LANGLEY GRANT
IN-37-CR
135349
REPRINT
REMOVED
30P.

First Semi-Annual Report

on

THE DYNAMIC CONTROL OF ROBOTIC MANIPUALTORS IN SPACE

(NASA GRANT NAG-1-801)
(July 31, 1987 to January 31, 1988)

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

Professor S. Dubowsky
Principal Investigator

(NASA-CR-182710) THE DYNAMIC CONTROL OF ROBOTIC MANIPULATORS IN SPACE Semiannual Report, 31 Jul. 1987 - 31 Jan. 1988 (Massachusetts Inst. of Tech.) 30 p CSCL 13I

N88-20646

Unclas
G3/37 0135349

TABLE OF CONTENTS

I. INTRODUCTION

This report briefly describes the work that was done during the first six months of our three year study on the dynamic control of robotic manipulators in space. As outlined in the original grant proposal, our research has focused on issues for advanced control of space manipulators including practical issues and new applications for the Virtual Manipulator. In addition, we have continued to develop simulations and also graphics software for space manipulators, which we began during our first NASA grant proposal in this area. We have completed the fabrication of our Vehicle Emulator System (VES) and are in the process of developing its control algrorithms.

The results of our work for this period are briefly described in this report. The attached appendices contain more detailed descriptions of some of our activities.

II. RESEARCH PROGRESS JULY 31, 1987 TO JANUARY 31, 1988

A. ANALYTICAL STUDIES

1. Virtual Manipulator Practical Issues

There are a number of issues that have been investigated for the practical application of the Virtual Manipulator. These include the effects of external forces, of internal gyroscopic forces, and of space manipulator parametric uncertainties. Some of these issues are discussed in the following paragraphs.

It was found that external forces such as gravitational gradients and solar radiation do not have any influence on the VM itself. However, over a period of time these small forces can change the space manipulator orbit trajectory, which changes the location of its base in inertial space, the

Virtual Ground location. Changes in the VG location occur very slowly compared to the duration of expected tasks in space. Therefore, for such cases these forces can be neglected for tasks which are completed in reasonable time.

The gyroscopic forces generated due to the coupling between the space manipulator rotation around the earth and the rotation of the joint actuators were found not to have an effect on the VM structure. However, the joint actuators do have to compensate for these gyroscopic forces.

There are many sources of space manipulator parametric uncertainty, which can result in errors in the VM construction. One such source is the thermal expansion of the space manipulator link lengths. The effects of uncertainty in the space manipulator link length and mass on the VM end point location were studied. As shown in Reference 1* the uncertainty in the VM end point location is about three times greater than the parameter uncertainties. For example, if these parameters are known within 1%, the VM end point location is known within 3%. Therefore, in order to control the end effector along a desired path, end point sensing may be required for accurate trajectory following.

2. New Virtual Manipulator Applications

In general, different manipulator paths will result in different disturbances on the spacecraft. In this study an algorithm was developed which finds manipulator paths that reduce these disturbances. First, a new tool called the Disturbance Map is generated. Then the Disturbance Map is used to find manipulator paths which minimize disturbances on the spacecraft.

* See Section III.(These documents have previously been provided to NASA)

The Disturbance Map is a map in the manipulator joint space and shows the directions of minimum and maximum disturbances on the spacecraft. The Disturbance Map allows for the heuristic selection of a path, which is mainly in the direction of the minimum disturbances of the spacecraft. As shown in Reference 2 such an approach can reduce disturbances on the spacecraft. In this example the disturbances on the spacecraft were reduced by a factor of 4.

The Disturbance Map was developed for a planar system. Currently, this method is being extended for spatial systems. Furthermore, path optimization algorithms will be combined with the Disturbance Map to find paths which minimize disturbances on the spacecraft.

In addition the Virtual Manipulator has been applied in connection with Neural Networks to find paths that minimize spacecraft disturbances, see Section 4 for more discusssion of this work.

3. Dynamics and Control Issues for Complex Configurations

The VM concept was extended to multiple arm and closed chain configurations, as shown in Reference 1. The extended VM concept is applicable to redundant spatial manipulators, which consist of revolute or prismatic joints.

The VM for multiple arm configurations depends on the number of manipulator arms. If the system consists of two arms, the VM developed for single open chain configurations can be applied to the space manipulator. If the manipulator consists of three or more arms a more complex Virtual Manipulator technique is required.

This new VM differs from the VM for open single chain systems. For example, if the space manipulator consists of three arms, the VM will also consists of three segments which are connected to each other by a spherical joint. A detailed description of such VMs can be found in Appendix I.

Systems with multiple arm and closed chain configurations are very complex and difficult to analyze with conventional analysis. Therefore it is not surprising to see that their VM is not as simple as the single open chain systems.

4. Advanced Control

Although advanced control algorithms for space manipulators will be thoroughly investigated later in the course of this three year research effort, we have already started exploring some of the related issues.

Our studies show that for various reasons it is not possible to simply use the control strategies, designed for present industrial manipulators, in space applications. Our research efforts in the area of advanced control will thus be aimed at extending existing strategies or developing new ones that will permit the effective use of manipulators in space.

For example, many tasks in space, such as the capture of a free-floating or tumbling tool or the unscheduled inspection of remote sites, require the use of free-floating manipulators. Therefore, we have been considering issues pertaining to the control of such manipulators.

