Teleoperation and Autonomy for Space Robotics

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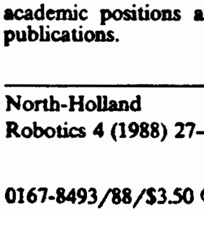
A logical enhancement to manned space flight includes the use of robots in space. To achieve this goal, there must be a phased program where the capabilities of the robot can evolve as technology advances. This paper will review some of the ways in which robots can be used in space. Then, a system architecture standard will be suggested which supports the evolution of robot control from teleoperation to autonomy. Finally, some areas of technology transfer will be discussed which are relevant to land-based robot operation.

Keywords: Control system, Sensory processing, Space, System architecture, Task decomposition, Teleoperation, World modeling.



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1. Introduction

There are several factors which contribute to the use of robots in space [1]. First, there is the cost factor. There is a lengthy procedure required to prepare an astronaut to work in an extra-vehicular activity (EVA), i.e. outside of the spacecraft. Since the astronaut cannot remain outside the spacecraft over an extended period of time, the cost of using an astronaut for all EVAs becomes prohibitive. Second, robots can enhance the activities of astronauts in the same way that any tool increases productivity. The astronauts would be able to achieve the same goals in less time. They would then be able to concentrate their energy on

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activities requiring levels of intelligence beyond the state-of-the-art in robotics. Third, the use of robots in space increases the probability of mission success. Robots do not experience the fatigue associated with human task execution. As a result, the tasks performed by a robot will have a predictable level of competence over a long period of time which ultimately translates into higher reliability. Finally, safety is a major concern in the space program. If robots are used to perform those activities which could prove dangerous, mission goals can be accomplished with less risk.

The requirements of the Flight Telerobotic Servicer (FTS) of the Space Station are driving the development of robot systems for space applications. Success in this program requires a reference model for the control system architecture. This is essential for several reasons. The control system cannot be developed as a static system but must evolve over time to take advantage of advances in technology. Consequently, the architecture must be sufficiently flexible to support telerobotics in the beginning of the program and to gradually support more autonomy of robot tasks. A standard reference model control system architecture will be presented which is able to supply this necessary framework. Another important aspect compelling the use of this architecture is that it provides a common reference model to which all designs must interface. Previous work in an automated manufacturing research facility (AMRF) at the National Bureau of Standards has shown that system integration is the most difficult challenge [2]. The value associated with such a standard means that there is an easy way to compare different design approaches in solving technical problems.

The next section considers robot activities in space. This is followed by the presentation of the standard reference architecture. Then, some benefits resulting from technology transfer from the program are discussed.

2. Robot Activities in Space

For economic as well as safety issues, robots will be used in space. The FTS of the Space Station program is accelerating research in this direction by providing the funding required to develop such capabilities.

The development of space robots is based on a gradual evolution from teleoperation to autonomy. In the early stages of FTS operation, teleoperation will be used. Astronauts will directly control the robot's activities. This will be done through force reflected master–slave control. Astronauts will be able to control the robot while staying within the pressurized environment of the spacecraft. They will be an integral part of the system. In this mode of operation, astronauts will be able to perform tasks such as removing and installing fasteners, removing and connecting umbilical cords, module replacement, etc. These capabilities can be applied to space station construction and routine maintenance of the structure, service and repair of satellite modules, contingency repair, etc. [3].

As research advances the state-of-the-art, there will be a natural evolution toward greater autonomy. It should be emphasized that autonomy and teleoperation provide a continuous spectrum of activities.

Autonomous capabilities will relieve astronauts from the tedious and repetitious subtasks which occur during the execution of a task. For example, in the beginning an astronaut would be required to connect an umbilical cord to a device using force reflected teleoperation. The first step toward autonomy allows the astronaut to pick up the umbilical cord using teleoperation, aim the vision system at the goal location, and then allow the robot to automatically perform the connection. Similar situations can be imagined for construction where the astronaut sets up the region for construction with the proper material, monitors the robot during autonomous operations, and then takes back control of the robot when the task is successfully completed. At any time during task execution, the astronaut can abort the autonomous behavior of the robot and take back control.

The basic assumption underlying the evolution from telerobotics toward autonomous operations is that there is some control system architecture which can evolve as the state-of-the-art advances. The next section will describe this architecture. A more complete description is available in [4].

3. NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)

There is a need to support both telerobot control, where a human is an integral part of the control loop, and autonomous control, where the human gives the robot commands which are automatically executed. In order to start with teleoperated control and evolve toward autonomous control without a complete redesign of the robot control system, serious thought must be given to the control architecture to be sure that the system has the ability to be easily modified as technological advances occur.

