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# ROBOTICS IN SPACE-AGE MANUFACTURING

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## ABSTRACT

The Marshall Center is developing robotics technologies to improve manufacturing of space hardware. This paper will cover application of robotics to:

Welding for the space shuttle and space station Freedom programs
Manipulation of high-pressure water for shuttle solid rocket booster refurbishment
Automating the application of insulation materials
Precision application of sealants
Automation of inspection procedures

Commercial robots are used for these development programs, but they are teamed with advanced sensors, process controls, and computer simulation to form highly productive manufacturing systems. Many of the technologies are also being actively pursued in private sector manufacturing operations.

## INTRODUCTION:

Millions have watched the astronauts use the space shuttle's Remote Manipulator System (RMS), but NASA's use of robotics is not limited to space. Here on earth, industrial robots are being used to manufacture and refurbish components for the space shuttle. In these applications, the robots have been found to reduce costs and to improve the quality of the conventional processes that they replaced. New applications, presently under development, promise to extend the advantages of robotic process automation to other shuttle components, as well as the space station Freedom.

In this discussion, some of the applications of commercial robots in manufacturing for the space program will be presented. It is hoped that some of the technology and approaches that are used by NASA will advance related private-sector industries.

## BACKGROUND:

Even as the first flight of the space shuttle was underway, engineers at NASA's Marshall Space Flight Center were beginning a program that would radically change the approach to building launch vehicle hardware. Since the new Shuttle's goal was to allow more frequent space flight at a lower cost, the old way of fabricating the flight hardware by largely manual methods was no longer practical. For this reason, the Productivity Enhancement Complex at MSFC was created to develop improved methods of manufacturing to reduce costs and improve consistency. This was done by bringing computer automation to bear on as many manual manufacturing applications as possible. To that end, modern industrial robots would come to play a vital role.

Most people would imagine that robots used for manufacturing tasks would be best applied in situations where a large number of parts have to be produced. Pictures of spot-welding robots in an auto plant producing thousands of car bodies and high-speed assembly robots fabricating electronic circuit boards probably come to mind. With the ability to lift loads exceeding 50 kilos and place them to within one millimeter of a programmed location without tiring, industrial robots have earned a prominent place in the manufacture of high-volume goods.

Other features of robots make them attractive for use in space flight hardware manufacturing. The ability to work in environments hazardous to humans makes them ideal for spraying insulating and coating materials, as well as the removal of these same materials. The control computers of modern industrial robots can coordinate the motion of as many as a dozen axes of motion while controlling a complex manufacturing process such as arc welding. This allows very consistent results even over very long processing times, improving overall quality by reducing the effects of operator fatigue and inattention. The universal programmability of a robot arm can allow the use of one piece of equipment on many applications and parts. In the past, the common way to mechanize operations was to design a special machine for each application, resulting in prohibitive equipment cost for small operations. The speed and endurance of a robot arm, coupled with computer data communications has made possible continuous inspection schemes, giving engineers more reliable data from which to determine the flight readiness of a part.

Before examining the areas of robotic activity it may be useful to briefly review the Shuttle Vehicle and the Space Station Freedom configurations. Unlike previous NASA vehicles such as the Mercury, Gemini, and Apollo series that used totally expendable launch systems, the Shuttle and most of its elements are completely reusable. Thrust for lift-off is provided by the two solid rocket boosters (SRB's) and the three Main Engines aboard the Orbiter. Fuel, in the form of liquid oxygen and hydrogen for the Main Engines is supplied by the large External Tank (ET). After the SRB's Expend their fuel, they are jettisoned and recovered for re-use on a future launch. When the orbiter has reached the appropriate altitude and velocity, the Main Engines are turned off and the External Tank released. The ET is the only element of the Shuttle's launch cluster that is not recovered at the present time, being destroyed by re-entry into the earth's atmosphere. A major feature of the Shuttle's unique capabilities is its re-usability and land-based recovery.

## PRESENT ROBOT APPLICATIONS:

Industrial robots are now used in flight hardware manufacturing for the application and removal of thermal protection systems for the Shuttle Solid Rocket Boosters, and for robotic welding of the Shuttle's Main Engines.

