

SpaceOps-2023, ID # 642

Attitude Determination and control Testbed for Nanosatellites

Eiman Alnaqbi^{1,3}, Shaikha Alghaithi¹, Hessa Alkaabi¹, Noura Alameri², Mohammed Atallah¹, Haitham Elshimy^{1,4}, Mohamed Okasha^{1,5}

¹ *Department of Mechanical and Aerospace Engineering, College of Engineering United Arab Emirates University.*

² *Department of Aerospace Engineering, College of Engineering, Khalifa University.*

³ 201803236@uaeu.ac.ae

⁴ haithamelshimy@uaeu.ac.ae

⁵ mokasha@uaeu.ac.ae

Abstract

This paper presents the design of a testbed for the attitude determination and control subsystem (ADCS) of CubeSats. The design of the testbed will be manufactured and tested to ensure its ability to test the CubeSat's attitude control accurately. The Helmholtz cage will be designed, built, and tested to provide a dynamic, 3-axis, uniform magnetic field to cancel out the earth's magnetic field and create an environment similar to the geomagnetic field. Any ferrous materials shouldn't be inside the cage during testing to ensure a uniform magnetic field. Even though CubeSats are generally affordable, one failure in orbit is quite costly in terms of money and time owing to the payload's preparation and launch. To avoid mission failures, a ground testing system for CubeSat ADCS is required. Based on our intensive research, the UAE lacks ADCS testing facilities. A CubeSat attitude determination and control simulation and testing platform must be constructed in the UAE to test and verify ADCS performance before launch. Pre-launch ADCS testing would fix attitude stability difficulties after launch. Therefore, our proposed project aims to develop low-cost hardware and software for testing nanosatellite and CubeSat attitude control systems. The experimental testbed can simulate the space environment, including the magnetic field and frictionless. The ADCS testbed consists of three components: the stand, the air bearing, and the platform. The main element is the air bearing, which can provide a multi-degree of freedom (DOF), simulate the frictionless space environment needed for the test, and rotate objects mounted to it in the roll, pitch, and yaw axes of rotation. The air bearing sits on the pedestal (stand) that holds all the testbed components together. The platform contains holes, which will keep the balancing masses and the tested CubeSat fixture in place. A Helmholtz cage consists of three pairs of coils that are positioned orthogonally and can provide a homogeneous magnetic field in any location inside the cage. An optimal value for the distance between each pair two coils maximizes the level of uniformity of the magnetic field produced inside the cage. In addition, an NX-Siemens is used to test the design structure. A stress analysis is applied in each sub-component to guarantee that a structure will perform as designed in a specific load situation by calculating the safety margin. Hence, it will be considered safe if the safety margin exceeds one.

Keywords: ADCS, CubeSat, Helmholtz cage, Air bearing, Balancing mass

Acronyms/Abbreviations

ADCS	Attitude Determination and Control Systems
DOF	Degree Of Freedom
U	Unit for CubeSat size
UAE	United Arab Emirates
UAEU	United Arab Emirates University
COTS	Commercial off-the-shelf
GNSS	Global Navigation Satellite System
MMU	Movable Mass Unit
COM	Center Of Mass
COR	Center Of Rotation
AWG	American wire gauge

1. Introduction

1.1 problem statement and purpose

Although CubeSats are relatively affordable, a failure in orbit is costly in terms of both cost and time due to payload preparation and launch [1]. Accordingly, to avoid mission failures, it is evident that a ground testing system for the nanosatellite's ADCS is required. Furthermore, extensive research has revealed that the UAE lacks ADCS testing facilities. The ideal test setup perfectly simulates the space environment and its variables, including frictionless, electromagnetic fields, vacuum, radiation, plasma, and neutral particles. Nonetheless, the proposed project's scope is limited to frictionless and electromagnetic fields. Its specific goal is to build a testing environment for the ADCS, which consists of two major components: the Helmholtz cage and the ADCS Testbed. Both have been designed using Siemens NX, and then a stress analysis was performed on each component to ensure that there are no issues with the load or the design's structure.

