulation of the PID Equation:

$$K_I = \frac{\tau_I}{K_c} \tag{6}$$

$$K_D = K_c \times \tau_D \tag{7}$$

$$u(t) = u_{bias} + K_c \times e(t) + \frac{\tau_I}{K_c} \times \int e(t)dt - K_c \times \tau_D \times \frac{d(PV)}{dt} \tag{8}$$

where:(K_p=K_c)

In the context of the control systems described in the equations [17], the variables are defined as follows: K_c represents the gain of the controller, essential for adjusting the system's response. denote the integral reset time, integral to the system's ability to eliminate steady-state errors. τ_D signifies the derivative time constant, contributing to the system's predictive behaviour. Lastly, u_{bias} is a constant value, typically set to match u(t) at the point of switching the controller from manual to automatic mode, facilitating a smooth transition without errors during activation.

2.2.2 Adaptive controllers

Unlike PID controllers, adaptive control systems adjust their parameters automatically in real time to maintain optimal performance, even under uncertain or changing conditions [18]. This makes adaptive controllers especially useful for non-linear or time-varying systems.

One prominent example of adaptive control is Model Reference Adaptive Control (MRAC). In MRAC, the control system updates its parameters continuously to ensure that the system's output matches a desired reference model. This approach is particularly effective in complex robotic applications, where environmental uncertainties or process nonlinearities are prevalent [15,16].

Adaptive Control Equations [19]:

i. Control Law with Constant Coefficients:

$$u(t) = \phi^T(t)\theta \tag{9}$$

ii. Estimation Error:

$$\widetilde{\theta}(t) = \theta - \widehat{\theta}(t) \tag{10}$$

iii. Tracking Error:

$$e(t) = y_m(t) - y(t) \tag{11}$$

iv. Controller Parameters Update

$$\widehat{\theta}(t) = \gamma\phi(t)e(t) \tag{12}$$

v. Augmentation Signal

$$e_a(t) = e(t) + \alpha\tilde{\theta}^T(t)\phi(t) \tag{13}$$

In the control system equations, key variables include u(t) for control command, $\phi^T(t)$ for filtered signal vectors and θ for controller parameters. Estimation error is represented by $\widetilde{\theta}(t)$, with actual and estimated controller parameters denoted by θ and $\widehat{\theta}(t)$, respectively. The tracking error $e(t)$is defined alongside $y_m(t)$ and $y(t)$ for model and plant outputs. Additionally, γ represents the adaptation gain and $e_a(t)$ with α define the augmented error and its associated gain.

This paper compares PID control and Adaptive Control on an industrial 6-axis KUKA robotic arm. The robotic arm performs welding tasks along both circular and square trajectories. The results demonstrate that while PID controllers perform adequately in controlled environments, MRAC provides superior accuracy and adaptability when dealing with process nonlinearities and uncertainties. This highlights the potential of advanced control schemes in enhancing robotic performance in complex industrial applications.

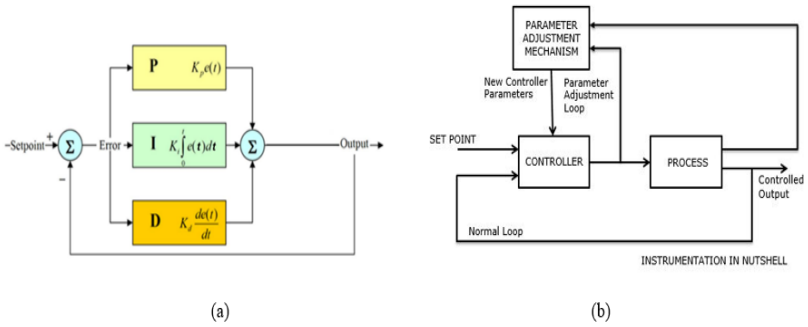


Fig. 1. (a) PID control blocks [20], (b) Adaptive control system block diagram [21]

2.2.3 Parameter Tuning

To implement the Proportional-Integral-Derivative (PID) controller and Model Reference Adaptive Control (MRAC) effectively, specific gain values and tuning procedures were employed. We used a trial-and-error approach guided by performance metrics (e.g., settling time, overshoot and steady-state error) for each trajectory:

i. <u>PID Controller Tuning:</u>

$K_p = 2.0, K_i = 0.10, K_d = 0.05.$

These values offer a moderate overshoot (approximately 2–3%), a relatively short settling time (~0.32 s) and a mean squared error (MSE) of about 0.01. In contrast, the square path demands higher gains to manage sharp corners effectively:

$$K_p = 2.5, K_i = 0.20, K_d = 0.10$$

This configuration results in an overshoot around 5%, a settling time of approximately 0.45 s and an MSE near 0.04.

