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We have acquired a unique facility that will allow us to conduct experimental research relating to precision motion control and target tracking in a high disturbance environment. The principal components include a six-degree-of-freedom (6-DOF) shaker table, active isolation stage, gimbal mount, and camera sensor. Individually, these components are valuable for research in guidance, tracking, control and related technologies. As an integrated system, this equipment provides a unique facility for performing sophisticated and meaningful research of direct relevance to a wide range of DOD programs. The shaker table is an all-electric six-degree-of-freedom platform. This table can emulate the aiming and pointing disturbances generated by a moving tank or aircraft. The active isolation stage will be used to reduce the effects of high frequency vibration, while the gimbal will provide azimuth and elevation motion for low frequency compensation and target tracking. Mounted on the gimbal is a camera capable of high speed imaging for target acquisition and tracking. Target images are generated by a projection system to permit research in target detection, recognition, and tracking. This integrated system provides a high performance testbed for implementing and validating new techniques for modeling, identification, signal processing, and control. Using real-time control processors, we plan to implement and demonstrate adaptive control algorithms that provide precision motion control with minimal dynamics and disturbance modeling and in the presence of unexpected and unpredictable system variations. This facility will also allow us to undertake new research projects in target acquisition and recognition.

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A Six-Degree-of-Freedom Shaker Table, Active Isolator, and Gimbaled Stage for Research in Precision Motion Control and Target Tracking

Final Technology Report for F49620-00-1-0216

University of Michigan project number F002765

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1 Project Overview

We have acquired a unique facility that will allow us to conduct experimental research relating to precision motion control and target tracking in a high disturbance environment. The principal components include a six-degree-of-freedom (6-DOF) shaker table, active isolation stage, gimbal mount, and camera sensor. Individually, these components are valuable for research in guidance, tracking, control and related technologies. As an integrated system, this equipment provides a unique facility for performing sophisticated and meaningful research of direct relevance to a wide range of DOD programs.

The shaker table is an all-electric six-degree-of-freedom platform. This table can emulate the aiming and pointing disturbances generated by a moving tank or aircraft. The active isolation stage will be used to reduce the effects of high frequency vibration, while the gimbal will provide azimuth and elevation motion for low frequency compensation and target tracking. Mounted on the gimbal is a camera capable of high speed imaging for target acquisition and tracking. Target images are generated by a projection system to permit research in target detection, recognition, and tracking.

This integrated system provides a high performance testbed for implementing and validating new techniques for modeling, identification, signal processing, and control. Using real-time control processors, we plan to implement and demonstrate adaptive control algorithms that provide precision motion control with minimal dynamics and disturbance modeling and in the presence of unexpected and unpredictable system variations. This facility will also allow us to undertake new research projects in target acquisition and recognition. This research facility will be relevant to DOD programs such as electronically controlled turrets, Airborne Laser, and Space Based Laser, all of which require precision motion control and target tracking in a high disturbance environment.

A related goal is to demonstrate new techniques for modeling complex systems through measured data. Using analytical and computational models as a starting point, engineers need to validate such models by means of test data. Such data is often corrupted by noise (due to noisy sensors and ambient disturbances) as well as by unmodeled nonlinearities. We believe that developing identification techniques that can extract model parameters from data in the presence of both noise and nonlinearities is a problem of fundamental technological importance. This program thus encompasses the problem of nonlinear identification.

2 Equipment Description

The equipment to be acquired under this project can be divided into 2 parts, namely, 1) the six-degree-of-freedom shaker table, and 2) the active isolator and tracker subsystem. We now describe this equipment and report on its current status.

2.1 Shaker Table

Disturbance generation is performed by a six-degree-of-freedom (6-DOF) shaker table. This shaker table provides a controlled motion platform in 6 degrees of motion, including both rotational motion (roll, pitch, and yaw) and translational motion (surge, heave, and sway). This number of degrees of freedom provides considerable versatility for performing motion control experiments.

The shaker table we have acquired was manufactured by ANCO Engineers of Boulder, CO. ANCO Engineers was chosen for this component because of their experience with multi-degree-of-freedom platforms using all-electric actuators. It was our desire to avoid hydraulic shaker tables which involve more complex installation.

The shaker table we have acquired can provide 4g actuation of a 300 lb payload at frequencies up to 200 Hz. Higher accelerations up to 9 g's are obtainable for lighter payloads. This specification represents an extremely capable piece of machinery that will have broad usefulness.

In order to provide 6-DOF motion, the shake table is actuated by 6 DC servo motors. The multi-axis motion is attained by means of linkages. Since these linkages are coupled, it is necessary to provide kinematically correct commands to obtain desired motions. To do this, the shaker table has an analog control system that provides good decoupled motion accurate to about 100 Hz. For higher frequencies, we are using a dSPACE 1103 real-time controller. The mating of a dSPACE system with a 6-DOF shake table provides an opportunity to develop innovative control algorithms for precision motion applications.