The method of controlling a free-floating manipulators depends on whether or not the spacecraft attitude and position are actively controlled. In cases where both the spacecraft attitude and position are controlled with reaction jets, various control algorithms can be used. As an example, we are studying a three link spatial manipulator on a spacecraft. Using reaction jets, the spacecraft is held stationary in its workspace. Then the time optimum manipulator motion, which does not cause saturation of the reaction jets, is calculated.

However, since reaction jets consume non-renewable fuel, it is desirable to minimize their usage. Without using reaction jets, the spacecraft attitude can actively be controlled by means of reaction wheels. It is thus free to translate. In this case, the VM concept can be applied to plan and control the manipulator position using control algorithms that were designed for fixed base manipulators.

If neither the spacecraft attitude and nor its position is actively controlled, then movements of the manipulator arm will induce translations and rotations of the manipulator base (spacecraft), because of the dynamic coupling of the two. For small arm movements, this mode of control may be advantageous as it avoids the use of jets or wheels to extend the spacecraft autonomous capabilities.

Another topic under consideration is that of force control in space. In order to replace or assist astronauts in assembly or repair activities in space, manipulators must be able to exert forces on objects. However, unlike their earth-based counterparts, space manipulators will exhibit a large degree of structural flexibility because of the mass limitations imposed on space manipulator arms. Docking mechanisms may also add significant flexibility. Preliminary results show that harmful instabilities may occur while exerting forces in the presence of flexibilities. More work will be devoted to this important issue in the coming months.

A further related topic is that of payload induced vibration. Payloads, such as the long slender truss elements that will be used in the construction of the space station, will be very flexible. Their dynamic behavior will directly affect the performance of the manipulator control system. These problems become very important for high performance, high bandwidth manipulators, and hence, they will obtain due attention in our development of efficient control algorithms for space manipulators.

Neural Networks were also used to find paths that minimize the disturbances of the spacecraft, as shown in Reference 3. In this study the neural network is first trained by giving it a path along with the corresponding disturbances of the spacecraft which occur when the manipulator follows that path. This process is repeated for a number of different paths. After the initial training, the network is capable of producing manipulator paths which take the end effector from its initial to its desired location, while minimizing the disturbances of the spacecraft.

B. SIMULATIONS AND SOFTWARE DEVELOPMENT

In order to develop a computer program capable of simulating the dynamics of an arbitrary spacecraft-manipulator system, a review of existing algorithms and programming techniques was conducted. Two of the most commonly used algorithms were evaluated in detail, namely the Lagrangian formulation and the Newton-Euler method. Unlike some of the other methods that have been studied, these two methods give the exact solution for the equations of motion, are relatively easy to implement and are fast enough to be used in off-line computer simulation. The Newton-Euler formulation was ultimately selected as the method that best suited our project'srequirement of speed, flexibility and ease of modification (see Appendix B).

This algorithm has been implemented in a spacecraft-manipulator dynamic simulation program. A version of the program is currently being tested. In order to enhance the capabilities of this program, we are developing graphic subroutines for displaying pre-processing data and final results. These subroutines will make this analytical tool more user-friendly and will provide a better understanding of the results.

An analytical study to implement the optimization techniques and the concept of the disturbance map (see Reference 2), has been completed. A series of numerical experiments will be conducted using the simulation program to determine possible algorithms to compute the disturbance map for an n degree of freedom manipulator. Furthermore, an evaluation of possible graphical representations for the disturbance map in an n dimensional space are under consideration.

C. EXPERIMENTAL STUDIES

We have completed the fabrication of our experimental test facility for mobile manipulators, which consists of a PUMA 260 manipulator mounted on a Vehicle Emulator System (VES). The Vehicle Emulator System comprises a six degree of freedom hydraulically driven Stewart mechanism, sensors and control computer. The manipulator and the VES are controlled by individual DEC PDP-11/73 microcomputers.

Mounted on the platform is a specially fabricated six degree of freedom force and moment sensor measures the static and dynamic loads between the manipulator and the platform. The platform's micro-PDP11/73 performs the vehicle emulation calculations including gravity compensation in order to emulate space conditions, and provides position commands to the analog controllers for the hydraulic joints. It also performs supervisory functions that check for approaching violations of the kinematic constraints, and verifies that the joints remain within acceptable error bounds.

The Vehicle Emulator System may be operated in either position driven or admittance control modes. In the position driven mode the VES imposes an arbitrary motion onto the base of the experimental manipulator corresponding, for example, to the motion of a vehicle moving under attitude control of jet thrusters. In the admittance control mode, dynamic forces due to manipulator motions measured by the force sensor, cause the platform to move as if, for example, the manipulator were free floating in space. The admittance control method can be used to simulate a wide range of vehicles with any dynamic model of the general form: $\underline{x}=f(\underline{x},\underline{x},t)$.

The VES is able to simulate vehicle motion of ± 150 mm and ± 30 degrees in any direction, and currently has a bandwidth of 5 Hz with a 20 kg load. A more detailed description of its control, as well as some initial test results can be found in Appendix C. Current efforts are focused on developing gravity compensation algorithms in order to use the system to simulate free floating space manipulator systems.

III. REFERENCES

1. Vafa, Z., "The Kinematics, Dynamics and Control of Space Manipulators: The Virtual Manipulator Concept," PhD. Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, 1987.

2. Vafa, Z., and Dubowsky, S., "Minimization of Spacecraft Disturbances in Space Robotic Systems," Proceedings of of the 11th AAS Guidance and Control Conference, Keystone, CO, 1988.