1.2 Project and Design objective

CubeSat is a small satellite that is easy to build, cost-efficient, and versatile. Therefore, a considerable number of CubeSats have been widely launched into space in the most recent years. Once the CubeSat is launched into space [1], an ADCS of reaction wheels and magnetorquers will appropriately position the satellite with respect to the reference orientation. Simulating a magnetic field and a frictionless environment in a lab setting is necessary to ensure the ADCS functions as intended in space. This project's primary goal is to test the ADCS of up to 12U CubeSats.

Furthermore, the space environment required for any CubeSat combines frictionless and magnetic fields, which can be simulated using two primary components: a Helmholtz cage and an air-bearing testbed. The team's primary focus is to design an ADCS testing subsystem, a testbed, and a Helmholtz cage to create the proper environment for the test.

1.3 Background

CubeSat started developing in 1999 to provide universities with affordable access to space, which has helped many significant universities create their own space programs. Any satellite weighing less than 300 kg is typically referred to as a small satellite (1,100 lb). However, a CubeSat must abide by standards that regulate things like its size, weight, and shape. CubeSats are nanosatellites used for various space missions, such as research, communication, and navigation missions, at a fraction of the cost of a fully developed satellite. The particular CubeSat requirements aid in cost reduction. CubeSats' standardized design allows corporations to mass produce components and supply off-the-shelf parts. Due to this, CubeSat engineering and development are less expensive than highly specialized tiny satellites. The fixed size and shape reduces the expense of shipping them to orbit and setting them up there. [1]

1.4 literature survey

Table1. Survey of spacecraft simulator;¹Worcester Polytechnic Institute's [2];²Norwegian University of Science and Technology [4];³Hawaii Space Flight Laboratory [8];^{4,5}Naval Postgraduate School[2016 Gia...]

Facility	DOF	Yaw	Pitch	Roll	Weight (Kg)	Tested CubeSat	Automatic Mass Balance
WPI ¹	3	360°	±45	±45		4U	
NUST ²	3	360°	±20	±20	60	12U	
HSFL ³	3	360°	±20	±20	50-100		
NP TAS2 ⁴	3	360°	±20	±20	800		YES
NPS TASS ⁵	3	360°	±30	±30	200		YES

The Worcester Polytechnic Institute's air bearing and stand were initially designed by the Worcester Polytechnic Institute's major qualifying project team in 2017 [3]. In 2018, a 4U CubeSat model can be positively affixed to the testbed, and the center of mass of the machine can be precisely adjusted. The Norwegian University of Science and Technology has developed a stand that can be adapted for different heights and has a variable center of mass. [4] The air bearings, on the other hand, can only rotate 20 degrees in pitch and yaw. The ADCS test facility was developed by the Hawaii Space Flight Laboratory and constructed by Astro-und Feinwerktechnik Adlershof GmbH. The ADCS testbed is able to evaluate small satellites weighing between 50 and 100 kg. With extensive experience in the attitude control of spacecraft dating back to 1989, the Spacecraft Attitude Dynamics and Control Laboratory at the Naval Postgraduate School (NPS) created its first air-bearing platform in 1995 in collaboration with Guidance Dynamics Corporation (GDC) [6]. Later on, NPS created two further tabletop air-bearing platforms with payloads of 200 kg and 800 kg and pitch angles restricted to 30° and 20°, respectively [6], [7].

2. Material and methods

2.1 Prioritized Needs and Requirement

The primary purpose of this research is to evaluate the ADCS subsystem that will be able to test of up to 12U CubeSats. ADCS subsystem-level testing requires simulating the CubeSat's frictionless and magnetic field environments. Main objectives of the project:

1. To create the appropriate test environment by designing and fabricating an ADCS testbed and a Helmholtz cage.
2. To validate the functionality of the ADCS, tests must be performed on a CubeSat prototype.

Project's requirements:

1. The testbed shall be capable of testing and housing a maximum of 12U CubeSats.
2. The test bed shall be capable of testing and holding a maximum volume of 65x35x35 centimeters.
3. The testbed shall be able to test and support up to 30 kg of mass.

Table 2. Requirement Summary Table

Requirements Summary
Lightweight material
Easy to adjust mass balance
Simple to use and safe
Accurate aluminium design
Platform suitable for testing up to 12U

2.2 Data collected

2.2.1 Problem Review

The main objective of this project is to develop and construct an ADCS testbed and a Helmholtz cage for low-cost testing of CubeSat navigation systems. A full electrical and mechanical system that is incorporated into the finished system will be provided for the testbed.

