Theoretical and Empirical Verification of a Mobile Robotic Welding Platform

A mobile robotic welding robot will be verified both theoretically and empirically using AWS and ASTM standards

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ABSTRACT

Traditional robotic welding, common in industries such as automotive production, becomes impractical in industries that use unstructured manufacturing techniques, such as shipbuilding. This is due in part to the scale of the manufactured systems and the size and locations of the weld. In these unstructured manufacturing environments, the state of the art for mechanized welding has historically consisted of a fixed-track system with a mechanical welding carriage that operates along the track. However, alternative mechanized welding approaches that make use of developments from the field of mobile robotics are being pursued. One example is the semiautonomous Mobile Robotic Welding System (MRWS). The MRWS is a lightweight mobile manipulator consisting of a two-degrees-of-freedom mobile platform and a three-degrees-of-freedom torch manipulator. The MRWS is capable of climbing ferrous surfaces by the use of permanent magnet tracks and positioning the welding torch along a weld joint. This system is designed to mechanize the welding process for a variety of weld joints with minimal setup time. Setup consists of placing the MRWS on the surface to be welded and driving to the intended weld joint. In order to be utilized in a manufacturing environment, such a system must be verified for the welding process it is performing. This paper demonstrates and verifies the MRWS as a valid alternative for mechanized welding in unstructured environments. The verification process consists of two components: design validation based on theoretical analysis of the MRWS system models to prove the weld process requirements can be met, followed by an empirical verification based on AWS weld test specifications for a specific, commonly used welding process. The design validation focuses on the two primary differences between the MRWS and proven fixed-track mechanized welding systems, torch motion control on a mobile platform, and impact of the MRWS magnetic feet on the weld process. The empirical verification was performed on a vertical groove weld on mild steel with uphill progression, 3G-PF.

Introduction

Expanding the use of robotics in industries that manufacture large products, such as shipbuilding, is a relatively new enterprise. In general, every ship is unique. Further, the size and scale of a typical ship combined with the high costs associated with dry docks or real estate immediately adjacent to the launch location has led toward a common manufacturing technique in which the structural components of the ship are assembled in multiple locations with only the final assembly occurring in the most expensive location. Some aspects of a common assembly line technique are used; however, due to the part/component differences, the assembly process is constantly changing from part to part. There are, however, significant benefits that can be achieved through increasing the level of automation within the shipbuilding process in the United States (Ref. 1). The same discussion applies to the Electric Power Generation Industry (EPI), in particular, steam plants and wind-energy production.

A number of researchers are investigating nontraditional robotic manufacturing techniques based on nonserial architecture, movable-base robotic manipulators in the shipbuilding and similar industries. These efforts have resulted in several alternative approaches for automating manufacturing processes in unstructured environments. One approach employs mobile, legged robotic platforms. Some examples of this approach are the ROWER project (Ref. 2), demonstrating a large-legged robot designed to travel through the hull of a ship while performing welding tasks and Robug (Ref. 3), a smaller-legged platform used for inspection and potential manufacturing purposes. Another approach is based on a cable-driven system with a multi-degree-of-freedom end effector. RoboCrane (Ref. 4) developed by NIST provides an example of this system. A third approach uses large-wheeled mobile robots to traverse the welding site. A large, wheeled platform that carries a six-axis robot called NOMAD (Ref. 5) is intended for welding large-scale structures such as those found in earth-moving equipment and bridge-fabrication industries. Several groups have been pursuing smaller, mobile climbing robots for welding. One such approach uses wheeled robotic systems, for example, the two-wheeled mobile robot designed specifically for fillet welds in lattice (Ref. 6). Another approach utilizes continuous-track robotic systems, which generally use attractive elements, such as suction cups, magnets, and gripping feet, that allow these systems to climb (Refs. 7–10). This research is driven by the need for improved tools for manufacturing tasks such as welding in large-scale manufacturing systems such as shipbuilding.

