THE JPL/KSC TELEROBOTIC INSPECTION DEMONSTRATION

David Mittman*, Bruce Bon, Carol Collins, Gerry Fleischer,
Todd Litwin, Jack Morrison, Jacquie O'Meara, Stephen Peters
Jet Propulsion Laboratory
California Institute of Technology, Pasadena, California

John Brogdon, Bob Humeniuk, Alex Ladd
Jose Lago, Mike Sklar, James Spencer, Dan Wegerif
Kennedy Space Center, Florida

ABSTRACT

An ASEA IRB90 robotic manipulator with attached inspection cameras was moved through a Space Shuttle Payload Assist Module (PAM) Cradle under computer control. The Operator and Operator Control Station, including graphics simulation, gross-motion spatial planning, and machine vision processing, were located at the Jet Propulsion Laboratory (JPL) in California. The Safety and Support personnel, PAM Cradle, IRB90, and image acquisition system, were stationed at the Kennedy Space Center (KSC) in Florida. Images captured at KSC were used both for processing by a machine vision system at JPL, and for inspection by the JPL Operator. The system found collision-free paths through the PAM Cradle, demonstrated accurate knowledge of the location of both objects of interest and obstacles, and operated with a communication delay of two seconds. Safe operation of the IRB90 near Shuttle flight hardware was obtained both through the use of a gross-motion spatial planner developed at JPL using artificial intelligence techniques, and infra-red beams and pressure

sensitive strips mounted to the critical surfaces of the flight hardware at KSC. The Demonstration showed that telerobotics is effective for real tasks, safe for personnel and hardware, and highly productive and reliable for Shuttle payload operations and Space Station external operations.

BACKGROUND*

Telerobotic systems are typically demonstrated with the operator in close proximity to the robot and with nearly instantaneous feedback to direct subsequent actions. However, many applications require ground-based control of remote space-based robots or local control over low-data-rate networks, each of which introduces a significant communication time delay that alters the nature of the operator interaction. Proposed solutions to the time delay problem, including remote site autonomy and a high-level operator interface, need to be tested in an environment where the delays are present.

Inspection tasks are typical of those that will be required of remote robots. One application of telerobotics is for Space Shuttle payload processing. To inspect Shuttle payloads, technicians walk

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above flight hardware to obtain access, and must rely on safety harnesses and expensive temporary scaffolding. A telerobotic system could significantly reduce the cost of payload inspection, and greatly improve the safety of the personnel, the payload, and the Shuttle.

While communication time delay can be avoided in an operational Shuttle "payload inspection robot," autonomous operation and high-level control would improve the cost-effectiveness and safety of the system. By building and demonstrating a prototype that can be controlled either locally or from a remote site, progress in both Shuttle operations and space tele-robotics can be achieved.

SPACE FLIGHT PROBLEM DOMAIN

Space Shuttle Payload Operations*

At KSC, access to payloads during pre-launch payload operations is very restricted. At the Operation and Checkout Building, where horizontal payloads are integrated into the payload bay, work-stands are sometimes built to lower technicians down between satellites to retrieve, replace or connect an object. After the integration of the horizontal payloads, the Shuttle is mated to its solid rocket boosters and external tank, and rolled out to the launch pad. Payloads which have to be integrated into the payload bay in a vertical configuration are first inserted into a canister at the Vertical Processing Facility, and are then shipped to the launch pad for integration. When the canister arrives at the launch pad, it is lifted into the Payload

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* For a thorough discussion of Space Shuttle Payload Operations see Kennedy Space Center [KSC], 1978.

Changeout Room (PCR). The PCR is a clean-room integrated into the Rotating Service Structure (RSS); the RSS is rotated against the Shuttle during pre-launch servicing activities.

The payload is first removed from the cannister and brought inside the PCR by the Payload Ground Handling Mechanism (PGHM). The PGHM is a very large device on an overhead beam that removes the payload from the cannister and inserts it into the payload bay. The RSS is then rotated into place in front of the payload bay, and the payload is moved into place.

