OVERVIEW OF SPACE TELEROBOTICS

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Abstract

This chapter discusses the need for space teleoperators and robots, here generically called telerobots, and describes the basic elements of such systems as well as their current capabilities, limitations and needed technical improvements. Rovers, which are intended for in-situ lunar and planetary exploration, as well as reconnaissance [1-3], involve many of the same basic technologies but are discussed only briefly here.

Introduction

In the years since 1957, when the launching of Sputnik thrust the world into the Space Age, vast resources have been invested in developing space systems. This investment has been enormously successful. Earth-orbiting satellites have revolutionized communications, intelligence gathering, weather prediction, resource management and navigation, and scientific satellites and spacecraft have provided a wealth of data that have dramatically improved our scientific understanding of the Earth, the solar system and the universe. Apollo astronauts have visited the moon, and spacecraft have flown by every planet in the solar system save Pluto.[1] Automated orbiters and landers, including Mariner, Magellan, Surveyor, Viking, and the Russian Veneras, have explored the Moon, Mars, and Venus, and the space shuttle and expendable launch vehicles now provide reliable means for placing large payloads in orbit.

Space-based capabilities and the improved scientific knowledge resulting from the investment in space are having significant practical effects. It is now possible, for example, using communications satellites in geosynchronous orbit, to broadcast television to billions of people in once-inaccessible areas. It is also possible to search for minerals and monitor environmental effects, such

[1] A Pluto mission, the Pluto Fast Flyby, which uses a micro-spacecraft, is currently under study by NASA.

as ozone depletion and the shrinkage of forested areas, from space and, using the Global Positioning System, to determine positions on or near the surface of the Earth to within one-hundred meters using inexpensive hand-held receivers [2][4]. With more elaborate scientific receivers, accuracies of about two centimeters can be achieved. [3]

Despite its successes, the international space program is in a state of flux due to economic pressures and the redefinition of priorities caused by the end of the cold war. The need for a space program and its focus are subject to intense debate, as illustrated by the battles in the U.S. Congress over funding for the space station. The economic and political expense of large missions is so high that international cooperation is a necessity, and space agencies are actively seeking ways to streamline operations and reduce mission costs. The costs of assembly or em - placement, inspection, servicing, and maintenance of large space assets will be significant. Large space assets cannot be launched already assembled. They must be launched in sections and assembled in space or emplaced on planetary surfaces after sites are prepared. Afterward, on an ongoing basis, they must be inspected, serviced, and maintained.

The Need for Space Teleoperators and Robots

The Apollo astronauts repeatedly demonstrated their ability to function on the Moon, and the brilliantly successful refurbishment of the Hubble Space Telescope in December, 1993 [6] demonstrated that astronauts can perform assembly, maintenance, and repair operations in space. The use of astronauts on a large scale for such operations, however, is far too costly and entails significant safety risk [7]. According y, space teleoperators and robots, generically called space telerobots, are being developed in the United States, Europe, Canada, Russia, and Japan for use on the space station and in planetary and Lunar scientific missions [8]. Space telerobots can extend astronaut capabilities and performance, thereby increasing mission performance and reducing costs. The space shuttle arm has been extremely useful in this regard

The space station, which now includes the Russians as partners and is again being redesigned to reduce its scope and cost, is currently the only space facility under development that will make

2 Military receivers are accurate to within about five meters.

3 Scientists used accurate GPS position determinations to great advantage in the recent Northridge earthquake in Los Angeles. Using fixed receivers, they were able to determine the movements of points in Los Angeles county nearly instantaneously [5],

usc of telerobots for construction, servicing, and repair.[4] Many mission concepts employing telerobots exist, however, and a telerobot flight experiment is being implemented under NASA sponsorships The space station is being designed to employ several telerobots, including the Canadian Space Station Remote Manipulator Systcm (SSRMS) and the Special Purpose Dexterous Manipulator (SPDM)[6] as wc]] as a pair of Japanese telerobots, part of the Japanese Experiment Module (JEM), to perform various operations in eluding assembly, in spection, repair, experiment tending, and so on. Other mission concepts currently under study that will require space telerobots include:

Lunar Observatories and Bases

Details depend upon whether manned bases or unmanned observatories are being considered. In either case, telerobots would be useful for excavation, construction, assembly, maintenance, inspection, calibration, and repair, and would be used in nuclear reactor and observatory site preparation and assembl y, solar panel emplacement, and habitation construction [9].

Science Satellites

Large astrophysical observatories, such as infrared telescopes, might be placed in high orbits, which arc largely inaccessible to astronauts. Telerobots could be used to replace cryogens, replenish attitude con trol system propellant, and perform module changeout, providing that the observatories are designed for ease of servicing. Telerobots could also bc used to service Earth ob - serving satellites, if they, again, are designed to permit it.

Ground Support Operations

Ground support operations are not missions in the usual sense, but support many individual missions by automating aspects of the ground operations necessary for fabrication, testing, and launch. Examples of ground support telerobot systems now under development include STAR (Satellite Test Assistant Robot), which is being developed to automate operations inside the large environ mental test chamber at the Jet Propulsion Laboratory,[7] HEPA, which automates air filter

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[4] Rover missions are being implemented, however. The Russian Mars '96 and United States MESUR/Pathfinder missions plan to put rovers on Mars in 1996 to make scientific observations and perform rover technology experi - ments.

[5] Professor David Akin of the University of Maryland is working on a telerobot flight experiment called Ranger.

[6] Scc later chapters in this book,

[7] STAR has already been used to test Cassini components.

inspection at the Kennedy Space Center in Florida, and the STS Tile Inspection and Maintcnancc Robot, which automates the waterproofing and inspection of the heat-resistant tiles on the Space Shuttlc.

Whether or not tclcrobots arc used in the above missions will depend upon economic tradeoffs. Placing tclcrobots and the ncccssary support equipment in orbit or on the Moon will bc expen-sive, and it must bc chcapcr to usc thcm than it is to usc astronauts and astronaut-operated equipment for construction and maintenance. It must also bc cheaper to scrvicc and maintain space assets than simply to discard thcm. Tclcrobots could bc used, for example, to scrvicc and maintain constellations of communication satellites like those in the Calling systcm[10, 11]. Calling satellites, however, arc projcctcd to cost lcss than ten million dollars each, and will bc launched several at a time. Space servicing would have to bc inexpensive to bc justifiable. Economic issues are addressed in chapter 2.

