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ROBOTIC AND AUTOMATIC WELDING DEVELOPMENT AT THE MARSHALL SPACE FLIGHT CENTER

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ABSTRACT

Welding Automation is the key to two major development programs to improve quality and reduce the cost of manufacturing space hardware currently undertaken by the Materials and Processes Laaboratory of NASA's Marshall Space Flight Center.

Variable Polarity Plasma Arc welding has demonstrated its effectiveness on Class 1 aluminum welding in External Tank production. More than three miles of welds have been completed without an internal defect. Much of this success can be credited to automation developments which stabilize the process.

Robotic manipulation technology is under development for automation of welds on the Space Shuttle's Main Engines utilizing pathfinder systems in development of tooling and sensors for the production applications.

This paper outlines the overall approacch to welding automation development undertaken at the Marshall Space Flight Center. Advanced sensors and control systems methodologies are described that combine to make aerospace quality welds with a minimum of dependancce on operator skill.

Background

The requirements of the Space Shuttle to carry the maximum payload possible into orbit demands that its structural elements be lightweight as well as strong. When joining the structural elements of the Shuttle, welding is a natural choice, since a welded joint adds negligible weight, and is strength approaches that of the parent material. In addition, a welded joint forms a hermetic seal to fluids and gases. For these reasons, the Space Shuttle's External Fuel Tank and Main Engines depend heavily on welding to meet their performancce requirements.

The External Tank holds the liquid oxygen and hydrogen for the Main Engines, and forms the structural backbone of the vehicle. Since the tank is carried almost all the way into orbit, every excess pound of tank metal reduces the payload of the orbiter by almost an equal amount. Even though it is made of lightweight aluminum, the walls of the tank must be as thin as possible to reduce weight. Because of this, the strength of the welded joints is highly critical, with every inch inspected for flaws by x-ray inspection and measured for proper geometry. Each Main Engine, with mazes of fluid passages and cooling lines, requires almost as much welding as the External Tank, with equally stringeht inspection requirements. It is no wonder that welding is a major cost driver in the manufacture of the Shuttle elements.

Introduction

Developments in welding automation over the last five years has enabled significant improvements in welding productivity for the Space Shuttle External Tank and Main Engines These developments are centered in two areas, the introduction of Robotic Welding for the Main Engines, and Variable Polarity Plasma Arc (VPPA) Welding for the External Tank (ET). Both approaches capitalize on the cost savings that can be realized by the elimination of welding rework in manufacturing.

When Non-Destructive Evaluation (NDE) techniques reveal a flaw in the weld, the part being manufactured must be removed from the production flow, the defect ground out, then rewelded in the defective area by hand. The part must then be re-inspected and re-repaired (if necessary). Sometimes expensive castings or forgings with hours of machining time invested must be scrapped because the defective weld cannot be repaired. Many hours of engineering time must be expended to determine whether a defective part can be used as-is, repaired, or scrapped. It has been estimated that repair of a weld on the Main Engine costs four times as much as the original weld. For these reasons, developments that would allow more welds to be made right the first time are imperative.

Traditionally, the major cause of defects in welds on the External Tank, and aluminum welding in general, has been porosity caused by trapped oxides in the solidified metal.[1] This is due to the tenacious oxide layer that forms on aluminum when exposed to atmosphere. When the welding process melts the aluminum, the oxide particles, having a much higher melting temperature, float in the weld pool, only to be trapped during solidification. To combat this, the welder used to spend a great deal of time in preparation for the weld by mechanically scraping the surface of the part around the weld joint to remove the oxide layer.

Variable Polarity Plasma Arc welding, since its introduction into ET production in 1983, has virtually eliminated porosity defects due to its violent agitation of the weld pool and the "Cathodic Cleaning" of its reverse current cycle.[2,3] In addition, the increased power density of the process has reduced the number of weld passes required for joining thicker sections and decreased thermally-induced distortion. More than three miles of production welding has been completed without an internal defect. Mechanical scraping of the parts is no longer required. In all, the new process has reduced welding rework by over 70%, and decreased the cost of the ET by an estimated 5%.