While this research has resulted in a large number of conceptual designs and prototypes for mechanized or robotic welding, there is a continued need to validate these designs and bring them into commercial practice. An important step includes documented weld verification process, but this procedure has not been
reported in the literature for any mobile robotic systems. For the purposes of this paper, weld verification is defined as the process of confirmation by examination of objective evidence that the requirements for a specific intended use can be consistently fulfilled (Ref. 13). Validation of the weld process is a general requirement for most shipyard joining processes, and in many cases is demanded by the customer (e.g., U.S. Navy). The validation process must encompass both the operator as well as the equipment used to perform the weld. The validation process generally consists of a combination of training and weld verification (based on AWS weld process qualification), leading to certification of weld operators. Traditional welding equipment, such as power supplies, are inherently a part of the weld verification testing. Since the fixed-track mechanized welding systems have been in service for a number of years, there is evidence that these meet validation standards, although a lack of validation examples are present in the literature (Ref. 14). This paper demonstrates and verifies a method for mechanized welding in shipbuilding and related industries that offers an alternative to the fixed-track systems. The method is based on the mobile, climbing skid-steer platform with welding gun manipulator called the Mobile Robotic Welding System (MRWS) as described in Ref. 8. The MRWS is designed to be a weld mechanization tool that requires very little setup time when compared to a fixed-track system. The fixed-track system requires a track to be accurately positioned and attached along the weld joint prior to the welding process. The time for track setup must be added to the weld time to get an overall process time. The use of a mobile robotic welding system eliminates the vast majority of the setup and take-down time, which improves the overall productivity of weld
In addition, this paper presents a method to demonstrate a level of weld validation for new, robotic welding systems. This is performed based on theoretical validation of the robotic welding machine at the time of design; therefore, it may be termed design validation (Ref. 13). The theoretical analysis focuses on the portion of the MRWS that deviates from the fixed-track system design. In particular, the MRWS is based on a kinematic arrangement that is significantly different from that of the fixed-track system to achieve similar gun motions. Further, the MRWS relies on a high magnetic flux density in the local vicinity of the weld joint while the fixed-track systems use a much lower magnetic flux to attach the track to the structure (and often other forms of mechanical attachment of the track to the welding surface are used). The theoretical analysis builds a justification for validation by comparing with existing mechanized weld systems. The empirical verification applies to the complete MRWS system through the AWS B2.1:2005 and D1.1/1.1M:2002 method for a specific weld type and orientation (Refs. 11, 12).

The remainder of this paper proceeds in the following order. First, a brief overview of the MRWS system is provided followed by a theoretical analysis and design validation approach of the MRWS for the welding process. Then, an empirical weld verification of a gas metal arc welding (GMAW) vertical groove weld on mild steel with uphill progression, 3G-PF, that was welded using the MRWS platform, is performed. The paper is completed with concluding remarks on the validation of the overall system.

**MRWS Overview**

The MRWS is a mobile robot based on two continuous permanent magnet tracks. The robot can climb ferrous (steel) structures in any orientation. The robot weighs approximately 60 lb and has a payload capacity of 100 lb that consists primarily of a commercial wire feeder, welding gun, gun manipulator, and sensor package. The robot has onboard sensors, processing, and a control algorithm that allows it to operate in a semiautonomous fashion.

The robot platform consists of two symmetric endless chain track units with attached magnetic feet. The magnetic track units provide propulsion to the robot while adhering to ferrous surfaces, allowing for welding in all positions. Also contained in each track unit is a suspension that aids in adhering to an uneven welding surface. Drive power is provided by DC brushless motors, and the control is a combined system of drivers and microcontroller to provide a closed-loop system. Figure 1 shows the MRWS as a field-ready system.

Robot navigation is defined globally by the operator through remote control, while the robot locally uses operator inputs to close the loop on gun trajectory control. During operation, the welder observes the weld in situ and makes gun tip position input and speed corrections as needed. An overview of the robot control diagram is shown in Fig. 2.

