NASA'S AUTOMATION AND ROBOTICS TECHNOLOGY DEVELOPMENT PROGRAM

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Abstract

This paper provides an overview of NASA's Automation and Robotics (A&R) technology development program, covering its objectives, development, assumptions, structure, content, plans, organization, and relation to other NASA A&R programs. This program is being carried out by the Office of Aeronautics and Space Technology (OAST), which has the responsibility to provide the long range, high risk, high payoff technology to maintain the United States' preeminence in Space, and to manage the Space Research and Technology program as a national resource to serve NASA, commercial and military needs. To do this, NASA promotes innovative technology options and insures timely technology readiness and transfer to user programs. One of these innovative technology options is Automation and Robotics.

1. Introduction

America's Space program is maturing. In the 1960s, the technological feasibility of both manned and unmanned missions was proven. In the 1970s with Skylab and Shuttle the utility of space operations was demonstrated. The focus of the 1980s is the development of technology to render space operations economically feasible for commerce and for science. Success in this endeavor will ensure that the 1990s and beyond will be the era of affordable and beneficial space missions.

Three key issues to enabling the economic feasibility for commerce and science are: 1) reducing the cost of mission control. This includes both the manpower for ground control and for astronaut on-orbit time spent in unproductive housekeeping functions. 2) Increasing the operational capability of the astronauts. This includes giving them the tools to enable the assembly, servicing and repair of spacecraft distant from their base vehicle. 3) Increasing the probability of mission success. This includes the capability to work around system failures and to immediately recapture and repair malfunctioning satellites launched from space. Without higher assurances of mission success, the difficulty of obtaining reasonable insurance will hinder commercial development of space. Innovative technology options for reducing mission control cost, increasing operational capability and increasing the probability of mission success lie in the field of automation and robotics.

In transitioning from the Shuttle to Space Station, the trend will be to increase the versatility and lifetime of space systems while reducing their complexity and cost. In terms of A&R this translates to transitioning from a human-managed, computer-aided system to a human-supervised, computer-managed system. This will be accomplished by developing intelligent automated "assistants" for performing two types of tasks, intellectual and manipulative. Intellectual (cognitive) tasks for automation include: planning, scheduling, fault diagnosis and information interpretation. Automation of manipulative tasks will focus on assembly, servicing and repair. While it is often useful to describe intellectual and manipulative functions separately, they are actually highly intertwined. For example, intellectual planning that does not lead to some action is of little practical use, and manipulative action that is not preceded by planning is dangerous. Remote manipulation in which all of the intellectual input is from the human controller is called teleoperation. When higher level goals are input by the human and the machine is left to determine how to implement them, the process is referred to as supervisory control and the remote manipulator is called a telerobot.

Automation and robotics are not new to NASA. Tom Wolfe's historical novel, The Right Stuff, dramatically made the point that the planned Mercury flights were so automated that the astronauts felt they would be little more than passengers. Unmanned missions such as Ranger and Viking were highly autonomous. NASA's heritage in robotics is obvious in the Viking Mars Lander and the Shuttle's Remote Manipulator System. While A&R have enjoyed a proud history at NASA, they have recently emerged as an even more highly visible agency focus. In September 1984 NASA Administrator James M. Beggs characterized this evolving agency focus on A&R when he said, "Since the dawn of the space age we have been sending unmanned automated extensions of our intelligence into space. Our manned spacecraft all have some degree of automation and plans for Space Station have always called for the use of remote manipulators and advanced control devices. Indeed, the Space Station offers the opportunity to develop the exciting potential of automation and robotics to the fullest. A new generation of

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these technologies could free humans in space for *the jobs they do best.*"

As A&R has achieved this new emphasis at NASA, the meaning of the term has also evolved. For example, previously at NASA, all automation has been of the "hard" or preprogrammed type, as opposed to automation based on artificial intelligence technology. Hard automation is efficient, precise and repeatable, but it is neither flexible nor robust in that if it fails it reverts to a more primitive mode of operation or it stops. It cannot operate outside of narrow tolerances in the environment. The goal of intelligent automation is to increase robustness by enabling workarounds automatically, and to increase flexibility by enabling it to cope with a greater variety of circumstances through increased sensing and through cognition based on that sensed data and on stored knowledge. The technology to achieve these capabilities is called artificial intelligence (AI).

Artifical intelligence is the discipline of developing and applying computing systems to produce characteristics usually associated with human behavior, e.g. speaking and understanding language, learning from experience, logical reasoning, problem solving, and explaining its own behavior. AI differs from conventional computing systems in that it does not depend on algorithmic solutions, but instead uses heuristics to make conclusions an incomplete or uncertain data. An expert system is a computer program that uses knowledge and inference to solve problems that are difficult enough to require significant human expertise for their solution.

There have been two related factors behind this increased NASA focus on A&R. The first is the inception of the Space Station project. The second is recent congressional interest which was made clear on July 18, 1984 in Public Law 98-371, which stated that NASA shall identify "space station systems for which advanced automation and robotics technology is not in use in existing spacecraft, and that the development of such systems shall be no less than 10 percent of the total space station costs."