When the payload has been inserted into the payload bay, it is not visible beyond the PGHM. Limited access to the payload is possible by crawling out onto platforms. "C" clamps, gangplanks and roll-out platforms are used to gain access inside the payload bay. It is sometimes necessary for a technician to climb out onto a gangplank in order to take close-up photographs or to remove lens dust-covers. A technician also has to remove tagged items just prior to launch. Twice for each launch, at the start of PCR operations and at their conclusion, technicians have to reach hazardous positions 65 feet above multi-million dollar payloads to attach grounding straps. This involves bolts and test gear which, if dropped, may cause extensive and costly damage to a payload, requiring removal and repair of the payload, with large "return from pad" consequences.

SPACE FLIGHT OBJECTIVES

One of the objectives of the JPL/KSC Inspection Demonstration was to aid Space Flight operations by demonstrating effective man/machine teamwork on a task that has applications to operational Shuttle

payload processing. To this end, it was necessary to demonstrate that a telerobotic system can: (a) operate in the complex environment of a Shuttle payload bay or PCR; (b) operate without significant risk to personnel, equipment or payload, reducing both the need for risky gangplank operations, and the chance of errors; (c) improve the productivity of payload operations, easing access to hard-to-reach areas; and (d) improve the reliability of payload operations.

SPACE STATION PROBLEM DOMAINS

Space Station operations for construction and maintenance require extensive access to the external portions of the Space Station. A variety of technologies exist which meet the need for external access, including Extravehicular activity (EVA), Flight Telerobotic Servicer (FTS) teleoperation, and ground-remote telerobotics, each with some advantages and disadvantages.

Extravehicular Activity

The use of EVA involves astronauts in space-suits performing assembly and servicing tasks outside of the Space Station.

Advantages.

One advantage of EVA for on-orbit construction and maintenance of the Space Station is that the astronauts at the work-site can better perceive problems and their solutions.

Disadvantages.

1. There are many risks to the astronaut performing EVA, including the possibility of death during Space Station construction and operations.

2. Astronaut productivity is lower due to the difficulty of performing dexterous operations in a bulky space suit which limits touch and vision.

3. There are large amounts of expensive astronaut on-orbit time required for EVA tasks, e.g. the required three hour pre-breathing period before exiting the vehicle.

4. Limited dexterity increases the possibility of mistakes and reduces reliability and safety.

FTS Teleoperation

The FTS allows astronauts inside the Space Station to perform teleoperation since teleoperation from Earth is not practical due to the communication delay.

Advantages.

The teleoperation of the FTS within the shirt-sleeve environment of the Space Station eliminates the risk to the astronaut due to EVA.

Disadvantages.

1. The limitations of tele-operation contribute to low astronaut productivity, although there is a significant potential for improvement though telepresence.

2. The teleoperation of the FTS, like EVA, requires large amounts of expensive astronaut on-orbit time.

3. The limited dexterity available with teleoperation, and the potential mistakes, reduce reliability and safety.

Ground/Remote Telerobotics

The use of ground/remote tele-robotics allows operators at a ground-based control station to

operate semi-autonomous telerobot(s) at the Space Station.

Advantages.

1. Eliminates the risk due to EVA.

2. Enhances productivity by allowing telerobotic operations to proceed continuously as long as there is work to be done, with no work stoppages for crew sleep or delays for pre-breathing. Partial autonomy allows one operator to control two or more telerobots.

3. Minimizes astronaut on-orbit time required for external servicing tasks; all robotic control is performed by ground technicians.

4. Enhances reliability since a telerobot can do repetitive assembly tasks automatically without boredom or distraction.

Disadvantages.

The operator's remoteness from the work-site limits the ability to perceive the work-site, thus making problem-solving more difficult and forcing increased reliance on machine autonomy.

Actual Space Station operations will, most likely, include some mixture of EVA, FTS tele-operation, and ground/remote tele-robotics, depending on requirements and available capabilities.

SPACE STATION OBJECTIVES

The task of the JPL/KSC Tele-robotic Demonstration was to aid Space Station operations by demonstrating effective remote task execution with a limited band-width, uncertain time delay between the operator control station and the work-site, thus overcoming the tele-operation time-delay problem. To this end, it was necessary to demonstrate that a telerobotic system can: (a) operate when the sensor and actuator systems are remote from the operator control station, when the communication band-width is limited, and when there is a variable communication delay of several seconds; (b) operate in a realistically complex flight hardware environment; (c) operate without significant risk to personnel, equipment, or payload, reducing both the need for EVA, and the probability of errors; (d) improve the productivity of operations in space by reducing the need for EVA thus freeing valuable astronaut time for other activities, by operating from the ground thus utilizing far less expensive ground-based personnel, and by allowing more time (even continuous) on-station; and (e) improve the reliability of space operations by reducing mistakes which might be made during EVA due to boredom and fatigue.

