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TECHNOLOGY TRANSFER AND EVALUATION FOR SPACE STATION TELEROBOTICS

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Abstract

The international Space Station (SS) must take advantage of advanced telerobotics in order to maximize productivity and safety and to reduce maintenance costs. The Automation and Robotics Division at the NASA Lyndon B. Johnson Space Center (JSC) has designed, developed, and constructed the Automated Robotics Maintenance of Space Station (ARMSS) facility for the purpose of transferring and evaluating robotic technology that will reduce SS operation costs. Additionally, JSC has developed a process for expediting the transfer of technology from NASA research centers and evaluating these technologies in SS applications. Software and hardware systems developed at the research centers and NASA sponsored universities are currently being transferred to JSC and integrated into the ARMSS for flight crew personnel testing. These technologies will be assessed relative to the SS baseline, and after refinements, those technologies that provide significant performance improvements will be recommended as upgrades to the SS. Proximity sensors, vision algorithms, and manipulator controllers are among the systems scheduled for evaluation.

1. Introduction

The NASA Office of Advanced Concepts and Technology and the Office of Space Systems Development have sponsored and continue to sponsor the development of technologies that will improve SS efficiency and reduce life cycle operation cost. Technologies that expand the role of telerobotic maintenance and reduce the need for astronaut extravehicular activity (EVA) are particularly important and accordingly have been emphasized in NASA's overall telerobotics program plan [1]. Every hour of crew EVA time saved by using a robotic manipulator can be dedicated to the station's primary mission: scientific and engineering research. The use of telerobotic manipulators in this fashion is especially worthwhile, considering the high overhead in crew time required for each hour of EVA activity. In support of this task, the NASA JSC Automation and Robotics Division (A&RD) has established a technology transfer and evaluation process to determine which available technologies offer the most potential.

NASA JSC has a history of taking a leading role in transferring and evaluating telerobotic technologies in support of the SS program. JSC A&RD actively supports the integration and evaluation of the Canadian Space Station Remote Manipulator System (SSRMS) and special purpose dexterous manipulator (SPDM). JSC has supported extensive studies to determine the SS maintenance requirements at various points during the program's development [2]. In situations when new technologies are required as part of SS trade studies, A&RD has taken advantage of existing technologies developed outside the SS program. For example, the proximity detection and collision avoidance system implemented for an SS viewing study used a very fast distance calculation routine developed at the University of Michigan [3]. Also, a recent ground control study at JSC was built upon predictive display technology developed at the NASA Jet Propulsion Laboratory (JPL) [4].

JSC A&RD recently completed building the ARMSS facility for use in testing new telerobotic technologies. This facility provides a high-fidelity hardware SS environment for performing simulated maintenance activities. Previous SS maintenance activities simulated at JSC have been evaluated using fixed base manipulators to

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represent the Canadian SPDM operating in isolated SS work sites. The ARMSS facility goes well beyond this fixed base environment and any other existing NASA SS maintenance testbeds. The ARMSS testbed reproduces the relative motion that is possible between the SPDM base and its work site. In addition, its full scale SS preintegrated truss (PIT) segment provides realistic visual cues and obstacles for performing end-to-end maintenance tasks.

Over the years, NASA has invested in extensive basic robotic research and development at NASA centers and NASA sponsored universities. The work ranges from manipulator control systems designed at NASA JPL to sensors for robot collision avoidance developed at the Goddard Space Flight Center (GSFC). The university projects include a telerobotic protocol for Ethernet communications developed at Rice University [5] and fault tolerant manipulator concepts currently in work at the University of Texas [6]. These programs have provided prototype software and hardware systems with great potential for meeting SS productivity improvement goals. However, this potential may be achieved only if the prototype technologies are tested and refined in advanced applications development environments such as the ARMSS testbed and then, if they continue to show promise, further refined through flight experiments.