That same public law gave birth to two groups: the Advanced Technology Advisory Committee (ATAC), a group of NASA experts which was formed to make the report mandated by Public Law 98-371 to Congress; and the Automation and Robotics Panel (ARP), a group of non-NASA experts from industry, academia, and government which was formed to provide an independent set of recommendations to NASA. More specific to the point of this paper, as a result of this congressional interest, NASA initiated an effort to focus its research and technology effort, as carried out by, the Office of Aeronautics and Space technology (OAST), in the directions then under development by ARP and ATAC.

The fields of artificial intelligence and of robotics are enjoying a surge of interest and activity not only at NASA, but throughout the rest of the world as well. This enthusiasm, however, must be tempered with an understanding of the state of the art. There are fewer than a half dozen expert systems in operational use in the United States, and while there are teleoperated remote manipulators in use in the nuclear and marine industries, none of them have built-in intelligence capabilities. However there is every reason to believe that an aggressive R&D program, which builds on the component technologies for telerobotics and expert systems currently under development in industry and academia, and which fosters the developments that are specific to NASA's needs, can engender an A&R technology base which forms the cornerstone of an era of affordable and beneficial space missions in the 1990s and beyond.

To this end OAST has developed an A&R technology development program. Its objective is to exploit the potential of artificial intelligence and robotics to: 1) decrease the cost of ground control, 2) increase the capability and flexibility of space operations, and 3) increase the probability of mission success. Artificial intelligence (AI) technology will be used to reduce the size of the ground control contingent, and telerobotics will be used to enable increased space assembly, servicing, and repair. The goals of the program are: 1) to decrease mission operations manpower by 75 percent, 2) to replace 50 percent of extra-vehicular activity (EVA) with telerobotics, and 3) to enable remote (e.g. geosynchronous earth orbit and polar orbit) assembly, servicing, and repair through telerobotics. The remainder of this paper describes this program.

2. Program Development

The OAST A&R program had its roots in the 1977 NASA Study Group on Machine Intelligence and Robotics, which was chaired by Carl Sagan. This group found the NASA had fallen behind the leading edge in computer science and that machine intelligence and robotics technology was essential to render future space missions economical and feasible. As a result of this study, OAST began research on artificial intelligence (AI) in 1980 with a focus on planetary missions. In 1980 a summer study was held on A&R for future missions. In 1982 OAST initiated a Computer Science program emphasizing AI and robotics. Also in 1982 the House of Representatives held hearings on robotics for terrestrial applications in which OAST participated. That was the beginning of the Congressional interest in A&R. In 1982 OAST initiated a Space Human Factors program which focussed on telepresence (teleoperation with advanced sensory feedback) and on the supervisory control of highly automated systems. In 1984 the legislation enabling space station was passed and Congress showed an increasing interest in A&R as demonstrated by Public Law 98-371. ARP and ATAC were formed in 1984, and OAST integrated the relevant portions of the Computer Science and Human Factors programs to focus on directions being espoused by ARP and ATAC. In 1985, the two integrated OAST programs were formally merged into a single A&R program, and a close coordination of this program with the Space Station Office was initiated.

3. Assumptions

When OAST initiated its focussed and augmented A&R program in late 1985, the new program was based on an 18 month planning effort by personnel from six NASA centers under the management of OAST's Information Sciences and Human Factors Division (Code RC). Two groups were formed: 1) on A&R Working Group consisting of two intermediate level (branch and division chiefs) representing each center and chaired by the Code RC A&R program manager, to integrate the proposals from each of the centers, and 2) an A&R Steering Group consisting of one high level (director for or division chief) participant from each center and chaired by the Code RC Division Director, to provide overall programmatic and management direction to the program. The Steering Group developed a set of planning assumptions which were followed in the development of the current OAST A&R program. These assumptions were:

(1) There will be two foci: telerobotics and systems autonomy (i.e. expert systems).

(2) Each focus will have a series of ground demonstrations of an evolutionary testbed to show increasing capability of integrated technologies.

(3) There will be a core technology program to develop the capabilities needed to enable the demonstration sequences.

(4) The resource balance will be 2/3 for core technology and 1/3 for the demonstration sequences.

(5) Any flight demonstrations will be funded in conjunction with the user codes (M and S) with OAST (Code R) funding only limited to initiation efforts.

(6) The two ground demonstration sequences will take place at a single, but possibly different, center.

(7) The core technologies will be developed at various sites.

(8) Government, industry and university research will be leveraged by investing 40 percent of the program funding out of house.

(9) For each focus, the technology development will be evolutionary rather than revolutionary, that is, it will begin with an early demonstration of current capabilities and move forward in aggressive but reasonable increments.

(10) Teaming arrangements will be established to link research centers, user centers, NASA program offices, and appropriate universities and industries.

4. Program Architecture

The conceptual architecture for an automated system is shown in Figure 1. The controller interacts with an Operator Interface station at which he can make control inputs and monitor the system. At the other end of the system is a Control Execution subsystem, which acts on the environment, and a Sensing and Perception subsystem which senses the effects of those acts. If the Operator Interface subsystem and the Control Execution subsystem are connected directly, it would not be considered an intelligent system, since the only intelligence involved would be that of the human controller. When an intelligent Task Planning and Reasoning subsystem is placed between the operator and the Control Execution subsystem, then the system can be termed automated or intelligent. There are degrees of intelligence. A highly intelligent system would have a Planner to determine subtask sequences, an Executor to turn those subtasks into machine commands, a simulator to predict what should happen, a Knowledge Base on which to make decisions should anything be off-nominal, a Monitor to determine what is happening, and a Diagnoser to make the determination of what did go wrong.

