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CubeSat Three Axis Simulator(CubeTAS)

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CubeSat three axis simulator(CubeTAS) is a CubeSat-scale simulator. To simulate frictionless microgravity environment for the ground test, CubeTAS is supported by a spherical air bearing, and bottom half is covered with aluminum hemisphere. The system is automatically balanced with sliding masses only using a new balancing algorithm. Inclinometers and stepper motors are used for automatic balancing. Attitude estimation is done with the measurements of a sun sensor and an inertial measurement unit(IMU). Reaction wheels and magnetic coils are installed for attitude control. To support the operation of CubeTAS , Helmholtz coil structure is installed around CubeTAS to simulate earth magnetic field, and Phasespace impulse camera system provides reference attitude with high accuracy.

I. Introduction

Since the CubeSat program was first started in 1999 by CalPoly and Stanford, a number of CubeSats have been developed and launched around the world, especially at universities. With an increasing number of CubeSat developments, there has been needs for ground testing and simulation testbed. To test spacecraft dynamics and attitude control system, ground simulation in frictionless microgravity environment is highly required. Air-bearing-based three axis simulator has been popular for it and this paper presents an air-bearing-based three axis simulator with a CubeSat-scale.

CubeSat three axis simulator(CubeTAS) has a lower half covered with aluminum hemisphere and its upper half is open. A pedestal with air bearing installed on top supports CubeTAS. Helmholtz coil surrounding CubeTAS generates a uniform magnetic field of $0.71 \times 0.69 \times 0.64 = 0.314\text{m}^3$ approximately and the Helmholtz coil control server controls the magnetic field strength based on the position relative to Earth. There is motion capture camera system, whose 3D cameras are mounted on the coil structure, providing reference attitude to CubeTAS and console system. A light source with quartz halogen lamp is installed as artificial sun light for sun sensor. Figure 1 is the overall system configuration and data flow.

CubeTAS consists of a single board computer(SBC), power management module, sensors, and actuators. SBC communicates with sensors and actuators and compute control commands. All sensors and actuators are directly connected to SBC except magnetic coils, which is connected to relay board.

SBC has ARM processor, which is incompatible with Intel CPU and its operating system is RTAI Linux. Therefore operating software is developed in Matlab/Simulink/Realtime Workshop for RTAI Linux target and compiled for ARM processor.

CubeTAS balances itself first using inclinometers and motors with balancing mass. Once it is balanced, the system estimates and controls the attitude using IMU, sun sensor, reaction wheels, and magnetic coils. Unlike previous balancing algorithms using momentum dumping devices, CubeTAS balancing algorithm uses sliding masses only.

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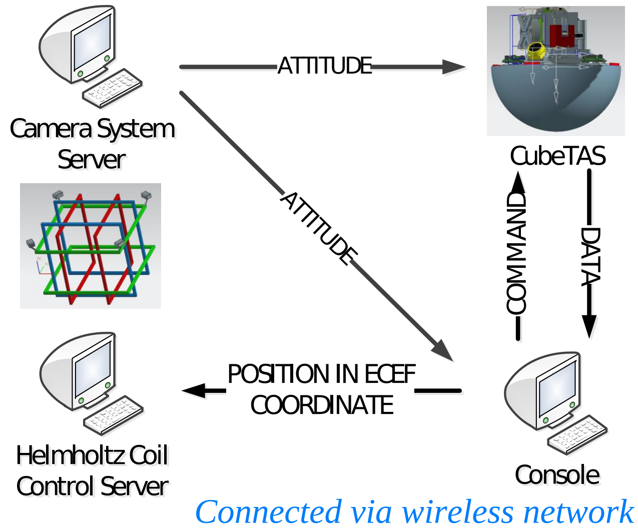


Figure 1. Overall System Configuration

II. Hardware Design

CubeTAS is a CubeSat-scale three axis simulator, which is an attitude estimation and control testbed for microgravity condition in space environment. To achieve microgravity condition, CubeTAS is supported by spherical air-bearing and has automatic mass-balancing system. CubeTAS also has attitude sensors and actuators on it. Moreover, CubeTAS has a wireless transceiver for communication with console and other supporting systems. Since the travel distance of the balancing masses is short and the weight of each balancing mass is approximately only 7% of the whole system weight, it is well designed to have C.G offset from the center of rotation of less than a millimeter.

