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Development of Air Spindle and Triaxial Air Bearing Testbeds for Spacecraft Dynamics and Control Experiments

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1 Introduction

The dynamics and control of spacecraft have been widely studied because of their technological significance [1,2,3]. In the classical case the spacecraft is assumed to consist of a single rigid body with three-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. Traditional actuation devices such as thrusters, reaction wheels, momentum wheels, and control moment gyros entail amplitude and rate saturation constraints, gyroscopic coupling, and coupling between translational and attitude dynamics. Additional difficulties arise when accounting for gravitational effects and 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.

The purpose of this paper is to describe a laboratory-based testbed that will be used 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, three-axis motion. As a precursor to this testbed, we have also developed an 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 various experiments that are under way. 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 gravitational effects.

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2 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 inch × 15 inch, 3/8-inch thick stainless steel platform is mounted on the rotor. The platform has 1/4-20 size tapped holes in a 1 inch grid for mounting components. Components can be mounted either above or below the platform.

To determine the attitude of the platform, a Heidenhain encoder model 1384 is used. 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 encoder signal is processed by a multiplier circuit to provide 200,000 points per revolution, for an effective angular 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 occurs. 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.

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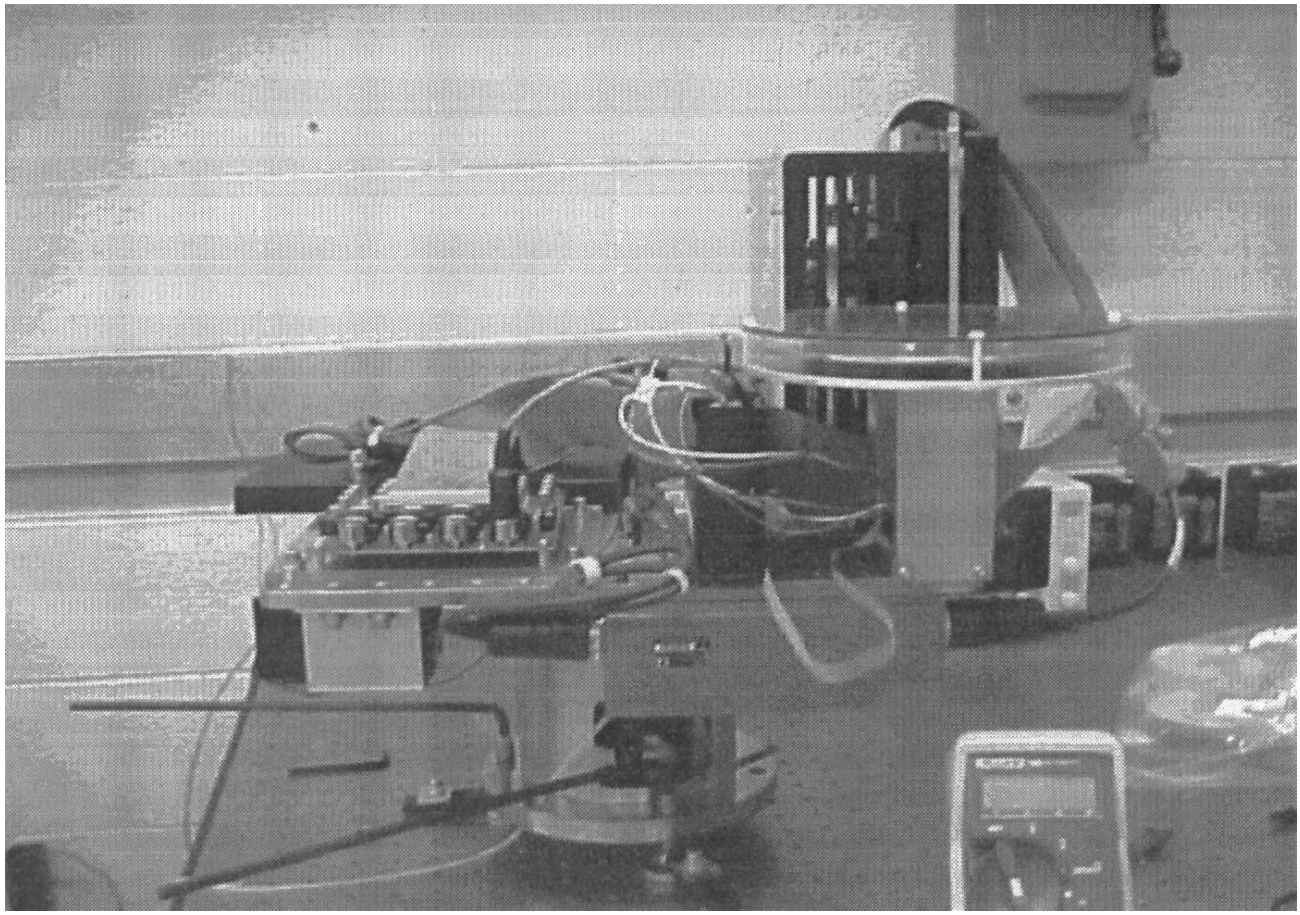