Major causes for weld rework on the SSME are not as easy to categorize. In general, manual welding has shown lower productivity and higher defect rates than mecahnized welds, and make up about half of the welds on the engine. Conventional automation approaches were not considered practical, since most welds had not previously been automated due to access constraints or their short length not justifying dedicated weld equipment for each weld. The universal programmability of robots seemed ideal, since one weld station could be programmed for an infinite variety of weld configurations. Seven Gas Tungsten Arc (GTA) robotic welding systems have been installed in the SSME production facility since 1986. They have replaced all conventional GTA welding automatic equipment and have automated about 15% of the remaining manual welds to-date. More precise control of the total welding process by the robots has reduced defect rates by about 12% below welds formerly automatic (but conventional equipment) and about 18% below formerly manual welds.[4]

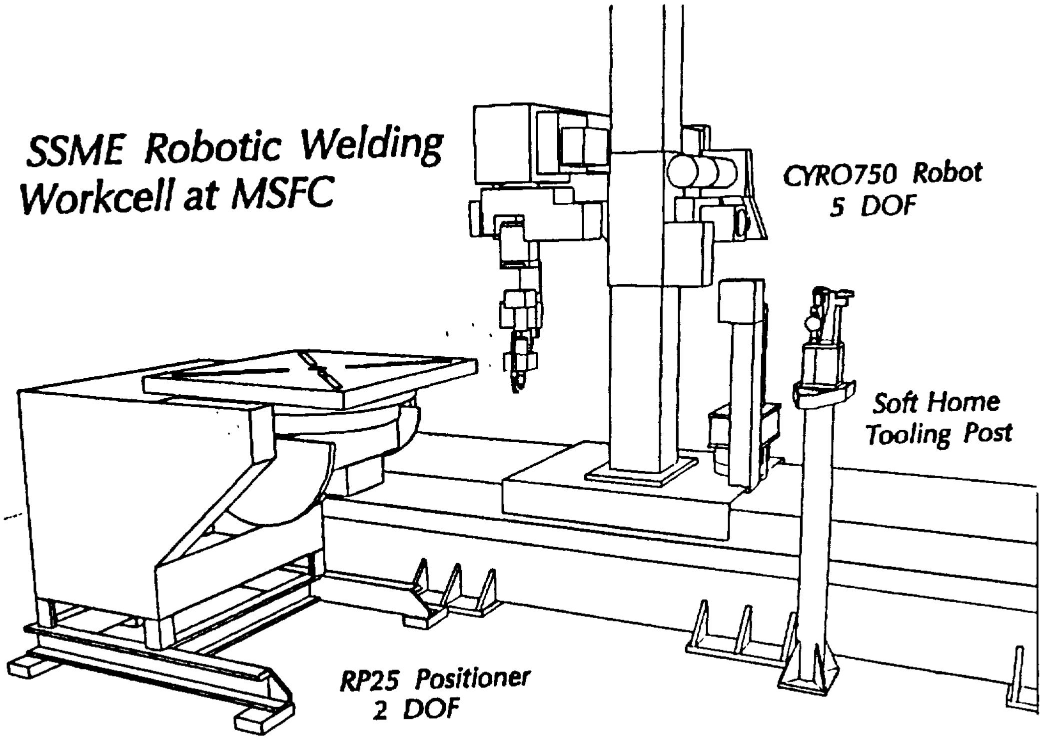
Robotic Welding

Application of robots to welding on the SSME, while considered to be highly successful now, defied conventional wisdom at its inception. Many experienced welding personnel doubted that the machines could be trusted to make aerospace quality welds. Robot manufacturers were accoustomed to welding programs that emphasised high-speed, repetitive operations. Production welders were suspicious of the robot's effect on their job security and unfamiliar with the technology.

It was felt, however, that robots could bridge the gap between the consistency of conventional, dedicated automation equipment and the adaptability of the human welder. In addition, robots with special features could bring new ideas to bear and improve the overall approach to welding.

