Low Cost Satellite Attitude Hardware Test Bed

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Abstract

Recent technological developments surrounding CubeSats and Commercial Off-The-Shelf space hardware have drastically reduced the cost of producing and flying a satellite mission. As the barriers to entry fall, space missions become a viable option for more students and research groups. Many of these missions require accurate spacecraft pointing and attitude control. Consequently, exposing students to the practical elements of spacecraft attitude sensing and control is more important than ever. To help address this challenge a novel low-cost test-bed for attitude control has been developed. This test-bed is suspended and relies on a neutrally stable universal joint to allow for 3 degrees of freedom attitude motion. This paper details the design and construction of the attitude test-bed and describes use as an educational platform.

1 Introduction

Technological progress in the world of CubeSats and Commercial Off-The-Shelf hardware are bringing the cost of staging a mission to space to unprecedented lows. This is making a satellite mission viable for more and more students and research programs.[1] Many of these missions require accurate spacecraft pointing and attitude control to achieve their objectives.[2,3] This presents a difficulty for most student groups and recent graduates because attitude estimation and control are complex subjects normally reserved for upper-level or even graduate-level students. Additionally, even when students are exposed to these subjects, it is in classroom settings that commonly lack the challenges and nuances of working with hardware. Exposing students to a hardware attitude test-bed will go a long way toward addressing this deficiency. Traditionally, attitude test-beds have been created using spherical air-bearings, which involve substantial cost and complexity.[4] To avoid these issues a novel attitude test-bed was developed by the Land, Air, and Space Robotics Lab (LASR) called the LASR Attitude Test-bed (LAT).

The LAT was initially developed to enable graduate and undergraduate research into attitude estimation and control algorithms. Equipped with reaction wheels similar to what could be found on a SmallSat class spacecraft, a MicroElectroMechanical Systems (MEMS) inertial measurement unit, and simulated attitude sensors, the attitude test-bed allows for realistic attitude control in the presence of noise. The system is integrated with MATLAB to make controlling it as simple as possible for students without extensive hardware programming experience. This system has been used to implement attitude estimation algorithms as part of a independent study and attitude control as part of a hands-on project to augment a graduate-level spacecraft control class that has relied solely on lecture and simulated work in the past. This paper details the design and construction of the attitude test-bed, describes its use as an educational platform, and presents initial student feedback.

2 Background

2.1 The LASR Lab

The Texas A&M Land, Air, and Space Laboratory (LASR) uses robotics to emulate the space environment for ground based hardware-in-the-loop testing. These include the Holonomic Omnidirectional Motion Emulation Robot (HOMER) and the Suspended Target Emulation Pendulum (STEP). HOMER is a robotic platform consisting of a 3 degree-of-freedom (DoF) base supporting a 6-DoF hexapod. It is designed for replicating motion based on the results of a dynamic simulation for a space vehicle.[5] The STEP is a 5-DoF simulation platform for contact dynamics. It consists of a 3.5 meter pendulum hanging from an active gantry that can suspend various targets and emulate the response of the target to impacts.[6] Together these systems allow for the simulation of space rendezvous and proximity operations in a ground based laboratory setting.

2.2 VICON System

VICON Motion Capture is a system of cameras and light-emitting diodes (LEDs) that was initially developed as a motion capture system for the entertainment industry. It use retro-reflective beacons mounted in a specific pattern to identify bodies and computes 6-DoF position and attitude with approximately 1 centimeter accuracy. The LASR lab has six VICON cameras mounted on the ceiling and thus creates a 3D workspace for robotic operations. This motion capture system can be used both to provide position information for robots control and to generate “truth” data on the performance of any system that has its own navigation mechanism.

