A Novel Gravity Compensation System for Space Robots

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ABSTRACT

Realistic experimental investigation of the behavior of space robots requires simulation on earth of the micro-gravity environment existing in space. This is particularly true due to the typically long reach and high structural flexibility of manipulators designed for low- or zero-gravity operation. Two-dimensional testbeds, using air bearings or suspension systems, may be satisfactory in some cases, but do not allow 3-D testing. Neutral-buoyancy testing is often used, but complicates the manipulator design and testing, and introduces inertial and viscous effects that can substantially affect dynamic behavior. Other "gravity-compensation" schemes have been implemented, but typically require high power, sophisticated sensing and precise control, and have restrictive bandwidth limits.

An approach which obviates most of these disadvantages is to suspend the robot with a cable from an electromechanical system that passively generates a vertical counterbalance force, while tracking the robot's horizontal motion actively or passively to minimize horizontal disturbances. We have implemented two such systems that enable realistic testing of our Self Mobile Space Manipulator (SM^2), a robot being developed to walk on the exterior structure of the Space Station Freedom. This paper provides an overview of our gravity-compensation systems including mechanical hardware, sensing and electronics, real-time control strategy and software, and experimental results.

1.0 INTRODUCTION

A problem common to many space-related projects is that of providing a realistic environment for testing on earth. In particular, a zero- (or micro-) gravity environment is needed to simulate orbiting facilities, while a low-gravity environment is needed for lunar simulation. In the field of robotics, both fixed-based robots ("arms"), and mobile robots ("rovers") may be highly sensitive to gravitational effects. Robot arms designed for orbital applications may be unable to lift themselves in earth's gravity. Mobile robots will exhibit much more dynamic behavior in the moon's low gravity relative to earth. Appropriate gaits for legged robots are likely to be different on the moon from those on earth, as evidenced by the Apollo astronauts' hopping gait. In general, mechanisms and structures for zero- or low-gravity applications will be relatively weak and compliant, and "gravity compensation" (GC) systems are needed to enable realistic testing of such systems on earth.

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Several different GC approaches have been used by others. Air-table testing has been found effective (e.g. Schmitz89), but is limited to 2-D experiments. Neutral-buoyancy testing under water has been widely used by NASA, but it requires a special tank and equipment, and the water's inertial and viscous properties can drastically affect system dynamics. Sato et al. (Sato91) built a sophisticated GC system that mirrors the movements of the test robot, and provides counterbalance forces through servocontrolled suspension cables; high power and rapid acceleration are required by this system for faithful GC. West (West89) developed a scheme of compensating for gravitational effects at the robot joints; such a scheme is workable only when joint torques and structures are adequate for 1-g operation.

Our particular objective was to provide a test environment for our "Self Mobile Space Manipulator" (SM^2), a robot with characteristics of both robot arms and mobile robots which is being developed to walk on the exterior of the Space Station Freedom (Xu92). SM^2 in its current form (Figure 1) is a slender, 7-jointed "walking stick" with end-effectors at both ends for grasping the I-beam struts of the Space Station truss. For testing SM^2, we needed a system that would allow six degrees of freedom (dof) at one or two support points on the robot, and would support up to about 30 pounds (14 kg) total. The approach we selected uses a passive counterweight/cable system to provide the vertical balance force, combined with an active/passive system to accommodate the horizontal motions. This approach yields good bandwidth and speed of motion, with minimum power requirement and control complexity. The approach was implemented in two GC systems as described below. Numerous technical challenges were addressed in developing the systems, including design of a special counterweight mechanism; minimizing of friction in cables, pulleys and rollers; development of a high-sensitivity, two-axis angle sensor; and development of real-time control software employing gain-scheduling.

