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An Intelligent, Free-flying Robot

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ABSTRACT

The ground-based demonstration of EVA Retriever, a voice-supervised, intelligent, free-flying robot, is designed to evaluate the capability to retrieve objects (astronauts, equipment, and tools) which have accidentally separated from the Space Station. The major objective of the EVA Retriever Project is to design, develop, and evaluate an integrated robotic hardware and on-board software system which autonomously: (1) performs system activation and check-out, (2) searches for and acquires the target, (3) plans and executes a rendezvous while continuously tracking the target, (4) avoids stationary and moving obstacles, (5) reaches for and grapples the target, (6) returns to transfer the object, and (7) returns to base.

1. INTRODUCTION

Space Station Freedom advanced automation and robotics has been the subject of numerous symposia and papers [1,2]. Appropriate roles for humans and machines in an evolving mix have been highlighted as a specific goal, with supervised intelligent system designs as ways to meet the needs of appropriate flexible-capability automation and robotics, thereby giving people-amplifier-type productivity gains. These roles are extremely important. New role definitions are enabled by symbolic processing and machine intelligence approaches to software, which also gives an ability to earn human trust while evolving in demonstrated reliable and capable operation.

The concept of supervised, intelligent, autonomous robotics provides for autonomous behavior of an intelligent type where human control is normally at a high level of goal-setting and involved in mixed initiative communication as a means of implementing decentralized, delegated management. By contrast, telerobotics provides a partially automated remote extension of human task performance with occasional control delegation for specific parts of tasks given to the telerobot for efficiency reasons. Teleoperation and telepresence provide remote extension of human task performance with the human essentially always in the loop.

This paper presents the need for extravehicular activity retrieval of objects and a potential solution in the form of a supervised, intelligent, free-flying space robot. An overview of a 3-year, 3-phase ground demonstration project is given , as are the eventual characteristics of the EVA Retriever. A description of the Phase I robot is given and Phase I results from an air-bearing floor demonstration are discussed. The Phase II software design is presented, including systems engineering studies of requirements, sensor-controlled motion based on real-time updating of a dynamic world model, and elements of the sensing, perception, reasoning and planning, action, and performance measurement.

2. THE NEED

Due to the extensive extravehicular activity (EVA) operations required by Space Station, there is a finite separation probability for astronauts, even when normally tethered, and for equipment and tools. A glove and camera have been separated and not retrieved in space operations previous to Space Shuttle, a tethered torque-wrench was accidentally separated on STS 51A, and other small item losses and near-misses have occurred.

The Space Station cannot chase separated crew or equipment even though crew safety is top priority. Other vehicles such as the Space Shuttle orbiter or orbital maneuvering vehicle will not usually be available. Many hours of real-time simulation of manned maneuvering unit (MMU) retrievals indicated short response time was critical and major risk to a second astronaut was involved, which was not acceptable. Equipment may be too valuable to lose because it is required in operations and replacement is not available on the station. There is also collision potential on later orbits which, though small, has occurred previously. The Space Station Program is considering making this retrieval a requirement.

3. POTENTIAL SOLUTION

A mobile (free-flying) space robot offers a potential solution. This might be teleoperated, but the quicker response and greater productivity of a supervised, intelligent, autonomous robot was judged to be the best solution if it could be made available in practical terms. However, significant technology advances will be necessary before even this simple, crucial application can be practically addressed. These advances will only be gained by implementing autonomous robot simulations and testbeds so as to gain experience with the developing technology.

Several previous efforts have laid a foundation for autonomous robot development including Shakey [3], JASON [4], the RPI Rover [5], the JPL Rover [6], and the Stanford Cart [7], among others. These first-generation autonomous robots were used to explore basic issues in vision, planning, and control. However, they were all seriously hampered by primitive sensing and computing hardware. More recent efforts have overcome many of these limitations, and very sophisticated second generation autonomous robot testbeds have evolved. Some of these efforts include the developments of HILARE [8], the FMC Autonomous Vehicle [9], the Autonomous Land Vehicle (ALV) [10], the various CMU mobile robots [7], and the Ground Surveillance Robot (GSR) [11]. A more general and complete discussion of autonomous vehicle history and technical issues has been given by Harmon [12]. While operational versions don't exist, much advantage can be obtained from these efforts.

By comparison, the space retrieval task seems simpler in some respects. While automatic control, such as is available in automatic guided vehicles (AGV), remotely piloted vehicles (RPV), and missiles, is not adequate here due to the dynamic environment, the more general solutions to vision and planning in completely unknown environments are not required. There are few objects in space; these are cooperative, and largely knowable. Supervision by voice is a natural, flexible means of providing the primary human-machine interface (supplemented with helmet displays) required. This requires limited natural language understanding integrated with the environment and task as well as functions like planning and reasoning. Complete intelligent autonomy of the R2D2/C3P0-type is not required nor achievable.

The free-flying space robot would operate near a spacecraft such as the Space Station in a primarily voice-supervised, autonomous mode for mobility and manipulation. It is intended to be an evolutionary system improving in capability over time and as it earns crew trust through reliable operation. It will operate in a dynamic much less well-structured environment than current industrial robots. Most planned actions cannot be tested except at execution. There is little repetition in its actions in the short term. Its sensing and perception provides real-time updates to a dynamic "world" model which is the basis of plans and actions. Knowledge by the EVA Retriever of its own past experience is intended through an episodic memory and retrospective processes such as summarization. Self-awareness is provided through sensing of internal states such as manipulator joints and health from fault detection and diagnosis with impact on planning. An intelligent human-machine interface with speech recognition, limited natural language understanding based on "state-change semantics" and voice synthesis is intended. EVA Retriever and crew will often cooperate in the same work envelopes. Safety, reliability, robustness, and maintainability in space are key attributes.

4. GROUND DEMONSTRATIONS

The EVA Retriever technology demonstration was established to design, develop, and demonstrate an integrated robotic hardware/software system which supports development of a space borne crew rescue and equipment retrieval capability through a phased set of ground-based simulations and physical demonstrations and evaluations. A Space Shuttle flight experiment would be a needed and plausible following step, preceding any space operations-related efforts.

Goals for each phase of a three phase project were established [13] in support of the overall goal of building and evaluating the capability to retrieve objects (astronauts, equipment, and tools) which have accidentally separated from their spacecraft. The Phase I goals were to design, build, and test a retriever system testbed by demonstrating supervised retrieval of a fixed target. Phase II goals are to initiate simulations and to enhance the testbed subsystems with significant intelligent capability by demonstrating target retrieval with avoiding of fixed obstacles. Phase III goals are to more fully achieve supervised, intelligent, autonomous behavior by demonstrating retrieval of a moving target while avoiding moving obstacles.

5. PHASE I DESCRIPTION

Phase I consisted primarily of an integration of the hardware and software into a functional system and subsequent demonstration of certain features of the intended behavior in simple form on the JSC Precision Air Bearing Floor (PABF), namely, supervised retrieval of a fixed target.

The integrated testbed free-flyer (Fig. 1) is an anthropomorphic manipulator unit with dexterous arms and hands built from a modified qualification test unit of the manned maneuvering unit (MMU) for mobility, Remote Technology Corporation dual 6-degree-of-freedom manipulators, a 3-fingered hand developed by the JSC Crew and Thermal Systems Division (CTSD), Inmos transputer 10-MIP processors, a Votan speech recognition and voice synthesis system, a 3-D laser imager from Odetics, a video camera and tracker processor by McDonnell Douglas, a robot body built at JSC, an arm and hand open-loop electronic control system, and software built by two JSC divisions. The vision sensors have 60 by 60 degree fields of vision.

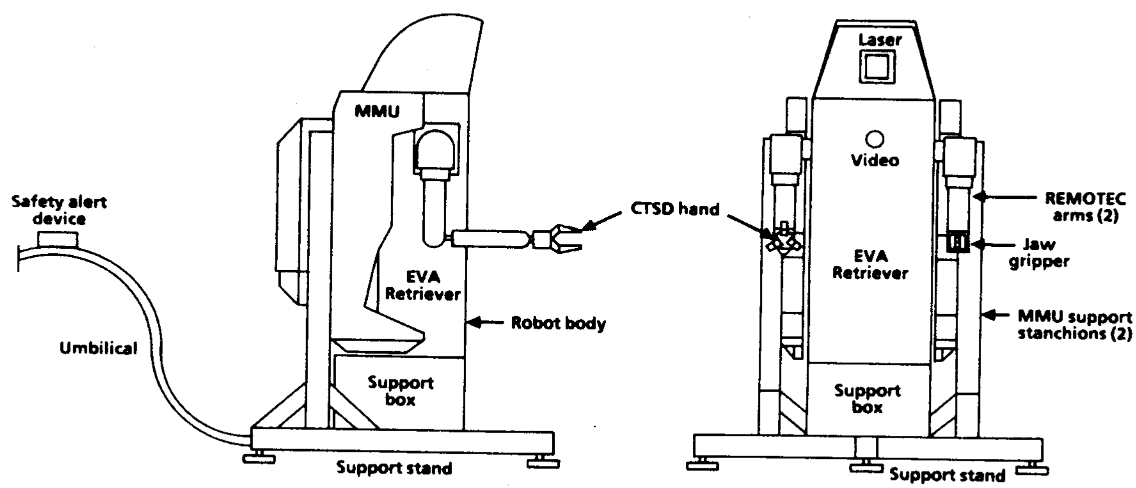

Figure 1. Retriever test article.