Figure 1: This control testbed is based on an air bearing spindle to allow low friction, unrestricted single degree of freedom rotation. This photo shows a reaction wheel actuator for torque input. Alternative actuators include fan thrusters as well as linear proof mass actuators for shape change actuation.

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. A Simulink toolbox has been developed for experimental implementation on the air spindle testbed. These experiments will be considered in a separate paper. Control of the air spindle is effected by means of an embedded processor, which is described below.

3 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 11-inch diameter aluminum sphere floats on a thin film of air which exits holes located in the surface of the cup. Compressed air 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 the 24-inch circular mounting plates. This shaft is designed to withstand stresses that might otherwise deform 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 $\times$ 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 $\times$ 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 70 psi supply 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.

This spherical air bearing is one of three 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.

4 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 onboard 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 six-degree-of-freedom inertial guidance. Nevertheless, a full complement of sensors with appropriate filtering algorithms is required.

The attitude estimation algorithm we have 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, twelve sensors are used, namely, a triaxial magnetometer, a triaxial accelerometer, a triaxial gyro, and three one-axis accelerometers.

For real-time on-board processing, we use an embedded processor developed by Quanser Consulting. This processor is based on a 486 processor with 4 GByte solid state hard disk and three Multi-Q I/O boards allowing 24 A/D channels, 24 D/A channels, and 24 encoder channels. The A/D and D/A channels have a resolution of 13 bits over a ± 5 V 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 have developed reaction wheels, fan thrusters, and proof mass actuators. Each reaction wheel actuator is based on the model 118896 100 Watt brushless DC motor manufactured by Maxon Precision Motors, Sachseln, Switzerland. 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. For the air spindle testbed we use a reaction torque cell and amplifier manufactured by Interface, Inc., Scottsdale, AZ, to close a torque loop.