This architecture holds both for intellectual and for manipulative tasks and emphasizes the interaction of the two. For practical purposes intellectual tasks generally refer to those which are primarily intellectual and which involve only simple mechanical movement as a result, while manipulative (telerobotic) tasks refer to those in which the manipulation component is quite complex. Only recently have programs been implemented to integrate the two. One of the first, and one of the most well known is DARPA's Autonomous Land Vehicle (ALV). In 1985 the ALV demonstrated that an intelligent system with a state of the art vision system could control a military vehicle's movement down a road at 5 kilometers per hour. Next year it will go twice as fast and will be able to follow the road around corners. The OAST program will leverage the more highly funded DARPA program as much as possible.

The OAST program has two foci, system autonomy and telerobotics, as described above. Each focus has a demonstration sequence. Underlying the two foci is a core technology program which is consistent with the architecture of an automated system as described in Figure 1. The core technology program has five elements: sensing and perception, task planning, control execution, operator interface, and system architecture and integration. The demonstration sequences are described in Section 5 of this paper, and the core technology program is described in Section 6.

While OAST is conducting research in each of the five core technology areas, it is also depending on technology development from other programs such as DARPA's Strategic Computing Initiative (SCI), of which the ALV described above

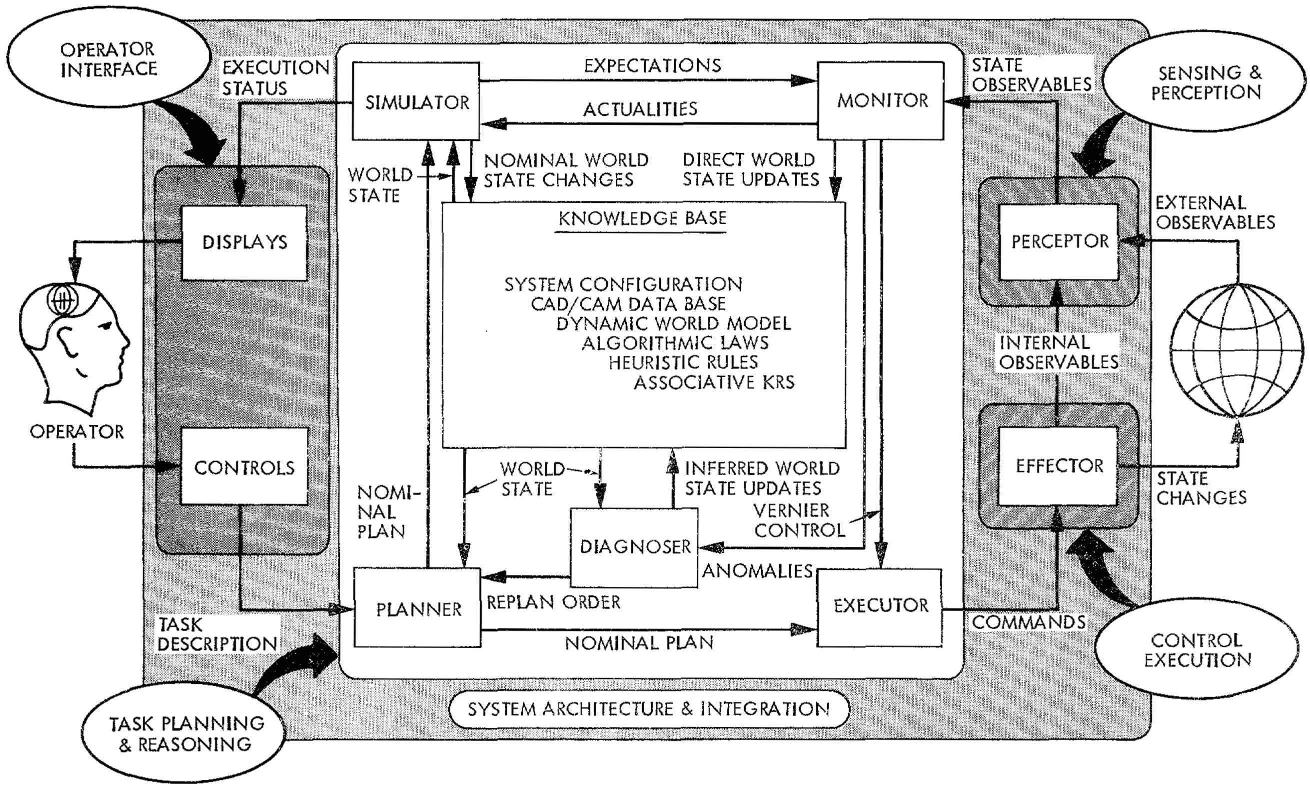

Figure 1. Automated System Control Architecture

is a part. In specific technology areas NASA will lead the technology development effort (e.g. space manipulators, robot mobility in space, man/machine interfaces, knowledge representation, acquisition tools for domain-independent systems, fluids transfer technology, and space repair technology). In other areas NASA will leverage the technology efforts of DARPA, NBS, industry and universities (e.g. robot/sensor integration, high-level robot programming languages, distributed database technology, knowledge-base system development, sensing algorithms). Finally in certain areas NASA will exploit available technology (e.g. lightweight motors, computer architecture, integrated circuit technology, display technologies).

