

AC 2009-1844: A TEST BED FOR STUDENT RESEARCH AND DESIGN OF CONTROL-MOMENT GYROSCOPES FOR ROBOTIC APPLICATIONS

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A Testbed for Student Research and Design of Control-Moment Gyroscopes for Robotic Applications

The attitude dynamics of a spacecraft with an attached robot arm is a subtle problem in dynamics and control. In this work, we discuss a robotic testbed designed to engage students in addressing this example of a complex class of rigid body dynamics. A planar, multi-degree-of-freedom robotic arm is designed and constructed with sensors and wireless communication to measure and record power usage and maneuver kinematics. Each arm segment is actuated by either direct-drive motors or a scissored pair of control-moment gyroscopes (CMGs) in order to allow the power requirements and capabilities of each design in a planar system to be compared. A scissored pair of CMGs is more like a joint motor than a single CMG because the output torque is aligned with the joint axis. The simplified dynamics of a scissored pair are also more easily understood at an undergraduate level. The testbed uses an air bearing system on a sheet of glass to support the arm segments, significantly reducing the effects of gravity and friction. Prior student groups have built and flown CMG-actuated robots on the NASA microgravity research aircraft. However, one flight per year provides little opportunity for feedback and design improvement. With an in-house test setup, students can design a series of experiments and verify their work throughout the year. This testbed will provide students with a research tool for exploring the differences between CMG and direct drive actuators.

Introduction

Experiential learning is an important part of an engineering education. Some universities are able to build and launch operational satellites¹. The Microgravity University at NASA's JSC in Houston, Texas, allows students to perform experiments in a weightless environment without the launch risks of actual spaceflight. Recently, student teams at Cornell University tested a robotic arm using control moment gyroscope technology as part of the Microgravity University².

The successes of the International Space Station and the NASA Space Shuttle depend on the capabilities of their robotic arms. Mission operations can be driven by current robotic arm technology. Robotic arms are used for everything from relocating massive cargo to manipulating delicate and sophisticated pieces of equipment, such as space telescopes and communication satellites. Because robotic arms have such a vital role in space ventures, advances in robot technology are critical in enabling space programs to expand their realm of possible missions.

The use of control-moment gyros (CMGs) in space robotics is presently in the early proof-of-concept stage³. CMG technologies per se are not new and have been used for spacecraft attitude control⁴. As joint actuators, they offer significant benefits to robotic-arm technology for space applications in cost and energy. The principal advantage of CMGs in robotic arm

technology is that they are “reactionless” actuators, meaning that the system does not directly transfer the drive torque of the robot arm back onto the base (e.g. the spacecraft). For example, a payload on a robot arm is able to reorient a camera or an array of sensors quickly without causing undesired vibrations. If the arm motions do not contribute significantly to the overall system dynamics, then the spacecraft attitude control can be significantly reduced. However, CMGs do not eliminate the inertial forces of the robot associated with D’Alembert’s principle. CMGs regulate the momentum internally, preventing it from generating a disturbance on neighboring systems. The testbed provides students with a physical example of how motion of one robot link affects its neighbors in the space environment and how CMGs and joint motors affect the overall robot motion. In essence, each link of the robot has its own attitude control system, with all the parts acting together to provide the necessary control in pointing tasks.

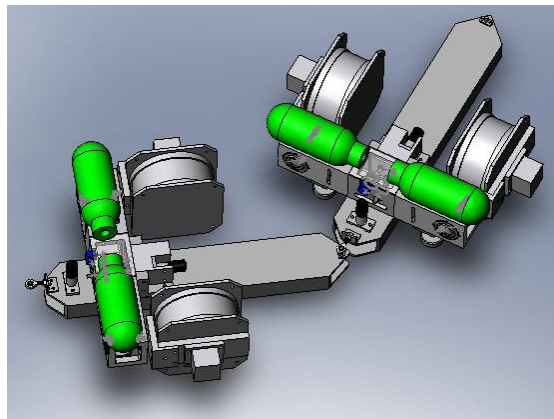


Figure 1. CMG-robot testbed CAD illustration

Recent theoretical studies on power for CMGs and conventional direct drives have shown a possible advantage for one drive or the other⁵. The student-built testbed is designed to determine if and to what extent this new actuation system improves capabilities of space robots. A primary goal of this research is to support students and researchers exploring space technologies or related fields with a feasible and sophisticated research tool.