Onboard software includes: (1) supervisory activation and monitoring, (2) simple predefined plans for rendezvous, station keeping, and grappling, (3) plan sequencing and execution with sensory feedback in a benign, initially unknown environment, (4) sequential robotic movements of the MMU, arms, and hands, (5) supervisory interruption, direct control, and resumption of autonomous sequences, and (6) sensor fusion for rendezvous tasks.

Primary communication and control of the EVA Retriever is performed by voice commands. The testbed voice commands are: (1) activate and quick activate, (2) search (parameter: astronaut, tool, home, generic), (3) rendezvous, (4) reach, (5) grapple, (6) wait, (7) manual, and (8) shutdown. The EVA Retriever provides pre-recorded voice responses based on its sensory data and status. The response options to the voice commands are: (1) activating, and ready to search, (2) searching for target, target not found, tracking target, and ready to rendezvous, (3) rendezvous, or rendezvous failure, (4) closing hand, (5) wait acknowledged, and waiting, (6) manual mode, and (7) fail-safing in progress, and shutdown complete. A standard personal computer provides command, data, and video displays for backup/additional control and status monitoring.

In addition to successfully integrating the hardware and software, as verified by collecting a number of test point-data sets, two retrieval scenarios were successfully demonstrated [14] on the PABF. The first scenario was for the EVA Retriever to search for and retrieve a tool and return to the home base. Tasks of this scenario included: activation, search for the tool, rendezvous with the tool, reach for the tool, grapple the tool, search for home base, and rendezvous with the home base. In the second scenario, the EVA Retriever initially was directed to search for an astronaut, then was redirected to search for and retrieve the tool and return to home base.

6. PHASE II SOFTWARE DESIGN

A number of systems engineering studies were conducted in support of the Phase II software design. Level A requirements for a projected Space Station version were developed in a conceptual design study [15]. Level B software requirements were derived in greater detail for this possible future Space Station application [16]. Space Station scenarios [17] were also described to aid in definition of dynamic situations needing reactive planning, and which will also be useful in defining a set of design reference missions. Phase II Level B software requirements were developed [18] as were Phase II PABF scenarios.

Various functions representing reasoning are introduced for the first time in Phase II software. Planning and replanning is based on: (1) simple reasoning about multiple conflicting goals whose priority is context dependent, (2) sensor-based knowledge of the environment, and (3) constraints such as flight rules or resource availability. Path planning to targets while avoiding obstacles is based on visual perception updating of the dynamic world model and reasoning about potential degraded capability. Grapple/grasp planning is based on visual perception updating for coordinated MMU, arm, and hand motions. Reasoning about data quality is provided. A mission control and assessment module provides decision making capability.

The choice of software architecture was based on experience with the Brooks layered subsumption architecture [19], reported experience with strict hierarchical and blackboard approaches, reported success of the DARPA ALV approach, and a desire to be compatible with the NASREM architecture [20].

The EVA Retriever software architecture incorporates a hierarchical decomposition of the control system that is horizontally partitioned into six major functional subsystems: sensing, perception, world model, reasoning, acting and performance measuring (See fig. 2). The design presented here utilizes hierarchical flow of command and status messages but allows horizontal flow of data between components at the same level. This approach handles multiple levels of abstraction well and permits the incorporation of special data paths between time critial components.

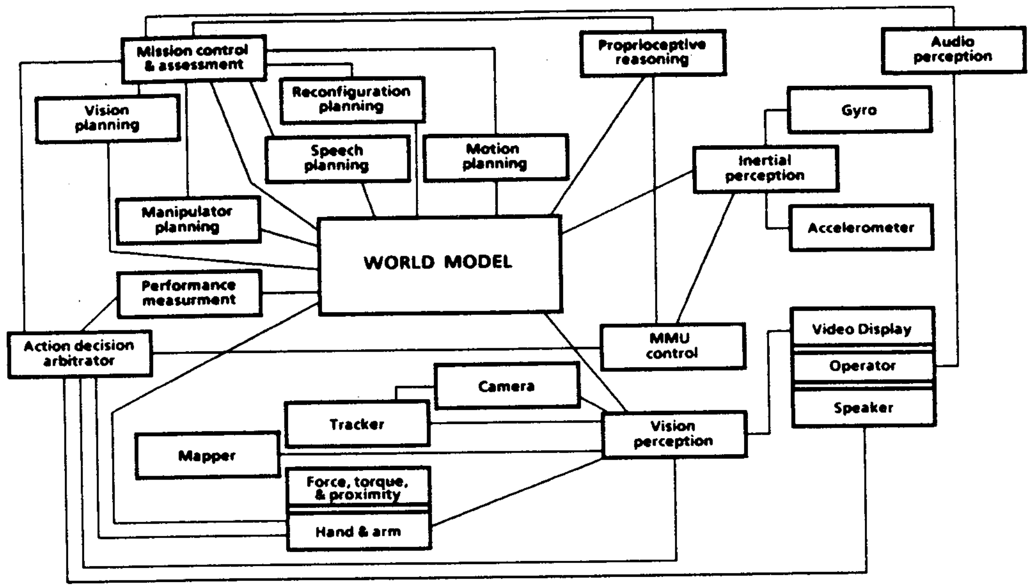

Figure 2. EVA Retriever Phase 2 software components.

Improvements in Phase II software in the sensing functions are: processing of range images to provide usable sketches, multisensor fusion to provide a sensor controlled robot, and expanded vocabulary recognition for supervisory override of most operations. The selected multisensor imaging approach to vision sensing and visual perception is based on the assessments that video intensity images and range images are basically complementary in information content, that they give enhanced segmentation of an image over either source alone, and that the combination is much more robust.

Perception software improvements in Phase II are: visual perception for multiple obstacle avoidance and grasp of different targets, information on arbitrary location and orientation of targets, self-awareness (proprioceptive perception) from fault detection and diagnosis of a portion of the MMU, and improved robot location from gyro, accelerometer, and vision.

The world model provides a representation of the external environment and internal status that is three-dimensional in space and dynamic in time. Acting as an intelligent central data base the world model has an episodic memory, data evaluation and estimation capabilities, and (limited) model based predictions of the EVA Retriever internal and external state. It contains a variety of general world knowledge as well as specific mission related facts such as space station proximity operations traffic control rules (simulated), mission rules/constraints, and object specific grapple rules/constraints.

The reasoning functions of the system are partitioned among the mission control and assessment, the action arbitrator, and the planning modules.

The mission control and assessment module develops and directs the execution of a mission plan. Commands are received from the operator through a voice recognition processor with comfirmation via voice synthesis. The module acts primarily as a plan execution monitor and as a meta planner delegating the creation and execution of detailed plans. Misson plan generation is based on dynamic knowledge of mission goals, constraints, and status as expressed in the world model. A set of cue action modules are utilized to initiate a wide range of monitoring, planning, and control actions. An internal assessment module triggers replanning whenever an expected cue fails to appear within an reasonable period of time.

The action arbitrator is the primary interface with the action subsystems. Under the supervision of the mission control and assessment module plan fragments are retrieved from the world model and transmitted to the appropriate action subsystem interface. Depending on the subsystem actions may be occurring in both a serial and parallel manner.

The planning module communicates with the mission control and assessment component and the world model. In general, the planning module responds to requests from the mission control and assessment component, issues data requests to the world model, and sends plans and status information to the world model. The total set of action primitives available to the planning module is based on the action requests recognized by the hand/arm, MMU, and the camera turntable subsystems.

The planning module consists of five functional planning components: vision, speech, motion, manipulator, and reconfiguration. For the current technology demonstration, the speech planning component was not implemented. The motion planner calculates a grid-based transition cost field based on safety zone and world model estimates of target/obstacle location and size. The transition cost field is dynamically updated in response to changes in obstacle location or number. The path is constructed of straight line segments with node location determined by a change in direction or the need maintain the target/body orientation required by the vision system. The vision planner constructs motion plans which support vision processing such as a search for an obscured target or positioning of the retriever for an analysis of a target grapple or degrapple. The module maintains internal models of vision sensors field of view given obstacles and plan move to see most probable part of a target region which has not been previously observed. The manipulator planner handles gross hand/arm positioning for grappling based on target type. A variety of closed-loop vision based control algorithms are being tested for fine grasping of small tools including an interesting reactive planner utilizing a potential field analysis. The reconfiguration planning module deals only with the MMU in the current prototype. This module uses both procedural fault diagnosis and isolation routines that have been incorporated into the MMU and a high level knowledge-based system to select reconfiguration strategies.

Research for other purposes in several related areas is being coordinated to possibly contribute to EVA Retriever Phase III. Notable here are: an effort on an autonomous agent with some emphasis in natural language understanding, general world knowledge, and autobiographical (episodic) memory for events experienced [21]; two related efforts in automated reactive planning [22, 23] with supervisory aspects; and an effort in machine qualitative reasoning [24].

7. CONCLUSIONS

A real need for retrieval of crew and objects in space near their prime spacecraft has been identified. The evaluation of the practical realization of a potential solution has been initiated in the form of a voice-supervised, intelligently autonomous robot. Successful demonstration of the first phase has been completed. Preliminary integration of the second phase software is largely complete at the time of writing this paper. Significant advances in intelligent software are planned to be evaluated in Phases II and III. Assessment of practicality will rest on experimental evidence when these are completed.

8. ACKNOWLEDGMENTS

This paper is based largely on an earlier version [25]. The EVA Retriever is a joint project of the Crew and Thermal Systems Division (CTSD), the Tracking and Communication Division (TCD), the Systems Development and Simulation Division SDSD), the Avionics Systems Division (ASD), and the Structures and Mechanisms Division (SMD), all of the Engineering Directorate at JSC, under funding from the JSC Director's Discretionary Fund. The contributions of the project teams encompassing civil servants and contractors to what is reported here are gratefully acknowledged.