Autonomy, Intelligence, and Performance

Autonomy and intelligence are indcpcndcnt concepts. An autonomous system is generally taken in robotics as being capable of achieving an externally-specified goal without further external inputs. Intelligent systems arc able to cope with com plcx situations, drawing conclusions and making control decisions appropriate to achieving their goals. A simple system can operate autonomously in simple situations, but may not bc successful at operating autonomously in situations with significant degrees of complexity and variability. }Icat-seeking missiles arc a good example: A heat-seeking missile with a relatively simple infrared sensor can function autonomously when a single unambiguous infrared object, such as a hot exhaust pipe, is present. Its control objective is simply to keep the ccntroid of the in frarcd intensity distribution centered in its field of view. If the sensor and control systcm can control the missile with sufficient bandwidth, it will fly up the exhaust pipe, destroying the target. When countermeasures, such as magnesium flare decoys are deployed, aiming the missile toward the centroid of thc infrared distribution will fail. In order to destroy the target, the missile must have a more intclli gent sensing and control system that can determine which of the multiple infrared objects is the appropriate one. Developing a sensing and control system that will work in the presence of countermeasures (which are designed to increase variability and complexity) is a challenging problem.

Temporal response requirements and problem complexity together dictate computational power requirements. Dealing with high-performance targets requires making control decisions in hard real time to achieve sufficient control bandwidth.

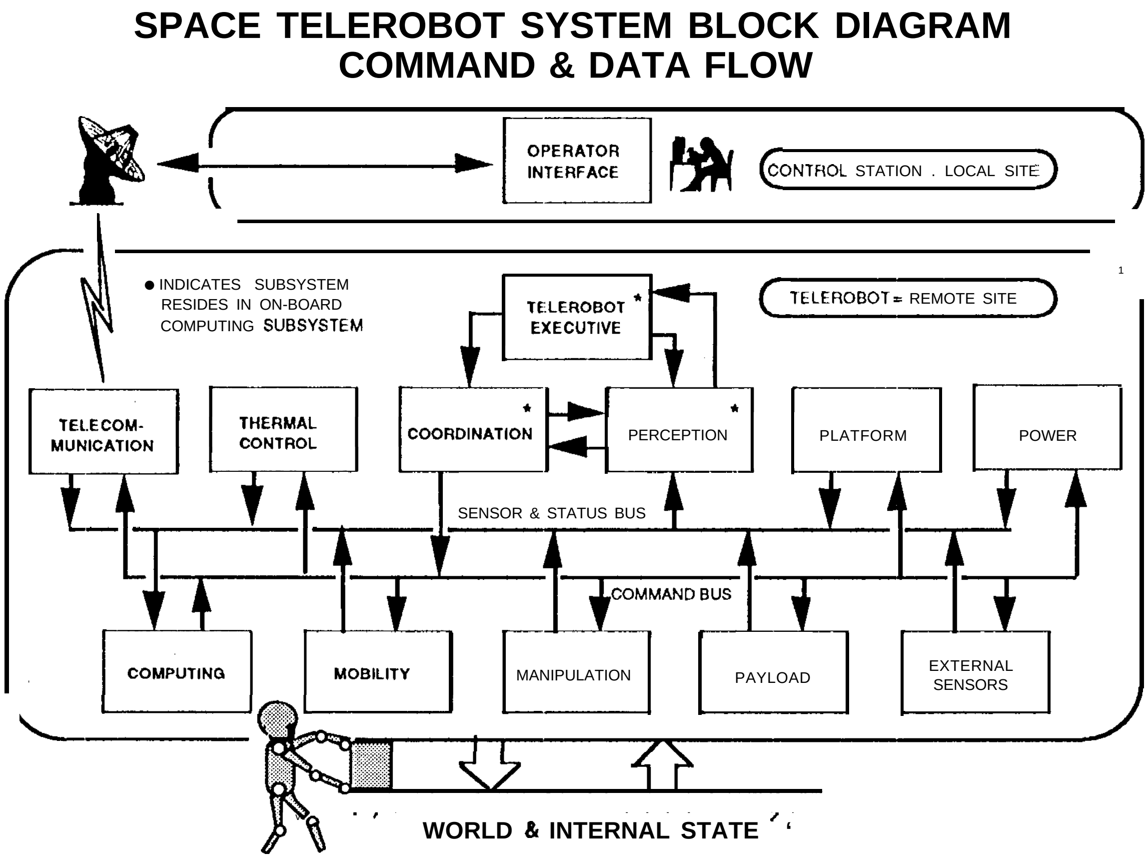

Fig. 1. Space telerobot system block diagram showing command and data flow. This diagram shows the major elements of a space telerobot system along with command and data pathways. The control station, which may be located in space or on the ground, is the local site. The telerobot is the remote site.

Space Telerobots

Telerobots are machines that perform physical tasks. The motivation for using them in space is to accomplish, more efficiently and safely, tasks that would otherwise have to be done by humans, and to perform tasks that humans are incapable of doing. We therefore want telerobots to perform tasks like inspection, maintenance, repair, module changeout, cleanup, tending science experiments, performing repetitive operations, capturing and despinning satellites, and so on.

Telerobot operations involve bringing objects, including the telerobots themselves, into prescribed mechanical states with respect to other objects. This means the telerobot must be able to locate and fetch relevant objects in space, move them to the appropriate locations, apply the correct forces when mating them, recognize error conditions, control mobility and attitude, etc. Telerobots may also need to cooperate with astronauts, other telerobots, and various types of equipment [12].

A typical space telerobot system includes a control station and a telerobot as shown schematically, along with command and data flow, in figure 1. The control station, also called the *local site*, includes the interface which the operator uses both to comprehend the remote task and control the telerobot. The interface displays a graphical or video representation of the telerobot's worksite (in stereo, perhaps) along with information describing the state of the telerobot, the task, etc. It also includes command menus and the devices, like joysticks, hand controllers, and mice, the operator uses to interact with, and command, the telerobot. The control station, which may be supported by powerful simulation and planning computers, communicates with the telerobot through a data link.

