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Microgravity Robotics Technology Program

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ABSTRACT

A research program to develop technology for robots operating in the microgravity environment of the space station laboratory is described. These robots must be capable of manipulating payloads without causing them to experience harmful levels of acceleration, and the motion of these robots must not disturb adjacent experiments and operations by transmitting reactions that translate into damaging reactions throughout the laboratory. Solutions to these problems, based on both mechanism technology and control strategies, are discussed. Methods are presented for reduction of robot base reactions through the use of redundant degrees of freedom, and the development of smoothly operating roller-driven robot joints for microgravity manipulators is discussed.

INTRODUCTION

A major function of the planned space station will be to provide a facility to conduct long-duration microgravity experiments. Efficient utilization of this laboratory, as well as the future commercialization of space, will depend on robotic manipulators for conducting experiments and performing processes.

The introduction of robotic manipulators will permit critical processes designed on earth to be carried out in space with minimal intervention of crew members. Furthermore, robots can potentially allow several experiments to share multipurpose instruments and work stations, further improving productivity. Other robot systems being considered (1) could enhance space station utilization by operating experiments, handling acceleration-sensitive specimens, and resupplying processes. These robot functions could be coordinated by on-board crew members, by principal investigators on the ground through teleoperation, or autonomously.

The microgravity environment (one thousandth to one ten-millionth of normal earth gravity) allows for experimentation and manufacturing which cannot be performed in earth's gravity. Stuhlinger (2) has summarized the estimates of critical acceleration levels for proposed space station experiments. In Figure 1, a plot of typical disturbances and the experiment requirement limits shows that there is essentially a constant level limit at low frequencies as well as a threshold frequency above which relatively higher acceleration levels are permissible. In the absence of disturbances, these requirements will be met at or near the flight path of the station. However, disturbances resulting from operation of the space station may increase the acceleration to unacceptable levels. If the space station is to be a useful facility for research, controls must be applied to insure the conservation of the required acceleration levels. Robots and task specific motion devices are expected to decrease acceleration disturbances by replacing uncontrolled human motion with the programmed, controlled motion of a machine. However, any motion can produce a reaction force, which may result in unwanted acceleration. Harman and Rohn (3) studied the impact of robot and crew motion on the acceleration environment in the laboratory module and found that poorly controlled robot movements have the potential of causing critical disturbances.

There are two related motion control problems associated with the operation of robots in a microgravity environment. The first involves the transport of specimens without exceeding predefined microgravity acceleration limits. This can be accomplished by moving the robot very slowly, increasing mission time, or (preferably) by optimizing the end-effector's trajectory and avoiding any sudden movements. In addition to precise trajectory planning, improvements are required in the construction of the manipulator itself, since conventional manipulators are not designed to operate smoothly enough to execute maneuvers while preserving very low acceleration levels at the end-effector.

The second motion control problem involves the transport of other objects relatively quickly while minimizing reaction forces transmitted to the robot's surroundings through attachment points. The simplest method for reduction of the base reactions is to move the robot arm so slowly that forces are maintained within acceptable levels. A better approach is to use mechanisms or control strategies to compensate for or cancel possible reactions. Use of reaction control techniques will improve robot productivity in situations that permit high accelerations at the end-effector, such as the transportation of nonsensitive test equipment or supplies.

The objective of the microgravity mechanisms and robotics technology program at NASA Lewis Research Center is to develop mechanisms, robot concepts, and control strategies which provide smooth motion, reaction minimization, and acceleration control for use in the microgravity laboratory environment (4). Elements of the robotics portion of the program are reviewed in this paper.

ROLLER DRIVES

Roller, or traction, drives provide significant benefits to robotic applications by offering smooth operation and eliminating backlash. The objective of traction-driven robot research in this program is to determine the suitability of traction drives for space robot applications, measure critical material and environment-related performance parameters, and exploit the beneficial characteristics of traction drives by developing suitable traction-driven robot joint concepts.

Background

Roller drives consist of smooth rollers that are held together in driving contact. Force, or torque, is transmitted from roller to roller by tangential frictional forces in the concentrated contact between them. Characteristics of roller drives which make them competitors to geared drives for precision servo or robot applications are discussed by Loewenthal, Rohn, and Steinetz (5) and include zero backlash, high torsional stiffness, low starting friction, low torque ripple, low velocity errors, potential for nonlubricated operation (due to low sliding), and over-torque protection (ability to slip at predetermined traction limits).

A space servomechanism investigated by Steinetz, Rohn, and Anderson (6) incorporated many of these beneficial servoactuator characteristics in a satellite control moment gyro drive. The high-torque roller drive, shown in Figure 2, was designed to operate dry in space using a thin, ion-implanted layer of gold on the hardened stainless steel rollers to prevent them from cold welding in the vacuum environment. Ground testing demonstrated the drive's zero backlash and relatively high stiffness. By combined analysis and test, the traction rollers contributed only 9 percent of the total system compliance. In addition, torque ripple was extremely low. Internal damping attenuated test rig torque oscillations from 7 percent at the input to 0.3 percent at the output. This study demonstrated roller drive suitability for servoactuator applications, which include robot joints.

