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THE NASA/OAST TELEROBOT TESTBED ARCHITECTURE

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Through a phased development as a laboratory-based research testbed, the NASA/OAST Telerobot Testbed provides an environment for system test and demonstration of the technology which will usefully complement, significantly enhance, or even replace manned space activities. By integrating advanced sensing, robotic manipulation and intelligent control under human-interactive supervision, the Testbed will ultimately demonstrate execution of a variety of generic tasks suggestive of space assembly, maintenance, repair, and telescience. The Testbed system features a hierarchical layered control structure compatible with the incorporation of evolving technologies as they become available. The Testbed system is physically implemented in a computing architecture which allows for ease of integration of these technologies while preserving the flexibility for test of a variety of man-machine modes. This paper reports on the development currently in progress on the functional and implementation architectures of the NASA/OAST Testbed and capabilities planned for the coming years.

1.0 PERSPECTIVE

With the advent of a manned Space Station and renewed Shuttle missions and in response to rising world competition, Congress has mandated the National Aeronautics and Space Administration (NASA) to vigorously develop automation and robotics with the goal of improving productivity in space while lowering overall mission cost, reducing risk to manned space missions, and, in the longer term, transferring robotics technology to industry so as to strengthen its global economic position.

NASA has apportioned each of its centers a role in bringing this mandate to fruition. The Jet Propulsion Laboratory (JPL) has been designated by the Office of Aeronautics and Space Technology (NASA/OAST) to be the lead center for identifying and developing flight qualifiable robotics system technologies through the development of a Telerobot Testbed. Technologies developed at JPL will be transferred to Goddard's Space Flight Center for integration with their Space Station Flight Telerobotic Servicer (FTS) and Shuttle Development Test Flight (DTF-1, DTF-2) arms. This paper describes JPL's ongoing efforts to realize these goals.

1.1 THE NASA/OAST TELEROBOT TESTBED PROJECT - PROJECT OBJECTIVES

The NASA/OAST Telerobot Testbed (TRTB) project is implementing a Telerobot Testbed at JPL for the purpose of developing, integrating, and testing telerobot subsystems and demonstrating new telerobot technologies. As a goal, the Telerobot Testbed seeks to identify and implement system technologies envisioned to be cardinal to flight telerobot systems. Technology research and development is conducted in support of NASA's manned and unmanned space programs and is designed to sustain on-orbit servicing, assembly, inspection and maintenance tasks.

Under the current plan, the Testbed will be upgraded each year to meet technology objectives identified in Reference 1. With time the Testbed is expected to progress to greater levels of machine autonomy. Testbed demonstrations are expected to grow in complexity, duration and automation. Successive years will build upon capabilities of previous years and technologies developed in earlier years will be incorporated into the Testbed permanently.

Technologies currently envisioned for implementation into the Testbed include traded and shared control allowing for enhanced man/machine interaction, Teleoperation with short time delays, autonomous operation in uncertain and cluttered environments, system fault recovery, operation in a dynamic environment, and dexterous manipulation. Testbed deliverables include mature Testbed Interface Specification and Functional Requirements documents, a database of Telerobot system and subsystem performance, and a series of capability demonstrations which provide an indication of the Testbed technologies' maturity and their degree of readiness for transfer to space operations. The TRTB project also expects to deliver a hardware and software database for ground and flight prototype systems which identifies, for the first time, Telerobot system performance criteria, power requirements, computing, data storage and bandwidth requirements, software algorithms for control laws, fallback approaches to task execution, and margins for system growth.

Through the Testbed project, future flight programs will come to understand technical tradeoff issues, understand requirements for qualifying flight Telerobot systems, and benefit from standardized interfaces and modularized hardware and software developed in the Testbed. From its experience the Testbed may grow to become a national resource for validating new space telerobot technology and flight operations sequences.

2.0 THE '89 NASA/OAST TELEROBOT CONCEPTUAL ARCHITECTURE

Conceptually, the NASA/OAST Telerobot Testbed architecture follows a hierarchical design philosophy which places the human and machine intelligences towards the top of the control hierarchy and the primitive or mechanical telerobot functions towards the bottom (Figure 1). Five subsystems, not including the human operator, comprise the Telerobot Testbed system. In descending order on the hierarchy they are: the Operator Control Station (OCS), Task Planning & Reasoning (TPR), Run Time Control (RTC), Sensing and Perception (S&P), Manipulators and Control Mechanization (MCM). Although the Testbed subsystems are physically located in the same facility, an artificial division was introduced between the higher level subsystems (Operator,OCS,TPR) and the lower level subsystems (RTC,MCM,S&P) in anticipation of having to accommodate missions where Operator and manipulators are separated by time delay. Such delays occur whenever the Operator and the worksite are separated by signal propagation time.

The Telerobot (TR) manipulator arms are controlled through one of two possible paths. In teleoperated modes, the Operator commands the manipulators directly through Hand Controllers available to him at the OCS. In autonomous modes, the machine intelligence (TPR) manipulates the arms through RTC. With time the Testbed project expects to fuse the direct path between MCM and the Operator with the autonomous path so that teleoperations, including shared control, will pass down through TPR. For telerobot systems whose local and remote sites are collocated, TPR/RTC will look like a wire connecting MCM and the Operator. Whenever the local and remote sites are separated by distance, the TPR will perform the function of simulating the remote environment so that in effect the Operator teleoperates locally. Task execution at the remote site will occur one delay time later.

The Testbed architecture may also be thought of as being composed of three layers. At the lowest layer is its physical makeup which includes subsystem hardware and software. At the next layer are the operational modes which define the states subsystems take on, and at the top layer are the Telerobot's fundamental capabilities. Capabilities may be defined as a specific configuration of selected subsystem states arranged to focus on a common mission goal. Complex tasks are constructed from these capabilities. These three layers are discussed in greater detail next.