The telerobot, or *remote site*, physically performs tasks under the control of the operator. A telerobot comprises one or more substantially anthropomorphic manipulators, each with several degrees of freedom, mounted on a platform which might be mobile (or free-flying). Illustrations appear in chapters 14-17. A space telerobot also has a sensor suite, usually including arm, platform, and mobility state sensors, force sensors, cameras and necessary computation and support systems as shown in figure 1. The cameras may also be mounted on multi-degree-of-freedom platforms. A telerobot's major subsystems are computing, coordination, external sensors, manipulation, mobility, payload, perception, platform, power, telecommunication, thermal control, and the telerobot executive. These are described further in the appendix.

If a telerobot has a high degree of autonomy, that is, if it can perform operations with no human assistance while they are being performed, it is operating robotically. If it more-or-less mimics motions input by a human operator using a hand controller or joystick, or if human operators must issue detailed commands, again during the operations, it is operating as a teleoperator. Typical telerobots merge both teleoperator and robotic capabilities.

Space Telerobots Vs Industrial Robots

Robots have limited intelligence and ability to perceive. To compensate, applications have historically relied either upon human presence in the control loop or upon imposing significant order on tasks so they could be programmed as relatively fixed motion sequences. In industrial robotics, imposing order has been achieved mechanically through fixturing coupled with robot repeatability and positioning precision.[8] Achieving good control performance and positioning precision with current control technology requires stiff manipulators, which tend to be massive. Relying upon fixturing and positioning precision is expensive, and is justifi able only when production runs are long enough to recover set-up and tear-down costs . Space telerobot operations have high added value, so runs need not be long, but massive telerobots and fixtures are unacceptable since mass is the strongest driver of launch costs. The need to minimize launch mass leads to robot and support structures that are lightweight, hence flexible, difficult to model (resulting in positioning uncertainty) and difficult to control. Thermal effects can cause ringing (this was a problem initially with the Hubble Space Telescope) which also degrades posi tioning precision and creates control problems. In addition, space telerobotic tasks are typically more varied than those of industrial robots and do not involve nearly as much slavish repetition. Finally, handling the diversity of tasks with a population of special-purpose robots is not tenable, due again to launch mass constraints as well as development costs. Space telerobots, therefore, cannot rely upon mechanically-imposed order. They must be versatile and adaptable, and must be capable of performing many different types of tasks with minimal setup and reconfiguration unless that setup and reconfiguration can be done easily.

Finally, the space environment itself is more difficult. Thermal and radiation effects, the lack of atmosphere, degradation due to atomic oxygen, and so on, all create engineering problems. Furthermore, the lack of gravity requires that objects must be positively retained, They cannot be simply set down or released, unless this is done with the utmost control, since they might escape to become high-velocity life- and mission-threatening projectiles.

Telerobot Control System Capabilities

As described in the previous section, models of a space telerobot, its operating environment, and the objects it manipulates will have significant uncertainty. Operating effectively and safely in

[8] Machine vision systems and improved controllers are now permitting the relaxation of fixturing and positioning precision requirements.

space, then, requires that a telerobot system, which, along with the remote telerobot, includes the human operators and ground support, be capable of accommodating uncertain tics. The system must be able to perform tasks which cannot initially be precisely defined, and which may have unplanned side effects, while avoiding unintended damage to itself and objects around it. To do this, the system must be able to determine the state of the task and relevant objects, iteratively determine the actions to take, predict their effects, and coordinate the subsystems to perform the actions while monitoring their effects to make sure they are consistent with the predictions. If the effects arc not consistent with the predictions, there is a potential problem. Finally, the control system must be able to monitor and maintain system health.

These capabilities, in turn, require that the system acquire and maintain representations of the workspace, the telerobot state, and the task, that it be able to recognize error conditions and success, that it be able to generate plans for error recovery, and so on. [9] It is also useful for the system to be able to improve its performance by representing and organizing past experience. Examples include learning the positions of objects, adjusting control gains to improve positioning performance, and on-line hand-eye calibration. The capabilities are generic, arising, in part, from the subtle interplay of action and sensing. [10]

We have considered the overall system including human operators. If timely human control and assistance cannot be provided because of operational constraints, the capabilities, which endow the system with a measure of autonomy, must be present in the telerobot's on-board control system. The requisite system sophistication depends upon task complexity.

Spacecraft like the Galileo Jupiter orbiter and probe have historically been termed robotic, but they differ in important ways from planetary rovers and the telerobots being considered here. They are more like preprogrammed machine tools than robots, Satellites and spacecraft have been restricted to operating in simple environments (empty space) and with control objectives that can be relatively easily characterized. They do not have, or need, the ability to sense and classify complex external situations and make quick decisions on-board. They operate in an open-loop manner for long periods, and most of the control decisions are made on the ground. In addition, they are not usually required, other than landing, to interact mechanically with the environment. [11] Rovers and space telerobots, on the other hand, must be capable of performing me-

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[9] Automatic plan generation is discussed in chapter 7.
[10] For example, perceiving the compliance of a structural element involves determining the response of the element to applied forces.
[11] The Viking lander's arm interacted mechanically with Martian soil during sampling operations.

chanical operations at reasonable rates [12] in uncertain natural or man-made environments. If they are being used where data rates are limited or communication delays are appreciable, they must have on-board sensing, decision-making, and control capabilities that can deal with greater uncertainty and complexity, especially if the task state can change unexpectedly. [13]

A Practical Approach to Space Telerobot Control

Developing intelligent robots that have great dexterity and motor skill, can reason deeply about tasks and operate independently with great versatility in complex environments, is an extremely difficult unsolved problem. While scientists generally agree that conscious, intelligent behavior arises from some sort of computational activity, after years of effort we still do not know how to characterize realistic environments in ways suitable for robotics, to describe the procedures for such apparently effortless activities (for humans and animals) as recognizing objects, or to build and program computing hardware to perform the computations. Human judgment is still essential for difficult situations.