Kuban and Williams (7) designed a manipulator arm for a space telerobot project. The arm incorporated a roller-driven joint to take advantage of zero backlash, low torque ripple, and low starting friction characteristics. This telerobot system concept includes a pair of arms, equivalent to a space-suited astronaut, arranged in a force-reflecting, teleoperator-controlled, master-slave arrangement. Each arm includes a wrist roll, plus three traction-roller-driven, differential, pitch-yaw joints. To simplify the control system and provide the necessary fineness of control, drive system backlash had to be eliminated. Since payload forces on the slave are reflected back to the master, the joints had to be easily backdriven. These requirements, plus the need to operate in a vacuum, were factors contributing to the selection of roller-driven joints. For the development of prototype hardware for this concept, a laboratory telerobot manipulator (LTM) has been constructed for ground testing. A precursor bench-top test rig (Figure 3) was built to check out the pitch-yaw joint concept and guide the final LTM design. The differential traction roller stage is visible towards the right in the figure. The rollers are hardened steel with ion gold plating to allow dry operation.

Design Considerations

The design of a roller drive for a robot or for any application depends on the traction performance (traction coefficient, load capacity, wear rate, and fatigue life) of the selected materials and roller configurations. This traction performance, in turn, depends on operating conditions. A considerable amount of data and design information for roller drive materials, lubricants, and geometries in high-power, transmission-type applications has been collected by Loewenthal, et al. (8,9). Development of space robot mechanisms requires performance data under typical operating conditions and environments, for example vacuum and thermal cycling. Limited data exist, but are generally for pure sliding conditions, not the combined rolling and sliding of a traction contact. Rohn (10) describes a unique test rig that will be used to investigate the effects of thermal vacuum environments on material performance. Several roller materials and surface treatments, including soft-metal plated steel and advanced polymers, have been identified for testing. Both materials have relatively high traction and low wear when operating dry in air or vacuum. The data generated in this program will aid the understanding of roller-traction contact phenomena in nonatmospheric environments as well as provide data to design, size, and evaluate future roller-driven robot actuators.

Design studies and hardware testing to develop smooth, reliable, space-compatible motion control devices are underway. Several concepts for robot actuators have been developed, including roller-gear drives (traction rollers in parallel with gears for higher torque capability) and roller-driven joints that incorporate built-in momentum compensation for reaction limitation. The specifications for these will depend to a large extent on the results of on-going space experiment automation and manipulation needs assessments. Promising drive designs will be tested and evaluated to assess performance and suitability for space laboratory robot system applications.

DYNAMICS AND CONTROL

The dynamics and control research supported by this program to date has focused on the operation of a robot while limiting transmission of reactions through its base to the surrounding environment. DeSilva, Chung, and Lawrence (11) developed a method for trajectory design which employs kinematic redundancy (additional degrees of freedom) for base reaction minimization. Manipulators used in space applications will, in general, have kinematic redundancy in order to facilitate the performance of tasks. For example, redundancy will be required for obstacle avoidance and to avert singular configurations. In certain applications, the redundant degrees of freedom can also be used to minimize base reactions. In simplest terms, moving the additional sections of the manipulator in a direction inertially opposite to the movement of the end-effector minimizes the base reactions.

In the case of a nonredundant robot, there is a unique combination of joint motions that satisfies the desired end-effector motion. For redundant manipulators there are an infinite number of solutions to the problem. In the procedure developed by deSilva, an optimization strategy is employed for identifying the joint motion solution set that minimizes the resulting base reactions.

The first step in this procedure involves determining the end-effector trajectory that satisfies acceleration and jerk limitations, in addition to the initial and final positions of the end-effector. Next, the end-effector trajectory is sub-divided into a sufficiently large number of segments. Joint trajectories at the redundant degrees of freedom then are determined for each time step so as to minimize a cost function containing the base forces and moments. Finally, the motion for the rest of the joint degrees of freedom are obtained from the specified end-effector position at the end of the time step. The procedure is repeated until the final end-effector position is reached. Typical results (Figure 4) demonstrate the outcome for a three-degree-of-freedom planar manipulator, where the cost function is defined as the sum of the squares of the base reaction forces and moments. Comparing the optimized and nonoptimized cost functions, it is clear that base reactions can be significantly reduced while performing the same trajectory in the same time.