5. Ground Demonstrations

Each focus of the OAST A&R program, telerobotics and systems autonomy, has a planned ground demonstration sequence. Planning these sequences has a number of benefits. It insures that the value of the component technologies will be tested in an integrated manner, and it permits a periodic evaluation of the overall state of the art in each field. It also provides an objective method for determining the component technologies to be developed, the desirable timeframe for each, and the relative funding to be provided for each. It provides a magnet for relevant component technologies being developed outside the program. Finally, and perhaps most importantly, it permits potential users to provide the program with feedback as to its potential usefulness, and as to how to make it more useful. The two ground demonstration programs (sequences) will now be described. Each begins with an early demonstration of current capability and proceeds with an evolutionary sequence of demonstrations through the late 1990s.

A. Telerobotics

The thrust of the telerobotics focus is to evolve the technology of remote manipulation from its current state of teleoperation (i.e. direct manual control of a remote manipulator by humans) to telerobotics (i.e. supervisory or task-level control of a remote manipulator) and then to evolve that to even higher levels of supervisory control. There are two possible paths to the development of intelligent, highly autonomous and capable robots. One is to proceed from teleoperation and provide successively greater numbers of automated features and capabilities. This approach provides high overall system capability because the sensory, perceptual, cognitive, and manipulative capabilities of both automation and the human are available. It also provides for a robust system because a human is available to take over when parts of the system fail or when unexpected anomalies occur in the environment or in the system being serviced. The alternative is to start with fully automated robots such as those used in automotive manufacturing and develop the technology to render them increasingly flexible. This approach holds the nearest-term promise of technology development which will be useful to terrestrial industry, and thus was the approach selected by the National Bureau of Standards in their robotics program. While both approaches have advantages, virtually all of NASA's advisors, including the five major aerospace contractors (General Electric, Hughes, Martin Marietta, TRW, and Boeing) that participated in the ATAC study to respond to Public Law 98-371 (see Section 2) selected the former, that is, to evolve teleoperation to robotics. Recently the Space Station Office was tasked by Congress with developing a remote manipulator flight-article to be ready for use at Initial Operating Capability (IOC), and they selected the approach of evolving teleoperation to telerobotics. This is also the approach selected by the OAST program, which is working closely with Space Station in their development of the remote manipulator.

Evolving teleoperation to telerobotics involves not only adding and evolving the capability for intelligence, but also improving the capability for dexterous manipulation. The present state of space remote manipulation is the Shuttle's Remote Manipulator System (RMS), which is designed to move payloads in and out of the cargo bay. When more dexterous, two-armed capability is needed, a suited astronaut is placed in foot restraints at the end of the RMS. Terrestrial teleoperation is capable of two-armed remote manipulation, but it is not very dexterous. The best such teleoperator is at the Oak Ridge National Laboratories (ORNL), and when used by a highly skilled operator, can assemble and disassemble nuclear power plant equipment. An even more capable device is now being built at ONRL. Neither version has artificial intelligence nor the capability to be upgraded for autonomy.

The telerobotics ground demonstration sequence is shown in Figure 2. It begins with a two-armed telerobot that can perform servicing (e.g. module exchange) on robot-friendly satellites, and has some limited autonomous capabilities. This will be the first telerobot ever built with its own intelligence for planning and control execution. More importantly, it will have an architecture to permit its level of intelligence to be increased in subsequent demonstrations. As the demonstration sequence progresses, the telerobot will become more autonomous and more flexible in handling different types of tasks, and it will become more robust in terms of detecting and working around anomalies autonomously.

In the second demonstration, the testbed will be able to grapple and de-spin a tumbling satellite. In the third, it will be capable of local mobility. Then comes the capability for fabrication, and finally at about the turn of the century, the goal is to have autonomous cooperating robots.

Figure 3 shows a concept drawing of the FY 1987 demonstration. The target FY 1987 demonstration is a satellite sevicing task in which highly structured coordination-level activities (e.g. grasp, move, open, etc.) will be enabled by an autonomous run-time control implemented through the teleoperative interaction by a human supervisor. Prototype tasks include Orbital Replaceable Unit (ORU) replacement and fluid transfer. Major milestones in FY 1986 include: completion of detailed testbed functional and mechanization designs, taskboard design and facility preparation, and fabrication of assemblies of the sensing and operator control subsystems.

The telerobot will have a generic control architecture which incorporates process-level planning, trajectory planning, and execution monitoring into an embedded run-time control system capable of dual-arm ORU exchange. This task will be typical of EVA ORU replacement tasks such as those that occurred on the Solar Max repair mission.