2. JSC Facilities

JSC maintains several robotic evaluation and integration facilities that provide support for SS. The Integrated Graphics Operations and Analysis Laboratory (IGOAL) supports non-real-time and real-time graphical simulation studies. IGOAL software is used extensively in determining the kinematic feasibility of many SS maintenance tasks. The Robotic Sensor Integration Laboratory (RSIL) provides support in the areas of sensor specification, design, and development and was used to refine the capaciflector sensor (described in a later section) provided by GSFC.

The Robotics System Evaluation Laboratory (RSEL) provides primary support for all SS tasks that require hardware simulation capability. The RSEL conducts qualifying tests using high fidelity robotic interfaces and orbital replaceable units (ORU's). Recent tests conducted in this laboratory with crew personnel were instrumental in the SS program decision to favorably consider ground control as a candidate for baseline operations [7]. Currently, prototype ORU's provided by the SS program are undergoing flight verification testing in the RSEL. In addition, the RSEL has provided the software and hardware tools that have been used to construct the latest JSC robotic laboratory addition, the ARMSS testbed.

ARMSS Testbed

The centerpiece of the JSC telerobotic technology evaluation facility is the ARMSS testbed. This 1-g simulator, shown in figure 1a, is NASA's highest fidelity SS maintenance environment for kinematic and contact tasks. It consists of three major components: an SPDM emulator, an SPDM mobility system, and a full scale SS PIT segment that together functionally reproduce the SS components shown graphically in figure 1b. In this simulated view the SPDM is attached to the SSRMS and is preparing to replace an ORU located on a PIT door.

The ARMSS testbed can trace its origin to the previously designed but never constructed Automated Robotic Assembly of Space Station (ARASS) testbed for the on-orbit assembly of the 5-meter SS truss. After the SS change to PIT segments, emphasis shifted from dexterous robotic SS assembly tasks to SS maintenance tasks, and design work began on a telerobotic maintenance testbed. As much existing hardware as possible was incorporated from the earlier testbed into the ARMSS testbed, including the mobility system and the commercial manipulators. New hardware, such as the PIT segment and the ORU's, was designed and fabricated. An Intel Multibus II multiprocessor computer system, which is the SS standard, was purchased, and control system software written in "C" was transferred from existing JSC simulators to the Multibus II to serve as a starting point. To insure an operational system at the earliest possible date, all coding for the system was continued in "C." In keeping in line with SS requirements for eventual migration to Ada, an Ada compiler was purchased for the Multibus II, and a portion of the control system has been converted.

<u>SPDM Mobility.</u> The SPDM emulator hardware is mounted to a servo-controlled tower/rail system to achieve part of the mobility the actual SPDM will have when attached to the SSRMS. The system controller permits independent placement for each manipulator, both horizontally and vertically, and the manipulators may be positioned to achieve arbitrary SPDM placement and orientation within a 20-ft by 20-ft plane perpendicular

Figure 1a. ARMSS facility

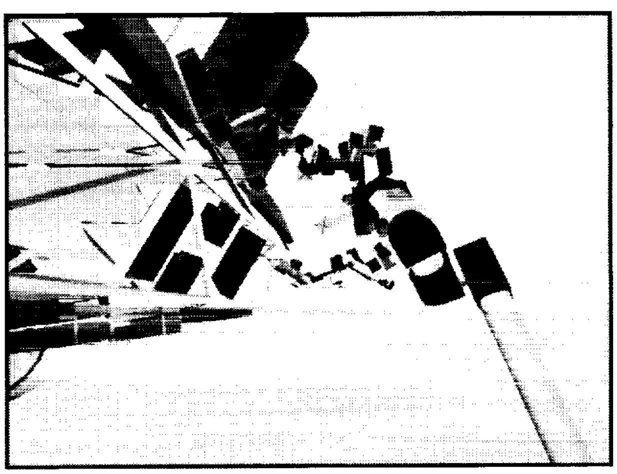

Figure 1b. Proposed SPDM attached to SSRMS

to the facility floor. The relative separation of the manipulators is adjustable to accommodate any future changes in the SPDM body design. Flexible cable trays run along the rails and towers providing power, data, and video communication to the manipulators.