ii. MRAC Parameter Settings: The MRAC design employed a second-order reference model with a natural frequency ω_n and damping ratio ζ. For the circular path, $\omega\, n$ was set to 1.5 with ζ=0.7. The adaptation gain was chosen as γ = 0.10 and an additional coefficient α=0.30 was introduced to form the augmented error signal. For the square path, ω_n was increased to 2.0 to handle abrupt trajectory changes more effectively. These parameter choices led to a lower MSE (around 0.0025–0.01) and faster or comparable settling times compared to the PID controller. The selected gains aim to balance rapid adaptation with stable performance. Although a trial-and-error method was used in this study, more systematic approaches (e.g., Ziegler–Nichols or optimization-based algorithms) could also be employed for finer tuning. The final parameter values proved robust enough to achieve the results presented in Section 3, demonstrating the MRAC controller's superior tracking accuracy and responsiveness relative to PID control.

2.3 Processing using Kuka KR 6 R900-2 Robot

In this research, the welding process will be conducted using the KUKA KR 6 R900-2 robotic arm, which is highly regarded in welding tasks for its exceptional precision and adaptability. It achieves a repeatability accuracy between 0.02 mm and 0.03 mm, which is essential for the high-quality execution of welding operations, ensuring the welds are strong and dependable. The six-axis design of the robot provides the versatility needed to weld in difficult-to-reach spots and at various angles, which is beneficial for a wide array of welding jobs. This robotic arm is frequently used in different welding processes, such as arc welding and spot welding, demonstrating its effectiveness and proficiency in these applications [22,23].

The table below illustrates the complete data for the used robot [24].

Table 1
Technical Data of KUKA Robot KR 6 R900-2

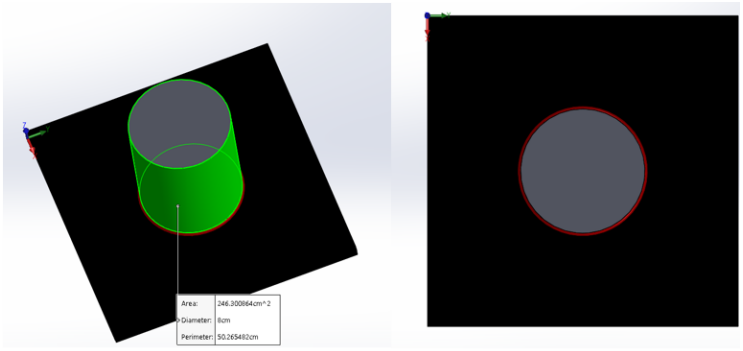
Specification	Value
Maximum Reach	901
Maximum Payload	6.7
Pose Repeatability (ISO 9283)	0.02
Number of Axes	6
Mounting Position	Floor; Ceiling; Wall; Desired angle
Footprint	208 mm x 208 mm
Weight	Approximately 55 kg

In this research, two welding paths - a circle and a square - were utilized to assess the KUKA KR 6 R900-2 robotic arm's precision and efficiency in handling different shapes. The circular path tested the arm's ability on curved surfaces, common in industrial tasks like pipe welding, while the square path, with its sharp corners and straight lines, evaluated its precision in angular welding tasks. These

paths provided a comprehensive evaluation of the arm's control systems. The study also involved a comparative analysis of two control systems, PID and Adaptive, to determine which offers better precision and consistency in welding, using performance metrics like response time and mean squared error.

2.3.1 Circular path welding

In this study, a circular trajectory representing a cylindrical object with an 8 cm diameter was modelled for welding onto a base plate. Using SOLIDWORKS, the welding path was precisely designed and marked in red with a 1 mm thickness. This 3D model was then converted into a 2D image for processing in MATLAB, allowing for applying image processing techniques to ensure accurate welding along the specified path.