3. Rudolph, S., "On the Potential Application of Parallel Distributed Processing Techniques for the Control of Free-Flying Robots in Space," Research Report, Department of Mechanical Engineering, MIT, Cambridge, MA, 1988.

NAG 1-801

APPENDIX B. PROGRESS REPORT ON DYNAMIC SIMULATIONS OF MANIPULATOR/SPACECRAFT SYSTEMS

I. Introduction

The overall plan for this research program is to study and develop new analytical tools for the understanding and control of space manipulator devices. The task with this overall program are:

To investigate and review existing algorithms and programming techniques developed in resent years for the dynamics and kinematic modeling of industrial robots and their potential application to space robot dynamics modeling. In the development of a computer simulation for robotic mechanism, the problem of formulating the rigid body equations of motion is been widely studied. Several approaches have been suggested which address the solution of this problem. Lagrangian formulation[5], virtual work[1], and the Newton-Euler recursive algorithm[2], are some of these methods. Most of them have been used in the solution of stationary or fixed manipulators in which the base of the robot is bolted to the floor. Space manipulators show a number of kinematic and dynamic problems due to the dynamic coupling between the manipulator and the spacecraft. For example, movement of the manipulator will disturb the attitude of the spacecraft carrying it.

A secondary objective of this effort will be to suggest guidelines for the development of a computer program for simulating the dynamics of free floating robotic systems. Those methods with the potential of achieving more flexibility and efficiency will have higher priority.

Based on the above investigation to develop a computer program capable of simulating the dynamic of an arbitrary spacecraft-manipulator system. The program should be flexible enough accept any configuration of manipulator including those with more than six degree of freedom in a three dimensional space. The program will require the ability to model the dynamic characteristics of the manipulator and its actuator as well as the spacecraft and its actuators (reaction wells and reaction jets).

To use the Computer-Aided Analytical tools developed in task 3 to study and develop new optimization techniques for path planning and control algorithm. One recently developed concept; the disturbance map[3], has been shown, for the planar case, to have the potential for finding the optimal manipulator path (trajectory) control which results in minimizing spacecraft disturbance. The work will explore the potential applications of this method in three dimensions and for a general *n* degree-of-freedom manipulator case. Moreover, the study will attempt to find numerical algorithms for determining and graphically visualize disturbance maps in the *n* dimensional space.

To study the sensitivity of space manipulator systems to changes in kinematic and dynamic parameters (mass, mass distribution, link dimensions, etc) will be studied. The objective of this effort is to understand and provide design guidelines for future space robot development. Because of the flexibility of the simulation program developed in task 3, it is possible to study different configurations of robotic mechanisms and determine the effects of changes in mass distribution, link configuration and kinematic parameters in general. Questions like the effects of redundancy in the disturbance map and robustness of the disturbance map to changes in manipulator parameters can be addressed.

II. Progress To Date

The investigation and review of existing algorithms and programming techniques has been completed. Among some of the most commonly mentioned algorithms in literature, two of the most commonly used has been evaluated in detail. Lagrangian formulation and the Newton-Euler method. Unlike some other methods studied[5], these two methods give the exact solution for the equations of motion, are relatively easy to implement and are fast enough to be use in off-line computer simulation. The Newton-Euler formulation was selected as the method that most best suited to the project requirement of speed, flexibility and easy of modification to accommodate for the moving base problem. See Section A for a detailed technical information and implementation of this algorithm.

The modification and implementation of this algorithm has been completed. A version of the program is currently under test. To enhance the capabilities of this program, graphic subroutines to pre-processing data and dispay results are under development. This will make this analytical tool more user-friendly and will provide a better understanding of the results.

An analytical study on optimization techniques and the concept of the disturbance map, developed by Zia Vafa[3], has been complete. Section B explores in more detail the concept of optimal robot control and the disturbance map. A series of numerical experiments are under development using the simulation program to determine possible algorithms to compute the disturbance map for an *n* degree of freedom manipulator. Also an evaluation of possible graphical representation of the disturbance map in an *n* dimensional space are under consideration.

III. Plans For Year Two.

The objectives for year 2 of this study are:

To complete the testing of the simulation program.

To complete the graphic subroutines for the preprocessing and post-processing of data.

Write documentation for future users.

A series of numerical experiments will be conducted with the purpose of understanding the dynamics of space manipulators. The results and evaluation of the data obtained from these experiments will be use to address question associates with optimal robot control and the disturbance map.

An analytical evaluation of the concept of disturbance map for an N dimensional space will be performed.

The usefulness of this concept for control purposes and optimal path will be investigated.

The disturbance map for an N dimensional space is an abstract graphic representation of the relation between disturbance of the spacecraft and manipulator movements. The disturbance map identifies the direction of joints movements which result in minimum and maximum disturbances of the spacecraft due to manipulator movements[3]. N dimensional vector fields are too complex to visualize. Alternatives for simpler graphical representation will be investigated. The emphasis of this investigation is to try to come up with a transformation operator that will transform the information contained in this N-dimensional space to a two or three dimensional space and have a qualitative and quantitative description of some of the kinematic and dynamics parameters of the system. This analytical tool could be used to compare dynamic and kinematic behavior of different configuration of manipulators.

IV. References

Walker M.W.,Orin D.E, "Efficient Dynamics Computer Simulation of Robotic Manipulator". Journal of Dynamic System, Measurement and Control Sept. 1982.