The SPDM three-dimensional motion capability is completed with the addition of a mobile PIT structure. The PIT rests in a wheeled cradle that may be moved in a horizontal plane relative to the tower system. An actuator drives a high ratio gearbox, which in turn drives a chain and sprocket that rotates the PIT within its cradle about its long axis. Rotation is available in both directions. Combined, the tower and PIT degrees of freedom permit the manipulators full access to all six faces on the PIT.

SPDM Emulator. The SPDM emulator uses two commercially available Robotics Research (RR) 1607 manipulators (figure 2a) combined with the proper tooling to provide a very good approximation to the proposed SPDM arm (figure 2b). Like the SPDM manipulators, each RR1607 manipulator has seven degrees of freedom. The extra degree of freedom permits motion of the manipulator joints while maintaining a fixed end effector position and orientation. This is very useful in avoiding joint travel limits and obstacles, and reorienting the cameras that are mounted on the manipulator elbows At the time the ARMSS testbed was being designed, the RR1607 manipulators with tooling yielded approximately the same 2-meter reach that was planned for the SPDM. Subsequently, the SPDM design was modified, and now its arms are about 2.5 meters long. However, this is not expected to be a problem since extra travel is available by moving the ARMSS manipulator bases to increase or decrease the distance between the RR1607's. Finally, the RR1607 has sufficient capability to lift a functional 6B ORU, which is the one of the most common types planned for SS.

The tooling along each manipulator approximates the planned SPDM ORU tool changeout mechanism (OTCM) design. The ARMSS OTCM is shown in figure 3. After a manipulator is moved into proper position, the parallel jaw grippers located at the end of the OTCM grapple onto an ORU interface. Located directly behind and in between the gripper fingers is a shaft mounted socket. This device, known as the rotary drive, is extended after grappling and engages a bolt located in the center of the ORU interface. The rotary drive is designed both to loosen and tighten the ORU bolt. A force/torque sensor mounted behind the gripper connects the gripper to the manipulator and provides feedback for compliance control whenever the gripper is in contact with an interface.

PIT Segment and ORU's. The 20-ft PIT segment contains faces from two separate SS mission build (MB) segments, MB4 and MB2, and provides a comprehensive robotic maintenance

