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Under this project we acquired equipment for research on spacecraft attitude dynamics. A single-degree-of-freedom air spindle and a triaxial air bearing were developed. In addition, we acquired embedded processors for real-time control implementation and inertial sensors for attitude control. For control actuation we developed reaction wheel actuators as well as linear proof mass actuators. This equipment is being used in ongoing research on spacecraft dynamics and control.

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A High-Precision Triaxial Air Bearing for Research in Spacecraft Dynamics and Control

Final Report for DURIP Grant F49620-99-1-0152

prepared for

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1 Introduction

Under this DURIP grant we acquired a unique facility that will allow us to conduct experimental research in support of space-related DOD objectives. This equipment reflects the increased emphasis within DOD and especially the US Air Force of the importance of space-based assets.

We are interested in rapid, accurate spacecraft maneuvers for surveillance and targeting. We therefore acquired a high precision triaxial air bearing manufactured by Space Electronics, Inc. for laboratory-based studies of spacecraft dynamics and control. This facility has custom features that will allow us to perform research of value to DOD programs.

A triaxial air bearing is a precision sphere levitated on a thin film of air so as to allow frictionless three-degree-of-freedom rotational motion. Air bearings manufactured by Space Electronics, Inc. are used in Government facilities and by DOD contractors to evaluate the dynamic performance of missiles, spacecraft, and reentry vehicles.

To design this facility, the Principal Investigator visited Space Electronics, Inc. to discuss specifications for the custom design of a triaxial air bearing suitable for the intended research. This spherical air bearing is one of 3 we know of being used for spacecraft dynamics and control experiments. The others are located at the Air Force Institute of Technology and Sandia Laboratories. Spacecraft testbeds based on hemispherical air bearings (with restricted roll and pitch) are located at Naval Research Laboratories and Georgia Tech.

We plan to use our triaxial air bearing for a wide range of research and educational projects. In particular, one of our primary near-term objectives is to develop and demonstrate shape change actuation technology for spacecraft attitude control. This technology, which does not require either thrusters or wheels, is well suited for precision attitude control. While the conceptual foundation of shape change actuation has been developed through AFOSR-supported research, the proposed experimental activities will be instrumental for transitioning this technology to DOD programs.

To develop spacecraft control technology, we have also acquired attitude control system hardware, including a magnetometer, gyros, accelerometers, proofmass actuators, and an embedded processor. This instrumentation gives us the ability to implement and demonstrate shape change actuation technology as well as other techniques for spacecraft attitude control.

One of our long-term research objectives is to experimentally implement, and thereby demonstrate, the technological benefits of shape change actuation. There are several reasons for seeking to demonstrate this technology. First, the theoretical foundation of shape change actuation is well established and the ideas are sufficiently mature to embark upon laboratory investigation. Next, the effects of interest are highly nonlinear and are difficult to capture precisely and convincingly through computer-based simulation. Finally, we believe that transition of this idea to operational spacecraft programs will not occur until the relevant effects have been validated in a laboratory setting.

2 Background

The dynamics and control of spacecraft have been widely studied because of their technological importance [1,2,3]. In the classical case the spacecraft is assumed to consist of a single rigid body with 3-axis torque inputs and with attitude and rate sensing. In practice, however, the situation may be far more complex. For example, any component of the spacecraft that deforms relative to other components will entail a change in the spacecraft mass distribution; in effect, the spacecraft becomes a multibody system. Similarly, structural flexibility and fuel slosh give rise to vibrational degrees of freedom.

Spacecraft control is also exacerbated by sensor and actuator nonlinearities. The use of traditional actuation devices such as thrusters, reaction wheels, momentum wheels, and control moment gyros entails amplitude and rate saturation constraints, gyroscopic coupling, and coupling between translational and attitude degrees of freedom. Additional difficulties arise when accounting for gravitational effects as well as external disturbances. All of these issues have technological implications.

A fundamental difficulty associated with spacecraft technology is the fact that ground-based testing must occur in a 1-g environment whereas the hardware will operate under zero-g conditions. Consequently, spacecraft control engineering must depend on first-principles analysis as well as extrapolation from 1-g testing.

In this report we describe the laboratory testbed that we developed to explore various issues and concepts in spacecraft dynamics and control. This testbed, described in Section 3, is based on a triaxial air bearing to allow experiments involving large-angle, 3-axis motion. As a precursor to this testbed, we have also developed a single-axis air spindle testbed which allows single-axis rotation. This testbed is described in Section 2.