The predecessor to this testbed was a series of CMG robots built by student teams at Cornell for use as a prosthetic arm^{7, 8} and later as a demonstration on board the NASA Microgravity Research Aircraft^{2, 9}. Our testbed improves on this heritage by allowing students and researchers to gain physical results without having to invest in performing tests in space or on microgravity flights. In addition to costs, the opportunity to run tests in space or onboard a microgravity flight is limited to once per year or less, keeping interested students from further developing the technology.

The CMG-robot testbed (Figure 1) provides several opportunities to students. First, it provides access to cutting-edge research, encouraging students to think big⁶. Second, because the project is not “canned,” students must develop careful experimental plans. Third, students can be introduced to the complex dynamics of a gyroscopic system (the CMGs) without the added burden of full three dimensional attitude dynamics. Fourth, students, especially in the development stage of the testbed, see all the benefits of careful physical system integration. This testbed has not been used in any courses or laboratories, other than recent work at Cornell

facilities. Hence no survey data on the impact of such testbed on student learning and educational values has been collected. However, this information would be useful in evaluating the efficacy of such testbed. One of the authors is a student in the Cornell University Leadership Alliance Summer Research Early Identification Program and has conducted this research with the other authors and student groups at Cornell. This project has been a successful fusion of research with Undergraduate-, Masters-, and PhD-level students.

Operating Principles, Theory, and Motivation

Actuator Design

An actuator is an object which induces motion onto another connected object. A drive design is the specific design of the actuator. CMGs and joint motors are both actuators. Because of their space-flight histories, they are the focus of this project.

Direct drives are the conventional actuators for robotic arm joints in space due to their extensive use on Earth-bound robots. Joint motors are simple in concept and design, so controlling and operating a single joint motor is straightforward and reliable. Students engaged in research on our testbed learn the fundamentals of traditional robotics while also exploring aerospace technologies.

CMGs have been used for attitude control on spacecrafts for decades now. CMGs have a strong tradition in spacecraft actuation, especially in large spacecraft such as Skylab and the International Space Station. A CMG is a form of momentum control that uses the embedded momentum of a spinning rotor to produce an internal torque onto the body it is attached to. CMGs are often compared to another reactionless actuator, the reaction wheel assembly (RWA). CMGs differ from RWAs in that they consist of constant-speed disks whereas RWA's consist of varying-speed disks. While operating a CMG, kinetic energy is never added to the rotor, $\Delta E_r = 0$. However, the rotor energy change for a RWA is $\Delta E_r = \frac{1}{2} I_r (\omega_2^2 - \omega_1^2)$. Because the change in kinetic energy of a CMG rotor is zero, the cost in energy can be a hundred times less than for a RWA in an identical system³. CMGs are chose over RWAs for this reason, even though students may prefer the simpler dynamics of RWAs.

CMG Operating Principles

CMGs are momentum control devices that produce high output torques. A CMG is a momentum actuator consisting of a constant-speed rotor and one or more motorized gimbals that change the direction of the rotor's angular-momentum vector, h . This change in angular momentum generates a gyroscopic torque, τ_c (Figure 2). Since the gimbal frame is rigid, the output torque is a constraint torque. Kinetic energy is never added to a CMG. The only energy added is the electrical energy necessary to overcome the friction in the rotor and to cause the rotor to be gimbaled. Thus, the overall CMG system requires minimal input energy and the

electrical energy required to overcome a given gimbal frame's inertia in space is relatively minute. This makes a CMG a highly desired drive for robotics. However, a single CMG only produces torque perpendicular to the rotor's spin axis, and the direction of τ_c changes as the gimbal rotates. A simple way to align τ_c with the joint axis of a robot is to use two CMGs in a scissored pair.