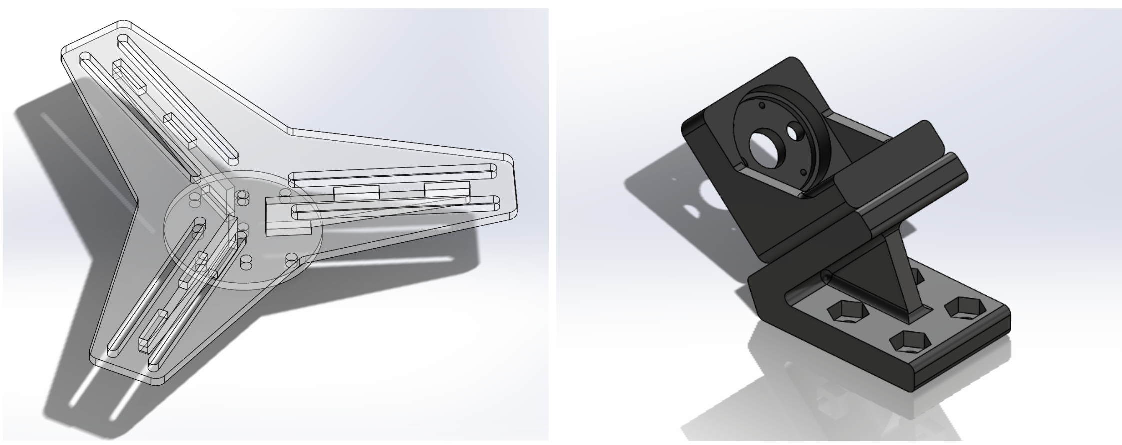
3 System Design

3.1 Physical Design

The objective of the LAT was to build a system that allowed for a large range of 3-DoF attitude maneuvers that avoided the complexity and cost of spherical air-bearing systems. To achieve this the air-bearing was replaced with a suspended universal joint. The universal joint can be constructed with substantially simpler and cheaper components than a spherical air bearing and it does not require a source of compressed air to supply lift.

Suspended from the universal joint mounted on the STEP is the LAT base, shown in detail in Figure 1(a). The base is made of laser cut acrylic and has two levels. The top level is for mounting the system's reaction wheels and the bottom is for mounting the system's electronic components. The top plate has three sets of two parallel slots arranged at 120° between them. These slots are intended to mount the LAT's reaction wheel mounts and allow for the wheels to be slid along them to balance the system.

The reaction wheel mounts, which can be seen in Figure 1(b), are designed to mount the reaction wheel motors at an angle of approximately 52.3 °. This arrangement results in the rotation axis of the 3 wheels being mutually perpendicular. The wheel rotation axis are intentionally not aligned with the body axis of the LAT, so that the weight of the system is evenly distributed. Each of these mounts holds a direct current (DC) motor mounted with a brass rotor. When powered the motors spin the rotors by applying torque, consequently, an equal and opposite torque is applied to the platform. When properly applied, these torques can be used to control the attitude of the LAT.



(a) Laser Cut Main Plates

(b) 3D Printed Wheel Mounts

Figure 1: LAT Parts Constructed using New Inexpensive Techniques.

3.2 Electrical Design

Mounted to the base of the attitude platform is a 3D printed housing for the LAT's battery and its control and sensing components. The battery is a common lithium polymer battery, frequently used for remote control vehicles. The main control board for the system is a Raspberry Pi B+ single board computer. This board interfaces with a custom motor controller board that provides power to the DC motors. The main board also connects to a set of MEMS sensors, including an accelerometer, magnetometer, and gyroscope. These sensors provide real-time data on acceleration, rotation rate, and magnetic field. Finally, telemetry is transmitted via Raspberry Pi and the lab wireless network to a control computer. This link is made directly available to MATLAB for data processing and command of the wheels. The electrical design utilized Commercial Off-The-Shelf components, when available, to reduce the total cost of the system, but it was required to design a custom motor controller board due to high starting current of the DC motors. The complete system is shown in Figure 2.

