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Development of Automated Welding System for Construction: Focused on Robotic Arm Operation for Varying Weave Patterns

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Abstract Welding is a significant part of the construction industry. Since most high-rise building construction structures rely on a robust metal frame welded together, welding defect can damage welded structures and is critical to safety and quality. Despite its importance and heavy usage in construction, the labor shortage of welders has been a continuous challenge to the construction industry. To deal with the labor shortage, the ultimate goal of this study is to design and develop an automated robotic welding system composed of a welding machine, unmanned ground vehicle (UGV), robotic arm, and visual sensors. This paper proposes and focuses on automated weaving using the robotic arm. For automated welding operation, a microcontroller is used to control the switch and is added to a welding torch by physically modifying the hardware. Varying weave patterns are mathematically programmed. The automated weaving is tested using a brush pen and a ballpoint pen to clearly see the patterns and detect any changes in vertical forces by the arm during weaving. The results show that the weave patterns have sufficiently high consistency and precision to be used in the actual welding. Lastly, actual welding was performed, and the results are presented.

Keywords Automated Welding, Weave Pattern, Mobile Welding Robot, Building Automation

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1. Introduction

1.1. Welder Shortage in High-rise Building Construction

Welding plays an important role in the construction industry. Since most high-rise building construction structures are megastructures that rely on a robust metal frame welded together, quality welding is critical to the safety and structural integrity of high-rise building construction (Red-D-Arc Welderentals, 2020). However, the construction industry has had difficulty attracting younger generations to become welders. In particular, the American Welding Society anticipates that by 2024 there will be a shortage of 400,000 welding workers (Tradesmen International, 2019).

In addition, a welding defect can damage welded structures and, in severe cases, may result in catastrophic accidents (Kim & Ahmed, 2018), and there inevitably will be inconsistency in welding quality when performed by a human. Defects and inconsistencies will also lead to a decrease in mechanical properties and a shorter service life for the product (H. H. Chu & Wang, 2016). Furthermore, studies have shown that welding exposes workers to an amplified amount of radiant and thermal energy, which increases the chance of welding defects in quality caused by poor vision or eye injuries (Lombardi et al., 2005). Therefore, an automated robotic welding system can help address these issues and challenges by providing consistent and efficient welding and help with the labor shortage.

1.2. Proposed Automated Mobile Robotic Welding System

The ultimate goal of this research is to design and develop an automated robotic welding system composed of a welding machine, UGV, robotic arm, and visual sensors. Embedded platforms, sensors, and a networking system are being integrated. In addition, as part of the software integration, visual Simultaneous Localization and Mapping (SLAM) for navigation and deep learning for robotic arm manipulation are being developed. When successfully developed, this welding robot will be able to navigate autonomously on a construction site while creating a map of the surrounding environment, detect an object of interest with minimal assistance from a user, detect a joint to weld, and perform welding. Figure 1 shows the overview of