Paul R.P.C., Walker M.W., Luh J.Y.S., "Online Computational Scheme for Mechanical Manipulators". Journal of Dynamic System, Measurement and Control June. 1980.

Vafa Z., "The kinematics, Dynamics And Control of Space Manipulators: The Virtual Manipulator Concept",PhD Thesis, Dept. of Mech. Engr.,MIT Cambridge, MA.,1987

Asada H., Slotine JJ. E "Robot Analysis and Control" John Wiley and Sons 1986

Hollerbach J. M., "A Lagrangian Formulation of Manipulator Dynamics and a Comparative Study of Dynamics Formulation Complexity", IEEE Transaction on Systems, Man, and Cybernetic, Nov 1980

Section A: Simulation Program -Technical Description

1. Program Overview

The simulation program is basically a collection of subroutines controlled by a main program. The program was written in FORTRAN running on an MicroVax II using VMS operating system. The Following table describe subroutines and their function.

Subroutine Name	Description
FORWARD.FOR	Computes the forward dynamics for the specified spacecraft-manipulator configuration. *Input* > Joint torque vector (including Base actuator forces) *Output* >Position, Velocity & Acceleration vectors in joint space.
INDYNA1.FOR	Computes the inverse dynamics problem for specified spacecraft-manipulator configuration. *Input* > Position,Velocity & Acceleration vectors in joint space.

	Output > Torque required
INDYNA2.FOR	Same as INDYNA1.FOR except that assumes zero joint velocity. *Input* > Position & Acceleration vector in joint space. *Output*> Torque required
KINEM1.FOR	Computes all necessary transformation matrices which describe the kinematic relationship of each link. *Input* > Denavit&Hartenberg parameters. *Output*> 4x4 transformation matrices.
MATRIX.FOR	A collection of subroutines designed to perform matrix operations.
MAIN.FOR	Main program. This program controls the flow of data between subroutine. NOTE: The main program will change depending on the application.

A typical application of the program would be the testing of new control algorithms for space manipulator systems.. Because of the modular structure of the program, it is possible to write a main program that includes the control equations. Figure A.1 shows the block diagram for this particular application with H(z) as the control law. All the state variables are available for control purposes.

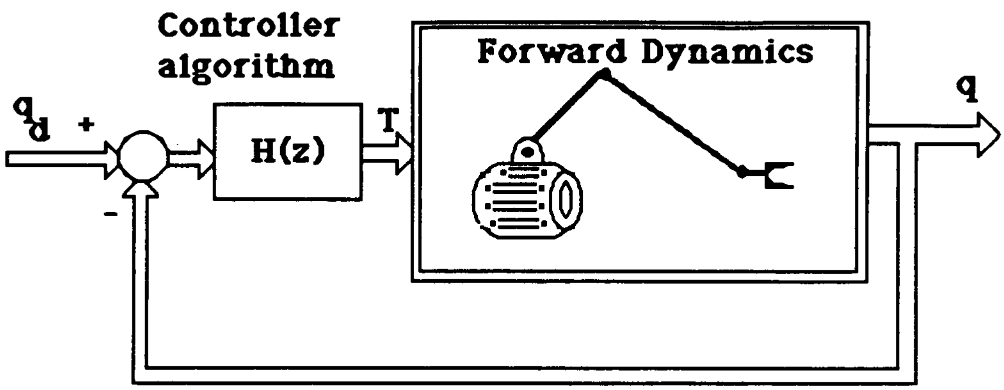

Figure A.1 Block diagram of the forward dynamic program with H(s) as the controller

Another important application would be the development of control laws based on computed torque schemes. Recall that INDYNA1.FOR will return the required torque given the actual position, velocity and acceleration on joint space. Figure A.1.1 illustrates a block diagram in which H(z) is replaces by INDYNA1.FOR and computes the required torque for a particular trajectory. The computed torque is then use as the input to the forward dynamics model.

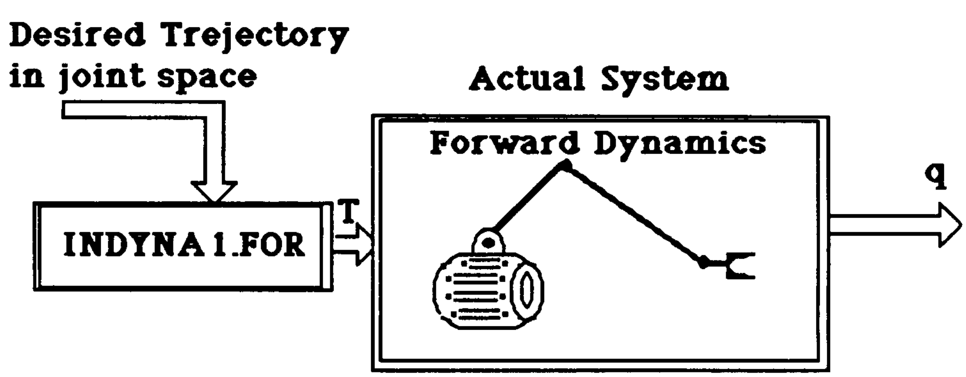

Figure A.1 .1 Block diagram of the forward dynamic program controlled by a computed torque control scheme.