## THERMAL PROTECTION PROCESSING

Thermal protection systems (TPS) are an integral part of any space vehicle and the Shuttle is no exception. The Orbiter itself is equipped with a covering of insulating tiles to protect it from the heat of re-entry. The SRB's and the ET must also be protected. The ET, though expendable, must be insulated to reduce boil-off of its cryogenic contents and to reduce the accumulation of ice prior to launch. The skin of the SRB's must be protected from aerodynamic heating during the ascent phase of flight and from the shock of hitting the water after parachuting back to earth. After recovery of the SRB's all of the TPS material must be removed, then re-applied before their next use.

The thermal protection system used for most of the SRB's is called the Marshall Sprayable Ablator (MSA). MSA is an epoxy-terminated urethane resin filled with various organic fiborous ingredients for strength. The result is a low-density ablator with the necessary insulation properties. It is applied to the SRB components by spraying, which replaces hand-layup of sheet cork material. This is accomplished at the Kennedy Space Center with a robot working in concert with a rotary table on which the part being sprayed is located. The robot and turntable are housed in a spray cell that coordinates the activity of the robot as well as the precise mixing of the components of the insulating material. The robot cell has been in operation since 1980 after favorable results were obtained from an MSFC prototype system.

Implementation of the four cells at KSC was by United Space Boosters, Inc. Three cells utilize six-axis gantry robots, with rotating tables. The motion of the tables are coordinated with the robot motion, allowing a component much larger than the robot to be sprayed using one setup (see figure 1).

Two TPS application cells perform a variety of tasks on the SRB nose cone, forward skirt, frustrum, and aft skirt, as follows:

Pre-cleaning of parts, using hot water spray
Spraying of the MSA material, using computer-controlled mixing equipment.
Sanding of cured MSA, to smooth the surface.
Application of a white hypalon sealant, for environmental protection.

The major incentives for using the robots for these processes are:

Protecting humans from the toxic propellants used for spraying.
Precise process control, made possible by having all mixing and spraying operations under computer control.
Ability to reach all parts of the component during a spraying operation.

## TPS REMOVAL

Complementing the robotic facilities for MSA application are the MSA removal cells. These systems remove the MSA material from the SRB's after their post-launch recovery. Removal of the partially-ablated material is necessary before re-application for the next flight.

A narrow, high-pressure stream of water is directed at the surface of the SRB component to strip away the old material. In the past, a rubber-suited worker would manually sweep a hand-held "car wash" type wand across the surface until sufficient material was removed. Due to the high pressures and the attendant reaction forces, worker fatigue was a problem. In addition, because a human could not accurately maintain a constant distance and surface feedrate, many spots would be missed, requiring another touch-up pass.

The introduction of a robot to perform this task allowed the stripping process to be controlled to a degree unattainable by its human counterparts. The consistent motion of the robot arm and integration with the control of the pumping equipment meant fewer touch-ups and less chance of damage to the underlying part. In operation, the system can be programmed to remove only the MSA, then pass over again to remove successive layers of paint and primer. Cleaning to the bare aluminum substrate is possible without damage.

The refurbishment facility at the Kennedy Space Center utilizes a NIKO gantry-type robot in concert with a part turntable to strip individual components of the SRB's. A new robot system, built at MSFC for stripping of the boosters before disassembly, is composed of a GMF robot mounted on a motorized transporter, to give the robot access to all surfaces. The systems operate according to pre-programmed motion and processing parameters.

## ROBOTIC WELDING

Eight robots are presently in use welding space shuttle main engines (SSME) at the Rocketdyne facility in Canoga Park, California. Six Cybotech H-8 robots weld small-to-medium-sized parts such as pump housings, and two Cybotech H-480 robots weld larger parts, including the engine's exit nozzle, which is slightly over three meters long and 2.6 meters in diameter. All robot stations have seven axes of motion and are equipped with two-axis part positioning tables.

SSME design calls for numerous welded joints, with each engine requiring approximately 530 linear meters of welds, on materials such as nickel-based alloys, stainless steel, and titanium alloys. Thicknesses range from 1.5 to 12 millimeters. The Gas Tungsten Arc (GTA) welding process is used by the robots. Some 75% of robotic welds are required to meet the most stringent requirements for SSME post-weld inspection, where X-ray, dye-penetrant, and ultrasonic methods must be used.