Chung and Desa (12) applied the previous approach for base reaction minimization to a two-joint, four-degree-of-freedom spatial robot planned for demonstration under this project. In this study, it was demonstrated that kinematic redundancy can be useful for minimizing base reactions for a spatial robot. The effect of various combinations of weighting functions on the base force and moment also was assessed. Since the cost function is defined as the sum of the squares of the base reaction forces and moments, a weighting function is needed to nondimensionalize the variables and balance the relative magnitudes of forces and moments. From these results it was determined that a suitable weighting matrix could be constructed by using average values of base moments and forces.

Chen (13) also incorporated the previously discussed strategies for base reaction minimization. In this work, a general computer program was developed to simulate and control manipulators with any number of links, joints, and degrees of redundancy. By applying this code to manipulators with various degrees of redundancy it was found that through the proper selection of redundancy it is possible to design manipulators that will be capable of operating with minimal base reactions.

The use of kinematic redundancy and other control schemes for base reaction compensation are discussed by Quinn and Lawrence (14). An extension of these ideas is presented in Figure 5, where measured reactions are used to identify the unknown inertial properties of a payload.

Since the previously discussed reaction optimization strategy assumes knowledge of the manipulator as well as the payload, this scheme would provide feedback to update the dynamic models when manipulating an unknown payload. Another promising approach for reaction minimization reported in this work is the use of actuators at the robot base. With actuators, such as moment gyros and proof mass actuators, base reactions can be greatly reduced. Control strategies for driving the actuators are relatively straightforward because the actuator controls are only concerned with the base reactions and do not need to have any information about the robot motions.

Several improvements to the base reaction control and redundant joint optimization schemes are planned for the future. The feasibility of combining the end-effector trajectory with the joint trajectory will be investigated. By optimizing both trajectories simultaneously, additional reductions may be realized in the base reactions. An evaluation of the effect of integrally minimizing the base reactions over time rather than at every instant in time also will be performed. Through use of an integral approach it may be possible to eliminate peaks in the resulting base reactions. Computational issues also will be investigated. For real-time operations it will be required that the optimization be performed faster than the robot is actually moving. This computational rate currently is not attainable, but could be possible with parallel processing or other computational methods. Studies on base reaction feedback control and design sensitivity also are planned.

MICROGRAVITY MANIPULATION DEMONSTRATION

A microgravity manipulator demonstrator is being constructed to evaluate advanced joint concepts and the specialized control strategies for base reaction and payload disturbance minimization. The main features of this demonstrator, as shown in Figure 6, are a four-degree-of-freedom traction-driven robot arm, a base reaction sensor, and a control computer. Brush (15) describes the selection of these components to provide flexibility in performing tests.

The control computer system will be based on the VMEbus architecture to allow expandable support for present and future testing needs. Robot position and velocity control will be managed by one 68020-microprocessor-based single-board computer with inputs from robot on-joint custom processors. The on-joint processors convert position and rate data from tachometers, resolvers, and encoders in the joint, and transmit the data to a module on the VMEbus, which places it in memory for the processor. An additional single-board computer will provide computational power for computing optimal path and joint trajectories.

The manipulator, constructed from two of the previously described LTM two-degree-of-freedom traction-roller-driven joints, will be mounted on a force and moment transducer to measure the base reactions. Commercial sensors using strain-gaged flexures and linear data reduction techniques (16) will give sufficient precision (12-bit) and accuracy (0.1 percent) for this demonstration, and a digital output for computer interfacing. The reaction sensor not only will provide verification of base reaction compensation strategies, but can also be used for identifying the inertial parameters of the robot, including an unknown payload.

The present demonstration project is intended to be the first step in microgravity manipulation experimentation. Envisioned future efforts include evaluation of real-time feedback of reaction forces for improved base reaction compensation, and measurement of end-effector acceleration and vibration to help address the problem of moving acceleration-critical specimens. Additionally, this test bed will allow experimental evaluation of advanced drive mechanisms.

SUMMARY

In order to fully exploit the opportunity for microgravity research, we must develop robots that meet the particular requirements of the space station environment. The research being performed under the microgravity robotics technology program at NASA Lewis Research Center will provide answers to questions about robotic controls, mechanisms, and materials. Results obtained to date include investigation into control schemes that are capable of minimizing robot base reactions; selection of a manipulation demonstration concept including a suitable arm, a control computer, and a reaction transducer; and design of a test rig to measure roller material performance under space-simulated conditions for use in future roller-driven robot joint concepts. These results, and future results, will help developers design robots for microgravity manipulation in the space laboratory.