3.0 THE '89 TELEROBOT TESTBED SYSTEM IMPLEMENTATION

Figure 2 is a functional diagram of the Telerobot Testbed as it is currently implemented. Higher level functions are grouped in subsystems toward the top of the hierarchy and lower level functions are grouped in subsystems toward the bottom. The Telerobot architecture is also divided between lower level functions concentrated at the remote site (all subsystems to the right of the Ethernet) and higher level functions concentrated at the local site (all subsystems to the left of the Ethernet). The TRTB project expects to introduce in FY '90 a delay capability into the Testbed to investigate teleop control algorithms with propagation delays between the Operator and manipulators. Testbed subsystems communicate over a common Ethernet local area network. A Network Interface Package software hosted on subsystem VAX computers supports the functions of accepting and transmitting packets of formatted commands or data. A description of the six TRTB subsystems follows:

3.1 OPERATOR CONTROL STATION SUBSYSTEM

The Operator Control Station sits at the top of the Telerobot Hierarchy providing an efficient, user friendly physical interface between the Telerobot Testbed Operator and Test Conductor (TC) and Testbed subsystems. OCS is composed of two work stations, multiple video monitors switchable to different camera or video buffer sources, a stereo vision display, speakers, microphones, three keyboards, a mouse, function switches, two Force Reflecting Hand Controllers (FRHC), and support computers.

The OCS software provides a table-driven system for easy editing or updating of command definition and data. A terminal emulation capability allows the Operator to interface directly through the OCS console with all other Testbed subsystems. Over the Testbed's common Ethernet, OCS accepts and displays information to the Operator or TC from the subsystems, and relays Operator commands back to the subsystems. Through the two Hand Controllers, the Operator teleoperates the two Testbed manipulator arms. Force/torque sensors at the end-effectors backdrive the Hand Controllers, allowing the Operator to "sense" forces and torques induced at the end effectors. Both the Operator and TC have limited voice control command capabilities, including system on/off/halt, camera arm movement, and selected teleop commands. Two cross-strapped "Panic Buttons" interface directly to the manipulator arms providing the Operator and TC with an overriding emergency halt capability.

3.2 TASK PLANNING & REASONING SUBSYSTEM

The Task Planning & Reasoning subsystem sits at the top of the autonomous control hierarchy providing the Telerobot's machine intelligence. TPR performs functions of high level task and gross motion planning. The subsystem interacts with the Operator accepting task assignment, plan changes, plan concurrences, and direct action requests and translates them into processes for RTC execution.

The subsystem consists of a gross motion spatial planner, task planner, a kinematics simulator, and a coordinator to pass knowledge between these reasoning engines. The task planner generates over-all task plans and selects the actions to be performed as appropriate to the current state of objects in the workspace and recently experienced manipulation failures. The gross motion spatial planner generates collision free paths through the workspace for the manipulator arm and carried object. The kinematics simulator conceives possible manipulator arm configurations to reach objects, approach points, or other features of the workspace.

TPR maintains a database of objects (World Model) in the worksite, including their locations/orientations, connectivity, and semantic relationships. During Testbed operations the database is routinely updated from sensor information provided either by S&P and MCM through RTC, or by Operator designation of objects in the workspace. The World Model also incorporates a Collision Detection unit and a geometric reasoner which maintains rules and information trees on relationships between objects in the workspace, logically deduces which changes in the relationships are permissible, and assists the Operator in correcting or completing positional information about objects in the knowledge database.

3.3 RUN TIME CONTROL SUBSYSTEM

The Run Time Control subsystem, together with TPR, provides the Telerobot with the capability to function autonomously. RTC's role is to provide fine motion and grasp planning commands to MCM.

RTC consists of a subsystem System Executive supported by robotics, interface, communications, and infrastructure support modules. Briefly, upon receiving commands from TPR or the Operator/OCS, RTC reformats them into internal RTC data structures, selects a script to match the requested TPR process, selects a path for the arms, kinematically simulates the selected sequence, checking for collisions, pose flips and joint stops, generates local motion and coordination level commands for the manipulator arms and end-effectors, and passes executable macros on to MCM and S&P. During operations RTC monitors sequence execution, evaluating and modifying ongoing actions as needed.

RTC maintains and intermittently updates a database of workspace object locations/orientations based either on information gathered from S&P and MCM or the Operator through TPR. The database maintains accurate geometric and inertial models of the three Telerobot arms and immobile objects in the workspace. A Geometric Relationship Evaluator accomplishes frame transformations and maintains correct connectivity relationships among objects in the workspace.

3.4 SENSING AND PERCEPTION SUBSYSTEM

The Sensing and Perception Subsystem performs four system functions: 1) It provides the Operator on five OCS monitors with live or still, stereo and mono black and white video images of the workspace from nine Testbed cameras and four video frame buffers and provides MCM with object location/orientation state data. Five of the cameras also serve to provide S&P with stereo machine vision; 2) S&P tracks an object in the workspace as it moves about, supplying estimates of the position, orientation, velocity and angular velocity of the object to the other subsystems. S&P's Time Code Generator provides both S&P and MCM with the synchronization signal required to coordinate, for example, machine vision and spinning satellite grappling in real time; 3) When commanded by RTC, S&P performs fixture verification on a stationary object or part of a stationary object in the workspace, supplying machine generated estimates of its position and orientation to RTC and MCM; 4) From a database of objects in the workspace, S&P provides wire-frame models of the objects for display as graphic overlays on OCS monitors. These overlays support the Object Designate and Fixture Verification functions.

3.5 MANIPULATORS AND CONTROL MECHANIZATION SUBSYSTEM

The Manipulator and Control Mechanization subsystem sits at the bottom of the Telerobot hierarchy providing the Telerobot with manipulation capability and the mechanical interface to the workspace. The subsystem consists of two six degree-of-freedom robot arms, actuators, servoed end-effectors, force-torque sensors, universal controllers, the two Force Reflecting Hand Controllers at the Operator console with their attendant electronics, Universal Controllers, a SUN which hosts trajectory generation software, a MicroVax which hosts communications interface software, Macros to enable a variety of Telerobotic actions, and a variety of other support software. MCM also provides and controls a third six degree-of-freedom arm for positioning the stereo vision camera arm.