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While it is undeniable that automated welding produces more consistent high-quality results, most welding on the SSME was done by hand. Welds with simple geometries, such as linear or circular paths in a single plane had used mechanized equipment, with good results, but this kind of application was limited. Since each engine had more than 4000 distinct welds, with many requiring complex torch motion, the cost to conventionally automate these was wildly prohibitive. In 1981, NASA engineers started investigating robots as a potential way around this problem.

A program was initiated develop robot controls to make them practical for the welding required on the SSME. The major development tasks were as follows:

> Specialized welding process control computers had to be integrated into the robot's motion control, since the welding commands available from conventional robots could not control all the parameters required for aerospace-quality welds.
> New methods for designing tooling and fixtures were developed so that the position of the weld joint was known by the robot.
> Improved robot programming techniques were needed to simplify the task for welding engineers and technicians.

Robotic welding on the SSME was implemented in production in 1986 after a coordinated development between NASA and Rocketdyne at Marshall Space Flight Center and at the production facility at Canoga Park. As benefits, the resulting welds:

> Require less joint preparation.
> Exhibit reduced distortion
> Produce fewer process-related defects. such as crater-cracking, even on crack-prone alloys.

Much of the credit for these benefits can be attributed to simply having the welding process under computer control, where the optimum parameters for a weld can be consistently repeated. The robot can control the weld at higher current levels, penetrating through thick metals without requiring a beveled edge. Reduced distortion on welded parts has resulted, since fewer weld passes are required for a given material thickness.

Another critical element has been advanced coordinated motion control, that maintains a constant torch velocity along the joint. The coordinated motion between the torch and part positioner has allowed the more complex parts to be welded in a preferred orientation. Even on very convoluted parts, the robot and positioner move together to follow the joint without resorting to "out of position" welding, which requires adjustments to the welding parameters to avoid molten metal dripping from under the torch.

More than 300 weld types have been converted to robotics to-date. These welds, though a small percentage of the total number per engine, are a high percentage of the more difficult and lengthy welds. Nearly fifty percent of the total length of GTA welds on the SSME are now being made robotically. As a result, weld quality acceptance has improved significantly.

## DEVELOPMENT ACTIVITIES

Other areas of robotic activity are presently under development that promise to expand the use of robots in the production of NASA's space flight hardware.

## SPACE STATION ROBOTIC WELDING

Rather than replace a conventional operation with a robotic one, the space station Freedom project is considering the use of robots for manufacturing from its inception. Welding of space station structural elements will be made using a robot utilizing two part positioners and the Variable Polarity Plasma Arc welding process. Approximately one-third of welds for the common module, logistics module, docking node, and cupola will be made with this system (see figure 2). Thirteen joints representing seven different configurations will be accommodated by the one system, avoiding the need for some five conventional dedicated tools. The robot also allows all welds to be made in the same orientation to gravity by use of coordinated motion. This feature will greatly simplify weld process development. Production robotic welding is scheduled to start in the fall of 1991.

## WELDING SENSORS

Sensors, incorporated into the operation of the robots, are being developed for SSME robotic welding. The large number of critical welds and the high part value of the engine components makes this an ideal application for feedback-controlled robotic welding. Rocketdyne will implement a pair of sensors, one to guide the torch accurately over the weld joint, the second to ensure correct weld penetration into the metal.

The seam-tracking sensor guides robot motion to follow joints to within .25mm of the seam. It adjusts torch position to correct for:

Inaccuracies in the robot program
Variation in part fit-up
Thermal distortion of the part during welding

The basic element of the seam tracker is a through-the-torch coaxial-view welding torch. A miniature closed-circuit tv camera in the top of the torch peers through the torch body to relay an image of the joint to the image processing computer. An electro-optic light valve in the torch adjusts the image intensity reaching the camera to compensate for varying light levels as welding current changes. Machine vision software in the computer analyzes the image, locates high-contrast points and determines the location of the seam. Corrections to the robot's path are then sent to the robot controller. The result is an automatic seam tracker and visual weld monitor that does not add any size to the weld torch, important for welding in limited access areas typical to the engine.