2. Program Algorithm

The program was developed based on the Newton-Euler recursive method developed by Luh, Walker, Paul[2] (inverse dynamics) and the Walker, Orin[1] (for the forward dynamics). These algorithms were originally designed for describing the dynamics of a fixed base robotic mechanism. The key concept of the Luh, Walker, Orin algorithm is to formulate dynamic equations in a recursive form, so that the computation can be accomplished from one link of the manipulator arm to another. Figure A.2 illustrate the outline of the original recursive computation algorithm.

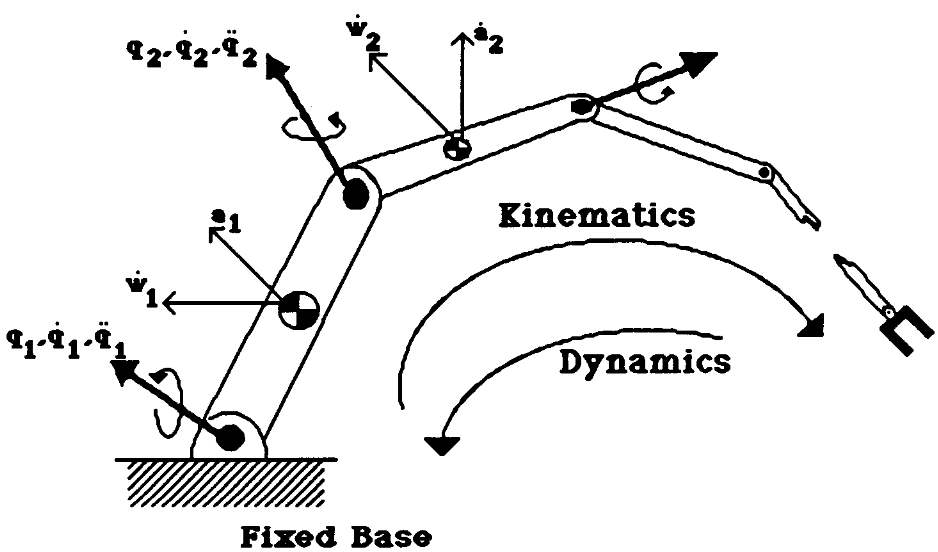

Figure A.2 Original recursive computation of kinematic and dynamic equations.

The recursive nature of the Luh, Walker, Paul algorithm, makes possible to modify the original algorithm to account for the dynamics of an extra body, e.i. the spacecraft. Note that in the first phase of the recursive Newton-Euler formulation all the kinematic variables needed for the evaluation of the Newton-Euler equations are determined. These include the linear and angular velocities and accelerations of each link member involved in the serial linkage. The algorithm starts with the first link. Given the joint displacement q_1, and the joint velocities $\dot{q}_1$ and $\ddot{q}_1$, the linear and angular velocities and accelerations of the centroid C_1 are determine. Then using the velocities and accelerations of the first link, denoted by v_{c1}, ω_1, a_{c1} and $\dot{\omega}_1$, we compute the velocity and accelerations of the second link with the data specified for joint 1, namely $q_2, \dot{q}_2$ and $\ddot{q}_2$.

This procedure is repeated until all the centroidal velocities and accelerations, as well as angular velocities and accelerations, are determined for all the links involved.

In our modified version of this method, see figure A.3, the algorithm starts with the spacecraft. Given the centroidal kinematic parameters of the spacecraft, namely the linear and angular position, velocity and acceleration of the centroid of the spacecraft, and the joint 1 displacement q_1, and the joint velocities $\dot{q}_1$ and $\ddot{q}_1$, the linear and angular velocities and accelerations of the centroid C_1 are determine. From here on the algorithm is the same as the original method.

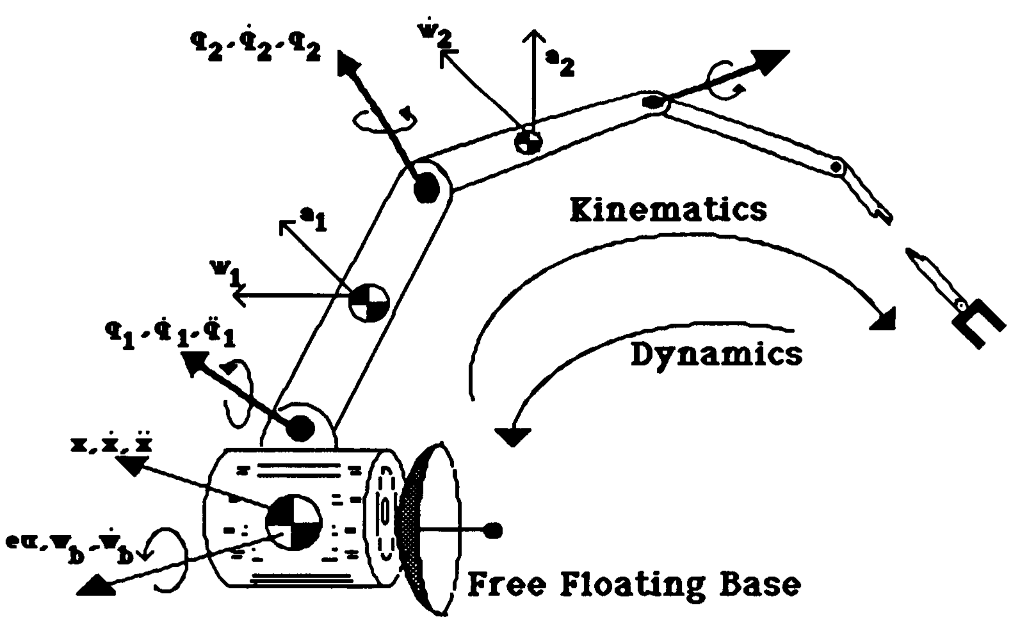

Figure A.3 Modified recursive computation of kinematic and dynamic equations.