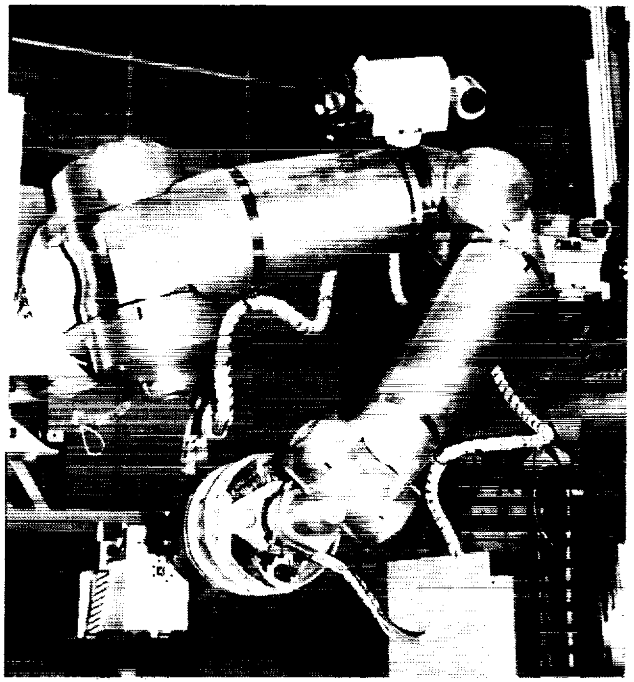

Figure 2a. RRK1607 manipulator

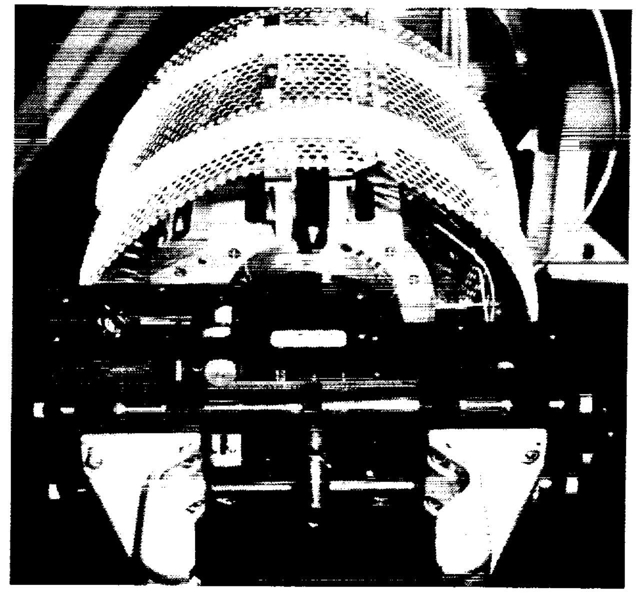

Figure 3. ARMSS OTCM

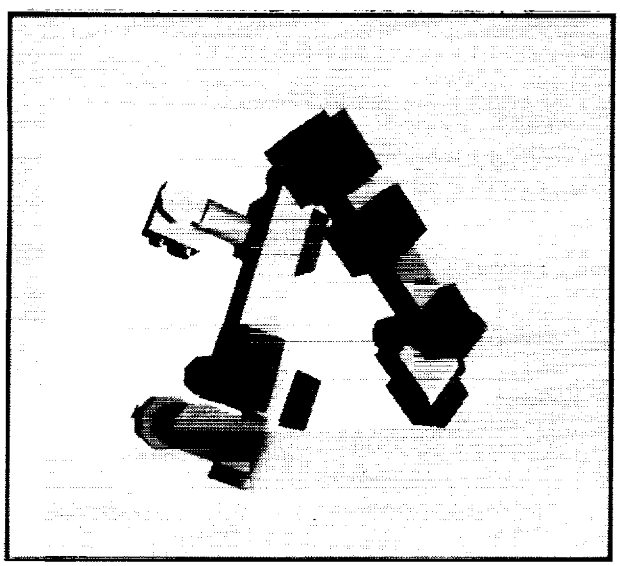

Figure 2b. Proposed SPDM ARM

testing environment. The structure is made of aluminum box section with a 4-in by 6-in cross section to match the SS PIT design. ORU doors are attached to two faces and contain attachment locations for both robot compatible 6B ORU's and various size noncontact 6B ORU mockups. The contact and noncontact ORU's may be rearranged to yield several possible configurations along the inside of doors. The SS program has designated that the doors will also be robot compatible, and the ARMSS PIT segment will be modified to accommodate the SS door design once it is released. Finally, utility trays are attached to several PIT sides providing realistic obstacles and viewing obstructions.

The ORU shown in figure 4 reproduces the functionality of one size 6B ORU. The interfaces for this ORU approximate the ones called for in the SS robotic system interface standards (RSIS) [8]. The manipulator grippers acquire the ORU by grappling the SPAR micro interface located on front of the box. A modified SPAR target located directly above the micro provides visual cues for manipulator alignment prior to grappling. The ORU is equipped with a box-to-cold-plate interface that slides into alignment guides located on the ORU carrier also shown in the figure. As the ORU is inserted and travels along the guides, it is pulled into position along the cold plate with the help of a manipulator force/torque compliance algorithm. The ORU is locked into place when the bolt located inside the micro engages the ORU carrier and is tightened down. An identical carrier may be mounted to any of nine locations on the PIT ORU doors.