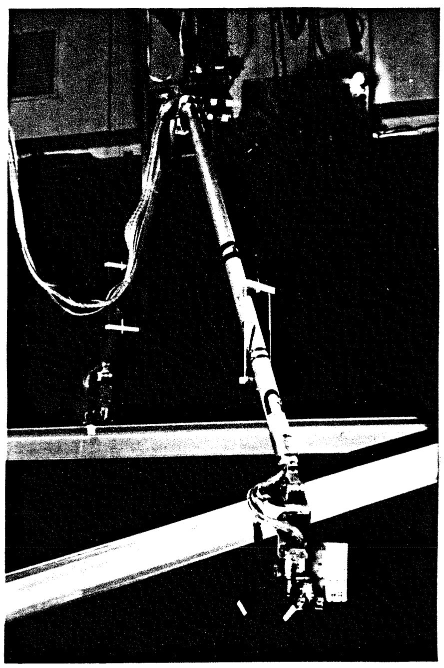

Figure 1. Photograph of SM^2 on truss.

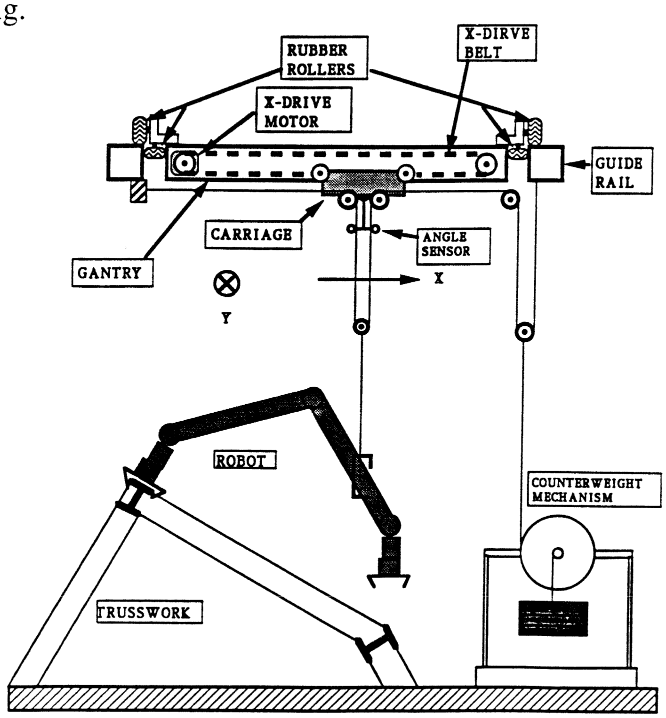

Figure 2. Diagram of Cartesian GC system supporting SM^2. The carriage moves in the X-direction, while the gantry moves in the Y-direction. Additional cable pulleys, not shown, allow the Y-motion.

The two GC systems we developed have many features and components in common, but are kinematically different. Common features include:

- An overhead mechanism for positioning a support point in 2 dof above the robot;
- A counterweight mechanism that generates a constant force for counterbalancing;
- A system of cables and pulleys for transferring the balancing force to the robot;
- Electronic hardware and a PC-based servocontrolled system.

The "gantry" system operates in Cartesian (X-Y-Z) coordinates, while the "boom" system operates in cylindrical (r-θ-Z) coordinates.

1.1 Gantry (X-Y-Z) System

The gantry system (Figure 2) is based on a horizontal beam ("gantry") that acts as a track for X-axis motion of a small carriage. Wheels at each end of the beam ride (in the Y-axis) on a pair of ceiling-mounted guide rails. The carriage provides a suspension point for the support cable to the robot, and has a two-axis angle sensor that measures deviations of the cable from the vertical. The support cable is routed from a counterweight mechanism through a series of pulleys in such a way that it decouples vertical and horizontal motions. Based on signals from the angle sensor, servo motors drive the X and Y axes through belt drives to keep the carriage directly above the robot, and the balance forces precisely vertical. The gantry weighs about 38 pounds (17 kg), and is guided by six rubber rollers and constrained by drive belts at the two ends. The carriage has a mass of about 0.9 pounds (0.4 kg), and is guided with steel rollers on a music-wire track. The friction is low enough (less than 4% of the load) so that we can operate the X-axis passively (without motor control), even with the motor and belt connected.