The second phase of the original recursive formulation evaluates the Newton-Euler equations with the computed kinematic variables to determine the joint torques. The algorithm now proceed with the recursive computation starting from the last link back to the proximal link. Figure A.4 shows the force/momentum relationship for free body diagram of links. From this figure we can summarize the Newton-Euler equations for the recursive mode.

(Ae.1) $$f_{i-1,i} = f_{i,i+1} - m_i a_{ci}$$

(Ae.2) $$N_{i-1,i} = N_{i,i+1} - r_{i,ci} \times f_{i,i+1} + r_{i-1,ci} \times f_{i-1,} + I_i \omega_i + \omega_i \times (I_i \omega_i)$$

Equation Ae.1 determines the coupling forces between link i-1 and link i namely $f_{i-1;i}$, based on coupling forces between link i and link i+1 and inertial forces of link i. Equation Ae.2 determines the coupling moment between link i-1 and link i based again in previous forces and moment coupling. For the modified version the procedure is repeated until the link 0, e.i. the spacecraft. Once the coupling forces and moments of each joint are determined, the joint torque can be computed depending on the type of joint i.e. revolute or prismatic. In our modified version of the Newton-Euler formulation the spacecraft has six actuators; one for each degree of freedom, which are consider elements of the joint torque vector.

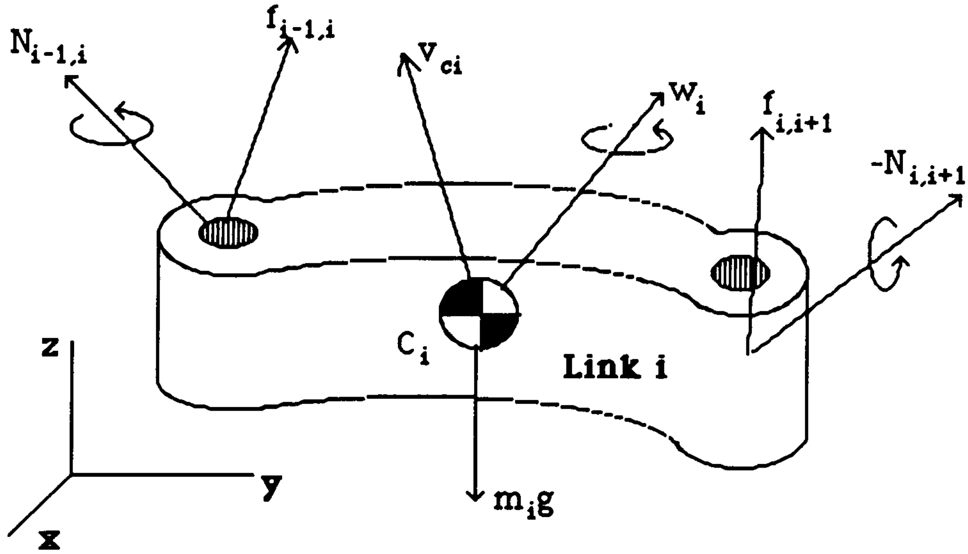

Figure A.4 Force/Momentum relationship for link i.

The forward dynamic subroutine was implemented based on the computational scheme developed by Walker, Orin1982 [1]. This method does not require an explicit analytical expression. Instead the general form for the equation of motion of the system is assumed as:

(Ae.3) $$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$$

where

is an N+6 x N+6 symmetric, nonsingular moment of inertia matrix,

$C(q,\dot{q})$ is an N+6 x N+6 matrix specifying centrifugal and Coriolis effects,

is an N+6 x 1 vector specifying the effect due to gravity,

τ is an N+6 x 1 vector of torques (forces) of each joint and spacecraft actuator,

N is the number of serial links in the robotic mechanism,

q is an N+6 x 1 generalized position vector which include the position and orientation of the spacecraft and joint angles,

q is the time derivative of q (generalized velocity vector),

$\ddot{q}$ is the time derivative of $\dot{q}$ (generalized acceleration).

Note from Equation (Ae.3) that the torques (forces) are linear function of the generalized acceleration. Therefore, if b is defined to be a bias vector which is equal to the torque (forces) due to gravity and centrifugal & Coriolis acceleration, then

(Ae.4) $$b = C(q,\dot{q})\dot{q} + G(q)$$

Thus, the generalized acceleration vector can be obtained by solving the linear equation

(Ae.5) $$H(q)\ddot{q} = (\tau - b)$$

The bias vector b can easily be computed by setting q and $\dot{q}$ to their current state, but letting $\ddot{q}=0$, and calling INDYNA1.FOR . That is, the torque computed by INDYNA1.FOR with these input values is equal to the bias vector b.

The difficult part in solving Equation (Ae.5) is in evaluating the elements of the matrix H(q). This is accomplished by setting q to its current state, but letting $\ddot{q} = e_j$, and calling INDYNA2.FOR, where e_j is an N+6 x 1 vector with the j^{th} element equal to 1 and 0 everywhere else. The torque (force) vector h_j computed by INDYNA2.FOR with these inputs is the j^{th} column of H(q). Once the elements of H(q) are determined, then the joint accelerations are optained by solving Ae.5. Figure A.5 present a block diagram of this procedure. Integrating the acceleration will give the velocity and position in the N+6 joint space.