- 1987 – STATIONARY ROBOT, SIMPLE SPACECRAFT SERVICING TASKS, SUPERVISORY CONTROL

  STATIONARY TWO-ARM TELEROBOT PERFORMS KNOWN SIMPLE TASKS ON COOPERATIVE SPACECRAFT USING HAND AND POWER TOOLS. LIMITED AUTONOMY

- 1990 – MOBILE ROBOT, SPACECRAFT SERVICING/RETRIEVAL, EXECUTIVE CONTROL

  MOBILE MULTIARM ROBOT PERFORMS KNOWN SIMPLE TASKS ON COOPERATIVE SPACECRAFT. LIMBER ARM INTERACTIVELY ACQUIRES AND DESPINS SPACECRAFT

- 1993 – SPACE SERVICING AND ASSEMBLY

  MOBILE MULTIARM ROBOT PERFORMS MODERATELY COMPLEX SERVICING AND ASSEMBLY TASKS INVOLVING MULTIPLE ELEMENTS

- 1996 – UNPLANNED REPAIR REQUIRING FABRICATION

  MOBILE, MULTIARM ROBOT INSPECTS, TESTS, AND REPAIRS DAMAGED STRUCTURAL AND MECHANICAL ELEMENTS. TASK INVOLVES DISASSEMBLY, CUTTING, AND MINOR FABRICATION

- 2000 – COOPERATIVE ROBOTS, COMPLEX GOAL-DRIVEN TASKS

  COOPERATING MOBILE TELEROBOTS PERFORM COMPLEX TEMPORARY AND PERMANENT REPAIRS OF DAMAGED ELEMENTS USING AUXILIARY SUPPORTS, GUIDES, AND POWER TOOLS. PERIODS OF AUTONOMY MEASURED IN MINUTES

Figure 2. NASA Space Telerobot Laboratory Demonstration Sequence

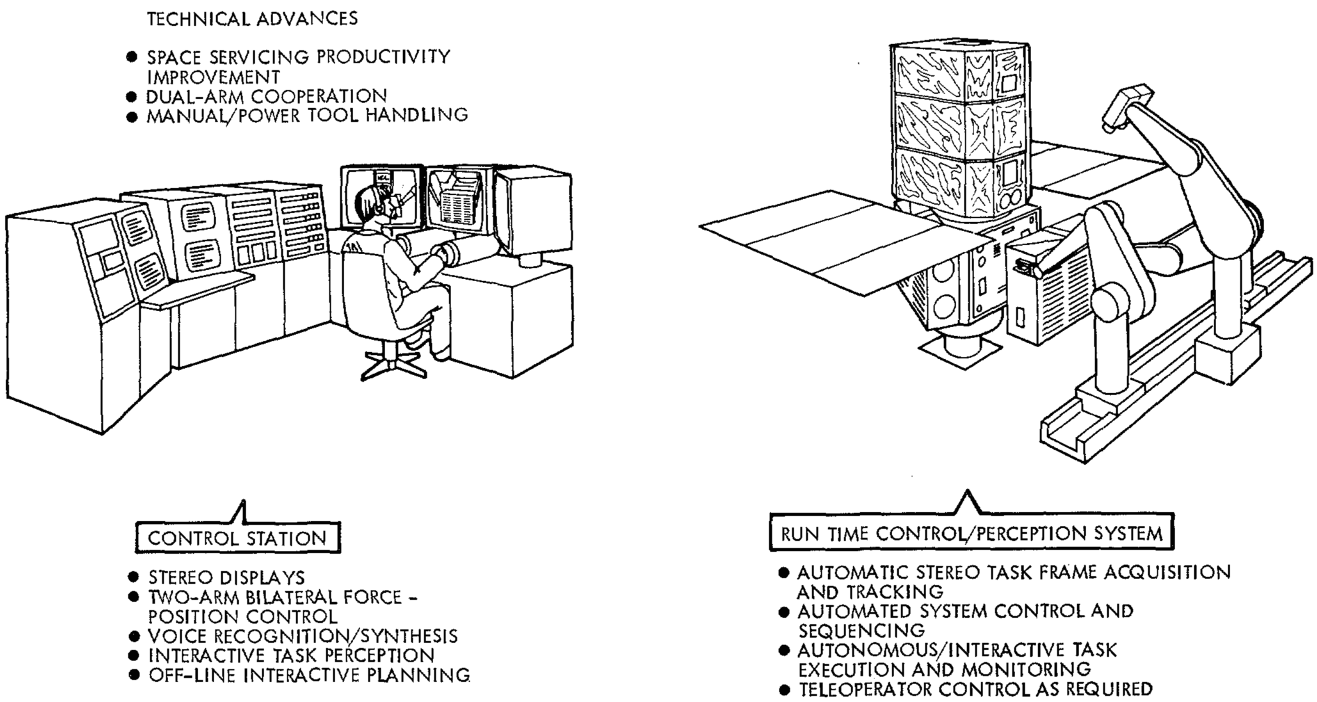

Figure 3. Space Telerobotics 1987 Demonstration

Coordination-level autonomy will be demonstrated in FY 1987. Process-level autonomy will be demonstrated in FY 1990. Process-level refers to a structured sequence of coordination-level tasks. An example of a process-level task would be "remove module from bay," which is comprised of coordination-level elements as: acquire task frame, detach panel, remove, stow, etc.

The Jet Propulsion Laboratory is responsible for the telerobotics ground demonstration program, and will be the site of the testbed,

B. System autonomy

The thrust of the system autonomy focus is to develop and integrate artificial intelligence technology for the intelligent automated control of complex dynamic systems. This means more than the ability to control the system automatically during nominal operation. It means that the automated control must be robust to both small and large anomalies, some of which have standard malfunction procedures and some of which are unanticipated or at least have no precedent. At the present time, all unanticipated problems, as well as many anticipated problems, and often even system monitoring during nominal system operation, are handled by humans. The goal of the systems autonomy focus is to reduce the size of the ground control contingent by developing and applying the techniques of artificial intelligence.