In Section 4, we describe the sensing, actuation, and processor hardware being developed for these testbeds. Next, in Section 5, we review the various experiments that are planned for the air spindle and triaxial air bearing. These include: identification of mass properties, stabilization and control with underactuation, attitude control using shape change actuation, control without exciting unactuated degrees of freedom, and attitude control with gravity gradient effects.

3 Air Spindle Testbed

The air spindle testbed shown in Figure 1 involves unrestricted single degree of freedom rotational motion and provides a convenient precursor to the more challenging triaxial air bearing. The air spindle testbed is based on the Model 4R Block-Head air bearing spindle manufactured by Professional Instruments, Inc., Hopkins, MN. This air spindle is extremely stiff to lateral forces and to pitch and roll moments. A 15" $\times$ 15", 3/8" thick stainless steel platform is mounted on the rotor. The platform has 1/4-20 size tapped holes in a 1" grid for mounting components. Components can

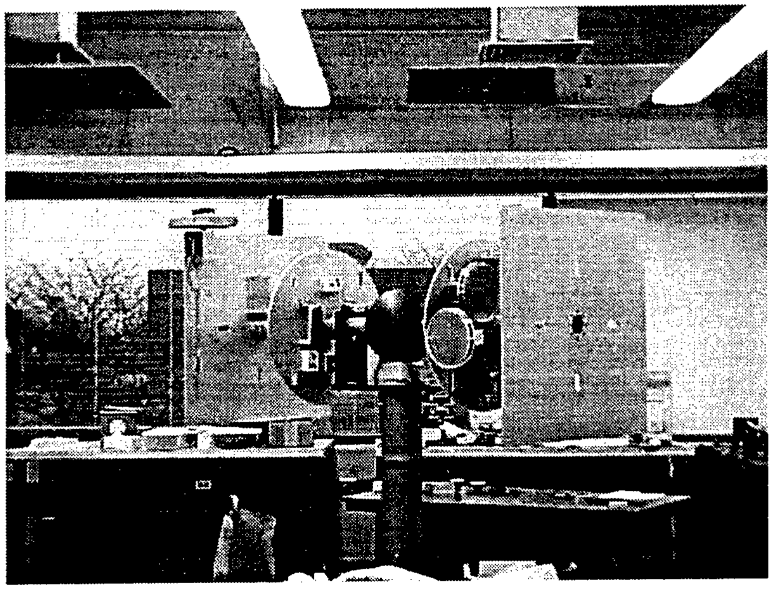

Figure 1: This control testbed is based on an air bearing spindle to allow low friction, unrestricted single degree of freedom rotation. This photo shows a reaction wheel actuator for torque input. Alternative actuators include fan thrusters as well as linear proof mass actuators for shape change actuation.

be mounted either above or below the platform.

To determine the attitude of the platform, a Heidenhain encoder model 1384 is used. In order to provide angle measurements in the rotating frame, the encoder disk is mounted to the air spindle stator, while the scanning unit is mounted to the rotor. These components are noncontacting. The signal wire from the scanning unit passes through the air spindle and through the center of the platform. The sinusoidal encoder signal is processed by a multiplier circuit to provide a resolution of 200,000 points per revolution, for an effective resolution of 6.5 arc seconds.

The air spindle friction is low relative to the inertia of the rotor and platform. Without additional components mounted, the $1/e$ damping time constant is on the order of 1 hr. To maintain this low friction and to allow unrestricted rotation, all hardware, including the encoder described above, has been designed for noncontacting, untethered operation.

The air spindle is sensitive to leveling. In particular, if the air spindle is not level and if the center of mass of all mounted components does not coincide with the rotational center, then pendulum motion can be observed. This motion can be reduced to a negligible level by leveling the platform using adjustment screws and by configuring the components so as to locate the center of mass at the rotational center.

Neglecting friction and the effects of imperfect leveling, the air spindle testbed has the dynamics of a rotational double integrator. Control algorithms for the double integrator with force or torque input have been extensively developed. In [4] these algorithms were compared under off-nominal conditions. In prior work, a Simulink toolbox was developed for experimental implementation.