MCM receives commands from and transmits information back to the Operator through one of two control paths. In teleoperation mode MCM receives position/orientation commands directly from the Operator through the FRHC's and returns force/torque information from the end-effectors. In autonomous modes MCM receives position/orientation and force/torque commands over the Ethernet from RTC and, if in shared control mode, returns position/orientation and force/torque data back to the Hand Controllers. Position/orientation states of objects in the worksite come to MCM from S&P.

4.0 THE NASA/OAST TELEROBOT TESTBED '89 OPERATIONAL SYSTEM CAPABILITIES

In FY'89 five new technology capabilities will be introduced into the Testbed: teleoperation with force reflection, traded control, single and dual arm shared control, Operator designation, and self calibration. These capabilities will augment the Reactive Control and Verification capabilities currently available in the Testbed. These capabilities were conceived as being cardinal or so-called generic in nature allowing complex tasks to be constructed from elementary ones. Shared control permits the human and machine intelligences to work cooperatively while traded control allows them to work sequentially. These capabilities are described next.

4.1 FORCE REFLECTION IN TELEOPERATION

In Teleoperation, the Operator controls the TR's manipulator arms by providing the six position/orientations through the Hand Controllers to MCM. Manipulator path planning, collision avoidance, arm coordination, and object manipulation are performed by the Operator in real time. The force-reflection capability returns force/torque information back through MCM to the Hand Controllers from the robot wrist sensors allowing the Operator to "feel" the force/torques at the end-effector.

4.2 TRADED CONTROL

In the most general sense, traded control is a transfer of control between Operator teleoperation and Telerobot autonomous control anywhere and at any time during task execution. In the TRTB's '89 version of Traded Control the Operator performs all gross motion planning, maneuvering the end-effectors to a point in the proximity of an object and transfers control to the Telerobot for autonomous manipulation of the object. Upon completion of the task the Telerobot moves its end-effector to a point in the vicinity of the object and offers to transfer control back to the Operator. During autonomous execution the Operator may elect to transfer control and continue task execution in teleoperation. Also, the Operator may elect to transfer to autonomous control during fine teleoperation execution. At all times the Operator has overriding control and can elect to Halt a task. MCM's role during traded control is to provide a smooth transition from teleoperation to autonomous control and back to teleoperation as well as the continuous control of arm trajectories through singularities.

4.3 SINGLE AND DUAL ARM SHARED CONTROL

In the most general sense Shared Control allows for manipulator control to be shared jointly between the autonomous Telerobot and the Operator teleoperating force reflecting Hand Controllers. Both single and dual arm shared control have been implemented into the Testbed.

In single arm shared control the Operator selects to control one or more of six possible object positions/orientations through one hand controller and MCM controls the remaining positions/orientations, as well as the six force/torque compliances applied to the object by the end-effector. Force reflection from the end-effector is optional.

The dual arm shared control capability makes possible coordinated dual arm manipulation of rigid objects. The Operator selects to control through one Hand Controller one or more of six possible positions/orientations of an object and the Telerobot controls the remaining positions/orientations as well as all force/torque compliances applied to the object by both arms.

4.4 OPERATOR DESIGNATE

The Operator Designate capability provides wire-frame models (WFM) of objects in TPR's database to the Operator to manually overlay over still camera images of the objects in the workspace on the Operator's OCS console and read out the locations/orientations of the objects. The Operator thus locates objects in the workspace for TPR for subsequent manipulation. Designation can also be used to update the location/orientation of known objects in the workspace, define obstacle regions, and designate generic objects.

4.5 SELF CALIBRATION

Self Calibration is an autonomous capability similar to Verification which provides the Telerobot databases with improved knowledge of an object's location/orientation in the workspace. It improves on the systematic error limitation inherent in Verification by measuring the relative distance between two objects instead of the distance between the objects and the camera.

4.6 REACTIVE CONTROL

Reactive Mode is a capability which enables spinning satellite grapple. S&P provides a continuous updated state vector of the satellite to MCM. MCM then determines arm trajectories required to grapple the rotating satellite.

4.7 VERIFICATION

Verification is an autonomous capability which provides Testbed databases with refined knowledge of the Testbed objects' location/orientation in the workspace. It improves on the error limitation inherent in Operator Designation. A verification is executed only after a Designation.

5.0 THE 1989 NASA/OAST TELEROBOT TESTBED VALIDATION DEMONSTRATION

Telerobot Testbed demonstrations are a synthesis of telerobot technology capabilities, convoked elementary task sequences, and human participation which, when arranged intelligently, engender robust telerobot activity mimicking human activity. They are the deliverables against which the degree of success of attaining TRTB project objectives is measured and against which the worthiness of identified technologies for space applications can be evaluated. Successful demonstration outcomes are a prerequisite to the Testbed technology receiving acceptance for space-based operations on manned and unmanned missions. Technology transfer to a flight project happens once a demonstration proves the technology to be safe and reliable and telerobot risks and performance are well understood.

The task selected for the 1989 Telerobot Testbed technology validation demonstration is an Earth Orbiting System (EOS) Orbital Replacement Unit (ORU) changeout. This demonstration will validate the five new TRTB technologies. In an operation mimicking on-orbit satellite servicing, a tray-looking ORU subtended by a large instrument mockup is exchanged with a smaller instrument mounted on a nearby stowage rack. Two bolts attaching the ORU to the platform are unbolted and, in a dual arm cooperative action, the ORU is detached from the EOS platform and mounted on the rack. The smaller instrument mounted on the stow rack is then removed by a single arm, attached to the EOS platform, and then bolted. Figure 5 depicts the ORU with its accompanying instrument, the stow rack, and the smaller instrument on the rack. Table 1 is a step by step top-level description of the demonstration. The first column lists the EOS tasks while the second identifies the '89 technology capabilities validated. The third column is an attempt to look beyond the demonstration and to identify those capabilities which are generic to flight telerobots--that is, those capabilities which a mature flight telerobot system is envisioned to possess.