(a) (b)

Fig. 2. (a) Cylinder diameter which represents the welding path diameter (b) 2D image shows the welding around cylinder

In the design phase for this research, the welding paths on both the cylinder and square base were distinctly marked in red in the SOLIDWORKS 3D models. This colour choice facilitated subsequent image processing in MATLAB by enhancing path visibility and accuracy in detection. The conversion of these models to 2D images allowed MATLAB's image processing tools to precisely track and ensure the robotic arm's accurate adherence to the designated welding path.

2.3.2 Square path welding

For the square welding path, precision design was conducted in SOLIDWORKS for a 10 cm square with a 1 mm weld seam. The path was highlighted in red for clear visual guidance. Post-design, a 2D image of this square with the welding path was created for MATLAB's image processing. This step was crucial for ensuring the welding operation precisely followed linear and angular paths, a key factor for achieving the required weld quality and accuracy.

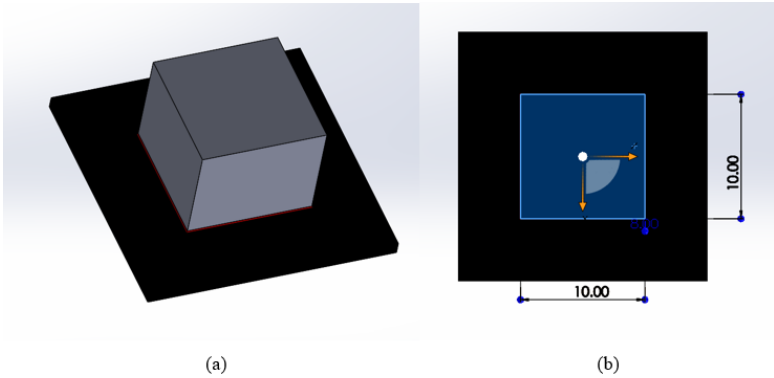


Fig. 3. Case 2: (a) Model of square welding on base (b) dimensions of 2D square welding path

In the research, MATLAB was utilized for data analysis, focusing on robotic arm control strategies. The evaluation was conducted to assess the effectiveness of these strategies. The next section will detail these results, showcasing the impact on robotic welding tasks.

3. Results

This section focuses on presenting and analysing the results from the MATLAB simulations. It's organized into two main parts: the first examines the results of the circular welding path and the second looks at the square welding path. In each part, the performance of both the PID and Adaptive control systems is assessed, using the path trajectories that were generated. The findings are shared through graphs and data that compare different aspects, such as accuracy, response times and the overall success of the control strategies. The robotic arm's performance, influenced by the different path geometries, is evaluated in a clear and unbiased way. The information provided goes beyond just the operational details of the robotic arm; it also sets the stage for a wider conversation about how effective these control systems are in real-world industrial use.

3.1 Results Circular Path Welding Results

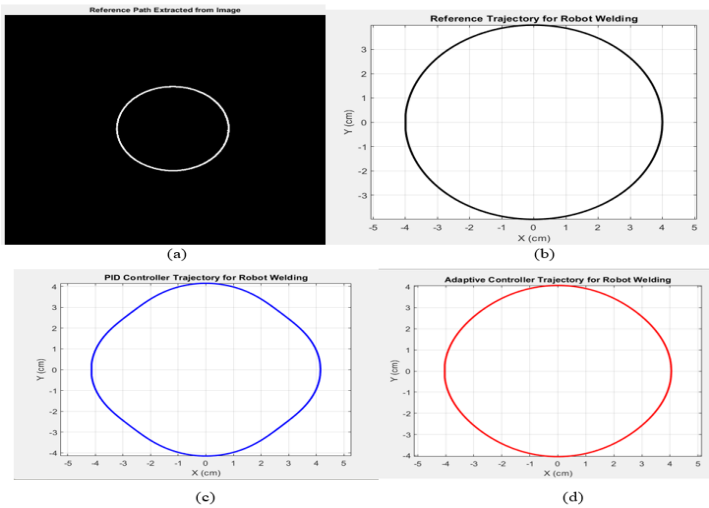


Fig. 4. Circular path welding with KUKA KR 6 R900-2: (a) Image processed path extracted by MATLAB (b) Welding reference path (c) PID controller trajectory (d) Adaptive controller trajectory