To address the coupling among actuators and to account for all degrees of freedom, we have focused our research on nonlinear identification and adaptive control techniques under related AFOSR research. Nonlinear identification is a problem of considerable practical significance since unmodeled nonlinearities often degrade the accuracy of sensors and actuators. In some cases, testing under quasi-steady-state conditions can be used to map the nonlinearities for later inversion and data correction. However, in certain applications, the inputs and outputs of the nonlinearity are not directly accessible and, furthermore, the nonlinear functions are tightly bound to linear dynamics which are equally uncertain. These issues are relevant to complex machinery in general and to the shaker table in particular due to the motor/amplifier dynamics and the nonlinear geometry of the linkages.

In research supported by AFOSR, we have developed techniques for both linear identification [1-3] and nonlinear identification based on system topologies that involve both static nonlinear maps and linear dynamics [4-10]. The system topology may be of various forms. For example, the static nonlinearity may precede the linear dynamics (a Hammerstein model), it may follow the linear dynamics (a Wiener model), or it may be interconnected with the linear dynamics via feedback (a nonlinear feedback model). These topologies and other variants provide a rich class of model structures for constructing nonlinear dynamical models.

The nonlinear identification techniques developed in [4-10] do not assume that the input and output signals of the static nonlinearity are accessible since to do so would violate practical constraints. Furthermore, unlike alternative nonlinear identification techniques, this work does not assume that the linear dynamics are known a priori. Furthermore, the objective of this research is to simultaneously identify the static nonlinear and dynamic linear portions of the nonlinear system.

In addition to nonlinear identification of the shaker table dynamics, we intend to develop and apply adaptive control techniques for precision motion control under uncertain and changing conditions. In particular, an adaptive controller must account for small yet dynamically significant variations in the transfer function characteristics of the motors and electronics. In addition, precision control must be maintained under a range of loadings which may change during operation. Our research in adaptive disturbance rejection [11-19] is applicable to this objective.

While precision control of the shaker table is one of our research objectives, the table will have substantial versatility for motion control experiments. For experiments involving active vibration suppression, the shaker table will provide a precisely controlled disturbance source for implementing and testing active vibration control technology. Relevant applications include aircraft and spacecraft vibration studies where the structure can be subjected to a multi-axis vibration spectrum. The shaker table can also be used to emulate the disturbance spectrum of moving vehicles for research in active isolation and pointing.

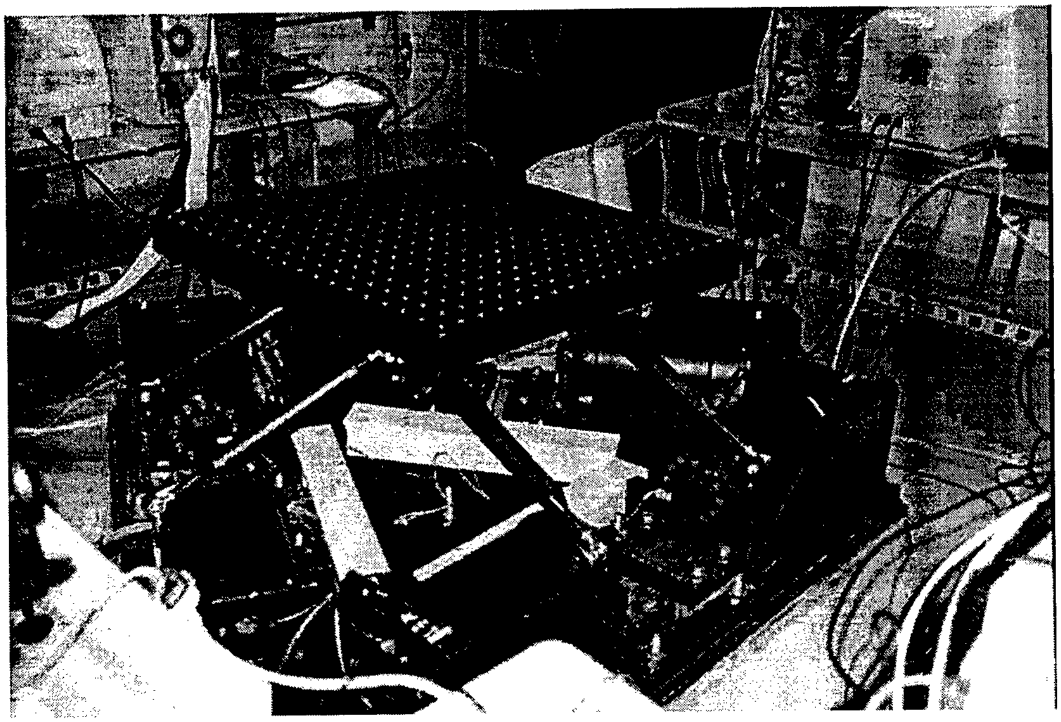

Figure 1: This is a view of the six-degree-of-freedom shaker table. The table is entirely electrical, and can be controlled by a combination of analog and digital controllers up to 4 g's and 200 Hz with a 300 lb payload.