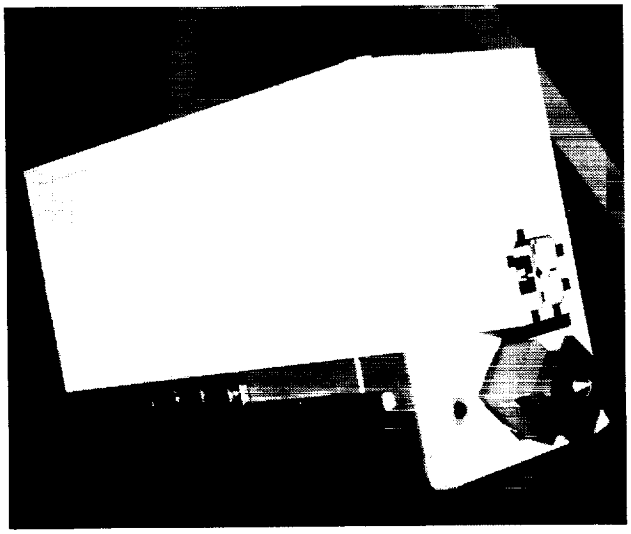

Figure 4. SS 6B ORU

Workstation and Video System. The ARMSS workstation shown in figure 5 reproduces the functional capability of the multipurpose applications console (MPAC) planned for SS. Two 486 personal computers (PC's) and one 386 PC run all the user interface and communications software. The ARMSS manipulators are controlled through SPDM displays that run on the upper left monitor and through two three-degree-of-freedom hand controllers located on either side of the workstation. A keyboard and a trackball are used to input data to the SPDM displays. Manipulator tooling is controlled through a combination of software display buttons and hardware switches located on the rotational hand controllers.

Two NTSC monitors, both with graphical overlay capability, provide video data to the operator. The video is controlled using either software displays or a push-button control panel on the upper right portion of the workstation. Both interfaces provide selection, pan and tilt, and zoom for each of the ARMSS cameras currently available. Referring back to figure 1, each manipulator has an end effector camera and an elbow camera. An SPDM head camera is approximated by a camera mounted just above one manipulator. A camera mounted to one tower simulates the elbow camera located on the SSRMS, which moves the SPDM from place to place. A single field camera may be moved as required to reproduce the capability of a relocatable SS PIT boom camera. All but the end effector cameras may be panned and tilted and zoomed, and each of these cameras has potentiometers for measuring pan and tilt position.

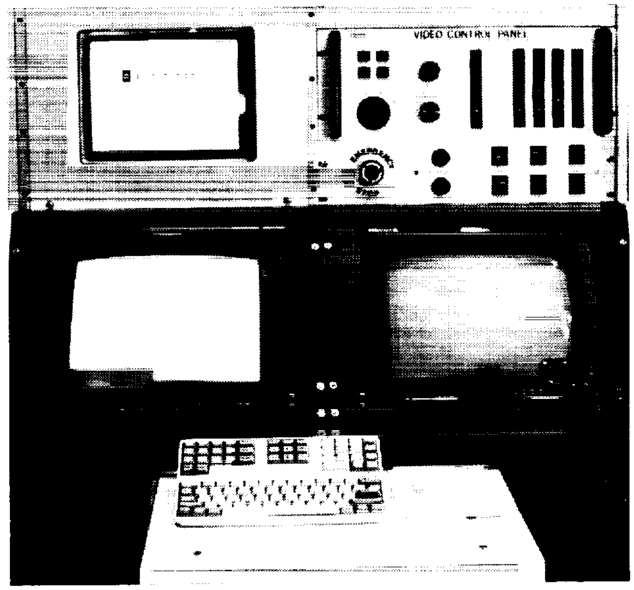

Figure 5. ARMSS MPAC workstation

This medium fidelity MPAC mockup uses the same interfaces for communicating with the manipulators and cameras that are specified for a high fidelity MPAC currently under development at JSC. The high fidelity MPAC replicates the video resolution and windowing capability specified for SS. It will also use the Sammi displays and controls software and the Lynx operating system planned for on-orbit operations. This high fidelity MPAC will be used to evaluate all SSRMS and SPDM displays as part of a separate JSC SS support project. The ARMSS workstation design did not incorporate these items due to a combination of cost and software maturity issues and only provides a subset of the SPDM control displays. However, when complete, the high fidelity MPAC will be interfaced with the ARMSS system and will be used to control the testbed when appropriate.