The gravity counterbalancing force is provided by a floor-mounted counterweight mechanism that uses a 10:1-diameter-ratio pair of cable drums to link the counterweight to the support cable. The 10:1 ratio reduces the effective inertia of the counterweights to 10% of the supported load. (A 1:1 ratio would effectively double the system inertia in the vertical direction, and cause drastic changes in the dynamic behavior of the robot.) The small drum has helical grooves to keep the cables (.032 inch/0.8 mm steel aircraft cable) aligned; eight cable strands in parallel support counterweights up to 300 pounds (136 kg). We use standard barbell weights, 2.5 to 25 pounds (1.14 to 11.4 kg), slotted to facilitate insertion/removal. The vertical disturbance to the robot due to system friction is typically 0.02 g (2% of the supported weight) or less. The counterbalance tension is transmitted to the robot in such a way that the horizontal motions are decoupled from the vertical, as shown in Figure 2. Additional idler pulleys, not shown in the figure, accommodate the Y-motion by guiding the cable in a stretched "N" shape as viewed from above. Idler pulleys were specially designed and made from Delrin plastic for minimum inertia and friction, and are supported on low-friction, precision ball bearings.

The GC system described above accommodates three (positional) dof (X, Y, Z). The other three (orientational) are obtained by various means at the interface with the robot. A swivel just below the support pulley (above the robot) provides yaw freedom. For supporting an early version of the robot along a small, tubular link, we used a large-diameter bearing around the link to allow twisting, plus a gimbal normal to the bearing. Our current system uses a ball and socket joint just below the link to provide the two dof.

The support point(s) on the robot must be selected properly for precise balancing. Modeling our robot as three point-masses connected by two rigid links, we can ideally balance the robot in any attitude with two support points. One of these may be the grasp point on the truss, while the other is a point along the outboard (free) link, as shown in Figure 2. Alternatively, we can find symmetrical balance points on the two links and support both points simultaneously. This can be accomplished by using both the gantry and boom systems together, as in Figure 1; or we can use a "spreader beam" that transfers the support from a single suspension point to two points on the robot, as shown in Figure 3. The beam must be very light to minimize beam vibrations that could lead to control instability. (One spreader beam supported 20 pounds (9 kg) at a 60-inch (152 cm) span, yet weighed only 0.26 pounds (0.12 kg).) Ideal balancing occurs only when the end-effector and joints at the free end are in a vertical line; other configurations generate significant discrepancies. In general, we have designed our experiments to stay near this ideal configuration. Using feed-forward terms in the robot joint control to compensate for these discrepancies is also a possibility.

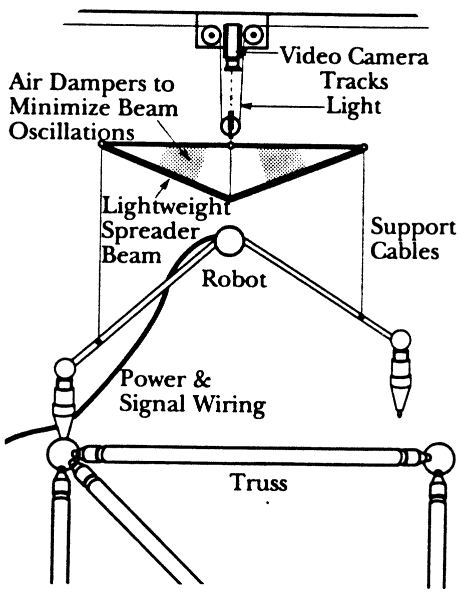

Figure 3. Spreader allows the GC system to support the robot at two points.

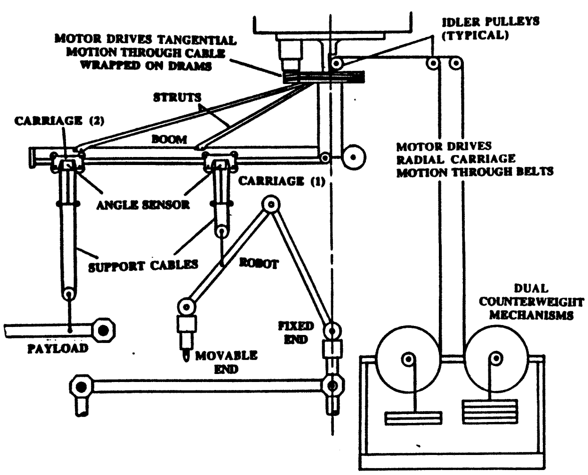

Figure 4. Diagram of the boom GC system supporting SM^2 and payload.