Testbeds must be able to integrate ADCS hardware components and integrate software estimation and control algorithms in order to test ADCS hardware. The mass balancing system will adjust the center of mass to be aligned with the center of rotation. The electrical system not only provides electrical signals to electrical devices, but it also receives electrical signals from devices. Lastly, the ADCS testbed and Helmholtz cage components will be designed using the software system, as will the electrical devices, all of which will be programmed using the software system.

2.3 Design criteria, constraints, and specifications.

2.3.1 Platform/Bed

The platform must hold both the test item (CubeSat) and the balancing masses and stabilize the CubeSat for testing. The platform's size depends on many resources, and the first one is the slip table of the thermal vacuum used in the National Space Science Technology Center. It contains the exact hole dimensions.

The diameter of the platform is 760 mm, based on the needed requirements. The holes are 6 mm in diameter, and the separating distance between the holes is 50 mm. There are also threaded holes in the middle of the table for mounting the hemispherical air bearing. On the platform's sides are holes for the x, y, and z balancing masses and the Arduino.

2.3.2 Stand

The stand must be heavy enough to hold the air bearing and the platform for testing. The pedestal is designed based on the selected air-bearing dimensions.

The base of the stand is 20 mm thick with a diameter of 650 mm, and the rod's height is 785 mm to be in the middle of the cage. The rod of the stand is shelled and has a small hole in the bottom of the rod to insert an air pressure pipe and install it in the air bearing. The top of the rod contains an interface plate to fix the stand and the air bearing. The base of the stand includes three holes to minimize the weight (to make it easier to carry or move), and the supportable triangles have a hole to help carry the stand easily.

2.3.3 Balancing Masses

The Balancing Masses, also called the Movable Mass Unit (MMU), are mainly working on aligning the center of mass (CM) of the CubeSat with the center of rotation (CR) of the air bearing. Designing the MMU consists of two types: manual and automatic. We chose a manual mass balance for the design because of its ease of conception and execution.

The balancing mass consists of four components: the mass holder, slotting rod, L-bracket, and main bracket. A mass holder's function is to adjust the masses by allowing the user to increase or decrease the mass based on the weight of the tested CubeSat, as well as to affect the platform's balance. In addition, the two rectangular holes are designed from the sides to provide the ability to add/remove the masses inside the box. The threaded rod inside the balancing mass holder gives you the ability to fix the masses inside the box using a nut. A slotting rod allows easy movement of the mass holder, keeps it set in place, and prevents rotating while testing by creating a hole in the box for inserting a screw and installing it with the slotting rod.

Table 3. Design Specifications Table

Design Specifications
Platform dimensions should be 65 * 35 * 35 CubeSat Standard.
2m, 1.9m, and 1.8m U-Channel
Plain aluminium sheets
Cost ≤ 55,000 AED
Table size 76cm x 35cm
Manufacture tolerance ± 0.02
Easy to operate by user

2.4 Components and Material

- Model DP82 power supply: its function is to be precise and have a power of up to 140 watts. The built-in voltage, current, and power measurements are displayed on a visible display in the lab power supplies. It will be used to control the current passing through the coils.

- MPU 6050: Both a gyroscope and an accelerometer are included on the MPU 6050, allowing us to measure rotation about all three axes, static gravity-related acceleration, as well as motion, shock, or dynamic acceleration brought on by vibration. It will help measure the orientation of the platform in the x, y, and z directions.

- Arduino is a tool for creating open-source electronics projects. You can write and upload computer code to a physical programmable circuit board (commonly called a microcontroller) using a piece of software called the IDE (Integrated Development Environment), which runs on your computer. It will be connected to the gyroscope so that the output can be generated in the Arduino software.

- Raspberry Pi 3 B+ has a 64-bit, four-core CPU operating at 1.4 GHz, a dual-band 2.4 GHz and 5 GHz wireless LAN, Bluetooth 4.2/BLE, faster Ethernet, and PoE functionality. It is the newest model in the Raspberry Pi 3 line. It's a sensor to gather data on the platform's stability and center of mass.