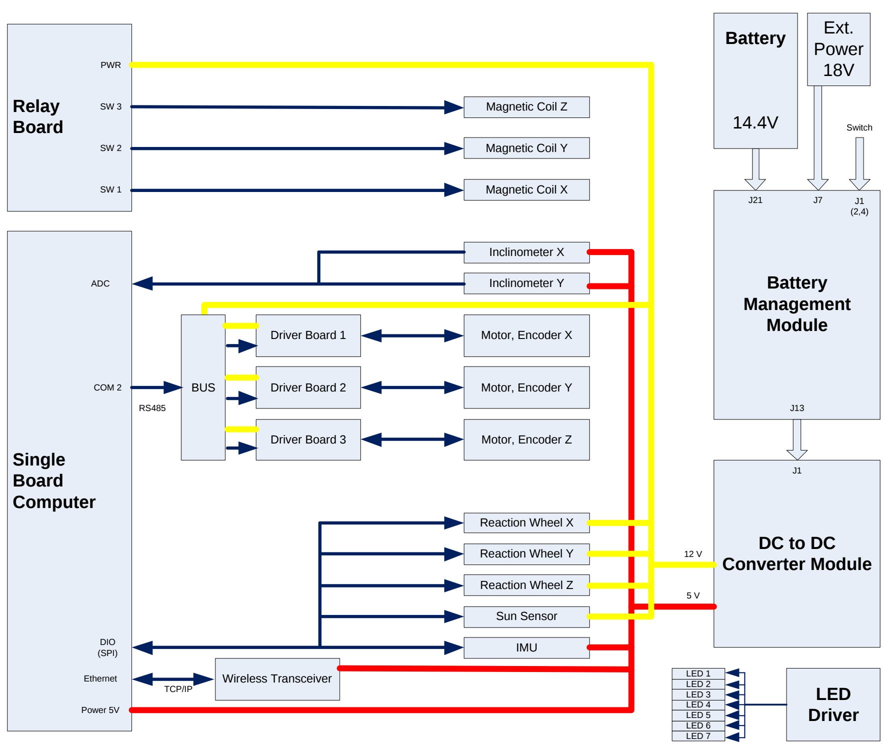


Figure 2. System Architecture

Table 1. List of Components

	Spec.
OBC	EP-9302, ARM9, SPI, RS-485, ADC
Relay Board	20 Relays
Battery Management Module	
DC to DC Converter	12V, 5V, 3.3V
Battery	14.4V, 3A, 234g
Inclinometer	$\pm 70°$, $0.01°$ resolution
IMU	3-axis, accelerometer, rate gyro, magnetometer
Sun Sensor	± 70 FOV, $0.1°$ accuracy
Motor	
Reaction Wheel	60 mNm @ 6500 RPM
Magnetic Coil	11.31×10^{-6} Nm @ 500 km altitude
Wireless Transceiver	802.11g, Ad hoc mode

II.A. System Architecture

Figure 2 is the system architecture of CubeTAS and shows how all the components are connected.

The mainboard of CubeTAS is TS-7200 of Technologic Systems, which has ARM9 processor and PC-104 form factor. It has various interfaces such as DIO, ADC, RS-232/485, and SPI. The system has another board, the relay board to control the current on magnetic coils. It is stacked on the mainboard and connected to the mainboard through PC-104 interface.

The power management system has battery, battery management module, and DC to DC converter. The battery has a capacity of $2470mAh$ and $14.4V$ output. The battery management module has two power inputs, which are $14.4V$ battery output and $18V$ external power. DC to DC converter converts the power from the power management module to ±12V, ±5V, and ±3.3V and provide power to all the components.