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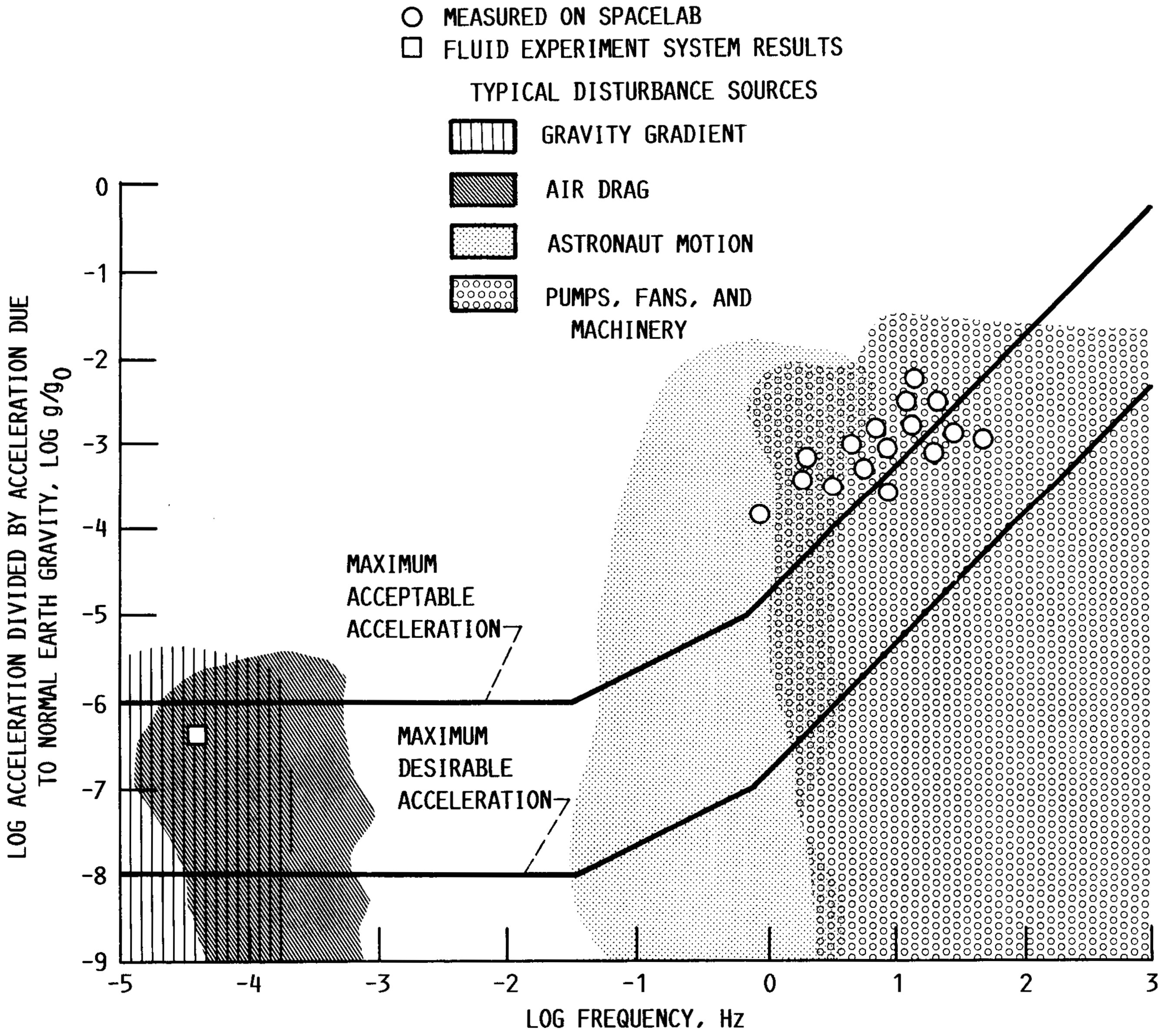

Figure 1.—Critical Acceleration Spectrum for Proposed Space Station Experiments (2).