The systems autonomy demonstration program has two goals:

1) Development and integration of generic software tools for the management and operation of complex dynamic systems.

2) Development, test and validation of system and subsystem planning and control technologies for automation of ground and on-board operations.

Ames Research Center is responsible for the systems autonomy ground demonstration sequence. The site of the demonstrations will be the Johnson Space Center. Demonstrations will be held in FY 1988, 1990, 1993, and 1996, as shown in Figure 4.

As can be seen in Figure 4, the capabilities of artificial intelligence technologies for control of complex dynamic subsystems will evolve from control of single subsystems in 1988, to control of multiple subsystems in 1990, to hierarchical control of multiple subsystems in 1993, and to distributed control of multiple subsystems in 1996. As the capability of artificial intelligence increases, the role of the remaining human supervisory controller changes. The AI demonstration capability will evolve from what might be termed an intelligent "aide" in 1988, to an "apprentice" in 1990, to an "associate" in 1996.

The implication is that as AI capability evolves, and as confidence in it increases, fewer people will be needed as controllers. However some controllers will remain. They will be fewer in number, have qualitatively different roles and responsibilities (i.e. higher levels of supervisory control), but they will retain the top-level authority and responsibility. They will

1988 AUTOMATED CONTROL OF MISSION OPERATIONS SUBSYSTEM ("INTELLIGENT AIDE") • MONITOR/SIMULATED CONTROL OF A SINGLE SUBSYSTEM • GOAL AND CAUSAL EXPLANATION DISPLAYS • RULE-BASED SIMULATION • FAULT RECOGNITION/WARNING/LIMITED DIAGNOSIS • SCHEDULING/RESCHEDULING • REASONING ASSUMING STANDARD PROCEDURES	1990 AUTOMATED CONTROL OF MULTIPLE SUBSYSTEMS ("INTELLIGENT APPRENTICE") • COORDINATED CONTROL OF MULTIPLE SUBSYSTEMS • OPERATOR AIDS FOR UNANTICIPATED FAILURES • MODEL-BASED SIMULATION • FAULT DIAGNOSIS FOR ANTICIPATED FAILURES • PLANNING/REPLANNING • REASONING ABOUT NONSTANDARD PROCEDURES
1993 HIERARCHICAL CONTROL OF MULTIPLE SUBSYSTEMS ("INTELLIGENT ASSISTANT") • MULTIPLE SUBSYSTEM CONTROL: GROUND AND SPACE • TASK ORIENTED DIALOGUE AND HUMAN ERROR TOLERANCE • FAULT RECOVERY FROM UNANTICIPATED FAILURES • PLANNING UNDER UNCERTAINTY • REASONING ABOUT EMERGENCY PROCEDURES	1996 DISTRIBUTED CONTROL OF MULTIPLE SUBSYSTEMS ("INTELLIGENT ASSOCIATE") • AUTONOMOUS COOPERATIVE CONTROLLERS • GOAL DRIVEN NATURAL LANGUAGE INTERFACE • FAULT PREDICTION AND TREND ANALYSIS • AUTOMATED REAL TIME PLANNING/REPLANNING • REASONING/LEARNING, SUPERVISION OF ON-BOARD SYSTEMS

Figure 4. Systems Autonomy Demonstration Program

insure that the changing needs and wants of the user communities are taken care of as well as possible, using available automation as a tool to see that changing tasks are accommodated as effectively, efficiently and safely as possible.

The initial demonstration (1988) will be of the "Integrated Communications Officer" (INCO) subsystem for the Shuttle. The INCO is a "front room" control position in Mission Control which manages shuttle communications and instrumentation systems. There are three support personnel in the "back room" assisting the INCO.

Candidates for the 1990 demonstration are being evaluated. They include: the electrical/environmental/consumables mechanical engineer (EECOM), the propulsion subsystem, the data-processing subsystem, and the payload subsystem.

6. Core Technology

The core technology program is responsible for developing the component technologies which are then transferred to the telerobotics and/or the systems autonomy demonstration programs for integration into the evolutionary test-beds. The core technology program has five areas: sensing and perception, task planning and reasoning, control execution, operator interface, and system architecture and integration. The particular R&D projects in each area change as developments are transferred to the testbeds. The current projects in each of the five areas will not be described.

A. Sensing and perception

The sensing and perception area will develop hardware/software systems for all types of sensing including: vision, tactile, force/torque, and proximity. At the present time there are two projects, both in vision sensing. The objective of research in machine vision is to develop the capability to recognize, acquire and track objects and to verify actions in space operations.

1) Programmable Image Feature Extractor, PIFEX (JPL)

In 1986 an end-to-end demonstration of the acquisition and tracking of simple unlabelled objects will be performed. Also underway is the testing and validation of a scheme for locating and tracking simple labelled objects. Development of a real-time vision processor will continue, culminating in 1987 in an implementation of a 120 module advanced image processing system, PIFEX, capable of some ten billion operations per second on image data. PIFEX will allow real-time identification of complex object features, stereo correlation, and other computation-intensive vision functions.

2) Focal Plane Array Processor (LaRC)

The second element of the sensing and perception area is the development of a focal plane array processor which will reduce the numerical computation load on a machine vision system by performing some of the data reduction optically at the sensor.