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APPENDIX A

PROGRAM SCHEDULE

NASA CONFERENCE ON SPACE TELEROBOTICS

FINAL PROGRAM
(UPDATED TITLES FOR PROCEEDINGS)

January 31 – February 2, 1989
The Pasadena Center
Pasadena, California

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Ames Research Center
Goddard Space Flight Center
Jet Propulsion Laboratory
Johnson Space Center
Kennedy Space Center
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Marshall Space Flight Center

Conference Co-chairs: A.K. Bejczy, H. Seraji, Jet Propulsion Laboratory

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T.B. Sheridan, MIT
L. Stark, University of California, Berkeley
D. Tesar, University of Texas at Austin
H. Van Brussel, Catholic University of Leuven
R. Volz, Texas A&M University

The theme of the conference is man-machine cooperation in space. The conference provides a forum to exchange ideas on the research and development required for application of telerobotics technology to the space systems planned for the 1990s and beyond. The conference is designed to (i) provide a view of current NASA telerobotic research and development; (ii) stimulate technical exchange on man-machine systems, manipulator control, machine sensing, artificial intelligence and system architecture; and (iii) identify important unsolved problems of current interest which can be dealt with by future research.

For information regarding the conference, contact G. Rodriguez, M/S 198-330, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109; telephone (818) 354-4057.

Telerobotics Working Group

The conference is sponsored by the Telerobotics Working Group of the NASA Office of Aeronautics and Space Technology. M. Montemerlo of NASA Headquarters and S.Z. Szirmay of the Jet Propulsion Laboratory co-chair this working group. Representatives from NASA centers and other research organizations are

D. Akin, Massachusetts Institute of Technology
J. Bull, Ames Research Center
R. Davis, Kennedy Space Center
S. Fisher, Ames Research Center
J. Haussler, Marshall Space Flight Center
A. Meintel, Langley Research Center
J. Pennington, Langley Research Center
D. Provost, Goddard Space Flight Center
C. Price, Johnson Space Center
L. Purves, Goddard Space Flight Center
C. Ruoff, Jr., Jet Propulsion Laboratory
E.C. Smith, Marshall Space Flight Center
J. Stocky, Jet Propulsion Laboratory
M. Zweben, Ames Research Center

PROGRAM AT A GLANCE

TUESDAY, JANUARY 31

7:00-8:30	REGISTRATION	
8:30-9:45	OPENING SESSION	C124
10:00-1:00	TECHNICAL SESSIONS / PANELS	
2-2:30	PLENARY SESSION 1: Ames RC	C124
2:45-6:00	Sessions TP1–TP10	

10:00-1:00

TECHNICAL SESSIONS	C310	TA1: Redundant Manipulators 1
	C312	TA2: Man-Machine Systems
	C314/5	TA3: Telerobot Architectures
	C324	TA4: Robot Sensing & Planning
	C112	TA5: Navigation
	C326	TA6: Neural Networks
	C301/2	TA7: Fundamental AI Research
	C124	TA8: Reasoning Under Uncertainty
PANELS	C305	TA9: Planning & Reas. in Sensor-Based Robotics
	C307	

2:45-6:00

TP1: Redundant Manipulators 2
TP2: Teleoperation 1
TP3: Telerobots 1
TP4: Telerobot Perception
TP5: Rovers
TP6: Parallel Processing
TP7: Spatial Representations & Reasoning
TP8: Ames Research Center
TP9: Machine Learning
TP10: Human-like Design for Robotics: Part I

WEDNESDAY, FEBRUARY 1

8:30-9:30	PLENARY SESSION 2: JPL and GSFC	C124
9:45-1:00	Sessions WA1–WA10	
2-2:30	PLENARY SESSION 3: LaRC	C124
2:45-6:00	Sessions WP1–WP10	

9:45-1:00	2:45-6:00
WA1: Flexible Arms	WP1: Manipulator Control 1
WA2: Robotic End-Effectors	WP2: Telemanipulation
WA3: Tele-Autonomous Systems	WP3: Flight Experiments: Systems & Sim.
WA4: Robotic Vision	WP4: Sensor-Based Planning
WA5: Telerobots 2	WP5: Special Topics
WA6: Multi-Arm Control	WP6: Robot Kinem., Dynamics & Control
WA7: Coupling of Symbolic & Numeric Systems	WP7: Robot Task Planning & Assembly
WA8: Goddard Space Flight Center	WP8: Langley Research Center
WA9: Reasoning with Geometry	WP9: Dexterity & AI
WA10: Graphics in Teleoperation	WP10: Human-like Design for Robotics: Part II

THURSDAY, FEBRUARY 2

8:30-9:00	PLENARY SESSION 4: JSC	C124
9:15-12:30	Sessions THA1–THA8	
2:00-4:00	PANEL DISCUSSION	C124
4:00-6:00	CLOSING RECEPTION	C316

9:15-12:30

THA1: Robot Arm Modeling & Control
THA2: Special Topics in Teleoperation
THA3: Telerobotic Space Operations
THA4: Manipulator Control 2
THA5: Flight Experiment Concepts
THA6: Manipulator Coordination
THA7: Issues in AI Systems
THA8: Johnson Space Center

KEY

Coffee Break

Plenary Sessions

OPENING SESSION
Chair: Dr. G. Varsi, Jet Propulsion Laboratory
Tuesday, January 31, 8:30-9:45 a.m.

Opening Remarks
Dr. G. Varsi, Jet Propulsion Laboratory

Conference Welcome
Dr. T.E. Everhart, Caltech

Evolving Space Teleoperation to Space Telerobotics: Research and Systems Considerations
Dr. M. Montemerlo, NASA Headquarters

Space Telerobotics Conference Objectives
Dr. A.K. Bejczy, Jet Propulsion Laboratory

PLENARY SESSION 1: NASA Ames Research Center
Tuesday, January 31, 2:00-2:30 p.m.
"Artificial Intelligence Research at NASA Ames"
M. Zweben, NASA Ames Research Center

PLENARY SESSION 2:
Jet Propulsion Laboratory
Wednesday, February 1, 8:30-9:00 a.m.
"JPL Space Robotics Program"
C. Ruoff, Jr., Jet Propulsion Laboratory

NASA Goddard Space Flight Center
Wednesday, February 1, 9:00-9:30 a.m.
"The Flight Telerobotic Servicer: NASA's First Operational Space Robot"
C. Fuechsel, NASA Goddard Space Flight Center

PLENARY SESSION 3: NASA Langley Research Center
Wednesday, February 1, 2:00-2:30 p.m.
"Telerobotics Research at Langley Research Center"
J. Pennington, NASA Langley Research Center

PLENARY SESSION 4: NASA Johnson Space Center
Thursday, February 2, 8:30-9:00 a.m.
"Telerobotic Activities at Johnson Space Center"
C. Price, NASA Johnson Space Center

PANEL DISCUSSION: Future Research Directions
Moderator: J. Stocky, Jet Propulsion Laboratory
Thursday, February 2, 2:00-4:00 p.m.

The intent of this session is to provide views on the state of telerobotics research and to identify the near-term barriers to the application of telerobotics to be addressed in future advanced technology activities. The panel members give opening statements, which are followed by a general discussion with the audience.

Tuesday Morning, January 31
10:00 a.m.-1:00 p.m.

TA1 - REDUNDANT MANIPULATORS 1
Chair: H. McCain, NASA Goddard Space Flight Center
C310

10:00 **"A 17 Degree of Freedom Anthropomorphic Manipulator"**
H. Vold, J. Karlen, J. Thompson, J. Farrell, P. Eismann, Robotics Research Corporation

10:30 **"A New Approach to Global Control of Redundant Manipulators"**
H. Seraji, Jet Propulsion Laboratory

11:00 **"Kinematic Functions for the 7 DOF Robotics Research Arm"**
K. Kreutz, M. Long, H. Seraji, Jet Propulsion Laboratory

11:30 **"Cartesian Control of Redundant Robots"**
R. Colbaugh, K. Glass, New Mexico State University

12:00 **"Kinematics, Controls, and Path Planning Results for a Redundant Manipulator"**
B. Gretz, S. Tilley, Ford Aerospace Corporation

12:30 **"A Complete Analytical Solution for the Inverse Instantaneous Kinematics of a Spherical-Revolute-Spherical (7R) Redundant Manipulator"**
R. Podhorodeski, R. Fenton, A. Goldenberg, University of Toronto

TA2 - MAN-MACHINE SYSTEMS
Chair: T. Sheridan, MIT
C312

10:00 **"Adjustable Impedance, Force Feedback, and Command Language Aids for Telerobotics"**
T. Sheridan, G. Raju, F. Buzan, W. Yared, J. Park, MIT

10:30 **"Variable Force and Visual Feedback Effects on Teleoperator Man/Machine Performance"**
M. Massimino, T. Sheridan, MIT

11:00 **"Teleoperator Comfort and Psychometric Stability: Criteria for Limiting Master-Controller Forces of Operation and Feedback During Telemanipulation"**
S. Wiker, E. Hershkowitz, J. Zik, Wisconsin Center for Space Automation and Robotics

11:30 **"Measurement of Hand Dynamics in a Microsurgery Environment: Preliminary Data in the Design of a Bimanual Telemicro-Operation Test Bed"**
S. Charles, R. Williams, Center for Engineering Applications

12:00 **"Human Factors Model Concerning the Man-Machine Interface of Mining Crewstations"**
J. Rider, R. Unger, U.S. Bureau of Mines

