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EVALUATION OF INERTIAL DEVICES FOR THE CONTROL OF LARGE, FLEXIBLE, SPACE-BASED TELEROBOTIC ARMS

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ABSTRACT

Inertial devices, including sensors and actuators, offer the potential of improving the tracking of telerobotic commands for space-based robots by smoothing payload motions and suppressing vibrations. In this paper, inertial actuators (specifically, torque-wheels and reaction-masses) are studied for that potential application. Batch simulation studies are presented which show that torque-wheels can reduce the overshoot in abrupt stop commands by 82 percent for a two-link arm. For man-in-the-loop evaluation, a real-time simulator has been developed which samples a hand-controller, solves the nonlinear equations of motion, and graphically displays the resulting motion on a computer workstation. Currently, two manipulator models, a two-link, rigid arm and a single-link, flexible arm, have been studied. Results are presented which show that, for a single-link arm, a reaction-mass/torque-wheel combination at the payload end can yield a settling time of 3 s for disturbances in the first flexible mode as opposed to 10 s using only a hub motor. A hardware apparatus, which consists of a single-link, highly flexible arm with a hub motor and a torque-wheel, has been assembled to evaluate the concept and is described herein.

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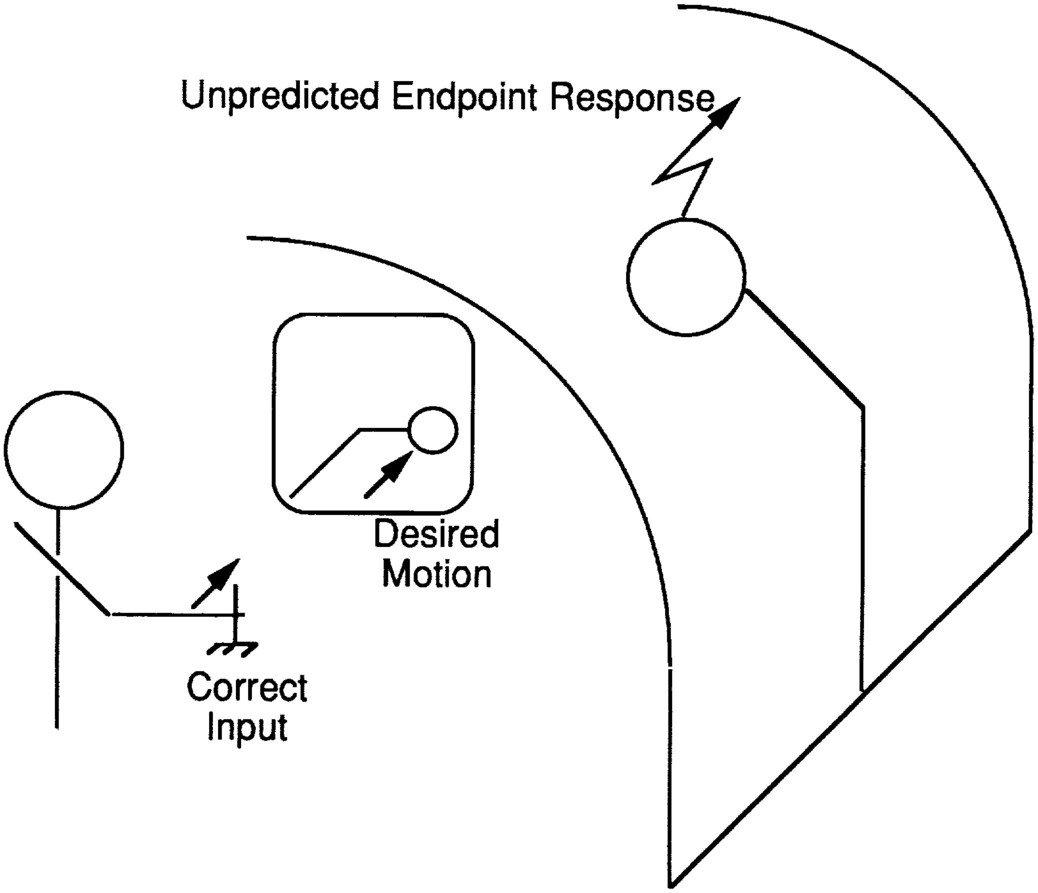
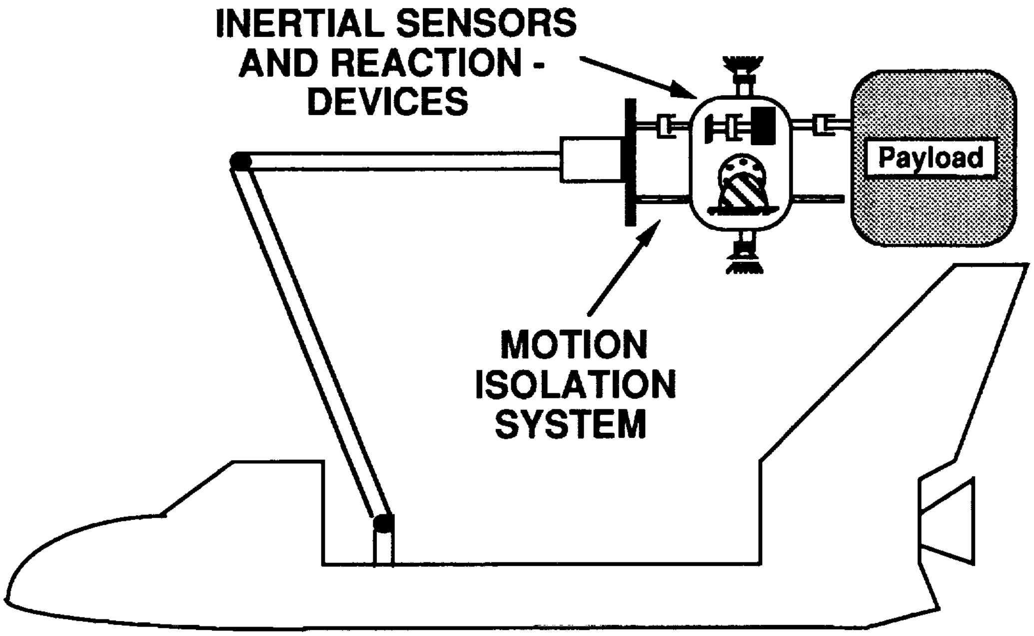
THE PROBLEM