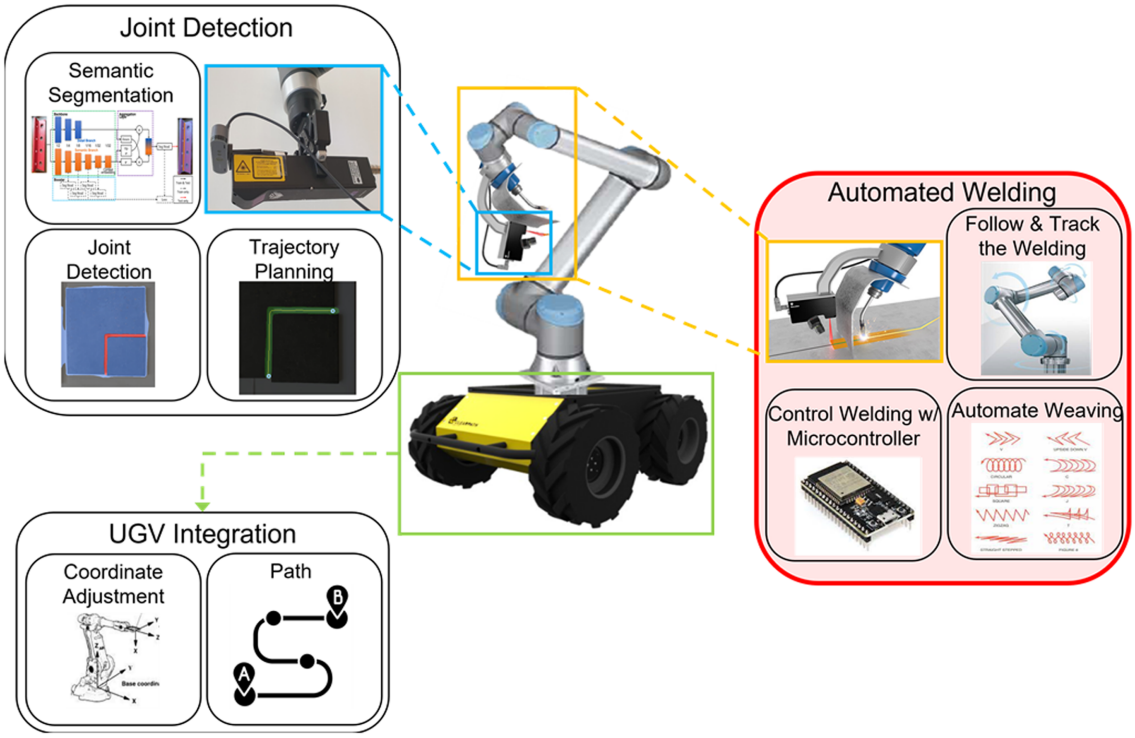


Figure 1. Overview of an automated mobile robotic welding system.

the proposed automated robotic welding system. This robot consists of three modules that are separately investigated:

1. Joint detection: A method for automatic detection of welding joints using visual sensors and a robotic arm that is aligned to the detected joints is being developed by utilizing deep learning algorithms
2. Automated welding: By analyzing the 3D scanned data, an algorithm is developed to control the robotic arm for automated weaving and joint trajectory tracking
3. Unmanned Ground Vehicle (UGV) Integration: By local coordinate integration, 3D mapping, and navigation, the UGV is used to develop an automated mobile welding system

The authors' preliminary study (Lee et al., 2022) focused on deep learning-based joint detection and motion planning of the robotic arm. This joint detection module detects the joint, determines the arm's relative position to the joint, and creates a welding path for the robotic arm. Given this welding path, the automated welding module performs welding, which is the focus of this paper. The hardware of this module is developed by physically modifying a welding machine and connecting it with a microcontroller that serves as a switch for the welding torch. Then, different weaving patterns are mathematically formulated and programmed into the robotic arm for automatic welding. This research prototype was validated using a pen and brush in place of the welding torch. With a pen and brush, horizontal and vertical movement can be easily captured, allowing the programming of fine arm controls. In addition, they allow for quick iteration of the arm controls for research development in a safe manner. Lastly, actual welding is performed, and the results are presented. The last module, UGV Integration is reserved for future research.

2. Background

2.1. Vision-based Robotic Arm Operation

Wen et al. (2017) presented a high-precision robust visual cooperative target localization method, where the markers, including a circle, a line, and dots, are employed and then localized with high detection rates. The proposed algorithm is very suitable for real-time visual measurement that requires high precision in aerospace. Ali et al. (2018) integrated vision system (i.e., a camera with the existing Scorbot to widen the capability of the integrated camera-robot system in industrial applications), which solves the issues of establishing a relevant sequence of operations, developing proper communication between camera and robot as well as the integration of the system components. Asadi et al. (2019) presented a mobile UGV equipped with a stereo camera and a robotic arm to remove obstacles along the UGV's path, where the stereo camera is employed to detect the obstacles in the surrounding environment, robot operating system (ROS) is used to capture the obstacle's relative location to the UGV to guide the robotic arm to

pick up and remove the obstacle.