The penetration control sensor measures the natural oscillation frequency of the molten weld pool by monitoring light intensity from the weld pool area with a photosensor. This frequency corresponds to weld penetration, characterized by weld back-side bead width. Current pulses cause the pool to oscillate; if the bottom of the pool is solid - not penetrated through the thickness of the part - the pool is stiff and oscillates rapidly at low amplitude. As the pool grows and penetrates with increasing power to the torch, frequency decreases and amplitude increases. A computer analyzes the oscillation frequency and amplitude then sends adjustments in the weld current to the process controller.

The welding sensors are in the final stages of testing on the production floor. Rigorous qualification procedures will accompany implementation. Production welding by sensor-guided robots should begin in 1991.

## MEASUREMENT SYSTEMS

The speed and accuracy of a robot's motion make it ideal for automating measurement and inspection tasks.

In one application investigated at MSFC, a robot was used to scan a contamination monitor over the inside of the solid rocket motor case to check for minute levels of contamination from grease and similar manufacturing residue. This residue could inhibit bonding of the fuel to the inside of the motor. The sensor measured the optical emission of contaminants stimulated by its ultraviolet light source. The light source is directed at the surface as the robot scans the component. A map of contamination levels was generated by correlating the location of the robot to the feedback from the sensor, giving engineers more complete information on which to base a decision to re-clean part of the surface. Manual scanning of the part was extremely time consuming, since the part is too large (four meters diameter by three meters high) to reach in one setup. The accuracy of the manual process is some fifty times less sensitive than the robotic method. The sensor that the robot uses requires precise control of the standoff distance, which cannot be maintained manually without touching the part. A written record of the part's cleanliness level is an added benefit for quality history. This sensing method has been implemented for cylindrical components using a lead-screw type manipulator. A robotic system for more complex geometries is being assembled at the production facility.

Another measurement application under development is to map the thickness distribution over the external tank's aluminum skin. At the pointed ends of the tank, the skin must be chemically milled to the proper thickness. This is now a slow, manual process, where the panel's thickness is measured in selected places, and a contour map drawn by hand on the skin in order to specify the required extent of masking on the surface. Once the mask over the excessively thick areas is removed, the chemicals can reduce these areas to their specified thicknesses. Use of a robot allows the whole panel to be mapped in one operation using an ultrasonic thickness gauge. An offline computer correlates the robot's position to the local thickness to produce a program to tell the robot where to scribe contour lines for removing the maskant.

## SIMULATION AND OFFLINE PROGRAMMING

Very exciting areas of development in robotics are simulation of a robot's motion and offline programming.

Space flight hardware, in many instances, can have more value than the robot performing the task. For example, when some of the robotic welds are made on the main engines, more than one million dollars worth of investment has already been incorporated in each part. For this reason, everyone must be assured that the robot will perform its task right the first time. Unfortunately, a trial part to practice on is very hard to obtain. In these cases, a CAD/CAM system is used to simulate the operation long before any money is invested in robot hardware. Before any large robots were delivered for welding the large SSME components, a computer simulation was conducted, making typical welds on the components for which the system was intended. This exercise found the ideal placement for the part vis-a-vis the robot, assuring that the robot could reach all welds and avoid collisions. Part tooling and facilities placement were well under way before the robots were delivered.

In the case of welding for the Space Station radial docking port structure, simulation and offline programming were essential for successful implementation. Due to the part's large size, workcell layout is critical. A 10 centimeter change in the location of the robot, part, or positioner could render the weld seam unreachable or cause a collision. The complex shape of the path requires precise programming of the path to assure that the seam is closely followed and the resultant simultaneous motion of the part and weld torch is smooth. Use of the design model of the part in calculating the motion reduces the error. Manually programming the path, based on our experience, would take more than a week, and would be very hard to modify if a slight change needed to be made.

Computer simulation proved indispensible for implementation of the mobile robot used in refurbishing solid rocket booster parts. Because of budgetary constraints, a robot large enough to reach every part on the booster was not feasible. A six-axis robot with an average-sized envelope was used. Computer kinematic simulations were used extensively to determine the proper position of the robot transporter to be sure that the areas that needed to be sprayed could be reached. Since an actual booster was not be available for teaching the robot programs manually, offline programming software was used to calculate every motion needed. Computer-generated pictures of the operation were created from the operator's viewpoint so that the robot position could be verified prior to program execution. All these programs were created at MSFC and transmitted to the Kennedy Center facility.