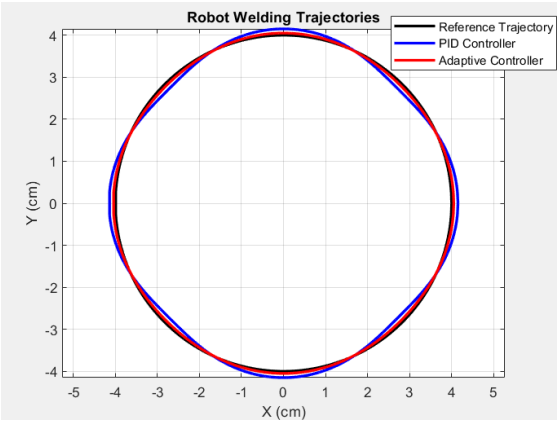


Fig. 5. Reference, PID and adaptive path trajectory for circular path

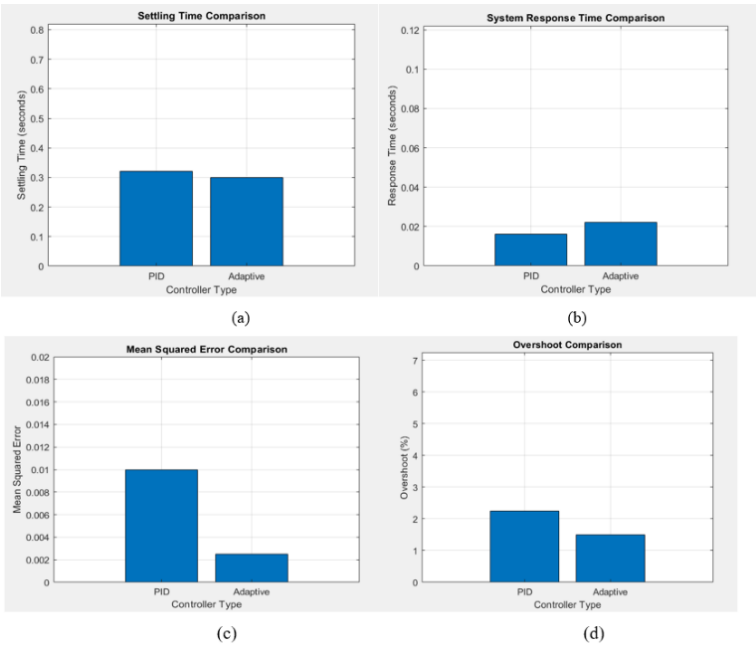


Fig. 6. Comparative Performance Metrics in Circular Path Welding with KUKA KR 6 R900-2: (a) Settling time (b) System response (c) Mean squared error (MSE) (d) Overshoot

3.2 Square Path Welding Results

This study used MATLAB simulations to evaluate control systems for welding tasks with a KUKA KR 6 R900-2 robotic arm. We tested two welding paths (circular and square) and found that the Adaptive controller consistently outperformed the PID controller in several key measures. It showed lower distance error (0.005 cm vs. 0.0805 cm), lower error percentage (0.12% vs. 1.61%) and lower mean squared error (0.0025±0.0005 vs. 0.04±0.005).

The Adaptive controller also responded faster (0.022±0.002 s) and settled more quickly (0.30±0.02 s) than the PID controller (0.027±0.003 s and 0.425±0.04 s, respectively). In addition, it limited overshoot more effectively (1.5%±0.2% vs. 5%±0.5%), which helped maintain stability when the square path changed direction suddenly. These findings are based on repeated simulations under the same conditions and paired t-tests confirmed that the improvements were significant ($p < 0.05$).

Overall, the results suggest that the Adaptive controller can offer better accuracy, faster response and greater flexibility for industrial robotic welding tasks.

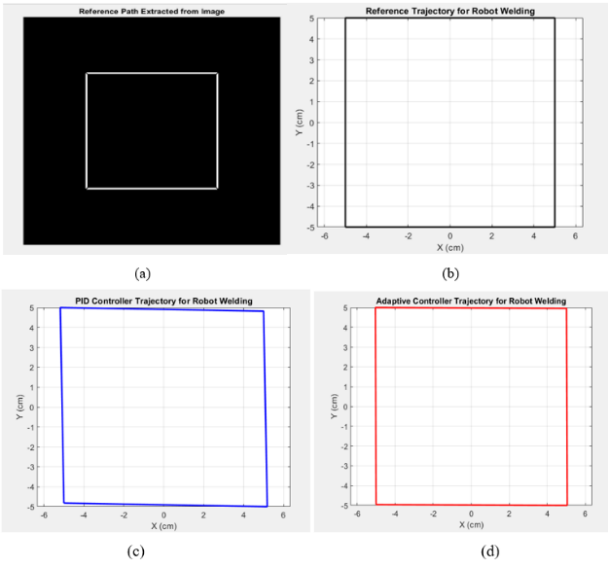


Fig. 7. Square Path Welding with KUKA KR 6 R900-2: (a) Processed image path extracted by MATLAB (b) Welding reference path (c) PID controller trajectory (d) Adaptive controller trajectory

