A Cost-Effective and Feasible Approach for CubeSat A.D.C.S. Validation

Mike Melendez, Zachary Gaines, Katherine Orozco, Cal Poly Pomona 2021

Abstract

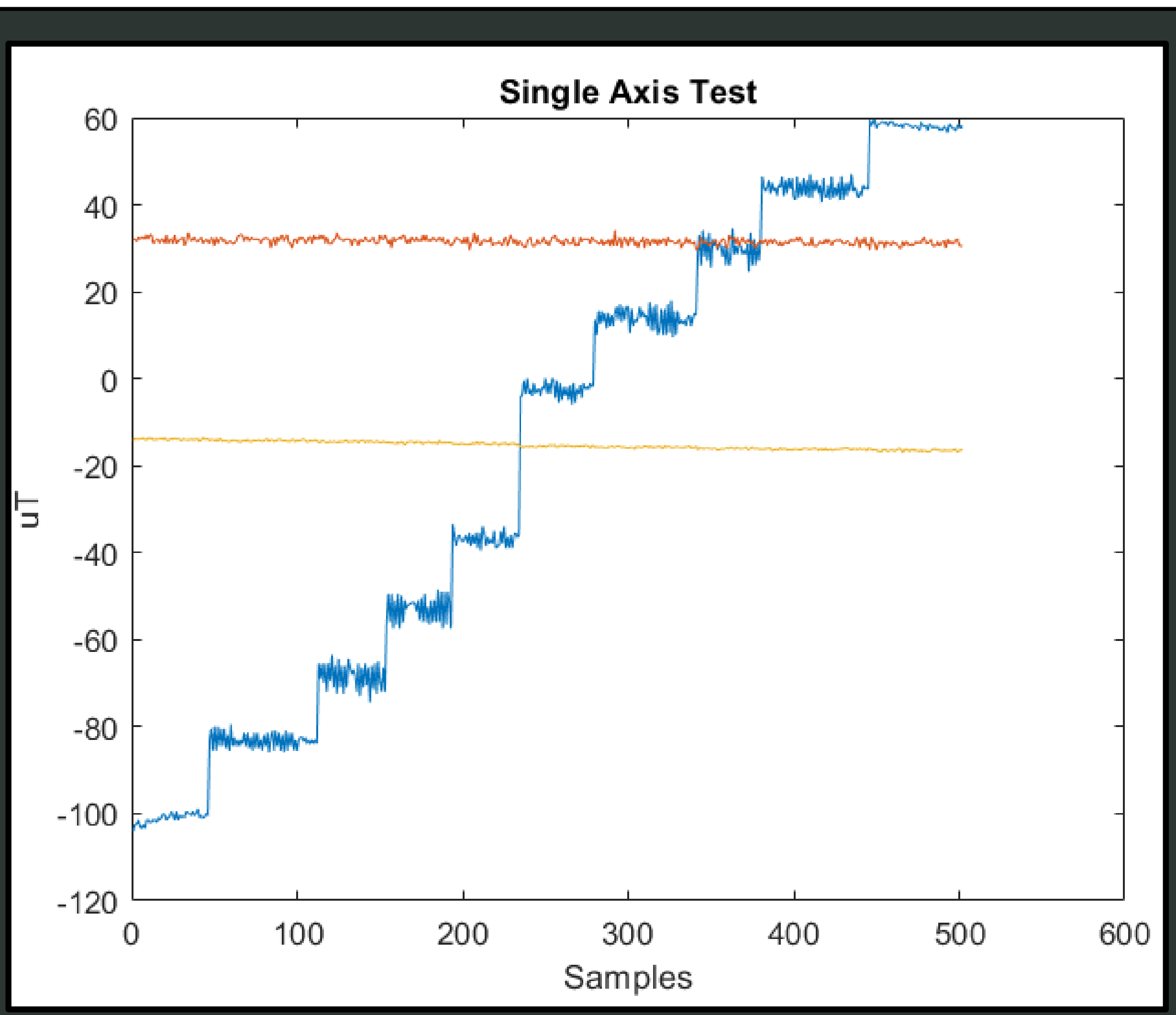
Over the last year, Cal Poly Pomona has made a significant push to become a consistent space-faring university through the development of CubeSats. These small satellites are complex in many ways, but arguably one of the most important and elaborate areas in development is the Attitude Determination and Control System (ADCS). In taking on the developmental challenge of ADCS design and implementation on the BroncoSat-1 Satellite, the team at Cal Poly Pomona wanted to have the ability to validate the on-orbit control systems. To accurately test the satellite's control system, an on-orbit environment needs to be simulated in a lab setting. To achieve this simulated test environment, two systems were needed, the first being a Helmholtz cage which allows for the simulation of Earth's magnetic field for any point in Low Earth Orbit and a balancing system seated on hemispherical air bearing that allows for frictionless rotation and the ability to align the center of rotation with the center of mass of the system which will negate the experienced gravity torques. Along with simulating the environment having the ability to get consistent refined data was an important requirement for the team that was met by implementing motion-tracking cameras that precisely follow and record the movements of the testbed.

