ROBOTIC CONTROL AND INSPECTION VERIFICATION

Virgil Leon Davis
Chief, Robotics Section, DM-MED-12
Kennedy Space Center, FL

ABSTRACT

This paper discusses three possible areas of commercialization involving Robots developed at John F. Kennedy Space Center (KSC), Florida.

(1) A 6-Degree of Freedom (6-DOF) Target Tracking System for remote umbilical operations

(2) An intelligent Torque Sensing End-Effector (TSEE) for operating hand valves in hazardous locations

(3) An Automatic Radiator Inspection Device (ARID), a 65 by 13 foot robotic mechanism involving completely redundant motors, drives, and controls

Aspects concerning the first two innovations can be integrated to enable robots or teleoperators to perform tasks involving orientation and panel actuation operations that can be done with existing technology rather than waiting for telerobots to incorporate artificial intelligence (AI) to perform "smart" autonomous operations. These operations are applicable to Space Station work, ground aerospace launch processing, and hazardous petrochemical or nuclear safing operations worldwide. The third robot involves the application of complete control hardware redundancy to enable performance of work over and near expensive Shuttle hardware. The consumer marketplace may wish to explore commercialization of similar component redundancy techniques for applications when a robot would not normally be used because of "reliability" (when an inadvertent move could result in damage to expensive components or personnel).

Introduction

The computer hardware and software systems in the Robotic Applications Development Laboratory (RADL) were designed to facilitate the development and application of advanced robotic control technology. KSC not only launches spacecraft but services these spacecraft on the ground: designing the support equipment, launch accessories, and computer hardware/software for ground spacecraft servicing.

KSC has implemented an integrated system that coordinates state-of-the-art robotic subsystems. It is a sensor-based realtime robotic control system performing operations beyond the capability of an off-the-shelf robot. The integrated system provides realtime closed-loop adaptive path control of position and orientation of all six axes of a large robot; enables the implementation of a highly configurable, expandable testbed for sensor system development; and makes several smart distributed control subsystems (robot arm controller, process controller, graphics display, and vision tracking) appear as intelligent peripherals to a supervisory computer that coordinates the overall system.

The integrated RADL system is currently providing an easy-to-use testbed for NASA sensor integration experiments. Advanced target tracking development is in progress concerning the mating of umbilicals used during space vehicle launch. Programmatic studies are underway to use laboratory capabilities to enhance the safety, productivity, and efficiency of KSC facilities for Shuttle and future ground processing operations. Projects are underway that should generate large operational cost savings through the integration of advanced technologies for ground processing operations, such as Orbiter tile and radiator damage assessment.

Robotic techniques to improve "Shuttle Orbiter inspection and closeout verification" (operations involving possible human- or mechanism-induced damage) are being investigated and implemented. Nondestructive test sensors, vision systems, and various kinds of distance ranging sensor systems can be integrated with the RADL systems to develop the prototype concepts for integrating robot parameters with large data-based graphics and artificial intelligence software systems. For example, the RADL robot can position a sensor with precise accuracy, report that position and orientation, provide distance sensory data, and integrate machine vision "electronic photographs" with graphics and AI software to furnish computer printouts providing automatic sizing and highlighting of exception data. This type of system is being proposed for Shuttle Orbiter radiator damage inspection, Orbiter tile damage/debonding assessment, and Orbiter contour measurements. The manual methods presently employed in these operations are very labor intensive and produce expensive serial-time flow constraints.

REMOTE UMBILICAL PLATE DOCKING/INSERTION

Realtime adaptive control is the necessary tool for tracking a Shuttle vehicle that rocks in the wind while stacked at the launch pad. This adaptive control is necessary in order to dock and insert umbilicals (consisting of a ganged connection of electrical and cryogenic/hypergolic fluid lines) without damage to the vehicle and without hazardous leaks. This reduces reconnect times of 14 to 34 hours to less than 15 minutes and eliminates hazards associated with umbilicals that would otherwise have to be connected at launch. The KSC environment is demanding: the system must withstand heavy acoustical shock and see through fog caused by the dumping of thousands of gallons of water onto the flames of the Shuttle main engines (conditions that exist right after an aborted launch when an umbilical reconnect would take place). These shock and blast conditions rule out sensitive laser tracking. The prototype system KSC is developing can be upgraded quite easily for this environment. For instance, an infrared filter can be added to the CCD camera and our 5 dots can be changed to infrared LED's to see through the water vapors without affecting the system architecture or changing the extensive software algorithms.

Also, KSC is tracking speeds at which the target can be blurred. KSC has already advanced the state of the art by developing algorithms and packaging off-the-shelf imaging hardware into process machines that significantly reduce the blurring of moving targets to allow more precise, smoother tracking.

KSC is studying adaptive control (trajectory perturbation based on realtime sensory feedback) with heavy inertial loads. KSC is attempting to precisely position 5,000-pound umbilicals (200 pounds initially) with pneumatic counterbalances on future heavier umbilicals. Research in industry has been done on compliance-aided insertion of resisters into mm-tolerance holes; however, KSC is designing heavy umbilicals (oriented perpendicularly with respect to gravity) to insert into mm-tolerance holes on an object randomly moving with wind-induced perturbations. This induces high torques into servo control motors and KSC has obtained stability under these extreme conditions.