Shaikat et al. (2020) proposed a computer vision-based robotic sorter, which can detect and sort objects by their colors and heights at the same time. This method utilized a camera with the computer vision software to detect various colors and heights, and used the Haar Cascade algorithm to sort the products, which assists a robotic arm with 6 degrees of freedom (DOF) to pick up and then place objects according to its color and height. Fang et al. (2020) proposed visual teleoperation with human-robot posture-consistent based on a deep neural network. It employed a novel mapping method to generate a dataset with human-robot posture consistent data to map human body data to the corresponding joint angle data of the robot arm. Then they trained a multi-stage visual teleoperation network by the human-robot posture-consistent dataset to teleoperate a robot arm. Sekkat et al. (2021) proposed a deep deterministic policy gradient approach that can be applied to a numerous-degrees-of-freedom robotic arm towards autonomous objects grasping according to their classification and a given ta the You Only Look Once v5 algorithm is employed for object detection. Also, backward projection is used to detect the three-dimensional position of the target, and then a neural inverse kinematics solution is utilized to compute the angles of the joints at the detected position to guide a five-degrees-of-freedom robotic arm that reaches the targeted object.

2.2. Considerations for Welding

2.2.1. Welding Types

The four primary types of welding are described below (Iowa Valley Community College, 2021):

1. Metal Inert Gas (MIG) welding - Gas Metal Arc Welding (GMAW): MIG welding is used to repair exhausts in automobiles and construct homes and buildings. It is the most commonly used welding technique. Shielding gas can be used that travels through the welding gun to protect it from contamination. In addition, this form of welding involves using a continuous wire called an electrode.
2. Tungsten Inert Gas (TIG) welding - Gas Tungsten Arc Welding (GTAW): TIG welding utilizes an electric arc similar to MIG welding. Unlike MIG welding, an electrode made of tungsten is used for TIG welding. Tungsten is one of the most rigid metals that will not dissolve or burn away.
3. Stick welding – Shielded Metal Arc Welding (SMAW): Stick welding has the advantage of being portable. It is commonly used in construction, maintenance and repair, underwater pipelines, and industrial fabrication. A consumable and protected electrode softens and combines metals by creating an arc between a covered metal electrode and the base metal workpiece. During the melting process of the stick, the protective cover also melts and shields the weld area from oxygen and other gases.
4. Flux-cored welding – Flux-cored Arc Welding (FCAW): As both continuous wire and power supplies are used in flux-cored arc welding, it is similar to MIG welding. The welding electrode is a hollow tube filled with flux and fed into the weld pool by the weld gun. FCAW can be divided into two methods: Self-Shielded Flux Cored Arc Welding (FCAW-S) and Gas-Shielded Flux Cored Arc Welding (FCAW-G). For FCAW-S, the gas cylinders are no longer needed since it is solely working with the flux core. A flux shield is used to protect against weather conditions when welding outdoors. In other words, FCAW-G will not be adequately performed in the construction site due to the weather conditions (e.g., wind).

Since FCAW-S is suitable for offsite welding and requires only one hand for welding, it will be used for automated mobile robotic welding in the construction site in this study.

2.2.2. Variables

Weave patterns, welding speeds, weld sizes, wire sizes, voltage, pre-heating, wire speed, tip distance, and wire type are all parameters that depend on other variables (such as workpiece thickness and material). As a result, no single welding standard can be applied to all applications. Instead, each welding standard establishes unique requirements for qualifying welding procedures and welders and fabricating requirements that must be met to comply with those service requirements. Therefore, Moore (2010) defined three significant variables which can critically affect the welding quality as described below:

1. Base metals: Welding certain metals is relatively easy, while welding others is more challenging. Base metals can be categorized as ferrous or non-ferrous. Different categories of ferrous metals are low-carbon, medium-carbon, high-carbon, high-strength low-alloy, and high-alloy steels, as well as ferritic stainless steels, martensitic stainless steels, austenitic stainless steels, and precipitation-hardened stainless steels. Alloys of aluminum, copper, nickel, titanium, and many others comprise non-ferrous metals (American Welding Society, 2005). Therefore, stainless steel is used as the base metal in this study.
2. Welding process: Despite technological advances, not all base metals can be welded with every welding process. Standards for welding specify that the welding process is an essential variable. Different welding processes are described in detail in chapter 2.2.1, and only FCAW-S is used in this study.
3. Joint design: Joint design usually falls under the category of non-essential variables. In some instances, however, an alteration in the weave detail may adversely affect the joint properties of a joint between dissimilar base metals. Therefore, only joints between the same base metals are used, and each weave pattern is tested at a time in this study. The weave

patterns are described in detail in chapter 2.2.3.

For other supplementary variables, a welder setting chart is used to determine the proper welding voltage, wire feed speed, and welding current depending on the thickness and size of the workpiece. For instance, 0.030, 0.035, and 0.045 inches wires are generally used for FCAW-S, according to the chart. Also, the welding procedure is the same when the used wire type is the same. The most frequently changed variables are heat, voltage, and wire speed controlled by a wire feeder, and the proper values for the variables are also instructed in the chart.

2.2.3. Weave Patterns

The welding weaving technique has been adopted for seaming low-carbon steel, and it is expected to improve welding efficiency and optimize weld quality. In this way, a wide weld bead could be obtained, and limited penetration of sidewall fusion would be avoided (Chen et al., 2014). Furthermore, under the much longer welding trajectory, welding weaving exhibits much lower linear energy than standard (stringer) welding, while heat input remains almost unchanged. This is crucial in order to obtain a weld seam with a narrower heat-affected zone (HAZ) and a minor residual deformation (Zhan et al., 2017).

In addition, the weave pattern varies according to the type of joint. Typically, the round weave is used for the butt joint, and the V-weave is used for the corner joint. Even though a weave pattern is commonly used for each joint type, most welders choose weave patterns based on their preferences. We, therefore, developed the eight most widely used weave patterns (e.g., convex, C-weave, curlicue, ladder, T-weave, triangle, V-weave, and zigzag patterns) using a robotic arm.

2.3. Welding Automation

Welding is one of the most critical and challenging tasks in construction. Welding automation could make this process more precise and straightforward, especially in harsh working conditions (B. Chu et al., 2008). Welding automation goes back to the 1990s when Nagata et al. (1997) first attempted to use a welding robot in the construction industry. The welding robot had a portable cartesian coordinate mounted on a carriage. It did the job of welding automation after mounting on a column by an operator.

Recently, Tavares et al. (2019) conducted research on Spatial Augmented Reality (SAR) for welding automation in the structural steel construction industry. SAR uses projected mapping techniques that provide Human Machine Interfaces (HMIs) to help human operations be performed with lower errors, high precision, and faster speeds. This system focuses on projecting the alignment information into the environment, which helps the operator tack weld the beam attachments. It also describes 3D beam perception for improving robotic seam welding operations. The collaborative robotic welding system presented in this study successfully used Building Information Modeling (BIM) to produce optimized information flow and perform complex welding tasks with reasonable accuracy.

In addition, Mao et al. (2010) proposed a mobile welding robot consisting of a rotating arc sensor used as a beam tracking sensor. Its design included a wheeled mobile body, two-dimensional motion platform, rotating arc sensor, and an ultrasound sensor used as an obstacle avoidance sensor. As a result, this welding robot achieved proper angle fillet automated welding in narrow spaces, which solves the problems of difficult operating conditions for welding.

Overall, the research on automated robotic welding still needs hand guidance to control the robotic system to identify the parts placements and has limited degrees of freedom, as well as difficult to apply the system to outside usage. In this study, automated eight different weaving is developed without the need for guidance by humans, and FCAW-S that can be used on construction sites is used for testing the proposed method.