The programming of robots, while allowing the machine to adapt to a variety of welds, also forms a permanent record of how the weld was accomplished. This aids in tracking down problems in welds after inspection. If a defect is found later, the robot's program can be interrogated for mistakes, and corrections made. A human welder may not remember how he made the weld earlier, and may not be able to duplicate his actions on subsequent welds. The precise motion of the robot and computer control of process parameters allows duplication of good welds at anytime in the future, as long as subsequent parts are presented to it in the same way. The robot controls the speed of the torch across the part and the energy flux of the torch, so that the amount of heat per linear distance along the seam can be accurately controlled. Coordinated motion between the robot and part positioning table allows the part to be presented to the torch at a preferred attitude with respect to gravity. This capability is not available to human or conventionally automated welders, and obviates the need to weld "out of position", with the attendant comprimises to keep the weld pool stable.[3]

A diagram of the pathfinder SSME robotic welding system at MSFC is shown in Figure 1.



Robotic Welding Example

The SSME main injector oxidizer inlet manifold welds are an example of the type of gains expected by the conversion from manual to robotic welding. This group of welds assembled a tube-type manifold onto the main injector, and as manual welds, were considered problems. The six parts required twelve manual welds to assemble it out of 0.157 inch thick Inconel 718 alloy. The edges of the parts had to be grooved because a manual welder could not keep consistent penetration on the thicker sections. This required eight to ten manual weld passes on each joint. The distortion caused by this much welding often caused it to be rejected in inspection

Conversion from manual to robotic allowed elimination of the groove joint preparation, welding to be reduced to two passes, and reduced distortion. This allowed the manifold to be machined as three parts instead of five. This cut the number of welds in the assembly by four. Overall, this resulted in manufacturing process flow and defect reductions as shown in Figure 2 below.