The RADL is located in a 50 by 100 foot high bay facility. Figure 1 depicts the left half of the facility. It has been recently expanded to provide space for a production model of the ARID robot. Several work cells (as shown in figure 1) are accessed by an ASEA IRB-90 six-axis industrial robot located on a 30-foot track. The IRB-90 has a reach of approximately 9 feet, a load capacity of 90 kilograms, and a repeatability of 0.005 inch. A central MicroVAX II mini-computer acts as the supervisory controller. Communication to peripheral systems (ASEA robot controller, AD/DA interface, and vision system) is established through custom serial connections. The system is connected via DecNet network to the local KSDN network and the National NASA SPAN network. The vision system, a Data Cube MaxVideo, incorporates a pipeline design approach, a VME bus with a 68020 processor, and a processed throughput of 30 frames per second. Additional sensors (force/torque, proximity) are also integrated in the system. Because of associated limitations, the original robot controller is now being replaced by a special-purpose high-speed flexible robot controller, which will provide direct access to each joint controller and provide 6-DOF adaptive control capabilities in realtime (30 Hz control updates for vision and 100 Hz for force-torque tracking).

The RADL prototype system consists of a vision-based 6-DOF tracking system attached to the ASEA robot and a target attached to a separate receptacle plate. Using a passive compliance end-effector, the robot is able to track and insert an umbilical plate mockup (which incorporates fluid, electrical, and data lines) into a receptacle plate mounted on a 3-DOF device that simulates the motion of the Orbiter (see figure 2). The passive compliance device uses nontactile vision tracking and is being augmented by an active tactile tracking system using force/torque reactive feedback to reduce mating forces.

Enhancements include the use of a counterbalance mechanism that removes loads from the robot and enables the robot to disconnect from the umbilical after mating. The robot will be turned off and the umbilical will free float with the counterbalance removing loads from the vehicle. This reduces vehicle design weight and allows more payload to reach space at reduced costs. A floating plate is also incorporated that reduces insertion loads, reduces connect/disconnect surges, and eliminates galling of sensitive cryogenic fluid coupling surfaces. Improvements also have been made in alignment and capture mechanisms to reduce forces, reduce galling, and ensure positive latching.

6-DOF Tracking

The major innovation is a robotic vision subsystem that measures the relative position and orientation of a specially designed target and provides realtime control to a large robotic mechanism. The subsystem uses standard image processing algorithms implemented directly in circuitry instead of computer programs that consume more time. This feature makes it possible to extract complete sets of target tracking data from successive image frames at the rate of more than 30 frames per second.

A solid-state video camera views the target, which consists of five bright or reflective circles, four located at the corners of a square and the fifth located at the center of the square but offset from the plane of the square (see figure 3). The raw image data is sent to image processing circuitry that performs a convolution difference-of-Gaussian edge-analysis filtering operation to clarify the picture elements representing the edges of the circles. On the Shuttle, the fifth circle could be implemented simply as a styrofoam thread-spool glued in the center of four painted circles.

The image is then processed further to obtain the centroids of the five circles. The locations of these centroids relative to each other and to the overall image frame are processed to obtain three Cartesian coordinates of the target relative to those of the camera. Triangulation calculations based on the vector relationships among the locations of the five circles and the central axis of the target yield the roll, pitch, and yaw angles that describe the orientation of the target relative to the line of sight and the field of view of the camera (see figure 4). Thus, the relative position and orientation of the target are determined in all six degrees of freedom (see figure 5). The offset of the central circle from the plane of the other four circles can be increased or decreased to increase or decrease the sensitivity of the subsystem to the pitch and yaw of the target and to provide more accurate distance-to-the-target information.

The output data may have to be transformed into spherical or other coordinates used by any other robot. However, this transformation can be performed easily in software. If the robot is changed, it is necessary only to change this software.

TORQUE SENSING END-EFFECTOR (TSEE)

The TSEE was produced from a Small Business Innovation Research (SBIR) project to develop an intelligent tool/gripper to open or close valves during hazardous maintenance or emergency work. The TSEE features servo control of jaw opening dimensions, nontactile/tactile sensors, and torque feedback to determine and maintain optimum seat pressure settings. This feedback provides reflective force feedback to an operator and to automatic computer-controlled operations enabling determination of valve position and preventing damage to valve seals. A Phase I SBIR (see figure 6) produced a small working model and a Phase II SBIR (see figure 7) produced a hardened mechanism with a user-friendly data base capable of operating in hazardous NEC Class I, Division I, Group B hypergolic/cryogenic environments. A version closer to the Phase I unit may be more suitable for petrochemical and nuclear applications where a smaller mobile robot (see figure 8) could be used to safe hazardous fires, or chemical or nuclear spills.

The TSEE's interchangeable gripper can locate a valve position and rotate continuously to open or close valves ranging from either 0.5 to 4.0 inches or 3.5 to 6.0 inches in size. Valves can be opened that have a torque range of 10 to 150 inch-pounds.. The TSEE has a unique nontactile torque sensor utilizing magnetoelastic phenomena.

The end-effector is used in conjunction with a computer controller that can interpret commands from an operator at a computer keyboard, from a parallel digital interface on the robot carrying the end-effector, or from a serial communications link to another computer. This lets the system open and close valves and determine if the valve is turning as expected from any of these operating modes.

The computer that controls the end-effector stores information about a range of valves whose positions need to be adjusted. Valves are identified to the system by labels that may be descriptive or numeric. Information in the valve data base is used to identify valves and to provide information on turning ranges, gripping forces, valve handle sizes, and current status or position of the valve. Once information has been put into the system, valve operations will keep the data base up to date.

