External Feedback Control Mechanism for 3- Axis Industrial Servo System Used in Welding Application

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Abstract

This paper deals with the monitoring and control of 3-axis Industrial servo system using auto tuning PI controller used in welding application. X and Y-axis servo motors are placed beneath the welding table to control the welding profile at varying speeds, enhancing overall welding performance. The welding electrode is fixed at the Z axis of the experimental system and it is connected through linear actuator. The linear actuator provides feed rate control of welding rod. Synchronization between Z axis and X/Y axis are done through motion control PLC programming, a closed loop simulation model is developed using MATLAB in Simulink platform. PI controller tuning parameters are obtained using auto tuning PI tuning model. The determined auto tuning PI controller tuning values were implemented for welding profile control. The movement of the linear actuator based on the type of electrodes (E6010, E6011&E6013) is controlled using motion control programming in PLC. The results of the present autotuning controller with autotuning values ensures the précised positioning control over the conventional hardware based PID control system.

Keywords: Feedback System; Autotuning PID controller; PLC; 2 Axis Industrial Servo System

1. Introduction

Servomechanisms are among the most widely used control systems for executing closed-loop control functions with high precision. These systems incorporate feedback and error correction techniques to minimize positional, velocity, and acceleration errors through control algorithms [1]. Error magnitude is typically measured using encoders or non-contact feedback mechanisms, enabling accurate system response. Historically, servomechanisms were introduced in gun-laying, fire-control, and marine navigation equipment, where precise aiming and tracking were essential. A typical servo system comprises a controller, command device, error signal amplifier, feedback element (usually an encoder), and a final control element known as the servo motor. The comparator evaluates the deviation between the setpoint and the actual signal, forming the basis for corrective action [2]. Servomotors, electrical rotary actuators integrate potentiometers or encoder modules to measure angular position, velocity, and acceleration profiles. These motors are driven by control units that regulate input power based on commands from the controller and feedback signals [3]. The term "servo" generally refers to systems operating under closed-loop control, where continuous monitoring and adjustment are key. Among various control strategies, the Proportional-Integral-Derivative (PID) controller remains the most prevalent in industrial applications [4]. It continuously monitors the error signal, defined as the difference between the setpoint (SP) and the process value (PV), and applies corrective actions through proportional, integral, and derivative components. However, derivative control can introduce noise, and the absence of integral control may delay convergence to the setpoint. As a result, Proportional-Integral (PI) controllers are often preferred for smoother operation. In advanced applications such as robotic welding, servomechanisms play a vital role in seam tracking and quality control [5]. Sensors integrated into robotic systems help replace manual welding in hazardous environments, ensuring consistent weld quality. Seam tracking systems, often powered by vision sensors and custom software, enable robots to follow weld paths accurately, improving the overall efficiency and safety of welding operations [6] [7]. Based on the literature study, it is found that PLC along with autotuning PID controller is rarely found to perform closed loop PID Control function of 2-axis Industrial servo Controller. Hence the present paper deals with simple and robust automatic PID controller for servo position applications to be used in industrial scale environments [8]. This work utilizes a closed-loop performance monitoring system for the welding process using a PLC-integrated PID controller and HMI interface. MATLAB Simulink function is used for simulation and précised positioning control over the conventional hardware based PID control system is achieved.

2. Methods

The block diagram of the 2-axis industrial servo system is illustrated in Figures 1 and 2. Encoder feedback from the X and Y axis servo motors is routed to their respective servo drives, which interface directly with the PLC controller for closed-loop position regulation [9]. A linear actuator is integrated into the Z-axis and governed by a PLC-based position control system, enabling precise vertical movement. Selector switches are deployed to configure actuator motion based on electrode type, enhancing operational flexibility [10]. The proportional gain parameter within the PID loop plays a critical role in achieving accurate positioning by continuously adjusting based on encoder feedback. Recent advancements in PLC-driven multi-axis motion control have emphasized interpolation techniques and high-speed feedback integration for enhanced precision [2]. Texas Instruments' dual-axis motor control framework using Fast Current Loop (FCL) and Software Frequency Response

Analysis (SFRA) demonstrates how modern microcontrollers can replace traditional FPGA setups while maintaining high bandwidth and low latency in servo applications. Additionally, Allen-Bradley's servo positioning assemblies highlight the importance of modular feedback systems and real-time diagnostics in industrial servo environments [11].