The robot platform supports a five-degree-of-freedom gun manipulator to provide local control of the gun. The gun travel angle is adjusted manually, while the gun translation, perpendicular to the weld joint, is actuated with a brushless DC motor, the work angle is adjusted by a geared servo motor, and the height of the contact tip is controlled by a linear actuator. Coordinated control of the robot platform motion and gun manipulator is provided by the onboard processor, allowing the gun motion to produce a variety of desired weld patterns. The gun manipulator is independently suspended from the platform to isolate it from any motion disturbances, as well as keep the gun adjustments relative to the surface local to the weld.

The weld operator interacts with the robot through a robot-control pendant, shown in Fig. 3. The control pendant allows the operator to drive the robot manually or to supervise its semiautonomous operation, and to define the weld motion characteristics such as forward and transverse speeds, dwell times, weld patterns, etc., remotely.

**Theoretical Validation of the MRWS for Welding Processes**

**Theoretical Validation Overview**

This section presents a theoretical basis for validating the MRWS for welding processes. When comparing the MRWS system with existing fixed-track welding systems, two fundamental differences arise in their design and operation that have the potential to impact the welding processes: 1) kinematic differences in achieving desired motions of the gun, and 2) variation in how tractive forces are generated between the welding platform and the surface on which the weld is performed. These are addressed in order in the following sections.

**Theoretical Validation Based on Motion Control**

The ability of the MRWS to provide necessary motion control is directly influenced by its kinematic arrangement. The gun motion is described by its position and time derivatives: gun velocity, acceleration, and so forth. To perform a desired weld, the gun must follow a specified weld trajectory in a smooth manner. This trajectory consists of both the geometric description of the gun position along with gun velocities and accelerations along the
path. A smooth trajectory requires, at a minimum, the ability to specify both robot position and velocity throughout the path motion. The kinematic arrangement of the MRWS defines the geometric position and velocity characteristics, and this is validated by comparing these capabilities in turn with an accepted reference system. For this work, the reference system is a fixed-base track system with mobile carriage. These fixed-track systems are well accepted for mechanized weld processes (for example, Bug-O, Gullco, and Koike track systems) (Ref. 14).

Considerations for gun position: For theoretical validation of gun position control, the gun manipulator on the MRWS must span the gun position space provided by the reference system while avoiding interior singularities (positions on the interior of the workspace in which the robot loses one or more degrees of freedom (dof)). The position kinematics of the MRWS system are compared to that of the reference system. Note that for this comparison, the mechanisms to control the work angle, travel angle, and gun plunge (tip depth) are considered common to both systems, and are not included in this analysis.

The MRWS is a mobile manipulator system consisting of a 2-deg-of-freedom tracked mobile platform connected in series with a 3-deg-of-freedom Prismatic-Revolute-Prismatic (P-R-P) serial gun manipulator. Prismatic and revolute refer to the type of single-degree-of-freedom joints used to form the gun manipulator. It is assumed that the mobile platform is on a planar surface. Figure 4 provides a schematic of the MRWS with gun manipulator. Frames (I), (R), and (T) denote the inertial, robot chassis centroid, and gun tip frames, respectively, and θ represents the rotation of (R) with respect to (I). The left and right tracks are actuated with inputs θl and θr, while d2, d3, d4 are the inputs to the P-R-P gun manipulator.

The length of the track is given by l while the distance between the centerline of the tracks is given by 2b. To consider the position kinematics, assume that the robot frame translates along the weld axis (z) by a distance \( d_1,_{\text{MRWS}} \), while the gun manipulator translates in a direction transverse to the weld axis in the plane of the surface. Then, a kinematic description of gun motion with the work angle and travel angle removed is given as

\[
T_{\text{TR}} = \begin{bmatrix}
1 & 0 & d_1,_{\text{MRWS}} \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

where \( d_1,_{\text{MRWS}} \) is the robot translation along the weld joint from the mobile unit, \( d_2,_{\text{MRWS}} \) is the translation of the toolbar and \( d_3,_{\text{MRWS}} \) is the translation along the gun (plunge).