A TSEE can be incorporated with the 6-DOF target tracking system to allow a remote operator (Space Station astronaut, Flight Telerobotic Servicer (FTS) remote controller, nuclear cleanup engineer, or fire fighter) to: (1) position or teleoperate the robot in front of a panel where it can see the target, (2) let the target tracker autonomously orient the robot at the correct angle and distance from the panel, and (3) activate a stored program to perform pretaught routines. The TSEE locates valves (which may be in the wrong position with stems in or out) through simple sensors and then performs pretaught operational sequences to "safe" an operation in a hazardous environment. This can be done with existing technology rather than waiting for telerobots to incorporate AI to perform "smart" autonomous operations. These two innovations (TSEE and 6-DOF tracking/orientation) are the key technologies to enable more sophisticated use of telerobotics, not just teleoperations, sooner in Space Station work, ground aerospace launch processing, and hazardous petrochemical or nuclear safing operations worldwide. This product can also enhance robotic applications in NASA and industry without redesigning existing valve panel facilities for robotics. It will provide safer and less serial-time operations in hazardous environments.

ORBITER RADIATOR DAMAGE INSPECTION

KSC (NASA) is working on a joint project with Lockheed (Kennedy and Palo Alto organizations) where Lockheed is developing a sensor system to examine and inspect the Orbiter radiators for damage (delamination and meteorite dings) while NASA is developing a robotic mechanism to transport the Lockheed sensor over the complex contours and 10.5 by 60 foot surface of the radiators. A prototype production system and future production models will be tested, certified, and installed in the Orbiter Processing Facilities (OPF) at KSC.

The objective of the project is to decrease the amount of time it takes to process an Orbiter before each mission. The efficiency of the radiators to dissipate radiant heat energy is dependent on their surfaces being clean and damage free. It presently takes 16 people 24 hours to inspect the Orbiter radiators to determine damage (dings, scratches, impacts) prior to continuing other work in the OPF. A robotic inspection system should reduce this to two people in 3 hours and provide accurate repeatable trend data and a quality inspection. Currently the operation is performed with an XYZ mechanism over the Orbiter that moves "buckets" large enough to carry men and equipment. The buckets are driven by highly skilled personnel. The visual inspection is performed using the naked eye and observations are recorded on a log sheet. This does not provide an accurate permanent record of damages and their locations. Small imperfections may be overlooked. This is a very uncomfortable, task-intensive, repetitive job.

The radiator panels are normally inspected twice during all OPF flows. The first inspection, postflight zonal inspection, is performed to detect any damage to the radiator panels that may have occurred in flight. The second inspection, immediately prior to payload bay closeout for flight, is performed to detect any damage that may have occurred during OPF processing. Other inspections are required if the radiators are removed from the payload bay doors and placed in storage.

Operations personnel are primarily concerned with anomalies that fall into two categories: (1) damage to the radiator panel surface silver Teflon tape and (2) damage to the radiator aluminum facesheet and honeycomb sandwich core. To date, inspection of the radiator panels has focused on only damage visible to the normal unaided human eye. Once a nonconformance condition is detected and documented, other techniques are performed to assess the damage severity.

Anomalies to the radiator surface include scuffs, scratches, tears, discoloration, delaminations, and bubbles in the silver Teflon tape. An automated inspection device must detect these anomalies and differentiate one from the other. The inspection tool will need to maintain a memory (damage log) of each radiator panel to determine if an anomaly was "new" or had been previously assessed and documented. Because most damage to the thermal control coating is not repaired, it is essential that the damage log provide a means for continual update and for referencing the cummulative surface area of minor unrepaired damage.

Anomalies to the radiator aluminum facesheet and honeycomb core include indentations (dents), scratches, pin holes, punctures, gouges, and meteorite strikes. The automated inspection device will be able to detect these anomalies and differentiate between defects that penetrate the facesheet from those that impact the facesheet but do not penetrate. As before, the inspection tool will maintain an automatically operated memory (damage log) of each radiator panel to determine trends and to quickly locate repair areas that are to be processed at a later date.

By automating this operation, most of the personnel will be relieved of their inspection duties so their talents could be used to perform other jobs more demanding of their skills. It would also provide a quickly accessible permanent record of radiator inspection data (damage assessment and precise location), reduce the amount of paperwork required to get the job done, minimize setup time to get ready for inspection, and provide expansion capabilities so that other functions could be performed on the radiators with the automated mechanism (e.g., cleaning). The overall goal is to achieve an efficient and less expensive operation.

Automatic Radiator Inspection Device (ARID)

The ARID mechanism was an evolutionary design culminating in a 4-degree-of-freedom robot (see figure 9). Lockheed originally envisioned that the ARID would be a camera traveling on a contoured beam shaped like the radiators, transported along two rails that lay along the edges of the Orbiter radiators (see figure 10). However, there were four major problems in implementing this configuration:

(1) Two of the major design goals were to not impact existing operations and to install the ARID without major modifications to the facility. The first simple concept would have led to producing a large mechanism (10 by 60 by 10 by 60 feet) which would have to be picked up by an overhead crane and moved into place with one transport rail latched in place to the Orbiter Processing Facility (OPF) platforms and the other transport rail suspended over the Orbiter's radiator hinges. This hanging structure would impact other operations that require the "buckets" to be moved. It would also have to be removed to open and close the radiator doors or to lower access platforms above the radiator to allow personnel access to payloads inside the Orbiter bay. Because of these facility impacts, the rail structure would have impacted serial flow, not reduced it

(2) A simple rod-like transport rail over the radiators was not feasible because of the 65-foot length required to span the cargo bay without resting on the Orbiter hinges. A truss assembly would have been required to reduce bowing and sagging of the structure, making it heavier and more difficult to move.

