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Design of an Electronic Control System for Automating the GMAW Welding Process

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ABSTRACT

This study aims to design and implement an electronic control system to automate the GMAW welding process, focusing on precise regulation of travel speed and travel length to improve repeatability, safety, and weld consistency. The methodology is organized into four stages: (1) needs analysis to define functional requirements, user constraints, and operating ranges; (2) system design covering hardware architecture, sensor and actuator selection, and embedded control logic; (3) implementation through microcontroller-based integration of a motion drive, user interface, and parameter-setting features; and (4) testing to verify accuracy, stability, and performance under realistic operating conditions. The results demonstrate that the system regulates welding speed with an accuracy of 92.54%–99.44%, while maintaining a maximum time standard deviation of 0.038 seconds, indicating stable motion over repeated trials. For welding length control, the system achieves an average absolute error of 0.35–0.5 mm, a percentage error of 0.17%–0.7%, and a standard deviation of 0.051 mm or less, supporting consistent endpoint positioning. In real-world welding tests, the actual weld length deviation ranges from 0.20 to 1.71 mm. It remains within ISO 13920 Class D tolerance limits, confirming practical applicability for general fabrication. The developed controller enables precise parameter control over a speed range of 100–800 mm/min and a length range of 50–300 mm, reducing the need for direct operator intervention and limiting human-induced variability. Overall, the system supports safer, more consistent welding operations and provides a scalable platform for integrating additional monitoring or adaptive control functions. Suitable for training, prototyping, and routine production trials. Future work will address adaptive control diagnostics.

1. Introduction

The fourth industrial revolution (Industry 4.0) is driving automation across various industrial sectors, including manufacturing, to improve production efficiency and quality [1], 2]. Automation is a technology that uses mechanical, electronic, and computer systems to replace human work [3][4]. Data from the Indonesian Ministry of Manpower shows that the manufacturing sector has the highest automation potential at 65%, including the welding industry. Gas Metal Arc Welding (GMAW) is one of the most widely used welding processes in industry due to its practicality and high-quality [5].

However, according to the American Society of Mechanical Engineers, manual welding still faces challenges, including welding defects. The two biggest factors are suboptimal welding processes (41%) and operator error (32%) [6]. The main causes of welding defects are shown in Table 1 below.

Table 1. Factors causing welding defects

No	Factors Causing Welding Defects	Percentage (%)
1	Suboptimal process	41
2	Operator error	32
3	Inappropriate methods	12
4	Incorrect selection of additives	10
5	Poor weld groove shape	5

(Source: American Society of Mechanical Engineers, 2001)

Based on these issues, it is necessary to optimize the welding process and reduce operator errors by mechanizing it and adding process parameters that can be set consistently. This is important because some parameters, such as current, voltage, and gas flow, can be controlled electronically. In contrast, welding speed (travel speed) is highly dependent on operator skill, making it prone to inconsistency [7].

In addition to technical factors, manual welding also poses health risks, particularly eye damage from exposure to UV radiation from the welding arc. Surveys show that most welders have experienced eye damage despite using protective equipment [8]. Based on these issues, there is a need for an automated GMAW welding system that can consistently regulate welding speed and length and reduce direct operator involvement. The purpose of this study is to design an electronic control system for GMAW welding that can regulate the direction of movement, speed, and weld length in response to desired inputs, thereby improving weld quality and reducing operator health risks.

2. Methodology

This research uses a design methodology with a process flow as shown in Fig. 1.