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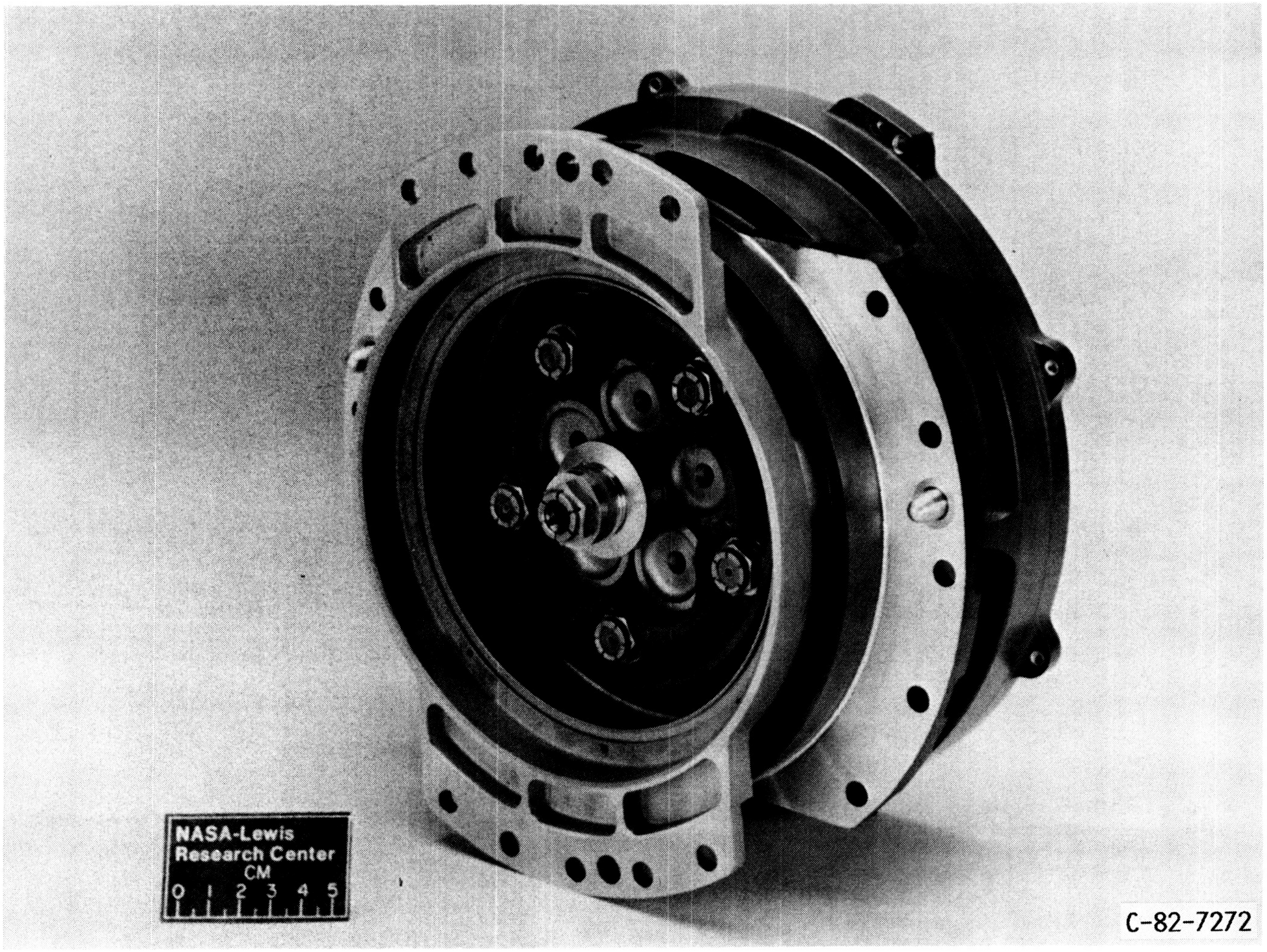

Figure 2.—Roller Traction Drive Prototype for Satellite Control Moment Gyro Drive Application.