CubeTAS has three sensor components; IMU, sun sensor, and inclinometers, and three actuators; reaction wheels, magnetic coils, and motors. However, IMU has three sensors; rate gyro, magnetometer, and accelerometer in it, therefore CubeTAS has 5 sensors actually. Two inclinometers and 3 motors are for the first stage, automatic balancing. Rate gyro, magnetometer, sun sensor, three magnetic coils and three reaction wheels are for attitude estimation and control. All the sensors and the actuators except magnetic coils are directly connected to the mainboard. Reaction wheels, sun sensor, and IMU use SPI of the mainboard. SPI devices share signal lines; CLK, MISO, and MOSI, but each device has own chip select line. Therefore each device communicate with mainboard through SPI lines only when its chip select is low. Three motors use a RS-485 serial port. Since commands from the mainboard are sent to all three motors, the command should specify the motor index so that each motor operates only when the command designate itself as target. Two inclinometers are connected to the optional MAX197 A/D converter on the mainboard. Magnetic coils are connected to the relay board. CubeTAS also has a wireless Ethernet transceiver to communicate with console and other supporting system through local wireless network.

Although LEDs and LED driver has no physical or signal connection with CubeTAS system, they are fixed on CubeTAS for attitude tracking. LED driver receives signal from the camera system server and make LEDs blink.

The details of CubeTAS components are listed in Table 1.

II.B. Mechanical Design

Mechanical design goal for CubeTAS is to make C.G offset to C.R within the capability of the balancing system and to fit bottom half in the hemisphere with $250mm$ diameter.

3D design was done on NX CAD software of Siemens. Locations of all the components were determined to reduce the C.G offset. System frame is designed to hold and fix the components and printed with plastic.

Figure 3 is the overview of the current design and Figure 4 is top, bottom, and side views. Reaction wheels are placed in upper half and the motors are in lower half. Sun sensor and driver boards for motors

