FINAL REPORT

for the period
March 1984- March 1985

SPACE ROBOT SIMULATOR VEHICLE

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Jet Propulsion Laboratory
Pasadena, California
Contract No. 956303

Principal Investigator:
Professor Robert H. Cannon, Jr.
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Stanford, California

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ABSTRACT

Robots will be an extremely important element in man's establishing an extensive and long-term presence in space. We are working to give these robots the superior operational charateristics they will need to maximize their usefulness in the space environment.

We have been building a Space Robot Simulator Vehicle (SRSV) under JPL funding to model a free-flying robot capable of doing construction, manipulation and repair work in space The SRSV is intended as a test bed for development of dynamic and strategic control methods for space robots. The vehicle is built around a two-foot-diameter air-cushion vehicle that carries batteries, power supplies, gas tanks, computer, reaction jets and radio equipment. It is fitted with one or two two-link manipulators, which may be of many possible designs, including flexible-link versions. Both the vehicle body and its first arm are nearly complete.

We have successfully simulated inverse dynamic control of the robot's manipulator using equations generated by the dynamic simulation package SDEXACT. In this mode, the position of the manipulator tip is controlled not by fixing the vehicle base through thruster operation, but by controlling the manipulator joint torques to achieve the desired tip motion, while allowing for the free motion of the vehicle base. One of our primary goals is to minimize use of the thrusters in favor of intelligent control of the manipulator. We intend to explore ways to reduce the computational burden of control, and to try other control algorithms including bang-bang control to improve response and decrease computation.

We aim further to explore cooperation between multiple arms and multiple robots in carrying out robotic tasks. This will require accurate force sensing and control, as well as the strategic control necessary to plan and carry out tasks involving more than one device. We will extend this study of strategic control to examine the task-level control of robots by humans, in order to reduce the real-time control burden placed on the human operator, and greatly improve the effectiveness of human/robot teams.

We look forward to proposing to NASA a demonstration of a space robot in the STS cargo bay. Such a project would allow us to test our dynamic and strategic control methods in the full three-dimensional case, and to establish the practicality of robots for orbital manipulation and assembly. We think that such a verification of our methods will lead to their application in truly useful space robots.

INTRODUCTION

Robots will be an extremely important element in man's establishing an extensive and long-term presence in space. The danger and inconvenience associated with human extravehicular activity will make it very difficult to maintain a space station without providing a mechanical substitute to perform construction and repair. Our research group is working to develop the enabling technologies for such space-borne robots.

Space robots will need numerous superior characteristics, including many that have not yet appeared in industrial, ground-based systems. They will need to be lightweight, limber, deft, facile, quick, friendly, low-powered, seeing, sensing, thinking machines. Above all, they must be capable of reasoning and strategizing — of carrying out tasks specified at a high conceptual level, by "thinking through" the best way to carry out any given task. Robots with dynamic speed and intelligent control will provide the flexible automation that will be important in achieving high levels of space robot performance.

We have aimed our research directly at attaining these goals for a space robot. We intend to study the design, dynamic control, human interfacing, and high-level task control that will make robots useful tools in space. In order to achieve this goal we are building a laboratory satellite; a model with which we will implement our control strategies at all levels. We hope that the results of our research may be directly transferred from this physical model to a physical satellite robot, when man's involvement in space requires it.

We consider this one of the primary goals of automation: to replace humans in a dangerous, unpleasant working environment with robots who can work harder, longer, and without extreme safety precautions or expense. We hope to develop a robot that will be effective and convenient to use, and that will change extravehicular construction and repair from a major undertaking to a routine matter, as it will need to be if humans are to maintain an extensive, productive, long-term presence in space.

Under NASA/JPL funding and encouragement during the period March 1984 - March 1985 we have made, we believe, a substantial start, which we describe in this report. Basically, it is our plan to construct a Space Robot Simulator Vehicle (SRSV), a laboratory device which will allow us to develop and test control techniques for a space robot (see Figure 1). It will be supported by a thin cushion of air to provide the same free motion characteristic of satellites. It will have two-link arms such as a satellite robot would, built to work in the plane of the support surface. It will have attitude and position control capability, as well as the ability to manipulate objects with its arms. We hope that the techniques that we develop on this test bed will be directly applicable to actual robot satellites.

So far, we have used JPL funding to build the central body of the vehicle (see Figure 2). It includes on-board power and gas supplies, power conditioning, computer, electronically-controlled reaction jets, two-way radio telemetry and rotational rate sensing. The vehicle may be manually controlled via radio by operating its thrusters. We are working on the position sensing systems to allow automatic position control; and on the construction of the arm itself.