3. Method

3.1. Hardware Development

Figure 2 shows the proposed automated robotic welding system. A Gocator 2350D 3D laser line profile scanner by LMI technologies, ESP32 microcontroller, and Forney Easy Weld 140 FC-I flux-core wire welder are attached to the 6-DOF UR10e robotic arm by Universal Robots. A laptop controls them via remote connection. Moreover, for validating weaving patterns, a brush pen and ballpoint pen are also attached to the arm for better visualization



Figure 2. Hardware setup for automated robotic welding.

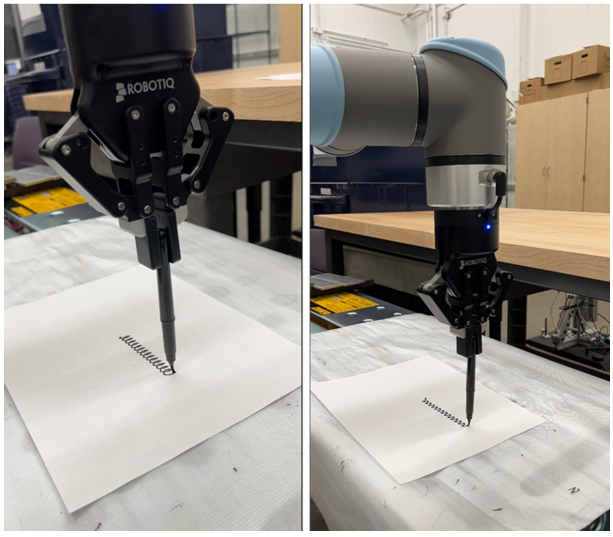


Figure 3. Creating welding weave patterns using automated robotic arm operation.

and research process that allows for fine controls of the robotic arm in a safe manner (see Figure 3).

To make the robotic arm automatically create the weave patterns, mathematic formulation and coding for each weave pattern are developed in Python. In addition, the Real-Time Data Exchange (RTDE) interface is used to synchronize external applications over a standard TCP/IP connection without breaking any real-time properties of the robotic arm. This functionality is useful for interfacing with Fieldbus drivers (e.g., Ethernet/IP), monitoring robot status (e.g., trajectory), and manipulating robot I/O (Universal Robots, 2022).

3.2. Welding Torch Control Using Microcontroller

The conventional welding torch has an ON/OFF switch at its handle for its operation. This has to be automated to achieve welding automation. The task is achieved by using a simple microcontroller connected to a hard-wired relay to the welding torch to replace the ON/OFF switch. The ESP32 microcontroller is chosen for this task as it is a low-cost, low-power system-on-chip (SoC) series with built-in Wi-Fi and Bluetooth capabilities. This is necessary as it enables the microcontroller to use the host system remotely.

A relay, which is a simple electronically operated switch, is used as the digital pins of the microcontroller can control it. The host system and the ESP32 have a built-in TCP/IP module used for communication. The communication is single-sided, where the host PC sends commands to the ESP32. For example, the ON/OFF signals are sent in the form of data packets from the host received by the microcontroller. The ESP32 then conveys those commands to the relay, which controls the welding torch. Communication is made possible by connecting the microcontroller and the host system to a single Wi-Fi network.

Figure 4 shows how the connections are made between the various peripherals. First, one end of the relay is connected to the ESP32. The DC+ and DC- pins of the relay are the power pins that need to be powered by the ESP32. The ESP32 has a 5V output which is connected to the DC+ pin of the relay. Next, the ground (GND) pin of the ESP32 is connected to the DC- of the relay. Finally, digital pin 4 is connected to the relay's input pin (IN), which receives the control signals from the ESP32.