Figure 5 presents a kinematic diagram of a fixed-base track system for mechanized welding. This kinematic description of the gun motion from the reference system is given as

\[
T_{\text{TR}} = \begin{bmatrix}
1 & 0 & d_1,_{\text{ref}} \\
0 & 1 & d_2,_{\text{ref}} \\
0 & 0 & 1
\end{bmatrix}
\]

Comparing Equations 1 and 2 demonstrates that the MRWS spans the gun position space of the reference system as long as

\[
dl_1,_{\text{MRWS}} \geq d_1,_{\text{ref}}
\]
\[
dl_2,_{\text{MRWS}} \geq d_2,_{\text{ref}}
\]
\[
dl_3,_{\text{MRWS}} \geq d_3,_{\text{ref}}
\]

which can be satisfied by the mechanical system design. Further, it is noted that no interior singularities exist when the work angle and travel angle are removed from the system kinematics.

Considerations for gun velocity: To provide smooth trajectories offered by the reference system, the MRWS must match the velocity capabilities of the reference system. While validation of the MRWS gun positioning capability was intuitive and involved a direct comparison of the geometric positioning behavior of the MRWS with the reference system, consideration of the velocity behavior is less intuitive. However, the process will proceed in a similar manner by comparing the manipulability ellipsoids (Ref. 15) of the MRWS to the reference system. The manipulability ellipsoid is a geometric representation of the velocity characteristics of a manipulator based on a singular value decomposition of the Jacobian matrix of the manipulator where the singular vectors define the direction, and the singular values define the magnitude of the axes of the manipulability ellipse (Refs. 15, 16). When placed in context with the welding process, a manipulability ellipse defined in the plane of the welding surface gives a measure of the maximum end-effector velocity that can be achieved based on a unit set of input joint velocities. Motion in any desired direction within the welding plane can be found as the length of a line parallel to that direction that passes through the center of the ellipse and is bounded by its edges (Ref. 16). For purposes of validation, the MRWS system is said to be validated for motion control if its manipulability ellipse spans a majority (75% or more) of the corresponding manipulability ellipse for the reference track-based system. The comparisons are performed in the following manner. Based on the kinematic arrangement of the MRWS (shown in Fig. 4) and reference system (shown in Fig. 5), the kinematic relationships between joint level and gun velocity are described in the form of the manipu-
lactor Jacobian (see appendix for details). A singular value decomposition of the system Jacobians is then carried out to define the manipulability ellipse of each respective manipulator. The results are shown for the output axes lying in the plane of the welding surface as shown in Figs. 6–8.

From the kinematic solution, it is noted that in a fixed-base track system, the manipulability ellipse is a unit circle and invariant with respect to actual mounting position of the gun while on the MRWS, the gun mounting location does play a role in determining the manipulability of the gun. This is shown in Fig. 6, where the manipulability ellipse of the MRWS (solid lines) and the fixed track system (dashed lines) are compared at various locations relative to the MRWS platform. In this figure, an outline of the MRWS is shown for scale purposes. From Fig. 6, the manipulability of the MRWS is seen to be symmetric about the local frame \( \mathbf{R} \) \( x \) and \( y \) axes of the MRWS platform. Three locations are identified on Fig. 6 in which to consider gun placement in detail: point A (leading edge of MRWS platform), point B (corner of MRWS platform), and point C (side of MRWS platform). Each gun location is shown in detail in Fig. 7. From Fig. 7, it can be seen that in all three positions, the manipulability ellipse of the MRWS with gun manipulator largely spans that manipulability of the fixed-track system kinematics. The minimum coverage occurs at location A, where the MRWS manipulability ellipse intersects 79% of the fixed track manipulability ellipse. This implies, based on the proposed criteria of 75% minimum coverage, that the MRWS provides acceptable motion control for all weld applications in which fixed-track mechanization is used.