At some future time we hope to test our control methods, for the full three-dimensional case, on a Space Shuttle demonstration payload. We would design and have built a satellite robot to demonstrate deft handling and assembly of materials in the Shuttle's payload bay (see Figure 3). The SRSV is intended as a precursor to such an experimental device, which in its turn will lead to robots to take on many of man's tasks in space.

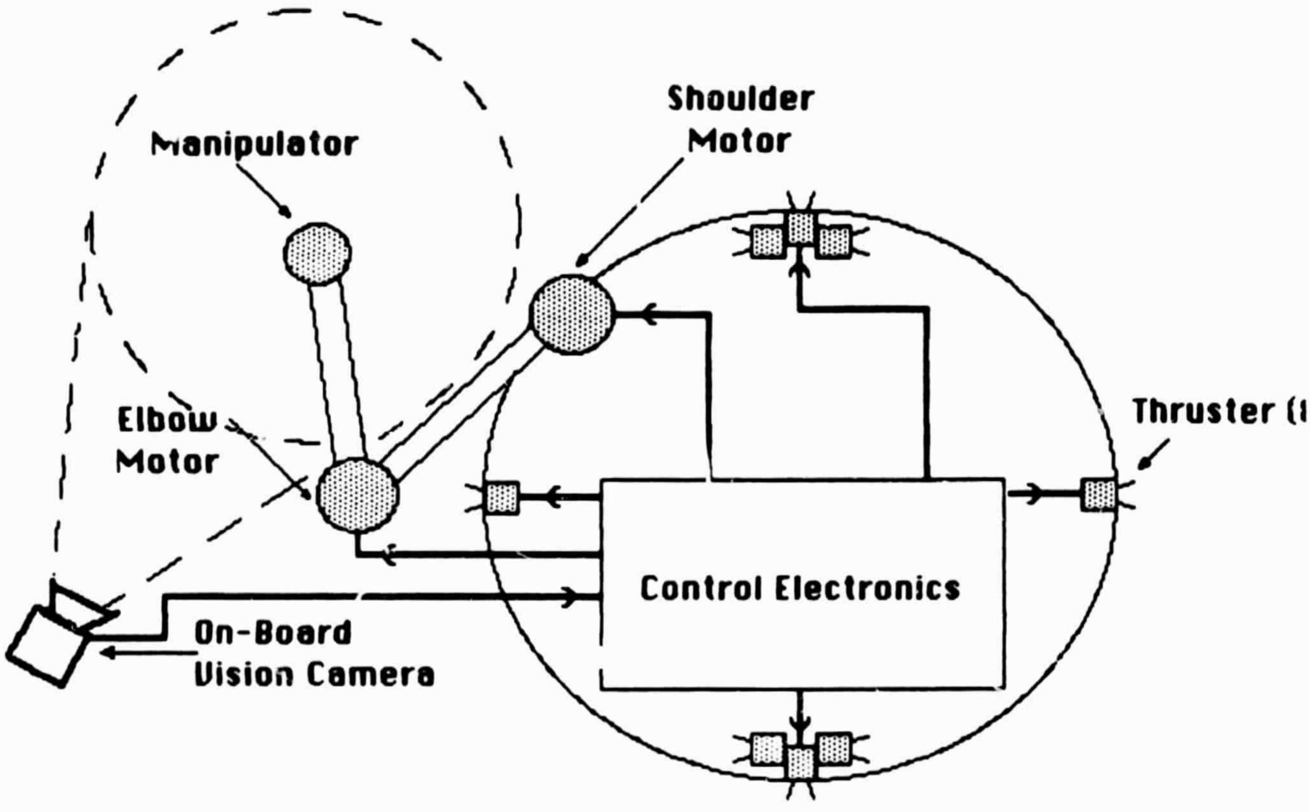

Figure 1: Schematic diagram of the Space Robot Simulator Vehicle. The on-board electronics control arm and thrusters based on data from the on-board vision system, which overlooks the operating region of the arm, and from a radio telemetry system transmitting position and command data from the laboratory computer.