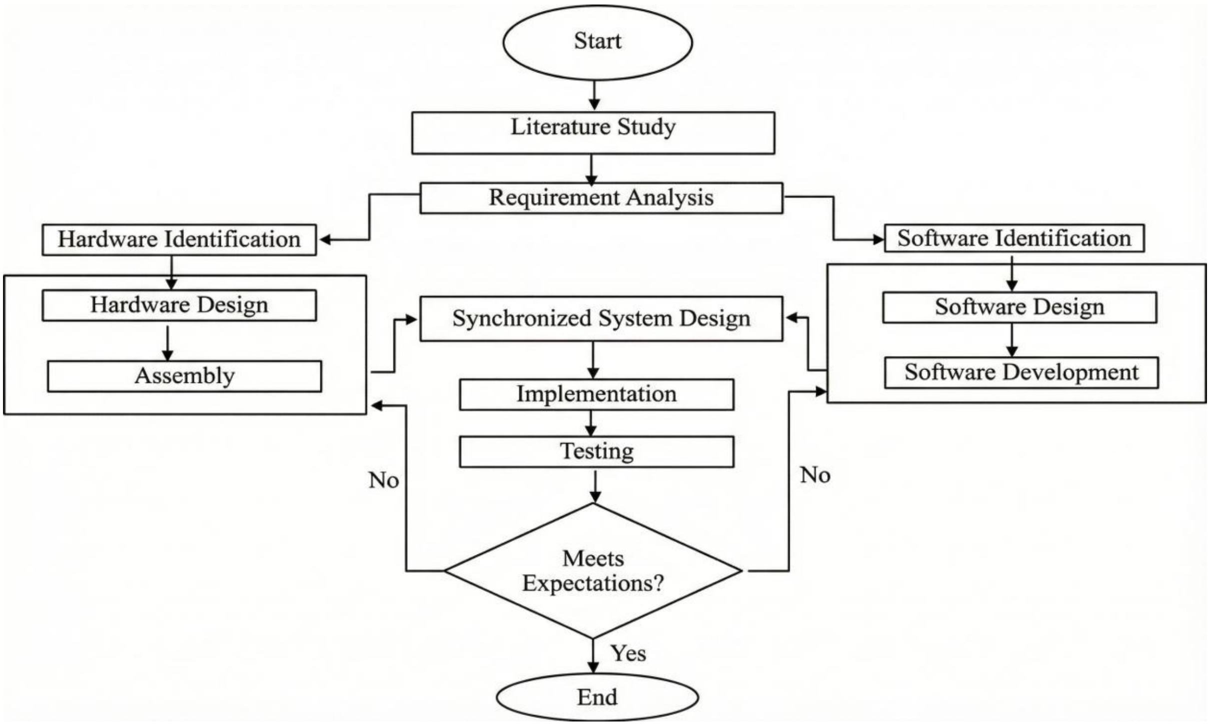

Figure 1. Product Design Flowchart

First, a literature review was conducted to gather existing information from various sources, including books, scientific journals, research articles, technical reports, and other relevant documents, with the aim of understanding the theoretical basis, concepts, and previous findings related to the research topic. Next, a needs analysis was conducted, and the tools and materials needed to design and realize the product were identified. The next stage included product design, implementation, and testing. Testing was carried out by collecting actual data and comparing it with the expected data. If the actual data matched expectations, the next step was to discuss and analyze the results. However, if the actual data did not match expectations, the software and hardware would be recalibrated.

3. Result and Discussion

This chapter on results and discussion presents the results of functional, performance, and welding tests of the electronic control system developed.

3.1 Design of the Electronic Control System Box

The construction of the control system box or casing is in accordance with the design concept described. The control system designed is shown in Fig. 2.

Figure 2. Electronic Control System Box

After all components were assembled in the control box, the next step was to create and input the instruction program into the Arduino Nano to conduct functional testing and determine whether the system ran according to the instructions.

3.2 Functional Testing

Based on the functional testing of the electronic control system for GMAW welding automation, all designed components and software functioned as expected. This test focused on verifying the basic functions of the system, including the user interface, stepper motor, relay as a substitute for the trigger switch on the welding rod, limit switch, and LCD. Based on the test results, the system has met the functional criteria specified in the system work diagram.

In the user interface test, the LCD functioned properly, displaying the necessary information, including system status, welding parameters, and navigation menus. The clarity and consistency of the words displayed on the LCD indicate that the user interface is well designed and easy for operators to understand. This shows that the system can provide accurate, relevant information to users, thereby facilitating the operation and monitoring of the welding process.

In addition to the LCD, user interface input components such as the left, right, and back buttons, as well as the rotary encoder for scrolling and entering, also functioned properly. This proves that the interface design meets user needs and provides accurate responses to user inputs. These buttons consistently control menu navigation and parameter settings, while the rotary encoder facilitates precise selection and confirmation of options. The combination of an informative LCD and responsive input components demonstrates that the user interface is ergonomically and intuitively designed.

Stepper motor testing shows that the motor can rotate clockwise (CW) and counterclockwise (CCW) in response to the button input. This proves that the control system can precisely control the stepper motor, a key component of this electronic control system.

3.3 Performance Testing

3.3.1 Accuracy and Precision of Travel Speed Parameters

Testing the performance of variable-speed control systems for GMAW (Gas Metal Arc Welding) process automation assesses the system's ability to follow a predetermined input speed. In this test, the theoretical time is calculated from the input speed and travel length, then compared with the actual time measured by the moving system.

Based on the test data, the average error percentage ranged from 0.56% to 7.46%, with the error increasing as the input speed increased. Using this average error value, the system's accuracy can be calculated by subtracting it from 100%. Thus, the system's accuracy ranges from 99.44% at 100 mm/min to 92.54% at 800 mm/min.

The graph of the error test results at various input speeds is shown in Fig. 3, which indicates that the error increases with increasing speed.