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1.2 Boom (Cylindrical) System

The boom GC system, Figures 1 and 4, uses a pivoted boom, rather than the gantry. It was developed for experiments with one end of the robot fixed below the boom pivot. It has a limited range of motion, but is faster than the Cartesian system, and provides two independent support points along the boom, for the robot and payload, for example. The two systems have overlapping work spaces and can be used together for greater system flexibility, such as for supporting two ends of the robot, or the robot and payload.

The boom system uses an identical carriage and track as the gantry system. However, the boom was designed for cantilever mounting and minimum mass. It is constructed from thin-wall aluminum tubing and light gauge sheet, pop-riveted together. Although the boom is 7 feet (2.1 m) long and deflects only 0.38 inches ((9.6 mm) with the rated load of 30 pounds ((13.6 kg) at its tip, it weighs only about 4.4 pounds (2.0 kg). The boom and track were assembled on a jig using shims to keep the track wires flat and level within 0.002 inch (0.05 mm), to enable the desired sensing accuracy of 0.001 radian. (The track provides the horizontal reference for the sensor.) A pair of DC motors and belts drive the radial motion of the two carriages. Peak radial acceleration is about 18 g.

An interesting feature of the design is the tangential drive system, which requires a high speed-reduction ratio to achieve the needed torque and boom acceleration. With reference to Figure 4, the motor attaches to a 10:1 gear reducer which drives a 1-inch (25 mm) diameter steel drum next to a 16-inch (40 mm) diameter epoxy-surfaced wooden drum attached to the boom. Aircraft cable (.031-inch/0.79-mm diameter) wrapped in a figure-8 pattern (three wraps) around the two drums transfers the torque, and steps it up by a 16:1 ratio, giving a total drive ratio of 160:1. The drive system is very smooth, low in friction and backlash, and easily back drivable. In fact, we often operate the system passively with minimal disturbance to the robot. Peak tangential acceleration is about 65 R/s/s, equivalent to a linear acceleration of 7 g at the middle of the boom.

The boom GC system has two independent counterweights and cable systems so it can support two separate loads. The two cables originate several inches apart from the left- and right-hand units, and run parallel over pairs or pulleys at the ceiling, down through the hollow spindle at the boom pivot, out along the boom, through the carriage pulleys and support pulley, and to the end of the boom. Decoupling of vertical and horizontal motions is similar to that of the gantry system. Boom swinging is limited to about 200 degrees by twisting of the cable pair on the pivot centerline.

2.0 SENSORS AND ELECTRONICS

Interfacing the servo motors to the control software are a number of sensors, motor-current amplifiers, analog/digital interfaces, a control computer, a system of enable/kill switches, and interconnect wiring. Figure 5 shows the electronics hardware schematically. The motors of the two GC systems are driven by four current amplifiers (PMI model VXA-48-8-16, 16 amp peak at 48 VDC) that receive analog outputs from 12-bit DACs on a Keithley Metrabyte DDA06 interface board that plugs into the control computer, a 16-MHz, 80286 PC. Analog sensors on the carriages and motor tachometers are interfaced through a Data Translation DT2805 12-bit, plug-in ADC board. The optical encoders mounted on the PMI motors and a separate unit for the Y-axis of the gantry system are read through a Technology 80 model 5314, 24-bit quadrature decoder board. The motors are enabled through a latching circuit via "enable" pins on the current amplifiers. Enable/kill functions are controlled by two portable enable boxes and by travel limit switches on the GC positioning system. The PC and electronics are mounted near the ceiling to minimize wire lengths, and are connected to the system with appropriate cable loops to accommodate the X-Y and r-θ motions. The PC keyboard and monitor are located at our robot control station for easy access.