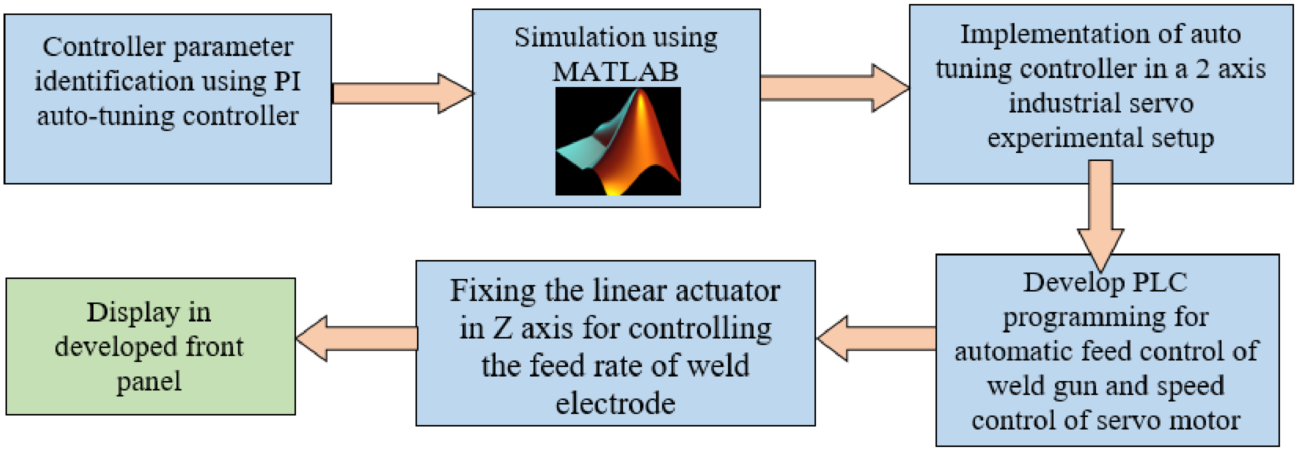

Figure 1. Process involved in welding quality control

For example, if the system needs to move to a distance of 10 cm from the initial position, the proportional parameter is initially set to zero. The control output is calculated using a formula that subtracts the feedback value from the desired position, thereby enabling the actuator to reach the target accurately. The integral parameter contributes to achieving the final position by integrating the feedback values received from the encoder over time [12]. Figure 3 illustrates the Simulink model of the mechanical system, which includes a step input and a PID auto-tuning controller. The model incorporates a transfer function to evaluate how the tuned PID parameters respond to system dynamics. It is observed that the tuned parameters closely match the practical tuning values used in the physical mechanical system. Figure 4 presents the tuned parameters obtained from MATLAB Simulink simulation. The simulation yielded a proportional gain of 17.959 and an integral gain of 140.095. In comparison, the practically tuned system values are a proportional gain of 9.845 and an integral gain of 120.545. This close alignment between simulated and practical PI parameters confirms the accuracy of the attained transfer function [8].