THE JPL/KSC TELEROBOTIC INSPECTION SYSTEM

The Robotics Applications Development Laboratory (RADL) at KSC includes a large ASEA IRB90 robotic manipulator on a track and various support computers for controlling the IRB90 and processing video data for machine vision applications. The ASEA IRB90 is an industrial materials-handling robot with a payload capacity of approximately 200 pounds, and a height of approximately nine feet. The IRB90 has been outfitted with a dual-camera platform. The work-site includes an inert PAM and support cradle in a ground support equipment (GSE) frame. The PAM, Cradle, and GSE frame were all obtained from the manufacturer; the Cradle had flown on a previous Shuttle mission, and was to be maintained in a flight-ready condition.

The Task Planning and Reasoning (TPR) and Sensing and Perception (S&P) subsystems were located at JPL, while the Arm Device Control (ADC) and Video Device Control (VDC) subsystems were at KSC (see Figure 1). TPR (Peters, Collins, Mittman, O'Meara, and Rokey, in press) was implemented in LISP on a Symbolics LISP machine, and used a VAX 11/750 as a network communications gateway. S&P (Gennery, Litwin, Wilcox, and Bon, 1987) was implemented in Pascal on a VAX 11/750 with 240 by 320 pixel frame buffers. ADC and VDC were implemented on a MicroVAX, with serial communications to the VME-based processors which contained the direct hardware interfaces to the IRB90 and the video cameras.

Communication between sub-systems took place over DECnet using an application layer called the Network Interface Package (NIP). The work-site, with IRB90, controller, video cameras and frame buffers, was located at KSC in Florida. The operator site, with computer and software providing a graphics operator interface, gross-motion spatial planning and machine vision, was located at JPL in California. Communication between the two sites was over a 9600 baud serial link on a shared network (PSCN), resulting in variable and unpredictable communication delays which average two seconds per round-trip transaction.

The intelligent technology used in the JPL software was primarily transferred from JPL's Telerobot Testbed project. This includes the Network Interface Package (NIP) used for all inter-subsystem communications, the graphical user interface (Mittman, 1988) and gross-motion spatial planner (Collins & Rokey, 1988) used by the TPR subsystem, and the machine vision system used by the

S&P subsystem. All software except the NIP required modifications and new interfaces for this task.

Work-space models for spatial planning, machine vision, and the user interface were derived from a CAD database supplied by KSC. Off-line software utilities at JPL provided transforms to move all models into the same coordinate system and allow calibration of the cameras which supply the images for machine vision. The control station (TPR) commanded S&P to perform its vision functions and also commanded the ADC to carry out the desired robot motions. The S&P subsystem at JPL commanded stereo images to be transmitted from the VDC subsystem at KSC. Using KSC-supplied descriptions of camera viewpoint locations, the S&P subsystem verified the spatial object database required by the high-level spatial planner, thus ensuring the safety of IRB90 motions.

New work performed for this task included implementation of the ADC and VDC subsystems at KSC, generation of IGES models for objects in the work-space, measurement of work-space points to enable calibration, transformation of IGES model data into the IRB90 coordinate frame, conversion of IGES models into the forms needed by the JPL software, generation of free-space maps for use in gross-motion spatial planning, calibration of video camera models for use with machine vision, and implementation of video processing software, including image sub-sampling, compression/decompression, and low-level feature extraction.