The shaker table was delivered and installed in October 2001. The table is shown in Figure 1.

2.2 Active Isolator

In many applications, sensitive equipment must be isolated from disturbances. While there are many situations where this is of concern, there are two that have particular relevance to DOD. The Airborne Laser (ABL) program has as its objective to fly a high-powered laser on a 747 to serve as a large standoff directed energy weapon against airborne threats. The requirements for target acquisition and beam accuracy are rendered difficult by the ambient vibrations of the platform.

Active isolation has several advantages over passive isolation including the ability to retune for changing disturbance spectra and the ability to point and track over limited angles. Air Force interest in active isolation for space applications is reflected by ongoing projects at AFRL. The Vibration Isolation, Suppression, and Steering (VISS) project uses voice coil actuators in a Stewart platform (6-DOF) configuration to suppress tonal disturbances and provide precision pointing and tracking to +/- 0.2 deg. Launch for this project is scheduled for December of this year. A related project is the Satellite Ultraquiet Isolation Technology Experiment (SUITE), which uses PZT stack actuators in a Stewart platform configuration for tonal suppression. Launch for this project occurred in 2001.

In view of DOD interest in active isolation technology, we have to acquired an active isolation subsystem under this project. The active isolator we have chosen is a voice-coil-actuated six-degree-of-freedom (hexapod) configuration. The isolator is a custom-designed unit built by Planning Systems, Inc., (PSI) of Melbourne, FL.

The PSI active isolation stage was designed to provide a versatile testbed for research purposes. Each leg of the isolated upper platform is instrumented with a relative displacement (capacitive gap) sensor as well as an accelerometer, while triaxial gyros and accelerometers are mounted on the upper platform. These sensors can be used in combination to implement novel active isolation control laws. In previous research on active isolation, we have developed control laws based on various performance metrics [20-22]. These performance metrics can be used to tailor the control law to account for the spectrum of the disturbance signal. With this DURIP equipment we will be able to implement and test these control laws and develop adaptive extensions for improved performance.

2.3 Target Generation and Imaging Subsystem

The target generation and imaging subsystem provides the means to generate target images as well as the ability to acquire, identify, and track these images. The components for this subsystem were provided by several vendors and integrated with the active isolation stage by PSI.

Target images are computer generated and displayed on a projection monitor. The target generation program allows us to synthesize single or multiple targets with different plume and hardbody geometries and flight characteristics. These targets are acquired and tracked by means of an optical camera mounted on a gimbal. The gimbal is a two-axis pan-and-tilt (elevation over azimuth) configuration, which is used for slewing the imaging camera for target tracking. The camera is a monochrome system with electronically adjustable focus and zoom. The camera is capable of 60 frames per second output, where each frame is 768 x 493 pixels. An associated frame grabber and software system can be used for programmable imaging operations such as target centroiding. The baseline output of the imaging system is two error signals, which indicate target location in the image plane.

The active isolator and tracking subsystem were delivered in June 2001. All systems were checked out satisfactorily. Figures 2-8 show the isolator, gimbal, and vision hardware.

2.4 Personnel

This development of the hardware was supervised by the Principal Investigator. Several students have been involved in the operation of the hardware, although no personnel costs were provided by this grant. Undergraduate students Adrian Koller and Eli Rosenberg assisted in the testing and operation of the vision system and gimbal. Seth Lacy and Suhail Akhtar were involved in the testing and operation of the shaker table and gimbal stage.

3 Instrumentation and Cost

1. **Disturbance Generation Subsystem.** This is a six-degree of freedom motion platform which provides commandable motion in pitch, roll, yaw, surge, heave, and sway. Stroke is +/- 2.5" in translational motion and +/- 5 degrees in rotation. Payload capacity to 300 lb with specified displacement, velocity, and acceleration. Includes custom breadboard mounting platform, analog displacement servo controllers for independent axis control, and amplifier cabinet.

   Vendor: ANCO Engineers, 4826 Sterling Drive, Boulder, CO 80301.
   Cost: $318,310.

2. **Active Isolation Subsystem.** This is a custom-designed, six-degree-of-freedom active isolation stage used to reduce the disturbances generated by the shaker table. Includes six proof mass actuator struts, linear amplifiers, capacitive displacement sensors, load- and disturbance-side accelerometers, signal conditioning, power supplies.

   Vendor: Planning Systems, Inc., 1901 South Harbor City Boulevard, Melbourne, FL, 32901.
   Cost: $ 163,500.

3. **Target Generation and Imaging Subsystem.** These components are used to generate and detect images that simulate target motion. The target generation subsystem uses an XGA LCD projection monitor (EPSON Powerlite 7300) to produce simulated target images. The imaging subsystem uses a camera (Hitachi KPM-2) to acquire the image for analysis and tracking purposes. The camera is capable of 30 frames per second with 768 × 493 pixels output, with an associated frame grabber for programmable imaging operations such as target centroiding.