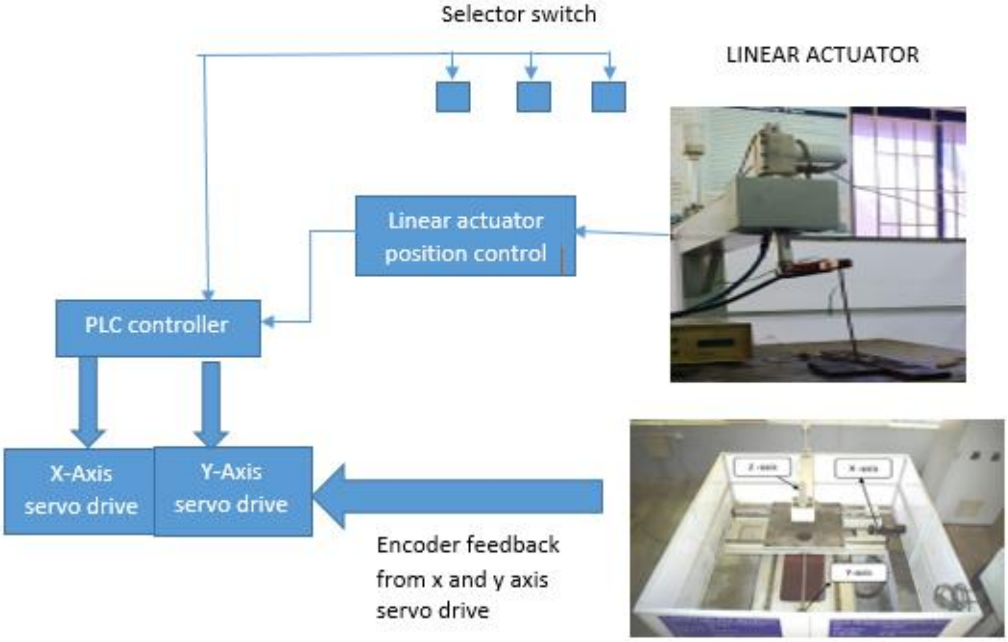

Figure 2. Closed loop speed control of linear actuator

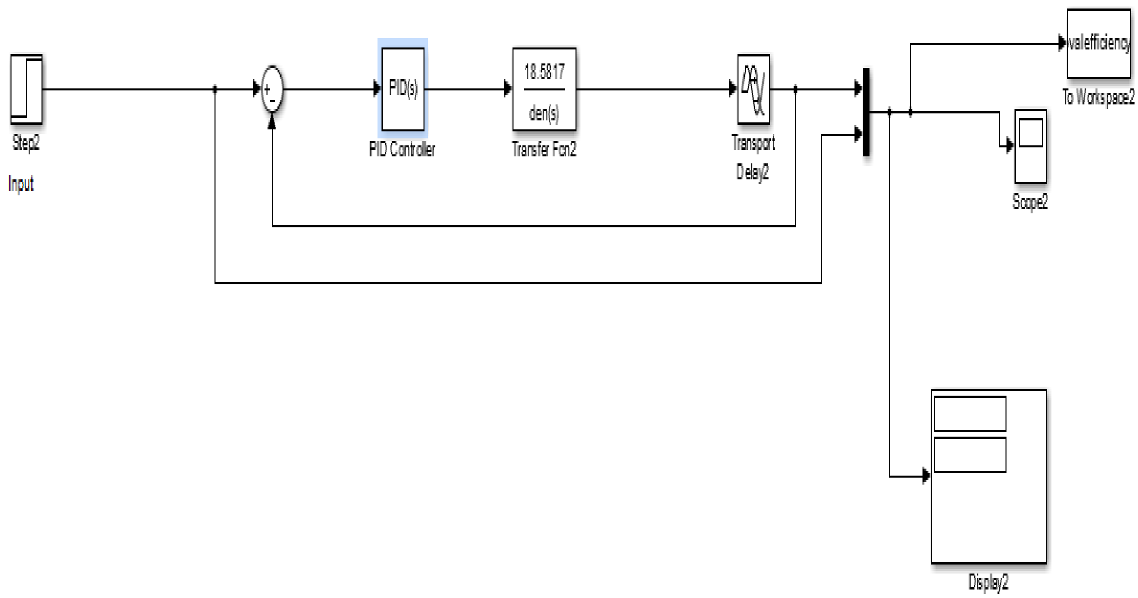

Figure 3. Transfer function model in MATLAB/Simulink

Figure 4 shows the controller tuning response taken from the MATLAB-SIMULINK platform. The response shows the block response and the controller tuning responses. This response is obtained from the transfer function of the two-axis industrial servo system. The auto tuning function of the PID controller shown as the tuned controller response which ensures that the model is perfect.