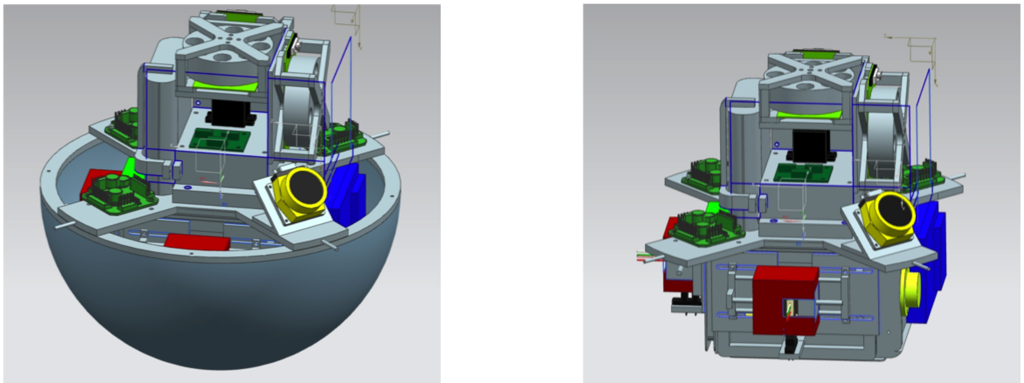


Figure 3. Overview

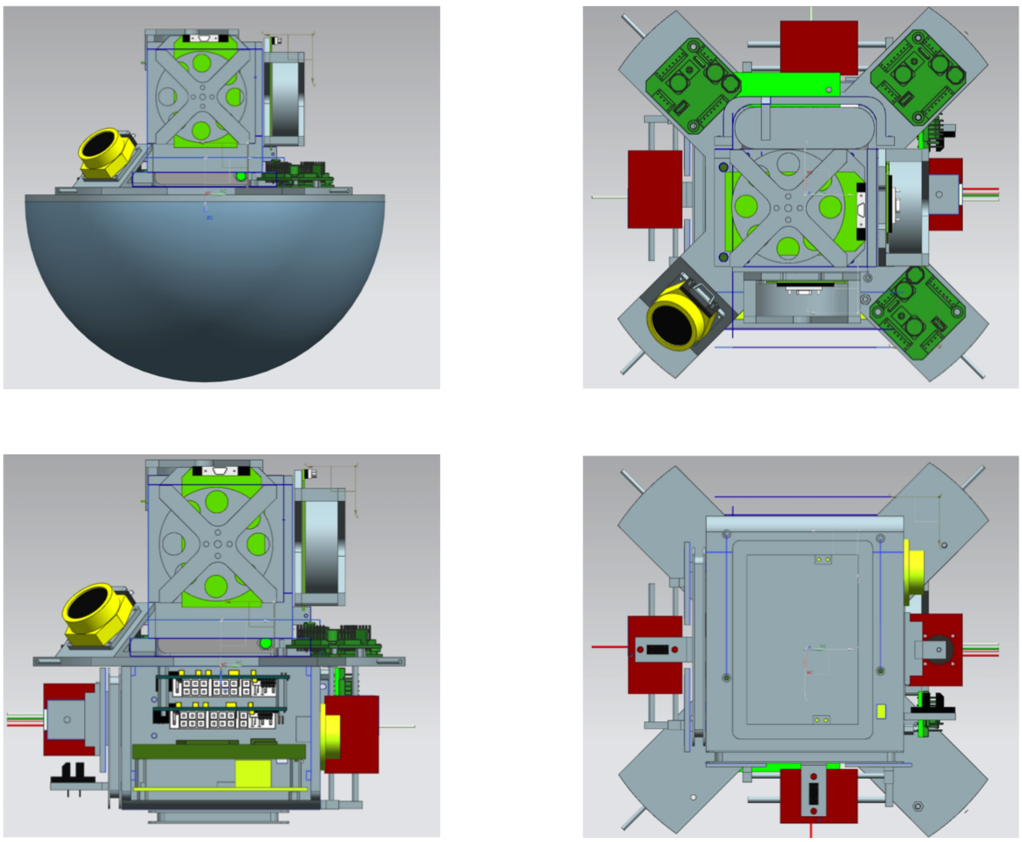


Figure 4. Side, top, and bottom views

are placed around the center plane, and inclinometers, magnetic coils, and wireless transceiver are fixed on the outside wall of lower half. Figure 5 shows two PC-104 boards and power management boards in the cube of lower half.

Total weight of the current design is $4.080kg$ and the weight of balancing mass including motor is $290g$. Since the travel distance of balancing mass is $30mm$ to each side, Tolerable C.G offset is $290/4080 * 30 = 2.1mm$

II.C. Hemisphere and Air bearing

For the minimum friction and micro gravity condition, CubeTAS operates on air bearing and the lower half of it is covered with aluminum hemisphere. The aluminum hemisphere is designed after load analysis

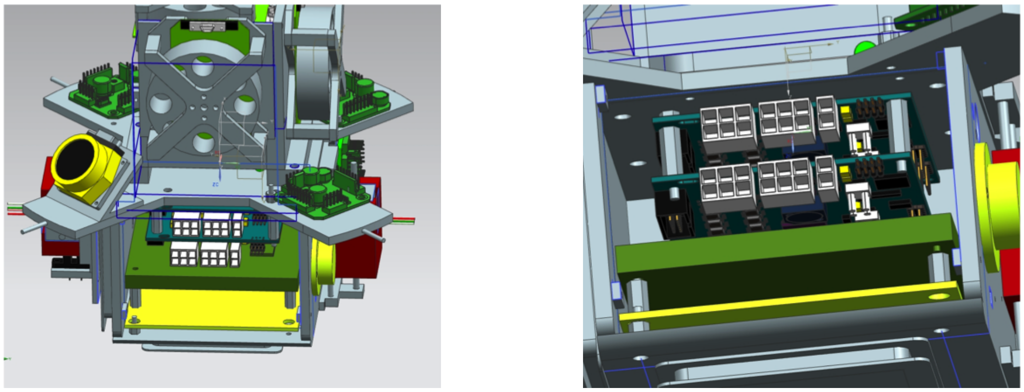


Figure 5. Inside of Bottom Cube

with applied force of $80N$. The thickness is $1mm$ and the mass is $840g$ including 4 bolts and band at center plane. The air bearing is coupled with the hemisphere and they are polished together to obtain the minimum residual torque.

The operating pressure of air-bearing is $60psi$ and the surface accuracy is $5micron$. It has $\pm 50°$ of operating range w.r.t 2 axis in horizontal plane and $360°$ for vertical axis.

