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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

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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

Student	Thesis Title	Date
Thomas, K.	"Design of the Supporting Structure for a Laboratory Long Reach Manipulator System Using Finite Element Analysis"	4/95
Ford, S.	"An In Situ Keel deformation Metrology System for the USS Constitution"	6/95
Raju, V.	"Design of an Experimental Systems for Modular Robotic Systems"	6/96

2. Masters Theses

Student	Thesis Title	Date
Rutman, N.	"Automated Design of Modular Field Robots"	6/95
Cole, J.	"Rapid Generation of Motion Plans for Modular Robotic Systems"	6/95

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.

Dubowsky, S., Durfee, W., Corrigan, T., Kuklinski, A. and Muller, U., "A Laboratory Test Bed For Space Robotics: The VEST Mod II, *Proceedings of the IROS '94 IEEE/RSJ/GI International Conference on Intelligent Robots and Systems-Advanced Robotic Systems and the Real World*, München, Germany, September 12-16, 1994 . Also published in *Intelligent Robots and Systems:*, by Elsevier Science, Amsterdam, pp. 463-475

Corrigan, T. and Dubowsky, S., "Emulating Micro-Gravity in Laboratory Studies of Space Robotics," *Proceedings of the 23rd ASME Mechanisms Conference*, MN, Sept. 1994 .

Dubowsky, S., Durfee, W., Kuklinski, A., Müller, U., Paul, I, and Pennington, J., "The Design and Implementation of a Laboratory Test Bed for Space Robotics: The VES MOD II," *Proceedings of the 23rd ASME Mechanisms Conference* , Minneapolis, Sept, 1994. Also accepted *ASME Journal of Mechanical Design,*

Dubowsky, S., Moore, C., and Sunada, C., "On the Design and Task Planning of Power Efficient Field Robotic Systems," Proceedings of *ANS 6th Topical Meeting on Robotics and Remote Systems* and *ANS Transaction.*, Monterey, California, Feb. 5-10,1995, pp. 501-508.

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

Cole, J., Dubowsky, S., Rutman, N. and Sunada, C. "The Application of Advanced Robotics and Sensor Technologies to the Preservation of the USS Constitution" *Proceedings of the Conference on the Technical Aspects of Maintaining, Repairing and Preserving Historically Significant Ships,* Sept., 1994, Boston, MA. .

Pisoni, A.C., Santolini, C. and Dubowsky, S. "Displacements in a Vibrating Body By Strain Gauge Measurements" *Proc. 3th International Modal Analysis Conference*, February 13-16, 1995, Nashville, TN .

Mavroidis, C., Rowe, P. and Dubowsky, S., "The Control of Elastically Mounted Manipulator Systems" *Proc. Ninth World Congress on the Theory of Machines and Mechanisms, September 1-2, 1995, Milano, Italy,.*

Dubowsky, S. "Dealing with Vibrations in the Deployment Structures of Space Robotic Systems" *Proceedings of the 5th International Conference on Adaptive Structures,* Sendai, Japan, De. 1994. (Keynote).

Yoshida, K., Mavroidis, C. and Dubowsky, S. "Experimental Research on Impact Dynamics of Spaceborne Manipulator Systems" *Proceeding of the 4th International Symposium on Experimental Robotics,* June 30-July 2, 1995, Stanford, California, pp. 271-277.

Farritor, S., Dubowsky, Rutman, N. and Cole, J. "A Systems Level Modular Design Approach To Field Robotics," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation,* Minneapolis, MN, April 24-27, 1996.

Morel , G. and Dubowsky, S., "The Precise Control Of Manipulators With Joint Friction: A Base Force/Torque Sensor Method," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation,* Minneapolis, MN, April 24-27, 1996.

Torres, M., A., Dubowsky, S., Pisoni, A. C., "Vibration Control of Deployment Structures of Long-Reach Space Manipulators: The P-PED Method," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation,* Minneapolis, MN, April 24-27, 1996.

Yoshida, K., Mavroidis, C., and Dubowsky, S., " Impact Dynamics of Space Long Reach Manipulators," *Proceedings 1996 IEEE International Conference on Robotics and Automation,* Minneapolis, MN, Apr., 1996.

Yoshida, K., Mavroidis, C., and Dubowsky, S., " Impact Dynamics of Space Manipulators Mounted on a Flexible Structure," Proceedings of the 3rd International Conference on Dynamics and Control of Structures in Space, London, England, May 27-31, 1996.

Morel. G. and Dubowsky, S., "High Performance Control of Manipulators Using Base Force/Torque Sensing," *Proceedings of XI CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators (ROMANSY '96)*, Udine, Italy, July 1-4, 1996.

Mavroidis, C., Dubowsky, S. and Thomas, K., "Optimal Sensor Location in the Motion Control of Flexibly Supported Long Reach Manipulators," *Proc. 1996 ASME Mechanisms Conference*, Irvine, CA, Aug, 1996.

Farritor, S. and Dubowsky, S., "On the Design of Rapidly Deployable Field Robotic Systems," *Proceedings ofthe 1996 ASME Design Methodology Conference* , Irvine, CA, August 19-22, 1996.

Torres, M. Dubowsky, S., Corrigian, T. and Pisoni, A. C. , "The Coupling Map Method for Path Planning of Long Reach Space Robotics Systems with Experimental Evaluation", *Accepted IEEE Transactions on Robotics and Automation.*

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.

September 1994, "The Application of Advanced Robotics and Sensor Technologies to the Preservation of the USS Constitution," Boston National Historical Park, Charlestown Navy Yard, Charlestown, MA.

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

November 1994, "The Control for Mobile Multi-Limbed Robots", University of B.C.,Vancouver, Canada.

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

November 1994, "On the Dynamics and Control of Long Reach Space Robotics Systems", University of Victoria, Vancouver, Canada.

December, 1994, "Dealing with Vibrations in the Deployment Structures of Space Robotic Systems" *Proceedings of the 5th International Conference on Adaptive Structures*, Sendai, Japan.

December 1994, "On the Dynamics and Control of Space Robots," Tokyo Institute of Technology, Japan.

December 1994, "On the Dynamics and Control of Space Robots," Kawasaki Heavy Industries, Japan.

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.

February, 1995, On the Design of Mobile Telerobotic Systems in Unstructured Environments, with Application to the Restoration and Preservation of Historic and Artistic Treasures and Sites, American Nuclear Society Sixth Meeting on Robotics, Monterey, CA, Feb, 1995, (Keynote Address).

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).

January, 1996, The Modular Design of Robotic Systems Using Genetic Algorithms," Laboratory of Fundamental Computer Science and Artificial Intelligence, INRIA Rhône Alps, Grenoble, France.

March, 1996, The Design Rapidly Deployable Systems Using Modular Methodology, The Engineering Design Center, Engineering Department, Cambridge University, Cambridge, England.

June 1996, On the State-of-the Art of Robotic Systems, Sandia National Laboratories, Albuquerque, NM.