   Vendor: Planning Systems, Inc., 1901 South Harbor City Boulevard, Melbourne, FL, 32901.
   Cost: $ 79,500.

4. **Two-Axis Servo Gimbal.** This is a servo-driven azimuth-elevation gimbal mount used to aim the camera for target acquisition and tracking.

   Vendor: Aerotech, Inc., Zeta Way, Pittsburgh, PA.
   Part number: AOM-300.
   Cost: $14,920.

5. **Motion Sensor.** This is a six-degree-of-freedom gyro/accelerometer package for measuring rotational rates and translational accelerations of the isolation platform.

   Vendor: BEI Systron Donner Inertial Division, 2700 Systron Drive, Concord, CA 94518-1399.
   Part number: BEI MotionPak.
   Cost: $19,800.

6. **Control processor.** This is a high performance real-time control processor for feedback control of the shake table, active isolation stage, and gimbal. Includes processor board with 16 A/D inputs, 16 D/A outputs and 7 encoder channels. Includes connector panel. Three units.

   Vendor: dSPACE, Inc., 22260 Haggerty Rd., Suite 120, Northville, MI 48167.
   Part number: ACE 1103, CLP 1103.
   Cost (for three units): $36,930.

7. **PC host computers.** This is a commercially available PC that will serve as host for the dSPACE control processor. Four units.

   Vendor: Dell, One Dell Way, Round Rock, TX 78682.
   Part number: 550 MHz PC with zip drive and 16 GB hard drive.
   Cost: $ 17,500.

8. **Accelerometer/gyro unit.** This is a custom 3-axis gyro and accelerometer sensor for feedback control of the shaker table.

   Vendor: Microstrain, Burlington, VT.
   Cost: $ 2,265.

9. **System Components.** This includes electrical and mechanical components needed to complete the system as well as spare and replacement parts. Included are PC software for data analysis, computer peripherals, transformer for the shaker table amplifiers, and miscellaneous hardware.
   Cost: $16,000.