12:30 **"Development of a Flexible Test-Bed for Robotics, Telemanipulation and Servicing Research"**
B. Davies, British Aerospace, UK

TA3 - TELEROBOT ARCHITECTURES
Chair: E. Freund, University of Dortmund
C314/5

10:00 **"Control of Intelligent Robots in Space"**
E. Freund, C. Buhler, University of Dortmund

10:30 **"Modularity in Robotic Systems"***
D. Tesar, M. Butler, University of Texas at Austin

11:00 **"A System Architecture for a Planetary Rover"**
D. Smith, J. Matijevic, Jet Propulsion Laboratory

11:30 **"The NASA/OAST Telerobot Testbed Architecture"**
J. Matijevic, W. Zimmerman, S. Dolinsky, Jet Propulsion Laboratory

12:00 **"Formulation of Design Guidelines for Automated Robotic Assembly in Outerspace"**
S. Dwivedi, West Virginia University, G. Jones, GSFC/NASA, S. Banerjee, S. Srivastava, Bowie State University

12:30 **"Automation and Robotics Technology for Intelligent Mining Systems"**
J. Welsh, U.S. Bureau of Mines

TA4 - ROBOT SENSING AND PLANNING
Chair: A. Koivo, Purdue University
C324

10:00 **"A Fast Lightstripe Rangefinding System with Smart VLSI Sensor"**
A. Gruss, L. Carley, T. Kanade, Carnegie Mellon University

10:30 **"Methods and Strategies of Object Localization"**
L. Shao, University of Michigan, R. Volz, Texas A&M University

11:00 **"A Laser Tracking Dynamic Robot Metrology Instrument"**
G. Parker, J. Mayer, University of Surrey, UK

11:30 **"Robot Acting on Moving Bodies (RAMBO): Interaction with Tumbling Objects"**
L. Davis, D. DeMenthon, T. Bestul, S. Ziavras, H. Srinivasan, M. Siddalingaiah, D. Harwood, University of Maryland

12:00 **"Real-Time Edge Tracking Using a Tactile Sensor"**
A. Berger, R. Volpe, P. Khosla, Carnegie Mellon University

12:30 **"Planning 3-D Collision-Free Paths Using Spheres"**
S. Bonner, R. Kelley, Rensselaer Polytechnic Institute

*No paper received for conference proceedings

TA5 - NAVIGATION
Chair: B. Wilcox, Jet Propulsion Laboratory
C112

10:00 **"Map Learning with Indistinguishable Locations"**
K. Basye, T. Dean, Brown University

10:30 **"Three-dimensional Motor Schema Based Navigation"**
R. Arkin, Georgia Institute of Technology

11:00 **"Periodic Gaits for the CMU Ambler"**
S. Mahalingam, Carnegie Mellon University,
S. Dwivedi, West Virginia University

11:30 **"Exploiting Map Plans as Resources for Action"**
D. Payton, Hughes Artificial Intelligence Center

12:00 **"Learned Navigation in Unknown Terrains: A Retraction Method"**
N. Rao, Old Dominion University, N. Stoltzfus,
S. Iyengar, Louisiana State University

TA6 - NEURAL NETWORKS
Chair: J. Barhen, Jet Propulsion Laboratory
C326

10:00 **" 'Computational' Neural Learning Formalisms for Manipulator Inverse Kinematics"**
S. Gulati, J. Barhen, Jet Propulsion Laboratory,
S. Iyengar, Louisiana State University

10:30 **"Multi-Layer Neural Networks for Robot Control"**
F. Pourboghrat, Southern Illinois University

11:00 **"A Hybrid Architecture for the Implementation of the Athena Neural Net Model"**
C. Koutsougeras, Tulane University,
C. Papachristou, Case Western Reserve University

11:30 **"A Design Philosophy for Multi-Layer Neural Networks With Applications to Robot Control"**
N. Vadiee, M. Jamshidi, University of New Mexico

12:00 **"A Neural Network for Controlling the Configuration of Frame Structure With Elastic Members"**
K. Tsutsumi, Kobe University

12:30 **"Real Time Neural Network Based Learning Control of a Telerobotic System with Visual Feedback"***
W.T. Miller, University of New Hampshire

TA7 - FUNDAMENTAL AI RESEARCH
Chair: A. Tate, University of Edinburgh, UK
C301/2

10:00 **"Coordinating the Activities of a Planner and an Execution Agent"**
A. Tate, University of Edinburgh, UK

10:30 **"Plan Recognition for Space Telerobotics"**
B. Goodman, BBN Systems and Technologies Corp., D. Litman, AT&T Bell Labs

11:00 **"Causal Simulation and Sensor Planning in Predictive Monitoring"**
R. Doyle, Jet Propulsion Laboratory

11:30 **"State-Based Scheduling: An Architecture for Telescope Observation Scheduling"**
N. Muscettola, S. Smith, Carnegie Mellon University

12:00 **"Focus of Attention in an Activity-Based Scheduler"**
N. Sadeh, M. Fox, Carnegie Mellon University

12:30 **"Cognitive Values and Causal Ordering"***
R. Bhaskar, A. Nigam, IBM T.J. Watson Research Center

TA8 - REASONING UNDER UNCERTAINTY
Chair: H. Stephanou, George Mason University
C124

10:00 **"A Boltzmann Machine for the Organization of Intelligent Machines"**
M. Moed, G. Saridis, Rensselaer Polytechnic Institute

10:30 **"Accumulation of Uncertain Evidence in Spatial Reasoning"***
A. Kak, Purdue University

11:00 **"Grasp Planning Under Uncertainty"**
A. Erkmen, H. Stephanou, George Mason University

11:30 **"Approximation Algorithms for Planning and Control"**
M. Boddy, T. Dean, Brown University

12:00 **"Multiresolutional Models of Uncertainty Generation and Reduction"**
A. Meystel, Drexel University

*No paper received for conference proceedings

Tuesday Afternoon, January 31
2:45-6:00 p.m.

TP1 - REDUNDANT MANIPULATORS 2
Chair: Y. Nakamura, University of California, Santa Barbara
C310

2:45 **"Redundancy Management Issues of Intelligent Machines"***
Y. Nakamura, University of California, Santa Barbara

3:15 **"Characterization and Control of Self-motions in Redundant Manipulators"**
J. Burdick, California Institute of Technology, H. Seraji, Jet Propulsion Laboratory

3:45 **"ARMS: The Audrey Redundant Manipulator Simulator for Interactive Exploration of Design and Control"***
D. Mittman, Jet Propulsion Laboratory

4:30 **"Multiple Cooperating Manipulators: The Case of Kinematically Redundant Arms"**
I. Walker, R. Freeman, S. Marcus, University of Texas at Austin

5:00 **"Reflexive Obstacle Avoidance for Kinematically-Redundant Manipulators"**
J. Karlen, J. Thompson, Jr., J. Farrell, H. Vold, Robotics Research Corporation

5:30 **"Preliminary Study of a Serial-Parallel Redundant Manipulator"**
V. Hayward, R. Kurtz, McGill University

TP2 - TELEOPERATION 1
Chair: S. Fisher, NASA Ames Research Center
C312

2:45 **"The JPL Telerobot Operator Control Station: Part I - Hardware"**
E. Kan, Jet Propulsion Laboratory, J. Tower, G. Hunka, G. VanSant, GE Aerospace

3:15 **"The JPL Telerobot Operator Control Station: Part II - Software"**
E. Kan, Jet Propulsion Laboratory, B. Landell, S. Oxenberg, C. Morimoto, GE Aerospace

3:45 **"Design of a Monitor and Simulation Terminal Master for Space Station Telerobotics and Telescience"**
L. Lopez, C. Konkel, Teledyne Brown Engineering, P. Harmon, System Dynamics, Inc., S. King, Teledyne Brown Engineering

4:30 **"Performance Evaluation of a 6 Axis High Fidelity Generalized Force Reflecting Teleoperator"**
B. Hannaford, L. Wood, Jet Propulsion Laboratory

5:00 **"Implementation and Design of a Teleoperation System Based on a VMEbus/68020 Pipelined Architecture"**
T. Lee, Jet Propulsion Laboratory

5:30 **"Human/Machine Interaction via the Transfer of Power and Information Signals"**
H. Kazerooni, W. Foslien, B. Anderson, T. Hessburg, University of Minnesota

TP3 - TELEROBOTS 1
Chair: R. Lumia, National Institute of Standards and Technology
C314/5

2:45 **"Trajectory Generation for Space Telerobots"**
R. Lumia, A. Wavering, National Institute of Standards and Technology

3:15 **"On the Simulation of Space Based Manipulators with Contact"**
M. Walker, J. Dionise, University of Michigan

3:45 **"Preliminary Results on Noncollocated Torque Control of Space Robot Actuators"**
S. Tilley, C. Francis, K. Emerick, M. Hollars, Ford Aerospace

4:30 **"Portable Dextrous Force Feedback Master for Robot Telemanipulation (P.D.M.F.F.)"**
G. Burdea, Rutgers University, T. Speeter, AT&T Bell Labs

5:00 **"Experiences with the JPL Telerobot Testbed 1 - Issues and Insights"**
H. Stone, B. Balaram, J. Beahan, Jet Propulsion Laboratory

5:30 **"The KALI Multi-Arm Robot Programming and Control Environment"**
P. Backes, S. Hayati, Jet Propulsion Laboratory, V. Hayward, McGill University, K. Tso, Jet Propulsion Laboratory

