A U.S.-Japan Collaborative Robotics Research Program

N95- 23698

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KEY WORDS AND PHRASES

Robotics, teleoperation, intelligent control, graphics user interfaces, space servicing.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) and the Electrotechnical Laboratory (ETL) have recently initiated a cooperative R&D effort in telerobotics. This new effort, sponsored by the U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of International Trade and Industry (MITI), has two major themes. First, our work broadens the outreach of space telerobotics R&D to international technical collaboration and facilities usage in the United States and Japan. This is natural, given plans for a common U.S.-Japan robotic presence on the International Space Station (the Japanese Experimental Module and U.S. Mobile Servicing Center), as well as ongoing U.S-Japan discussions of possible shared ground control assets. Second, our work fosters development and demonstration of new operator interface technologies to improve the flexibility and reliability of ground-to-orbit telerobotic operations. This new technology is important, given the continuing imperatives to off-load platform maintenance from the extravehicular activity/intravehicular activity (EVA/IVA) crew to on-board robot assists under direct ground mission control [1]. Permanent human capability and productive science on platforms such as the Space Station will otherwise be delayed.

COMMON TRADITIONS, COMPLEMENTARY STRENGTHS AT ETL AND JPL

JPL and ETL share a long-standing interest in human-computer cooperative control of robots, and its applications in casually structured tasks such as space assembly and servicing, hazardous materials handling, and telescience. Use of such supervised autonomy [2], versus total robotic automation, is necessitated because computer control of robots is not yet adequate to make complete task plans, learn tasks at the cognitive and motor skill of humans, or execute tasks with the dexterity of human servo-motor performance. At the other extreme, purely manual control of robots by teleoperation is often time-consuming and fatiguing, poorly suited to repeated actions of high precision, and impractical in scenarios where the operator's sensory feedback is significantly time-delayed. As regards the technologies they bring to the NASA-MITI collaboration, JPL and ETL have chosen complementary approaches to developing supervisory automation. JPL's approach, consistent with its space operations charter, derives from computer-augmented teleoperation [3, 4], the goal to date having been to maximize manual tasking dexterity and telepresence, and extend both to multiple-second time-delay remote-servicing scenarios. For example, JPL, utilizing its development of a dual eight-degree-of-freedom force reflecting teleoperator with multi-mode controls (position, force, rate, compliance, shared computer control of some axes) has recently re-enacted various aspects of the Solar Maximum Satellite repair mission conducted on shuttle flight STS-13; in this earth laboratory simulation, JPL telerobotically performed key sequences of this benchmark 1984 dual-EVA shuttle-bay servicing mission. Two JPL enabling technology developments have been *calibrated preview/predictive graphics displays* [4] and *shared compliance control* [3]. Using such a preview/predictive graphics operator interface and a related robot compliance control, JPL and NASA Goddard Space Flight Center (GSFC) recently performed simulated ground-to-orbit space telerobotic servicing under multiple-second variable communication time delay, wherein JPL successfully changed out an Orbital Replaceable Unit (ORU) of a Hubble Space Telescope-like spacecraft mock-up located some 4000 kilometers distant at GSFC [4].

By comparison to the above JPL work, ETL has recently emphasized higher level intelligent and cooperative control interactions between humans and robots [5, 6]. Consistent with a strong interest in flexible assembly operations, ETL seeks to relieve operator fatigue through automation, yet allow the operator to manually interact with robot automation with ease if needed. For example, ETL has demonstrated *intelligent and cooperative control* in robotic chemical assay by flame test. The robot, under supervised autonomy, sets up, pulverizes, samples and flame-tests chemical substances, with the operator intervening to graphically re-designate locations of desired actions or teleoperate to deal with task anomalies. ETL has developed the MEISTER (Model Enhanced Intelligent and Skillful Teleoperational Robot) system architecture to enable such supervisory control [5]. A key design feature of this architecture is the embedding of environmental and control knowledge within a collection of task-oriented object models, wherein the model representation itself is "object-oriented," e.g., each object model contains self-knowledge such as position and orientation with respect to world coordinates ("object localization") and its affixment relationships to other objects. The object models embed both generic and specific handling knowledge, such that the commanding of a control operation, e.g., **pick_and_ place**, invokes a linked hierarchy of processes, including the automatic sequencing of basic camera-viewing primitives [6].