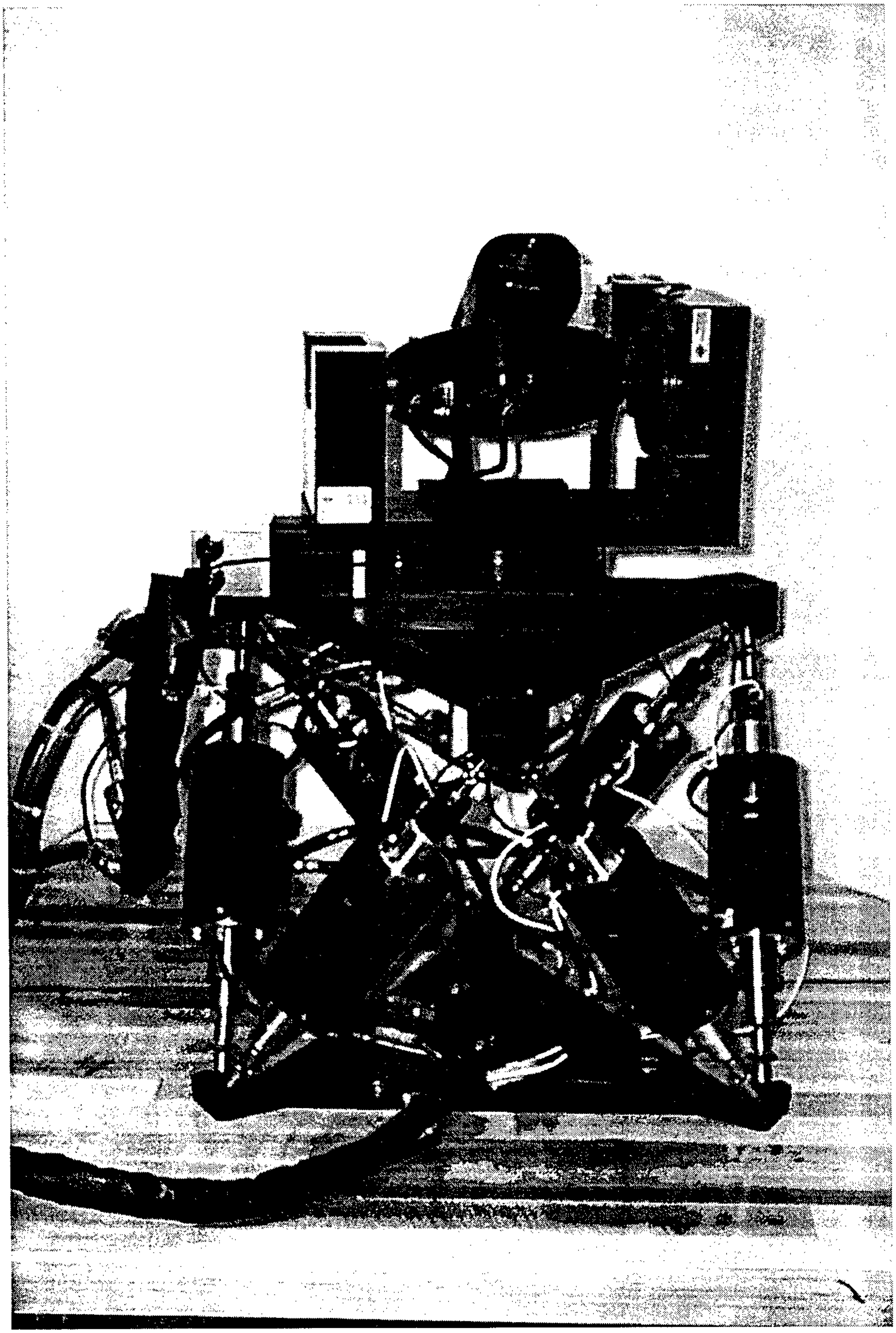

Figure 2: This is a full view of the active isolator with tracking gimbal and camera. The gimbal is an azimuth-elevation stage.

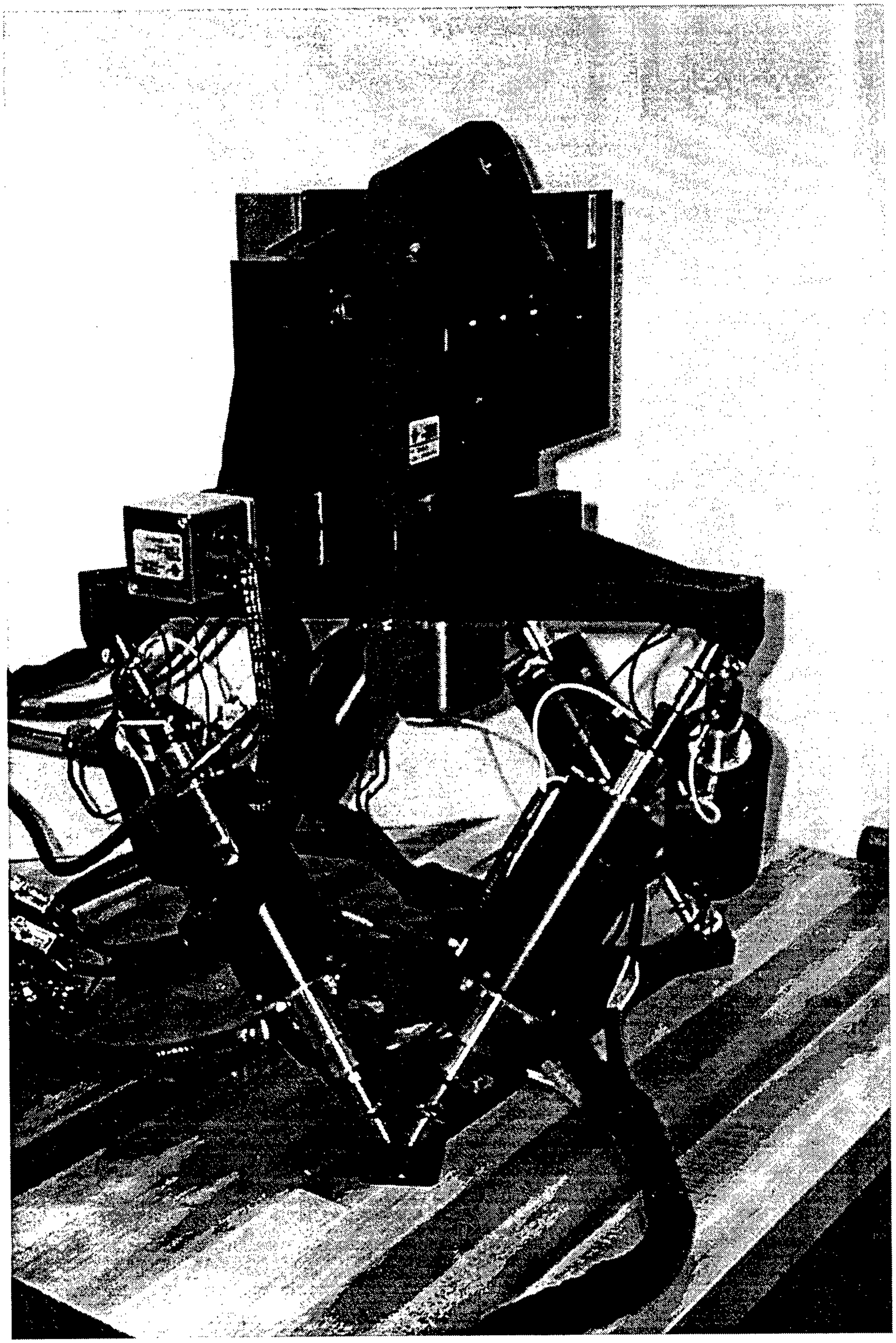

Figure 3: This is a side view of the active isolator. The cube under the gimbal stage is a 3 axis accelerometer and 3 axis gyro package for inertial stabilization of the platform. There is also a pair of gyros mounted under the camera to allow inertial stabilization of the camera.