Control Architecture. The ARMSS control architecture outlined in figure 6 is based on the SS Multibus II standard. Separate processors are used to reproduce the relevant portions of the SS Mobile Servicing Systems Operations and Management Control Software (OMCS) and the SPDM control software. The OMCS processor receives commands from the ARMSS MPAC workstation, performs high level validity checks, and returns manipulator status back to the workstation. An Intel 386 20-MHz processor located in the same card cage runs the SPDM control system emulation software that communicates with the robotics research embedded processors.

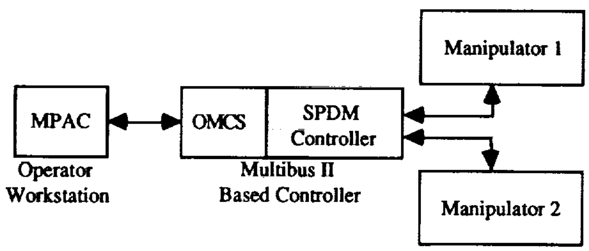

Figure 6. ARMSS control architecture

SPDM Control System Emulation. The Multibus II control software is designed to emulate all the SPDM kinematic and contact capabilities appropriate to a 1-g simulator. A detailed description of SPDM control software can and does fill several volumes; therefore, only the most important capabilities pertinent to SS maintenance are highlighted below.

The SPDM emulation software currently permits an operator to command each manipulator using the following baseline modes: end effector position and velocity, joint position and velocity, and pitch plane velocity. Prestored or operator position inputs are read by the SPDM software and converted to rate commands, which are sent to the RR embedded motion controller. The software constantly monitors a hand controller switch that must be engaged during operator commanded position moves. Motion may be stopped and restarted via this switch. Operator velocity command inputs are scaled by the software and limited to stay within SPDM specifications before being sent to the RR motion controller. Pitch plane, or null space, motion of the seven-degree-of-freedom manipulators commands are processed in a similar fashion. The SPDM emulation software is currently being expanded to queue up data for use in following prestored and ground commanded sequences.

One of the most important SPDM features available in the ARMSS software is force/torque compliance. The control software reads in data from the end-effector-mounted force/torque sensors and calculates commands to relieve contact forces that occur during ORU insertions and removals. The compliance commands are added to the hand controller commands, and the resulting "shared control" commands are sent to the manipulator. In addition, the emulation software provides a very simple form of gravity compensation by allowing an operator to bias out the force/torque sensor prior to initiating contact operations.

The SPDM emulation software provides coordinate transformations for both manipulator commands and feedback data. In addition, manipulator health is constantly monitored and provided back to the operator. Also, the ARMSS software commands the grippers and rotary drives used in ORU replacement operations based on SPDM specifications.

Communications and Ground Control Capability. Now that ground control of the SPDM is being favorably considered by the SS program as a viable means to reduce the maintenance burden for crew personnel [7], software and hardware that cannot be run on the SS due to power limitations will be considered for remote use. The ARMSS facility was designed with this requirement as a baseline and utilizes the TeleRobotic Interconnection Protocol (TelRIP) software [4], developed at Rice University, as the standard for communications with remote computers. TelRIP is a socket based data exchange mechanism, which allows multiple processes and processors to communicate in a common environment. Processes communicate through routers (TelRIP applications, which manage the flow of data between processes). Each application process contains a TelRIP stub, which maintains the socket connection with one router. Numerous, as well as remote, interconnections may be created over an Ethernet-TCP/IP network as multiple routers can maintain connections to each other as well as local processes.

All communications between the MPAC workstation and the Multibus II are run via TelRIP and include manipulator mode selection, hand controller inputs, tool operation, feedback data, and camera control. After incorporating TelRIP, ground based workstations such as the JPL Operator Control Station (described in a later section) have full access to the ARMSS testbed. The only exception is live video that cannot be accommodated along a shared Ethernet. If the operator control station is relocated to JSC, live video is readily available. In addition, TelRIP software routines developed at JSC to simulate ground-to-orbit data delays [3] and a separate PC based video delay system are available. For very high fidelity ground control simulations, a network has been established at JSC to route telemetry and video through the actual TDRSS system via a JSC communication station.