The Operator's role in the EOS validation demonstration will be to initiate each task step, select the control modes, designate fixtures in the workspace, and perform all gross arm motions. The Telerobot's role in the EOS validation demonstration will be to visually identify familiar objects in the workspace after a Designation, calibrate the relative positions of objects before a transfer to traded control, perform fine motion planning and arm/tool manipulation, and while in shared control, control selected position/orientations and all force/torques applied to object by the manipulator arm or arms.

6.0 MEASURING TELEROBOT TESTBED SYSTEM PERFORMANCE

The Telerobot Testbed performance will be measured at three levels and evaluated at a fourth. These levels are inclusive of all possible functions for the TRTB. More generally, these levels are valid for other robot architectures and are suggested as a framework from which to evaluate the adequacy of telerobot performance.

At the lowest level of system performance are level 1 subsystem stand-alone tests which validate the hardware and software designs of the telerobot subsystems. These tests seek to verify performance against design requirements, and typically consist of software execution checks, intramodule information transfer, hardware voltages, etc. At level 2, performance tests seek to verify performance against subsystem interface requirements and consist of inter-subsystem compatibility tests between the telerobot subsystems. Level 2 tests typically consist of transmitting and receiving commands correctly between subsystems, properly processing commands, switching among video displays, timing checks, etc. Tests at levels 1 and 2 when they are unsuccessful are typically typified by rework of hardware or software elements.

Ultimately, however, telerobot performance must be measured at the system level. It is here that the telerobot's technology capabilities are tested. Unlike a single purpose tool, thousands of tests can be performed to demonstrate telerobot capability performance. However, if chosen intelligently, a finite number of tests or technology validation demos are sufficient to prove technology capability robustness to perform demonstration tasks and in turn the telerobot's performance limits can be assessed. Of course telerobot work in space will undoubtedly be reduced to a finite number of tasks and those tasks will be specifically checked multiple times in multiple configurations in the Testbed before attempt is made on-orbit. Level 3 system performance, not yet wholly defined, is measured in such terms as tolerance to expected and unexpected changes in the environment, reliability, error recovery, tolerance to measurement errors, stability, and database consistency. When tests at level 3 are unsuccessful or degraded, they are typically corrected by design modification or capability modification/reconceptualization. Limits to performance are assessed through multiple demonstrations with multiple tasks.

At the highest level of test the Telerobot's generic capabilities are validated and its degree of readiness to perform specific space servicing operations is evaluated. No physical tests are made at this level. Rather performance observed during level 3 demonstrations serves to validate the TRTB's readiness to perform multiple space servicing operations. The criteria for evaluating system performance here is to match the Telerobot capabilities against those envisioned for flight missions, including backup operations, redundancy and fault protection in system/operations, delineate limits to the Telerobot's performance, understand its handicaps, and understand risks inherent in its design.

7.0 THE NBS NASREM CONCEPTUAL ARCHITECTURE

The National Bureau of Standards (NBS) has advanced a conceptual telerobot architecture known as the NBS Standard Reference Model as its candidate for space Telerobots. In its most general form NASREM (Figure 3, Reference 7) is partitioned into three hierarchies, each with six vertical levels plus the interface between the robot and the World. As with the NASA/OAST architecture, higher functions are placed towards the top and lower functions towards the bottom. Conceptually, the Operator can interact directly at any level. All modules have access to a Global memory, NASREM`s database. Modules within each hierarchy (vertical data flow) accept commands from higher level modules and transform them into instructions for lower level modules. Across hierarchies (horizontal data flow) modules interact through the World Model with modules in another hierarchy and at any level. The NASREM architecture accommodates growth by adding more levels at the top. For example, NASREM's Service Bay level accommodates one telerobot executing multiple tasks at different sites and the Service Mission level accommodates multiple telerobots operating at multiple jobs at multiple sites.

The TRTB project calls for developing and validating technology which ultimately will be integrated with GSFC's Space Station Flight Telerobotic Servicer (FTS) and Development Test Flight (DTF-1, DTF-2) arms. Since FTS has accepted a requirement to conform to the NASREM telerobot architecture, a mapping was established between the NASA/OAST Telerobot Testbed architecture and the NASREM architecture (see Figure 4, Ref. 6). Roughly, the NASA/OAST Telerobot functions described earlier are reproduced by the first four NASREM levels.

7.1 DIFFERENCES BETWEEN THE NASREM AND THE '89 NASA/OAST TELEROBOT ARCHITECTURES

Comparison of the NASREM and NASA/OAST architectures reveals subtle differences. However, the differences between the two architectures are deemed minor and do not preclude technology transfer from the NASA/OAST Telerobot Testbed to the NASREM FTS. A list of these differences follows:

1) NASA/OAST World Model vs NASREM Global Database

TPR, RTC, and MCM utilize separate, subsystem-specific but consistent data bases whereas NASREM uses one integrated data base. In the NASA/OAST design database, information flows directly and to some extent simultaneously between subsystems while in the NASREM architecture information must flow serially into and out of the Global Database. Thus TRTB subsystems need neither to interrupt other subsystems nor be time-coordinated when accessing database information. Dashed lines in Figure 3 depict data flow which is direct in the JPL Testbed but must pass through the GDB in the NASREM architecture.