While we cannot yet automate intelligent behavior, lower-level behaviors like moderately-complex sensor data interpretation, motion and force control are easily automated. Furthermore, robots perform well in environments that are relatively predictable and on tasks that have reasonable dexterity demands. Once an (accessible) object is pointed out to a robot system, for example, it is fairly straightforward for the robot to acquire it automatically if it is easy to grasp and manipulate. Even complex tasks are comprised of simpler elemental subtasks, so a powerful approach to building robotic systems is to *automate the lower-level functions and detail management while relying on humans to provide overall guidance and handle difficult situations.* Thus humans, who become bored during repetitive tasks, perform the high-level intelligent functions at which they excel, while telerobots physically perform the tasks. Where a telerobot is capable, it operates autonomously. When it needs assistance, the operator provides it, issuing detailed commands when necessary, That is the essence of telerobotics.

To summarize, a practical approach to developing useful telerobot systems [12] is to:

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[12] This is driven by the need to complete missions in a reasonable time, which is driven, in turn, by system survivability and mission operations costs. If one could operate extremely slowly in a static environment, pure remote control would be acceptable even with significant data rate limitations and communication delays.
[13] For example, moving along a trajectory in free space toward a planet whose position can be predicted to extremely high precision is a computationally simpler task than moving about and operating in an imprecisely-known cluttered space, without suffering or causing damage,

- Automate lower-level functions by developing reliable control algorithms that adapt on the basis of sensory information

- Rely upon human operators for providing overall task guidance and supervision, and for handling special situations (repair of damage is an example)

- Develop advanced interfaces and tools that aid in planning and managing telerobot tasks and permit the operator to communicate easily with the system at mu] tiple levels of detail

Currently wc must give telerobots detailed commands, either in the form of macros or in the form of motion commands generated by joysticks and hand controllers, and human operators must bc prepared to assist thcm in locating and identifying objects. As autonomous system technology advances, we will be able to delegate higher levels of decision making to telerobots, reducing the load on human operators and ground control and telecommunication systems while improving telerobot performance. This is represented schematically in figure 2.

Ground Control

The usc of telerobots, like the Shuttle Remote Manipulator System (SRMS), controlled by astronauts in space, can significantly increase the productivity of space operations, as been demonstrated on numerous shuttle flights. Space-controlled telerobots allow astronauts, working in the comfortable shirtsleeve environment inside their spacecraft (intravehicular activity, or IVA), rather than outside in space suits (extravehicular activity, or EVA), to acquire and manipulate payloads such as satellites, space station modules, and orbital replacement units (ORU's). IVA reduces both preparation time,[14] which is significant, and risk over EVA. Since a telerobot control system can scale human-generated command inputs, astronauts can also use (smaller) telerobots to perform small operations like calibrating instruments and tending laboratory experiments.[15] [16]

[14] According to the Fislwr-Price study, the time spent in preparation is at least five times the time spent doing EVA work,
[15] Different robots would bc used, but the control stations could be identical,
[16] Teleoperator-based devices arc now being applied in non-invasive surgery. By scaling and filtering, the effective resolution of a surgeon's motions can be improved and the ever-present tremor can be attenuated.

Space-controlled telerobots arc important for the space station because, as the Fisher-Price study [7] has shown, there is far less astronaut EVA time available than is needed to perform the necessary inspection and maintenance operations. The study also showed that the performance of IVA astronauts using simple telerobots to perform tasks was equal to or better than the performance of EVA astronauts performing the same tasks,