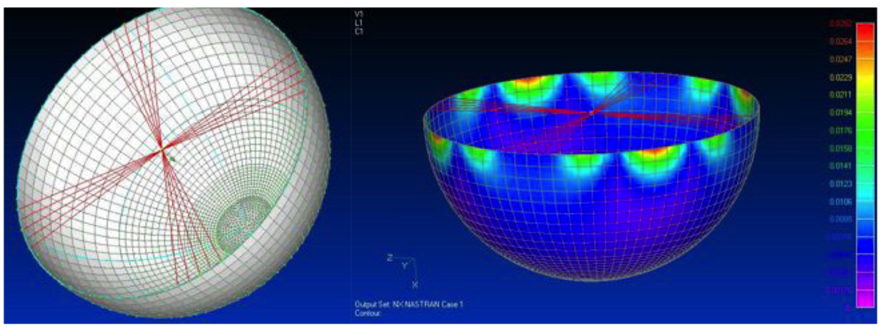


Figure 6. Load Analysis

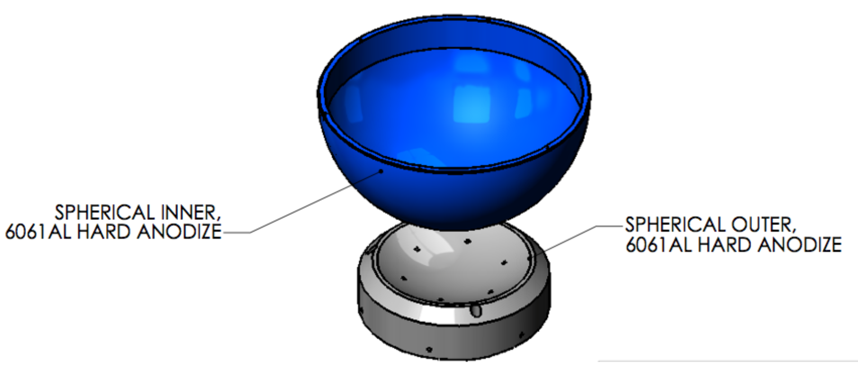


Figure 7. Aluminum Hemisphere with Air Bearing

III. S/W Development

Software for CubeTAS has been developed for automatic balancing and attitude estimation and control. The program reads data from all the components and send commands to them. These communications are performed in hardware interface functions such as SPI, ADC, and RS-485. In addition to hardware interface functions, algorithm functions like automatic balancing, attitude estimation, and attitude control functions are also implemented. For the estimation and control, the program runs in realtime.