2) Time Delay Between Local and Remote Sites

In future developments, the Telerobot Testbed expects to accommodate time delays between the local (Operator/TPR) and remote (RTC/MCM/S&P) subsystems whereas the NASREM architecture does not specifically address this issue. Tests in teleoperations show that deterioration in eye/arm coordination makes it impossible for a human to perform complex tasks with the Telerobot arms whenever the round trip time delay between the Operator and end-effectors is greater than two seconds. The NASA/OAST architecture expects to accommodate teleoperations under such conditions with a more robust TPR than is required without time delay and without a requirement for synchronization between the Operator and the remote manipulator arms. In this concept the Operator interacts with a TPR generated simulation of the manipulators and sensors, rather than with the actual Testbed manipulators. Forces on the end-effectors are predicted based on TPR/RTC's model of the world. The Operator's interactions with the simulation produce commands which are sent to the remote site for execution and the remote site asynchronously returns status messages.

3) Data Base Updates

The NASA/OAST Telerobot Testbed is concerned with paths and tasks in the vicinity of an object in the work-space while NASREM is concerned with activities in the whole workspace. Thus when updating the Testbed databases only subsystems with an interest in the ongoing activity are updated. The update is restricted to information about the local work space only and the Operator is required to be cognizant of activities in the rest of the workspace. In contrast, updating the NASREM Global Data Base requires an extensive run through the entire database, thereby introducing a potential delay in task execution.

4) Operation Modes

The NASA/OAST architecture follows the NASREM philosophy in that the Operator can interact with the telerobot at all levels in the hierarchy. However, NASA has implemented teleoperation, shared control, and traded control modes whereas NASREM is a yet undefined mix of teleoperation and autonomous control.

5) Kinematics

NASREM incorporates knowledge of robot kinematics at the E-move level and lower while the NASA/OAST architecture incorporates it at the TPR level and lower, thereby providing the TRTB with a more robust level-4 capable of increased task planning, task replanning, and path planning.

6) Dynamics

NASREM incorporates knowledge of robot dynamics at the primitive level and lower while the NASA/OAST architecture incorporates it at the RTC level and lower, thereby providing the TRTB with a more robust level-3 capable of increased local path planning and recovery.

8.0 SUMMARY AND CONCLUSIONS

NASA is embarking on a program dedicated to increasing productivity on-orbit while reducing mission costs and risk to astronauts. Its Jet Propulsion Laboratory has been designated as the lead center for identifying and developing flight robotics technologies. JPL is currently implementing a Telerobot Testbed project which seeks to 1) provide a testbed for robotics system integration and technology demonstrations, 2) provide a laboratory or prototype laboratory where flight operations can be evaluated, 3) transfer technology to NASA standard telerobotic arms used on Space Station and STS such as the GSFC FTS and DTF systems, 4) and, for the first time, identify system issues and performance criteria for flight telerobots.

This paper described the TRTB's system architecture (Figures 1, 2) as well as its five new capabilities. Criteria for testing telerobot system performance at the subsystem design level, at the integrated system level, and at the demonstration level, and evaluating its generic capabilities were discussed. The role of demonstrations in the Testbed and the demonstration chosen for the '89 Testbed were described.

Technology developed and tested in the TRTB will be transferred to GSFC's FTS and DTF arms as candidate technology for implementation. The teleoperated FTS and DTF arms have accepted requirements to conform to the NASREM architectures. Differences between the NASREM and NASA/OAST architectures were identified and for the first time a mapping (Figure 4) between two telerobot architectures was established.

9.0 ACKNOWLEDGEMENTS

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REFERENCES

1. JPL D-5692, Final Draft "Telerobotics Project Plan," Aug. 19, 1988 (JPL Internal Document).

2. JPL D-3693 Revision 3, "Functional Requirements Telerobotic Testbed Project," November, 1988 (JPL Internal Document).

3. "Interface Specifications for the 1988 Telerobotic Testbed," W.F. Zimmerman, November, 1988 (JPL Internal Document).

4. "Real-Time Hierarchically Distributed Processing Network Interaction Simulation," W.F. Zimmerman and C. Wu, Proceedings of the 21st Annual Simulation Symposium, pp. 207-226.

5. JPL Interoffice Memorandum 347-88-837, "Results of SUN Network Interface Protocol Performance Study" (JPL Internal Document), W.F. Zimmerman, September 1988.

6. JPL Interoffice Memorandum 343-88-319, Rev. A, "NASREM and the JPL Telerobotics Testbed" (JPL Internal Document), W.O. Keksz, May 26, 1988.

7. "NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)", J.S. Albus, H.G. McCain, R. Lumia, National Bureau of Standards Robot Systems Division, 12/4/86.