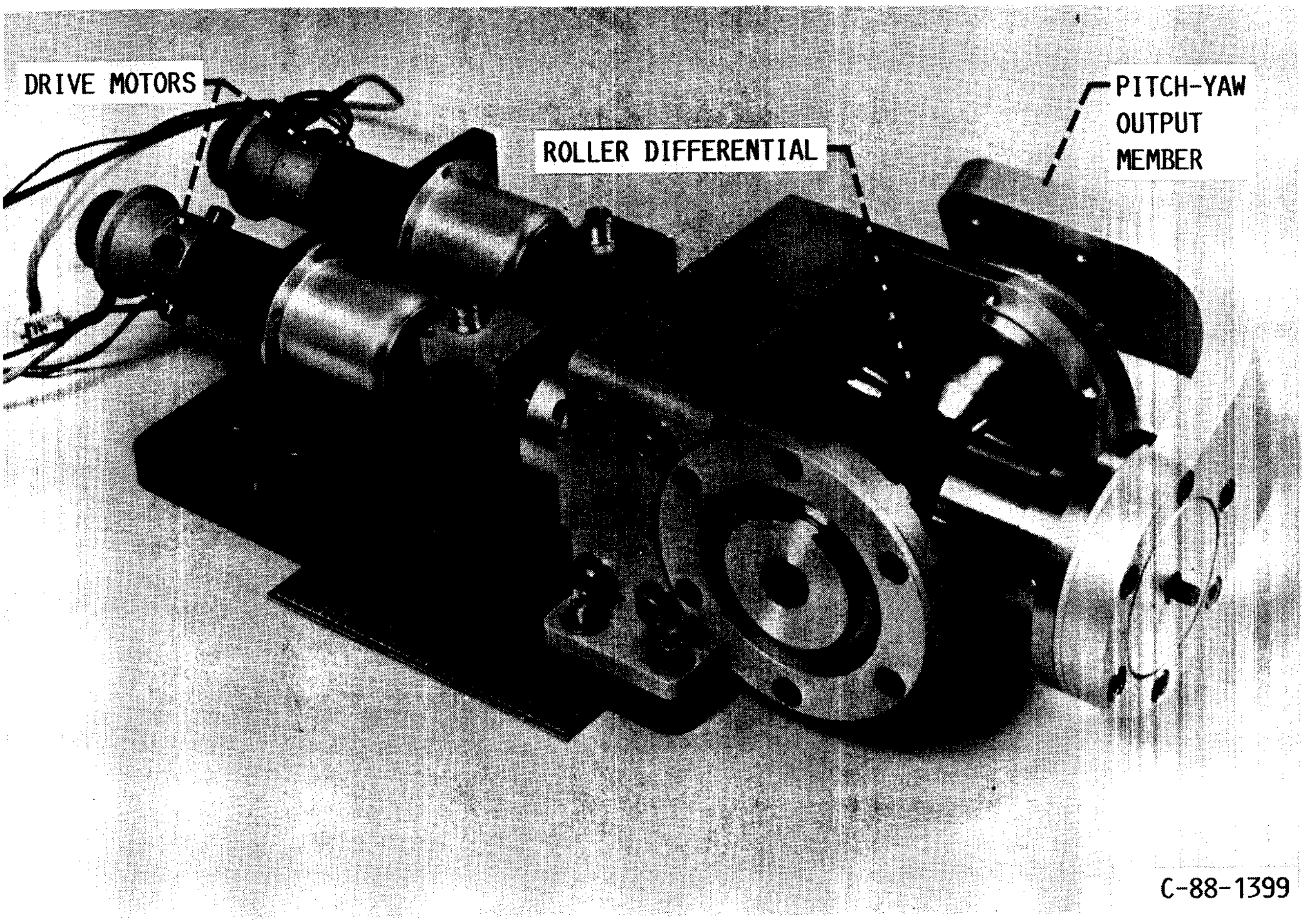

Figure 3.—Bench Test Roller-Driven Differential Joint for Oak Ridge National Laboratory Telerobot Manipulator Project (7).