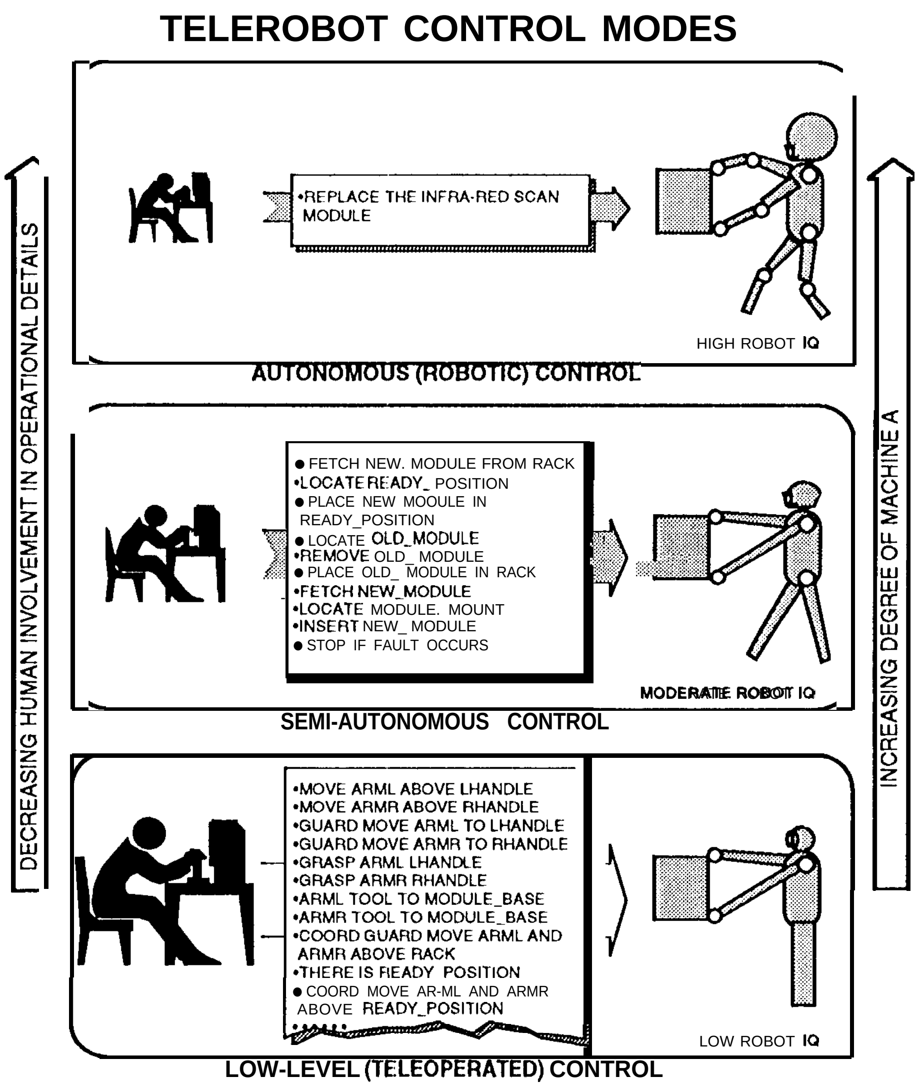

Fig. 2. Telerobot control modes. In low-level, or teleoperated, control, the telerobot has little autonomy, forcing the operator to issue detailed commands. This is tedious, and requires high data rate communicant ion channels for the operator's visual and state displays, As telerobot autonomy improves, less detailed commands arc required, This eases the burden on the operator and reduces data rate requirements because less state data is needed and visual displays need not be updated as often. Missions with limited data rate channels and significant communication delays require a high degree of autonomy to achieve good performance.

Controlling telerobots from the ground (ground control) is potentially much more effective than controlling them from space. The total hourly cost of a ground-based operator is orders of magnitude less than that of an astronaut in space, and ground-based operators are more efficient since they work in a normal office environment. They are also at much less risk. In addition, ground control stations can have greater computing resources available, can be configured to support many operators, and are easier to maintain. The Fisher-Price study [7] recommended ground control for the space station to reduce crew workload. Other studies have recognized the advantages of ground telerobot control, and have recommended it for both Space Station and Lunar operations [9, 13]. Ground control would also enable telescience, allowing terrestrial scientists to perform (remotely) experiments in space.

Ground control of space telerobots is attractive, but it places significant demands on the control system. In order to avoid damage and be capable of performing difficult tasks like acquiring tumbling satellites, a telerobot, whether it employs space or ground control, must be able to respond quickly to rapidly evolving events (like accidents and motion perturbations) that cannot be predicted. In addition, telerobot movements must always be stable and predictable. Unanticipated (by either human controllers or automatic planning systems) motions cannot be tolerated.[17] All this requires high-rate, possibly data-rich control loops with low latency. Because of data rate limitations and communication delays inherent in space communication systems (up to several seconds even for low-earth orbit) and resulting potential stability problems, it is impossible to close such loops on the ground.[18]

Ground control naturally partitions the overall control system into ground (local) and space (remote) components. Because of the latency and limited data rates of communications with the ground, the space-based component must be capable of operating with some degree of autonomy. That is, given intermittent high-level terrestrial instructions and assistance, it must be capable of gathering and interpreting data, making decisions, and taking appropriate actions in response to the local situation and task goals. As in the example of the heat-seeking missile described above, a simple control system will suffice if the environment is simple and control requirements are not demanding. As the environment becomes more complex and control requirements escalate, greater on-board autonomy and intelligence are required. This may be true even if astronauts are on site and all control loops are closed in space, because data traffic on the space station itself may involve appreciable latency.

[17] Reflexes maybe an exception, but they are planned in a sense, in that the system must enable or anticipate them and must control their scope.

[18] For example, down-linking real-time video from orbit for ground processing and control signal calculation and up-linking the results.

The State of the Art In Space Telerobotics

As we have seen, telerobot systems incorporate both teleoperator and robotic elements. Some current telerobot systems are nearly pure teleoperators, while others have significant robotic capabilities.

The operator interfaces of both pure teleoperator and telerobot systems include visual displays, panels or menus to select operating modes and control lights, cameras, and auxiliary devices. In addition, they usually include one or more position controllers or joysticks for generating commands for the remote site (see figure 2). In many laboratory systems the visual displays are implemented in powerful graphics computers that can display color stereo pairs which can be viewed with special active glasses that are synchronized with the frame rate of the displays. Advanced telerobot systems under development also include tools for task management, collision avoidance, visual recognition and tracking, planning, modeling, calibration, and so on, which may be implemented at both the local and remote sites. See chapters 5-9.

Joysticks provide rate information. That is, the deflection of the joystick represents the instantaneous velocity of the remote device according to the convention currently in effect. It may represent commanded axis velocity or the commanded velocity of a coordinate frame embedded in the telerobot. The position of a position controller actually represents the commanded position of the remote device in the current (remote) coordinate frame. If they are suitably equipped, position controllers can be back-driven by contact or error signals from the remote site (or simulated remote site) to give a sense of contact to the operator. This is referred to as force reflection. A joystick or position controller can also be used much like a mouse to move a cursor around the visual display, pull down menus, etc.

Teleoperators

Teleoperators are often master-slave systems. The master is a (perhaps scale) replica of the slave. The operator, watching a visual representation of the worksite, performs a task by moving the master as if it were performing the task. The master is thus a position controller since the operator is issuing position commands. The time-varying positions of the master arm joints are uplinked to the remote site as time-varying position control inputs for the slave servos. The slave therefore executes a scaled copy of the master's motion. When the slave contacts the environment, position error signals are generated. These are downlinked to the master and are used to backdrive its joints, giving a sense of contact with the remote task. A slave's axes arc coordinated implicitly because it is geometrically similar to the master.

In non-replica master-slave systems the master and slave arc not geometrically similar. Axis coordination is handled by a computer in the control loop that continually maps the present position of the master handle into the (scaled) position of the slave hand. The computer uses master kinematics to calculate the Cartesian position of the master handle in space and slave kinematics to transform this position into position commands for the slave axes, thus making the slave hand perform the same (scaled) Cartesian motion as the master handle. Again, error and contact signals arc used to back-drive the master, giving a sense of contact with the remote environment.

When velocity joysticks rather than position controllers are used, a computer again maps the velocities commanded by the joystick into instantaneous velocities of a coordinate frame em bedded in the hand, using slave kinematics to calculate the corresponding slave joint velocities.

The master-slave exoskeleton being developed at JPL,[19] which has five-fingered hands and replicates much of a human's arm and finger motion, reflects forces to the operator. A so-called *human-equivalent* system, it can be used in situations that demand dexterity and fine motor control. As in all teleoperator systems, the operator views the worksite, or an image of it, and moves the arm and hands to complete the task. Since forces arc reflected to the joints, the operator's sense of presence at the remote site, *telepresence*, is enhanced.