B. Task planning and reasoning

This area covers the artificial intelligence R&D which will form the basis for intelligent monitoring, planning, operating and diagnosing of systems both in ground control and in telerobots. It has three elements.

1) Decision Making (JPL)

This tasks includes interactive goal-driven planning, spatial planning for multi-arm telerobots and planning with uncertainty. The approach on interactive, goal driven planning will be to integrate DEVISER and PLAN-IT. The FAITH diagnoser program will begin extension to allow multiple, temporal and spatial failure reasoning with intelligent search-space reduction and the ability to reason about permissible execution deviations due to uncertainty. Plan-driven execution monitoring will continue with the development of plan simulation capability.

The approach in knowledge-based system development tools is to complete a prototype of the Multiple Reasoning Engine (MRE). The Multiple Reasoning Engine is composed of a Blackboard, Conditions Model, Memory Model, Process Model, Reasoning Engine Design Language (REDL), Graphics Debugging Tool, and a Time Representation Model. The approach on integration of knowledge-based subsystems will be to use the blackboard interface of the MRE for integrating subsystems into a cooperating structure. The blackboard architecture allows data, task requests, and knowledge to be shared among the various knowledge-based subsystems.

2) Computer Assisted Design (CAD) Planner (GSFC)

CAD based telerobot planning consists of using the detailed computer-readable geometric descriptions of spacecraft and payloads that result from the computer aided design (CAD) process, and transforming them into a knowledge base useable to automatically plan the robot motions needed to accomplish servicing tasks. Two basic types of robot plan can be built by AI programs operating against this geometric knowledge base: the macro-plan that defines the sequence of operations and the gross motions needed to avoid obstacles, and the micro-plans, for instance, that might cover the motions needed to get the tool and use it to remove a bolt. An important consideration in either type of plan is that the execution of the plan has to involve real world uncertainties and the consequent modifications of the plan to accommodate them when necessary.

3) Knowledge Based Systems (ARC)

The primary focus of the research is the development of AI technologies leading to advanced machine intelligent systems for imagery and pattern recognition applications. The critical research component centers around knowledge engineering and includes technology elements such as: knowledge extraction and understanding from multiple data sources; representation of that knowledge; maintenance of data base consistency; automated software development, verification and validation to minimize the need for skilled knowledge engineers; and machine learning algorithms. Research products include expert systems development tools for planning, scheduling, fault diagnostics, monitoring and control, world simulation, systems analysis/interpretation/configuration, and training; executive controllers; and machine intelligent systems.

C. Control execution

The objective of this research is to develop, evaluate, and apply telerobotics guidance and control technology for space applications, and to advance the state of the art in manipulator control. The approach is to investigate cooperative human/machine tasks and to augment teleoperator functions through the application of advanced computer- and sensor-based control technology, to automate the system and to elevate the operator to a higher level of supervisory control. There are three elements.

1) Telerobot Guidance and Control (LaRC)

In 1986 basic research in adaptive control of manipulators will be investigated both in the ROBSIM robotics simulation and on actual manipulator hardware in the Intelligent Systems Research Lab (ISRL). The primary emphasis is the implementation and evaluation of adaptive control algorithms to handle varying loads and inertias, and to address the interaction of a manipulator mounted on a moving base. Algorithms for the coordinated control of multiple manipulators performing a cooperative task will be developed and evaluated in early 1986. A joint program with NBS and the Army will result in a prototype laser scanning/designator system which will be evaluated in the ISRL. A high accuracy proximity sensing design based on the laser system is being developed. These basic research results will be implemented in late 1986 to accomplish a realistic space servicing task. Fairchild has developed a satellite refueling connector which will be tested on a future shuttle flight. The refueling task will be automated in the ISRL so that the task can be accomplished faster, and the human can function as a supervisor, with manual (teleoperator) control available as a back up or contingency option.

2) Teleoperator Control (JPL)

The objective of this work is twofold. (1) Development and evaluation of modular and expandable distributed microcomputer hardware and software system matching the natural needs of real-time mechanization of manipulator control in space applications. (2) Development and evaluation of new prototype smart and effectors with microcomputers integrated into the end effectors for sensor and control data handling and interfaced to the overall distributed real-time manipulator computer control system. The natural needs of advanced manipulator control in space include: (a) distribution of real-time control computing between control station and remote manipulators equipped with smart end effectors and tools and (b) the use of alternative, interchangeable and interactive control techniques like (i) generalized force-reflecting hand controller equipped with force-reflecting hand trigger, (ii) sensor-referenced automatic control and (iii) supervisory control, including interface to task planning expert systems. The notion of expandable control mechanization includes the capability of extending the distributed microcomputer system to the coordinated control of multiple-arm systems.

3) Limber Manipulator Control (ARC-Stanford)

The long term objective of this research is to develop methods for controlling satellite based manipulators during the real time performance of orbital assembly and handling tasks. The research focus is on fast, precise control of the endpoints of manipulators using direct spatial measurements of endpoint position and target position, and development of control strategies for teleoperation at a supervisory level, i.e. giving the astronaut cogent dynamic insight and task management authority. Included with this research effort is the demonstration of air cushion vehicles equipped with flexible (limber) manipulator systems. These vehicles are being used to obtain precise data on the dynamics and control of service spacecraft intended to interact with target spacecraft via flexible manipulators. Problems involving the realtime control and execution of autonomous systems are part of the overall research effort. Research in the Task Planning and Reasoning element of the core technology program is being integrated into this effort.