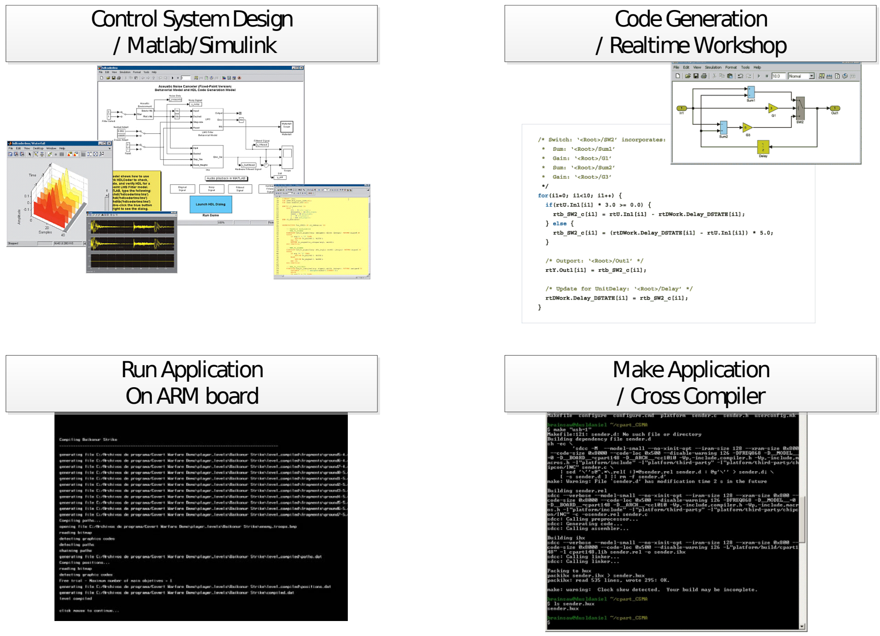


Figure 8. Development Process

III.A. Development Environment

The target system, CubeTAS has Cirrus EP9302 processor with ARM9 core and RTAI Linux for operating system, whose kernel version is 2.4 and RTAI patch is done by Technologic Systems, while the development system is PC-compatible 32-bit Linux system. Since development and target systems have different CPU model(ARM and Intel), GNU ARM toolchain for PC Linux is used to make executables for ARM processor. Software development of the system model starts on Matlab/Simulink as a simulink model, then Realtime Workshop generates source codes from it. Finally, compiling the source codes with cross compiler gives an executable for the target platform. The development process is described in Figure 8.

III.B. Simulink Model

Each hardware interface and algorithm is implemented as an individual s-function block in Simulink model. In Figure 9, yellow blocks are hardware I/O interfaces and the blue ones are algorithms. The upper three blocks do automatic balancing of CubeTAS and the other blocks in lower half are for attitude estimation and control.

Analog to digital conversion block reads the outputs of the two inclinometers and passes them to automatic balancing algorithm block, then the algorithm block calculates the control commands for the motors. The SPI block in the attitude control part interfaces three different types of components, which are five in total. They are an IMU, a sun sensor, and three reaction wheels. The SPI block read sensor measurements from the sun sensor and IMU and pass them to the attitude estimation block. Using the attitude information from the attitude estimation block, the attitude control block calculates control commands for three reaction wheels and three magnetic coils , then send commands to the SPI block and the relay board block.

III.C. Automatic Balancing

General automatic balancing algorithms for three axis simulators use sliding masses and momentum dumping devices like reaction wheels or control momentum gyro(CMG).[2] A new automatic balancing algorithm with sliding masses only is developed for CubeTAS. It first balances X and Y axis, where Z axis is opposite gravity direction, with a new adaptive dynamic nonlinear feedback control law. After balancing X and Y axis, the remaining Z axis is balanced using extended Kalman filter for estimating Z axis offset. This algorithm will be presented in AAS/AIAA Astrodynamics Specialist Conference 2011, Alaska.[1]

