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FIRST SEMI-ANNUAL REPORT
on
RESEARCH ON

CONTROL OF A FREE-FLYING ROBOT MANIPULATOR SYSTEM

Submitted to
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INTRODUCTION

This report reviews work performed during the first 6 months of the subject contract by the Stanford Aerospace Automation Laboratory for NASA's Ames Research Center. The research being performed under this contract is successor to research begun in 1983 under the sponsorship of NASA's Jet Propulsion Laboratory under contract NAS7-100.

The goal of our research is to develop and test control strategies for a self-contained, free flying space robot. Such a robot would perform operations in space similar to those currently handled by astronauts during extravehicular activity (EVA). Use of robots is intended to reduce the expense and danger attending EVA both by providing assistance to astronauts and by eliminating the need for human EVA for many tasks. These operations can thus be rendered safer and much less expensive, which will greatly enhance the scope and flexibility of space assembly and repair activities.

The focus of our work is to develop and carry out a program of research with a series of physical Satellite Robot Simulator Vehicles (SRSV's), two-dimensionally freely mobile laboratory models of autonomous free-flying space robots such as might perform extravehicular functions associated with operation of a space station or repair of orbiting satellites. (It is planned, in a later phase, to extend our research to three dimensions by carrying out experiments in the Space Shuttle cargo bay.)

The SRSV, which is described in greater detail in the sections that follow, was first conceived and designed under the prior JPL contract. Much of the mechanical fabrication of the body of the spacecraft model was also completed, as well as the purchase and installation of the 10-ton granite surface plate upon which the vehicle operates.

During the first 6 months of the current contract, we have continued the development of the SRSV, and of some of the controller subsystems. The two-link arm has been fitted to the SRSV base, and we have explored the open-loop characteristics of the arm and thruster actuators. We have begun building the software foundation necessary for use of the on-board computer, as well as hardware and software for a local vision system for target identification and tracking.

The SRSV Space Robot Model

The main body of our laboratory Satellite Robot Simulator Vehicle (SRSV) consists of a two-foot-diameter air cushion vehicle (ACV), shown in Figure 1. The ACV is supported on a film of gas approximately .005 inch thick. The gas film is maintained between the base of the vehicle and a large granite surface plate (table) measuring 6×12 feet and ground flat to an accuracy of .001 inch. The base of the vehicle is also machined flat to .001 inch. The table is carefully leveled to eliminate gravity-induced accelerations of the vehicle. The vehicle is equipped with eight thrusters for computer control of orientation and location. An angular rate sensor is also included to sense rotation of the main body.

The SRSV is currently equipped with a single two-link arm. The arm's joints are supported on individual air-cushion pads of their own, and they operate in the two dimensions of the granite table surface. Each joint of the arm is equipped with a direct-drive brushless torque motor for control and an optical encoder for angle sensing. A television camera locates targets that are marked with infrared light-emitting diodes.

The SRSV is a two-dimensional experimental model of a satellite robot. The current version has five degrees of freedom. Experimental results from the control of the SRSV will serve as a foundation for extending control methods to the case of actual space robots with twelve or more degrees of freedom. We intend ultimately to demonstrate control of a full three-dimensional space robot (in the Space Shuttle bay), using the same type of control algorithms as we are about to begin testing with the SRSV.

Our recent progress has been in the final construction of the SRSV, and in early development of the software needed to program and operate the vehicle. These advances are reviewed below.