SUMMARY OF FIRST-YEAR RESULTS

Hardware and communications were installed, integrated, and tested. The PAM Cradle and inert PAM were acquired and IGES models were

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Operator

Task Planning and Reasoning

Arm Device Control

KSC

JPL

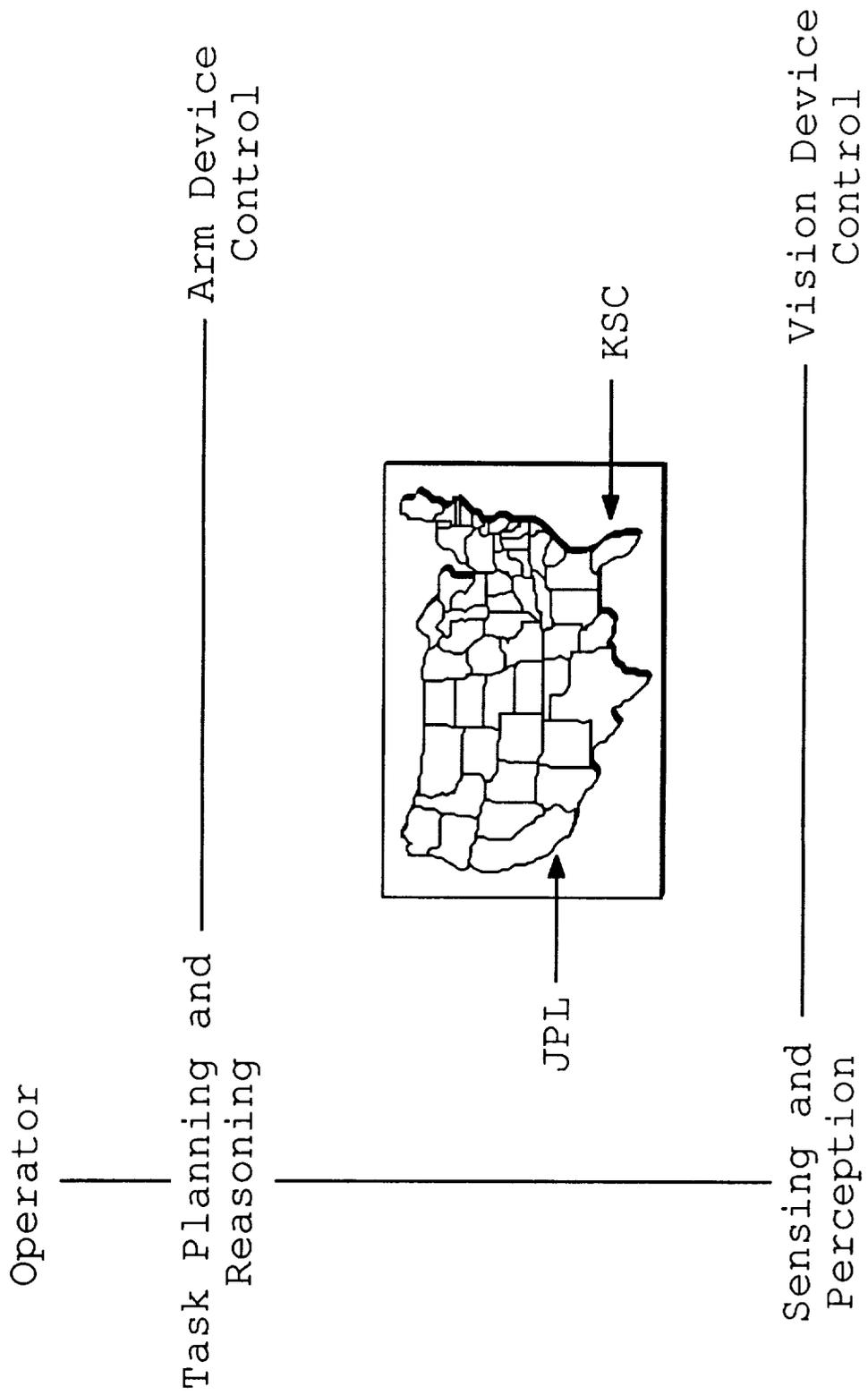Sensing and Perception

Vision Device Control

Figure 1: Logical Block Diagram

created. Device control software was developed at KSC, including communications with JPL software. JPL Sensing & Perception (S&P) subsystem was modified for the needs of this task. The JPL Task Planning and Reasoning (TPR) subsystem was modified and extended for this task, providing gross-motion spatial planning, a direct interface to KSC for IRB90 control and a graphical user interface. A successful capability test was performed, including: (a) control of a robotic manipulator from a distance of 3000 miles with variable time delays averaging two seconds, (b) motion into an occluded, covered region in a very constricted work-space, (c) use of a gross-motion spatial planner to avoid collisions, (d) use of machine vision to verify location of modeled objects, and (e) operation on real flight hardware.