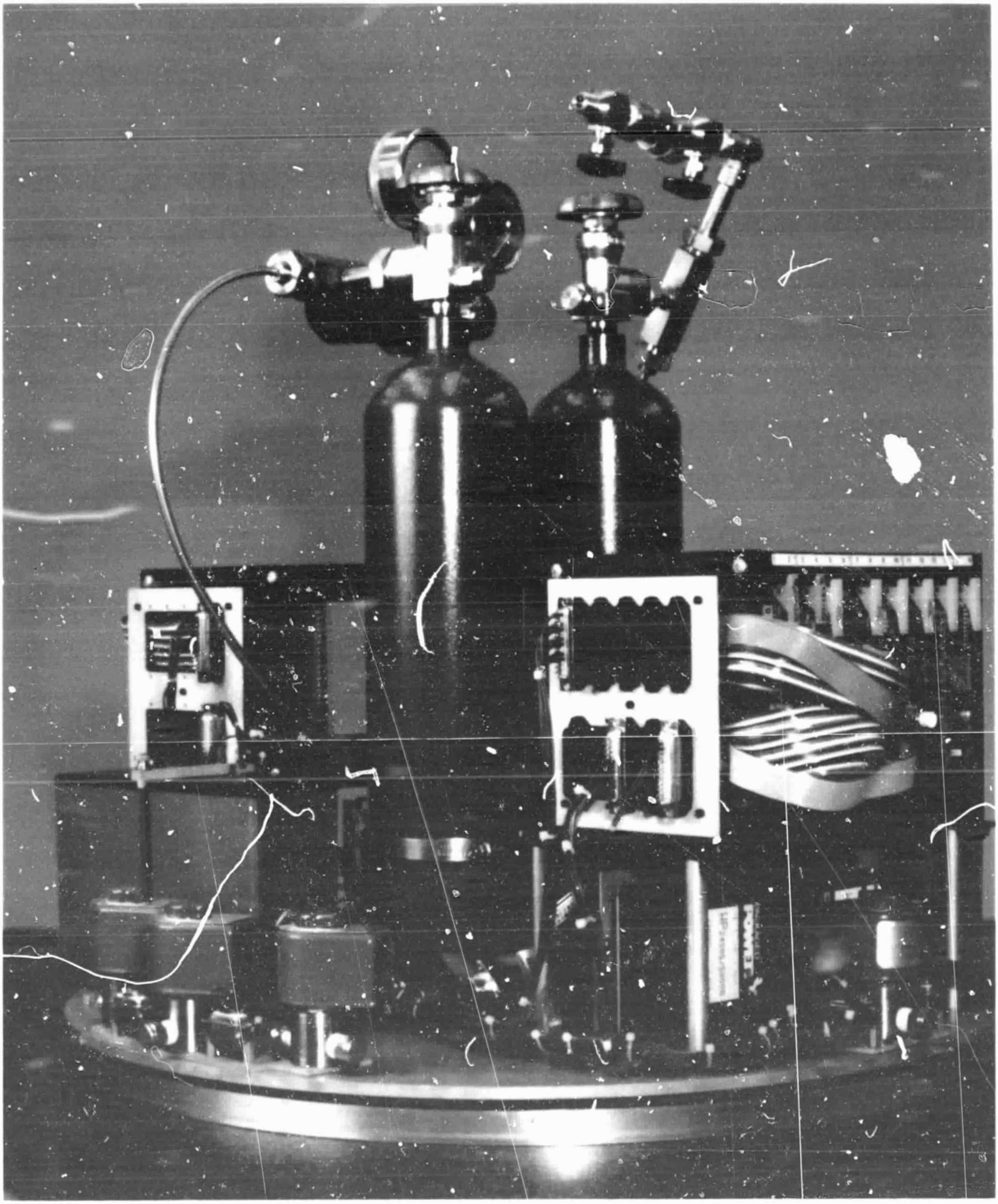

Figure 2. Photograph of the central body of the Space Robot Simulator Vehicle. The green objects are thruster solenoids: the orifice plugs can be seen attached to the thruster valve bodies. The regulator and filling mechanism can be seen at top, as well as computer and power conditioning equipment, right; analog electronics, left; angular rate sensor connector, center; batteries, far left and right. The arm is not yet fitted.