The problem addressed in this research is illustrated in this chart. A human operator moves a hand-controller according to what is perceived as the correct input to maneuver a payload. This is based on observation of the payload via an out-the-window view and closed-circuit television monitors. Based on the hand-controller input and joint sensors, the control system moves the payload via a kinematic linkage. The motion, instead of being what the operator expects, is characterized by unwanted motions which result from the inability to predict the motion of the system based solely on sensors at the joints (typically angle encoders) and from complex structural vibrations. The prediction errors and the structural vibrations are related to the size of the linkage. For the space shuttle remote manipulator (approximately 50 ft. in length) the vibrations can be in the order of 6 in. peak-to-peak with a frequency as low as 0.2 Hz. This behavior, therefore, limits precision payload operations and results in loss-of-time in planning actions and waiting for vibrations to settle after excitation.



SOLUTION CONCEPT

The idea is to place an inertial control unit at the interface between the payload and the kinematic linkage. This unit would possibly use torque-wheels, reaction-mass actuators, reaction-jets, and motion isolation subsystems to isolate the payload from vibrations of the kinematic linkage and still allow transmission of the payload maneuvering loads eliminating the problems with non-collocation in the design frequency range. The purpose of the unit is to isolate the payload from structural vibrations of the kinematic linkage and to reduce or eliminate lags in the response of the linkage which are caused by structural vibrations and nonlinearities in joint motor response. The sizing of the inertial components is, thus, a function primarily of the characteristics of the linkage and, is believed, independent of the payload.



CONTROL WITH CONVENTIONAL JOINT MOTORS

One approach to the problem is to employ additional inertial sensors to determine the track of the payload, and to develop a control law that overcomes the difficulties in non-collocation of the control actuators (at the joints) and the desired response variables (at the payload-end of the arm). Over approximately the last fifteen years, this approach has been researched with no adequate resolution of the problem for precision operations with large, flexible robot arms. This chart lists some of the difficulties. The major one is non-collocation of the actuators with the point of interest. The phase of all vibrations in the control system bandwidth must be predicted accurately in order to get high gains in the control loop, or the control system must be gain stabilized resulting in a low loop-gain with associated poor performance. This difficulty has led us to another hardware-based approach of using inertial actuators (torque-wheels, reaction-mass actuators, etc.) to solve the problem.