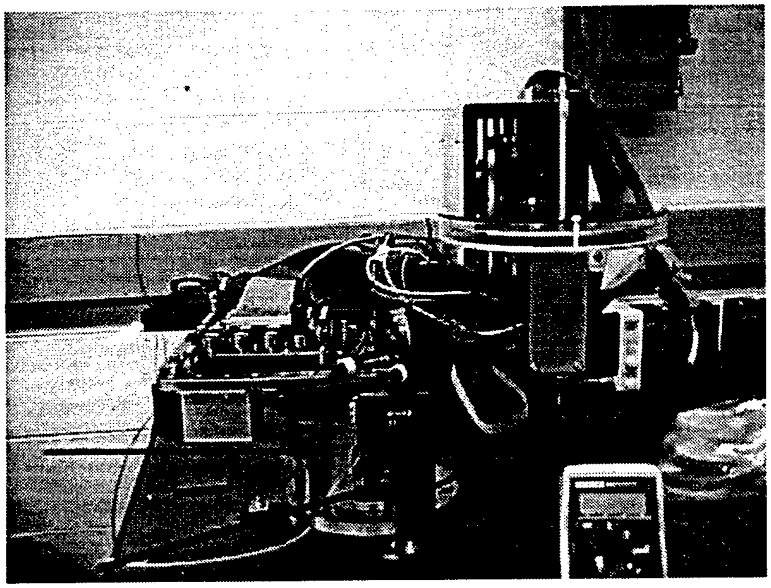

Figure 2: Triaxial Air Bearing Testbed. This testbed, which is based on a spherical air bearing, allows low friction, three-dimensional motion with unrestricted roll and yaw and ±45° pitch.

Control of the air spindle is effected by means of an embedded processor, which is described below.

4 Triaxial Air Bearing Testbed

The triaxial air bearing testbed shown in Figure 2 is based on a spherical air bearing manufactured by Space Electronics, Inc., Berlin, CT. The aluminum sphere of diameter 11 inch has an aluminum oxide coating of .005 inch. The sphere floats on a thin film of air that exits holes located in the surface of the cup. Air at 70 psi is supplied to the cup by means of a hose that passes through the center of the vertical support.

A one-piece 32 inch stainless steel shaft passes through the center of the sphere and extends between a pair of 24-inch circular mounting plates. This shaft is designed to withstand stresses that might otherwise distort the sphere. All mounting plates are made from 1/4-inch aluminum alloy with 1/4-20 holes tapped in a 1 inch grid. The 14-inch aluminum extension shafts connect the circular mounting plates to the 30-inch × 30-inch square mounting plates. The distance between the square plates is thus 5 feet. All shafts have hollow interior to allow wiring through the sphere and between any two points. Access holes of size 1 inch × 2 inch are cut into the plates and shafts to allow cable jacks and plugs to be passed between connection points. The total weight of the levitated components described thus far is 180 lb. At this air pressure, the air bearing can support an additional 180 lb of components.

The spherical air bearing allows unrestricted motion in yaw (motion about the vertical axis) and roll (motion about the longitudinal shaft axis). The plates and shafts are designed to allow $\pm 45°$ pitch (motion about a horizontal axis) at all roll and yaw angles.

5 Control Hardware

Since the triaxial air bearing can rotate about three axes, it is not possible to use encoders as with the air spindle testbed to determine attitude. One approach is to determine attitude by observing the air bearing from an external frame and then transmitting the data to the on-board processor. Although this approach is feasible using a camera system, it is expensive and cumbersome. Instead we chose to take an inertial guidance approach. Since the testbed does not undergo translation, the inertial guidance problem is not as difficult as full six degree of freedom inertial guidance. Nevertheless a full complement of sensors with appropriate algorithms is required.

The attitude estimation algorithm we developed will be described in detail elsewhere; here we provide only a summary. Using a 3-axis magnetometer, we are able to determine the direction of magnetic north; however, rotation about that direction is unknown and can only be ascertained by determining the direction of the gravity vector. To do that, we require triaxial accelerometers, which, under non-rotating conditions, can determine the direction of the gravity vector. Under rotating conditions, however, the centripetal acceleration is sensed by the accelerometers and is indistinguishable from the effect of gravity. To overcome this problem, centripetal acceleration can be determined indirectly by using knowledge of the angular velocities and angular accelerations. We thus use a triaxial gyro in conjunction with three additional accelerometers. Combining these measurements yields full attitude information. In summary, our attitude estimation algorithm uses twelve sensors, namely, a triaxial magnetometer, a triaxial accelerometer, a triaxial gyro, and three one-axis accelerometers. The full complement of sensors was partially complete at the time of this report.