The fundamental paradigm of the control system is shown in *Fig. 1*. The control system architecture is a three legged hierarchy of computing modules, serviced by a communications system and a global memory. The task decomposition modules perform real-time planning and task monitoring functions; they decompose task goals both spatially and temporally. The sensory processing modules filter, correlate, detect, and integrate sensory information over both space and time in order to recognize and measure patterns, features, objects, events, and relationships in the external world. The world modelling modules answer queries, make predictions, and compute evaluation functions on the state space defined by the information stored in global memory. Global memory is a database which contains the system's best estimate of the state of the external world. The world modeling modules keep the global memory database current and consistent.

3.1 Task Decomposition – H modules (Plan, Execute)

The first leg of the hierarchy consists of task decomposition H modules which plan and execute the decomposition of high level goals into low level actions. Task decomposition involves both a temporal decomposition (into sequential actions along the time line) and a spatial decomposition (into concurrent actions by different subsystems). Each H module at each level of the hierarchy consists of a job assignment manager JA, a set of planners $PL(i)$, and a set of executors $EX(i)$. These decompose the input task into both spatially and temporally distinct subtasks as shown in *Fig. 2*.

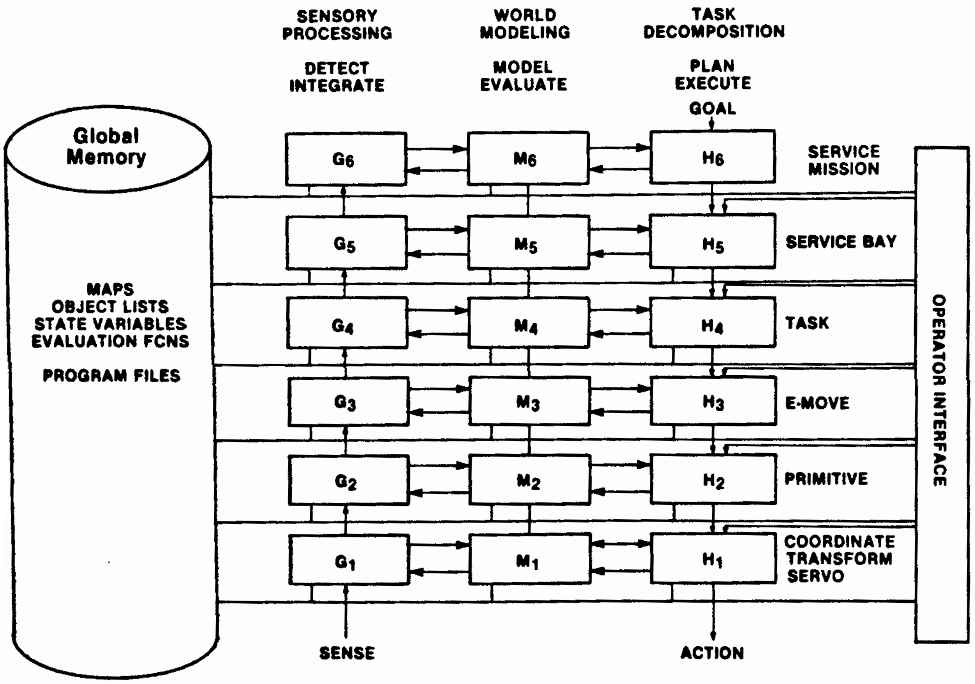

Fig. 1. A hierarchical control system architecture for intelligent vehicles.

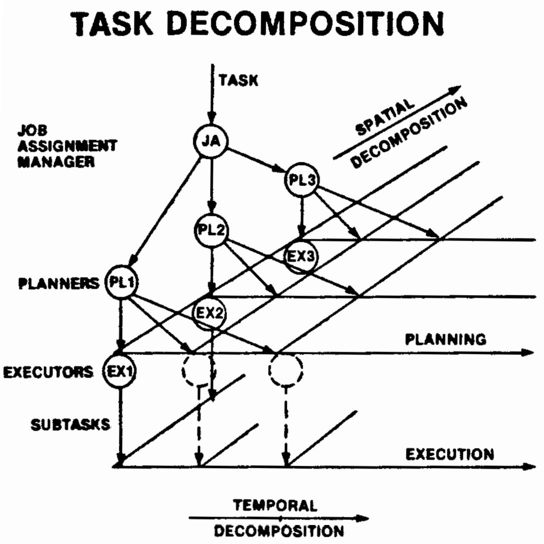

Fig. 2. The job assignment *JA* performs a spatial decomposition of the task. The planners *PL* (*j*) and executors *EX* (*j*) perform a temporal decomposition.