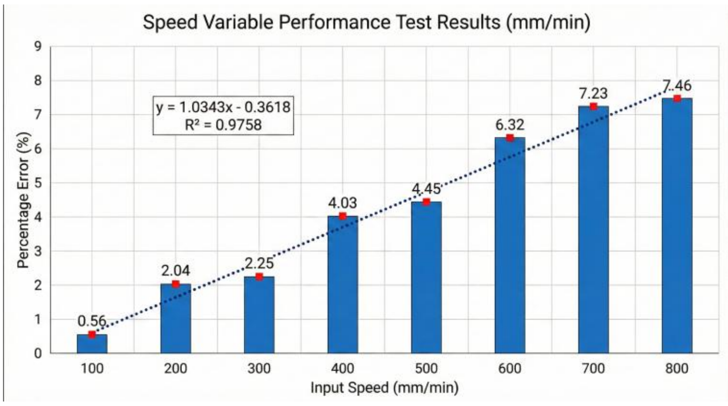

Figure 3. Graph of Error Test Results at Various Speed Inputs

The graph above also shows the linear regression equation $y = 1.0343x - 0.3618$. The regression results indicate a positive linear relationship between input speed and error, with a coefficient of determination (R^2) of 0.985, indicating that the regression model explains approximately 98.5% of the data variability. This indicates that higher input speed is associated with greater error.

This phenomenon can be caused by various factors, including limitations of the microcontroller used in the system, namely the Arduino Nano [9]. The Arduino Nano has limitations in processing speed and time resolution, so the higher the speed set, the more difficult it is for the system to maintain movement stability. In addition, mechanical factors, such as friction in the welding holder and actuator response delays, also contribute to increased errors at high speeds. The accuracy of this test is also an important factor in assessing the system's reliability. In this test, a time resolution of up to microseconds has been used to ensure that the difference between theoretical and actual times can be measured with high accuracy.

In addition to accuracy, the system's precision was analyzed using standard deviation. The standard deviation in this test indicates how consistently the system maintains the set input speed. From the graph in Fig. 4, the combined standard deviation per input ranges from 0.015 to 0.038, as indicated by the red dots. The relatively small standard deviation values indicate that, despite errors in accuracy, the system still has a good level of precision, as the variation between experiments is relatively small. In other words, the system may not consistently achieve the desired speed absolutely, but the deviation remains consistent.

In this test, researchers used a manual stopwatch to record the system's travel time over a certain distance. However, manual recording can lead to potential errors due to delayed responses when stopping the stopwatch. Human hands cannot always stop time exactly when the motor stops. This can lead to additional deviations in the data and contribute to the measured error rate.

Overall, this control system has fairly good accuracy and precision in tracking the input speed, though error increases at high speeds. The average accuracy is still above 90%, and the standard deviation is small. The main factors influencing the error are the control system's limitations, variations in motor performance, and limitations of the manual testing method.

3.3.2 Accuracy and Precision of Travel Length Parameters

In this test, the operator-entered length is compared with the actual length of the moving system from point 0 to the stop. Based on the test results, the average absolute error increased from 0.35 mm at a length of 50 mm to 0.5 mm at a length of 300 mm. However, the percentage error actually decreased from 0.7% to 0.17%. This shows that even though the absolute error increased, the error proportion relative to the input length decreased.

Errors in the test results can be caused by several technical factors related to the linear motion mechanism and control system. One of the main causes is backlash on the leadscrew, which is the gap or slack between the leadscrew thread and the nut that can cause inaccuracy in the system's movement. This backlash occurs due to mechanical wear or manufacturing tolerances in the leadscrew and nut components, so that when the system changes direction, there is a delay before the actual movement occurs. In addition, operators who perform measurements can contribute to errors due to variations in measurement techniques or subjective interpretation of results. Thus, the errors observed during testing are not only due to the electronic control system itself but also to mechanical factors and human error in the measurement process.

The test results graph shows the linear regression equation $y = 0.0321x – 0.33083$. The gradient of 0.0321 indicates that for every 1 mm increase in input length, the actual length increases by approximately 0.0321 mm.

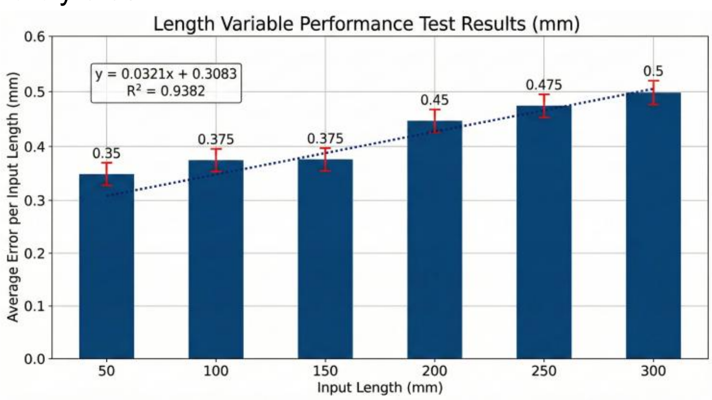

Figure 4. Error Test Results Graph for Various Input Lengths

In terms of precision, the low standard deviation of 0-0.051 mm indicates good consistency in repeated measurements. As seen in the Test Graph, the red dots representing the standard deviation show slight variations in the measurement results, indicating that the system maintains precision despite an increase in absolute error.