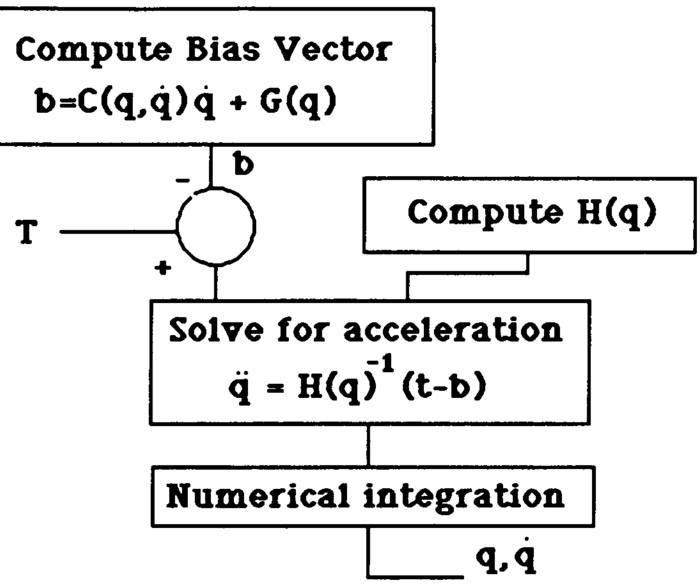

Figure A.5 Computational procedure for the Walker,Orin method.

Section B- The Disturbance Map

1.Basic Concept.

The concept of the Disturbance Map, developed by Zia Vafa (1987)[3], is an analytical tool to identify the directions of joints movements which result in minimum and maximum disturbance of the spacecraft due to manipulator movements[3]. The map has proved to be useful for planar manipulators with two or up to three degrees of freedom, for graphically visualize the relation between the trajectories of the manipulator joints and the disturbance of the spacecraft.

In order to understand the idea first define the manipulator joint space to be the space spanned by the manipulator joint position, q, and the spacecraft attitude, X. The spacecraft motion seen form an inertial frame, δX, as function of the manipulator motion can be expressed as

(Be.1) $$\delta X = F(q,X)\,\delta q$$

where F is a 3 X N matrix (for the three dimensional case) and is function of the manipulator position, q, and the spacecraft orientation X. If we now redefine our coordinate system and express the spacecraft motion δX in term of a local coordinate system attach to the spacecraft $\delta X'$, F will be function only of q. Therefore equation (Be.1) can be written as

(Be.2) $$\delta X' = F(q)\delta q$$

A singular value decomposition of the matrix F(q) will indicate the directions of minimum and maximum spacecraft movements in joint space. If the minimum disturbance is equal to zero, moving in this direction will not affect the spacecraft attitude. Transforming this minimum disturbance vector to world coordinate space or performing forward kinematic in this vector we find that there is a direction in which the end effector will move and will not affect the spacecraft.

The Disturbance Map and Redundant Manipulators.

A minimum of six degrees of freedom are needed in a manipulator to specify position and orientation of the end effector within the work space for an non-moving base manipulator. That is, given the position and orientation for the end effector within its reachable inertial space, there is only one close form solution for the position of the joint angles. A non-moving base manipulator with more than six degrees of freedom will have more than one solution to its in joint space for a given position and orientation of the end effector. Because of this fact, manipulators with more than six degree of freedom are consider redundant.

A six degrees of freedom manipulator with moving base will still be able to reach the desired end effector position and orientation but at the expense of disturbing its base position and orientation. Also the joint angles solution would be different form the non-moving base case. If we write the spacecraft disturbance/joint movement relationship, equation Be.2, for this specific case we have that $\delta X' = F(q)\delta q$ where F(q) is a 3X6 matrix. A singular value decomposition of F(q) will show that there are six orthogonal directions in joint space in which depending on their particular singular values we will have some disturbance of the spacecraft. For those singular values equal to zero we will have zero disturbance in their specific directions. Recall that F(q) is function of the space angles, therefore it is possible to find values of q, e.i. configuration of the arm, in which F(q) becomes singular. For this particular point in the disturbance map we will be able to move in that particular direction without disturbing the spacecraft. If we find one singular value equal to zero we will have one direction of zero disturbance in the joint space. If we map this direction vector to the inertial space we will have one specific direction in which we can move the end effector without disturbing the spacecraft. In other words, we are free to move in one direction out of the six available in world coordinate for that specific position in joint space. If we have two singular values, then we have two directions in joint space which will result in zero disturbance of the spacecraft. Mapping again this two direction vectors to the six dimensional inertial space we have two directions in where to move without disturbing the spacecraft. Our goal is to have three singular values equal to zero at all time so we can have three direction vectors to compensate for the three disturbance angles. This can be done by designing the robotic arm with more degrees of freedom, e.i. more links. A singular value decomposition of the matrix F(q) for a 9-links manipulator, for example, will show that we always have three singular values equal to zero. That is, for any point in the nine dimensional space of the disturbance map, we have three direction in which to move without disturbing the spacecraft. This shows that a 9 link manipulator has the capability of satisfy the end effector position and orientation and will make the disturbances of the spacecraft equal to zero. The disturbance map can be used to find closed form solutions for the 9-link manipulator. Also several redundant manipulator configurations can be evaluated using the disturbance map in order to optimize kinematic and controller design.