For this system, the team was operating under very tight budgetary and scheduling restrictions, which led to a simple design at its roots but robust enough to enable basic ADCS testing and validation. With current industry trends, there will be a continuing increase in launch opportunities for small satellites in the years to come, and the ability for new groups to be able to verify their control systems with cheap yet efficient systems will also become more necessary as they try and meet more frequent launch cadences.

Helmholtz Cage

In order to simulate the earth's magnetic fields, the team set out to build a 3-axis Helmholtz enclosure. A Helmholtz enclosure is comprised of 3 Helmholtz coils, where each coil corresponds to an axis on the x-y-z plane. Each Helmholtz coil consists of two large coils of wire connected in series, making sure the current flows in the same direction. When a current is sent through the Helmholtz coil, a uniform magnetic field is created at the center of the two large coils—creating an enclosure allows the magnetic field to be altered from all sides, allowing the team to emulate the earth's magnetic field.

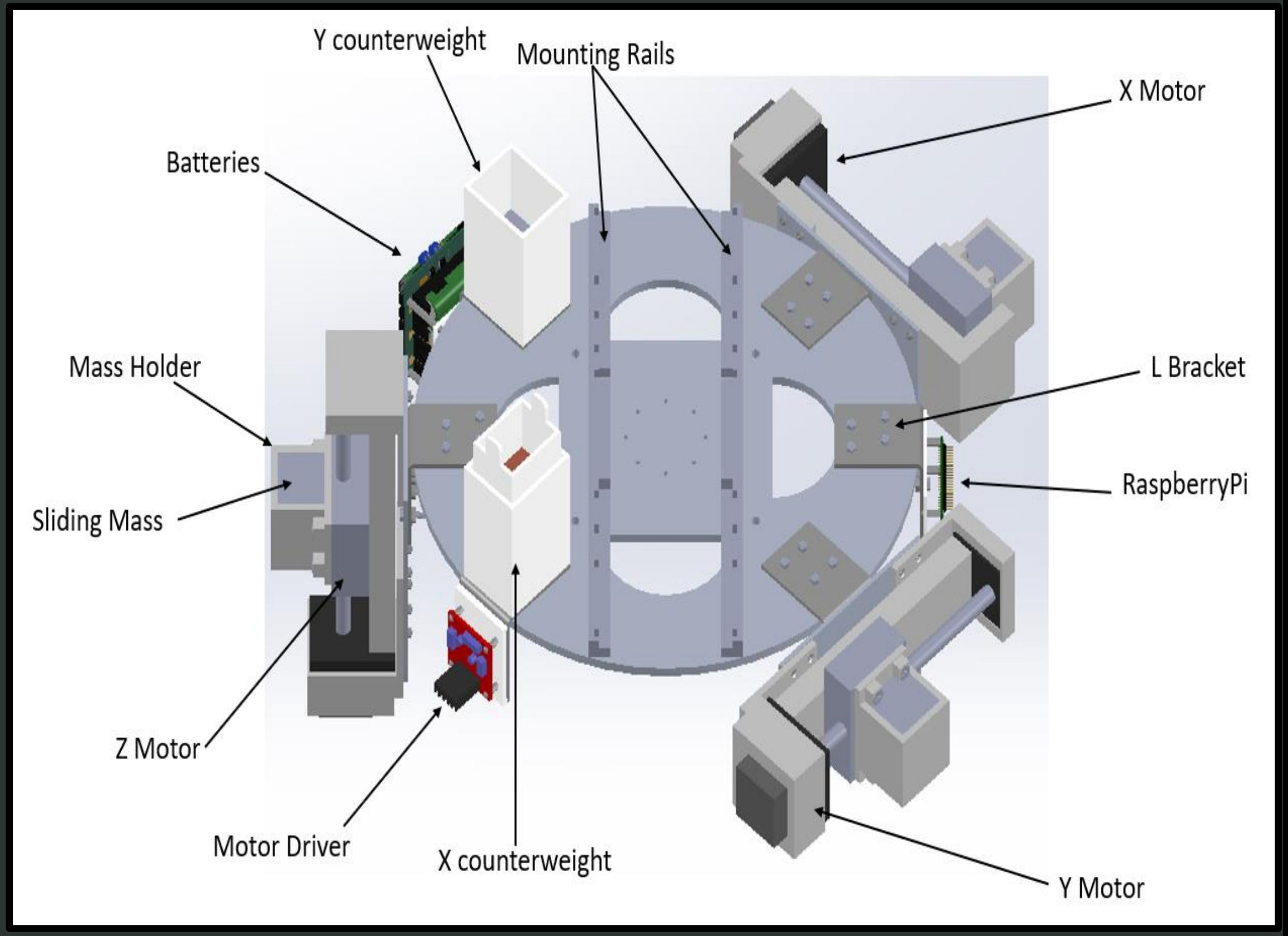
For the build, each coil of wire used approximately 44ft of 20AWG wire. The coils were wrapped around a frame 27 times. The dimensions of the fames varied, with the x-axis being 49x49 inches, the y-axis being 47x49 inches, and the z-axis being 47x47 inches. The coils were powered by three separate 13V 10A power supplies, where the outputs were controlled with bi-directional motor drivers, allowing the total output current range to be between –10A to 10A. After a series of tests, it was determined that the nominal output range of each Helmholtz coil produced a magnetic field range of approximately 160 uT, as was expected.