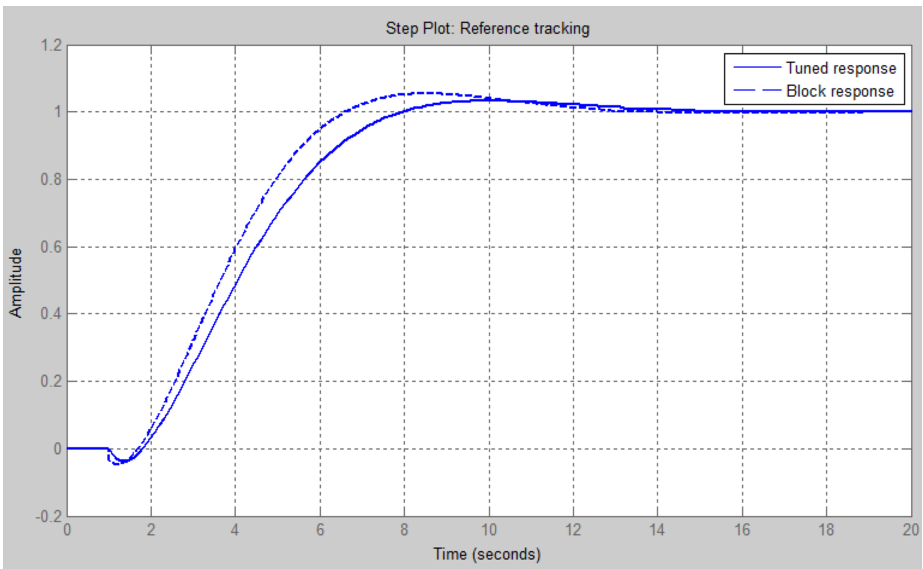

Figure 4. Response of transfer function block & PI tuning controller

From the simulation results, it is ensuring that the developed transfer function model gives accurate positioning for the given set of points of 10cm and 20cm. The simulation results depict that auto tuning parameters can give a better result in the real time experiment system also. Figure 5 shown gives the output for the step input 10cm. The auto tuning controller achieves the set point at 92 seconds and the rise time is 60sec. When the operating point changes to 20 cm as shown in Figure 6, the auto tuning controller provides the results ensured the performance of the auto tuning controller. The developed tuning parameters can be used in the real time servo control experimental hardware [11].