3.3 Software Design

The software for interfacing and controlling the LAT was written in MATLAB and designed to be extremely simple, to lower the barrier for students to interface with the system. When activated the software on the platform starts all the electronics and wait until a command is sent by the user using MATLAB on the control computer. The provided commands include:

1. Receiving data from the MEMS sensors
2. Receiving battery voltage and current at all motors
3. Sending velocity commands to the wheels
4. Sending body-axis torque commands to the platform.

These commands allow a user's program to collect the sensor readings and generate control commands for the wheels.

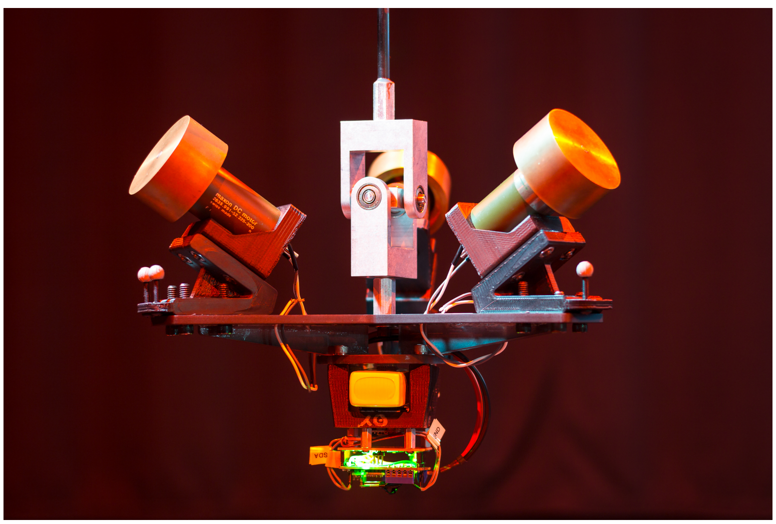


Figure 2: The LAT Suspended in View of VICON

4 Educational Application

There are two main topics where the LAT will serve as an educational platform:

Spacecraft Attitude Estimation The determination of a system's orientation in space based on inputs from sensors

Spacecraft Attitude Control Attempting to achieve some desired attitude and attitude rate, given the current state

4.1 Attitude Estimation

The objective of estimation algorithms is to generate usable information for a system based on the measurements available. Estimation is especially important in the presence of "real world" factors such as noise and latency that can cause simpler methods of converting sensor information to fail. This makes practical estimation difficult to teach in a classroom setting. Substantial time and effort is required to generate a simulation that accurately reproduces the dynamics of a system as well as the non-ideal factors that make estimation challenging. The LAT provides students with a practical estimation challenge and allows easy access to actual sensor data to evaluate their algorithms.[7]

4.2 Attitude Control

Attitude control can be a non-intuitive subject because of the non-linearities involved and, unlike most other control problems, the lack of interaction with the environment. One of the objectives of the LAT is to help student gain exposure to the practical application of attitude control. It is also designed to expose students to difficulties that are normally not addressed when attitude control is taught in class. There is limited and discrete control authority, command latency, and it is possible to saturate the wheels (driving them to their maximum speed imparts the maximum possible angular momentum). Additionally, because the wheel rotation axes are not aligned with the principal axes of the body, control is slightly more challenging.

Using the LAT will provide students with experience of how theoretical algorithms perform under real world constraints and help prepare them for facing similar issues once they enter the workplace.[8]

5 Results

The LAT hardware and software has been used for various educational purposes during the semesters of Fall 2015 and Spring 2016.

5.1 Attitude Estimation Independent Study

During Fall 2015, it has been implemented as an independent study on attitude estimation. A Multiplicative Kalman Filter (MKF) for attitude was developed and run on the LAT to generate real-time estimates of the platform's attitude. There were two modes for filter, one using highly accurate measurements simulating those from a star tracker, and a second with less accurate measurements simulating what would be used when a spacecraft has only a sun sensor and magnetometer. Results showing how well this filter tracked the system's attitude can be seen in

Figure 3 and different errors from these two filters can be seen in Figure 4. This effort resulted in the publication of a conference paper in the student paper competition of the AAS 39th Annual Guidance and Control Conference.