TP4 - TELEROBOT PERCEPTION
Chair: R. deFigueiredo, Rice University
C324

2:45 **"Image Enhancement of Convex Polyhedral Objects by Optimal Illumination"***
A. Gateau, R. deFigueiredo, Rice University

3:15 **"How Do Robots Take Two Parts Apart?"**
R. Bajcsy, C. Tsikos, University of Pennsylvania

3:45 **"Techniques and Potential Capabilities of Multi-Resolutional Information (Knowledge) Processing"**
A. Meystel, Drexel University

4:30 **"Perceptual Telerobotics"**
P. Ligomenides, University of Maryland

5:00 **"Reasoning about Perception for Robotic Control"***
M. Schoppers, R. Shu, Advanced Decision Systems

5:30 **"Building an Environment Model Using Depth Information"**
Y. Roth-Tabak, R. Jain, University of Michigan

*No paper received for conference proceedings

TP5 - ROVERS
Chair: C. Weisbin, Oak Ridge National Laboratory
C112

2:45 **"HERMIES-III: A Step Toward Autonomous Mobility, Manipulation and Perception"**
C. Weisbin, B. Burks, J. Einstein, R. Feezell, W. Manges, D. Thompson, Oak Ridge National Laboratory

3:15 **"First Results in Terrain Mapping for a Roving Planetary Explorer"**
E. Krotkov, C. Caillas, M. Hebert, I. Kweon, T. Kanade, Carnegie Mellon University

3:45 **"Planetary Rover Technology Development Requirements"**
R. Bedard, Jr., B. Muirhead, Jet Propulsion Laboratory, M. Montemerlo, M. Hirschbein, NASA

4:30 **"Rice-obot I: An Intelligent, Autonomous, Mobile Robot"**
R. deFigueiredo, L. Ciscon, D. Berberian, Rice University

5:00 **"Satellite-Map Position Estimation for the Mars Rover"**
A. Hayashi, University of Texas at Austin, T. Dean, Brown University

5:30 **"Robotic Sampling System for an Unmanned Mars Mission"**
W. Chun, Martin Marietta Space Systems

TP6 - PARALLEL PROCESSING
Chair: C.S.G. Lee, Purdue University
C326

2:45 **"Efficient Mapping Algorithms for Scheduling Robot Inverse Dynamics Computation on a Multiprocessor System"**
C.S.G. Lee, C. Chen, Purdue University

3:15 **"Robot Control Computation in Microprocessor Systems with Multiple Arithmetic Processors"***
B. Li, S. Ahmad, Purdue University

3:45 **"Parallel Algorithms for Computation of the Manipulator Inertia Matrix"**
M. Amin-Javaheri, D.E. Orin, Ohio State University

4:30 **"Neural Computation for Real-Time Assembly Scheduler"***
P. Chang, C.S.G. Lee, Purdue University

5:00 **"Parallel Complexity: Which Algorithm to Choose or Develop for Parallelization? A Case Study of Computation of the Manipulator Inertia Matrix"***
A. Fijany, Jet Propulsion Laboratory

5:30 **"Parallel Algorithms and Architectures for Computation of the Manipulator Inverse Dynamics"***
A. Fijany, A. Bejczy, Jet Propulsion Laboratory

TP7 - SPATIAL REPRESENTATIONS AND REASONING
Chair: C. Laugier, LIFIA-IMAG, France
C301/2

2:45 **"Planning Robot Actions Under Position and Shape Uncertainty"***
C. Laugier, LIFIA-IMAG, France

3:15 **"Planning Robot Actions Under Position and Shape Uncertainty (Continued)"**
C. Laugier, LIFIA-IMAG, France

3:45 **"Innovative Design Systems: Where Are We, and Where Do We Go From Here?"***
D. Navinchandra, Carnegie Mellon University

4:30 **"Organising Geometric Computations for Space Telerobotics"**
S. Cameron, University of Oxford, UK

5:00 **"GARE: Geometric Analysis and Reasoning Engine"***
R. Desai, R. Doshi, R. Lam, J. White, Jet Propulsion Laboratory

5:30 **"A Tesselated Probabilistic Representation for Spatial Robot Perception and Navigation"**
A. Elfes, Carnegie Mellon University

TP8 - NASA AMES RESEARCH CENTER
Chair: M. Zweben, NASA Ames Research Center
C124

2:45 **"A Survey of Planning and Scheduling Research at the NASA Ames Research Center"**
M. Zweben, NASA Ames Research Center

3:15 **"Situated Control Rules"***
M. Drummond, NASA Ames Research Center/Sterling Software

3:45 **"Integrating Planning and Reactive Control"**
S. Rosenschein, L. Kaelbling, Teleos Research

4:30 **"Learning in Stochastic Neural Networks for Constraint Satisfaction Problems"**
M. Johnston, Space Telescope Science Institute, H-M. Adorf, Space Telescope 1 - European Coordinating Facility

5:00 **"Integrating Planning, Execution and Learning"**
D. Kuokka, Carnegie Mellon University

5:30 **"An Integrated Architecture for Intelligent Agents"***
K. Thompson, P. Langley, University of California, Irvine

*No paper received for conference proceedings

Wednesday Morning, February 1
9:45 a.m.-1:00 p.m.

WA1 - FLEXIBLE ARMS
Chair: W. Book, Georgia Institute of Technology
C310

9:45 **"Modeling, Design, and Control of Flexible Manipulator Arms: Status and Trends"**
W. Book, Georgia Institute of Technology

10:15 **"Dynamical Modeling of Serial Manipulators with Flexible Links and Joints Using the Method of Kinematic Influence"**
P. Graves, Lockheed Engineering & Sciences Co.

10:45 **"Capture of Free-Flying Payloads With Flexible Space Manipulators"**
T. Komatsu, M. Uenohara, S. Iikura, Toshiba Corporation, H. Miura, I. Shimoyama, University of Tokyo

11:30 **"Technology and Task Parameters Relating to the Effectiveness of the Bracing Strategy"**
W. Book, J. Wang, Georgia Institute of Technology

12:00 **"Manipulators with Flexible Links: A Simple Model and Experiments"**
I. Shimoyama, University of Tokyo, I. Oppenheim, Carnegie Mellon University

12:30 **"Experiments in Identification and Control of Flexible-Link Manipulators"**
S. Yurkovich, A. Tzes, F. Pacheco, Ohio State University

WA2 - ROBOTIC END-EFFECTORS AND HAND CONTROLLERS
Chair: G. Bekey, University of Southern California
C312

9:45 **"Autonomous Dexterous End-Effectors for Space Robotics"**
G. Bekey, T. Iberall, H. Liu, University of Southern California

10:15 **"Design and Control of a Multi-Fingered Robot Hand Provided With Tactile Feedback"**
H. Van Brussel, B. Santoso, D. Reynaerts, Catholic University of Leuven, Belgium

10:45 **"Traction-Drive Force Transmission for Telerobotic Joints"**
D. Kuban, D. Williams, Oak Ridge National Laboratory

11:30 **"Force/Torque and Tactile Sensors for Sensor-Based Manipulator Control"**
H. Van Brussel, H. Belien, C.-Y. Bao, Catholic University of Leuven

12:00 **"Redundant Sensorized Arm + Hand System for Space Telerobotized Manipulation"**
A. Rovetta, P. Cavestro, Polytechnic University of Milan, Italy

12:30 **"Impedance Hand Controllers for Increasing Efficiency in Teleoperations"**
C. Carignan, J. Tarrant, STX Systems Corporation

WA3 - TELE-AUTONOMOUS SYSTEMS
Chair: R. Volz, Texas A&M University
C314/5

9:45 **"Tele-Autonomous Systems: New Methods for Projecting and Coordinating Intelligent Action at a Distance"**
L. Conway, University of Michigan, R. Volz, Texas A&M University, M. Walker, University of Michigan

10:15 **"An Advanced Telerobotic System for Shuttle Payload Changeout Room Processing Applications"**
M. Sklar, D. Wegerif, McDonnell Douglas Space Systems Co., L. Davis, NASA Kennedy Space Center

10:45 **"Robotic Tele-Existence"**
S. Tachi, H. Arai, T. Maeda, Ministry of International Trade and Industry, Japan

11:30 **"Redundancy of Space Manipulator on Free-Flying Vehicle and Its Nonholonomic Path Planning"**
Y. Nakamura, R. Mukherjee, University of California, Santa Barbara

12:00 **"Guidance Algorithms for a Free-Flying Space Robot"**
A. Brindle, H. Viggh, J. Albert, Boeing Aerospace

12:30 **"Telepresence System Development for Application to the Control of Remote Robotic Systems"**
C. Crane III, J. Duffy, R. Vora, S.-C. Chiang, University of Florida

WA4 - ROBOTIC VISION
Chair: L. Stark, University of California, Berkeley
C324

9:45 **"3D Model Control of Image Processing"**
A. Nguyen, L. Stark, University of California, Berkeley

10:15 **"Weighted Feature Selection Criteria for Visual Servoing of a Telerobot"**
J. Feddema, C.S.G. Lee, O. Mitchell, Purdue University

10:45 **"Model-Based Computer Vision Applied to Structured Objects"***
W. Wolfe, University of Colorado, M. Magee, University of Wyoming, D. Mathis, C. Sklair, Martin Marietta Astronautics Group

11:30 **"Trinocular Stereovision using Figural Continuity, Dealing with Curved Objects"**
R. Vaillant, O. Faugeras, INRIA, France

12:00 **"A Fast 3-D Object Recognition Algorithm for the Vision System of a Special-Purpose Dexterous Manipulator"**
S. Hung, National Research Council of Canada

12:30 **"Use of 3D Vision for Fine Robot Motion"**
A. Lokshin, T. Litwin, Jet Propulsion Laboratory

*No paper received for conference proceedings

WA5 - TELEROBOTS 2
Chair: K. Corker, BBN Systems and Technologies Corp.
C112

9:45 **"Telerobotic Workstation Design Aid"**
K. Corker, E. Hudlicka, D. Young, N. Cramer, BBN Systems and Technologies Corp.