3.4 Welding Test

This test was conducted to determine the performance of the control system with a direct welding load, both on the surface of an iron plate and to join iron plates. A descriptive analysis of the welding results is presented in Table 2.

Table 2. Table of Plate Surface Welding Test Results

No	Input Welding Speed (mm/s)	Input Length (mm)	Weld Length (mm)	Mean Absolute Error (mm)	Mean Absolute Percentage Error (%)	Standard Deviation (mm)
1	200	100	102.50	1.66	1.66	1.75
			102.96			
			100.80			
2	250	100	102.40			
			102.50			
			98.44			
3	300	100	102.70			
			101.18			
			101.18			
4	350	100	98.60			
			97.62			
			100.10			
5	400	100	101.30			
			100.52			
			98.62			

The test results show that the developed GMAW welding automation system has an average absolute error of 1.66 mm, corresponding to an error percentage of 1.66% relative to the target weld length of 100 mm, and a data dispersion level (standard deviation) of 1.75 mm. These results indicate that the weld length produced ranges from 101.66 ± 1.75 mm to 103.41 mm. The precision level measured at a standard deviation of one sigma (1σ) has shown good consistency in the initial development phase. In addition to surface-welding tests, the researchers also conducted tests on joining materials using 5 mm steel plates and a joint length of 50 mm. The test results showed that this automation system was capable of joining materials with an actual weld length of 50.20 mm, indicating an error of 0.20 mm.

To evaluate the quality of welding results, this study uses ISO 13920, an international standard that specifies general tolerances for welded constructions [10]. The ISO 13920 tolerance classes are shown in Table 3.

Table 3. ISO 13920 for Linear Dimension Tolerances

Tolerance Class	Nominal Size Range (mm)					
	2 - 30	>30 - 120	>120 - 400	>400 - 1000	>1000 - 2000	>2000 - 4000
A	±1	±1	±1	±2	±3	±4
B		±2	±2	±3	±4	±6
C		±3	±4	±6	±8	±11
D		±4	±7	±9	±12	±16

In this evaluation, tolerance class D was selected, which provides a tolerance limit of ±4 mm for linear dimensions between 30 mm and 120 mm. Class D in this standard refers to rough tolerances intended for structures that do not require a high degree of accuracy. The selection of class was based on the fact that the welding automation system is still in the early stages of development, so the primary focus is on achieving basic stability before further improvements in accuracy and precision. The test results show that all data is within the tolerance range specified by ISO 13920 tolerance class D, indicating that the electronic control system for GMAW welding automation meets the quality requirements of ISO 13920 tolerance class D.

Further analysis shows that dimensional deviations are mainly due to thermal deformation, which causes the welding material to expand during welding. This phenomenon causes the weld material to expand, increasing the weld length. In addition, differences in weld length can occur due to differences in the height of the wire relative to the specimen to be welded or the arc length at the start of the welding process for each test sample, which can result in differences in the arc ignition time or a delay in the welding wire touching the workpiece when the stepper motor starts operating to run the welding rod, thereby affecting the final length of the weld, which can result in a weld length that is less than or exceeds the target length input by the operator. When the system was tested without a welding load, as previously done, the deviation ranged from 0.35 mm to 0.50 mm. These results indicate that the basic position control mechanism is functioning correctly, and the deviations observed during welding are primarily due to the physical characteristics of the welding process.

4. Conclusion

This research successfully designed and implemented an electronic control system for GMAW welding process automation that is capable of regulating travel speed parameters (welding speed) with a speed range of 100 to 800 mm/minute and travel length (welding length) with a welding length range of 50 to 300 mm with sufficient accuracy and precision. The system performs well and consistently, as demonstrated by functionality and performance testing, with all components, including stepper motors, relays, limit switches, and user interfaces, functioning as designed. Testing shows that the system has high accuracy at low speeds, reaching 99.44%, and minor errors in welding length settings with an error rate between 0.17% and 0.7%. Although accuracy decreases at high speeds, with an error of up to 7.46% due to microcontroller limitations and mechanical factors, precision remains stable, with a maximum standard deviation of 0.038 seconds. The welding results also meet the ISO 13920 Class D tolerance standard, with a tolerance of ±4 mm for lengths between 30 and 120 mm. Overall, this system reduces dependence on operator skills and lowers health risks due to exposure to welding light and fumes. The addition of continuously adjustable parameters improves welding quality and process efficiency, although improvements in mechanical aspects and speed control are still needed to achieve optimal performance.

Conflict of interest

The authors declare no conflict of interest.

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