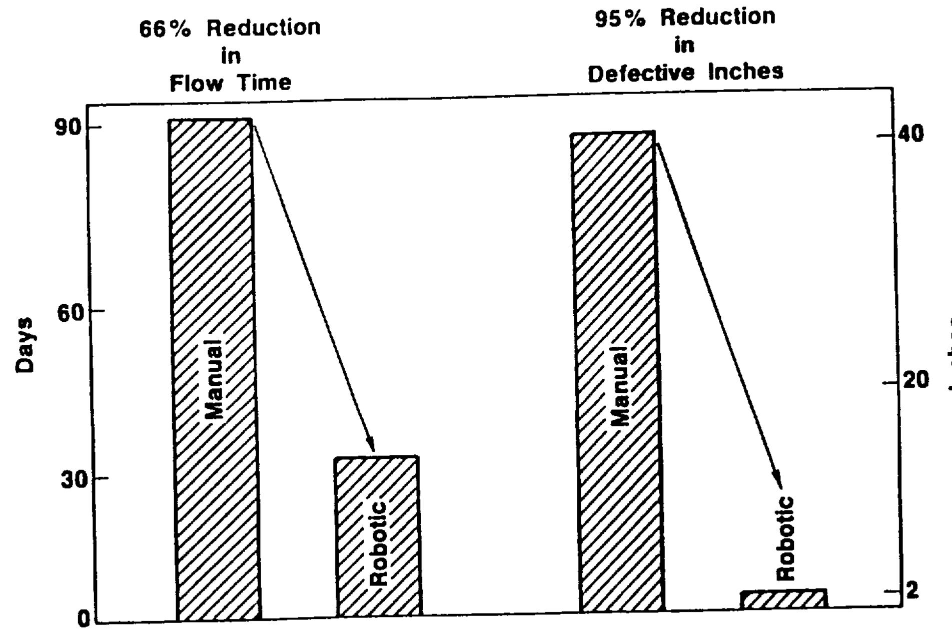


Figure 2, Main Injector Weld Productivity Improvements

Robot Developments

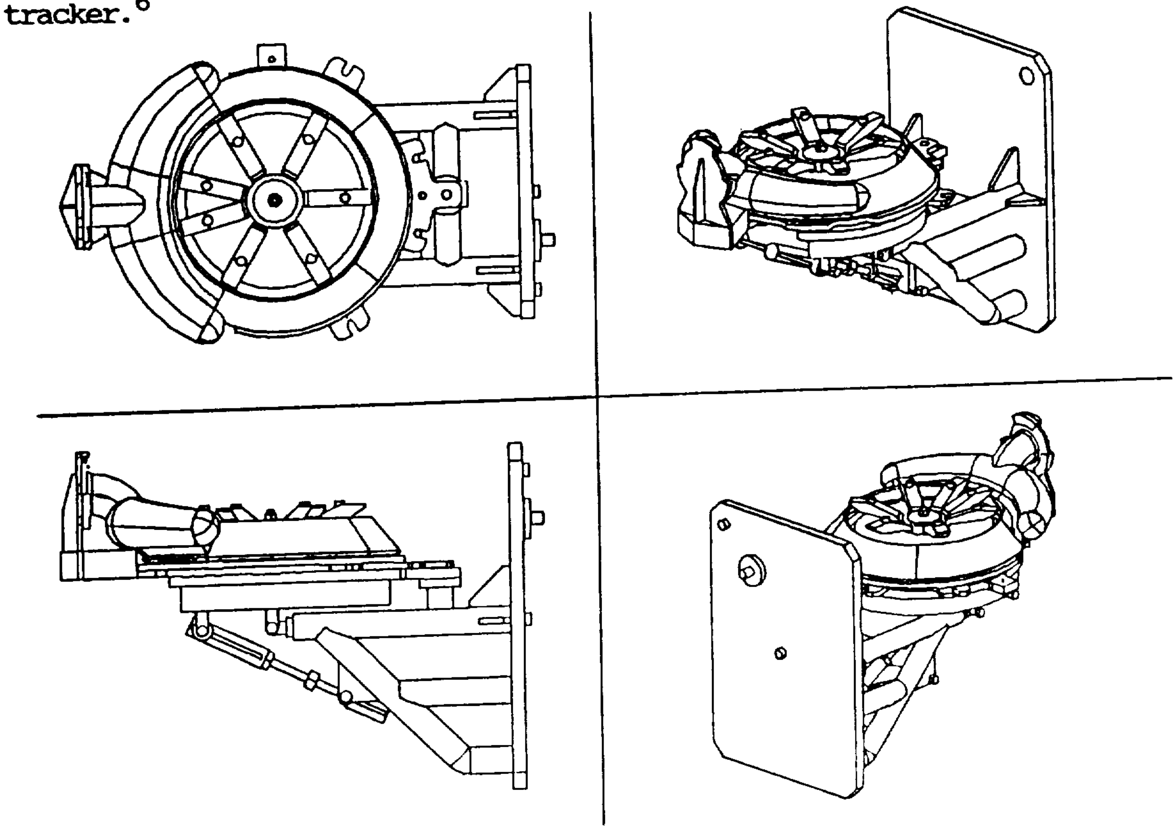
The SSME has a goal of 80% robotic welding conversion by 1992. In order to meet this goal, developments are underway to give the robots greater capability than presently available. The overall method to improve the robot's capability is to reduce the level of effort required to set up for each new part.[5]

The approach falls into four categories:

1. Tooling Development
2. Seam Tracking
3. Weld Penetration
4. Offline Programming

Tooling is being designed to properly align each part so that it is presented to the robot in a known, repeatable configuration. The tool pictured in Figure 3 is for the Main Injector Oxidizer inlet manifold, and properly aligns and clocks the part into a known position. This allows the robot to use the same program to weld duplicates of the same part.