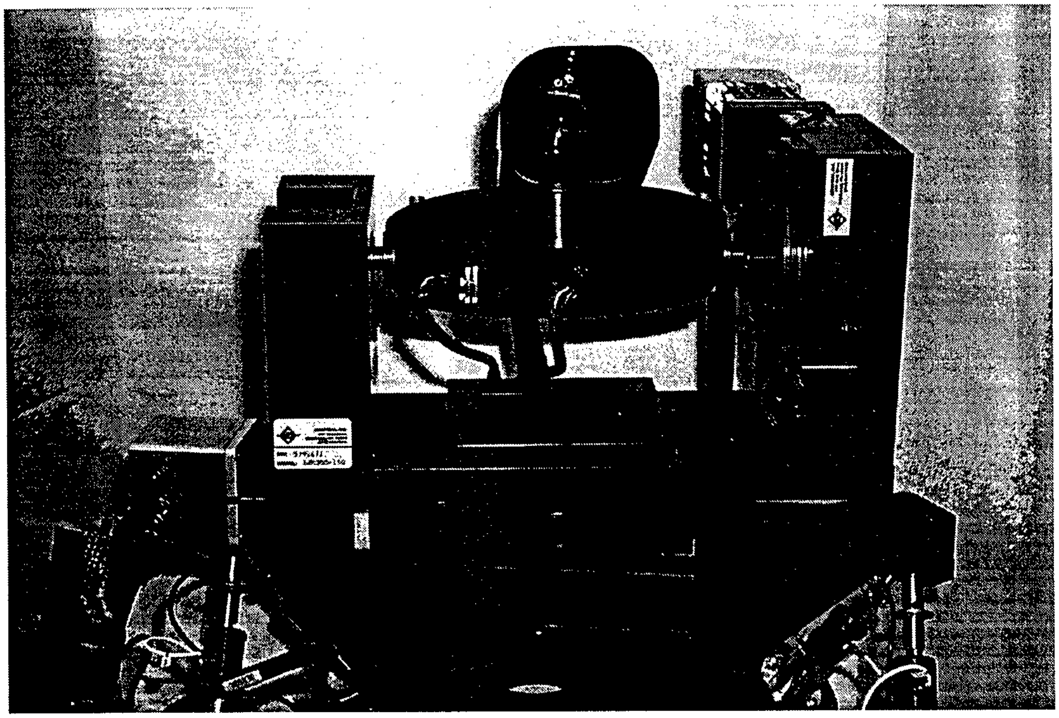

Figure 4: This is a view of the camera. A separate PC is devoted to real-time image processing.

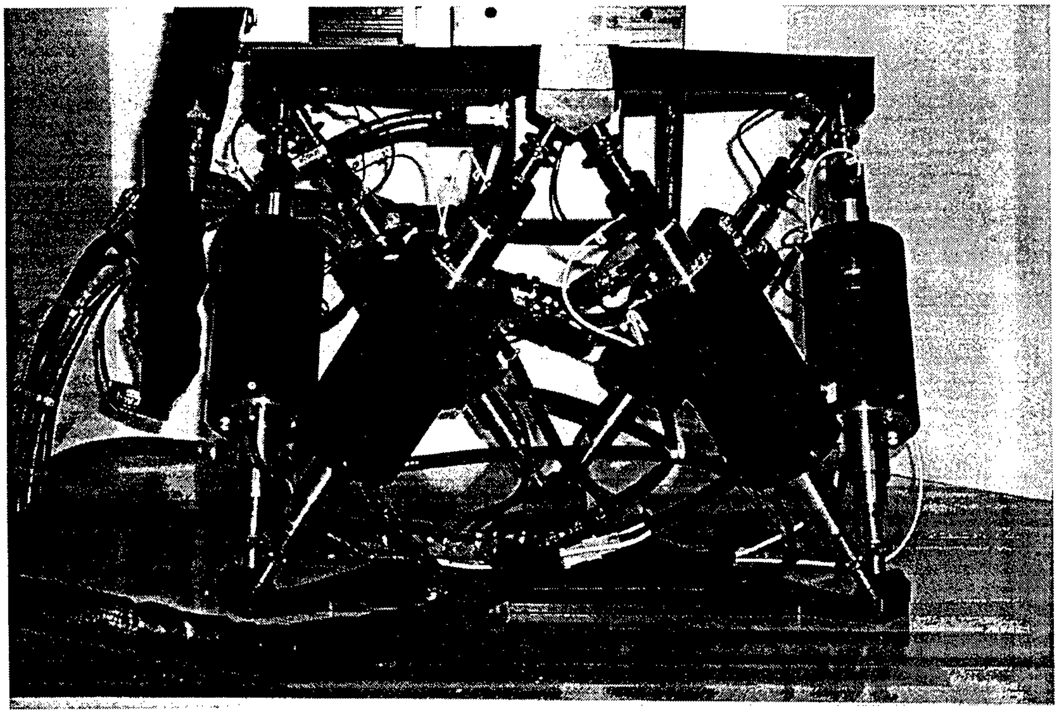

Figure 5: This is a close-up view of the 6 linear actuators used for active isolation.