For real-time on-board processing, we use embedded processors developed by Quanser Consulting. These processors are based on 486 and 586 processors with 4 GByte solid state hard disk and Multi-Q I/O boards allowing up to 24 A/D channels, 24 D/A channels, and 16 encoder channels. The A/D and D/A channels have a resolution of 13 bits over a ± 5 volt range. The A/D sampling occurs sequentially with an acquisition time of 20 μsec per channel, while the D/A latency is 5 μsec per channel. The operating system is based on the Quanser Consulting WinCon real-time controller which is compatible with the MathWorks Real-Time Workshop for implementing controllers programmed in Simulink. Communication with the host PC for experiment monitoring, parameter modification, and data acquisition is accomplished through a wireless ethernet connection.

For control actuation we developed reaction wheels and proof mass actuators. Each reaction wheel actuator is based on a 100 watt brushless DC motor manufactured by Maxon (model 118896). This motor allows 2.8 A max continuous current at 5000 rpm, 729 mN-m stall torque, and 38.2 mN-m/A torque constant. To calibrate the reaction wheels we use a reaction torque cell and amplifier manufactured by Interface, Inc., Scottsdale, AZ. This torque cell will be used on the air spindle

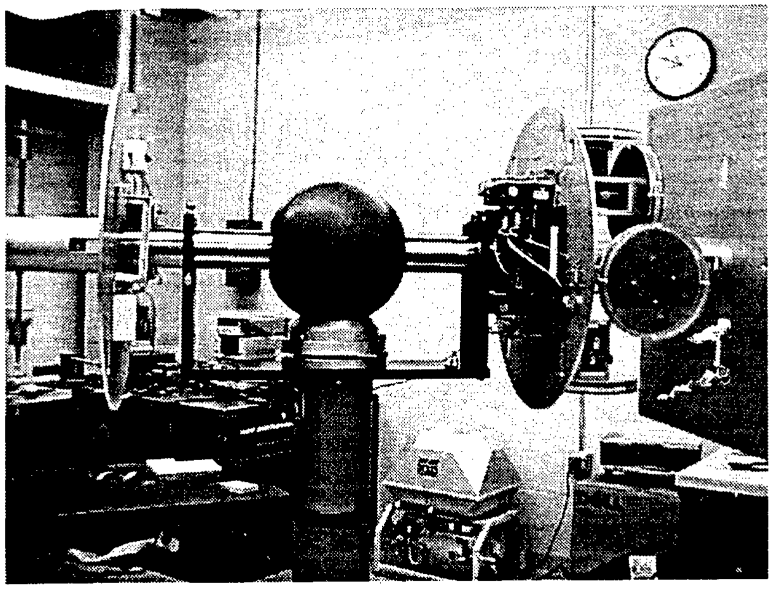

Figure 3: Six reaction wheel actuators can be used to control the triaxial air bearing, with two reaction wheels devoted to each rotational axis. Power is supplied by 12-V lead acid batteries connected to PWM amplifiers.

testbed to close a torque loop.

Mounted on the shaft of each motor is a 1/8-inch thick steel disk of radius 7 inch. Maximum measured spin rate is 8500 rpm. Each motor is driven by a brushless servoconductance (current-regulated) PWM amplifier manufactured by Copley (Model 5121V). This trapezoidally commutated amplifier is capable of 10 A continuous and 20 A peak. Electric power for a pair of motors and a pair of amplifiers is provided at 24 V by a pair of 12-V lead acid batteries each rated at 1.3 A-hr. A total of six reaction wheels and six amplifiers have been mounted on the triaxial air bearing (see Figure 3).

While each motor is equipped with a 500-line encoder giving a resolution of $360/2000^{\circ}$, the wheel angle is used only for modeling and diagnostic purposes. For control purposes, we use the frequency converter feature of the Model 5121 amplifier to obtain a synthesized tachometer signal from each motor's Hall sensor. This allows us to monitor each motor's spin rate and stored angular momentum.