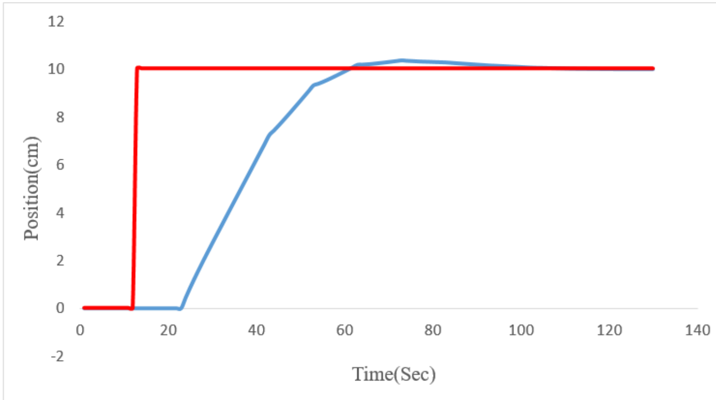

Figure 5. Tuned response for step input of 0 to 10 cm

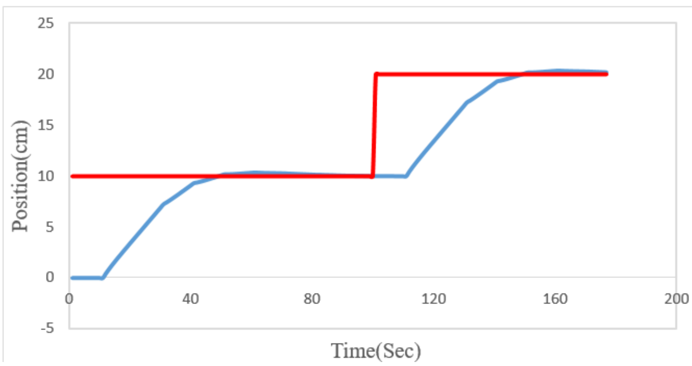

Figure 6. Tuned response for step input of 10 to 20 cm

3. EXPERIMENTAL VALIDATION

An electric arc welding set up is clamped in the 2-axis industrial system as shown in Figure 7 that makes the 2-axis into 3-axis industrial servo system that is made to follow a desired path [13] and it can be controlled by the PLC programming. Different electrodes are chosen for welding application and the timing is noted. Based on the mode selected in the selector switch, the driving unit is synchronized with the linear actuator for that particular speed.

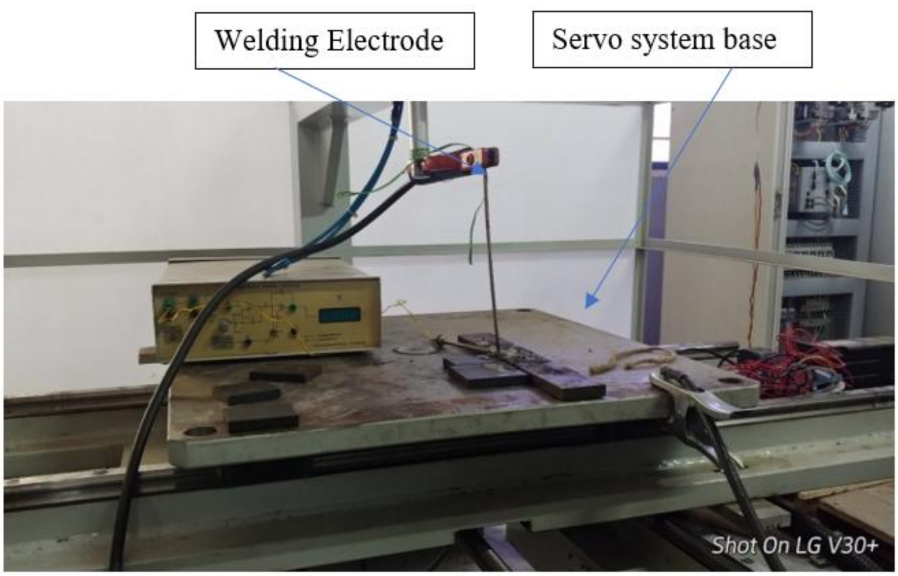

Figure 7. Servo system with welding unit

The welding process involves 3 steps namely, preparation, welding & analysis. In the preparation process the calibration, PLC programming, weld parameter definition and the proper setting of the work piece which makes the proper finishing of the welding is shown in Figure 7, [14]. In the welding process stage, the seam profiling whether the servo drive is following the path and the temperature is measured and in the analysis stage, automatic weld-rod feed rate controller is implemented for controlling of the Z-Axis and the auto tuning controller for seam profile making for the synchronizing of the servo drive and the Z-Axis for the proper finishing. The actuator control is done by the PLC programming and a selector switch for different electrode. The electric arc welding apparatus is fixed in the 2-Axis industrial servo system and check whether the setup is working properly without any disturbance that makes a proper welding. The seam tracking welding rod is implemented and the PLC programming for the path following is done. Arc welding process uses a welding power supply to create and maintain an electric arc between an electrode and the base material to melt metals at the welding point [15]. Jogging is the functional block used in the PLC to make the X and Y axis servo motor to move in X and Y axis direction manually. Figure 8 and 9 shows the MAJ instruction – motion axis jog instruction is used to move the servo with the help of input pushbutton. As long as the push button is pressed, the servo is moving with the reference speed set in the MAJ instruction. The MAJ instruction uses immediate and process type timing [16-18].