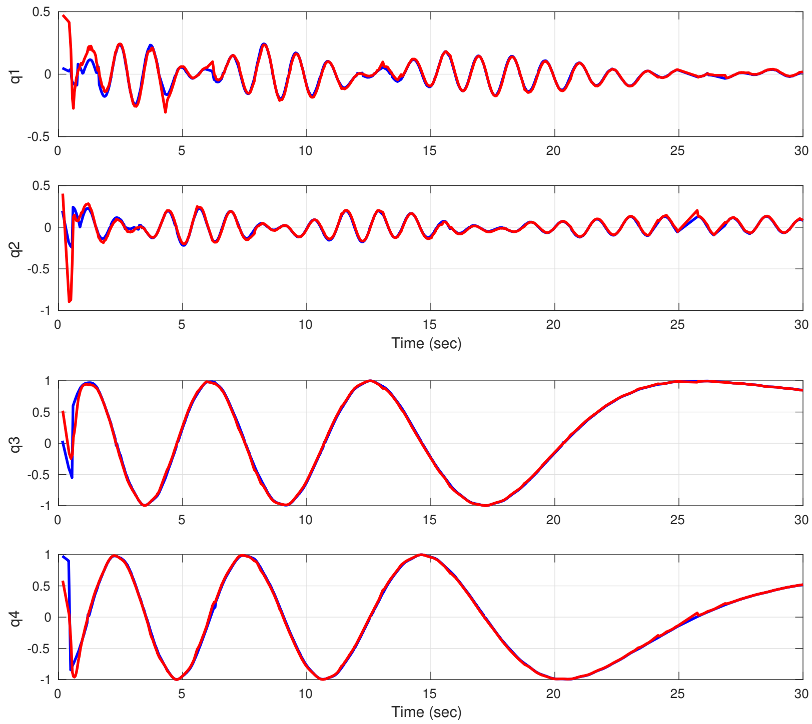
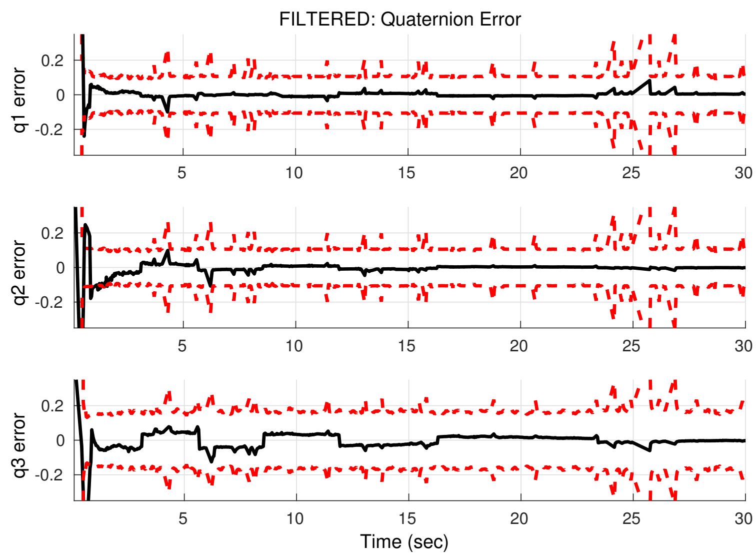
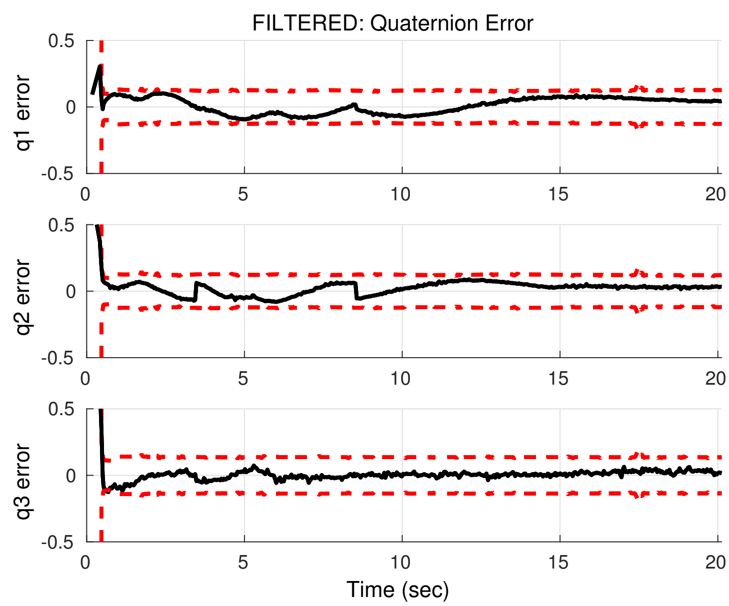