NEAR-TERM PLANS AND PROGRESS

JPL and ETL separately fund their U.S.-Japan telerobotics R&D cooperation through projects respectively entitled "Distributed Space Telerobotics," and "Interoperation Technology for Long-Distance Robotics." These efforts, which independently develop their component technologies, converge in jointly implemented overseas system demonstrations. The first planned experiment (US-FY95) is *truss-based telerobotic deployment of a solar-powered Orbital Replaceable Unit (ORU) and electrical connectors.* This operation will be performed from JPL by a joint ETL-JPL team controlling an ETL robot. There will be a reciprocal operations experiment (US-FY96) from ETL to JPL where a joint JPL-ETL team will perform *telerobotic servicing of a limited-access ORU in a simulated Space Station environment.* In general, these experimental demonstrations and underlying technology developments highlight *robust telerobotic operation under uncertainty.* Major sources of operational uncertainty include effects of time delay, limited camera viewing, and lack of prior task knowledge. We are addressing two corresponding key technology needs [1]. The first technology need is to develop *an intelligent interface for operator visualization of complex workspaces*, as motivated by the requirements to safely perform robotic servicing tasks in physically obstructed, limited viewing access structures, and also to maximize viewing automation under well-structured operating conditions. Desired capabilities include a computer planned-and-task-synchronized presentation of the global workspace that fuses remote multi-camera video with 3-D graphics, and correlates this display with operator information requirements for specific task processes and interventions. Measurable outcomes will include: a) reduction of the operations time used for manual camera control during a task, which often outweighs manipulation time, and usually requires an additional operator, b) the capability, through a coherently integrated presentation of real and synthesized task views, to safely operate in scenarios where camera viewing alone is inadequate. JPL refers to this work as ***Intelligent Viewing Control (IVC)***, which is well-motivated by the limited camera resources and on-orbit time available for their use in future Space Shuttle/Space Station external robotic operations [1]. Other important IVC applications are areal surveillance, medical viewing, and flexible automation workcells. ETL and JPL both conduct related R&D, with ETL emphasizing object-based models for camera view planning. JPL, emphasizing the real-time integration of 3-D graphics and an AI-based view controller, carried out this year proof-of-concept robotics experiments with a first-cut IVC subsystem implementation.

The second, complementary technology need is to develop a *ground control interface for dexterous robotic tasking under extended (2-10 s) and intermittent time delays*, as motivated by the requirement to safely telemanipulate in casually structured, and a priori less-well-modeled scenarios. The problems of teleoperation at time delays exceeding one second are well known [2], and the most recent predictive graphics-based approaches [4], per above, have as yet advanced reliable operations to one-to-four seconds' delay for a priori well-modeled tasks. The desired new capabilities are to elevate the predictive graphics-and-compliance control paradigm [3] to a more flexible "teleprogrammed" form of supervisory control. In this new approach, the operator still manually inputs motions to a modeled task environment.

However, rather than these continuous operator motions being sent directly to the robot, they are first parsed by computer to discrete low-level autonomous commands, which are then communicated to the remote site asynchronously. Once received, the commands are interpreted by the robot controller as simple guarded motion control primitives referenced to real-time robot sensor data. This approach enables introduction of intelligent, corrective robot behaviors to compensate for problems that the time-delayed operator cannot immediately address -- we note some preliminary progress below. Measurable outcomes of this work will include: a) successful demonstrations of the teleprogrammed mode at time delays up to 10 seconds for representative **align, cut, grasp, insert and detach** operations, b) application to situations where prior object model knowledge is of low quality (re: shape, position, orientation), requiring either significant qualitative control adaptation by the robot and/or on-line task model refinement by operator-interactive 3-D graphics acquisition-and-calibration. JPL refers to this work as ***Intelligent Motion Control (IMC)***, which is well-motivated by needs for more flexibly structured ground control of spacecraft EVA/robotic maintenance and telescience handling on the Space Station [1].

ETL and JPL initiated experimental interactions and reciprocal engineering visits between our robotics laboratories in fall 1993. To date, ETL-JPL have performed several simple experiments to verify basic inter-lab operability. Also, JPL, working with the University of Pennsylvania, implemented and demonstrated important elements of an IMC subsystem.

ETL->JPL Remote Operations. JPL and ETL engineers, working together at ETL's Intelligent Interface Systems Lab, remotely commanded the guarded motion trajectory of an 8-degree-of-freedom JPL arm about the perimeter of a satellite ORU access panel door, simulating a proximity operations inspection (eye-in-hand camera).

JPL->ETL Remote Operations. JPL engineers commanded a robot at ETL in simple pick-and-place operations, via a high-level control interface. JPL sent the ETL robot control commands via a socket connection over Internet, from a LISP control program at JPL, to another LISP robot control program at ETL. Workspace models that enabled successful execution were resident within the robot control program at ETL.

Intelligent Motion Control. JPL, working with University of Pennsylvania researchers [7] installed at JPL a real-time robot controller and command interfaces that compose the robot site of a "teleprogramming" facility, wherein the operator will command a time-and-space distant robot over communication links that may have variable delay. The fundamental University of Pennsylvania contribution in this work includes development at JPL of a novel layered behavioral control architecture. When active, this behavioral control replaces a more conventional hybrid position/force control, as conventionally used to correct quantitative variations in robot force and position along various axes of robot tool or gripper contact with an object of interest [3], and can autonomously compensate and strategically correct for undesirable qualitative changes in the task state, as determined by the robot sensors. For example, the controller can assist a time-delayed operator in dealing with sudden, unpredictable disturbances and variations in contact with a workpiece being serviced, or object encountered. JPL-UPenn successfully demonstrated in January 1994 use of the behavioral controller to puncture and slice a Kapton tape seam securing satellite thermal blankets about a replica ORU main electronic box (MEB) access panel door. The controller successfully managed multiple, unpredictable metal-to-metal sidewall contacts as a cutting tool traveled laterally in a 2-mm-wide groove of a continuous 40-cm path sweep. Such tasks have challenged the skills of even experienced human operators in teleoperations tests.

ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. JPL participants include Won Soo Kim, Eric Paljug, and Stephen Peters; the ETL team includes Kazuo Machida and Yujin Wakita, and a collaboration with Kawasaki Heavy Industries, Inc. The authors appreciate the assistance of Charles Weisbin (JPL) and Kunikatsu Takase (ETL) in developing the NASA-MITI cooperation.

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