The other end of the relay has two pins. One is the communication pin, and the other is a normally open (NO) pin. Usage of the NO pins means that the relay is open (switched OFF) in normal conditions and should be switched ON by the digital pin of the ESP32. Alternatively, a normally closed (NC) pin can also be used, implying the circuit is usually closed (switched ON). An emergency switch has been included between the relay and the welding gun. It acts as a safety measure in case of malfunctioning of any peripherals. A welding gun power supply is used to power the gun. However, both the terminals (positive and negative) are not directly connected

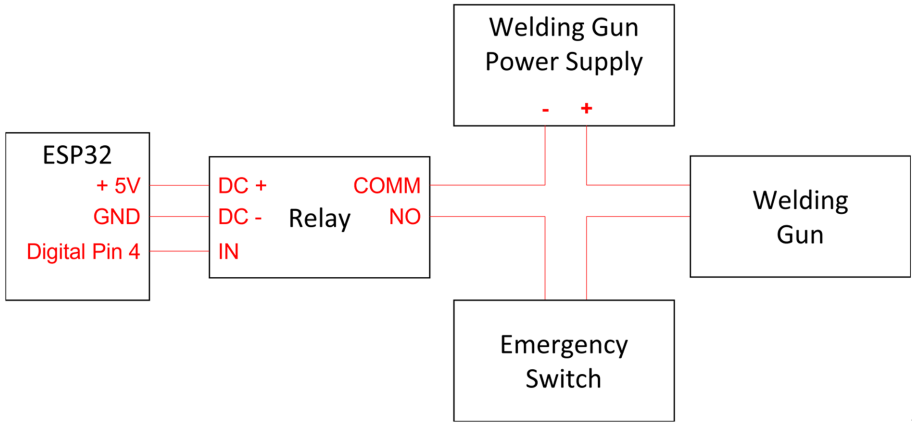


Figure 4. Electrical design of connection for controlling the welding torch using ESP32.

to the gun. Instead, the positive end is connected to the gun, and the negative end is connected to the relay (COMM pin), so the final operation of the gun can be controlled by the relay. Finally, the NO pin is connected to the safety switch which is connected to the welding gun. Figure 7 depicts the complete setup for controlling the welding torch using the ESP32 microcontroller based on the designed electrical connection (see Figure 4).

3.3. Weaving Pattern

This study uses two motions with the Cartesian position for path planning: linear and circular motions. Linear movement makes the robotic arm move from the current pose to the target pose with specific acceleration and velocity. Circular movement is similar to linear movement, but it has the second waypoint and the blend radius of the target pose to move in the round. Figure 5 illustrates how the robotic arm makes the circular movement when reaching the waypoint's radius by defining the radius in a given waypoint. When the circular movement reaches the waypoint radius again, it blends into the next movement. The circular movement is used only for convex, C-weave, and curlicue weave patterns that have curved patterns.

Figure 6 shows the pseudo-code of the automated weaving for a single circular motion of convex pattern using the robotic arm operation. To run the automated weaving, the required data are the width of the weave pattern, the number of repetitions of the single pattern,

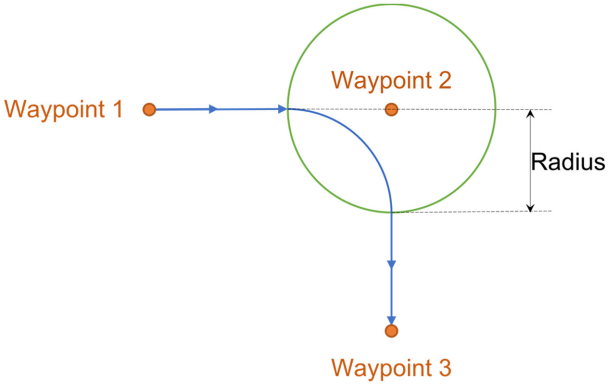


Figure 5. Circular path with indication of radius.

the radius of circular motion, acceleration, speed, and current pose of the robotic arm, which consists of a 3D position (x_c, y_c, z_c) and 3D orientation (ax_c, ay_c, az_c). Then, the system calculates the second and third waypoints so that the robotic arm can move from the current pose (first waypoint) to the target pose (third waypoint) via the second waypoint. The algorithms for other weave patterns are designed similarly to the proposed method.