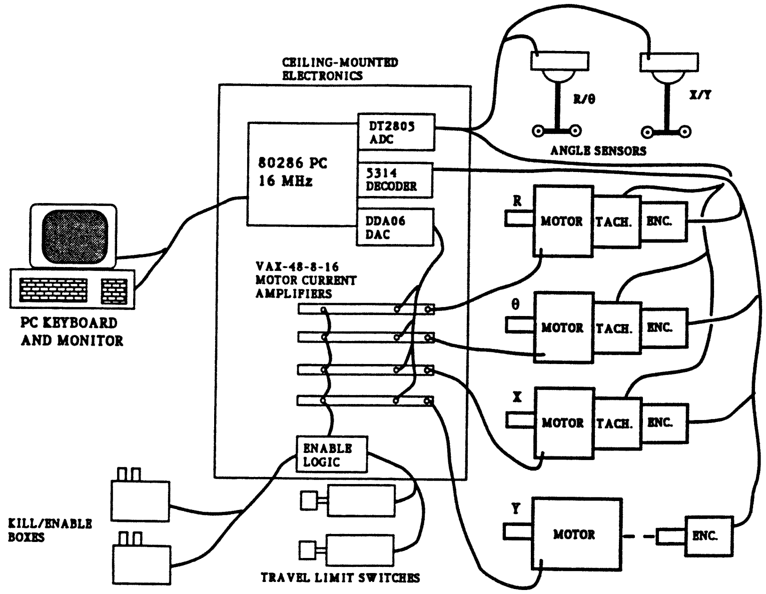

Figure 5. Block diagram of the electronics hardware.

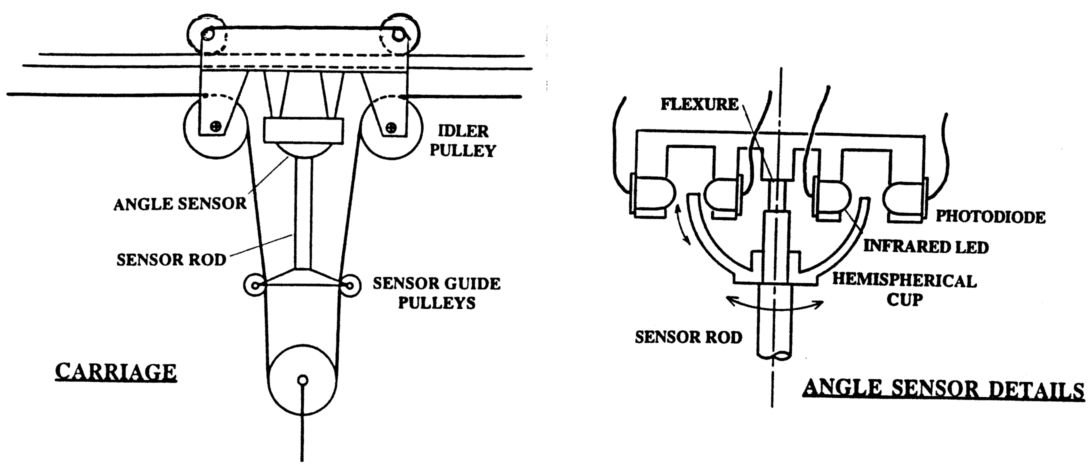

Figure 6. Angle sensor providing error signals for horizontal tracking of the robot.

The carriage-mounted angle sensor is a key element of the system. A rod with a pair of small idler pulleys hangs from the bottom of each carriage, and follows the X-Y (r-θ) deviations of the control cables from vertical (Figure 6). The rod drives the angle sensor, which produces two outputs used as error signals for the servocontrol. The angle sensor was developed specifically for this application, and uses an analog optical principle. A hemispherical cup connected to the rod controls the degree of occlu-

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sion of a light beam, which is related to the position of the cup edge. The difference in photodiode currents on the two sides is amplified and calibrated to indicate the angular deflection of the rod. Sensitivity over the normal range of operation (+/- 0.1 radian) is about 90 v/rad (90 mv/mrad), so sub-milliradian angles are readily detected. The geometry effectively decouples the two measurement axes.