For shape change actuation we use a pair of linear inertial actuators custom designed by Planning Systems, Inc. of Melbourne, FL. Each actuator has a 1.73-lb moving magnet/linear bearing assembly as its proof mass with a 4.5 inch end-to-end travel. A U-channel linear motor made by Aerotech,Pittsburgh, PA, model BLMUC-79, is the drive component of the actuator. An integrated Renishaw linear encoder measures proof mass position with a resolution of 1 micron. Each actuator is driven by a Glentek model SMA 8705 sinusoidally commutated servo-amplifier powered by 24-V batteries. With these components each actuator is capable of 5 lb continuous and 15 lb peak force. Figure 4 shows these actuators are shown mounted on the air spindle testbed.

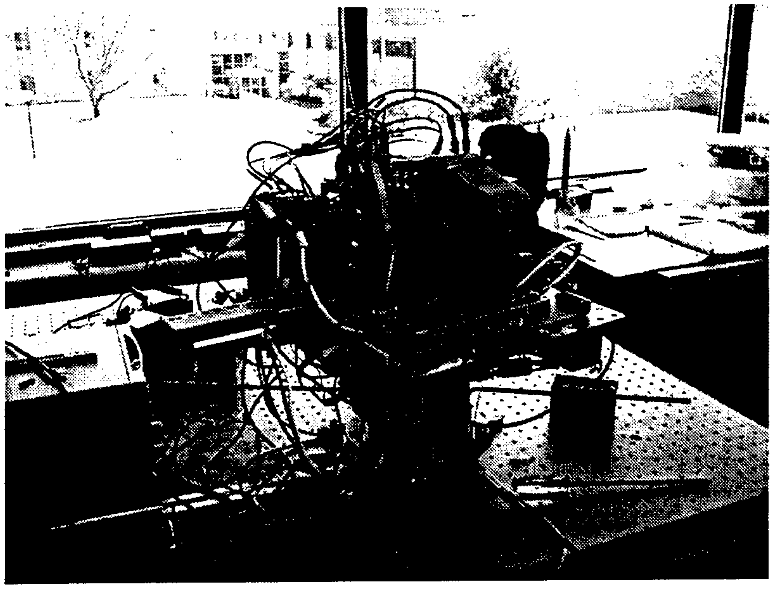

Figure 4: Linear motors for the 1D spacecraft experiment. These linear motors are mounted on the air spindle testbed for attitude control using shape change actuation.

6 Experimental Objectives

Identification

Our first objective is to determine the inertia tensor of the testbed once the control hardware is mounted. A starting point for this objective is the identification technique developed in [3]. Since the approach of [5] is based on torque inputs without stored momentum (for example, thrusters), extension to reaction wheel actuation is required.

Stabilization and Control with Rotors

Three-axis attitude control with torque actuation and without inertia modeling was considered in [5], while classical 3-axis stabilization results were unified in [6]. Stabilization and attitude control with two actuators was considered in [7,8,9]. Finally, single-axis stabilization of rotation about the intermediate axis was considered in [10]. This method was extended to achieve asymptotic stabilization in [11]. Intermediate axis stabilization is a key experimental objective. We are also interested in stabilizing the rotational motion of the system with the center of mass located vertically above the pivot point. This is an interesting generalization of the free rigid body case to the system in the presence of gravity.

Attitude Control using Shape Change Actuation

An alternative approach to attitude control is to exploit the attitude drift that occurs as a result of shape change actuation, that is, dynamic changes in the spacecraft mass distribution. This approach is distinct from control by reaction wheels which do not change the mass distribution of the spacecraft. In practice, either linear, articulated, or asymmetric rotational devices can be used. For the air spindle and triaxial testbeds, we plan to use the linear proof mass actuators to dynamically change the mass distribution. The theoretical foundation for this approach is given in [12,13].

Attitude Control with Unactuated Degrees of Freedom

Another problem of practical importance is attitude control with unactuated degrees of freedom. This problem arises when a spacecraft possesses a payload that is indirectly affected by the attitude motion. A classic case of importance is fuel slosh. These effects can be emulated on both testbeds. Theoretical treatment of these problems is considered in [14,15].

Attitude Control with Gravity Gradient Effects

Gravity gradient effects have long been considered for their impact on spacecraft attitude stability. Our objective is to consider these effects in conjunction with shape change actuation to ultimately effect rotation in yaw, which is not directly affected by gravity.

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