FEEDFORWARD CONTROL -

- **NO DISTURBANCE REJECTION**

FEEDBACK CONTROL -

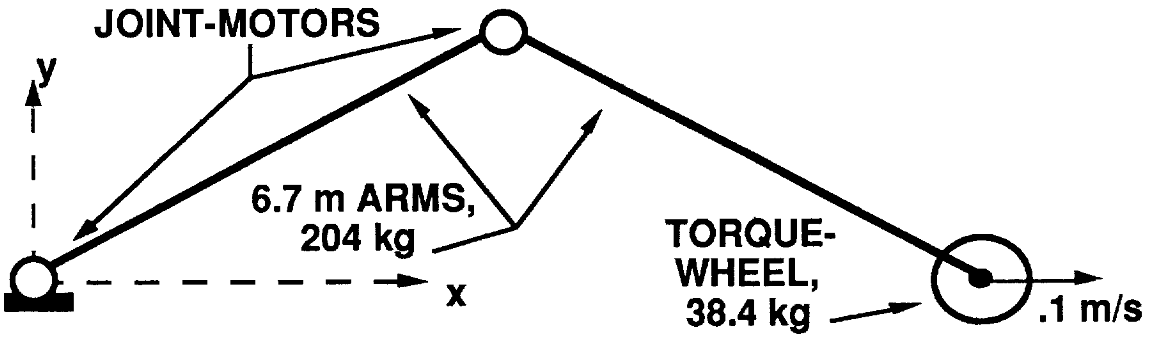
- **NON-COLLOCATION CURRENTLY LIMITS GAIN**

ALTERNATIVE -- USE COLLOCATED DEVICES

BATCH SIMULATION

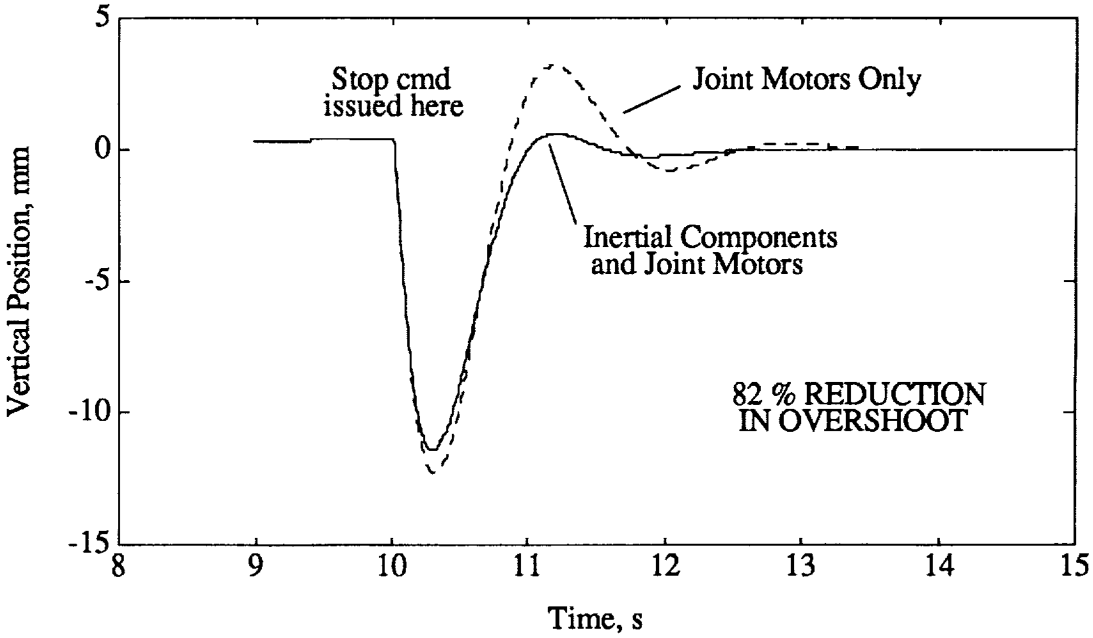
MODEL

A batch simulator has been used to study space-based arms of the Space Shuttle Remote Manipulator System (RMS) class. The simulator includes the dynamics of a planar model of a two-link arm and a torque wheel attached to the free end. The diagram illustrates the arm model used. Dynamic elements included in the simulator are two links, the joint motors, and the torque-wheel. Parameters of the arm were selected to be representative of a large, space-based, RMS-class robotic arm. Specifically, the links are of equal length, 6.7 m, and each has a mass of 204 kg. Parameters of the torque wheel are similar to those of the Langley torque-wheels. The torque-wheel total mass was 38.6 kg and its maximum output was 60 N-m at .5 Hz. The simulator implements a digital joint motor controller as well as the torque-wheel controller. The joint motor control scheme uses inverse kinematics to generate joint angle commands from telerobotic translational command inputs and a proportional-integral-derivative (PID) controller that generates joint motor angular velocity command signals given the joint angle commands. The torque-wheel controller uses collocated rate feedback.