D. Operator interface

The goal of the operator interface research is to develop the capability to evolve human control of remote manipulation from teleoperation (manual control of remote manipulator) to supervisory control (giving task-level commands and letting the computer generate the implementation plan). This includes being able to monitor the telerobot, to aid it in doing what it is not yet capable of doing automatically, and to take over when the automation fails or degrades into a telepresence mode (i.e. teleoperation with rich sensory feedback). There are three elements:

1) Operator Station Human Factors (JPL)

New operator control/information interface concepts will be designed and tested in a stand alone mode and in an integrated control station environment, focusing the development and data-gathering/modelling efforts on human factors issues related to operator interface with dual arm telerobots. Experimental investigation will be carried out on: (1) the effects of alternative display techniques of visual and non-visual sensor information on operator's perceptive/cognitive performance, (2) operator's manual control performance using generalized Task-level and force-reflecting control techniques, including the effect of microgravity on operator performance, and (3) language-like interface methods to supervisory control of telerobots. Function allocation between operator and sensor/computer/based-automation will be investigated for various task and operational constraints, including time delays, using appropriate task boards. A feasibility study is also carried out for automating stereo vision systems.

2) Visual/Tactile Feedback (JPL-NOSC)

The objective of this research effort is to develop and evaluate tactile display systems suitable for integrating tactile information into the direct human and supervised control of remote manipulators. The effort covers both unimodal and cross-modal information feedback possibilities and methods. Also included in this research work is the development of techniques (i) for combined tactile and visual information displays, (ii) for mixing tactile (cutaneous) sensor data with robot hand internal state (kinesthetic/proprioceptive) sensor data to create haptic information, that is, to recognize shapes of objects by grasp, and (iii) for mixing tactile data with robot hand motion to create information on shapes, contours, etc.

3) Supervisory Control (JPL-MIT)

The objective of this research is to develop a quantitative understanding of human factors parameters involved in supervisory control of remote space manipulators. The supervisory control concept covers a broad spectrum of human involvement in the remote control: bilateral task-level manual control exercised through an adjustable computer loop, shared and traded manual and automatic computer controls referenced to task models and to sensor information, use of task planning expert systems for on-line reconfiguration and monitoring of automatic computer controls, language-like interface to intelligent computer control of manipulators, etc. Included in this research effort are issues of human operator control and information interface to the operation of dual-arm robots equipped with dexterous and effectors.

E. System architecture and integration

This area focuses on computing and telerobot architectures for real-time execution of autonomous functions. System control architectures enable smooth integration of these functions. There are three elements.

1) Spaceborne Symbolic Processor (ARC)

The focus of this research is a spaceborne VHSIC symbolic processor capable of handling a minimum of 22,000 rules with an execution rate of 8,000 rules per second (equivalent to 8 mega-instructions per second). Functional characteristics of the processor include 40-bit data-tagged parallel architecture capable of accommodating new evolving architectural designs without impact on the existing hardware or software environment; vendor-independent data and bus interfaces capable of accommodating evolving peripheral subsystems such as an optical read-write disk; operation in a vendor-independent distributed computer environment; control strategies for maintaining data-base consistency; fault-tolerant capabilities for fault testing, identification, isolation, and resolution via software control and implementation; and radiation resistance (minimum of 10n to the 5th rads). The research effort also includes the programming environment for a parallel architecture and will support common LISP, Prolog, Ada, and C. Several potential architectures are currently being evaluated and include state of the art machines developed by Symbolics, Inc. (NASA sponsored effort in conjunction with IR&D), TI (DARPA sponsored effort), DEC (IR&D) and Stanford (DARPA and NASA sponsored effort).

2) Satellite Design for Servicing (GSFC)

This work addresses the problem of how satellites and payloads need to be designed to facilitate their servicing by robots. This work has the added benefit that such design guidelines tend to also make this equipment more easily servicable by humans on the ground or in space. Considerations cover such areas as the design of fasteners; electrical/gas/fluid connectors; the size, function and number of replaceable modules; visible markings for automatic identification; and the design of tapered guides, etc. to decrease robot accuracy requirements. The 1986 work will involve collecting existing information on the design of satellites for servicing. Existing information exists in the Goddard MMS, GRO, ST operations and Space Station programs. This information will be used to develop point designs of space payloads that reflect robot friendly design characteristics.

3) Beam Assembly Telerobot (HDQ-MIT)

The MIT Space Systems Laboratory has a grant to develop technologies for increasing the capability of telerobots to perform on-orbit operations such as assembly, and to evaluate those capabilities using a neutrally buoyant telerobot called the Beam Assembly Teleoperator (BAT) in the MSFC Neutral Buoyancy Facility as a simulation of the space environment. Using capabilities previously developed under this grant, they also evaluate the allocation of tasks to EVA astronauts and to telerobots. Using BAT together with the Multi-Mode Proximity Operations Device (MPOD); which is operated with a human on-board rather than remotely, as the BAT, the relative advantages and limitations of near versus remote telerobotics will be evaluated. Also covered under this grant is the interaction of EVA and telerobotics with the design of satellite mechanisms such as latches, connections and interchangeable modules. Students in this program spend periods of time at JPL both as internships and as a technology transfer mechanism.