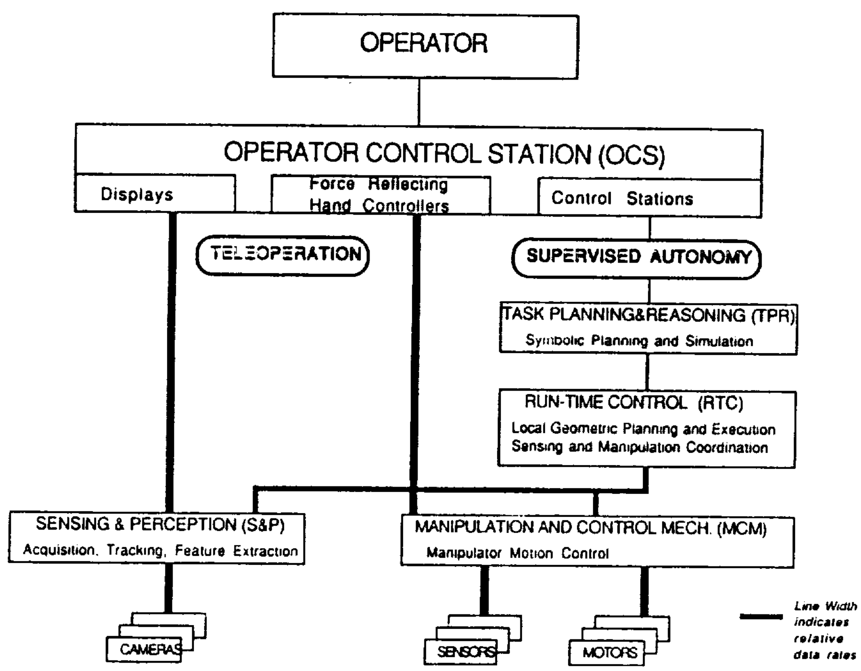

FIGURE 1: THE NASA/OAST TELEROBOT TESTBED ARCHITECTURE - '89 CONFIGURATION

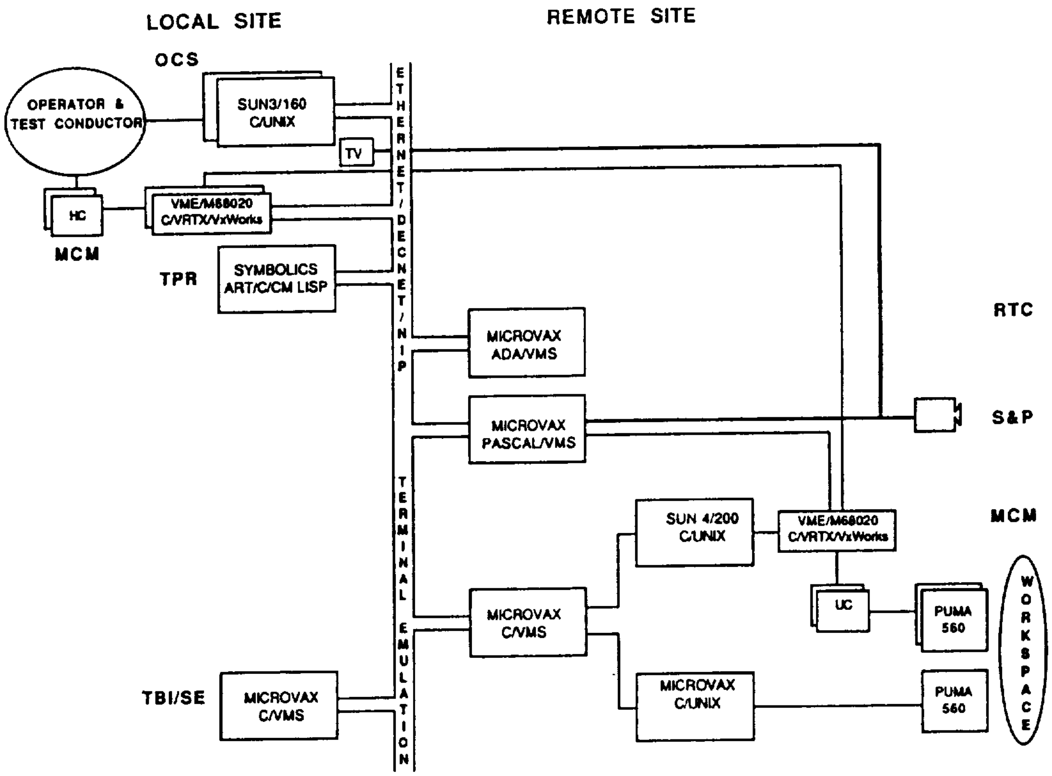

FIGURE 2: THE NASA/OAST TELEROBOT TESTBED IMPLEMENTATION ARCHITECTURE - '89 CONFIGURATION

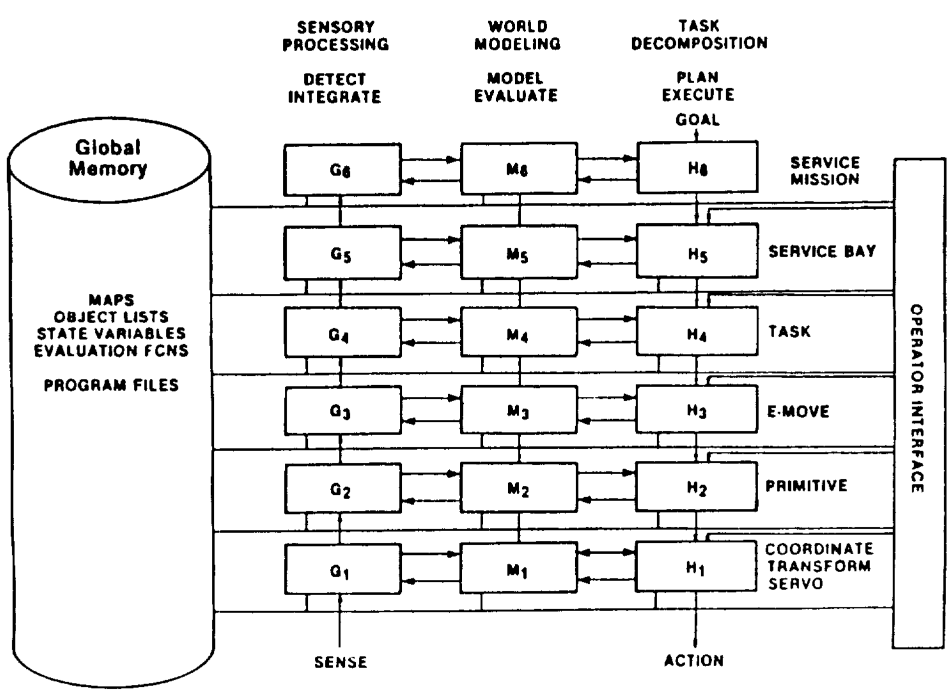

FIGURE 3: THE NBS NASREM STANDARD REFERENCE MODEL

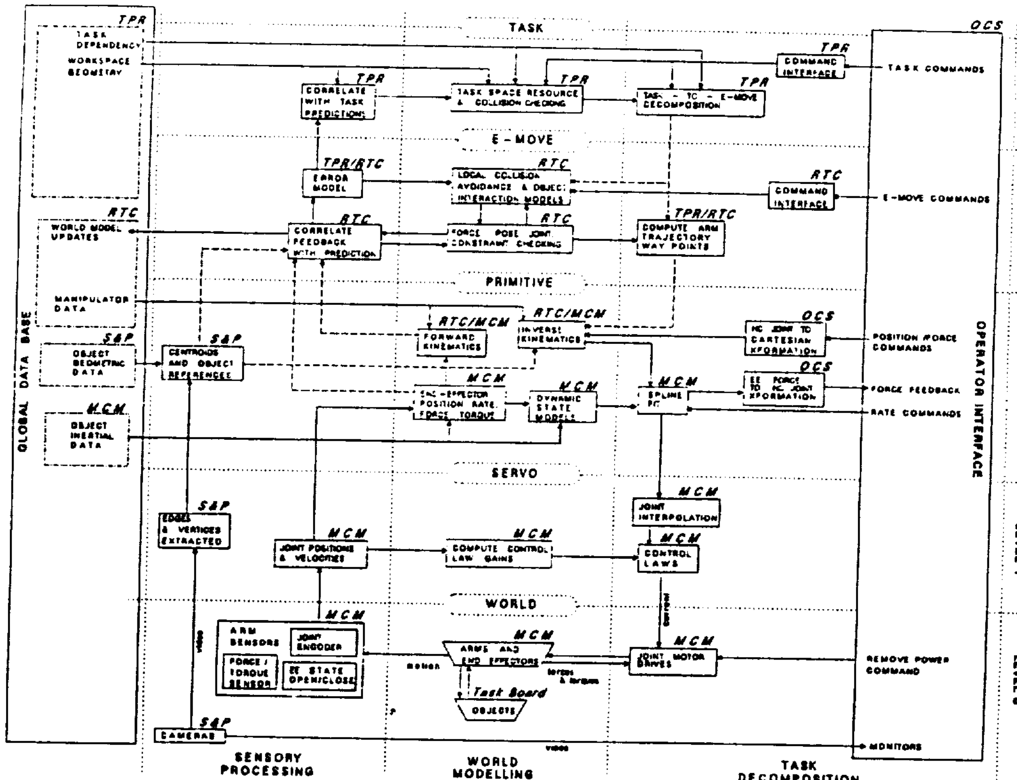

FIGURE 4: NASREM ARCHITECTURE OVERLAID ON THE NASA/OAST TELEROBOT ARCHITECTURE

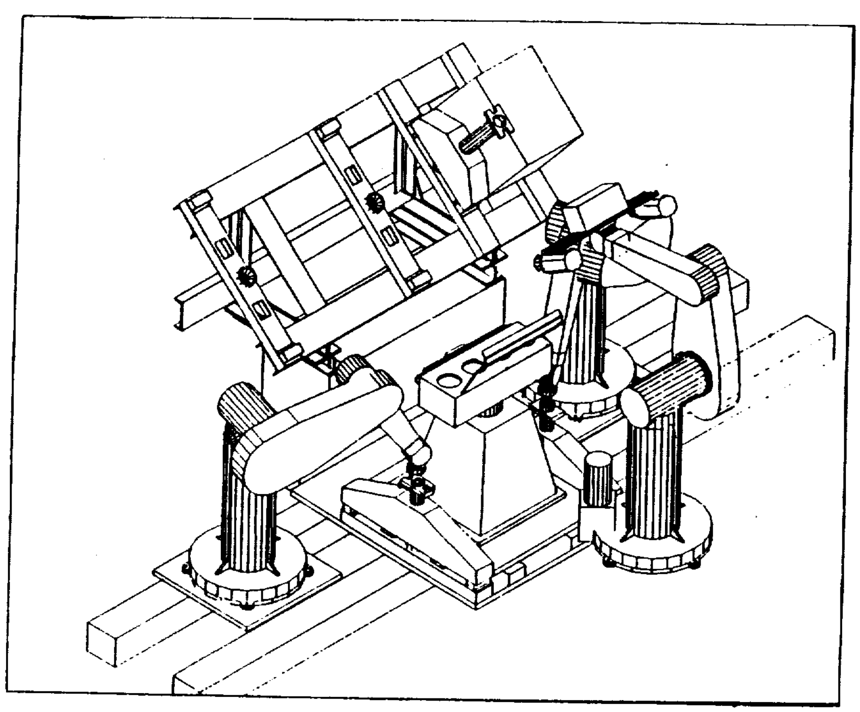

FIGURE 5 THE NASA/OAST TELEROBOT TESTBED EOS PLATFORM SERVICING - 1989 DEMONSTRATION

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TABLE 1: THE '89 TELEROBOT TESTBED VALIDATION DEMONSTRATION

EOS TASKS	'89 CAPABILITIES VALIDATED	GENERIC CAPABILITIES VALIDATED
1 - OPERATOR LOCATES ARMS, TOOLCRIB, STOWBIN, OBJECTS IN WORKSPACE	CAMERA VISION FOR OPERATOR	OPERATOR VISUALLY IDENTIFIES OBJECTS/FEATURES, LOCATIONS/ORIENTATIONS IN THE WORKSPACE
2 - IDENTIFY FOR TELEROBOT ARMS, TOOLCRIB, STOWBIN, TASKBOARD, BOLTS ON ORU/INSTR.	OCS DESIGNATE FUNCTION; DATABASES UPDATED	TELEROBOT VISUALLY IDENTIFIES OBJECTS/FEATURES, LOCATIONS/ORIENTATIONS IN THE WORKSPACE; COMMUNICATIONS BETWEEN TELEROBOTIC SUBSYSTEMS AND OPERATOR; UPDATES DATABASE
3 - MOVE ARM-1 TO VICINITY OF TOOLCRIB	TELEOPERATIONS (SINGLE ARM, GROSS ARM MOTIONS)	TELEOPERATION (SINGLE ARM, GROSS MOTIONS)
4 - GET WRENCH	TRADED CONTROL - TRANSITION FROM/TO TELEOPERATIONS TO/FROM AUTONOMOUS CONTROL	AUTONOMOUS FINE MOTION PATH PLANNING, ATTACHING TOOL TO END-EFFECTOR