BATCH SIMULATION RESULTS

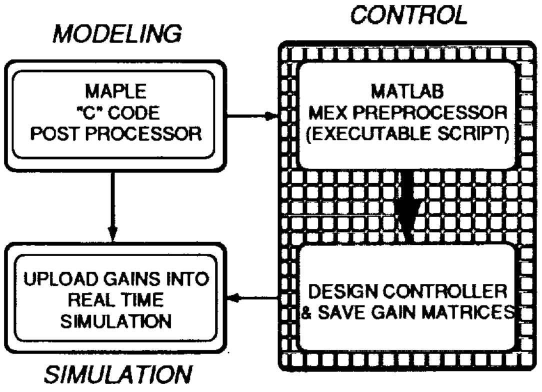
A simulation study was undertaken to suppress vibrations following an abrupt stop input. The arm was given command inputs for horizontal translation of the end-point at a constant velocity for 10 seconds followed by an abrupt stop The time history compares the vertical motion responses, which are ideally zero, both with and without the torque-wheel. The torque-wheel, while operating within its design capability, substantially affects the second overshoot of the vertical motion response. The conclusion is that, subject to the limitations of a batch simulation, a torque-wheel of the size developed at the NASA Langley Research Center can be of value in the control of the arm.



REAL-TIME SIMULATOR

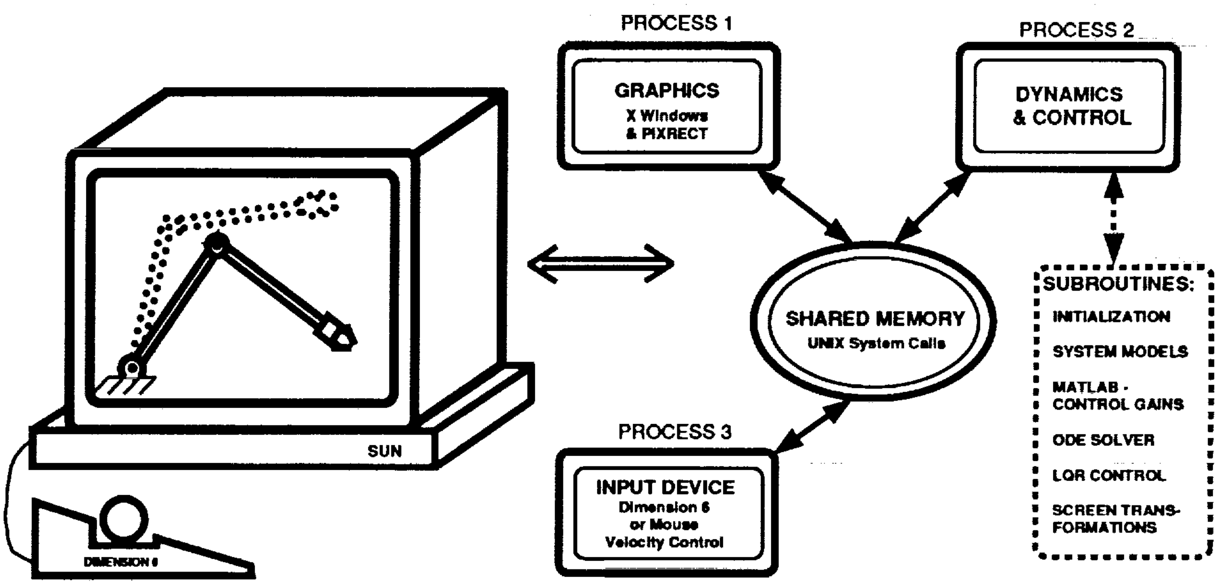
INTEGRATED SOFTWARE ENVIRONMENT

Modelling, control, and simulation of flexible link manipulators requires a set of reliable and efficient software tools. Symbolic manipulation programs represent one of the most versatile software environments currently available for modelling complex dynamical systems. This versatility provides the researcher a high degree of flexibility in terms of the ability to implement theoretically different modelling methods. In addition to their versatility, most of the symbolic manipulation programs have the ability to be integrated with commercially available control design packages. The integration of different software packages is primarily related to the sophisticated pre- and post-processing capabilities available within the respective packages. The figure below presents an integrated software environment which utilizes two commercially available packages for modelling and control, and an in-house developed real-time simulator. The symbolic manipulation program is used to generate executable "C" code for the flexible link manipulators system models. This code is then the input to the control package's preprocessor which converts the "C" code into executable script. Control design may then be accomplished by uploading the preprocessed script. The output of the control design, i.e., the gain matrices, may then be directly uploaded into the real-time simulator.