3.2 World Modeling – M modules (Remember, Estimate, Predict, Evaluate)

The second leg of the hierarchy consists of world modeling *M* modules which model (i.e. remember, estimate, predict) and evaluate the state of the world. The "world model" is the system's best estimate and evaluation of the history, current state, and possible future states of the world, including the states of the system being controlled. The "world model" includes both the *M* modules and a knowledge base stored in a global memory database where state variables, maps, lists of objects and events, and attributes of objects and events are maintained. By this definition, the world model corresponds to what is widely known throughout the artificial intelligence community as a "blackboard" [5]. The world model performs the following functions:

1. Maintain the global memory knowledge base by accepting information from the sensory system.
2. Provide predictions of expected sensory input to the corresponding *G* modules, based on the state of the task and estimates of the external world.
3. Answer "What is?" questions asked by the executors in the corresponding level *H* modules. The task executor can request the values of any system variable.
4. Answer "What if?" questions asked by the planners in the corresponding level *H* modules. The *M* modules predict the results of hypothesized actions.

3.3 Sensory Processing – G modules (Filter, Integrate, Detect, Measure)

The third leg of the hierarchy consists of sensory processing *G* modules. These recognize patterns, detect events, and filter and integrate sensory information over space and time. The *G* modules at each level compare world model predictions with sensory observations and compute correlation and difference functions. These are integrated over time and space so as to fuse sensory information from multiple sources over extended time intervals. Newly detected or recognized events, objects, and relationships are entered by the *M* modules into the world model global memory database, and objects or relationships perceived to no longer exist are removed. The *G* modules also contain functions which can compute confidence factors and probabilities of recognized events, and statistical estimates of stochastic state variable values.

3.4 Operator Interfaces (Control, Observe, Define Goals, Indicate Objects)

The control architecture defined here has an operator interface at each level in the hierarchy. The operator interface provides a means by which human operators, either in the space station or on the ground, can observe and supervise the telerobot. Each level of the task decomposition hierarchy provides an interface where the human operator can assume control. The task commands into any level can be derived either from the higher level *H* module, or from the operator interface. Using a variety of input devices such as a joystick, mouse, trackball, light pen, keyboard, voice input, etc., a human operator can enter the control hierarchy at any level, at any time of his choosing, to monitor a process, to insert information, to interrupt automatic operation and take control of the task being performed, or to apply human intelligence to sensory processing or world modeling functions. *Table 1* illustrates the interaction an operator may have at each level.

Table 1
Operator interaction at each level

Level	Type of interaction
At the servo	Replica master, individual joint position, rate, or force controllers.
Above level 1	Joy stick to perform resolved motion force/rate control.
Above level 2	Indicate safe motion pathways. Robot computes dynamically efficient movements.
Above level 3	Graphically or symbolically define key poses. Menus to choose elemental moves.
Above level 4	Specify tasks to be performed on objects.
Above level 5	Reassign telerobots to different service bays. Insert, modify, and monitor plans describing servicing task sequences.
Above level 6	Reconfigure servicing mission priorities.

The sharing of command input between human and autonomous control need not be all or none. It is possible in many cases for the human and the automatic controllers to simultaneously share control of a telerobot system. For example a human might control the orientation of a camera while the robot automatically translates the same camera through space.

3.5 Levels in the Control Hierarchy

The control system architecture described here for the FTS is a six level hierarchy as shown in *Fig. 3*. At each level in this hierarchy a fundamental transformation is performed on the task.

Level 1 transforms coordinates from a convenient coordinate frame into joint coordinates. This level also serves joint positions, velocities, and forces.

Level 2 computes inertial dynamics, and generates smooth trajectories in a convenient coordinate frame.

Level 3 decomposes elementary move commands (E-moves) into strings of intermediate poses. E-moves are typically defined in terms of motion of the subsystem being controlled (i.e. transporter, manipulator, camera platform, etc.) through a space defined by a convenient coordinate system. E-move commands may consist of symbolic names of elementary movements, or may be expressed as keyframe descriptions of desired relationships to be achieved between system state variables. E-moves are decomposed into strings of intermediate poses which define motion pathways that have been checked for clearance with potential obstacles, and which avoid kinematic singularities.

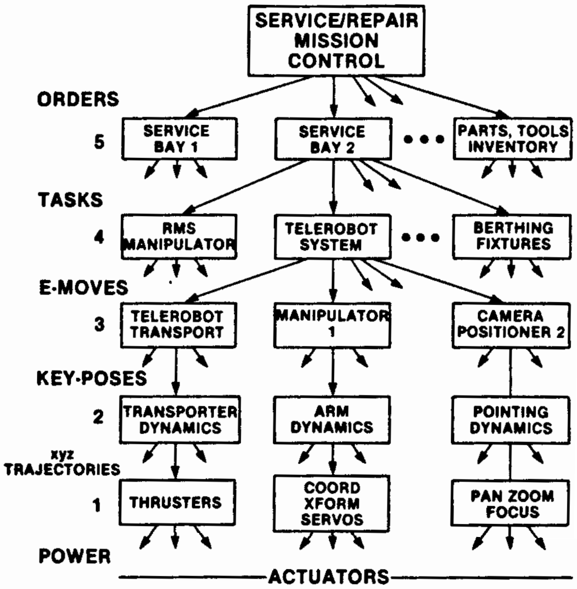

Fig. 3. A six level hierarchical control system proposed for multiple autonomous vehicles.