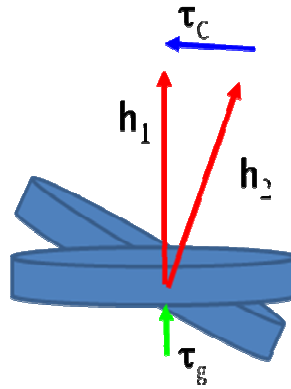


Figure 2. Illustration of torque produced by CMGs

Scissored-Pair CMGs

The direction of the output torque of the single CMG in Figure 2 is not constant because it depends on the gimbal angle and rate, ϕ and $\dot{\phi}$. A scissored pair consists of two identical CMGs with parallel gimbal axes and opposite gimbal angles¹⁰. Each CMG has a rotor angular-momentum vector equal in magnitude to the other, but not in direction, hence $h_{r1} \neq h_{r2}$. The scissored pair of CMGs shown in Figure 3 produces a net output torque along a designated, body-fixed, axis. For a planar-robot system, the desired torque will always lie along the joint axis. This axis will always be perpendicular to the operating plane of the testbed and is easily controlled by a scissored-pair CMG configuration.

The angular momentum vector of the rotor in a CMG will never change in magnitude due to the constant-speed of the disk. Because of the symmetric design, all torques in directions other than the designated joint axes are cancelled out in a scissored pair. This allows the magnitude of the output torque in the desired single direction to be controlled by the change in the gimbal angle, $\Delta\phi$.

The output torque of the scissored pair is limited by the speed and torque capabilities of the gimbal motor and the maximum gimbal angle. When $\phi = \pi/2$, no further torque can be produced on the robot. In an arbitrary array of CMGs on a satellite, the torque is also limited by internal singularities—alignments of the CMGs that result in a loss of control torque even though the system in another configuration could easily produce the correct torque^{11, 12}. The limitations of a scissored pair are similar to the saturation singularities of any actuator.

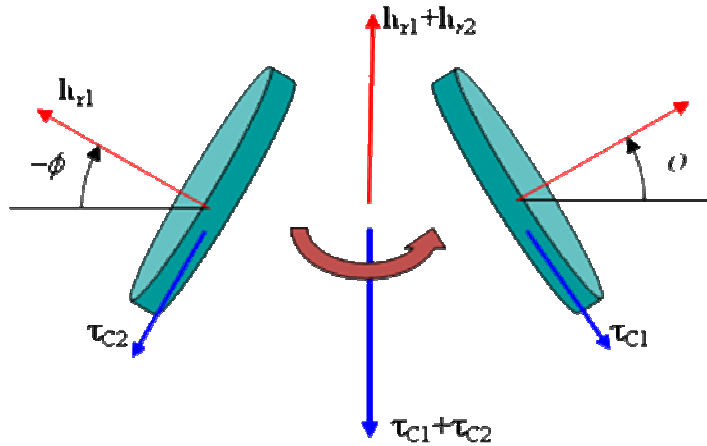


Figure 3. Scissored pair kinematics

A drawback of using a scissored pair of CMGs instead of a direct drive is that the CMGs will have more mass and more moving parts. In producing the same motion as a single joint motor, scissored pairs will be using two momentum control devices as compared to one direct drive. However, the spacecraft base must have some kind of attitude control, and one area of student-led research is to determine how CMGs on the robot benefit the overall system by reducing the mass of the spacecraft base.