If the teleoperator control system implements *shared* control, some task degrees of freedom can be controlled by the control system while others are controlled by the operator. In cleaning a window, for example, the operator could control the x-y position of the cleaning head while the control system controls the normal force and makes sure the head remains normal to the surface.

Consider inserting a threaded fastener into its hole prior to tightening. The fastener is already being held in a power driver that is being grasped, in turn, by the slave arm. To complete the task in teleoperator mode with low-latency high-data rate communications using a position controller, the operator would note the position of the hole and obstacles in the visual display of the remote workspace, The operator would then decide how to move the fastener to the hole and, watching the fastener in the display, would move the position controller to bring the fastener to the hole while avoiding collisions, checking visually for alignment, and watching for the position controller excursions and stiffness changes that indicate contact or collisions. When the fastener en-

[19] The exoskeleton is described briefly in chapter 5.

tered the hole or contacted the surface near the hole, the operator would mentally observe the stiffness behavior of the position controller in response to small motions about the hole. The stiffness behavior has a different character depending upon whether the fastener is entering the hole, in the hole, bottomed, on the edge, or on the surface near the hole. Once the fastener was in the hole the operator would actuate the driver while exerting a small axial thrust force and nulling the radial forces and moments. If the system had shared control, it could restrict velocity and control normal forces as the operator moved to contact. Then, as the driver was actuated, it could maintain axial alignment as the operator sensed and adjusted the normal force during tightening.

If there is significant communication delay, both force reflection and shared control can have stability problems. In addition, for delays greater than about half a second, force reflection and visual delay can become confusing to the operator. Hence, in cases with significant communication delay and/or limited data rates, normal teleoperation cannot be performed. In those cases it is necessary for the operator to interact with CAD models of the slave and the task that may be overlaid on visual imagery. The operator uses the position controller or joystick to drive the CAD model of the slave. Virtual contact force feedback to the operator can be used as well, based on simulating the mechanical interaction of the CAD model of the slave, driven by the operator, with the CAD model of the task. The resulting simulated motions are previewed on the display. If they are suitable, the commands are formatted and uplinked to the slave, which will respond after some delay. This is similar to the off-line programming of industrial robots. It requires that the slave have a more sophisticated control system, with greater autonomy, than that required for simple master-slave control.[20] It is necessary, for example, for the remote site to know the operator's *intent* in issuing particular motion commands, since it must correct small anomalies itself. Intent, which can be associated with an operating mode, can be uplinked to the slave as part of the command stream. Module insertions and other tasks have been demonstrated in the laboratory using this approach as is described in chapters 3-6.

Using CAD models requires calibration. The CAD model must be accurately aligned with the actual imagery, if it exists. In any case, the master and slave must be aligned (calibrated) with the remote worksite. This problem also exists for telerobots, as will be described more fully below.

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20 Long communication delay and/or a low data rate means that local autonomy is critical to achieve throughput, It can take a significant amount of time to get imagery back from the remote site. From Mars, for example, it can take several days to return a panorama. Sending back parameters that characterize the environment is a potential simplifying approach, but that requires the on-board capability for characterizing the remote environment. For remote missions, the number of control actions per day may be severely limited. In the 1996 Mars microrover mission, for example there will be only about one control interaction per day. In earth orbit, the situation is not so difficult.

When dealing with limited data rates and communication delays, the distinction between teleoperator and telerobotic systems becomes blurred.

The shuttle manipulator (SRMS) is essentially a teleoperator that is controlled with a pair of rate joysticks, each with three degrees of freedom. The operator views the manipulator and task directly, or through various cameras, and moves the two joysticks to control arm velocity (speed and direction). One joystick controls arm position; the other controls hand orientation. The SRMS has been invaluable to shuttle operations, but using it is tedious since little is offered in the way of automation tools for reducing workload. For example, waiting for bending transients to die out between motions and checking for collisions, current operational requirements, are time consuming.[21]

Telerobots

Systems with robotic capabilities are able to use pre-defined CAD models of the telerobot, the workspace, and workpieces, along with macros or routines for specific tasks, to generate small task plans and collision-free paths. Moving the hand to contact is an example of a specific task that might be defined by a routine. The operator supervises the task, resolving difficult situations and determining what routines or macros to use. He can specify a task and then relinquish control to the telerobot, which returns control when either the task is complete or an impasse is reached. The operator can also seize control at any time. Thus control is *traded* back and forth between the operator and the telerobot.

The operator specifies a task through a combination of moving the telerobot with the joysticks or position controllers to record positions along with forces, perhaps, and other data, selecting macros or task names from a menu or by entering text,[22] and designating objects and/or locations in the display in response to prompts from the system. Parameters are either stored in the macros and routines or are supplied by the operator at the system's request,

In performing the fastener-insertion task described above with such a telerobot, the required CAD models and sensor-based macros or routines for inserting fasteners would have been defined in advance or created as necessary by the operator on line. Using a keyboard or a menu, the operator would specify that the system was to insert the fastener. If the system did not know the

21 Collision prevention, stability, flexibility, and control are discussed in chapters 9-13.
22 Giving symbolic names to important task elements like coordinate frames and part features,

location of the hole, it would prompt the operator to designate its location in the display. If the system *did* know the hole location it would highlight the location in the visual display for the operator to verify. If the location in the visual display did not correspond with the highlighted location, it would indicate calibration errors which would be addressed as described below. It might also request the fastener identity, if it were unknown, so appropriate control parameters could be recalled. If it did not know the path, the system would prompt the operator to designate points along the path. If it did know, or could plan, the path, it would display the points and prompt the operator to verify them. The system would then display a preview of the insertion. If acceptable, the operator would allow the system to proceed.

If visual calibration were a problem, the system would move the fastener, still in the driver, to a location visible in the visual display and show an overlay indicating where it thought the fastener was located,[23] prompting the operator to designate, in the display, where the fastener was *actually* located. The system could thus calculate the local calibration correction, assuming arm kinematics were well-calibrated.