In addition to gun-mounting location, the MRWS kinematics demonstrates dependence on the orientation between the platform longitudinal axis and weld axis (\( \theta \), Fig. 3). The manipulability ellipse of the MRWS with gun located at point A (Fig. 6) is compared with the fixed track system for increasing values of \( \theta \) from 5 to 35 deg in Fig. 8, and the area of intersection is constant at 79%. From Fig. 8, it can be seen that the effect of MRWS orientation is a rotation of the manipulability ellipse and does not change the area of intersection with the manipulability ellipse of the fixed-track system. Thus, this demonstrates that the MRWS provides acceptable motion for all weld applications and is invariant to the alignment between the MRWS platform and the weld joint.

**Ttractive Magnet Interaction with the Welding Process**

The MRWS generates tractive forces with the welding surface through a track consisting of a series of permanent magnets. The number and density of these tractive magnets are much greater than that commonly found on fixed-track welding systems. The introduction of a magnetic field to the welding process can interfere with the welding process through magnetic arc blow and must be investigated to determine positions where the magnetic flux will not interfere with the welding arc. The MRWS track is designed to contain the magnetic field generated by the magnetic feet to a small region encompassing the tracks, and to position the welding process outside of this region. To evaluate the track design, a finite element analysis (FEA) model of the MRWS-generated magnetic field is studied, validated with empirical data, and used to define acceptable locations for the welding gun. The acceptable regions are defined as those that demonstrate a magnetic field less than the allowable field as identified for typical welding processes. These values are shown for a variety of welding processes in Table 1, which is adapted from Ref. 17.

An analysis of the magnetic field associated with the tracks of the MRWS adhering to ½-in.-thick steel is presented in Fig. 9. The plot color scale for FEA results...
are defined so that the gray region is an average magnetic flux greater than 10 gauss while the blue regions are less than 10 gauss. Therefore, the gun should not be located in gray regions due to potential magnetic arc interaction (a magnetic flux higher than 10 gauss). All blue areas around the tracks are suitable regions for any of the welding processes listed in Table 1. The numerical analysis is reinforced with physical testing of the MRWS in the same arrangement. The MRWS was placed on a large (assumed seminfinite, given robot size to sheet ratio) ¼-in.-thick sheet of steel and an AlphaLab, Inc., DC Gaussmeter M1HS was used to measure the normal component of magnetic flux around the mobile platform. The meter readings were compared with the numerical analysis and demonstrated strong agreement with the FEA results. Furthermore, in-service welding has been done in a variety of gun positions in the blue region shown in the FEA plots. During these welds, no visible magnetic arc blow was seen, and no defects typical of magnetic interference were found.

The results of this analysis and physical testing demonstrate that the MRWS offers suitable regions for gun positioning that will satisfy the limits of all welds demonstrated in Table 1. In particular, the focused applications for the MRWS are the short-arc GMAW process (second row) and pulse-arc GMAW process (similar requirements to GTAW, first row, Table 1). Therefore, these analyses demonstrate that the MRWS meets the weld process requirements for GMAW and GTAW applications that are employed on other mechanized platforms.

MRWS Empirical Verification

Empirical Verification Overview

This section presents an empirical basis for verifying the MRWS for a specific welding process. The process chosen was a GMAW vertical groove weld on mild steel with uphill progression, 3G-PF. This weld process was viewed as a common weld joint performed in a typical shipyard. The empirical test is based on the American Welding Society (AWS) procedure qualification for a vertical groove weld. The test methods required for a groove weld are visual examination, tension test, and guided bend test (root bend) (Ref. 11). All tests performed comply with the American National Standards Institute (ANSI) – AWS D1.1/D1.1M:2002 standards (Ref. 12).

The experimental setup and equipment are outlined followed by the experimental results. Accordingly, a detailed discussion of how the samples compared to the AWS specifications are presented.