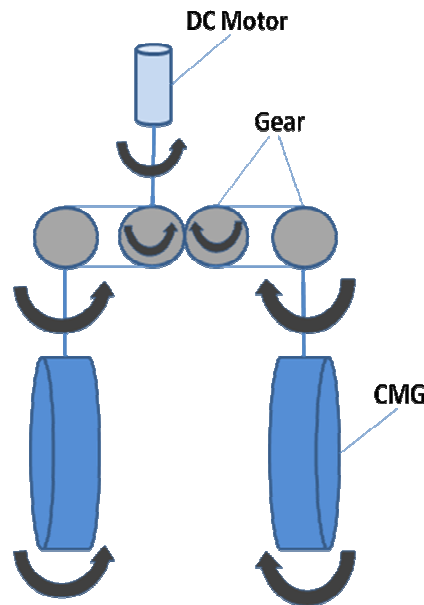


Figure 4. A Geared Scissored-Pair

The scissored pair used on this testbed was built by the Cornell CMG team. A schematic of the geared scissored-pair they had built is shown in Figure 4. Both of its rotors are in a vacuum chamber to eliminate air drag on the disks and substantially reduce the power required to drive the rotors. Both rotors are gimbaled with one motor through a chain system. Obvious drawbacks

to a geared scissored pair are the friction and backlash in the gears within the chain system. A geared pair is selected to reduce or possibly eliminate misalignment in the pair causing unequal gimbal angles. The students also are spared the task of synchronizing multiple motors. Fewer motors in the scissored pair also reduces the electrical energy requirement.

Power Requirements

Comparing the approximate power equations of output torques for both CMGs in a scissored pair and a single joint motor when actuating a planar, two-segment robotic arm, the terms in the equations do not match⁵. The approximate power used by CMGs to actuate a two-link, planar robot may be written in terms of the joint torques and velocities⁵:

$$P_{CMG} = |\tau_1 \dot{\theta}_1 - \tau_2 \dot{\theta}_1| + |\tau_2 \dot{\theta}_1 + \tau_2 \dot{\theta}_2|$$

The power for the same two-link, planar robot actuated by joint motors is:

$$P_{Joint} = |\tau_1 \dot{\theta}_1| + |\tau_2 \dot{\theta}_2|$$

The difference in these equations implies that the power requirement for a particular maneuver is not the same for both drives. Depending on the planned maneuver, a power advantage is possible for one drive or the other. The potential advantages in energy consumption of CMGs versus joint motors have not been formally demonstrated in a physical system.

A critical step in advancing robotic-arm technology is to determine if CMGs are a better suited drive design for robotic arms than are conventional actuators. For this reason a hardware test demonstrating whether theoretical conclusions about CMGs power advantages are correct is needed. These power equations provide real-world motivation to the students developing the robotic-arm testbed. If a robust tool that aids researchers in exploring the power usage between the two drives is developed, then reactionless robotics may make an introduction into space research.

Hardware Demonstration

The rest of this paper discusses the design of a two-segment, two-DOF planar-robotic system that is used to examine and compare the power requirements for the two compared drive designs. Each segment is dually actuated by either two CMGs in a scissored pair or by a 12 V DC motor at the segment joint. Onboard measuring sensors and wireless communication systems examine the differences in power and capabilities between the drives.

The architecture of this test will involve a two dimensional experiment in which a two segment robotic arm is designed to be driven by both conventional joint motors and CMGs in scissored-pair configuration. The range of motion of each segment will be $\pm 90^\circ$ from straight out, allowing many different movement routines to be performed. The arm will move on a horizontal glass platform with pressurized air feed air feet serving as air bearings to levitate the body allowing the two dimensional test to be performed without any effects of friction or gravity. Each segment is 0.61 m long, so a square sheet of glass (1.2 m x 1.2 m) is used as the workspace for the robot. A selection of the requirements used to design the testbed are included in Table 1.