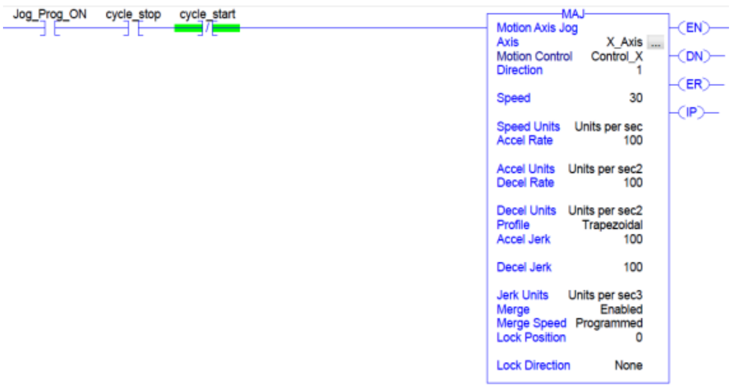

Figure 8. MAJ Instruction in X-Axis

Figure 9. MAJ Instruction in Y-Axis

The Motion Axis Gear (MAG) instruction, shown in Figure 9 provides electronic gearing function with respect to X and Y axis servo motor. The ratio given to MAG instruction say 1:2, makes the x axis servo to move in the reference speed mentioned and Y axis servo is moving with double the time as the reference speed. The MAPC instruction, shown in Figure 10 executes a position cam profile set up by a previous Motion Calculate Cam Profile (MCCP) instruction. This is the main part of the Studio 5000 PLC programmer instruction which id used to derive the profile for welding application [19]. The required welding profile is given with respect to master and slave axis coordinates. Mater axis is X is considered as the virtual axis and slaves are X and Y axis servo motor positions; The cam profile co-ordinates will be generated and feed in to the CAM database of the MAPC instruction.

Figure 10. MCCP Instruction to create welding profile

The MAM instruction, shown in Figure 11 moves an axis to either a specified absolute position or by a specified incremental distance. The MAM instruction uses immediate and process type timing. The Motion Axis Position Cam (MAPC) instruction, shown in Figure 12 provides motion position in accordance with the MCCP instruction. The master and slave axis profiles generated by the user through MCCP instruction will be copied to MAPC instruction for position control functions. Motion Axis Position Cam (MAPC) instruction and Motion Calculate Cam Profile (MCCP) instruction together used to provide welding profiles.