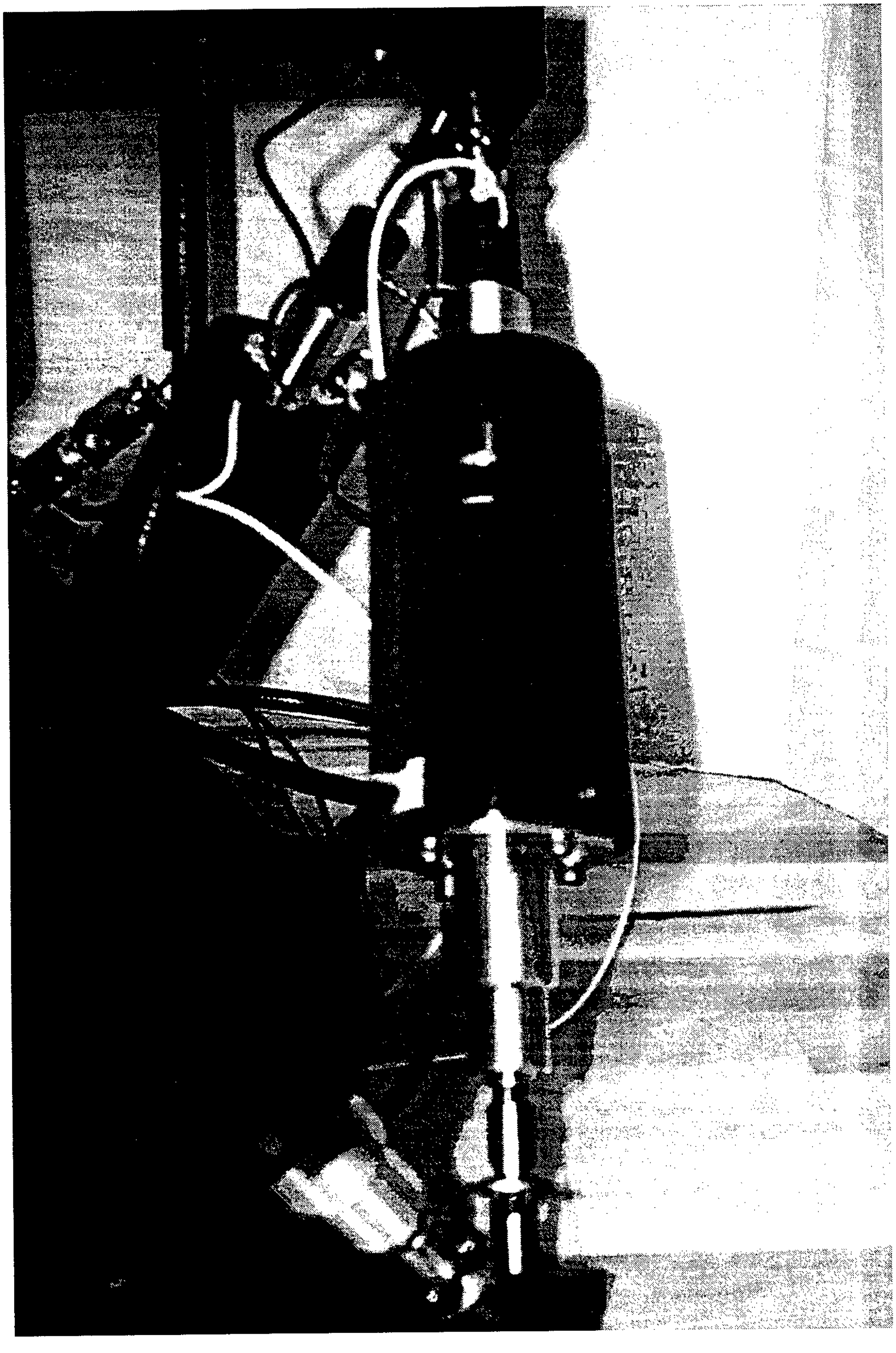

Figure 6: This is a close-up view of a single linear actuator. Each linear actuator has 1 inch stroke, and is instrumented with a capacitive displacement sensor and piezo accelerometer. This combination of sensors allows us to implement a variety of control algorithms.