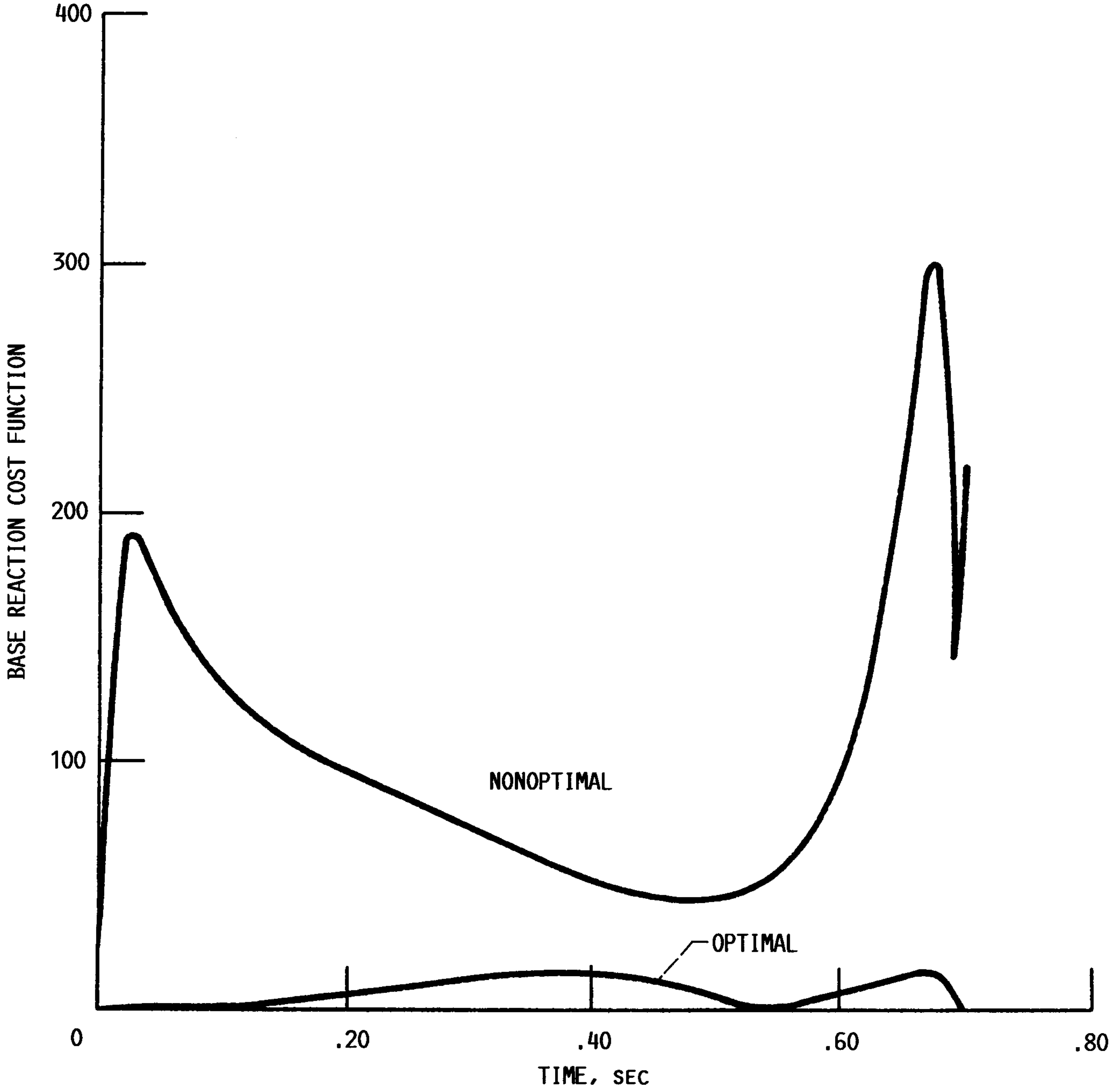

Figure 4.—Typical Optimization of Base Reactions for Three-Joint Planar Manipulator Over Arbitrary Trajectory. Cost Function is Defined as Sum of the Squares of Reaction Forces and Moments (11).