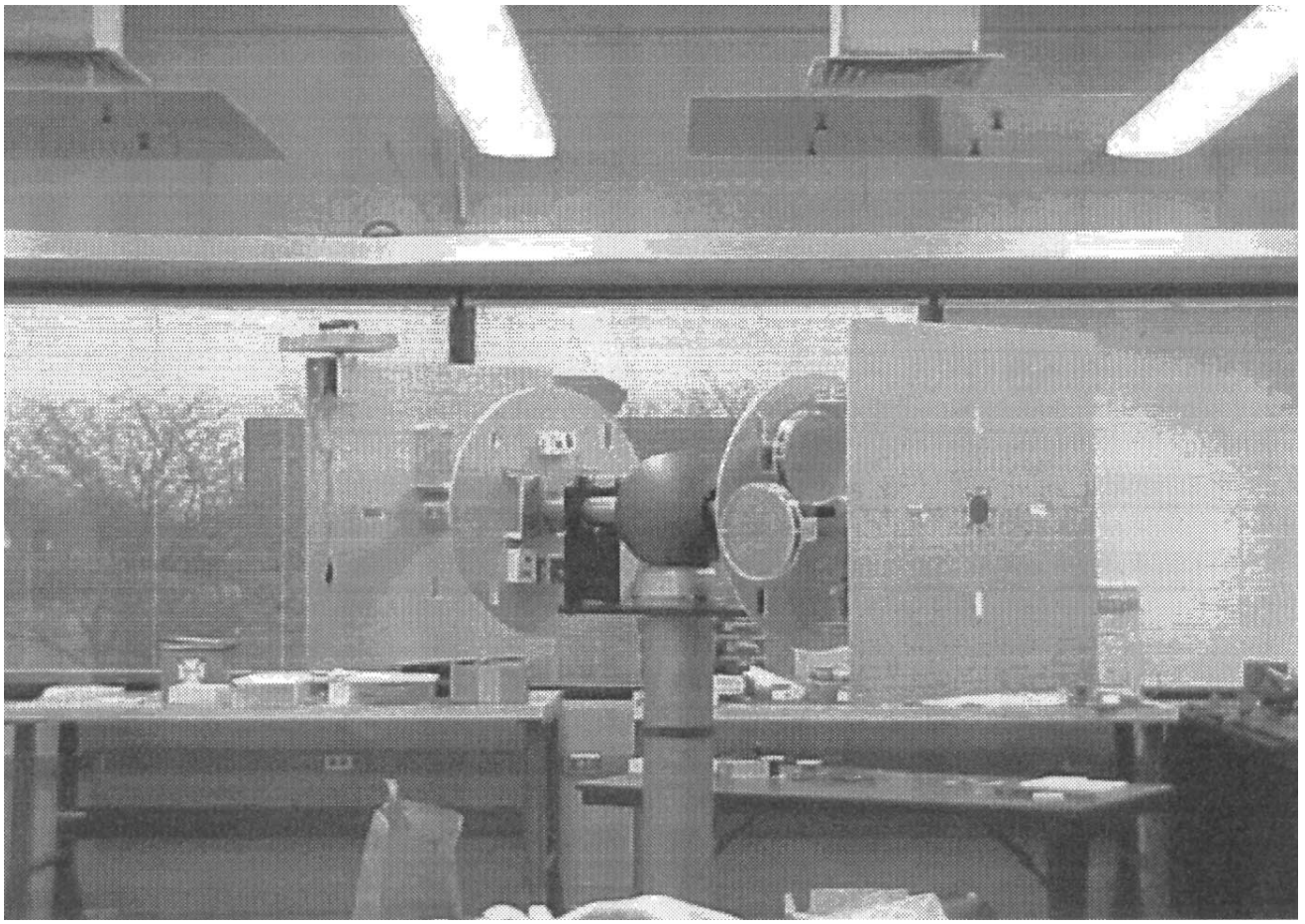


Figure 2: Triaxial Air Bearing Testbed. This testbed, which is based on a spherical air bearing, allows low friction, three-dimensional motion with unrestricted roll and yaw and $\pm 45°$ pitch.

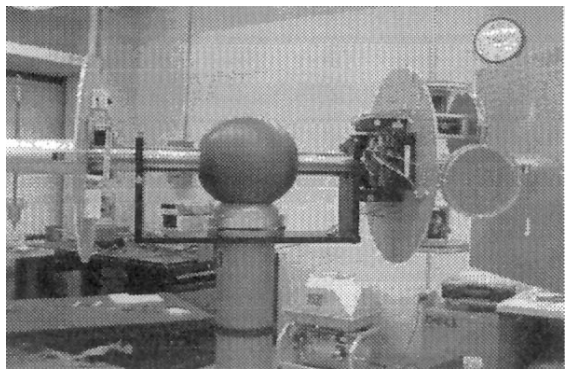


Figure 3: Six reaction wheel actuators can be used to control the triaxial air bearing, with two reaction wheels devoted to each rotational axis. Power is supplied by 12-V lead acid batteries connected to PWM amplifiers.

Mounted on the shaft of each motor is a 1/8-inch steel disk of radius 7 inch. Maximum measured spin rate is 8500 rpm. Each motor is driven by the model 5121 brushless servoconductance (current-regulated) PWM amplifier manufactured by Copley Controls Corp., Westwood, MA. 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 VDC by a pair of 12-V lead acid batteries each rated at 1.3 A-hr. 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 shaft angle measurement 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 the Hall sensor measurement. This allows us to monitor motor spin rate and stored angular momentum.

Additional torque actuation is provided by a pair of fan thrusters custom-designed by Quanser Consulting, Inc. These thrusters operate on ± 24 VDC, and are open-loop speed controlled. When mounted on the square plates, the effective torque of each fan is of the same magnitude as the torque of each reaction wheel.

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 model SMA 8705 sinusoidally commutated servo-amplifier manufactured by Glentek, Inc., El Segundo, CA, powered by 24 VDC. With these components each actuator is capable of 5 lb continuous and 15 lb peak force.

5 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 stabilizing controllers with 2-axis actuation were given 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 a generalization of the free rigid body to include gravitational effects.

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. In our experimental setup we can 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 problems are considered in [14,15].

Attitude Control with Gravity Gradient Effects

Gravity gradient effects can impact spacecraft attitude stability. We consider these effects in conjunction with shape change actuation to effect rotation in yaw, which is not directly affected by gravity.

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