(3) Trend photographs of an old image must be aligned with a new image for comparison. If the alignment is off by more than 10 pixels or if the light angles are different, then the image will look different in the vision system processor's eyes. The bulky mechanism would have to be fitted with alignment offsets to allow for x, y, and z, and orientation differences for each vehicle and to allow for imprecise placement of the Orbiter in the OPF. This would have further complicated the design and introduced complex manual alignment procedures.

(4) The forward radiator panel (see figure 10) has a 5.71-degree of slope (covering an area 7 inches high by 70 inches long). This eliminates a fixed track design from being able to access all four side panels.

During the design, it became readily apparent that all these problems could be minimized through a flexible robotic mechanism that could: (1) provide a quick, software-programmed "frame shift operation" eliminating parking offset adjustments, (2) be cantilevered from under access platforms located adjacent to the radiator panels and moved out of the way when necessary so as to not impact facility operations, and (3) be reprogrammed or be expanded to support other future changes. This robotic flexibility will be advantageous for future update of the system to allow for cleaning of the radiators by the ARID rather than by men hanging over the sides of buckets. In the near future, as the use of the robot becomes more of a standard operation, as people get more accustomed to using automation, and after the ARID proves itself to be reliable, a modification will be made so that it can actually clean the radiators by "hand rubbing" the delicate surface.

Figure 11 depicts the first in-house mechanism concept (a PPRP robot). It consisted of a 65-foot prismatic rail to traverse the length of the four radiator panels, a prismatic cart to reach from the outer edge of the door to the Orbiter's hinge, and another prismatic rack-and-pinion rail with a rotary joint to move the inspection device over the contoured surface of the radiators. There were also problems with this configuration that caused it not to be implemented.

(1) Grease drippings from the Thompson rails and the rack-and-pinion gears used in such a design would pose problems in cleanliness. For example, radiators are covered after they are cleaned allowing upper platforms to be lowered (see figure 12). If they were not covered, dirt or tiny objects could fall on them as personnel walk on the platforms to access experiments in the payload bay.

(2) A PPRP device would have created problems with the management of lines and cables as the cart moved back and forth.

(3) The required inspection path would carry the vision system payload 6 inches above the radiator surface (see figure 12). However, this configuration required many closeup pictures and would have produced an excessive amount of data. The time to process this data would not have significantly reduced operational timelines.

To solve the first two problems, the design quickly evolved into a PRRR mechanism (see figure 13) in which the cables could be routed within an enclosed space (bending at the joints rather than being dragged over the width of the radiators). Seals can be installed on the joints to eliminate grease drippings.

In order to solve the third problem, Lockheed (the designers of the payload) requested that NASA KSC (the robot designers) investigate designing a mechanism that would allow taking photos from 6 feet away. This design would require that the upper access platforms be raised and another revolute joint be installed to lift the nose of the device (refer to point A of figure 13). Also, it would have made it difficult to design the robot to allow for later modification so it can reach the radiator surface for cleaning. However, a 6-foot inspection proved to be too far away to obtain reliable photos even with zoom lens. Also, since the designers did not want the device to hit and damage the radiators if it fell, it was determined that a 24-inch inspection distance would be the required sensing position above the surface of the radiators. The link lengths of the robot were then designed so the robot could transport the sensor over the work envelope (described in figure 13) without hitting the radiators at its extreme lower position. A mechanical stop keeps the robot within this work envelope. The link lengths were designed so the stops could be removed later and still be long enough to reach the surface of the radiators for any future tactile tasks.

During the development of the ARID by NASA, Lockheed was performing prototype sensor developmental tests. These tests revealed that a small vision sensor could be built (but it had to be aligned with the radiator panels to pick up all defects). Therefore, to use it on the 5.7-degree sloped surface of panel one, the smaller sensor required that the robot be designed with a fifth rotation axis (PRRRR configuration). At this time, the design of the robot was 90 percent complete, and this modification would have added too much weight and control complexity. A larger sensor could be built that did not require precise orientation, but the larger vision sensor would not fit into the operational envelope required to tuck the robot into a stowed position. The final solution was to build a "crook" or offset in the robot to enable use of the larger sensor (refer to figure 9).

The tolerances are so tight in the OPF that the robot arm must be moved in order to open and close the doors of the Orbiter. It was first thought that a hinge could be added in the area indicated by point B of figure 13. This, together with a revolute joint at point A, would allow the arm to be moved to a horizontal plane and then, using the hinge, be moved out of the way and stowed in parallel with the track itself. However, the payload bay doors are not strong enough to be opened on the ground in zero gravity conditions; therefore, when opening and closing the radiator doors, a strong-back device is attached to the outside surface to provide structural support. CAD drawings of the facility revealed that this strong-back device would pass at two places through the only area in which the prismatic track could be mounted (see figure 9). It would also pass through the robot arm if it were stowed in front of the track.