Thus, robot kinematic simulation and offline programming has proven to be especially critical to aerospace applications where many programs need to be written for just a few parts, which may not be readily available. It can also be valuable to determine the range of tasks that can be applied to limited robot resources. Control of the programs used by the robot in production can be improved, for better quality control.

## SUMMARY

The National Aeronautics and Space Administration has identified robotic technology for automation of manufacturing tasks for the space shuttle and space station Freedom. Although these tasks differ from traditional applications of industrial robots, they have proven to reduce costs while improving quality.

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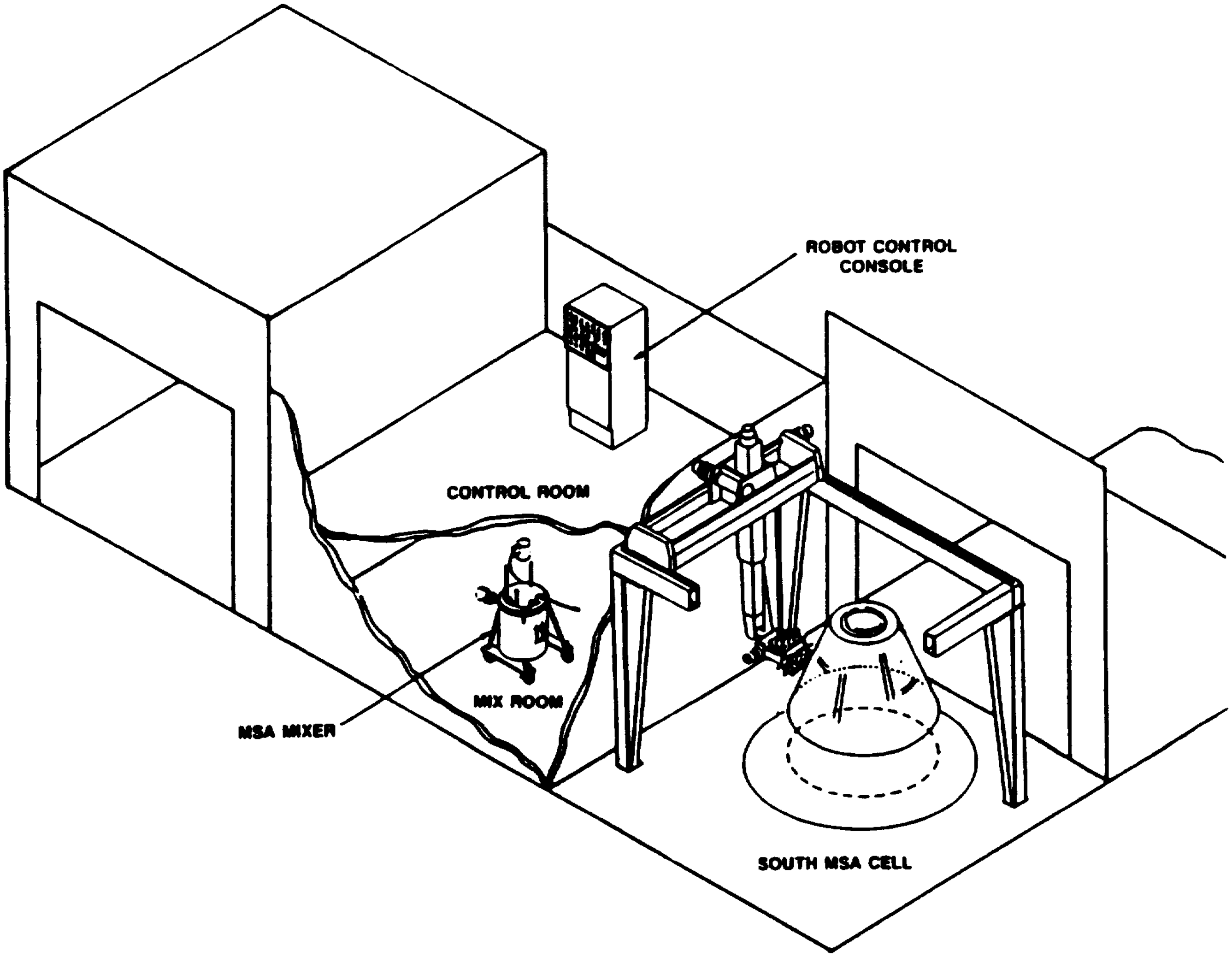