4. Experimental Setup

Figure 7 shows the experimental setup for the automated robotic welding. An arts portable pocket brush pen

```
algorithm convexPattern is
    input: width of the pattern w,
           number of repetition n,
           current pose (x_c, y_c, z_c, ax_c, ay_c, az_c),        // (position, orientation)
           acceleration a,
           speed v,
           radius r
    output: via pose (x_v, y_v, z_v, ax_v, ay_v, az_v)
           target pose (x_t, y_t, z_t, ax_t, ay_t, az_t)
for repeat the loop n times
    receive current pose (x_c, y_c, z_c, ax_c, ay_c, az_c) from the system    // first waypoint

    increase x_c by 0.40 * w
    decrease y_c by 0.35 * w
    set the changed pose as via pose (x_v, y_v, z_v, ax_v, ay_v, az_v)        // second waypoint

    increase x_c by 0.35 * w
    decrease y_c by 0.80 * w
    set the changed pose as target pose (x_t, y_t, z_t, ax_t, ay_t, az_t)     // third waypoint

    move the arm in circular motion from (x_c, y_c, z_c, ax_c, ay_c, az_c)
        via (x_v, y_v, z_v, ax_v, ay_v, az_v) to (x_t, y_t, z_t, ax_t, ay_t, az_t) with a, v, r
end
```

Figure 6. Pseudo code of the automated weaving for the convex pattern.

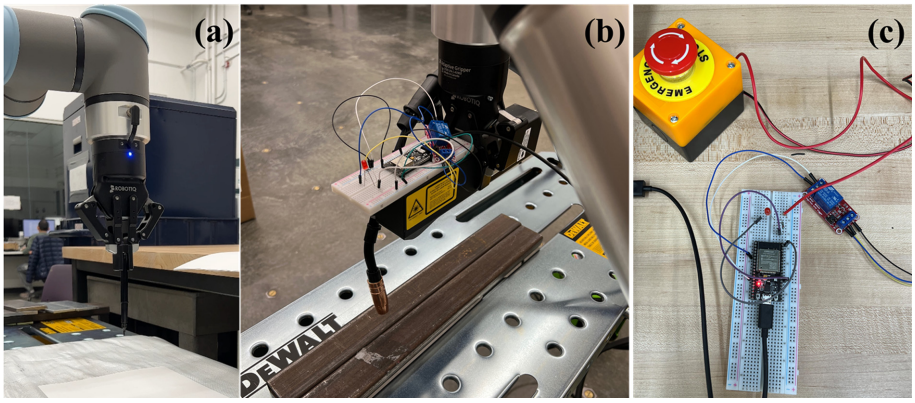


Figure 7. Experimental setup for automated robotic welding (a) brush pen with the robotic arm (b) welding torch connected to the microcontroller with the robotic arm (c) microcontroller with emergency stop switch.

(medium point) with FP10 ink by Pentel and a round stick extra life ballpoint pen with 1 *mm* point by Bic are used in this study (see Figure 7(a)). The eight most widely used weave patterns are depicted in Table 1 (Koestler, 2012) (Instructional Materials Service, 2002). All eight patterns are tested with 10 *mm* widths and 15 repetitions of every single pattern for each weave pattern.

For the test of automated weaving using the welding torch, the torch is connected to the ESP32 microcontroller with the emergency switch (see Figure 7(b) and (c)). The microcontroller is controlled by an Alienware laptop (CPU: Intel Core i9-8950HK, GPU: GeForce GTX 1080 8GB, RAM: 32GB) with Ubuntu 18.04 through wireless communication. Besides, the steel plates are welded using automated weaving for the convex pattern.

5. Results and Validation

Table 2 shows the results of the eight most widely used welding weave patterns created by the proposed methods using the robotic arm. The robotic arm moves from the bottom to the top of the patterns. The T-shape and triangle patterns by the brush pen are split at the end. This is because the brush pen ink is getting dried while drawing the patterns. Overall, the results show that the consistency and precision of the patterns are high enough to be applied to the actual welding.