Seam tracking is being approached by the use of a special hollow GTA welding torch that has a camera built inside. A computer monitors the image to align the robot over the seam during welding. This compensates for slight part-to-part differences and distortions from heat input. It can also allow fewer points to be used in programming of new parts, since the sensor can assure accurate tracking. The hollow torch allows viewing of the weld area without the access constraints of an "add-on" type seam tracker.[6]



Weld penetration control is under development to compensate for slight heat-sink variations between parts. It takes advantage of the difference in accoustic emmission activity between partial and full penetration welds, and adjusts the weld current to maintain full penetration of the joint.

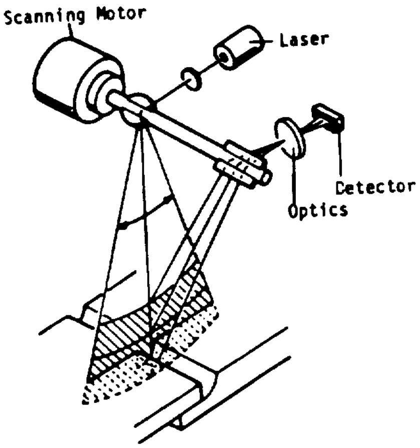
Offline programming utilizes CAD/CAM and graphics computers to reduce the need to stop production welding to program for new parts. Conventionally, robots have been programmed by setting up the parts to be welded, then moving the robot along the seam, entering a requisite number of program points. Offline programming uses a CAD/CAM system to model the robot cell and allow the weld engineer to create a program for the robot. New programs are simulated in graphics before "downloading" to the robot. This can simplify the complicated coordinated motion programs required for many welds.[7] The system is also planned for use as an archiving tool, with the robot sending data back to the central computer as it makes the weld, for a permanent record.

Variable Polarity Plasma Arc Welding

Use of the VPPA welding process in ET production has virtually eliminated internal weld defects. The majority of defects encountered now involve problems that can be detected by external observation of the weld geometry. The process is controlled by a computer that can repeat a weld schedule with accuracy, and will allow a programmed amount of operator override. The approach taken in VPPA controls development is to relieve the operator from the requirement of constant attention to the process to one of supervision. To this end, seam tracking, weld bead profile measurement, and video observation are under development.

Seam tracking will be utilized to align the welding torch over the seam during the penetration pass, and align second pass directly on top of the penetration pass. The strength of the weld is dependent on proper alignment of the second pass.

Weld bead profile measurement has been demonstrated to provide control of the welding process for certain conditions. A laser is projected onto the weld just after it solidifies. A solid-state camera picks up the reflection of the projection and the system computer calculates the profile. A schematic diagram is shown in Figure 4. The system has been demonstrated to detect slight assymetries in the weld profile and correct them by rotating the plasma torch. Corrections to other welding parameters are possible by analysis of the bead profile as well.



Video observation of welding has historically been difficult. The intensity of the weld arc saturates any camera. The addition of neutral density or spectral filters reduces overall intensity at the expense of contrast. Since the area of interest in a welding process is at the interface between the bright, hot metal and the cool parent material, a system of video observation is needed that provides the contrast in spite of the bright arc. A system has been developed by Control Vision, Inc., that utilizes a laser to illuminate the area around the arc. The observation camera filters out all but the wavelength of the laser. The result is a picture of the weld with all traces of the arc removed. This system is being evaluated for observing the plasma keyhole during welding.

Conclusion

Presently, sensor and control developments are directed towards controlling specific, independent process parameters. In order to develop a truly automated welding process, however, the inputs from multiple sensors will have to be synthesized and the basic interrelationships between direct and indirect process parameters determined. Preliminary studies are underway, using mathmatical heat flow models, to provide insight into decoupling process parameters.

These investigations are critical to the development of welding systems for in-space welding. Due to limitations on EVA time, the welding process will need to be autonomous in order to construct large structures in space. Through these investigations, a greater understanding of the basic physics of the welding process will be gained, and have application to welding on earth.

Over the past five years, welding automation has progressed from simply mechanizing what a man was doing to controlling processes beyond what a man could be expected to accomplish. Only a very small percentage of Shuttle welds are still performed by hand. This progress bodes well for development of space- based welding as well as more productive welding on earth.

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