Figure 1:
TPS Application System

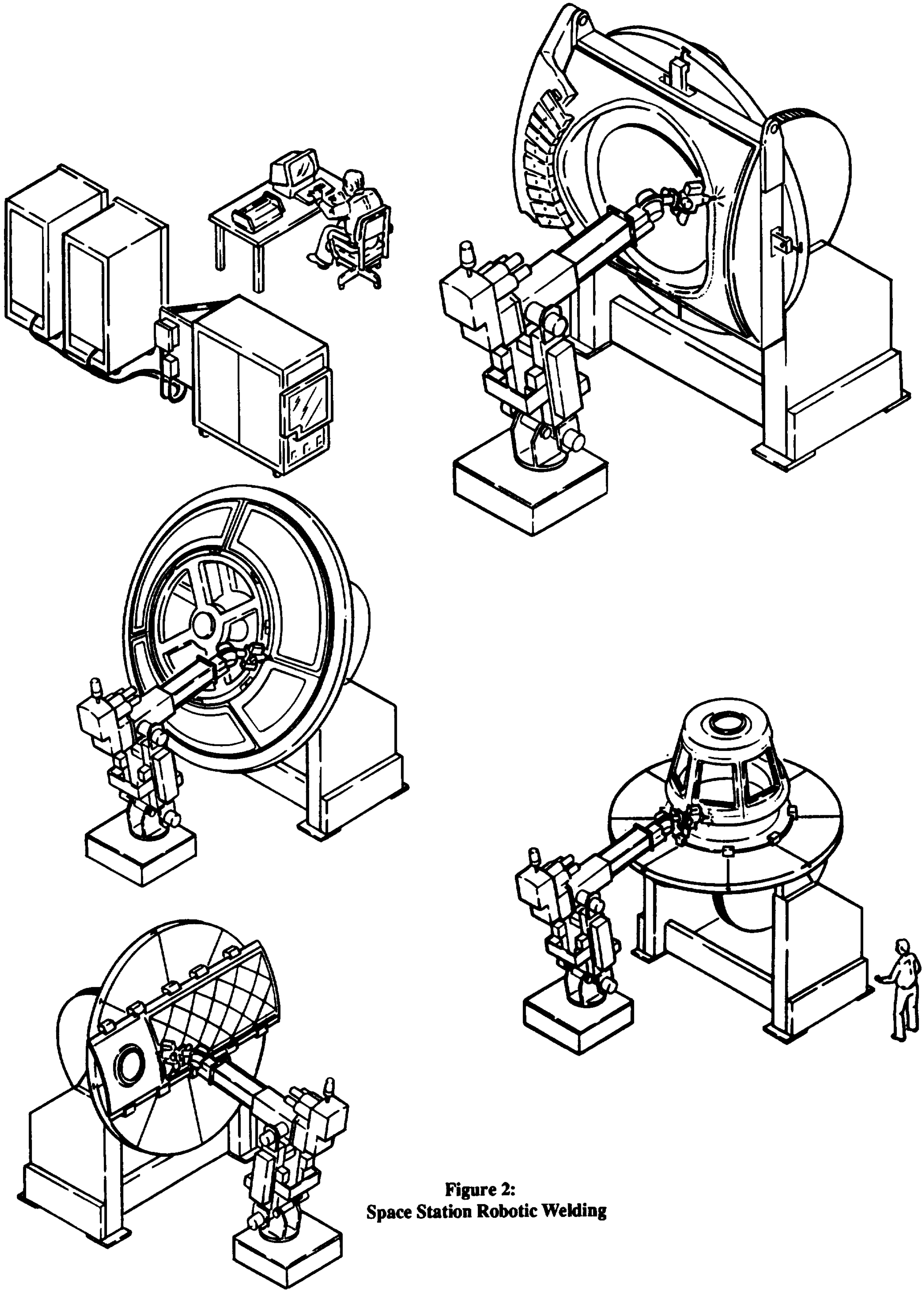

Figure 2:
Space Station Robotic Welding