Figure 8 depicts the consistency and accuracy of the results. When two metal plates align two endpoints of every curve or line, all patterns are shown between the covered object. It demonstrates that the results are consistent. In addition, the widths of both top and bottom of the pattern are 4 in (10 mm; see Figure 8), which is the same as the target input of the experiment. Therefore, it also indicates that the results are accurate.

Figure 9 illustrates the result of the automated robotic welding with the convex weave pattern using the FCAW-S machine. Although the FCAW-S method is generally considered unclean welding, it can create a weld with high strength. Furthermore, some spatter are created around the pattern since the surface of the steel plate is not clean. However, the result still shows it has consistent width and distance between each weave.

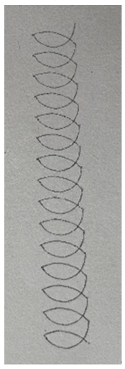
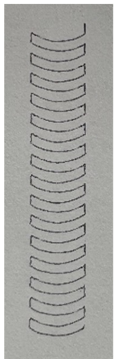
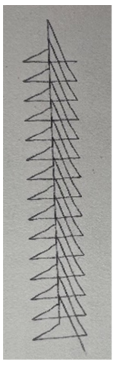
6. Future Works

As described in Section 1.2, this study is a part of vision-based automated mobile robotic welding. Further research on UGV integration is needed to add mobility to the developed robotic welding system to complete the entire research. As illustrated in Figure 10, the integration of UGV with the developed welding robotic system will

Table 1. Eight most widely used welding weaves

Convex	C	Curlicue	Ladder	T	Triangle	V	Zigzag
							

Table 2. Welding weave patterns created by robotic arm operation

Method	Convex	C	Curlicue	Ladder	T	Triangle	V	Zigzag
Ballpoint pen								
Brush pen								

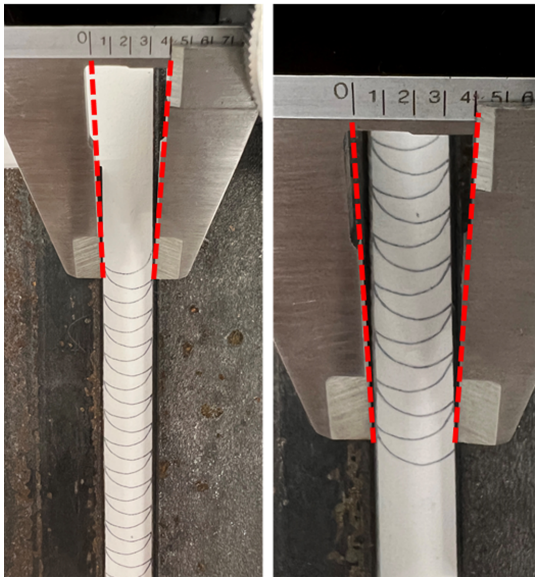


Figure 8. Width measurement: a) top and b) bottom of the weave pattern.

enable unlimited movable ranges on the X and Y axes. This robotic system can secure most ground-level structural components during the construction project. The trajectory plan for the UGV and robotic arm will be re-designed to perform scanning and welding for large metal components. The study on portable and automatic welding systems will be carried out by integrating various technologies,



Figure 9. Result of the automated robotic welding with the convex weave pattern.

including camera, scanner, robotic arm, welder, LiDAR, and UGV.

7. Conclusion

This paper presents a robotic welding system and focuses on automated weaving using the robotic arm. In addition, the ESP32 microcontroller was used to control the switch on the welding torch to automate welding rather than pressing the switch manually. The weaving automation was tested using a brush pen and a ballpoint pen. It appeared that the majority of the weave patterns have sufficiently high consistency and precision to be



Figure 10. Conceptual design of mobile welding robot.

used in the actual welding. The result of the actual welding test on convex weaving using the FCAW-S machine also validated our achievements. Further research on this study will be conducted to add mobility to the proposed robotic welding system by integrating UGV in the future. Our lastly developed system will be used to navigate autonomously in a construction site while creating a map of the site and following a trajectory generated automatically from a user-definable target destination, detect welding joints using a visual sensor, and perform welding.

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