10:15 **"Space Robotic System for Proximity Operations"**
P. Magnani, M. Colomba, Tecnospazio S.p.A., Italy

10:45 **"Modeling and Sensory Feedback Control for Space Manipulators"**
Y. Masutani, F. Miyazaki, S. Arimoto, Osaka University

11:30 **"Control Strategies for a Telerobot"**
J. O'Hara, Brookhaven National Laboratory, B. Stasi, Grumman Space Systems

12:00 **"Autonomous Sensor-Based Dual-Arm Satellite Grappling"**
B. Wilcox, K. Tso, T. Litwin, S. Hayati, B. Bon, Jet Propulsion Laboratory

12:30 **"Thread: A Programming Environment for Interactive Planning-level Robotics Applications"**
J. Beahan, Jr., Jet Propulsion Laboratory

WA6 - MULTI-ARM CONTROL
Chair: J. Luh, Clemson University
C326

9:45 **"Compliance of Dual-Robot Systems for Internal and External Forces"***
J. Luh, J. Tao, Clemson University

10:15 **"Stability Analysis of Multiple-Robot Control Systems"**
J. Wen, Rensselaer Polytechnic Institute, K. Kreutz, Jet Propulsion Laboratory

10:45 **"Experiments in Cooperative Manipulation: A System Perspective"**
S. Schneider, R. Cannon, Jr., Stanford University

11:30 **"On the Manipulability of Dual Cooperative Robots"**
P. Chiacchio, S. Chiaverini, L. Sciavicco, B. Siciliano, University of Naples, Italy

12:00 **"Controlling Multiple Manipulators Using RIPS"**
Y. Wang, S. Jordan, A. Mangaser, S. Butner, University of California, Santa Barbara

12:30 **"Time Optimal Movement of Cooperating Robots"**
J. McCarthy, J. Bobrow, University of California, Irvine

WA7 - COUPLING OF SYMBOLIC AND NUMERIC SYSTEMS
Chair: M. Fox, Carnegie Mellon University
C301/2

9:45 **"Reflections on the Relationship Between Artificial Intelligence and Operations Research"**
M. Fox, Carnegie Mellon University

10:15 **"What Kind of Computation Is Intelligence? A Framework for Integrating Different Kinds of Expertise"**
B. Chandrasekaran, Ohio State University

10:45 **"A Design Strategy for Autonomous Systems"**
P. Forster, University of Edinburgh, UK

11:30 **"Learning in Tele-autonomous Systems using Soar"**
J. Laird, E. Yager, C. Tuck, M. Hucka, University of Michigan

12:00 **"Robust Robot Execution and Task Combination"***
W. Troxell, Colorado State University

12:30 **"Design of a Structural and Functional Hierarchy for Planning and Control of Telerobotic Systems"**
L. Acar, University of Missouri-Rolla, U. Ozguner, Ohio State University

WA8 - NASA GODDARD SPACE FLIGHT CENTER
Chair: H. McCain, NASA Goddard Space Flight Center
C124

9:45 **"The Flight Telerobotic Servicer Project: A Technical Overview"**
H. McCain, NASA Goddard Space Flight Center

10:15 **"The Flight Telerobotic Servicer Tinman Concept: System Design Drivers and Task Analysis"**
J. Andary, D. Hewitt, S. Hinkal, Goddard Space Flight Center

10:45 **"The Flight Telerobotic Servicer: From Functional Architecture to Computer Architecture"**
R. Lumia, J. Fiala, National Institute of Standards and Technology

11:30 **"Research and Development Activities at the Goddard Space Flight Center for the Flight Telerobotic Servicer Project"**
S. Ollendorf, Goddard Space Flight Center

12:00 **"The Goddard Space Flight Center (GSFC) Robotics Technology Testbed"**
R. Schnurr, M. O'Brien, Goddard Space Flight Center, S. Cofer, Digital Equipment Corp.

12:30 **"Test and Validation for Robot Arm Control Dynamics Simulation"**
H. Yae, S.-S. Kim, E. Haug, University of Iowa, W. Seering, K. Sundaram, B. Thompson, MIT, J. Turner, H. Chun, Cambridge Research, H. Frisch, R. Schnurr, Goddard Space Flight Center

*No paper received for conference proceedings

Wednesday Afternoon, February 1
2:45-6:00 p.m.

WP1 - MANIPULATOR CONTROL 1
Chair: T. Hsia, University of California, Davis
C310

2:45 **"Cartesian Control Schemes for Robot Manipulators"***
T. Hsia, University of California, Davis

3:15 **"An Improved Adaptive Control for Repetitive Motion of Robots"**
F. Pourboghrat, Southern Illinois University

3:45 **"Direct Adaptive Control of a PUMA 560 Industrial Robot"**
H. Seraji, T. Lee, Jet Propulsion Laboratory, M. Delpech, C.N.E.S., France

4:30 **"Model Based Manipulator Control"**
L. Petrosky, Westinghouse Advanced Energy Systems, I. Oppenheim, Carnegie Mellon University

5:00 **"Discrete-Time Adaptive Control of Robot Manipulators"**
M. Tarokh, University of California, San Diego

5:30 **"A Discrete Decentralized Variable Structure Robotic Controller"**
Z. Tumeh, Georgia Institute of Technology

WP2 - TELEMANIPULATION
Chair: D. Tesar, University of Texas at Austin
C312

2:45 **"Construction and Demonstration of a 9-String 6 DOF Force Reflecting Joystick for Telerobotics"**
R. Lindemann, Jet Propulsion Laboratory, D. Tesar, University of Texas at Austin

3:15 **"Response to Reflected-Force Feedback to Fingers in Teleoperations"**
P. Sutter, J. Iatridis, N. Thakor, Franklin and Marshall College

3:45 **"The Jau-JPL Anthropomorphic Telerobot"**
B. Jau, Jet Propulsion Laboratory

4:30 **"A Procedure Concept for Local Reflex Control of Grasping"**
P. Fiorini, J. Chang, Jet Propulsion Laboratory

5:00 **"Performance Limitations of Bilateral Force Reflection Imposed by Operator Dynamic Characteristics"**
J. Chapel, Martin Marietta Space Systems

5:30 **"Sensor-based Fine Telemanipulation for Space Robotics"**
M. Andrenucci, M. Bergamasco, P. Dario, University of Pisa, Italy

WP3 - FLIGHT EXPERIMENTS: SYSTEMS AND SIMULATORS
Chair: A. Bejczy, Jet Propulsion Laboratory
C314/5

2:45 **"ROTEX-TRIIFEX: Proposal for a Joint FRG-USA Telerobotic Flight Experiment"**
G. Hirzinger, German Aerospace Research Establishment, A. Bejczy, Jet Propulsion Laboratory

3:15 **"Test and Training Simulator for Ground-Based Teleoperated In-Orbit Servicing"**
B. Schafer, German Aerospace Research Establishment

3:45 **"Concept Synthesis of an Equipment Manipulation and Transportation System (EMATS)"**
W. De Peuter, ESTEC, E. Waffenschmidt, Dornier-System GmbH, West Germany

4:30 **"Force-Reflective Teleoperated System With Shared and Compliant Control Capabilities"**
Z. Szakaly, W.S. Kim, A. Bejczy, Jet Propulsion Laboratory

5:00 **"Information management in an Integrated Space Telerobot"**
S. Di Pippo, ASI-Italian National Space Agency, G. Pasquariello, IESI-CNR, Italy, G. Labini, ASI-Italian Space Agency

5:30 **"Redundancy in Sensors, Control and Planning of a Robotic System for Space Telerobotics"**
A. Rovetta, S. Vodret, M. Bianchini, Polytechnic University of Milan, Italy

WP4 - SENSOR-BASED PLANNING
Chair: M. Mason, Carnegie Mellon University
C324

2:45 **"How to Push a Block Along a Wall"**
M. Mason, Carnegie Mellon University

3:15 **"Global Models: Robot Sensing, Control, and Sensory-Motor Skills"**
P. Schenker, Jet Propulsion Laboratory

3:45 **"3-D Vision System Integrated Dexterous Hand"**
R. Luo, Y.-S. Han, North Carolina State University

4:30 **"A Layered Abduction Model of Perception: Integrating Bottom-up and Top-down Processing in a Multi-Sense Agent"**
J. Josephson, Ohio State University

5:00 **"RCTS: A Flexible Environment for Sensor Integration and Control of Robot Systems - The Distributed Processing Approach"**
R. Allard, B. Mack, M. Bayoumi, Queen's University at Kingston

5:30 **"Vehicle Path-Planning in Three Dimensions Using Optics Analogs for Optimizing Visibility and Energy Cost"**
N. Rowe, D. Lewis, U.S. Naval Postgraduate School

*No paper received for conference proceedings

WP5 - SPECIAL TOPICS
Chair: S. Hackwood, University of California at Santa Barbara
C112

2:45 **"Vacuum Mechatronics"**
S. Hackwood, S. Belinski, G. Beni, University of California, Santa Barbara

3:15 **"Uniform Task Level Definitions for Robotic System Performance Comparisons"**
C. Price, NASA Johnson Space Center, D. Tesar, University of Texas at Austin

3:45 **"Linear Analysis of a Force Reflective Teleoperator"**
K. Biggers, S. Jacobsen, C. Davis, University of Utah

4:30 **"Real-Time Cartesian Force Feedback Control of a Teleoperated Robot"**
P. Campbell, Lockheed Engineering & Sciences Company

5:00 **"Optimal Payload Rate Limit Algorithm for Zero-G Manipulators"**
M. Ross, D. McDermott, Lockheed Engineering & Sciences Co.