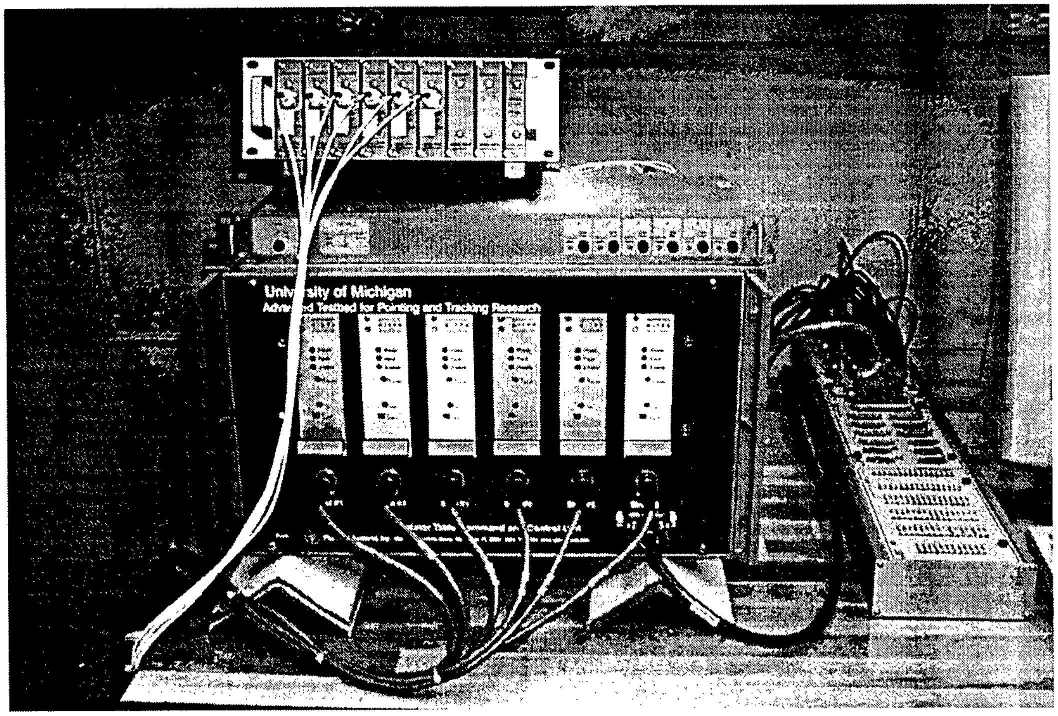

Figure 7: These boxes house the amplifiers and signal conditioning electronics for the capacitive sensors, accelerometers, and linear actuators. The panel on the right allows connection to the dSPACE system used to control the active isolator.

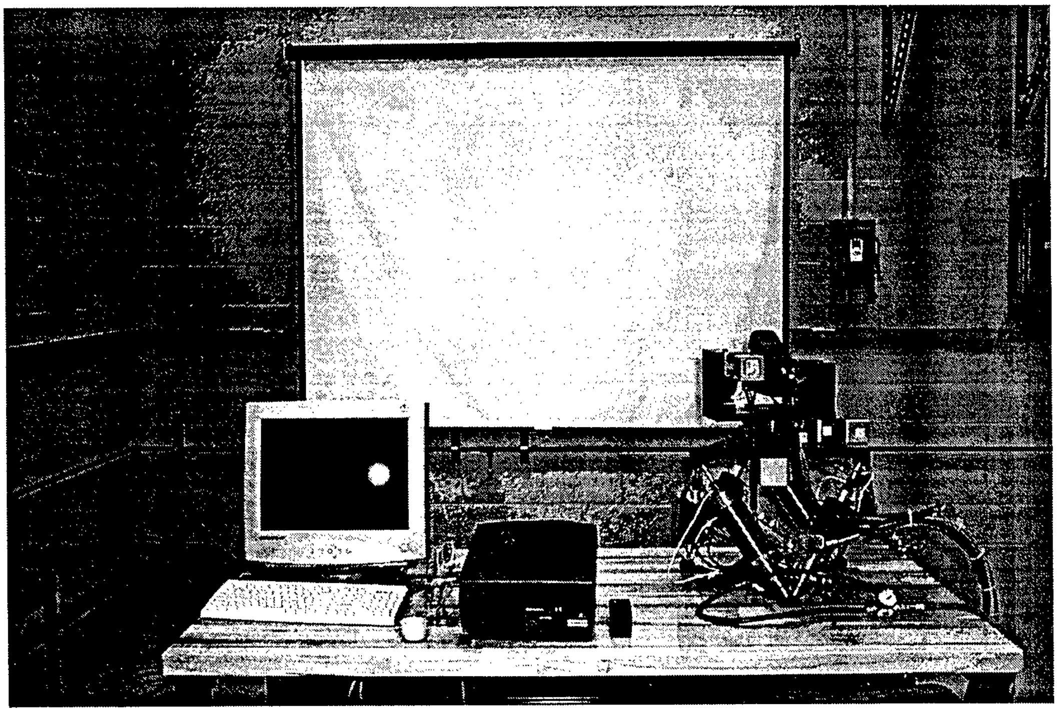

Figure 8: In the center of the table is the projector used to project target images on the screen for tracking experiments. The active isolator will be mounted on the shaker table for final integration.

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