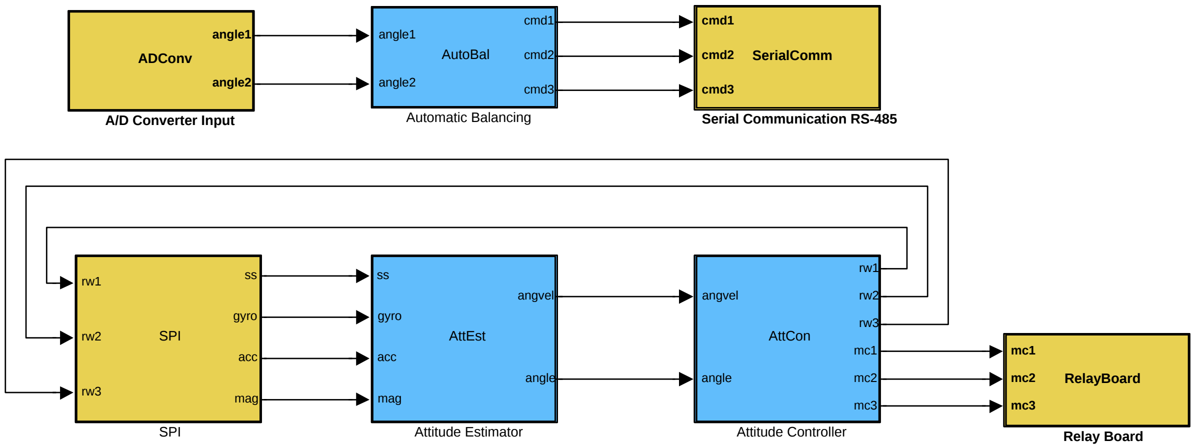


Figure 9. Simulink Model

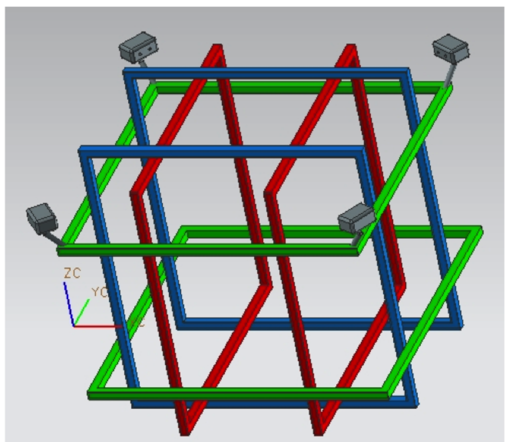


Figure 10. 3D Cameras on Helmholtz Coil

IV. 3D Camera Tracking System

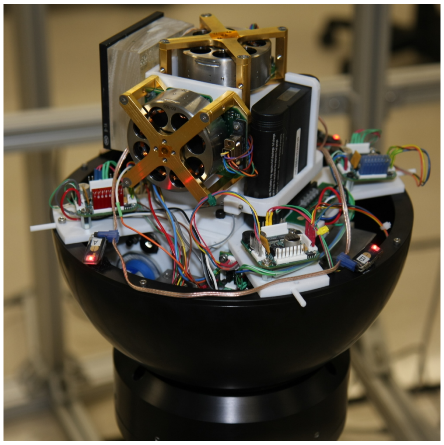
To get precision attitude data, Phasespace impulse camera system is used to track CubeTAS attitude. The whole system consists of 3D cameras, server, LED station, LED driver, and LEDs on target object. The 3D cameras are installed on Helmholtz coil structure as in Figure 10 and the LED driver and LEDs are fixed on CubeTAS. The cameras have wired connection with the server so that the system can capture the motion with high frame rate(480 fps), however the server transmits commands to LEDs via LED station by wireless and LED driver receives the commands and make LEDs blink. Point and attitude tracking resolutions are known as $1mm$ and $0.02°$.

V. Conclusion

This paper presented the development and design process of CubeSat three axis simulator. Unlike previous three axis simulators, it is designed to test and simulate CubeSat-scale system. It can do three axis maneuver on air-bearing with minimum friction.

Figure 11 is pictures of current CubeTAS and the whole system. CubeTAS development is still ongoing project. Since it is short of one reaction wheels, a dummy mass is in place of it. Also Helmholtz coil set up is ongoing, too.

CubeTAS is a three axis simulator for small-scale simulation, which was not easy to perform with previous big simulators. With this kind of small simulator, cost and space effective simulation compared to big simulator, can be possible in laboratory level.



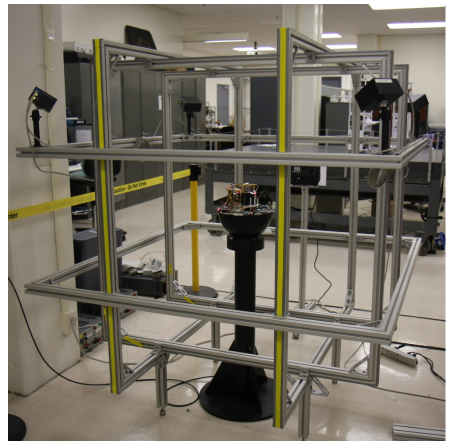


Figure 11. CubeSat Three Axis Simulator(CubeTAS)

Acknowledgments

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References

[1]Chesi, S., Pellegrini, V., Cristi, R., Gong, Q., Romano, M., *Automatic mass balancing for small Three-Axis spacecraft simulator using sliding masses only*, submitted to AAS/AIAA Astrodynamics Specialist Conference 2011

[2]Kim, J.J. and Agrawal, B.N., *Automatic Mass Balancing of Air-Bearing-Based Three-Axis Rotational Spacecraft Simulator,* Journal of Guidance, Control, and Dynamics, Vol. 32, No. 3, 2009, pp. 1005–1017