Table 1. Testbed requirements

System-level requirement	Flowed-down requirements	Metrics
Unencumbered planar motion	Space for at least two robot links	Link length < 0.6 m
	Removable base	-90 to 90 deg joint range of motion
CMG and joint torque capabilities	Detachable joint motors	Two control outputs per link
	Control available to operate CMGs and joint motors together	
Measure power difference for a given maneuver	Record current and voltage at motors	Six analog inputs per link
	Use feedback control to perform identical maneuver	At least two links

The significant data from this test are the power inputs and the system responses. The current and voltage inputs for each electrical component on each segment provide the power input data. The robot's accuracy of response will be measured by recording the motion of the robot arm for a given movement. These two measurements, power and joint angles, will be the results used to determine which maneuvers CMGs are better suited for use in robotics in space applications.

Electronics

The testbed electronics fulfill two roles: Control and Measurement. Both systems include software and communication with the robot. Matlab is used as the software interface for both the controller and data acquisition. A Measurement Computing USB-1408fs DAQ board provides digital and analog input/output for interacting with the sensors and motors. The Matlab data acquisition toolbox allows communication directly with the DAQ board.

The motors are controlled by sending a signal to the analog output terminal and from there through a high-power op-amp (LT1210 and OPA544) to the motors (Figure 5). The amplifier provides the current needed and extends the analog output range (a 2.5V reference subtracted from a 0-5V signal) to match the motors' range (+/-12V). Both the gimbal and the arm joint use a Faulhaber 2232 DC motor with a series 20/1 gearhead at a ratio of 86:1. These motors can produce up to 8.7 W at the shaft and were selected to provide significant agility to the testbed. The rotors are powered by Faulhaber 1724 DC motors on a separate circuit. Rotor speed is set off-line before the experiments are run.

The testbed's sensor system is primarily responsible for measuring the power consumed by the different systems. The model of the system uses the cross product of torque and velocity to calculate power. For this system, electrical power is measured. The voltage and current are measured at the motor using $\text{Power} = \text{Current} * \text{Voltage}$. To check the performance of the system, a potentiometer is used to measure the joint angle. Another potentiometer measures the gimbal angle to facilitate traditional CMG control methods.

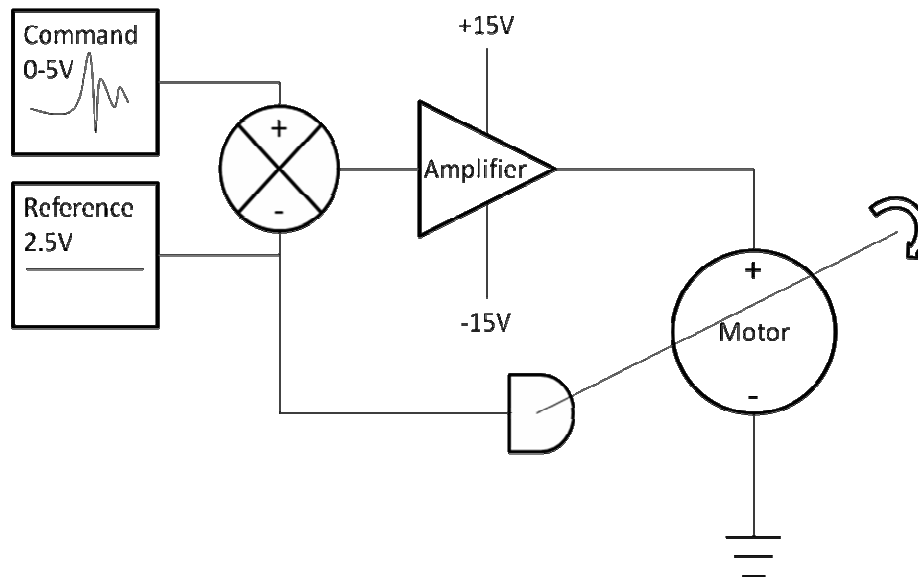


Figure 5. Motor driver

The DAQ board is mounted directly onto the arm segment. Communication with the off-board computer wirelessly uses a Belkin wireless USB hub. This high-bandwidth hub requires that we have a receiver close to the robot (<4m) and in line-of-sight. Lithium ion batteries provide the power to the systems, with the exception of initial rotor spin-up, which occurs before the experiment begins.