REAL-TIME SIMULATION ENVIRONMENT

To evaluate the usefulness of inertial actuators for maneuvering and vibration control of single and multi-link flexible manipulators, a real-time man-in-the-loop simulator has been developed. This simulator utilizes a SUN workstation to graphically display the dynamic response of the manipulator system as well as permit man-in-the-loop control through the use of an external input device. The workstation serves as a computational platform which is used to sample the input device, solve the nonlinear equations of motion, and graphically display the resulting motion. Currently, several manipulator models have been developed and successfully implemented in this simulator. These include both a two-link rigid arm and a single link flexible arm. In addition to simulating elastic and rigid body motions, task scenarios are also simulated. A typical task involves maneuvering the manipulator to a payload, capturing the payload, and then maneuvering the payload/manipulator system to a specified target. This payload capture task will facilitate the further evaluation of inertial actuators for man-in-the-loop control of flexible manipulators. The simulator, as shown below, consists of three processes which pass data back and fourth via the shared memory UNIX interprocess communication facilities resident on a SUN workstation.



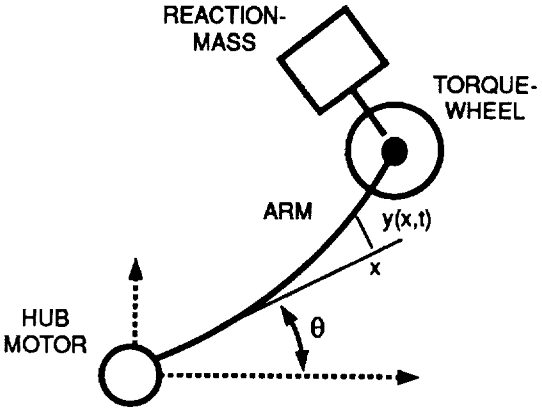
REAL-TIME SIMULATIONS

MODEL

The model used in the real-time simulator is a long single link flexible manipulator that is similar in physical dimensions to the Space Shuttle's Remote Manipulator System (RMS). The flexible arm, as shown below, is equipped with three actuators, one hub actuator and two inertial tip actuators. The inertial actuators used for this model are a torque-wheel, which is used to provide a torque input about the arm's bending axis, and a reaction-mass actuator to provide an input force in the arm's plane of motion.