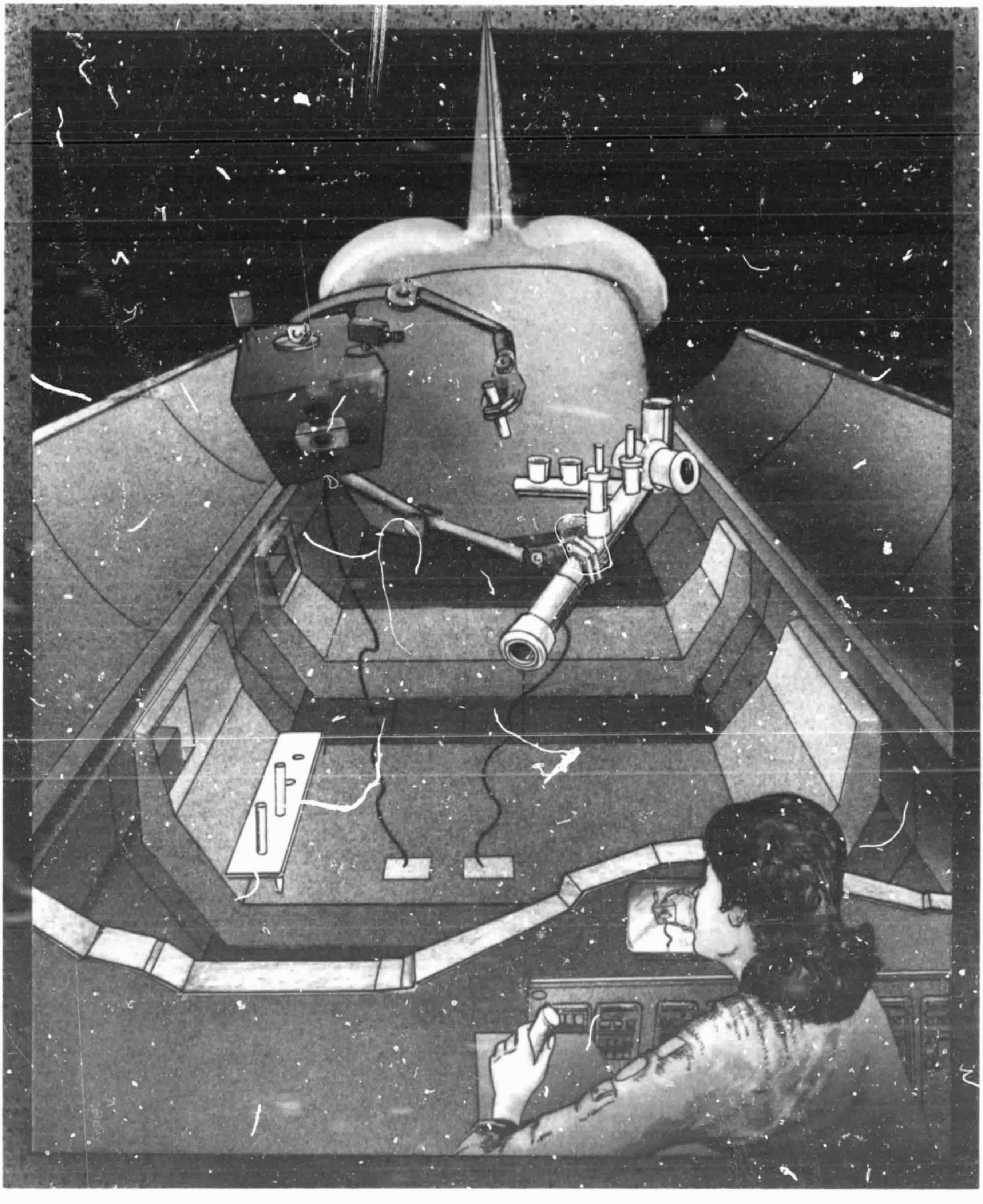

Figure 3. Demonstration space robot operating in the space shuttle's cargo bay. The robot could operate in the mode shown, using a "leg" to fix workpieces as well as in free-floating grasping and assembly modes.

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DESIGN AND CONSTRUCTION OF THE SPACE ROBOT SIMULATOR VEHICLE

The Space Robot Simulator Vehicle (SRSV) is intended as the focus of our research into the control of satellite robots. The immediate purpose of the vehicle is to study the dynamic control of its 2-link manipulators, with the goal of applying the knowledge gained to actual orbital robots.

The SRSV when completed will consist of an instrumented two-foot-diameter air cushion vehicle, with attached two-link arms. The SRSV rides on the surface of a very flat granite table. It can control its position and attitude thereupon via gas jets, operated via computer control of solenoid valves. Each two-link arm operates in the plane of the tabletop, and is supported on its own air-cushion pads. This design, allowing completely free motion of vehicle and arm, provides a good two-dimensional approximation to the microgravity environment. Fitting and operating various manipulator arms, including flexible ones, will be easier because they will not be required to support themselves against gravity.

The vehicle and arm pads are supported on a .004-inch layer of gas, which is maintained by introducing compressed nitrogen at 1.0-1.5 psig at the center of the plate (see Figure 4). The flow of gas through the thin support layer is very slow, allowing the vehicle to be supported for a long time with relatively little gas. Both the lower surface of the vehicle base, and the granite surface plate or table upon which it is supported, are ground to tolerances of .001 inch in order to allow this small gap to be maintained.