Experimental Setup and Procedure

The test samples were fabricated using the MRWS with a Lincoln Electric Power Wave® 455 welding machine, and Power Feed® 10 wire feeder, set up for pulsed spray gas metal arc welding. The weld was performed on 0.5-in.-thick ASTM A36 structural steel using a B-U2a-GF groove type with 0.125-in. steel backing. The weld groove had a 45-deg angle and a root opening of ¼ in. The electrode used was 0.045-in.-diameter ER70S-6E, and the gas mixture was 95% argon 5% oxygen at a flow rate of 35 ft³/h. Three weld passes were completed, each using a trapezoidal weave pattern. The welding machine was utilized in pulse program mode with settings of 17.5 V, 110 A, 120 in./min wire speed, and 0.97 trim setting. The MRWS settings used were 2–4 in./min travel speed, 0.5-in. contact tip-to-work distance (CTWD), and 12 deg of forward gun angle. Weave speed and dwell times were varied during the process to create a uniform bead.

Once welded, a visual inspection was performed, and metallurgical samples were removed. The steel backing was removed, and the plate was machined flat (eliminating the curvature due to welding distortion). Tensile and root bend test specimens were then cut from the welded plate in accordance with the AWS specification. Reduced section tensile samples were loaded using an MTS 810 servo-hydraulic load frame. All samples were loaded until failure at a constant displacement rate of 0.200 in./min. Base metal reduced section tensile samples were also prepared to get a more accurate value of the tensile strength of the A36 steel whose published tensile strength has a wide range of 58,000–79,800 lb/in.² of possible values. Root bend test samples were also
Test Results and Discussion

Reduced section tensile samples: AWS states that the tensile samples can break in the welded area as long as tensile strength is no less than the published minimum tensile strength of the base material, in this case A36 structural steel whose published tensile strength is 58,000–79,800 lb/in.². This published range is very large and, therefore, base metal tensile samples are included to get a better understanding of the tensile strength of the base metal. Figure 11 shows the stress vs. displacement overlay plot of seven reduced section tensile samples, five welded and two base metal samples. It is shown that the welded samples reached a higher stress level than the base metal samples, the red horizontal line of the graph represents the maximum value for the base metal samples. It should be noted that the welded samples did break in the welded area; however, post-failure inspection did not reveal any inclusions or areas with incomplete fusion.

Conclusions

The MRWS is a mobile welding robotic platform designed to perform the same types of welds currently mechanized using fixed-track systems. The advantage of the MRWS is that it eliminates the majority of setup time associated with fixed-track systems. The MRWS can eliminate a large portion of the nonvalue-added time in setting up for a mechanized weld. This paper demonstrates the validity of the MRWS in performing GMAW-type welds on plate steel. This validation process consisted of two parts: theoretical validation considering kinematic arrangement, motion control capability, and magnetic interaction, and empirical verification based on the AWS qualification standards for a 3G-PF vertical groove weld. For theoretical validation, kinematic arrangement and magnetic field interaction are identified as the primary differences between the MRWS and traditional, track-based mechanized weld tools. The motion-control capability (which stems from the kinematic arrangement) of the MRWS was validated by comparing the ability to track smooth trajectories as defined by the reference system through comparison of the positioning and velocity characteristics. When comparing the positioning capability, it was demonstrated that the MRWS can meet the positioning requirements at the design stage through range of motion of the transverse and plunge axes. When comparing the velocity capability, it was noted that the MRWS met the imposed requirements with a manipulability ellipse that spanned 75% or more of the reference manipulability ellipse for all gun locations and orientation of the MRWS to the weld joint. This is deemed as an acceptable (validated) standard. The magnetic field interaction was tested by again comparing possible gun locations with an allowable magnetic field induced by the magnetic tracks. This comparison showed that the MRWS was well within the limits for all welding types defined. Finally, an empirical weld test was performed to AWS and ASME specifications. All tests called for by the AWS qualification were met or exceeded by the weld performed by the MRWS demonstrating a verified system for this weld configuration. This is an important step forward for the introduction of mobile robotic fabrication in unstructured environments. The ability for mobile welding robots to perform welds that can be certified and pass stringent qualifications is an essential step in increasing the level of automation in unstructured manufacturing environments.