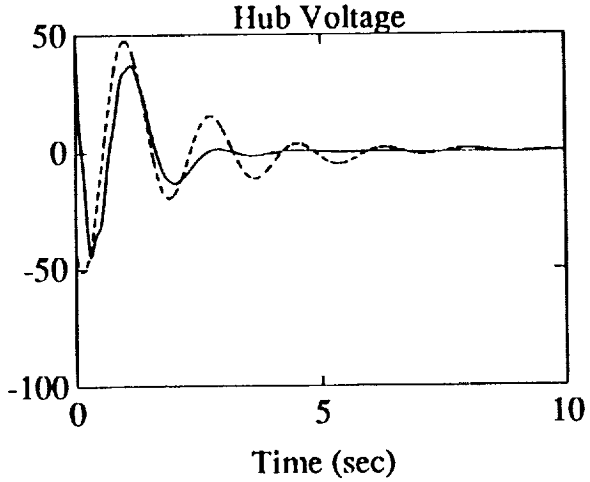
Model Parameters

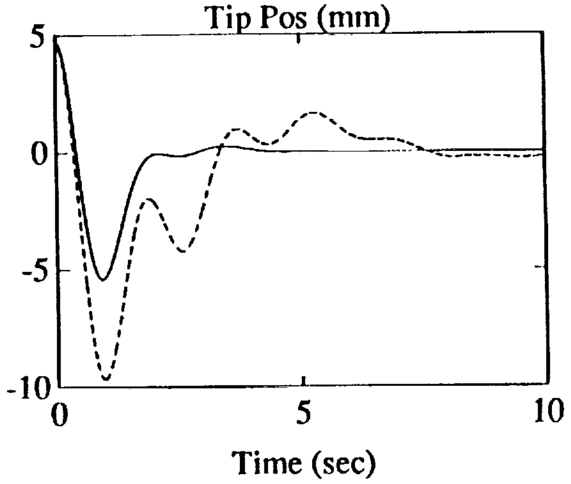
HUB MOTOR
T_{max}=2.8 N-M, ω_{max}=213 rad/s, E_{max}=50 Volts
TORQUE-WHEEL MOTOR
T_{max}=67.8 N-M, ω_{max}=6.5 rad/s, E_{max}=50 Volts
REACTION-MASS MOTOR
F_{max}=128 N, $\dot{y}_{pmax}$=1 M/s, E_{max}=50 Volts
ARM
ρ=55.16 Kg/m, E=1.38e11 N/M^2, L=13.42 M, I=2.08e-5 M^4



REAL-TIME SIMULATION RESULTS

The time history results, as shown below, present the disturbance rejection capabilities for both models, i.e., models with and without inertial actuators. The disturbance considered herein was a perfect first mode displacement initial condition. The analysis and control models both considered three flexible modes, corresponding to the first three "cantilever type" modes with the appropriate boundary conditions to account for the inertial devices. For control system design, a full-state feedback law was obtained using Linear Quadratic Regulator (LQR) design theory. The selection of the Q and R weighting matrices required several iterations to satisfy state constraints on the inertial actuators, e.g., maximum torque-wheel velocity, reaction-mass stroke, and reaction-mass velocity. The objective for the controller design was to achieve operation of the inertial devices near their maximum specifications. The simulation results show that the model using the inertial actuators (solid line), for this type of disturbance, reduced the tip position settling time by more than sixty percent over conventional hub motor only control (dotted line).