Two solutions were needed before the robot could be installed without modifying structures within the facility. First, an area (or "cubbyhole") at one end of the payload bay doors was located to store a folded-up arm (refer to the crosshatches in figure 13). If the arm was not foldable, it would have to be removed to open the doors. There was just enough space available in the cubbyhole to redesign the arm and joints to fit and still enable reach capability for a 24-inch nontactile inspection path and a 6-inch cleaning path. Second, in order to eliminate all facility impacts, the track was sectioned so that two short removable pieces could be quickly unbolted and slid back. These two modifications allowed the strong back passage through the track's operational envelope and resolved the final problems during the design evolution of the inspection robot.

Redundancy Requirements

Since this is the first robot that will be installed next to flight hardware (and especially since it hangs over the radiator doors), the reliability of the robot is extremely important. Recently, several suspended loads at various NASA facilities have had mechanical failures that caused them to drop onto a Spacecraft or flight hardware. If this occurs at the launch pad, not only could an $80 million Spacecraft be damaged, but it would cause an aborted launch. This produces expensive consequences resulting in large amounts of serial-time/money to replace and repair. The existing inspection "buckets" have even collided with the radiator doors and bent them upward. The robot has been designed to not hit any of the radiator panels even in worst-case parking conditions. However, the robot was also designed (for future use) where it could actually touch the entire surface of the radiators. When, and if, the stops and mechanical constraints are removed, the robot control system must be so reliable that there can be no inadvertant moves to cause even "dings" or "scratches" to the sensitive surface. To prevent this from occurring, the ARID has been designed so that it contains complete control system component redundancy and additional mechanical constraint redundancy.

Electromechanical design of each joint includes redundant drive shafts, bearings, harmonic drives, brakes, transmission chains, encoders, and motors (see figure 14). They are sized for the load, torques, and the space available in the stowage position. Electrically, the control system includes redundant motor servocontrollers, redundant indexers, and two separate control computers. Mechanically, redundancy exists by adding a special cable/pulley configuration (not shown) at joints two and three that prevents the arm from colliding with the radiators even if both redundant brakes or motor drive chains fail.

Two motors in parallel could possibly be expected to "fight" each other, but there is a 400-to-1 transmission gear ratio and a small torsional compliance in the harmonic drives and development in the laboratory has resulted in synchronous control of redundant motors. Also, drive components are balanced relative to the load. Therefore, any noticeable motor torque imbalance caused by component failure will be detected and used to shut down the system. The internal motor resolvers are compared against duplicate incremental encoders to provide redundant sensor feedback to enhance troubleshooting by the two computers. Once the fault is identified, the operator can shut down one side of the drive, release its brake, and use the remaining drive to fold the arm back into its tucked position and stow it in its "cubbyhole." In the case of a failure that requires repair of the robot, this will allow the doors to be closed without having to dismantle the robot arm and will enable the operational workflow to continue. A master computer and the slave computer each compare its own calculated kinetic positions, cross-check positions with each other, and check sensor feedback before allowing parallel-commanded moves to continue. The redundant system will be used in a "fail-safe" mode. If one computer fails, the other computer is switched in as a lone controller allowing the operation to continue to a safe conclusion.

Additional computer interfaces include digital/discrete control of brakes, emergency stop, digital sensors, limit switches, a manual control pendant, and a Lockheed-developed vision system computer data bank. The teach pendant allows manual override and speed control, and provides individual control of the position of all joints of the robot.

Simplication is the key to the design. Links 2, 3, and 4 of the robot will basically operate in a plane. The arm will be positioned to a location, the joints will be locked, and then the arm will travel lengthwise down a panel (using only the motors in link 1's prismatic axis). Next, the revolute joints will be unlocked and the arm will be lowered to another position that extends outward from the Orbiter (refer to figure 13). Then the arm will be moved lengthwise again. Photographs will be taken without stopping as the system moves at 4 inches per second. After an automatic scan, the operator may wish to look again at an anomoly or take a "still" photograph. He then can either program that position for an automatic move or manually drive the robot to a point that requires more resolution.

CONCLUSION

The first two innovations discussed in this paper (6-DOF Target Tracking System and TSEE) were designed and developed by contractors (Adaptive Automation Incorporated, and Automated Dynamics Corporation, respectively) working from specifications and with close guidance from NASA. These innovations can be integrated to perform tasks involving orientation and panel operations by using existing technology to perform "smart" autonomous operations. The third innovation (an ARID robot) was designed by NASA engineers. Contractor support is being used to fabricate and install the robot, to detail the teach pendant, and to develop the vision sensor. NASA engineers and co-op students performed the detail design of the joints, links, controls, and kinematics; and they performed kinematic, static, and dynamic analyses of this newly developed robotic mechanism as an "in-house" NASA developmental project. It is significant to note that the ARID robot involves the application of complete control hardware redundancy to enable performance of work above and near expensive critical Shuttle hardware (see figure 15). There are applications in which a robot would not normally be used because of "reliability" or in situations where an inadvertent move could result in damage to expensive components or even more expensive personnel. In such applications, the consumer marketplace may wish to explore commercialization of these component redundancy techniques. The three innovations discussed in this paper are applicable to Space Station work, ground aerospace launch processing, industrial safety, and hazardous petrochemical or nuclear safing operations worldwide.