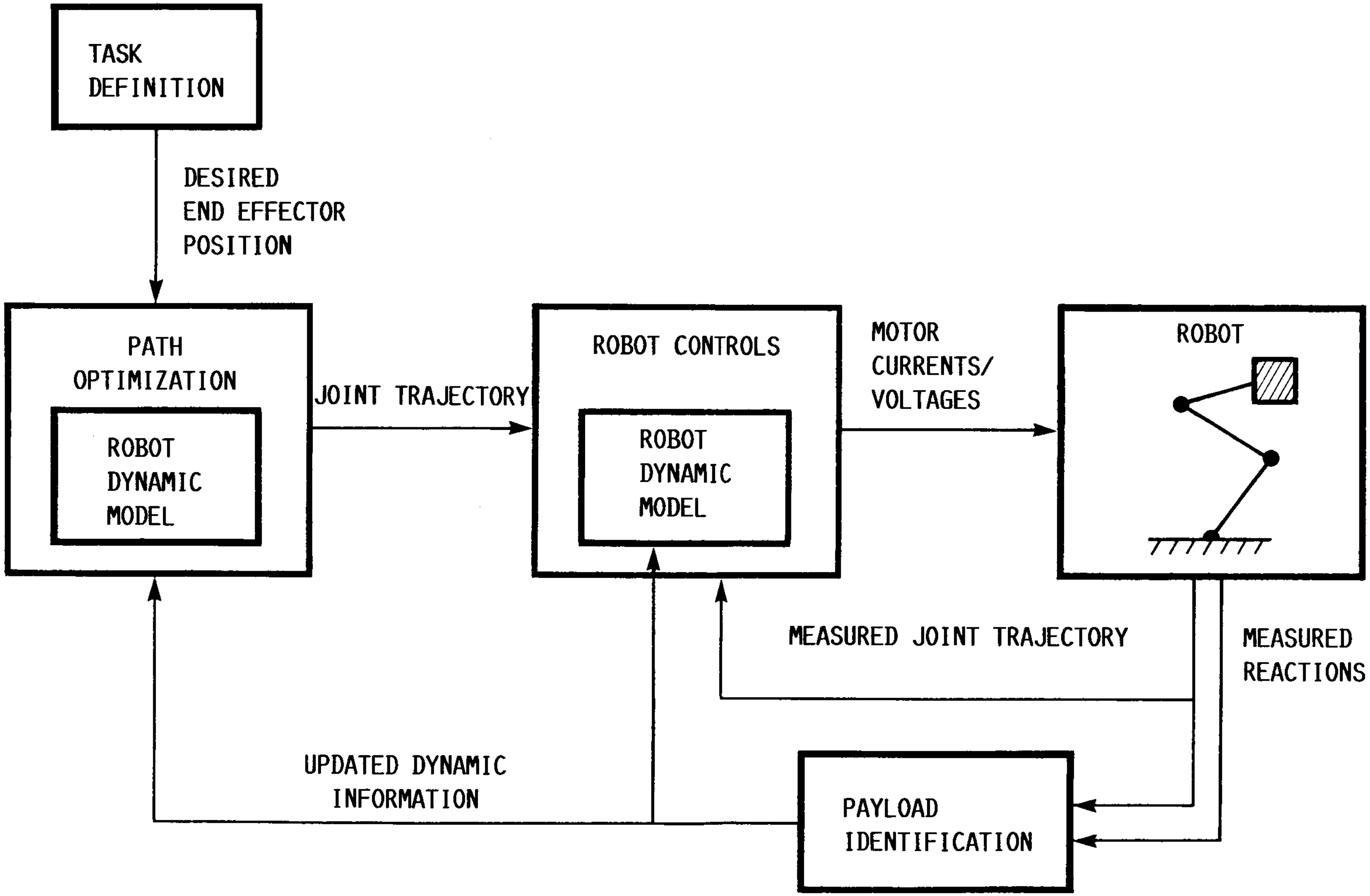

Figure 5.—Control Scheme for Optimized Reaction Control With Unknown Payload.

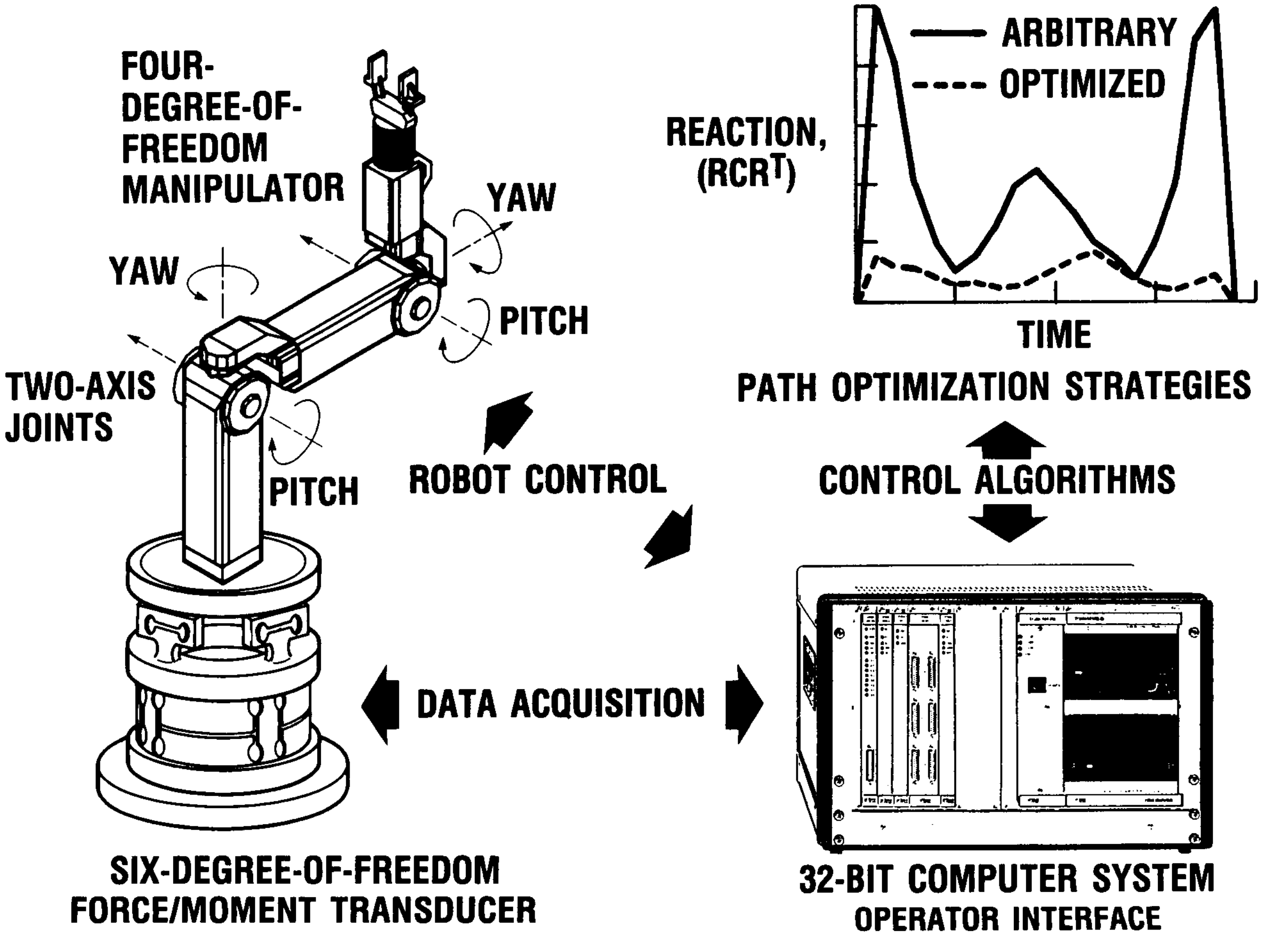

Figure 6.—Microgravity Manipulation Demonstration Test Bed (15).

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16. Abstract

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