Balancing System Design

The balancing system is broken into a couple of principal components, the first being the circular plate, which acts as a support platform for six subassemblies that are individually mounted onto the plate using a simple L bracket. The design essentially turns the circular plate into a sectioned-off octagon, allowing for the mounting of each subassembly and precise locations to counteract the moments produced by each subassembly. The X and Y motor assemblies are mounted 90 degrees from each other, and both are 135 degrees from the Z motor. The other three subassemblies support the motors in which they hold the power bank, computer, and the Z-axis motor driver, and these are placed in these locations to distribute out the weight as evenly as possible, but the addition of two counterweights where it is needed to make the baseline system be able to negate any self-imposed moments. All components were mounted on custom plates with the lighter components having the plates made of PLA and the heavier motor assemblies being mounted on aluminum plates. The motor assemblies each weight about two kilograms and the batteries right at 500 grams and the rest of the components add another three and a half kilograms to have the entire balancing system weight right at 10 kg.

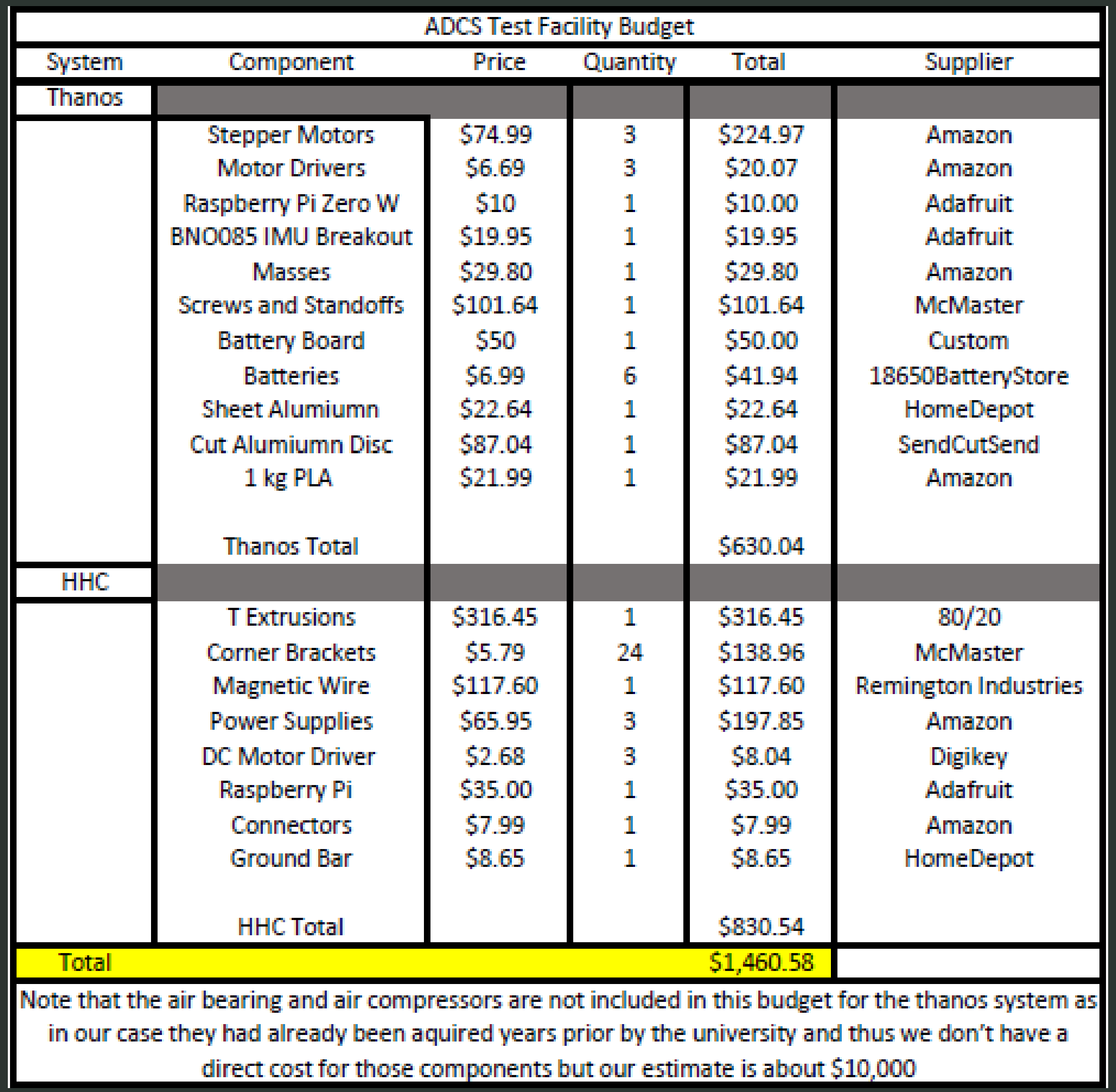
To ensure the safety of the cube satellite during testing, a mounting mechanism was implemented which is composed of mounting rails, a set of rods, and a top cap. The mounting rails have grooves built into them which keep both ends of the cubesat from sliding off the rails. These grooves are placed in specific areas to accommodate for 1U, 2U, and 3U satellites. The top cap and rods safely compress the satellite and ensures that it is secure. The system was programmed using Python to allow users to operate the motors from a computer remotely. Users are allowed to input any number of rotations to turn the motors and shift the positions of the masses. The program also displays magnetic forces, tilt angles, and acceleration data provided by an inertial measurement unit integrated into the system.



Balancing System Performance

For the balancing system, the team set out to make a system that can do two main things that align the center of mass of the system with the center of rotation and two to make it usable with little change for CubeSats 1U-3U form factors. There is a standard configuration for the system, meaning that the sliding masses are all set to 400grams and counterweights to adjusted accordingly, and in this configuration, it allows for very versatile use without compromising the system's accuracy. In this configuration, a balancing resolution of ±70 µm can be achieved. While this configuration allows for acceptable resolution depending on testing needs and the mass along with the center of mass offset from the geometric of the CubeSat test article, the sliding masses could be adjusted to increase accuracy or to be able to bring the center of rotation within ±70 µm expected test conditions. Also, it is important to note that for each test article, required analysis can quickly be done in a solid works program for the required additional mass that needs to be added that is proportional to the test article mass to enable the functionality of the test article Z-axis motor.