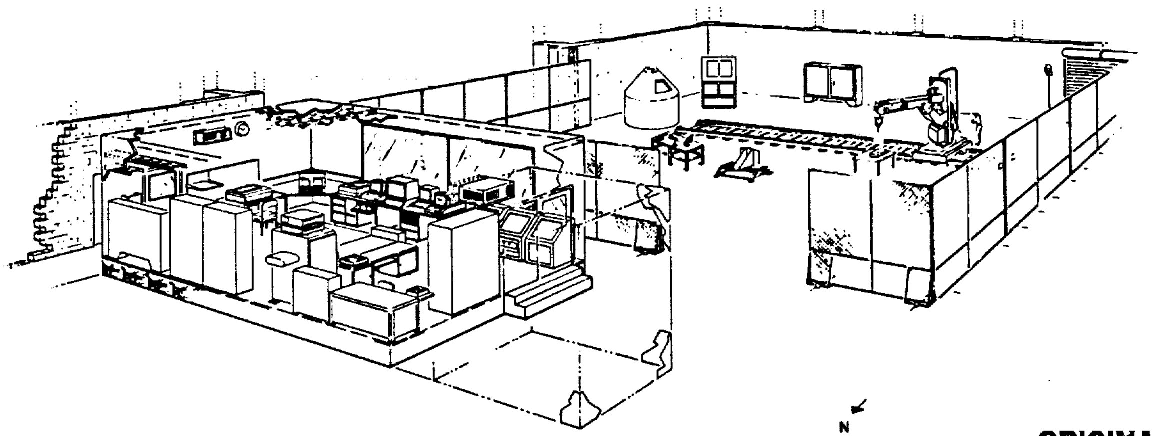

Figure 1. Robotics Applications Development Laboratory (RADL)

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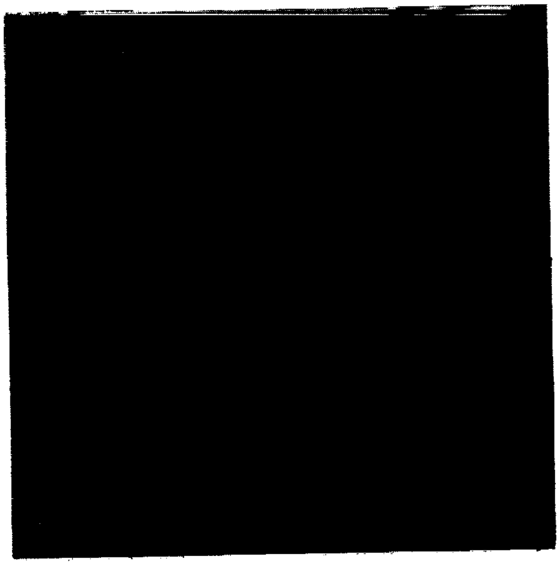


Figure 2. Remote Umbilical Mating
With Dynamic Simulator Target

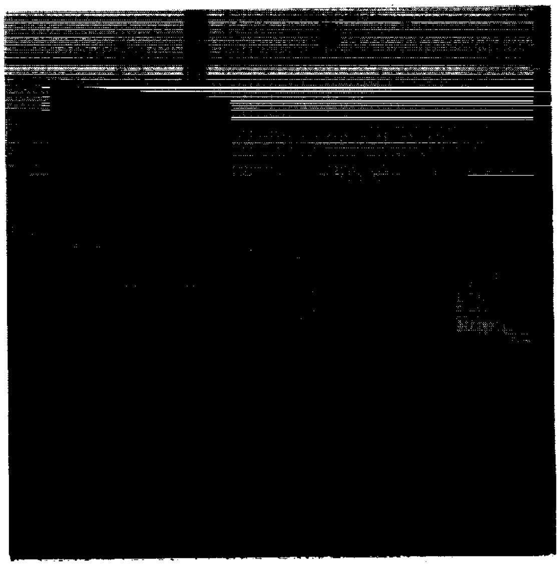
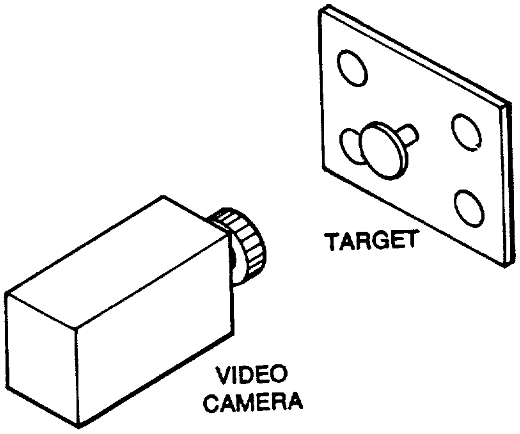


Figure 4. 6-DOF Target Discrimination
in the RADL



The Five Bright Circles of the target are positioned in such a way that the video images of them can be processed into data on the position and orientation of the target relative to the camera.