On-line local calibration is a significant problem that has a representational component and a kinematic component. The representational component deals with ensuring that the internal representation of the worksite is metrically equivalent to the external environment. It is important because the processes for planning, collision avoidance and deciding where to look for features necessarily operate on an internal representation of the world. The kinematic component deals with ensuring that the commands for positioning an appendage at a physical location or aiming the vision system at a physical point actually do so. Calibration has been locally corrected by designating corresponding features on the visual displays and their CAD model overlays [14]. It can also be corrected using image processing and computer vision techniques.

Telerobots with features similar to those just described exist in a number of laboratories. Satellite tracking and capture along with autonomous servicing [15] have been demonstrated at JPL. Supervised autonomy has been demonstrated many times (see chapters 3-6). The ROTEX flight experiment demonstrated autonomous vision-based free-floating object capture and telerobotic assembly operations [16, 17].
Flight systems incorporating many of the same features are being developed for the space station as described in chapters 14-17. The new systems represent a significant improvement over the shuttle manipulator, but advances are still needed to increase productivity and safety and improve the ability of telerobots to perform difficult tasks, such as repair, autonomously, Repair opera-

23 Based on arm kinematics.

tions can involve structural damage, which distorts geometry in unknown ways and therefore cannot be modeled in advance. Repair can also involve cutting and forming operations, which are more difficult than insertion and fastening operations, and may require enhanced dexterity. The operator must be intimately involved in repair tasks to comprehend the situation, construct models and decide how to proceed. As a class, servicing tasks are much simpler for telerobots than repair tasks if space systems are rationally designed.

Needed Telerobot System Improvements

- Automatic worksite modeling for collision avoidance with rapid, interactive on-line model building for recognizing, and keeping track of, objects in the workspace

- Automatic/interactive calibration of CAD models with the physical worksite and the identification of anomalies

- On-1ine mechanical calibration to compensate for thermal effects and drift

- Ability to lock on and track objects, based upon their geometrical structure, without requiring labels or targets

- Improved dexterity and contact motion control

- Integration of flexible structure control to suppress bending modes

- Systematic integration of perception, reasoning, planning, control, and interface capabilities so it is easy for operators to define new tasks and convey intent, and so the number of uplinked operator commands can be reduced.

Supporting Technologies

Supporting technologies needed to realize the above telerobot improvements include:

- Improved telerobot architectures that can naturally fuse information from different sensory modalities, can easily store and retrieve relevant memories, and can easily deal with the dynamic control reconfiguration involved in identifying, controlling and coordinating, the telerobot and its entire set of sensors and actuators as it moves about its environment performing tasks

- More capable, low-power, low-mass, error-tolerant flight computing, including alternative forms like special-purpose processors and hardwired neural networks, so the demanding computational requirements of autonomous robots can bc satisfied

- Computing and interface standards to make the systcm programming problem tractable

- Integration of sensors and structures (smarter structures) so robust task and telerobot state estimates can bc made

- Efficient, low-mass sensors and actuators

Conclusions and Summary

Space telerobots, which merge teleoperator and robot characteristics, are needed to improve the productivity of space missions, and are needed for missions such as lunar base construction and space station maintenance because of the high cost and low productivity y of EVA astronauts. Telerobots might also bc used for other tasks, but the decision to do so will be based on economic tradeoffs. Controlling space telerobots from the ground could make them ex tremel y attractive, but ground control places stringent demands upon their control systems because of communication delays, data rate limitations, and task uncertainties. To compensate while preserving performance, telerobot s ystems will need greater intelligence and autonomy, which arc independent concepts related to environmental and task complexity that have a profound impact on telerobot system performance. Extremely intelligent robots arc far beyond the state of the art, but useful systems can be built around the concept of humans supervising telerobots. This ap - preach permits robots to do what they are capable of doing while freeing human operators to concentrate on the higher-level aspects of the tasks.

The shuttle manipulator, the only operational space telerobot, is useful but relatively crude. State-of-the-art laboratory telerobots have advanced features, such as automated collision avoidance and interactive task execution using macros, that could notably improve space operations and arc being incorporated in future flight systems. Problems such as the need to wait for bending transients to dic out, the need for on-line calibration, and the need for more automatic model generation, that should bc addressed by telerobot research and development programs remain, however. Developing these capabilities will require advances in a number of supporting technologies including systcm architectures, flight computing, sensors, and actuators.

Advancing space telerobot technology will improve industrial robots, helping to make thcm more adaptable and easier to set up and use, and will therefore improve economic competitiveness. Since space telerobotics must seek greater autonomy, it will also have a beneficial effect upon service robots and aids for the disabled, including smart manipulators, legged wheelchairs, active braces for stabilizing limbs, and perception systems that can sense hazards for the blind. Medical robotics also stands to gain. Telesurgical operations on animal tissue from the United states to Italy have already been demonstrated. Likewise, of course, advances in these other areas will benefit space telerobotics.

Appendix

Telerobot Subsystems

This appendix briefly describes the telerobot subsystems that do not have obvious descriptions. These include the computing, coordination, external sensors, manipulation, mobility, perception, payload, platform, telecommunication, and the telerobot executive subsystems. The subsystems are shown schematically in figure 1, which also shows the control station along with command and data flow:

The **Computing** subsystem, which is under the control of the telerobot executive, is the aggregate of computational devices aboard a telerobot, including general- and special-purpose computers low-level controllers, sensor pre-processors, and other dedicated electronics. All control resides in the computing subsystem. The telerobot executive, perception, and coordination subs ystems reside in the computing subsystcm aswell.

The **Coordination** subsystem, which performs kinematic and dynamic computations as necessary and coordinates the behavior of the various subsystems and devices that are under the control of the executive, resides in the computing subsystem as hardware and/or software. For cx ample, it coordinates the manipulator, mobility, and platform actuators during coopcrative moves, issuing commands to the actuator controllers. It receives state information from telerobot actuators and from external sensors (interpreted by the perception subsystem) and can, in advanced systems, send predicted state information to the perception system so task evolu tion con sistenc y can be determined, that is, to determine if the task is proceeding as predieted. The coordination subsystem is analogous to the motor control systems of animals. It also controls the payload subsystem.