For all the system movements, multiple sensors are used to give feedback to the user. Onboard the balancing system itself, there is a nine degree of freedom IMU that constantly reads out the degree of offset that the system is experiencing as well as give feedback of the motion of the system in comparison to both the onboard computers on the test article and in comparison, with the OptiTrack motion cameras that can pick up movements with 0.1mm of accuracy.



ADCS Test Facility Budget					
System	Component	Price	Quantity	Total	Supplier
Thanos					
	Stepper Motors	$74.99	3	$224.97	Amazon
	Motor Drivers	$6.69	3	$20.07	Amazon
	Raspberry Pi Zero W	$10	1	$10.00	Adafruit
	BNO085 IMU Breakout	$19.95	1	$19.95	Adafruit
	Masses	$29.80	1	$29.80	Amazon
	Screws and Standoffs	$101.64	1	$101.64	McMaster
	Battery Board	$50	1	$50.00	Custom
	Batteries	$6.99	6	$41.94	18650BatteryStore
	Sheet Alumiumn	$22.64	1	$22.64	HomeDepot
	Cut Alumiumn Disc	$87.04	1	$87.04	SendCutSend
	1 kg PLA	$21.99	1	$21.99	Amazon
	Thanos Total			$630.04	
HHC					
	T Extrusions	$316.45	1	$316.45	80/20
	Corner Brackets	$5.79	24	$138.96	McMaster
	Magnetic Wire	$117.60	1	$117.60	Remington Industries
	Power Supplies	$65.95	3	$197.85	Amazon
	DC Motor Driver	$2.68	3	$8.04	Digikey
	Raspberry Pi	$35.00	1	$35.00	Adafruit
	Connectors	$7.99	1	$7.99	Amazon
	Ground Bar	$8.65	1	$8.65	HomeDepot
	HHC Total			$830.54	
Total				$1,460.58	

Note that the air bearing and air compressors are not included in this budget for the thanos system as in our case they had already been aquired years prior by the university and thus we don't have a direct cost for those components but our estimate is about $10,000

Budget

A significant objective for creating this system was to keep it as cost-efficient as possible and establish a simple way to procure the necessary components so that students could replicate this system with ease. The cost of the system was dramatically reduced by going with a majority consumer off the shelf components and then also for any custom needs of the system 3D printers were easily employed to manufacture specific components. It is important to note that at Cal Poly Pomona, the spherical air bearing was already present and granted dramatic cost savings with consumer-grade air bearings costing a few thousand dollars. Earlier in the design process, the team investigated creating a simple spherical air bearing and found many examples of it being done and could be a beneficial alternative to buying a commercial bearing, though there is an expected dropped in system performance, so some additional changes might be necessary to have the system perform to a suitable level. Additionally, with the budgetary restrictions, the support equipment that would be beneficial to use for the construction of the entire system was not available for the team to use and did lead to some discrepancy from the models to the real system and extra inaccuracies in performance.

Future Work

Although the current balancing system satisfies the basic demands for A.D.C.S. testing, a few improvements that the team intends to make will look to enhance testing accuracy and streamline the testing process. Our initial step will involve the refinement of our control system by converting it into a fully automatic version. This will allow the balancing system the ability to stabilize its platform on its own with very minimal interaction between tests and easily switching test articles. Other potential improvements include the addition of flywheels to the system which would allow for better pointing and directional control testing. Also, our team plans to implement a more efficient way to exchange the shifting masses for different ones to alter the moment of inertia of the system based on the size and mass of the satellite undergoing testing.

In addition, further improvements are yet to be made on the Helmholtz Cage. The next iteration will require the design of custom hardware to optimize the use of the coils. The custom PCB will allow for the control of three coils, using three bi-directional motor drivers. In addition, current sensors and a magnetometer will be added to verify that the correct output is generated from the coils. For additional safety measures, a fail-safe will be implemented. Finally, the team will update the current software used to operate the Helmholtz enclosure, aiming to optimize simulation profiles and implement a more refined control and user interface.