Figure 3. Tech Brief

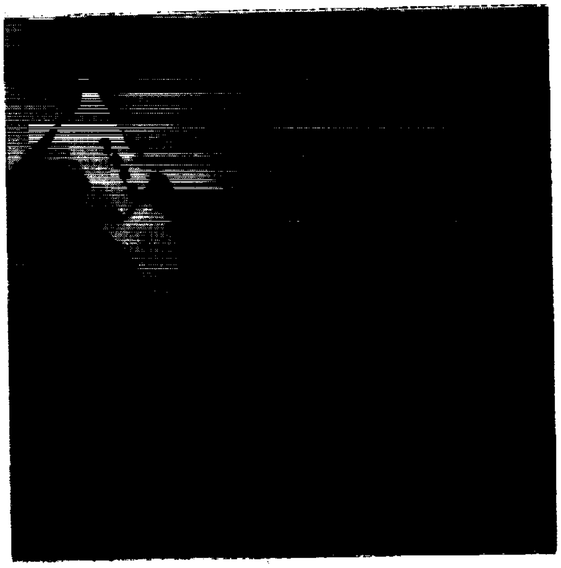


Figure 5. 6-DOF Robot Target Tracking

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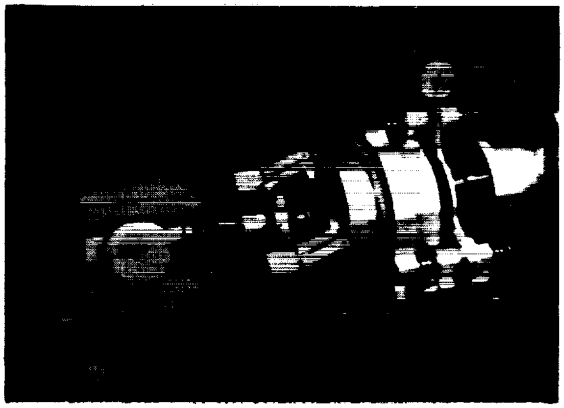