3. Technology Transfer Process

The technology transfer process includes three phases: coordination, implementation, and evaluation. During the coordination phase, JSC and a development center work together to identify candidate technologies that are suitable for SS applications. Once a technology is identified, a joint technology transfer plan is worked out with the contributing center, detailing the activities that each center will conduct to support the transfer.

Concurrence of this plan by both JSC and the development center signifies the beginning of the implementation phase. This is the longest phase of the process and involves the physical transfer of the technology to JSC. Supporting software is transferred to JSC, and JSC procures any specialized hardware required to host the technology. If appropriate, the technology is initially implemented in JSC RSEL using equipment that is compatible with the ARMSS architecture. This interim step is needed to reduce downtime on the high fidelity ARMSS testbed since it is most efficiently used as an evaluation facility with crew personnel as opposed to a debugging platform. The integration phase is completed when the JSC test coordinator and a representative from the development center agree that the transferred technology is performing properly.

Evaluation is the final phase in the transfer process. This phase begins with the completion of a test plan for the candidate technology. Test readiness reviews are held with the contributing center prior to test start. Tests are conducted to determine if the technology provides a performance improvement relative to the SS baseline. Representatives from crew training, mission operations, engineering, and the flight crew office perform controlled evaluations with and without the candidate technology. The evaluation phase is completed when the test report is produced. Technologies that provide performance enhancement are recommended to the SS program office.

The success of the technology transfer process hinges on choosing those technologies that will not only provide a performance enhancement to SS but also require minimal, or at most gradual, changes to SS hardware and software. For example, a new ORU grappling target that reduces operator workload and ORU changeout time would be installed on replacement ORU's. The target would be incorporated into future SS hardware replacements and not require a costly set of on-orbit replacements. The same is true for ground based telerobotic control software. Enhancements to a ground based system that do not affect the interface between the ground control center and SS would have a greater chance of acceptance than a control system that required additional onboard computing power. All candidate technologies for transfer are evaluated within this context.

4. Candidate Technologies

The following candidate technologies are either in the coordination or implementation phases of the transfer and evaluation process.

Flat Target

The first technology scheduled for transfer and evaluation using the ARMSS facility is the JPL flat target. This target is used as an ORU grappling aid and is viewed through a camera located on a manipulator end effector. As indicated by the name, the flat target is very thin. However, through the use of micro-lenslet array technology it produces a target that is projected approximately 1 inch from the face of an ORU. Thousands of quartz lenses that make up the target face produce this projected effect. The benefit is a low profile target that can be easily attached to an ORU and yet still provide three-dimensional alignment cues normally achieved with a much larger and heavier target.

The flat target is now in its third generation. Evaluations at JSC using the first two generations have provided useful feedback to JPL designers. The third generation target is expected to provide three times the resolution seen with the second generation. Using the ARMSS testbed, ORU changeouts will be performed with both the SS baseline target and with the flat target. Quantitative and qualitative test data will be collected, analyzed, and delivered to JPL for use in future refinements. This evaluation is expected to begin during the late summer of 1993.

Surface Inspection (SI)

The JPL SI system is a set of software routines for capturing and processing video images using a robot-mounted camera. An operator uses this system to drive a manipulator over a surface in either a manual or automated mode. The current surface views are compared to previously captured images using a video differencing algorithm. The system alerts the operator to any significant difference, and if appropriate, the operator logs the location of a flaw for future reference and/or repair. The SI system cancels out ambient lighting effects by using a set of controlled lamps that is also mounted on the manipulator. Images are processed under both ambient and a combination of ambient and controlled light. The images are subtracted to remove the ambient light effect. The user interface provides the operator with complete controls for all subsystems: manipulator, cameras, lighting, and image database.

The JPL SI system is scheduled for integration into the ARMSS facility during 1994 for testing under simulated SS lighting conditions. Crew personnel will evaluate the system in both manual and automated modes for inspection along the PIT mockup. Plans have been made to modify an ORU to show micrometeoroid damage. Significant work has already been completed with a partial transfer of the SI system to JSC RSEL. The software has been modified to work with the TelRIP communication system, and the SI user interface is currently being used to drive a JSC RR manipulator.