Figure 3: Filtered (Red) and VICON (Blue) Quaternions During a Tumble



(a) Filter results with the star tracker



(b) Filter results with the sun sensor and magnetometer

Figure 4: Results from the Two Filter Modes Developed on the LAT.

5.2 Attitude Control Final Project

On Spring 2016, for the spacecraft attitude control class, LAT was offered to the students as an optional final project. The main goal was to apply the principles the students had developed in simulation over the semester to the implementation of a controller in hardware. The students implemented a rate-free rotational motion tracking controller to follow a reference trajectory and angular velocities, without direct angular velocity measurements. The controller inputs were calculated based on the attitude coordinates (live quaternion measurements by VICON system), reference states from the desired trajectory, and filter states. The students had access to the laboratory facility and were provided with all required files to communicate with LAT and VICON. The results achieved by one of the students can be seen in Figures 5, 7, and 6.

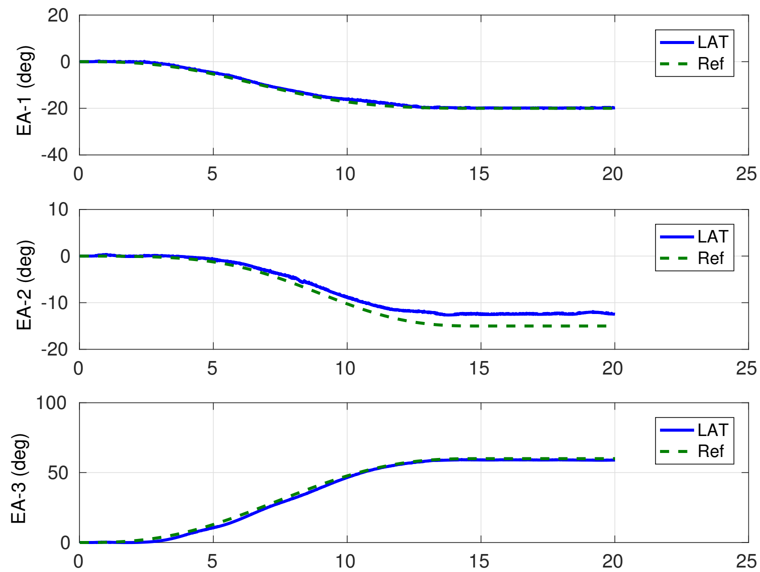


Figure 5: Euler Angles - Rate-free Rotational Motion Tracking

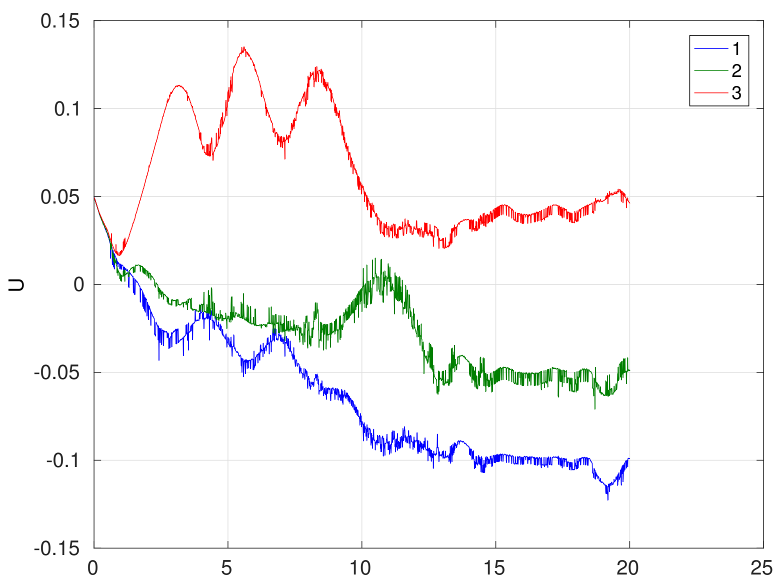


Figure 6: Applied controls - Rate-free Rotational Motion Tracking

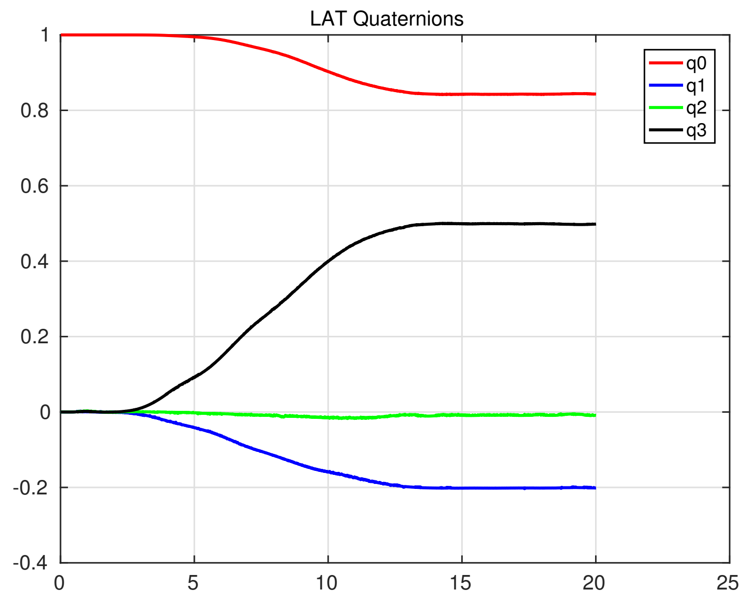
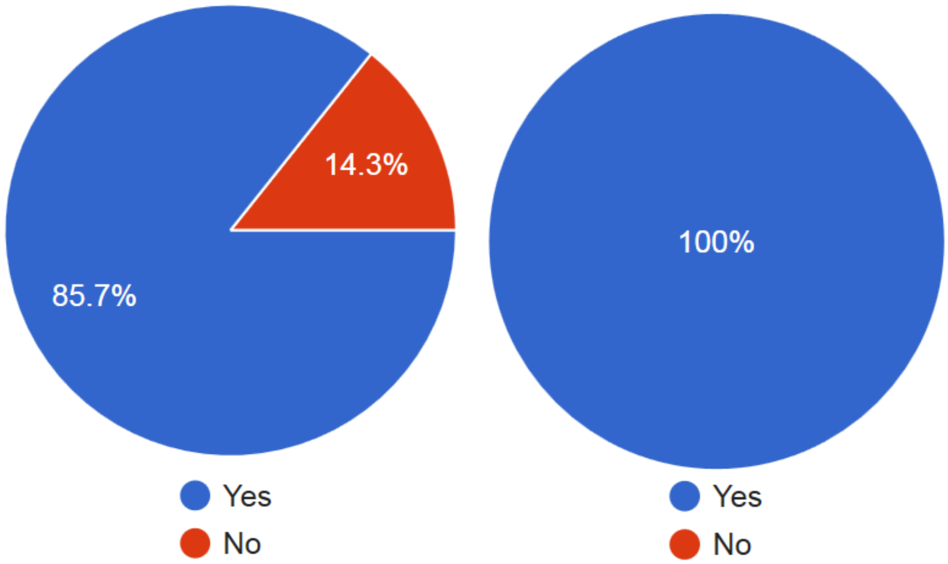