References

4. Pan, J., Yan, B., Gao, L., Zhang, H., Lu, and traditional, track-based mechanized weld tools. The motion-control capability (which stems from the kinematic arrangement) of the MRWS was validated by comparing the ability to track smooth trajectories as defined by the reference system through comparison of the positioning and velocity characteristics. When comparing the positioning capability, it was demonstrated that the MRWS can meet the positioning requirements at the design stage through range of motion of the transverse and plunge axes. When comparing the velocity capability, it was noted that the MRWS met the imposed requirements with a manipulability ellipse that spanned 75% or more of the reference manipulability ellipse for all gun locations and orientation of the MRWS to the weld joint. This is deemed as an acceptable (validated) standard. The magnetic field interaction was tested by again comparing possible gun locations with an allowable magnetic field induced by the magnetic tracks. This comparison showed that the MRWS was well within the limits for all welding types defined. Finally, an empirical weld test was performed to AWS and ASME specifications. All tests called for by the AWS qualification were met or exceeded by the weld performed by the MRWS demonstrating a verified system for this weld configuration. This is an important step forward for the introduction of mobile robotic fabrication in unstructured environments. The ability for mobile welding robots to perform welds that can be certified and pass stringent qualifications is an essential step in increasing the level of automation in unstructured manufacturing environments.

References


Visual inspection of the as-deposited weld: AWS states the weld should be free of cracks, all craters shall be filled to full cross section of the weld, the face of the weld shall be flush with the surface of the base metal and merge smoothly with the base metal, no undercut should exceed 0.031 in., and, finally, the root shall be inspected and there should be no evidence of cracks, incomplete fusion, or inadequate joint penetration. Figure 10 shows a macroscopic picture of an as-deposited weld and the polished and etched cross section of a weld performed with the MRWS. The macroscopic photograph shows adequate weld reinforcement and no visual cracks, undercuts, or voids. The cross section of the weld nugget, as-deposited (etched with Nital solution), has adequate penetration of all three passes and there are no voids or incomplete fusion of the weld.

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Root bend samples: AWS states that the convex surface of the bent sample should be examined for surface discontinuities, all discontinuities shall not exceed the following dimensions: 0.125 in. measure in any direction on the surface, 0.375 in. — the sum of the greatest dimension of all discontinuities exceeding 0.031 in. but less than or equal to 0.125 in., 0.250 in. maximum corner crack length. The tested samples show very little discontinuities on the convex surface and had no corner cracking. Figure 12 shows a macroscopic view of the convex surface with the major discontinuities highlighted; the vertical lines are positioned just outside of the root of the weld to base metal interface, which is barely visible. No edge cracking was seen, and this is a clear indication of the penetration depth of the root pass achieved using the MRWS.

Conclusions

The MRWS is a mobile welding robotic platform designed to perform the same types of welds currently mechanized using fixed-track systems. The advantage of the MRWS is that it eliminates the majority of setup time associated with fixed-track systems. The MRWS can eliminate a large portion of the nonvalue-added time in setting up for a mechanized weld. This paper demonstrates the validity of the MRWS in performing GMAW-type welds on plate steel. This validation process consisted of two parts: theoretical validation considering kinematic arrangement, motion control capability, and magnetic interaction, and empirical verification based on the AWS qualification standards for a 3G-PF vertical groove weld. For theoretical validation, kinematic arrangement and magnetic field interaction are identified as the primary differences between the MRWS and traditional, track-based mechanized weld tools. The motion-control capability (which stems from the kinematic arrangement) of the MRWS was validated by comparing the ability to track smooth trajectories as defined by the reference system through comparison of the positioning and velocity characteristics. When comparing the positioning capability, it was demonstrated that the MRWS can meet the positioning requirements at the design stage through range of motion of the transverse and plunge axes. When comparing the velocity capability, it was noted that the MRWS met the imposed requirements with a manipulability ellipse that spanned 75% or more of the reference manipulability ellipse for all gun locations and orientation of the MRWS to the weld joint. This is deemed as an acceptable (validated) standard. The magnetic field interaction was tested by again comparing possible gun locations with an allowable magnetic field induced by the magnetic tracks. This comparison showed that the MRWS was well within the limits for all welding types defined. Finally, an empirical weld test was performed to AWS and ASME specifications. All tests called for by the AWS qualification were met or exceeded by the weld performed by the MRWS demonstrating a verified system for this weld configuration. This is an important step forward for the introduction of mobile robotic fabrication in unstructured environments. The ability for mobile welding robots to perform welds that can be certified and pass stringent qualifications is an essential step in increasing the level of automation in unstructured manufacturing environments.