Capaciflector

The GSFC capaciflector is a device that measures the frequency of an oscillating electric field emanating from a flat antenna. As an object enters the field, it affects the permeability of the surrounding space and alters the oscillation frequency. The change in the frequency correlates to the distance between the antenna and the object. This device, also known as a capacitance proximity sensor, holds significant promise as an alignment aid for telerobotic ORU insertion.

A capaciflector prototype was transferred to JSC RSEL during 1992. After initial testing in JSC RSEL and consultations with the GSFC developers, a modified version of the sensor, which has greater thermal stability, was designed and developed at JSC. A graphic user interface that will provide short range proximity data to an operator is currently in work. After completion, the interface along with an ORU equipped with a set of capaciflectors will be integrated into the ARMSS control system. The benefits of the capaciflector versus the baseline ORU insertion alignment aids will be assessed during late 1993.

Operator Control Station (OCS)

The OCS developed at JPL is a prototype system for remotely controlling a manipulator system using saved sequences and intelligent macros. The system is designed for use when communication delays are several seconds long and direct teleoperation is not efficient. The OCS provides two main capabilities: a world model calibration system and a telerobotic control interface. The calibration system uses a combination of machine and human vision to accurately update the position of simulated objects and to build new ones on line. The telerobotic control interface is used to create and validate sequences in simulation before downloading to a manipulator. The sequences are stored in a convenient hierarchical fashion for use in executing entire tasks and may be easily modified by the user. The OCS was originally designed for interfacing with telerobotic devices located at JPL that have a higher level of autonomy than is currently baselined for the SPDM. However, much of this technology holds promise for use in ground control operations.

The OCS system has already been transferred to JSC and is currently undergoing integration with an RR manipulator. The system is being modified to use the TelRIP communications software, and additional handshaking is being incorporated to accommodate the SPDM baseline. Integration into the ARMSS facility is scheduled for late 1993. After an initial evaluation that adheres to the SPDM baseline capabilities, future testing that includes modifying the SPDM to include higher level capabilities or reflex actions will be planned.

HexEYE

The HexEYE proximity sensor is under development at the University of Southern California in conjunction with NASA JPL. The HexEYE is an optical-based proximity sensor that derives its name from the hexagonal configuration of its individual sensor units. This compact sensor has a footprint of approximately a square inch and provides distance data accurate to .3 millimeters within a 10-centimeter range. Ongoing refinements are expected to increase the range capability while still maintaining accuracy. HexEYE technology transfer activities are scheduled to start in 1994.

Exoskeleton

The JPL exoskeleton controller is an alternative to the planned SS hand controllers. This force-reflective exoskeleton fits around the arm and hand of a human operator and provides anthropomorphic manipulator control. This advanced controller will be incorporated into a ground control system during 1994 and will remotely drive an ARMSS manipulator. To use a force-reflective system in ground control, pseudoforces must be used to counter the effects of time delays in the communications loop. As part of the integration process, software will be developed to provide pseudoforces.

Remote-Site Robot Controller

The Langley Research Center is currently developing an advanced remote-site robot controller. This controller hosted on a manipulator local processor will provide a significantly higher level of automation than is currently planned for the SPDM. The intent is to elevate the operator to higher levels of supervisory control. It is expected that this system will complement the JPL OCS described above. The transfer and integration of this controller to the ARMSS facility is currently being planned.

5. Future Activities

NASA is continuing to invest in advanced telerobotic research and development activities in support of space exploration. Many of the generic technologies developed as part of this telerobotics program have the potential, when properly implemented, to improve SS productivity. In addition to the technologies already discussed above, current development activities throughout the NASA telerobotic community are being reviewed for technology applicable to SS. Work on fault tolerant robotic architectures at the University of Texas and icon based task control at Stanford University are among the technologies expected to be evaluated for SS in the future.

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