The initial design of the SRSV was begun in April 1984, soon after it was suggested by Dr. Ewald Heer, then of JPL. Some of the long-lead-time items were quickly ordered, notably the granite table upon which the model is supported. Purchased with funds from both our NASA-Langley and our NASA-JPL contracts, the table has a surface size of 6 ft. x 12 ft. and thickness of 20 inches. The large dimensions will allow complex target-acquisition and obstacle-avoidance maneuvers, and provides sufficient stiffness so that the vehicle does not respond to deformation of the surface due to the weight of the SRSV.

Much of our work under the contract so far has been toward the design and manufacture of the SRSV itself. At this time the body of the vehicle is nearly complete (see Figure 2), lacking only some electronic wiring and the installation of angular-rate and vision sensors. The various parts of the first two-link arm are being machined, and the arm itself will soon be attached. The vehicle currently may be operated manually via a radio link through the on-board computer, to perform attitude and position control with the on-board thrusters. Since position sensing equipment is incomplete, the vehicle is not yet automatically controllabie.

The air-cushion base of the SRSV consists of a 2 foot-diameter, 3/4 inch-thick aluminum plate with the bottom surface ground very flat. Support gas is supplied via a tube to the center of the plate. In order for the plate initially to be lifted and the gas film established, a plenum of 5 inch diameter and .06 inch thickness is machined into the middle of the plate bottom. A very few psig of pressure in this plenum is sufficient to lift the plate off when flow is started, so that the gas film may form.

The onboard equipment of the SRSV is attached to a 1/4 inch chassis plate that rests atop the base plate on three spacers. This arrangement eliminates distortion of the base that might result from direct attachment of equipment. Two D-size (medical) gas cylinders, standing vertically on each side of the plate's center, provide gas for all vehicle functions via a 70 psi regulator. An 8088-based computer system built on an STD-bus backplane provides on-board computing. Two 12-volt, 12-amp-hour batteries provide on-board power which is conditioned by several DC-DC converters. Eight solenoid valves vent nitrogen through small jets under computer command to control attitude and position. An angular rate sensor measures the rate of rotation of the satellite body for dynamic calculations.

The arm consists of two links of 12 inches each, driven directly by motors mounted at shoulder and elbow. The elbow motor is supported on an air cushion maintained under a metal pad, as is the "wrist", so that no vertical support is required of the arm links. Both motor axes are vertical, so the arm commands a region of the table directly adjacent to the vehicle. A video camera will be supported on the vehicle over the region of operation of the arm, so that it can detect the position of the tip of the arm as well as targets within the arm's reach. Its output will be processed to derive arm and target positions and orientations. An overhead camera will finally detect global position and orientation of vehicle, targets and obstacles for target approach and obstacle avoidance planning.

The design of the SRSV has been guided at all times by the necessity to make it as nearly as possible a prototype for a practical robot demonstration satellite. Sensor design, dimensional scaling, attitude and position control and all other aspects reflect as far as possible a realistic robot design. We hope thereby to achieve results that will be directly applicable to the control of the robot satellite itself.