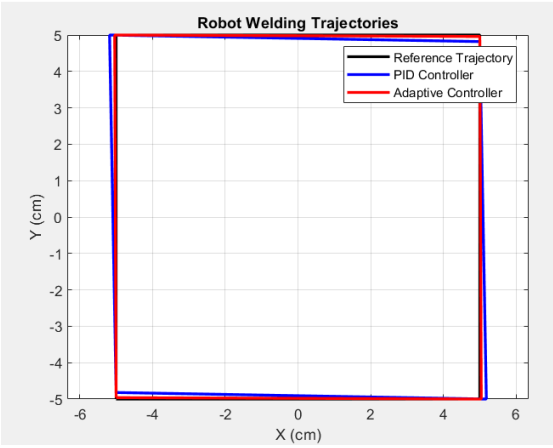


Fig. 8. Reference, PID and adaptive path trajectory for square path

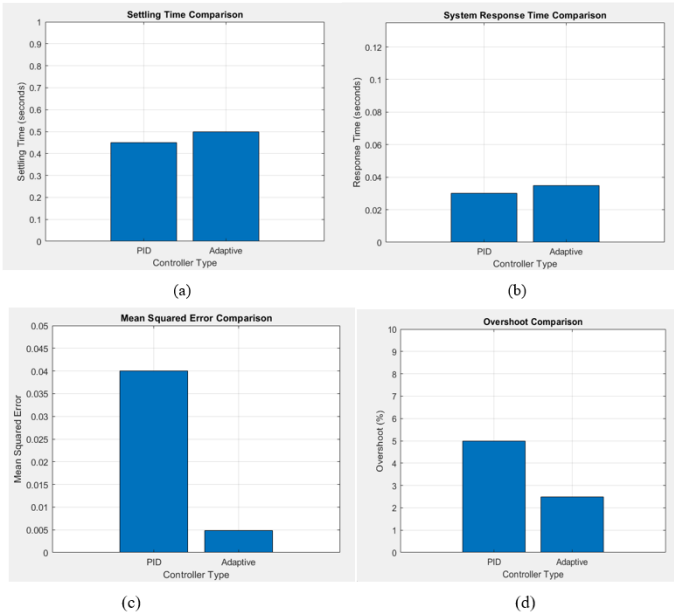


Fig. 9. Square path welding performance metrics with KUKA KR 6 R900-2: (a) Settling time (b) System response (c) Mean squared error (MSE) (d) Overshoot

Table 2
Performance metrics for PID vs. Adaptive controllers on welding paths

Specification	Value	Circular Path - Adaptive	Square Path - PID
Error in Distance (cm)	0.01	0.005	0.0805
Error Percentage (%)	0.25	0.12	1.61
Mean Squared Error	0.01	0.0025	0.04
System Response Time (seconds)	0.016	0.022	0.027
Overshoot (%)	2.25	1.5	5
Settling Time (seconds)	0.32	0.3	0.425

4. Conclusions

In this study, the KUKA KR R900-2 robotic arm was assessed for welding tasks on circular and square paths, highlighting the importance of image processing in trajectory tracking. The Adaptive controller consistently surpassed the PID controller, offering better accuracy, quicker response times and reduced overshoot. The combined use of SOLIDWORKS for design and MATLAB for analysis further demonstrated the benefits of integrating modelling and control tools to enhance robotic performance. Despite these encouraging results, several areas warrant further investigation. Future research could explore more complex or irregular welding trajectories, commonly encountered in industrial settings. Studies examining sensor inaccuracies, environmental disturbances and actuator inconsistencies would provide deeper insight into the robustness of real-world implementations. Additionally, incorporating advanced sensing technologies or machine learning algorithms could improve adaptability in dynamic or unpredictable environments.

Lastly, refining control strategies through advanced parameter optimization methods—such as evolutionary algorithms or neural networks—could help improve system efficiency and flexibility even further. Addressing these topics can lead to more reliable and versatile robotic welding applications across various industries.

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