5 - MOVE ARM-1 TO VICINITY OF ORU	SAME AS (3)	SAME AS (3)
6 - REMOVE BOLT-1 ATTACHING ORU TO EOS PLATFORM	TRADED CONTROL:SELF-CALIBRATION	AUTONOMOUS FINE MOTION PATH PLANNING, ENGAGE BOLT, TWIST BOLT OFF, UPDATE DATABASE
7 - MOVE ARM-1 TO VICINITY TOOLCRIB	SAME AS (3)	SAME AS (3)
8 - RETURN TOOL TO TOOLCRIB	TRADED CONTROL	AUTONOMOUS FINE MOTION PATH PLANNING, RELEASE TOOL TO TOOLCRIB
9 - REPEAT PROCEDURE WITH ARM-2	SAME AS (3) THROUGH (8)	CAPABILITY TO OPERATE TWO ARMS INDIVIDUALLY
10 - MOVE ARM-1 AND ARM-2 TO VICINITY ORU	TELEOPERATIONS (TWO ARMS, GROSS ARM MOTIONS)	TELEOPERATION (DUAL ARM, GROSS MOTION)
11 - GRASP HANDLE-1 ON ORU	TRADED CONTROL; SELF-CALIBRATION	AUTONOMOUS FINE MOTION PATH PLANNING, RETURN TO OPERATOR IF UNRESOLVABLE ERROR OCCURS, GRASP HANDLE WITH FORCE CONSTRAINT, UPDATE DATABASE.
12 - GRASP HANDLE-2 ON ORU	TRADED CONTROL; SELF-CALIBRATION	SAME AS (11)
13 -DETACH ORU FROM EOS PLATFORM	DUAL-ARM SHARED CONTROL - REMOVE OBJECT ATTACHED BY TWO PINS. OPERATOR PROVIDES POSITION/ORIENTATION OF OBJECT AND TELEROBOT AUTONOMOUSLY PROVIDES POSITIONS/ORIENTATIONS AND FORCE/TORQUE COMPLIANCE APPLIED TO ORU BY BOTH ARMS.	TELEROBOT REMOVES OBJECT ATTACHED BY TWO PINS WITH COORDINATED DUAL-ARM ACTION, MAINTAINING POSITION/ORIENTATION, FORCE/TORQUE CONTROL. OPERATOR PROVIDES PATH PLANNING AND SENSES FORCE/TORQUES.
14 - MOVE ORU TO STOW RACK	SAME AS (13) - MANIPULATE OBJECT	TELEROBOT MANIPULATES OBJECT WITH COORDINATED DUAL-ARM ACTION, MAINTAINING POSITION/ORIENTATION, FORCE/TORQUE CONTROL. OPERATOR PROVIDES PATH-PLANNING.