5:30 **"Assembly of Objects With Not Fully Predefined Shapes"**
M. Arlotti, V. Di Martino, IBM Rome Scientific Center

WP6 - ROBOT KINEMATICS, DYNAMICS AND CONTROL
Chair: F.E.C. Culick, California Institute of Technology
C326

2:45 **"Recursive Multibody Dynamics and Discrete-Time Optimal Control"**
G. D'Eleuterio, C. Damaren, University of Toronto

3:15 **"The Effects of Gear Reduction on Robot Dynamics"**
J. Chen, University of Maryland

3:45 **"Recursive Newton-Euler Formulation of Manipulator Dynamics"**
M. Nasser, Lockheed Engineering & Sciences Company

4:30 **"Kinematic Sensitivity of Robot Manipulators"**
M. Vuskovic, San Diego State University

5:00 **"Efficient Conjugate Gradient Algorithms for Computation of the Manipulator Forward Dynamics"**
A. Fijany, R. Scheid, Jet Propulsion Laboratory

5:30 **"On the Stability of Robotic Systems with Random Communication Rates"**
H. Kobayashi, X. Yun, R. Paul, University of Pennsylvania

WP7 - ROBOT TASK PLANNING AND ASSEMBLY
Chair: A. Sanderson, Rensselaer Polytechnic Institute
C301/2

2:45 **"Precedence Relationship Representations of Mechanical Assembly Sequences"**
L. Homem de Mello, Carnegie Mellon University, A. Sanderson, Rensselaer Polytechnic Institute

3:15 **"Using Multiple Sensors for Printed Circuit Board Insertion"**
D. Sood, M. Repko, R. Kelley, Rensselaer Polytechnic Institute

3:45 **"An Overview of the Intelligent Machining Workstation"***
D. Bourne, Carnegie Mellon University

4:30 **"Design and Manufacturing Intent"***
D. Bourne, Carnegie Mellon University

5:00 **"Determining Robot Actions For Tasks Requiring Sensor Interaction"**
J. Budenske, Honeywell Systems and Research Center, M. Gini, University of Minnesota

WP8 - NASA LANGLEY RESEARCH CENTER
Chair: J. Pennington, NASA Langley Research Center
C124

2:45 **"The Laboratory Telerobotic Manipulator Program"**
J. Herndon, S. Babcock, P. Butler, H. Costello, R. Glassell, R. Kress, D. Kuban, J. Rowe, D. Williams, Oak Ridge National Laboratory

3:15 **"Robotic Control of the Seven-Degree-of-Freedom NASA Laboratory Telerobotic Manipulator"**
R. Dubey, J. Euler, R. Magness, University of Tennessee, S. Babcock, J. Herndon, Oak Ridge National Laboratory

3:45 **"The Control of Space Manipulators Subject to Spacecraft Attitude Control Saturation Limits"**
S. Dubowsky, MIT, E. Vance, Center for Naval Analyses, M. Torres, MIT

4:30 **"System Architectures for Telerobotic Research"**
F. Harrison, Langley Research Center

5:00 **"Comparison of Joint Space Versus Task Force Load Distribution Optimization for a Multiarm Manipulator System"**
D. Soloway, Langley Research Center, T. Alberts, Old Dominion University

*No paper received for conference proceedings

Thursday Morning, February 2
9:15 a.m.-12:30 p.m.

THA1 - ROBOT ARM MODELING AND CONTROL
Chair: G. Saridis, Rensselaer Polytechnic Institute
C310

9:15 **"Dynamic Characteristics of Macro/Mini-Manipulators: Application to Space Robot Systems"***
O. Khatib, Stanford University

9:45 **"Application of Recursive Manipulator Dynamics to Hybrid Software/Hardware Simulation"**
C. Hill, Lockheed Engineering & Sciences Co., K. Hopping, Boeing Electronics Co., C. Price, NASA Johnson Space Center

10:15 **"Kinematics & Control Algorithm Development and Simulation for a Redundant Two-Arm Robotic Manipulator System"**
M. Hennessey, P. Huang, C. Bunnell, FMC Corporation

11:00 **"Inverse Dynamics of a 3 Degree of Freedom Spatial Flexible Manipulator"**
E. Bayo, M. Serna, University of California, Santa Barbara

11:30 **"A Control Approach for Robots With Flexible Links and Rigid End-Effectors"**
E. Barbieri, Tulane University, U. Ozguner, Ohio State University

THA2 - SPECIAL TOPICS IN TELEOPERATION
Chair: W. Seering, MIT
C312

9:15 **"Preshaping Command Inputs to Reduce Telerobotic System Oscillations"**
N. Singer, W. Seering, MIT

9:45 **"Performance Constraints and Compensation For Teleoperation With Delay"**
J. McLaughlin, B. Staunton, The Aerospace Corporation

10:15 **"Flight Telerobotic Servicer Control From the Orbiter"**
T. Ward, D. Harlan, Lockheed Engineering & Sciences Company

11:00 **"Teleoperation Experiments with a Utah/MIT Hand and a VPL DataGlove"**
D. Clark, J. Demmel, J. Hong, G. Lafferriere, L. Salkind, X. Tan, New York University

11:30 **"Instruction Dialogues: Teaching New Skills to a Robot"**
C. Crangle, P. Suppes, Stanford University

12:00 **"Interset: A Natural Language Interface for Teleoperated Robotic Assembly of the EASE Space Structure"**
D. Boorsma, MIT

THA3 - TELEROBOTIC SPACE OPERATIONS
Chair: D. Akin, MIT
C314/5

9:15 **"Space Operations Testing of Telerobots in Neural Buoyancy"***
D. Akin, MIT

9:45 **"Establishing Viable Task Domains for Telerobot Demonstrations"**
W. Zimmerman, Jet Propulsion Laboratory

10:15 **"The Telerobot Workstation Testbed for the Shuttle Aft Flight Deck: A Project Plan for Integrating Human Factors into System Design"**
T. Sauerwein, NASA Goddard Space Flight Center

11:00 **"Multi-Level Manual and Autonomous Control Superposition for Intelligent Telerobot"**
S. Hirai and T. Sato, Ministry of International Trade & Industry, Japan

11:30 **"An Alternative Control Structure for Telerobotics"**
P. Boissiere, R. Harrigan, Sandia National Laboratories

12:00 **"Integration of a Sensor Based Multiple Robot Environment for Space Applications: The Johnson Space Center Teleoperator Branch Robotics Laboratory"**
J. Hwang, P. Campbell, M. Ross, Lockheed Engineering & Sciences Company, C. Price, D. Barron, NASA Johnson Space Center

THA4 - MANIPULATOR CONTROL 2
Chair: T. Tarn, Washington University
C324

9:15 **"Unified Approach to the Control of Non-redundant/ Redundant Rigid/Flexible Robot Arms"***
T. Tarn, Washington University, A. Bejczy, Jet Propulsion Laboratory

9:45 **"Requirements for Implementing Real-Time Control Functional Modules on a Hierarchical Parallel Pipelined System"**
T. Wheatley, J. Michaloski, R. Lumia, National Institute of Standards and Technology

10:15 **"The JPL Telerobot Manipulator Control and Mechanization Subsystem (MCM)"**
S. Hayati, T. Lee, K. Tso, P. Backes, E. Kan, Jet Propulsion Laboratory, J. Lloyd, McGill University

11:00 **"On Discrete Control of Nonlinear Systems With Applications to Robotics"**
M. Eslami, University of Illinois at Chicago

11:30 **"Robust Control of an Industrial Manipulator"***
M. Cohen, L. Daneshmend, McGill University

12:00 **"A Spatial Operator Algebra for Manipulator Modeling and Control"**
G. Rodriguez, K. Kreutz, A. Jain, Jet Propulsion Laboratory

*No paper received for conference proceedings

THA5 - FLIGHT EXPERIMENT CONCEPTS
Chair: L. Jenkins, NASA Johnson Space Center
C112

9:15 **"Flight Experiments in Telerobotics - Orbiter Middeck Concept"**
L. Jenkins, NASA Johnson Space Center

9:45 **"Robotic Systems: An Important Asset to the SDS"***
D. Nussman, S. Greene, Dynamics Research Corporation

10:15 **"Experimental Study on Two-Dimensional Free-Flying Robot Satellite Model"**
Y. Umetani, K. Yoshida, Tokyo Institute of Technology

11:00 **"The Astronaut and the Banana Peel: an EVA Retriever Scenario"**
D. Shapiro, Advanced Decision Systems

11:30 **"Computed Torque Control of a Free-Flying Cooperating-Arm Robot"**
R. Koningstein, M. Ullman, R. Cannon, Jr., Stanford University

12:00 **"Next Generation Space Robot"**
T. Iwata, M. Oda, R. Imai, National Space Development Agency of Japan

THA6 - MANIPULATOR COORDINATION
Chair: A. Meystel, Drexel University
C326

9:15 **"Coordination in a Hierarchical Multi-Actuator Controller"**
A. Meystel, Drexel University