Air Supply

Each arm segment is levitated on the flat glass surface by a trio of 40 mm carbon-mesh air bearings attached to ball-end mounting screws. The air supply for the air bearing comes from two 25 liter-3000 psi rate-limit medical oxygen tanks with pressure regulated to provide a constant lift. At 60 psi each bearing can support a load of 50 lbs with flow rate of 0.74 normalized-liters-per-minute (NLPM). The air supply pressure can be adjusted to maintain an adequate fly height (5 microns) while minimizing the flow rate to maximize operation time. With each individual segment weighing approximately 55 lbs, this provides several hours of operation for the air bearings, sufficing a wide variety of testing. The schematic in Figure 6 shows the air regulator (Flow Select 100) and needle valve needed to reduce the gas pressure between the tanks and the air bearings. It is not recommended to allow more than 100 psi flow through the air bearings.

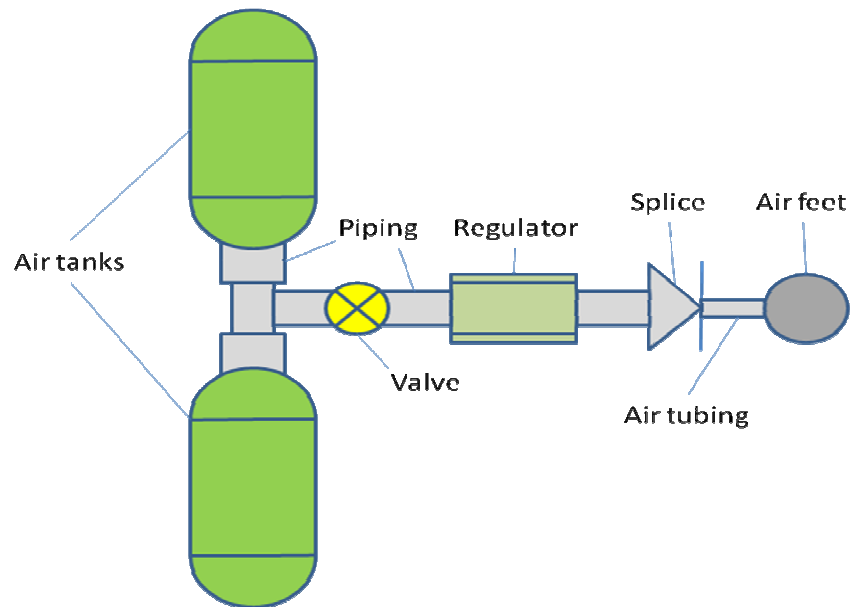


Figure 6. Air supply system

Structure

A 24" x 4" x 1.25" rectangular tube provides a stiff frame for each arm segment. All structural components comprise of 6061 Aluminum. The scissored-pair frame hardware used on the testbed is the same hardware the 2007 Cornell CMG Team built for a similar robotic assembly that was designed to fly aboard the NASA Microgravity Research Aircraft. Because the hardware is not designed for this specific robot, the scissored-pair framework was modified to maintain the range of motion for the testbed, 90° from straight out, and to connect the scissored-pair to the robot frame. Another mounting plate positions an air bearing directly under each CMG for maximum support.

Conclusion

The purpose of this testbed is to provide researchers a hardware tester to explore the potential advantages of CMGs and direct drives. This tool demonstrates the capabilities of a reactionless robotic arm. The testbed is simple, robust, and capable of demonstrating a wide range of 2 D maneuvers. As the first dual actuated robotic arm that compares a momentum drive to a direct drive in a frictionless range of motion, the testbed will provide future hardware comparison tool developers with a model to reference designs with. Further, the control laws of this two-segmented, planar-motion robotic arm will be used in future, more complex arms.