15 - ATTACH ORU TO STOW RACK	SAME AS (13) - TWO PIN INSERTION	TELEROBOT INSERTS OBJECT (TWO-PIN INSERTION) WITH COORDINATED DUAL-ARM ACTION, MAINTAINING POSITION/ORIENTATION, FORCE/TORQUE CONTROL. UPDATES DATABASE. OPERATOR PROVIDES PATH PLANNING AND SENSES FORCE/TORQUES.
16 - UNGRASP ORU HANDLES	TELEOPERATIONS (UNGRASP)	TELEOPERATION (UNGRASP COMMAND)
17 - MOVE ONE ARM TO VICINITY OF SMALL INSTRUMENT	SAME AS (3)	SAME AS (3)
18 - GRASP HANDLE ON SMALL INSTRUMENT	SAME AS (11)	SAME AS (11)
19 - DETACH SMALL INSTRUMENT FROM STOW RACK	SINGLE-ARM SHARED CONTROL - REMOVE OBJECT ATTACHED BY ONE PIN. OPERATOR PROVIDES POSITIONS/ORIENTATIONS FOR ARM AND TELEROBOT PROVIDES FORCE/TORQUE COMPLIANCE APPLIED TO INSTRUMENT. FORCE REFLECTION ENABLES OPERATOR TO FEEL FORCES AT END-EFFECTOR.	TELEROBOT REMOVES OBJECT (ONE PIN) WITH SINGLE-ARM ACTION MAINTAINING POSITION/ORIENTATION, FORCE/TORQUE CONTROL. OPERATOR PROVIDES PATH PLANNING AND SENSES FORCE/TORQUES INDUCED ON OBJECT.
20 - MOVE SMALL INSTRUMENT TO VICINITY OF EOS PLATFORM	SAME AS (19) - MANIPULATE OBJECT WITH FORCE FEEDBACK	SAME AS (3)
21 - ATTACH SMALL INSTRUMENT TO PLATFORM	SAME AS (19) - SINGLE PIN INSERTION	SAME AS (19) - SINGLE PIN INSERTION; SELF CALIBRATION
22 - MOVE ARM TO VICINITY OF TOOLCRIB	SAME AS (3)	SAME AS (3)
23 - GET WRENCH	SAME AS (4)	SAME AS (4)
24 - MOVE ARM TO VICINITY OF SMALL INSTRUMENT	SAME AS (3)	SAME AS (3)
25 - BOLT SMALL INSTRUMENT TO PLATFORM	TRADED CONTROL; SELF-CALIBRATION	AUTONOMOUS FINE MOTION PLANNING, ENGAGE BOLT, TWIST BOLT ON, UPDATE DATABASE.
26 - RETURN TOOL TO TOOLCRIB	SAME AS (8)	SAME AS (8)