The **External** Sensor subsystem senses the state of the external world. Sensors may include (possibly stereo) cameras and other non-contact devices such as laser and multi-spectral scanners and thermometers. Sensor pointing and deploying devices are considered part of the platform; their motions arc coordinated with other devices by the coordination subsystem. Sensor information is interpreted by the perception subsystem.

The **Manipulation** subsystem is a telerobot's arms and hands, including arm state sensors and actuators. Manipulator control resides in the computing subsystem.

The **Mobility** subsystem includes the devices, with the necessary state sensors, that move a telerobot about. Mobility system types include wheels, thrusters, legs, and rails. Telerobots operating in zero-g would probably employ thrusters, legs (with grasping feet), tracks, rails, or another manipulator. 24 Those operating on planetary surfaces might usc legs, wheels or tracks, the choice depending upon the predominant operating environment. As with the manipulation sys tcm, mobility system control resides in the com puting systcm. Legged mobility and manipulator systems arc quite similar. Both employ limbs, specialized for particular roles, that can be used to manipulate objects or move the telerobot.

The **Perception** subsystem receives input from the various state and external sensors as wc]] as the telecommunication system. In sophisticated telerobots it computes a summary of the world, telerobot, and task state, which is used by the telerobot executive and the coordination subsystcm. In simple s ystems, the perception subsystem may just perform transformations on sensory data.

The **Payload** subsystem is the collection of elements, not part of a telerobot itself, that a telerobot uscs and (perhaps) controls to perform its tasks. Tools like power fastener drivers and cutters arc examples. If a telerobot were being used for scientific purposes, its payload

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24 The Canadian SPDM is slated to be positioned by the SSRMS

might include various scientific instruments which the telerobot would position and actuate to make scientific measurements.

The **Platform** subsystem comprises the actuators and devices, like camera and antenna pointing systems and body joints, that make up the body of a telerobot.

The **Telecommunication** subsystem, which receives information from the control station, provides a bit stream of commands and data that is decoded by the perception subsystem. The telecommunication system also encodes bit streams from telerobot sensors and the executive, transmitting them to the control station, which has its own receiver/transmitter (not shown). The telecommunication system does not include any required antenna pointing systems. They are considered part of the platform,

The **Telerobot Executive,** which resides in the computing system, schedules and controls the overall high-level behavior of a telerobot's subsystems, except for automatic fault protection and reflexes. It receives operator commands and instructions as well as world, telerobot, and task state information from the perception subsystem. In advanced telerobots the executive includes planning, reasoning, behavior prediction, and fault diagnosis tools. The executive can issue commands to both the perception and coordination subsystems. The perception subsystem might, for example, be commanded to look for a particular pattern as the coordination subsystem scans the environment with a camera system.

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References

1. Reynolds, K. "Rocky IV, Literally Out of This World," *Road and Track Magazine,* April, 1993.

2. Pivirotto, D. and Dias, W. *United States Planetary Rover Status-1989,* JPL publication 90-6, Jet Propulsion Laboratory, Pasadena, CA, June, 1990.

3. Ruoff, *C. et* al. *Autonomous Ground Vehicles: Control System Technology Development,* Final Report, JPL Task No. 80-2021, Report ETL-075, U.S. Army Engineer Topographic Laboratories, Ft. Belvoir, VA, October, 1984.

4. Bayer, W., "Interview With Randy Hoffman, President and CEO, Magellan Systems Corp.," *Space* News, Jan 10--16, 1994, pp 22.

5. Hotz, R. L., "Where in the World Arc You," *Los Angeles Times,* Feb 7, 1994, pp 1.

6. Begley, S. and Annin, P., "We Slan~-Dunked It," *Newsweek Magazine, Dcc 20, 1993,* pp 100-102.

7. Fisher, W. and Price, C. *Space Station Freedom External Maintenance Task Team, Final Report,* NASA Lyndon B. Johnson Space Center, Houston, TX, July, 1990.

8. Whittaker, W., Kanadc, T. et al. *Space Robotics in Japan*, JTEC Panel Report, Japanese Technology Evaluation Center, Loyola College, Baltimore MD, January, 1991, NTIS Report #PB91-100041.

9. Dias, W., Matijevic, J., et al., Directions for Lunar Construction: A Derivation of Requirements from Construction Scenario Analysis. in *Engineering, Construction, and Operations in Space III*, V1 1992, proc Space '92, Sadeh, Sture, and Miller, eds.

10. Tuck, E. Patterson, D., Stuart, James R., and Lawrence, M. *The Calling*[SM] *Network: A Global Telephone Utility,* publication of the Calling Communications Corporation, 1993.

11. Seitz, P., "New LEO Satellite Venture Proposes Ambitious Plans, " *Space News,* July 11, 1993.

12. Varsi, G., Ruoff, C., et al. *ProjectedAutomation Technology Requirements 1992-2011,* JPL Publication # JPL D-9306, Jet Propulsion Laboratory, Pasadena, CA, May, 1992.

13. Swanson, P. Space *Station/OACT Robotics Technology Study,* Phase I report briefing to NASA/OACT, McDonnell-Douglas Corporation and Oceaneering Space Systems, 10 September, 1993.

14. Bon, B., Wilcox, B., Litwin, T. and Gennery, D. "Operator-Coached Machine Vision for Space Telerobotics." *In SPIE Symposium on Advances in Intelligent Systems, Conference on Cooperative intelligent Robots in Space,* Boston, Massachusetts, November, 1990.

15. Schenker, P. et al. "NASA Telerobot Testbed Development and Core Technology Demon - strati on, "Proc *SPIE Conference on Space Station Automation (IV)*, Vol 1006, Cambridge, MA.

16. Sanchez, V, “Robust Robot Vision Techniques for Grasping Floating Objects under μ-Gravity,” In *Proc 3d European In-Orbit Operations Technology Symposium*, ESTEC, Noordwijk, ‘I’he Netherlands, 22-24 June, 1993.

17. Hirzinger, G., et al. "Sensorbased Space Robotics--ROTEX and its Telerobotic Features," In *Proc 44th Congress of the International Astronautical Federation,* paper # IAF-93-U.6.591, Graz, Austria, Ott 16-22, 1993.