Figure 7: LAT Quaternions - Rate-free Rotational Motion Tracking

After concluding the final project with the spacecraft control class we conducted a survey to get information about the students background and evaluate the class experience with using the LAT. Selected results from this survey are presented in Figure 8. These results show that despite this being a graduate level controls course a reasonable number of students had never had to implement a control in hardware before (about 15%). Additionally, all the students thought the LAT was a useful supplement to the course and several suggested it be used as larger component of the class. From the responses it can be seen that the project exposed students to common challenges hardware implementation presents such as an imperfect dynamic model, sensor noise and calibration, and communication problems. These difficulties are generally not considered during simulation projects in class, but are frequently present in real life projects and research work. The following are two responses to “How did the LAT improve your understanding of the theory taught in class?” that demonstrate the usefulness of the LAT for teaching attitude control:

> “It reinforced what we learned in class and also taught me the importance of using gains etc., which don’t seem to be as necessary in simulations.”
>
> “How the performance is susceptible to initial conditions errors and time delay in sending the control commands when working with continuous controllers.”



(a) Have you implemented a controller in hardware before?

(b) Do you think the LAT was a useful addition to the course?

Figure 8: Selected Class Survey Responses.

5.3 Additional Educational Applications

During the 2015 Fall semester, the platform was presented to students during a spacecraft dynamics class (Figure 9). The goal of this demonstration was to show the students a real Inertial Measurement Unit (IMU) collecting real-time gyroscope and accelerometer data illustrating how it changed according to the attitude state and dynamics of the platform.

Figure 9: LAT Being Used for Classroom Demonstration.

The LAT was also presented at the Texas A&M Physics and Engineering Festival, on April 09^{th} 2016, at the Aerospace Engineering booth (Figure 10). The festival is an event with interactive science and physics demonstrations open to the general community. The LAT was used to demonstrate the principle of conservation of angular momentum. The momentum exchange between the reaction wheels and the platform displayed how reaction wheels control attitude of spacecraft in orbit, an application the general public tends to be completely unfamiliar with. We received significant positive feedback from the public about the live demonstrations and the way the LAT exhibited complex subject matter in a way that was easy to see and understand.

Figure 10: LAT at Texas A&M Physics and Engineering Festival

6 Future Work

We are currently undergoing a design revision for the LAT based on feedback we received. During the Summer 2016, all the platform designs, software, and documentation will be released open-source so that other schools and laboratories who are interested can construct their own system. We hope to also release a basic library of control and estimation codes that can be used with the LAT for educational purposes.

7 Conclusions

A simple test platform for demonstrating attitude control and estimation, the LASR Attitude Test-bed (LAT), was constructed. The system was built using new manufacturing techniques, such as 3D Printing and laser cutting as well as commercial off-the-shelf components to make it as inexpensive as possible. The LAT provides a simple MATLAB interface to access sensor data and control a set of 3 reaction wheels and is suspended on a neutrally stable universal joint to allow for attitude motion with 3 degrees of freedom. The platform was then used as part of multiple classes to prove its pedagogical value and has resulted in a student publication. The LAT was shown to provide substantial educational benefits to students by exposing them to components of attitude estimation and control that are normally overlooked in a classroom environment. Once the design system is publicly available, educators everywhere will be able to use the LAT to expose students to the concepts they need for the design and control of actual space systems.

8 Acknowledgements

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