The results acquired from this testbed could possibly initiate an increase in research for reactionless robotics in space applications. A change in the standard drive design used for space-robotics can be invested into with the support of test data from this testbed.

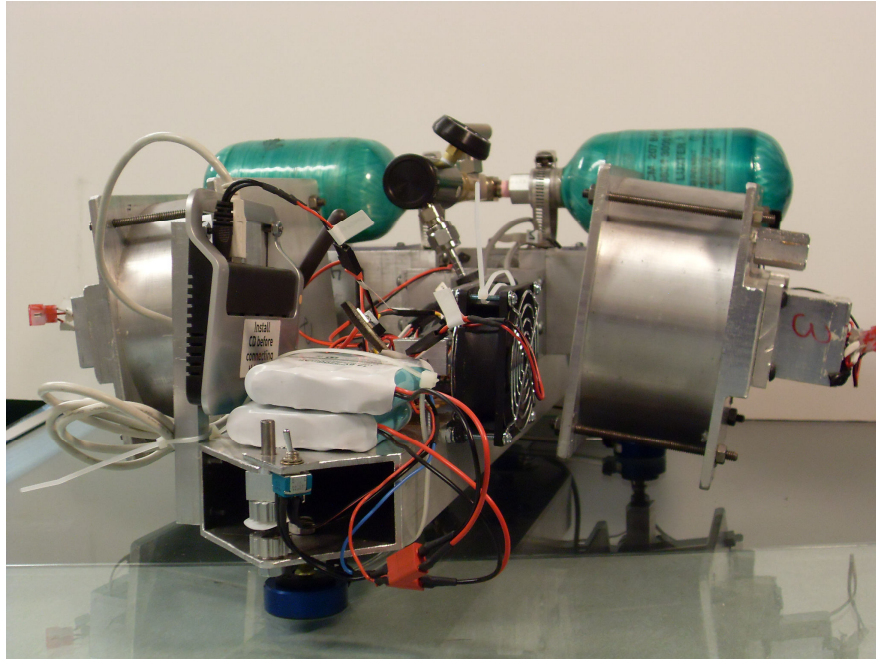


Figure 7. A fully assembled segment

Student Benefits and the Future of the Testbed

By incorporating this student project, undergraduate research programs will be able to provide exposure to advanced research concepts in robotics and space-systems to their students at a relatively feasible means. Having student exposure to advanced research topics and to high level research and engineering is crucial in producing high quality technical graduates for the professional scientific and engineering communities.

Spacecraft actuation subsystems are notoriously difficult to experiment with on the ground. The microgravity space environment is challenging to reproduce, typically requiring expensive tools and instruments to simulate. This testbed design offers a hands-on experimental setting which captures the essential physics of the final space application using simple off-the-shelf components. Such experiments can be incorporated in engineering courses and research laboratories.

This project allows undergraduate students to develop as young researchers and engineering designers. In future versions of the testbed, students have to do relevant research to understand the dynamics of CMGs and what the research community desires in a research tool of this type. Just as this first testbed utilizes a mix of hardware from the Cornell CMG teams of previous years and new hardware designed for our needs, future students will be able to redesign critical components to meet new objectives. Since students will build or modify the testbed using their own designs, they will have an opportunity to significantly improve on their design skills by machining or fabricating mechanical components themselves, and gain realistic feedback on the quality of their design work. Experience is a key fundamental of good design work.

Unfortunately, the aerospace community is likely to lose a wealth of such experience as a generation of engineers and scientists nears retirement.

This project connects several fields of engineering: mechanical and electrical design, space-systems engineering, and dynamics. The teamwork component of this project greatly enhances the benefits for students. The completion of this complex project will require the team to have exceptional communication skills across unfamiliar disciplines, a skill highly valued in industry and emphasized to students.

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