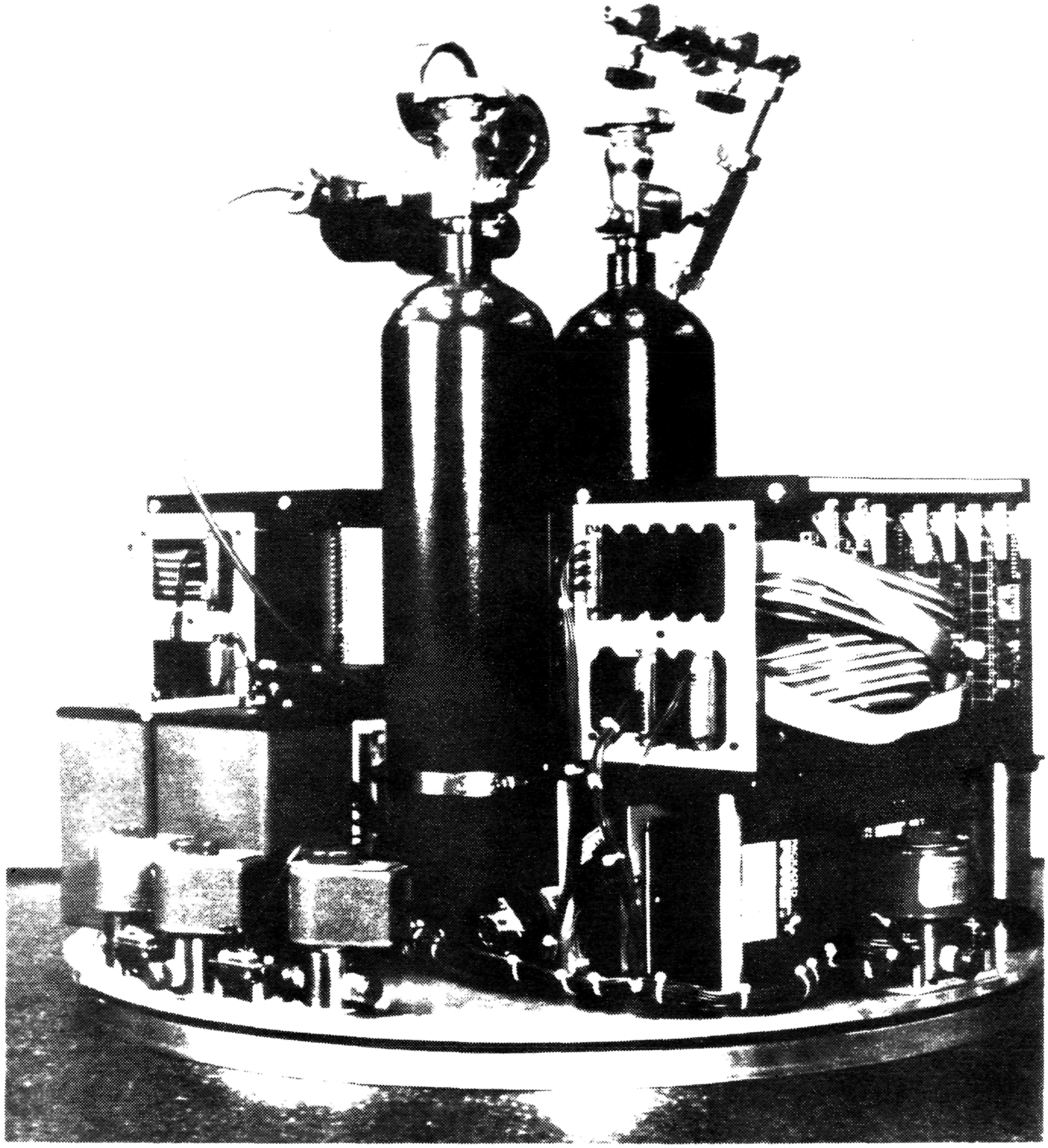

Figure 1: *Body of Satellite Robot Simulator Vehicle. A set of three thrusters can be seen to the left; two are for orientation control and the center one for position. The onboard computer, batteries, power supplies, and gas bottles are also visible.*

PROJECT RESULTS

Advances in Construction and Characterization of the SRSV

The SRSV is currently equipped with a single two-link arm. The arm is supported by air-cushion pads at elbow and wrist, and driven by direct-drive motors mounted at the shoulder and on the elbow pad. The two-link arm operates in the horizontal plane defined by the surface plate, and is intended to simulate the three-dimensional arm of an actual satellite robot.

The arm has been built and mounted at this time. It is driven by a pair of Inland Motors torque motors, for which special housings have been machined, including bearings and shafts. The arm links are made from thin horizontal strips of aluminum, which are intended to provide stiffness in the direction of actuation. Flexibility in torsion and bending allows the air-cushion pads at elbow and wrist to operate without dragging due to side forces. The links are mounted low, in a plane close to the center of gravity of the pads, to minimize the torque component of the forces they impart to the pads. Each pad consists of a 7-inch disk of half-inch thickness, machined flat on the bottom surface with a shallow central air plenum to provide an initial lifting force.

The arm motors require operating current, which is controlled by the on-board computer. Because the motors require 21 volts input to achieve rated torque, and because the on-board batteries supply 24 volts, we have built a bridged voltage-to-current converter to drive each motor. Because each motor is driven from both the positive and negative power rails, instead of about a common rail, nearly the full battery voltage may be applied. The current controllers are built with Apex high-power operational amplifiers that handle the large currents required. The time required for a full-torque slew about the shoulder joint is approximately 6 seconds. We are considering going to larger and heavier motors in order to improve arm response, and to increase the dynamic coupling from motions of the arm to the heavier base.

Characterization of SRSV actuators

The SRSV is equipped with two kinds of actuators. The torque motors that drive the arm joints are described above. Eight compressed-gas thrusters also provide control of vehicle attitude and location by venting nitrogen from solenoid-controlled valves under computer control. The vent on each valve consists of a simple hole drilled in a plug at the valve exit. Because of the low gas-supply pressure, 70 psi, an expansion nozzle is of little use.

The linear acceleration imparted to the SRSV by a single thruster has been found to be $.05 ft/sec^2$, or $.0017g$. The primary function of the thrusters is to make small adjustments to the SRSV's position relative to a target. The thrusters are also used (in pairs) to control the SRSV's angular orientation, or attitude, about the vertical axis.