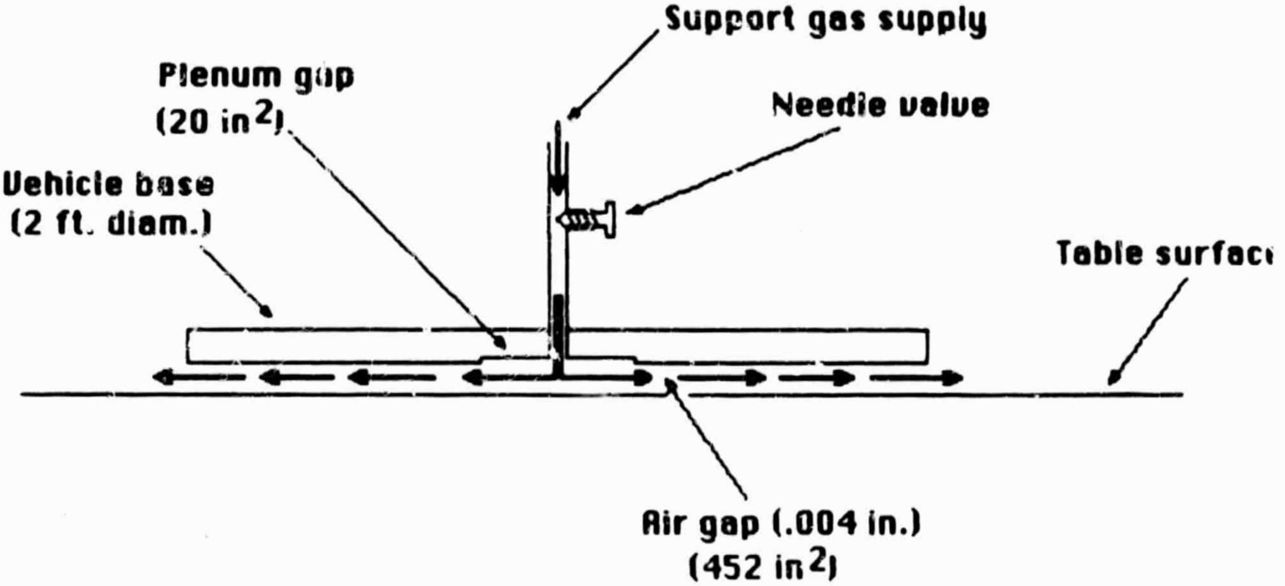

Figure 4: Air-cushion support of Space Robot Simulator Vehicle. Gas is supplied through a needle valve from the 70 psig supply, and flows through the air gap to support the vehicle over the table surface. The plenum gap is included to allow for initial lift-off of the vehicle and establishment of the air gap.

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DYNAMIC CONTROL OF SPACE ROBOT SIMULATOR VEHICLE

Overview

Our objective in controlling the Space Robot Simulator Vehicle is to achieve precise control of the manipulator endpoint, in absolute space or relative to a target. This is complicated by the fact that the body of the SRSV is not rigidly attached to any support, but is free to translate in the two horizontal dimensions and to rotate about its vertical axis. The satellite robot it represents will have three degrees of freedom in both translation and rotation. The SRSV body and the satellite will therefore both respond to all reaction forces due to the motion of their arms.

It is this inertial compliance of the SRSV body that makes its control an interesting and unusual problem. Earthbound manipulators may be controlled through their joint angles alone; that is, by setting joint angles the controller can achieve the desired endpoint position within the limits imposed by the lack of absolute structural rigidity. This is the approach taken by the designers of most of today's production robots, and is the reason that most such manipulators are enormously large and heavy with respect to their rather small payloads. Designers who depend on joint angle control must eliminate flexibility in their robots, as flexibility converts directly into inaccurate manipulator positioning.

Reversal of this trend toward large, heavy manipulators has been a continuing goal of research at our Center for Automation and Manufacturing Science. Our solution focuses on the cause, the dependence on joint angle control. Our robots are unique in sensing and controlling the endpoint position itself, allowing accuracies limited only by our position sensing equipment and by the precision with which we may exercise dynamic control.

Such direct endpoint control is quite difficult. It is an example of noncolocated control, in which the sensed variables (manipulator position) are physically separated by flexible structures from the driven elements (motors). Colocated control insures that a certain class of dynamic compensators will result in stable control of the system: but it requires just the kind of joint-angle control that we are trying to eliminate. Noncolocation introduces dynamics between driver and sensor, and forces a more sophisticated control; but it allows the lightweight and deft robots that we seek.

As we have pointed out, this direct endpoint control is, for the SRSV, not just an improved control, but a necessary one for precision and speed. In the absence of a fixed base, the kind of rigid robot favored by today's manufacturers is impossible. Manipulator control requires the coordination to correct for its lack of a fixed base. The problem closely resembles that of the lightweight, earthbound robots with which we work, and so meshes well with the other projects within our laboratory. Our experimental work will focus on precise endpoint control relative to targets and in absolute space, by direct sensing of endpoint position.

Simulation of Inverse Dynamic Control of SRSV, and Further Plans

Inverse dynamics is one means of deriving the control necessary to produce a given motion of some portion of a dynamic system. In the case of the Space Robot Simulator Vehicle, it is used to force an approach to target by the tip of the two-link arm along a specified type of trajectory. For a space robot possessing more degrees of freedom, inverse dynamics would be applied to control all six variables of position and orientation of the manipulator.

We have realized inverse dynamic control of a simulation of the SRSV on a VAX-782 computer. The simulation derivative equations were generated by SDEXACT, a dynamic simulation program written by Dan Rosenthal and Mike Sherman (of which JPL owns a copy). They were combined with a numeric integrator in order to achieve simulation of the system.

The SDEXACT equations maintain a mass matrix that represents the relationship between forces and torques imposed on the system, and the resultant linear and angular accelerations. It also calculates the inertial forces and torques about each joint at each instant. By combining these inertial forces and torques with active ones applied to the system, and solving the linear equation involving this vector of forces and the mass matrix, the program derives the accelerations (velocity derivatives) necessary to conduct the integration of states. The displacement derivatives being simply equal to the velocities, the entire set of derivatives necessary for the simulation integration are generated. Using the dynamic analysis procedures developed by Professor Thomas Kane of Stanford University, SDEXACT forms an extremely efficient set of equations to effect such a simulation.