Figure 6. Small Phase I TSEE

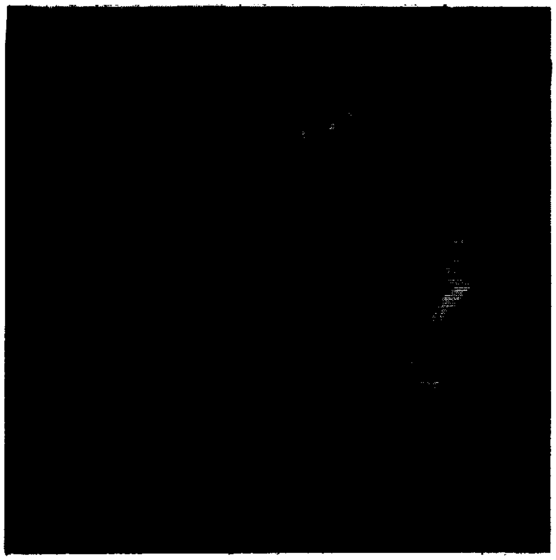

Figure 7. Large Phase II TSEE

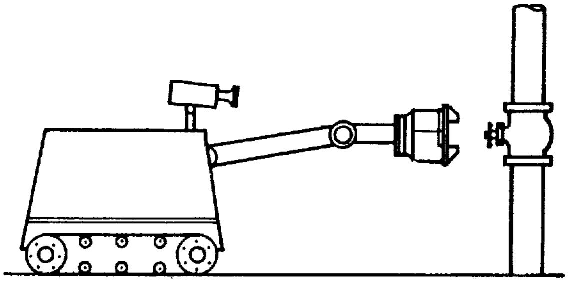

Figure 8. Remote Operation of TSEE

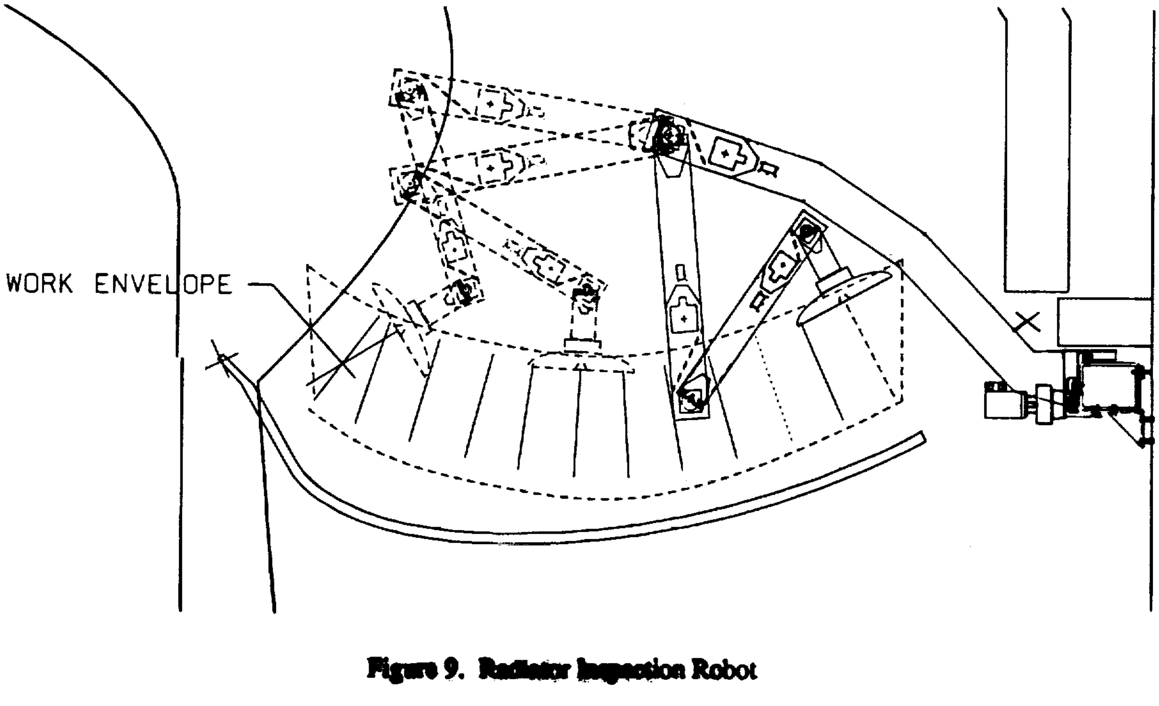

Figure 9. Radiator Inspection Robot

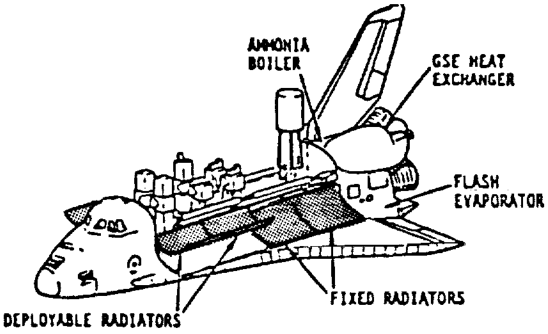

Figure 10. ARID Work Envelope

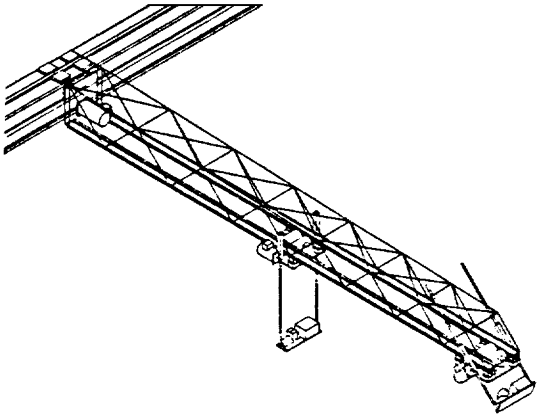

Figure 11. Early Concept

ORIGINAL PAGE IS
OF POOR QUALITY

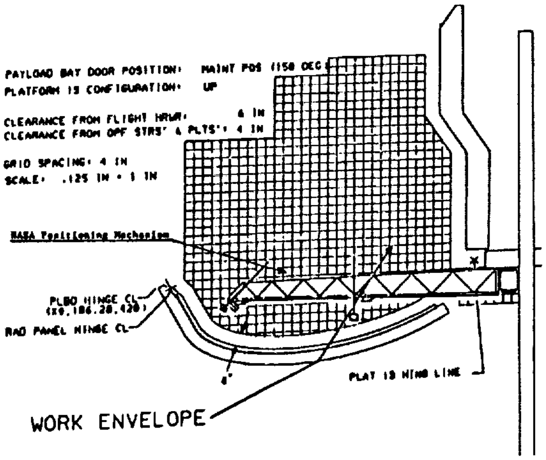

Figure 12. Concept for 6-Inch Inspection

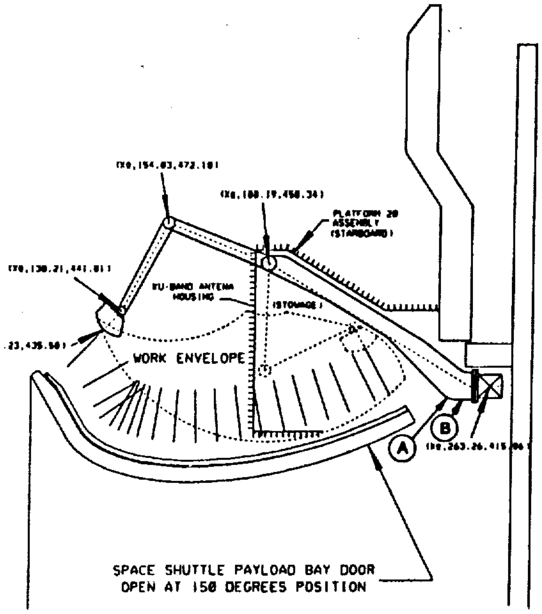

Figure 13. 24-Inch Inspection Work Space

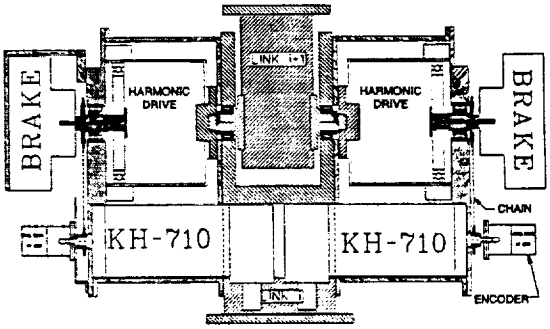

Figure 14. Redundant Drive Components

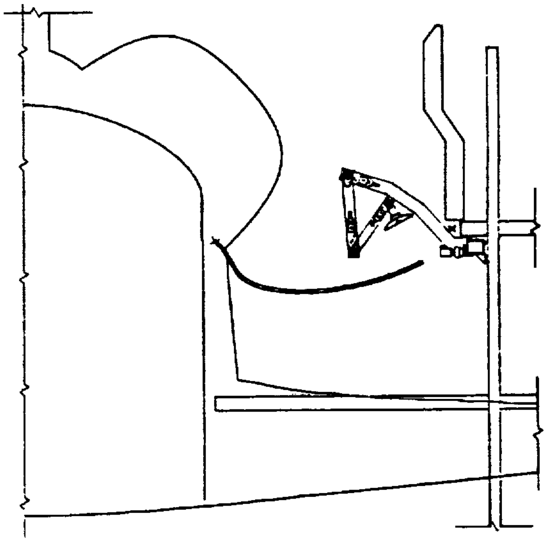

Figure 15. Final ARID Configuration