Figure 11. MAM Instruction to move welding arc to a specific position

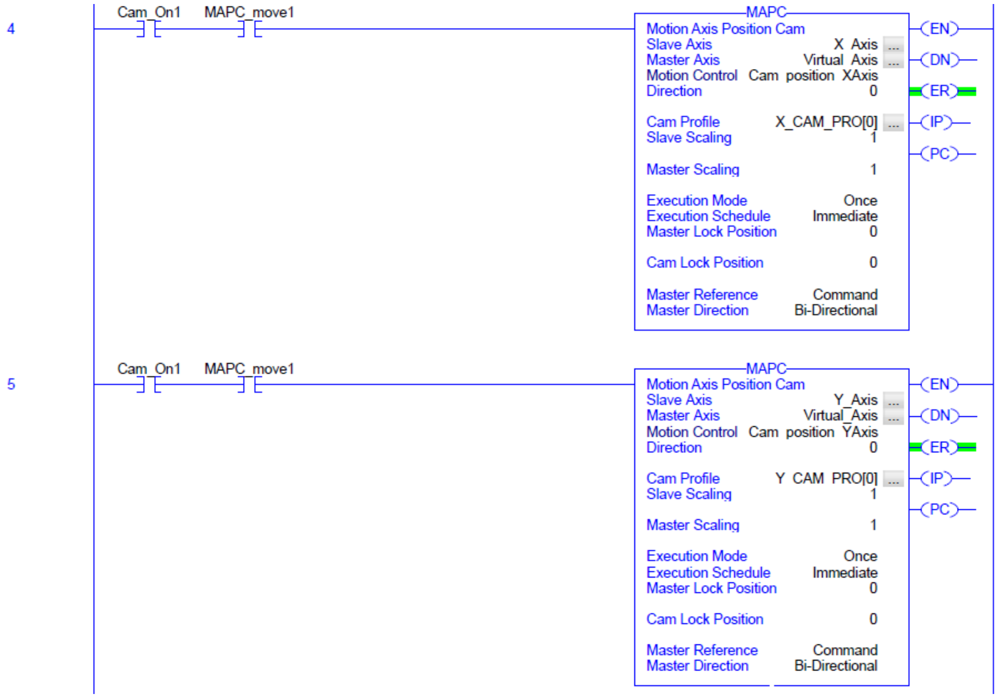

Figure 12. MAPC instruction to make welding profile on X and Y axis

Figure 13 depicts the program to control the actuator motion by connecting it with the pin 30 and 31 to move the actuator up and down and the feed rate is controlled by the digital output. For proper welding process and to get a smooth process the actuator motion and the servo drive is to be synchronized by adjusting the speed of the servo drive and also the timing of the actuator movement and also the timing of actuator is varied for different electrode [20].

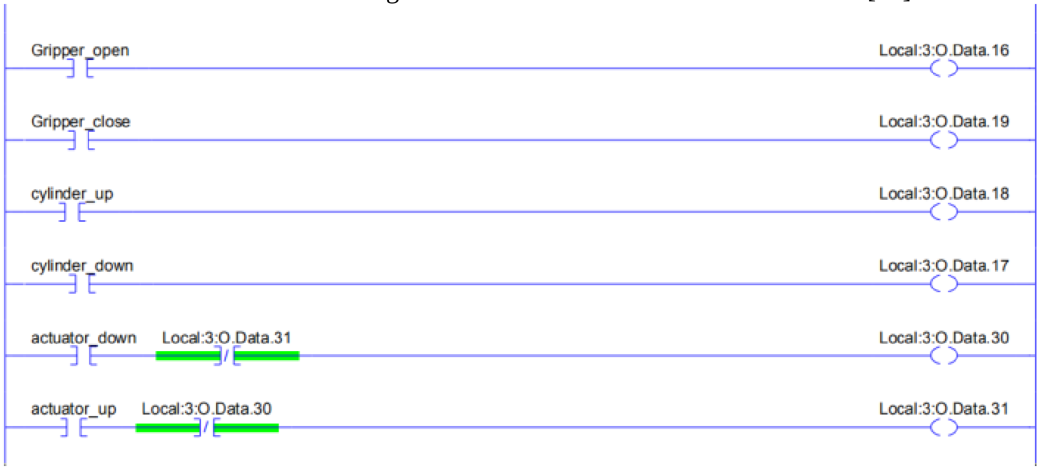

Figure 13. Linear actuator position controls

4. Results and Discussion

For the electrode E6010, dynamic responses in terms of position, velocity, and acceleration are captured and illustrated in Figures 14, 15, and 16. These plots provide insight into the welding process behavior specific to this electrode, including the temporal profile associated with its complete utilization. The system employs a selector switch mechanism to facilitate seamless switching between different electrode types, ensuring adaptability and control continuity across varying welding conditions. For the electrode E6011, the response is taken for position, velocity and acceleration which is shown in the Figures reflects how the welding process take place for this electrode and the timing for complete usage of electrode and a selector switch is used for different electrodes. Similarly, or the electrode E6013, the response is taken for position, velocity and acceleration which confirms the accurate position angle control and the time taken to complete the usage of electrode. Welding rod feed rate is controlled by controlling the voltage given to the linear actuator through PLC programming. The performance analysis of different electrodes is listed in the Table 1.

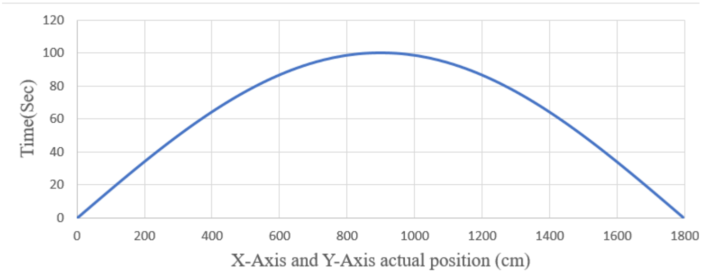

Figure 14. Position Response for achieving Semi-circle welding profile for electrode E6010