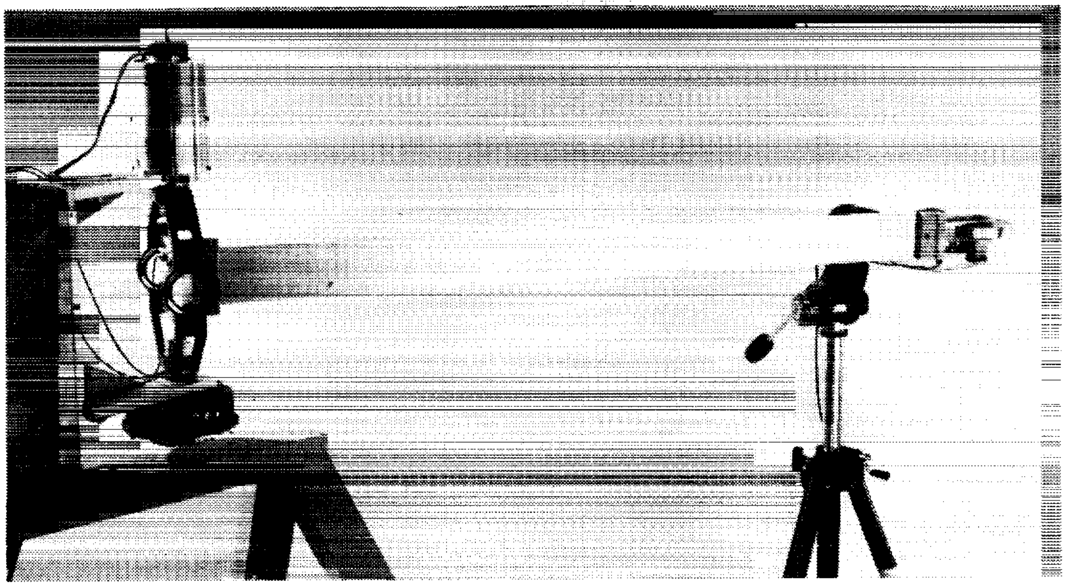




HARDWARE TESTBED

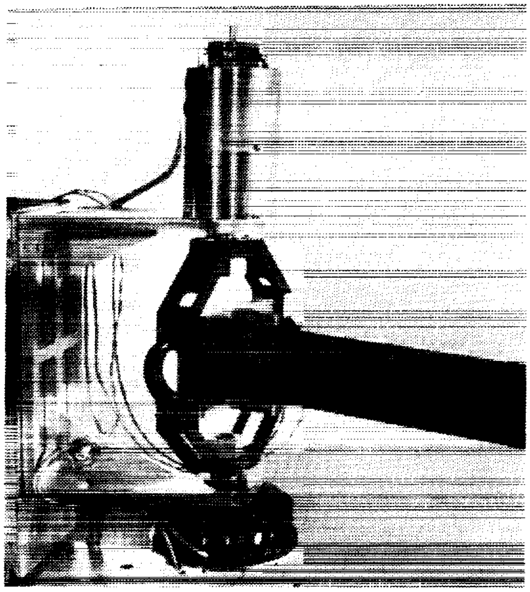
FLEXIBLE ARM EXPERIMENTAL SETUP

The flexible arm test article consists of three major elements: a base-mounted hub assembly (on the left), a flexible beam (at the center), and a beam-tip sensor-actuator assembly (on the right). The hub assembly is comprised of a gimbaled bracket (to provide a rotational, one degree-of-freedom motion to the root of the beam about the vertical axis), a torque motor (to drive the gimbaled bracket), a low rate capability tachometer, and an angular position resolver (to provide rate and position measurements, respectively). The design of the beam was accomplished using constrained optimization. The constraints consisted of maintaining 2-deg/ft-lbf in static torsional stiffness and a 0.8-Hz for the frequency of the lowest bending mode. The optimization criteria was to minimize the end deflection of the beam as subject to gravity loading. This produced an 891-mm long beam with a 75x2.38-mm rectangular cross-section made of Al 6061-T6. The tip sensor-actuator assembly is comprised of a torque wheel with an optical sensor for flywheel rate detection. Both manual and automatic control tests can be conducted using a control computer that has A/D and D/A converters and a timer for precise timing of data sampling processes. An analog-output, hand-controller will be used to provide manual inputs. A linear accelerometer will be mounted on the tip bracket to sense the tip acceleration. A proximity sensor, mounted on an independent pedestal near the tip of the beam, generates a signal for feedback control, for driving an oscillograph display, and for performance monitoring of manual and automatic control tasks.



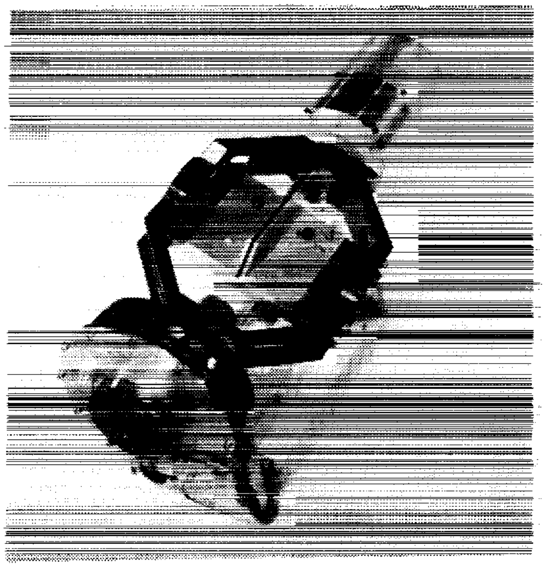
BASE-MOUNTED HUB ASSEMBLY

The photograph depicts the gimbaled bracket with the mounted beam. The hub torque motor appears in the lower part and also provides the support for the hub tachometer, mounted underneath the torque motor housing. The angular position resolver (sine-cosine wire-wound potentiometer) is mounted on the top end of the gimbal axle.



HUB TORQUE MOTOR AND TACHOMETER ASSEMBLY

The photograph depicts a bottom view of the hub torque motor showing a view of the low rate capability tachometer.



BEAM-TIP SENSOR-ACTUATOR ASSEMBLY

The photograph depicts the tip sensor-actuator assembly. The torque wheel fork-bracket provides support for the flywheel axle as well as the optical sensor for flywheel rate detection. The linear accelerometer will be mounted on the tip bracket to sense tip acceleration. Near the tip an independent pedestal holds a beam proximity sensor. This sensor generates a signal for feedback control, for driving an oscillograph display, and for performance monitoring of manual and automatic control tasks.