References

4. Pan, J., Yan, B., Gao, L., Zhang, H., Lu,
Appendix

The MRWS is a 5-deg-of-freedom mobile manipulator with input vector \( \mathbf{q} \) as given by

\[
\mathbf{q} = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \tag{A1}
\]

with

\[
\begin{align*}
\theta_1 &= \frac{\theta_1}{l_1} \\
\theta_2 &= \frac{\theta_2}{d_2}
\end{align*} \tag{A2}
\]

and \( \theta_1, \theta_2 \) are left/right track inputs and \( d_2, \theta_3, d_3 \) are the inputs to the P-R-P gun manipulator. The direct kinematics of the mobile tracked portion of the robot system can be given (Ref. 8) as

\[
\mathbf{T}^R_T = \begin{bmatrix} -s_w & 0 & l_0 \\ c_w & 0 & -s_w l_1 \\ 0 & 0 & 1 \end{bmatrix} \tag{A7}
\]

where \( c_w = \cos(\theta_w), s_w = \sin(\theta_w), l_0, l_1 \) are the offsets along \( x_R \) and \( z_R \), respectively, to the gun and \( \theta_w = -\pi/2 \) when the work angle is ignored.

The kinematics of the base (A3) and manipulator (A5) can now be combined to define the kinematics of the mobile manipulator as

\[
v^T_v = v^R_v + v^T_T, x \mathbf{v}^R_T = \mathbf{J}^T \tag{A8}
\]

or

\[
v^T_v = \mathbf{J}_v^T \mathbf{q}_v \tag{A9}
\]

where \( \mathbf{S}(\mathbf{a}_v) \) is the skew symmetric matrix of \( \mathbf{a}_v \) and \( \mathbf{a}_v \) is given as the fourth column of the homogenous transformation \( \mathbf{T}_v^R \). This yields the MRWS system Jacobian matrix as

\[
\begin{equation}
\begin{Bmatrix}
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\end{Bmatrix}
= \begin{Bmatrix}
\mathbf{J}_1 \\
\mathbf{J}_2 \\
\mathbf{J}_3 \\
\mathbf{J}_4 \\
\end{Bmatrix}
\end{equation}
\]

with

\[
\mathbf{J}_1 = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & c_w & s_w l_1 & 0 \\ 0 & s_w & -c_w l_1 & 0 \end{bmatrix} \tag{A10}
\]

\[
\mathbf{J}_2 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & d_s s_{w} - c_w & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{A11}
\]

\[
\mathbf{J}_3 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & d_s c_{w} - s_w & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{A12}
\]

\[
\mathbf{J}_4 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & d_s c_{w} - s_w & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{A13}
\]

\[
\mathbf{J}_5 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & d_s c_{w} - s_w & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{A14}
\]

\[
\begin{equation}
\begin{Bmatrix}
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\frac{\partial \mathbf{y}}{\partial \mathbf{q}} \\
\end{Bmatrix}
= \begin{Bmatrix}
\mathbf{J}_1 \\
\mathbf{J}_2 \\
\mathbf{J}_3 \\
\mathbf{J}_4 \\
\end{Bmatrix}
\end{equation}
\]