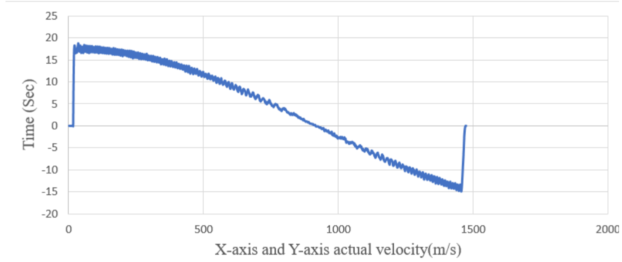

Figure 15. Velocity Response for achieving Semi-circle profile for electrode E6010

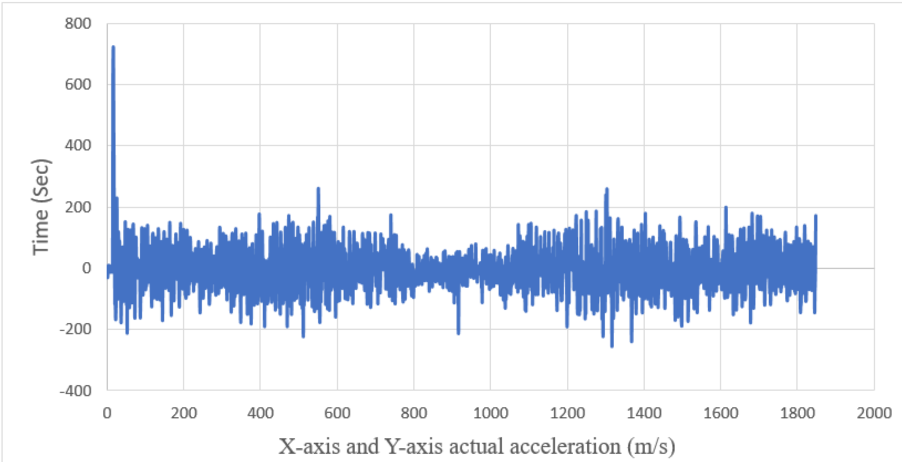

Figure 16. Acceleration Response for achieving Semi-circle profile for electrode E6010

Table 1 confirms that the timing taken for different type of welding material differs and also the welding voltage and acceleration. Similar kind of welding profile may be created and fed to the two-axis automatic control system, which will enhance the accuracy of the welding process.

TABLE 1. Electrode Performance Analysis

TYPE	STROKE TIMING (SEC)	VOLTAGE (V)	POSITION (MM)	ACCELERATION (MM/S^2)
E6010	37	18	1700	210
E6011	32	20	1810	230
E6013	27	23	1850	240

5. Conclusion

The experimental study successfully demonstrates a closed-loop performance monitoring system for the welding process using a PLC-integrated PID controller and HMI interface. By implementing coordinated three-axis control, movable X and Y axes for weld material positioning and a linear actuator-driven Z axis for welding gun movement. This system achieves enhanced precision and responsiveness. Real-time monitoring of servo motor speed and base metal temperature via HMI enables proactive safety measures, including emergency shut-off during abnormal conditions. Comparative analysis of electrodes E6010, E6011, and E6013 reveals distinct performance profiles in terms of temperature stability and response time, offering valuable insights for electrode selection based on application-specific requirements. Overall, the integration of PLC, HMI, and servo-driven actuation establishes a robust framework for intelligent welding automation, paving the way for scalable industrial deployment and adaptive process optimization.

Authors' Contributions

All authors contributed equally to the study's conception, design, data collection, analysis, interpretation, and manuscript preparation. All authors read and approved the final manuscript.

Ethical Approval

Not Required.

Consent to Publish

Not Applicable

Competing Interests

The authors declare that they have no relevant financial or non-financial interests to disclose.

Data Availability Statement

The datasets generated and/or analysed during the current study are not publicly available due to the nature of the industrial research but are available from the corresponding author upon reasonable request

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