9:45 **"Distributed Communications and Control Network for Robotic Mining"**
W. Schiffbauer, U.S. Bureau of Mines, Pittsburgh Research Center

10:15 **"Computer Simulation and Design of a Three Degree-of-Freedom Shoulder Module"**
D. Marco, U.S. Naval Postgraduate School,
L. Torfason, University of New Brunswick,
D. Tesar, University of Texas at Austin

11:00 **"A Collision Avoidance System for a Spaceplane Manipulator Arm"**
A. Sciomachen, P. Magnani, Tecnospazio S.p.A., Italy

THA7 - ISSUES IN AI SYSTEMS
Chair: N. Sridharan, FMC Corporation
C301/2

9:15 **"Real-Time Performance for Interactive AI Systems"***
N. Sridharan, FMC Corporation

9:45 **"Generic Task Problem Solvers in Soar"**
T. Johnson, J. Smith, Jr., B. Chandrasekaran, Ohio State University

10:15 **"Temporal Logics Meet Telerobotics"**
E. Rutten, L. Marce, IRISA/INRIA, France

11:00 **"An Efficient Temporal Logic for Robotic Task Planning"**
J. Becker, Martin Marietta Astronautics Group

11:30 **"The Indexed Time Table Approach for Planning and Acting"**
M. Ghallab, A. Alaoui, LAAS-CNRS, France

12:00 **"Reactive Behavior, Learning, and Anticipation"**
S. Whitehead, D. Ballard, University of Rochester

THA8 - NASA JOHNSON SPACE CENTER
Chair: C. Price, NASA Johnson Space Center
C124

9:15 **"Shuttle Remote Manipulator System Mission Preparation and Operations"**
E. Smith, Jr., NASA Johnson Space Center

9:45 **"A Comparison of the Shuttle Remote Manipulator System and the Space Station Freedom Mobile Servicing Center"**
E. Taylor, NASA Johnson Space Center,
M. Ross, Lockheed Engineering & Sciences Co.

10:15 **"Dexterous Manipulator Flight Demonstration"**
E. Carter, Lockheed Engineering & Sciences Co.

11:00 **"An Intelligent Free-Flying Robot"**
G. Reuter, C. Hess, D. Rhoades, L. McFadin, K. Healey, J. Erickson, NASA Johnson Space Center, D. Phinney, Lockheed Engineering & Sciences Company

11:30 **"Smart Hands for the EVA Retriever"***
C. Hess, NASA Johnson Space Center

12:00 **"Machine Vision"***
R. Juday, NASA Johnson Space Center

*No paper received for conference proceedings

Panels on Artificial Intelligence

TA9 - PLANNING AND REASONING IN SENSOR-BASED ROBOTICS
10:00 a.m.-1:00 p.m.
Moderator: A. Kak, Purdue University

Panel: S.-S. Chen, University of North Carolina
T. Kanade, Carnegie Mellon University
B. Kuipers, University of Texas at Austin
T. Linden, Advanced Decision Systems
A. Tate, University of Edinburgh, UK

This panel discussion is designed to address issues in planning, navigation, frameworks for reasoning, spatial databases, geometrical reasoning, sensor fusion and spatial reasoning.

TP9 - MACHINE LEARNING, KNOWLEDGE ACQUISITION AND SEMI-AUTONOMOUS AGENTS
2:45-6:00 p.m.
Moderator: A. Rappaport, Carnegie Mellon Univ./Neuron Data

Panel: B. Gaines, University of Calgary, Canada
J. Laird, University of Michigan
T. Mitchell, Carnegie Mellon University
G. Boy, CERT/ONERA, France

The purpose of this panel is to review the state of the art in the fields of machine learning and knowledge acquisition and to relate those critical advances of AI to telerobotics. Telerobotics involves capturing knowledge where the domain theory is often incomplete, performing tasks using this knowledge and automatically adapting it to new situations. AI architectures involving multiple reasoning techniques and learning capabilities are necessary to assist human and robot performance. Telerobotics is a preferred application area; those advanced AI techniques and their use in this domain should in turn provide important insights to AI researchers.

WA9 - REASONING WITH GEOMETRY
9:45 a.m.-1:00 p.m.
Moderator: H.R. Keshavan, Northrop Research Center

Panel: F. Arbab, University of Southern California
R. Desai, Jet Propulsion Laboratory
R. Hoffman, Northrop Corp.
D. Hunter, Northrop Corp.
F. Prinz, Carnegie Mellon University
S. Smith, Northrop Corp.

The panel was formed to present techniques and problems in geometric modeling, geometric reasoning, representing and reasoning with uncertainty, topological reasoning, process planning and CAD directed vision.

WP9 - INTERACTIONS BETWEEN DEXTERITY AND AI FOR A ROBOT
2:45-6:00 p.m.
Moderator: J. Latombe, Stanford University

Panel: B. Donald, Cornell University
M. Genesereth, Stanford University
A. Haddad, Lockheed
M. Mason, Carnegie Mellon University
J. Pertin-Troccaz, CNRS, France
K. Salisbury, MIT
P. Schenker, Jet Propulsion Laboratory

The purpose of this panel is to discuss the interdependence of robot dexterity and autonomy; that is, the interactions between the physical capabilities and decision capabilities of a robot. The issues it was formed to address include dexterity, redundant arms, dexterous hands, sensor-based motion primitives, whole robot manipulation, AI methodologies and autonomy. The panel also has another function: to present new, challenging ideas for modeling, computational, inferential, and combinatorial issues in spatial reasoning and AI.

Panels on Humanlike Design

TP10 - HUMANLIKE DESIGN FOR ROBOTICS: A HELPFUL METAPHOR OR RED HERRING? PART I: VISION
2:45-6:00 p.m.
Moderator: L. Stark, Univ. of California, Berkeley

2:45-2:55
"Human Scanpaths"
L. Stark, Univ. of California, Berkeley
Cognitive models control active looking in a top-down perceptual process.

2:55-3:15
"Statistical Dependency in Visual Scanning"
S. Ellis, NASA Ames Research Center
Statistical testing provides evidence for the Stark/Norton/Ellis "scanpath" hypothesis.

3:15-3:40
"Top-Down Image Processing for Robotic Control"
A. Nguyen, University of California, Berkeley
An image processing scheme has been developed, for telerobotic control, that rests extensively on a model of the telerobot working environment to control the robots and the cameras viewing the robotic scene. Parameter updating of the model is obtained in a rapid, robust fashion since image processing only occurs in these specialized regions of interest where positional feedback is essential.

3:40-4:10
"Image Processing"
R. Brodersen, Univ. of California, Berkeley
Rapid processing of video images is possible with VLSI chips to compute Hough transforms, centroids, etc., and with these chips embedded in specialized computer architectures. This bottom-up processing is based upon engineering filtering theory and is in the leading edge of image processing.

4:10-4:15
"Vision for Space Telerobots"
B. Wilcox, Jet Propulsion Laboratory
The visual environment for space telerobotics is very different from the natural, terrestrial, visual environment which evolved human vision (e.g., harsh lighting, deep shadows, highly specular surfaces, man-made structures, etc.). A vision system designed for this environment is described.

4:30-5:00
Panel Discussion

WP10 - HUMANLIKE DESIGN FOR ROBOTICS: A HELPFUL METAPHOR OR RED HERRING? PART II: LOCOMOTION
2:45-6:00 p.m.
Moderator: L. Stark, University of California, Berkeley

2:45-3:10
"Human Locomotion"
V. Krishnan, San Francisco State University
The multiple muscles involved in generating joint torques in human locomotion provide an opportunity for optimization to constrain the redundancy. A set of experimental studies was used to evaluate candidate optimum criteria and the results suggested that energy minimization was important.

3:10-3:40
"Hopping Locomotion"
M. Raibert, MIT
A set of demonstration hopping robots with one to four legs has been studied to evaluate this interesting mode of locomotion for a variety of tasks. Some insights into biological locomotion have come from this biomimetic system.

3:40-4:10
"Mobility Enhancement Using Active Coordination"
K. Waldron, Ohio State University
The kinematic and energetic elegant engineering solution that wheels provide has made wheeled locomotion ubiquitous in our modern industrial society.

4:10-4:30 BREAK

4:30-4:40
"Specialized Wheels"
G. Paine, Jet Propulsion Laboratory
Large hooped wheels prove to be successful on the irregular terrain of the moon. This disproves the notion that wheels are a good invention only after the invention of the road.

4:40-5:10
Panel Discussion

Panel on Graphic Overlays in Teleoperation

WA10 - GRAPHICS AND GRAPHIC OVERLAYS IN TELEOPERATION
9:45 a.m.-1:00 p.m.
Moderator: D.B. Diner, Jet Propulsion Laboratory

9:45-10:15
"Graphic Overlays in High-Precision Teleoperation: Current and Future Work at JPL"
D.B. Diner, S. Venema, Jet Propulsion Laboratory

10:15-10:45
"Virtual Environment Workstation for Telepresence and Telerobotic Supervisory Control"*
S. Fisher, NASA Ames Research Center

10:45-11:15
"Head-Mounted Spatial Instruments II: Synthetic Reality or Impossible Dream"
S. Ellis, A. Grunwald, Technion, Israel

11:30-12:00
"The Effects of Overlay Graphics on Telepresence"*
R. Pepper, Naval Ocean Systems Center

12:00-12:30
"Use of Graphics in Decision Aids for Telerobotic Control"
T. Sheridan, J. Roseborough, H. Das, K.-P. Chin, S. Inoue, MIT

12:30-1:00
Panel Discussion

APPENDIX B
INDEX BY AUTHOR

APPENDIX C

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