FINAL REPORT

of

A RESEARCH PROGRAM

on

The Design, Planning and Control of Robotic Systems in Space

July 22, 1994 to September 30, 1996

GRANT NUMBER: NAG 1-1637

Submitted to

Automation Research Branch
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

by

The Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
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Principal Investigator
EXECUTIVE SUMMARY AND INTRODUCTION

A. Program Motivation and Objectives

In the future, robotic systems will be expected to perform important tasks in space, in orbit and in planetary exploration. In orbit, current technology requires that tasks such as the repair, construction and maintenance of space stations and satellites be performed by astronaut Extra Vehicular Activity (EVA). Eliminating the need for astronaut EVA through the use of space manipulators would greatly reduce both mission costs and hazards to astronauts. In planetary exploration, cost and logistical considerations clearly make the use of autonomous and telerobotic systems also very attractive, even in cases where an astronaut explorer might be in the area. However, such applications introduce a number of technical problems not found in conventional earth-bound industrial robots. To design useful and practical systems to meet the needs of future space missions, substantial technical development is required, including in the areas of the design, control and planning.

The objectives of this research program were to develop such design paradigms and control and planning algorithms to enable future space robotic systems to meet their proposed mission objectives. The underlying intellectual focus of the program is to construct a set of integrated design, planning and control techniques based on an understanding of the fundamental mechanics of space robotic systems. This work was to build upon the results obtained in our previous research in this area supported by NASA Langley Research Center in which we have made important contributions to the area of space robotics.

B. Accomplishments

This program was proposed and accepted as a three year research program, a period of time necessary to make the type of fundamental developments to make a significant contributions to space robotics. Unfortunately, less than a year into the program it became clear that the NASA Langley Research Center would be forced by budgetary constraints to essentially leave this area of research. As a result, the total funding we received under this grant represented approximately one year of the original, proposed and approved, funding. For some time, there was substantial uncertainty that even this very reduced level of funding would be provided. The spending of the reduced available funds was spread just over two years to provide the support to permit the MS students who had joined the program to receive their master’s degree and terminate their studies in this area.
Because of the funding uncertainties and levels provided, the scope of the work was substantially reduced from the proposed level. Our work mainly focused on completing and documenting our research. Our previous NASA sponsored work had produced a number of new and important results in the area of space robotics. Significant theoretical results have been obtained that contribute to our understanding of the fundamental nature of space robotic systems. During this shortened and greatly reduced funded program our work focused on extending and experimentally validating some of the algorithms we had developed during our previous work. The work did not attempt to begin development of new basic approaches and concepts.

In a related matter, we had been working on a NASA funded IN-STEP Program with Martin Marietta, The University of Puerto Rico and NASA Langley to prepare a flight robotics experiment that would test our theories on the control and planning of flexibly supported space robotic manipulators. We were competing with approximately six other teams. It was expected that one or two of these teams would be selected to design and build a flight experiment. At the completion of the Phase A study NASA chose not to select any of these programs for Phase B. It is not clear that the Phase A study results were ever technically evaluated.

During this period we continued to make important contributions to the international space robotics research. We have had several international researchers, sponsored by their home countries-- Canada, Italy, France, Germany, and Japan--working in our laboratory. These researchers have learned a great deal and they have also made very meaningful contributions to the technical objectives of our program.

In summary, the program yielded important technical results in the area of the dynamics and control of manipulators in space. The work has also had an important influence both here in the United States and abroad. The technical papers and student theses that document the contributions of the program during this period are listed in the following section.

**THESES, PAPERS, LECTURES AND VISITING RESEARCHERS**

Papers and theses written, presented or published during the current three year period (7/94 to 9/96) are listed in this section.

**A. Student Theses**

During this period, the program has given non-degree research opportunities to 3 undergraduates under MIT's Undergraduate Research Opportunity Program (UROP).
In addition, the following students who have contributed to this program, have completed their degrees and written the following theses:

1. Bachelors Theses

<table>
<thead>
<tr>
<th>Student</th>
<th>Thesis Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thomas, K.</td>
<td>&quot;Design of the Supporting Structure for a Laboratory Long Reach Manipulator System Using Finite Element Analysis&quot;</td>
<td>4/95</td>
</tr>
<tr>
<td>Ford, S.</td>
<td>&quot;An In Situ Keel deformation Metrology System for the USS Constitution&quot;</td>
<td>6/95</td>
</tr>
<tr>
<td>Raju, V.</td>
<td>&quot;Design of an Experimental Systems for Modular Robotic Systems&quot;</td>
<td>6/96</td>
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2. Masters Theses

<table>
<thead>
<tr>
<th>Student</th>
<th>Thesis Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutman, N.</td>
<td>&quot;Automated Design of Modular Field Robots&quot;</td>
<td>6/95</td>
</tr>
<tr>
<td>Cole, J.</td>
<td>&quot;Rapid Generation of Motion Plans for Modular Robotic Systems&quot;</td>
<td>6/95</td>
</tr>
</tbody>
</table>

3. Ph.D. Theses

None

B. Research Affiliates

During this period the following visiting researchers and researchers in residence have also contributed to our program:

Pisoni, Attilio Carlo  
Ancona University  
Ancona, Italy

Dr. Mavroidis, Constantinos  
University of Paris IV  
Paris, France

Prof. Yoshida, Kazuya  
Tokyo Institute of Technology  
Tokyo, Japan

Dr. Rudolph, S.  
Stuttgart University  
Stuttgart, Germany

Dr. Guillaume Morel  
The CNRS Robotics Laboratory of Paris  
Paris, France

Dr. Phillipe Bidaud  
The CNRS Robotics Laboratory of Paris  
Paris, France

Dr. Guang Jun Liu  
University of Toronto  
Toronto, Canada
C. Period Technical and Professional Papers

During this period the following technical and professional paper were published or accepted for publication.


Mavroidis, C., Rowe, P. and Dubowsky, S., "Inferred End Point Control of Long Reach Manipulators", Pro. IEEE International Conference on Intelligent Robots and Systems, IROS 95, Pittsburgh, PA, August 1995.


Invited Lectures

As part of our technology transfer efforts Professor Dubowsky gave the following invited lectures and seminars during this period related to our NASA sponsored results.


October 1994, "Space Robotics Technology and its Applications to the Preservation of the USS Constitution," University of Wisconsin-Madison, Dept. of Mechanical Engineering, Madison, WI.


November 1994, "On the Dynamics and Control of Space Robotic Systems," Simon Fraser University, School of Engineering Science, Burabay, B.C., Canada.


January 1995, "On the Dynamics and Control of Long Reach Robotic Systems, with Application to Space Station Alpha and the USS Constitution", UCLA, Dept. of Mechanical, Aerospace and Nuclear Engineering, Los Angeles, CA.


October, 1995, "The Dynamics and Control of Long Reach Manipulators," Laboratoire de Mécanique des Solides, Université de Poitiers, Poitiers, France.

September-November 1995, Series of six seminars on "The Dynamics and Control of Robotic Manipulators," Robotics Laboratory of Paris, Université Pierre et Marie Curie (Paris VI).