On-board Computer System Development

The Satellite Robot Simulator Vehicle is equipped with an on-board computer based on the Intel 8088 microprocessor and built on the STD microcomputer bus. The computer includes the 8087 numeric data coprocessor, which is capable of fast arithmetic calculation with high-precision real numbers. The STD bus makes it possible to add various analog and digital interfaces to the computer for control of the SRSV. As the 8088 processor is also used in the IBM PC personal computer, many development tools are available for software development for that processor.

The computer was delivered with a basic set of software for program loading and debugging, which has allowed us to run primitive programs for systems testing. We are beginning work on system software for the on-board computer in order to allow programming in higher-level languages as well as run-time communication with control programs. Our approach has been to emulate a minimal subset of the MS-DOS operating system supplied with the IBM PC, so that on-board programs may run as they do on the PC. A serial communications link to the laboratory computers is completed through the radio transmitter and receiver mounted on the SRSV. More results for this project may be expected in future reports.

The existing computer software, and hardware interface routines, have been used to implement an open-loop control interface via the serial radio link. The operator may exercise both translational and rotational thrusters as well as both arm joint motors. The controller is realized via the on-board computer, and demonstrates both the radio link and all actuator interfaces.

Vision System Development

The SRSV is equipped with a TV camera for detecting and locating targets with which it is to interact. Such a local vision system is highly desirable for spacecraft manipulator systems, and much effort has gone into the duplication of a vision system as versatile as the human's for the purposes of object identification, obstacle avoidance, navigation, approach and manipulation. Our approach is to develop simpler "surrogate" vision systems to use in the manipulator-control and robot-vehicle guidance we are developing.

Our surrogate vision systems take advantage of special conditions. The SRSV is a two-dimensional simulator of the weightless environment, and thus its vision system need resolve objects in only two dimensions. The system may be further simplified by requiring it to track only objects marked with bright points of light. These points can be readily identified and tracked, as opposed to the more computationally intensive job of contour and object recognition.

The system is built around a miniature TV camera and an IBM PC-XT, and consists of a hardware interface board for the PC, and software on the PC which performs operations not implemented in hardware.

The hardware interface board accepts a video signal from the TV camera and detects (by threshold) bright pixels during a frame scan. The horizontal (x) and vertical (y) coordinates of each bright pixel are then stored internally. At the end of each frame scan, the computer is signaled, and the software takes over.

The software consists of an interrupt service routine which retrieves the pixel coordinates from the board, and a pixel "bundler", which associates pixels with defocused light points. These light points correspond to the lights originally placed on the objects to track. This information can then be passed to a type of Kalman filter for evaluation of the object's status. Testing software consisted of a task which prints out point coordinates (for TV-frame / workspace mapping), and an additional task which displays the points on the computer's graphics screen. This software was implemented under the QNX real-time multitasking operating system.

The operational system handles approximately 6 light points at a degree of focus that generates 4-5 pixels per light point, at a 30 Hz frame rate. The resolution (camera limited), is 600(horizontal) x 400(vertical). for local camera sensing, this corresponds to about 1.5mm in a 1mx0.6m workspace.

The speed of the current system is limited by the interlaced nature of TV video frames. If a point is moving sufficiently fast, its pixels will appear skewed when the interlaced sections of the video frame are combined for pixel assembly into points. This occurs when the motion is on the order of 10 pixels per frame, and is not a real problem with the current dynamic system, which exhibits motions which will not approach this limit.

Other Project Activities

The SRSV project has generated considerable interest in both industry and government for the applicability of its results to both industrial and space-borne mobile manipulators. One of the most interesting and immediate proposals for the SRSV has been made in meetings with Dr. Ronald Larsen, Dr. Henry Lum, and and Dr. Ewald Heer, at the time our contract monitor at JPL. This proposal is to test control of a lightly tethered satellite robot in the bay of the Space Shuttle, for simple manipulation and assembly operations. Nothing would demonstrate the feasibility of space robots, that we are attempting to show, like a successful demonstration of such operation in three dimensions, in the microgravity environment.

Industrial officials have also expressed interest in results that might arise from experiments in strategic control and path and task planning that we are considering for the SRSV. The vehicle represents an excellent test bed for such research, combining a structured work environment with excellent mobility in the plane. The dynamic control problems of operating (flexible) manipulators from a mobile, compliant base has many potential parallels in the industrial environment.

Future Plans

In the next six months, through August of 1986, we hope to bring the SRSV to a state of readiness for full dynamic control. Substantial software progress will be necessary in order to allow efficient development and testing of control algorithms. The vision system currently being tested in an IBM PC will need to be integrated into the on-board computer, and its software adapted to the local processor. We will gain considerable experience with the SRSV during this time which will represent a foundation for our development of real-time control algorithms for control of the SRSV.