3.0 CONTROL AND PERFORMANCE

A linear mathematical model of the boom system and a single carriage was developed under the following assumptions:

- Small sensor angles
- Negligible non-linear centrifugal and Coriolis terms
- Negligible system damping and friction
- Stiff servo control of SM^2's endpoint position

Under these simplifying assumptions, the following angle-to-torque transfer functions result for the sensors and motors corresponding to the radial and tangential directions of the boom:

$$\frac{\alpha_r}{\tau_r} = \frac{-1}{a_r(m_c l s^2 + m_{robot} g)} \qquad \frac{\alpha_t}{\tau_t} = \frac{-r_c N_t}{(J_{boom} + m_c r_c^2)\, l s^2 + m_{robot} g r_c^2}$$

where α_r and α_t are the respective radial and tangential sensor angles, τ_r and τ_t are the motor torques actuating the r and θ axes, respectively, l is the length of the pendulum, m_c, m_{robot}, and J_{boom} are the respective masses/inertias of the carriage, robot (modeled as a point mass at the suspension point), and boom, a_r is the radial motor's gear radius, and N_t is the tangential motor's gear ratio (see Figures 7 and 8).

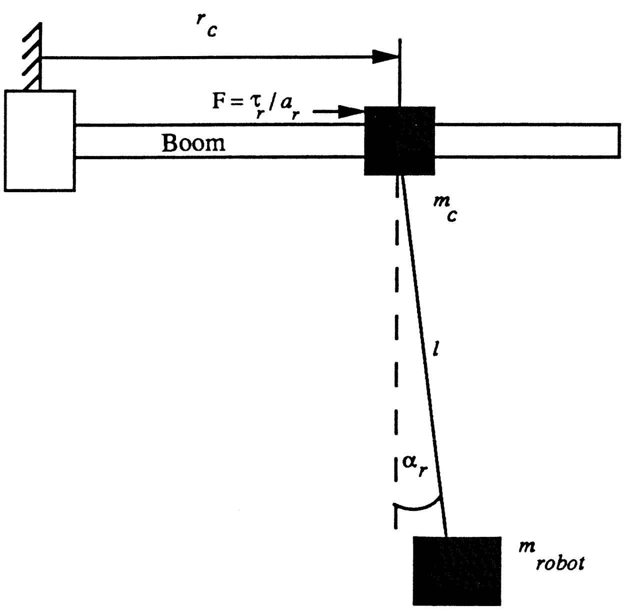

Figure 7. Radial control model

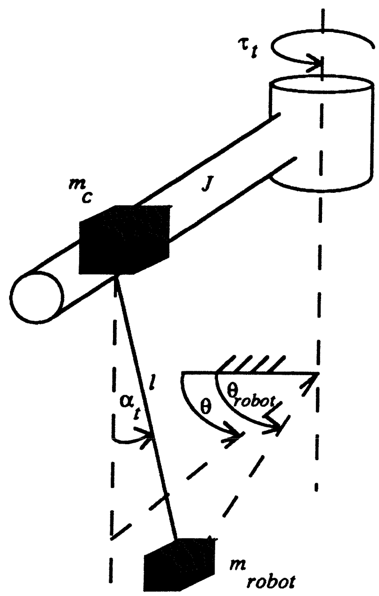

Figure 8. Tangential control model

Active control in the form of a critically damped PD control loop was used in both axes in order to improve on passive performance. The sensor signals were too noisy to provide useful approximations of the velocities $\dot{\alpha}_r$ and $\dot{\alpha}_t$. However, in the case of the θ-axis, for which the motor gearing was high enough for the tachometer to provide a fairly clean motor velocity signal, the kinematic relationship $l\alpha_t \approx r_c(\theta_{robot} - \theta)$, which is evident from Figure 8, was exploited to estimate $\dot{\alpha}_t$. Since knowledge of the actual robot velocity would have increased system complexity by requiring communication between the PC running the GC software and the workstation controlling SM^2, this velocity was set to zero in the time-derivative of the above expression, resulting in the approximation $\dot{\alpha}_t \approx -(r_c\dot{\theta})/l$. Although this only yields strictly correct results when the robot is still, it provides an estimate of the sensor angle velocity adequate to significantly improve GC boom performance in the θ-direction. In the case of the *r*-axis, very small derivative gains resulted in instability. The addition of mechanical damping through dashpots improved stability and reduced sensitivity to high-frequency excitation in both axes.