Some of these same quantities are used in the inverse-dynamic control of the SRSV. Since the mass matrix describes the sensitivity of the various degrees of freedom of the system to the on-board actuators, it can be used to derive the actuator drives necessary to achieve a specified motion of the system. In our simulation, this motion has been defined as a second-order critically damped approach to the origin by the manipulator tip, in the orthogonal X and Y table coordinates. The tip acceleration necessary to follow this trajectory from any current tip position and velocity is calculated at each time step, and the arm motor torques necessary to achieve this tip acceleration are calculated using the mass matrix as well as other quantities available from the simulation equations.

The critical experimentalist will point out that this is the worst kind of simulation. Quantities involved in the simulation itself are being used by the controller in order to drive the simulation. The simulation is not an end in itself, however, and should not be considered a finished product: rather, it is a tool to develop and debug software for the control of the physical system. The same control routines will be used with the SRSV itself, calculating the dynamics from the angles and positions generated by the sensors themselves. The recursive flaw of the simulation will then be eliminated.

The simulated control works well (see Figure 5). A graphic representation of the SRSV as it progresses through a target approach clearly shows the interaction of the arm and vehicle motions as the arm tip approaches and holds at the target position. The simulated vehicle rotates first one way and then the other as the arm snaps the forearm right and then reaches left from the shoulder to approach and follow the target position.

Note that this simulation includes no attitude or position thruster operation. Our goal is not to operate the thrusters so that the arm operates from a fixed base, but to control the arm to allow for the free motion of the base. Thrusting gas will be far too precious a commodity in space to waste it in making up for deficient dynamic control. We are in fact interested in looking at ways for a satellite to "leap" from place to place in a large space station in order to achieve the same savings in reaction mass: we feel that trading sophisticated control for fuel savings in orbit will nearly always be a good deal.

One clear difficulty with the control method we have described is its computational intensity. Constant recalculation of dynamic coefficients will be a large burden on the onboard processor or processors, that can only increase in going from our two-dimensional model to the three-dimensional satellite robot. We are therefore interested in studying how to reduce this computational burden, or to split it between multiple processors, perhaps operating at different rates. It may be possible to recalculate the mass matrix at a lower rate than the sampling rate of the controller, in a separate processor or asynchronous program. A table look-up scheme may even suffice for deriving the positioning sensitivity of the manipulator to joint torques. Variations on bang-bang control may provide better accuracy and disturbance rejection: it will be interesting to see how it works in this strongly coupled, nonlinear system.

As we have pointed out, all of these studies will need to be conducted in the context of the physical simulator vehicle being constructed in this lab, and not just in computer simulation. The point of the experimental study of robots is to examine the interaction of controllers with the real world: with the imperfections and disturbances that can never be fully modeled in the deterministic, consistent environment of the computer. The simulations we are conducting are a precursor to the real work of controlling the robot, and a tool in developing the algorithms to do that control.

The Space Robot Simulator Vehicle is intended as a test-bed to examine many methods of controlling a satellite manipulator. With its help, we hope that the first actual development of a satellite robot can be founded on experience in its design and control gained in laboratory studies of its two-dimensional predecessor.

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VARIATIONS ON THE ROBOTIC THEME

The robot satellite is capable of several physical variations for increased utility. We hope to model several of these variations in order to study the changes in control that result. In addition, other changes to the vehicle will be useful in studying advanced problems that we foresee in the basic robot satellite.

Flexiblity of structural members is a classic problem in spaceborne devices. In the case of the orbital robot, the flexibility of the manipulator arm itself can be a significant problem, particularly as the scale of the system grows. There exist other examples of flexible articulated systems requiring control: one is the Space Transportation System's own SPAR manipulator. Another example is one of our group's main interests; lightweight and quick earthbound robots. We intend to study both floating and fixed-base flexible manipulators using the same air-cushion technology as in the SRSV vehicle itself. This will be particularly convenient with flexible arms of two links or more, since the upper arm need not support the large torsional forces that would be imposed by the forearm. We hope to extend our understanding of the control of both satellite robots and industrial manipulators, by the study of flexible arms with the Space Robot Simulator Vehicle.