APPENDIX C. REPORT ON THE EXPERIMENTAL MANIPULATOR AND VEHICLE EMULATOR SYSTEM.

The experimental test facility for mobile manipulators consists of a PUMA 260 manipulator mounted on a Vehicle Emulator System (VES), see Figures 1 and 2. The Vehicle Emulator System comprises a six degree of freedom hydraulically driven Stewart mechanism, sensors and control computer. The manipulator and the VES are controlled by individual DEC PDP-11/73 microcomputers. The PUMA 260 was selected to show that advanced control algorithms can be successfully implemented on manipulators with standard mechanical designs. Its custom controller was developed to enable advanced control algorithms to be implemented quickly in high level languages, such as Pascal or C. As high level control algorithms are developed, they are first linked with a simulation package in the computer that models the dynamics of the PUMA. Control routines that test successfully can then be linked, without any change, to the I/O interface routines and run on the real manipulator.

This specially fabricated six degree of freedom force and moment sensor measures the static and dynamic loads between the manipulator and the platform. The motion of the Stewart mechanism is achieved by controlling the extension of its legs. Hydraulic actuation was chosen because of the large power requirements of a high bandwidth positioning system. The position of each actuator is sensed using potentiometers, and controlled by a high gain analog controller. The platform's micro-PDP11/73 performs the vehicleemulation calculations including gravity compensation in order to emulate space conditions, and provides position commands position commands to the analog controllers for the hydraulic joints. It also performs supervisory functions that check for approaching violations of the

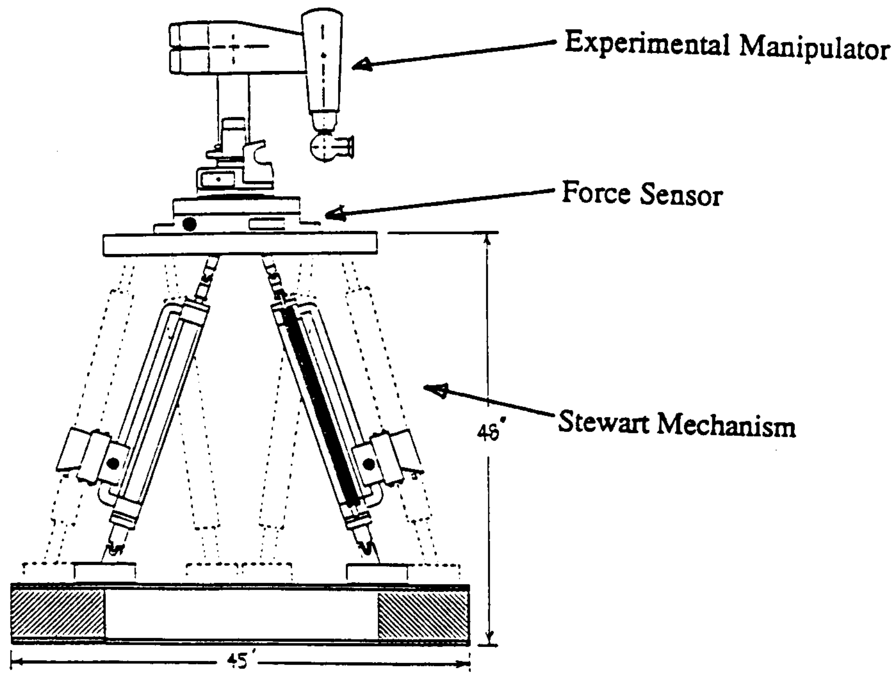

Figure 1. Vehicle Emulator System and Experimental Robot

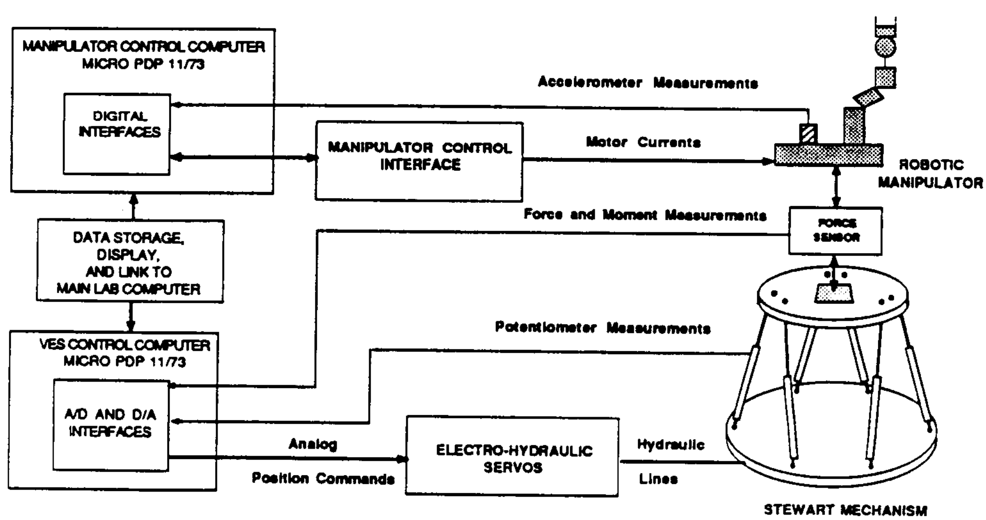

Figure 4. Schematic Diagram of the Experimental System

Figure 2. Schematic Diagram of Experimental System Control