Level 4 decomposes object task commands specified in terms of actions performed on objects into sequences of E-moves defined in terms of manipulator motions. Object tasks typically define actions to be peformed by a single multiarmed telerobot system on one object at a time. Tasks defined in terms of actions on objects are decomposed into sequences of E-moves defined in terms of manipulator or vehicle subsystem motions. This decomposition checks to assure that there exist motion freeways clear of obstacles between keyframe poses, and schedules coordinated activity of telerobot subsystems, such as the transporter, dual arm manipulators, multifingered grippers, and camera arms.

Level 5 decomposes actions to be performed on batches of parts into tasks performed on individual objects. It schedules the actions of one or more telerobot systems to coordinate with other machines and systems operating in the immediate vicinity. For example, Level 5 decomposes service bay action schedules into sequences of object task commands to various telerobot servicers, astronauts, and automatic berthing mechanisms. Service bay actions are typically specified in terms of servicing operations to be performed by all the systems (mechanical and human) in a service bay on a whole satellite. This decomposition typically assigns servicing tasks to various telerobot systems, and schedules servicing tasks so as to maximize the effectiveness of the service bay resources. *Level 6* decomposes the satellite servicing mission plan into service bay action commands. Mission plans are typically specified in terms of satellite servicing priorities, requirements, constraints, and mission time line. The level 6 decomposition typically assigns satellites to service bays, sets priorities for service bay activities, generates requirements for spare parts and tool kits, and schedules the activities of the service bays so as to maximize the effectiveness of the satellite servicing mission. To a large extent the level 6 mission plans will be generated off line on the ground, either by human mission planners, or by automatic or semiautomatic mission planning methods.

4. Technology Transfer

Section 2 described some specific ways in which robots can be used in space. While such tasks are targeted to space, they require the development of a set of generic skills which can be applied to a large number of land-based problems. It is instructive to consider these generic skills before attempting a list of possible areas of technology transfer.

In the previous section, a control system architecture was presented which supports the evolution from teleoperation to autonomy. As research developments are incorporated into the control system architecture, the robot will display progressively more intelligent behavior. One generic capability will be in the area of task decomposition. The robot will be able to perform complex tasks as well as to detect and correct any unexpected events occuring during task execution. Task representation is certainly an issue because the proper representation of a task will greatly aid decomposition and execution.

Closely related to task decomposition is planning. At the lowest levels of intelligence, plans are pre-stored. Planning is implemented by choosing among the pre-stored plans. As machines become more intelligent, it becomes impractical to prestore plans and real-time planning must be performed. The real-time planning concept is supported in the control architecture presented in Section 3.

Sensor processing, especially as related to updating the information required by a world model, will undergo significant development as the autonomy of robots increases. Related to this processing is the development of coordination for multiple manipulators. Since the telerobot will have a minimum of two arms, coordination of the arms in the execution of a task is imperative.

Finally, the development of the space telerobot will add significantly to the experience in system integration. Robotics is a multi-disciplinary activities and there will be a concerted effort to combine many technologies in order to create a working system.

The generic capabilities that must be developed as robots achieve greater autonomy have relevance to myriad land based activities. Naturally these capabilities can be applied to such activities as assembly, maintenance, and material handling. The robot will be able to perform these tasks with a much higher level of reliability than is currently available today. For example; advance planning will allow anomaly detection and correction which is not now achieved.

Technology transfer will also occur in the area of new, more powerful methods of robot programming. The current methods of programming are often tedious and time consuming. Furthermore, the programmer has relatively little confidence about the correctness (or even the safety) of his program.

Methods for advancing the state-of-the-art in planning will develop new techniques for reasoning about events. There are direct implications concerning error recovery due to unanticipated events. This leads toward a better understanding of goal-driven intelligent machines.

Finally, the realization of a space telerobot requires computer hardware. The trend is away from single processors toward multiple processors sharing the computational burden of the application. All subsystems are eventually connected during a system integration phase. The experience resulting from this system integration may have the most far-reaching impact on land based applications since it is not limited to robotics and can be applied to any system.

5. Conclusions

This paper has dealt with several aspects related to the use of robots in space. Within the Space

Station project context, several important robot activities have been identified. These activities extend the state-of-the-art in robotics and have direct relevance to land-based robot tasks. An architecture which supports the evolutionary development of the robot has been presented. Using this architecture, the transition from the teleoperated mode to more autonomous modes of robot operation is one of gradual rather than abrupt change.

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