We also intend to work with a system incorporating two cooperating arms on a single vehicle. The two arms of the human being are essential for many tasks, and particularly so in the microgravity environment. We would like to study both the dynamic control and the coordination of such arms in performing orbital tasks. It will be a considerable control challenge to coordinate two arms, particularly from a satellite with no rigid base. The results of this research will again be applicable to earthbound satellites built with two arms, or to cooperating fixed-based robots. We feel that coordinated cooperating arms will contribute heavily to robotics.

Another aspect of cooperation is that between two different robots. This is particularly important in space, where enormous but weightless structural members may need to be handled by two or more satellite robots for transportation or fitting. Mobile land robots will also find this aspect of cooperation useful for many tasks. The study of multiple cooperating SRSV's will be useful in developing cooperation strategies for both land and space-based robots.

In every one of the above examples, force sensing and control of a highly sophisticated level will be quite essential to the simultaneous control of multiple cooperating manipulators. This will be one focus of our research into both fixed and free-floating cooperating manipulators.

Research with the Space Robot Simulator Vehicle is not a closed-end project, but is capable of many extensions that will generate useful results for both land and space applications. We hope that it will allow us to approach space automation on the foundation of considerable control experience, as dynamic and strategic control will be some of the most important components of progress in space automation.

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HIGH-LEVEL CONTROL OF SATELLITE ROBOTS

Satellite robots will depend on control by ground or space-based human operators for some time to come. Such remote control of robots is difficult, and the human time and the communications necessary for control will be expensive. It will be preferable to minimize the time commitment required of the human controller, placing as much of the control burden as possible on the electronics. Our approach is to raise the operator's involvment to the task level, where he will specify jobs to be performed by the robot and can focus elsewhere while his orders are carried out. Since the robot may take a long time to perform a task, the operator can save a great deal of time by avoiding personal real-time control of the robot.

This time savings may make it possible for a single local operator to guide several robots in their various tasks, rather than requiring a one-to-one assignment of humans to machines. This will result in a great savings in the staffing of a space station, in the effectiveness of space station personnel, and in the satisfaction of the personnel themselves. It will dramatically increase the efficiency of a station staffed by a small number of astronauts, allowing them a much higher level of productivity: it would also allow ground-based operation of space robots without many of the control problems associated with real-time teleoperation in the presence of delays.

Our current research goals extend into the two interfaces necessary for such high-level control. The operator must describe the task to be performed and the robot's environment to the computer. The computer must then perform the necessary dynamic and strategic control of the satellite necessary to complete the task. We have separated these two processes at what we consider a natural division: at the point where the operator's description of task and environment are passed to the robot control system.

The first requirement is a means for the operator to describe a task clearly and conveniently to the computer. The operator must be able to "sketch" the details of the task, including only that data which the robot is not able to gather for itself. This of course includes the specific assignment, as well as data that is dependent on the judgement of the operator and his ability to see and understand the robot's environment. He must indicate the location and shape of obstacles, necessary operations, places to perform assigned tasks, and so forth. Many of the fine details may be derived from *a priori* information in the computer concerning elements of the environment, such as satellites and construction materials. Once the operator has delivered his assignment, he can turn to other work in confidence that his orders will be carried out.

The operator will describe the task by a combination of graphical, literal, and even oral means. The robot will have the ability to sense its position and attitude, and that of other objects, via relatively simple vision processing. The robot can combine this information with the operator's physical description of the individual objects to develop a complete model of its surroundings. The robot can then carry out its assigned task without further intervention by the operator, until it is completed or an exception is detected — a condition that fails to match the task model originally provided to the machine.

The robot's task performance is our second research goal in high-level control. The system will have to accept a model of its environment as developed by its sensing system and the operator, and perform both the strategic and dynamic control necessary for its assigned task. It will need to plan paths of travel and approach targets according to the location of obstacles and the configuration of the target itself. It will need to accomodate different burdens attached to the robot and their effect on the dynamics of the robot's motion, as well as on its effective shape in obstacle avoidance. It will have to cooperate with other robots during certain tasks, and to avoid collisions with them at other times. It will need to detect exceptions, and to take sensible, immediate action until the operator intervenes. It will need to perform all of these tasks, and more, with a minimum of operator intervention.

We believe that robots will be an essential part of man's long-term presence in space. The expense and danger of having humans involved in day-to-day extravehicular tasks must be a great burden on the space station effort, and will need to be eliminated for such an effort to succeed. The enabling technology will be directly applicable on the ground as well, in the control of many kinds of land-based and marine mobile robots with their similar problems of control and human operation. We hope to push the operator's job further and further from the routine and tedious. We hope to develop the high-level computer control that will make earth and spaceborne robots efficient and convenient to use for the many tasks they should be able to perform.

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