DIFFICULTIES OVERCOME

As might be expected in the first year of a task, numerous difficulties and delays arose. PSCN mistakenly installed a synchronous line instead of an asynchronous line, and the Symbolics NIP version proved to be unusable due to compiler incompatibilities with a new operating system. A VAX NIP server with a custom interface between the VAX and Symbolics machines was created.

The IRB90 controller was of limited use because the proprietary nature of the information contained within the controller made it impossible to obtain accurate IRB90 kinematic parameters. An IRB90 kinematic model was constructed from the IRB90 printed documentation.

The IRB90 controller interface did not accommodate joint controlled motion, the mode used by JPL's gross-motion spatial planner. Motions were planned in joint space,

then passed through the forward kinematics of the IRB90 model to derive Cartesian end-effector positions for commanding.

Software was implemented to convert IGES model data and transform it into the IRB90 coordinate frame. Limitations in the CAD system from which the IGES data originated required that conversion software be written with operator interaction to aid in designating IGES object connectivity. Additional software was implemented to compute a homogeneous transformation between IGES model and IRB90 coordinate systems when given a set of points measured in both frames.

Camera calibration within the S&P subsystem was conducted with a poor dispersion of calibration points. The iterative fit of the camera model to the measured data did not converge. Existing software was modified to allow for the manual editing of the initial camera model estimates. Editing was accomplished with a graphic display showing the measured calibration points and calibration images. The elimination of outlying calibration points and the selection of a good initial estimate allowed the camera models to converge.

POSSIBLE IMPACTS ON SPACE FLIGHT AND SPACE STATION

Modifications in Requirements

In order to provide for the increased activity of ground/remote telerobotic operations, modifications will need to be made which provide the appropriate level of communication with Earth. Modifications of the FTS for proximity sensors, increased video coverage, and required local processing should also be made, e.g. for reflex actions. An Operator Control Station and processing

facilities on Earth would also be required as part of the Space Station design. To make the operations more amenable to robotic manipulation, tools and jigs should be designed.

Benefits

The benefits of ground/remote telerobotics for the space station include a 24 hour/day work cycle for Space Station assembly with alternating ground personnel controlling the assembly robots, and improved astronaut safety through reduced EVA. Reliability is also improved by eliminating repetitive, menial, and tiring tasks from the operator's work-load.

FUTURE PLANS

There are many plans for future work, as time and budget allow. The following are a sample of the items which will be incorporated into the present system at a future time.

Kennedy Space Center

1. Development of requirements and design proximity sensors for the IRB90.

2. Design, build and integrate a two degree-of-freedom articulated "boom" extension to the IRB90.

3. Design, build and integrate a video camera system for the extended IRB90.

4. Develop an accurate kinematic model of the extended IRB90.

5. Install the TPR subsystem software on a artificial intelligence workstation located at KSC.

Jet Propulsion Laboratory

1. Expansion of the IGES world model to allow for more flexible operations, and more viewpoints. This requires the addition of a fine-motion spatial planner.

2. Improvement of the operator interface and overall system speed.

3. Addition of fine-motion spatial planning to enable the IRB90 to move to arbitrary positions.

4. Development of models for a modified IRB90 and a new camera system.

5. Transition of the machine vision system to a next-generation VME-based hardware platform.

FUTURE CHALLENGES

The JPL/KSC team faces some future challenges which can be met by a well-designed research effort.

Proximity Sensing

The design of the proximity sensors should aid in increasing safety, while the information from the sensors should be utilized for spatial planning.

Spatial Planning

1. Improvement of gross-motion spatial planning by speeding the graph generation.

2. Integration of fine-motion with gross-motion spatial planning.

3. Development of spatial planning for an incompletely or erroneously modeled environment.

4. Integration of spatial planning tools with operator interface to resolve spatial

problems and to make the spatial planning faster and more reliable.

Perception

1. Localization of objects when a *priori* location is unknown.

2. Characterization of known objects.

3. Effective modeling of a complex environment.

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