An interesting feature of the transfer function associated with the θ-axis is its dependence on the carriage position r_c. This is physically reasonable: as the carriage moves towards the base of the boom, the correction of a given sensor-angle error corresponds to an ever larger boom θ-motion. Because r_c typically varies between 0.4 and 2.0 m during robot motion, it is inadequate to simply select a setpoint for r_c, say, in the middle of the boom, and calculate the PD gains on that basis. Instead, the PD gains for critical damping based on the transfer-function model are continuously recalculated based on the current value of r_c, resulting in uniform GC performance irrespective of the carriage position.

Figure 9 compares the passive and active error performance of the boom GC system. During two nearly identical approximately 9-second moves, the robot followed an X-Y trajectory having a maximum velocity of 0.8 m/sec. The resulting horizontal disturbance force as a percentage of the supported weight remained under 9% in the passive case. The introduction of the active control scheme described above brought these forces under 2%.

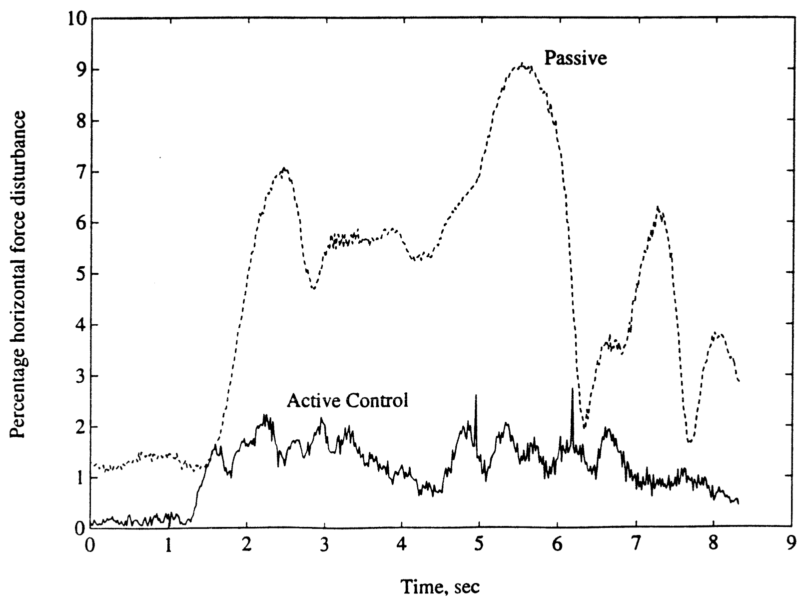

Figure 9. Horizontal disturbance force vs. time for a typical robot X-Y trajectory.

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4.0 DISCUSSION

The GC systems we have developed have advantages over other schemes being used, but also have drawbacks. Our approach requires no active control or power for the vertical axis, and the cable suspension is forgiving of small horizontal errors. The balance force is easily adjusted with weights, but balancing is ideal only in selected robot configurations. The counterweight increases the "vertical inertia" by 10%, but this has not been a problem. The frictional disturbances (about 0.02 g) are small compared to the robot's friction. The main drawback of our approach is the restriction of motion due to the support cables and "gimbal" attachments to the robot. We minimize these problems by using the minimum number of support points possible.

How would we improve the system? First, our experience shows that one axis of horizontal motion (the carriage) may be passive with little degradation of performance. This would eliminate the motors, drive system and control electronics for one axis, and would allow the use of a single-axis angle senor. Second, the difficulty in keeping the guide tracks rigid and precise (as a sensor reference) suggests a sensor reference independent of the track structures. A laser of other optical alignment system appears feasible, especially if only a single axis of measurement is needed.

5.0 CONCLUSION/SUMMARY

As an alternative to air-table testbeds, neutral-buoyancy facilities, and sophisticated, fully-active GC systems, we have developed two GC systems for testing our SM^2 space robot using a combination of cable suspension with passive counterweights, and a horizontal servoncontrolled tracking mechanism. The counterweight mechanism applies a practically constant balancing force on the robot, with minimum friction, inertia, and no active control or power requirement. The cable suspension allows high-bandwidth motions with minimal disturbance. Simple servomechanisms track the horizontal motions. Disturbances to the robot are typically less than 0.02 g.

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