The following diagram shows the different components, some of them mechanical and others electrical, that operate together in order to cancel out the earth's magnetic field and simulate the space environment.

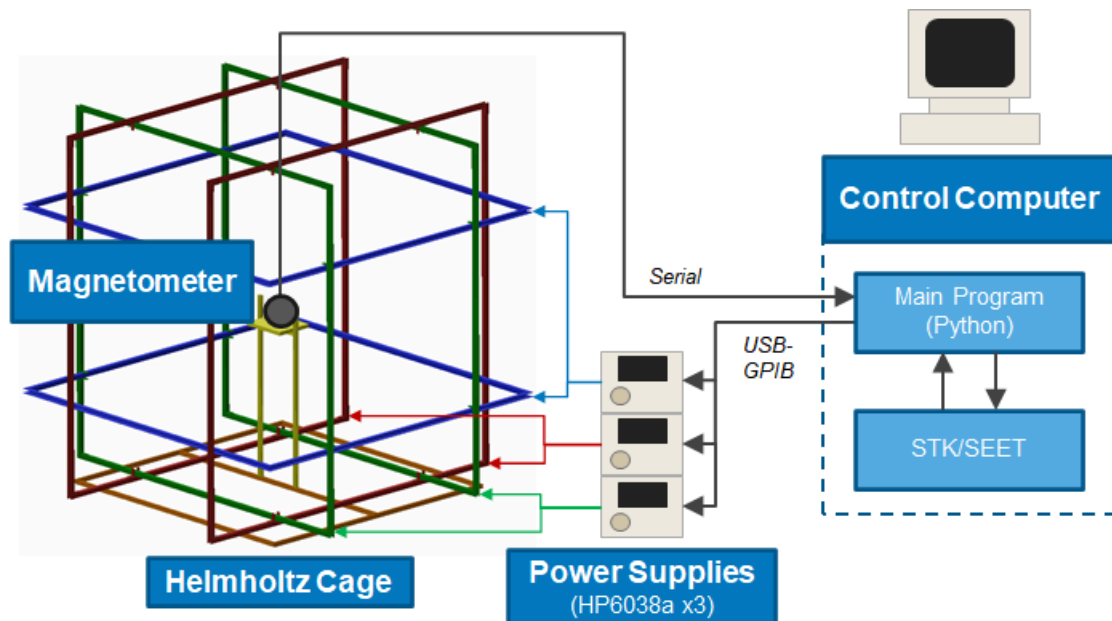


Figure 1. Helmholtz cage Schematic

The MATLAB-based application that powers the cage's control software is mostly accessed through a unique GUI. The software's four primary features are as follows [11]:

- Examining the connections to the magnetometer and power source
- Creating an equation that connects the input voltage and the output magnetic field strength on each axis will calibrate the cage.

- Conducting "static" tests in which the user can explicitly set the input voltages on each axis or the required magnetic field strength
- Running "dynamic" tests to replicate magnetic fields in orbit (WIP) using a time-varying input from a file, such as the results of a Systems Tool Kit (STK), simulates

Aluminum will be used to manufacture/fabricate the cage and testbed because they must be made of non-ferromagnetic materials, which are non-magnetic and contain no iron (ferrous) to avoid disturbing the generated magnetic field also because they are light materials.

The project will prioritize the health, welfare, and safety of the general public, which will result in an ethical design that takes into account both environmental and human safety by using safety materials and dressing safely when accessing the test location (the clean room). Additionally, since the honesty of engineers is one of our top goals, all sources used were from trusted companies and research, and all sources were acknowledged to prevent plagiarism. Several engineers with experience in the space industry will test the design to ensure success.

3. Theory and calculation

3.1 Schematics and flow sheets defining the preliminary design and its relationships

Axes movement

Axes movement is a reference axis used to describe the orientation of the CubeSat and where it is exactly located or pointed. The testbed is designed to have three-axis movement in pitch, roll, and yaw.

3.1.1 Air bearing

In order to make the testbed system experience a frictionless environment similar to the space environment, we need an air bearing to do this job. The air bearing has a 3-DOF rotation; it should move in all three axes: roll, pitch, and yaw, with 45 degrees in roll and pitch and 360 degrees in yaw.

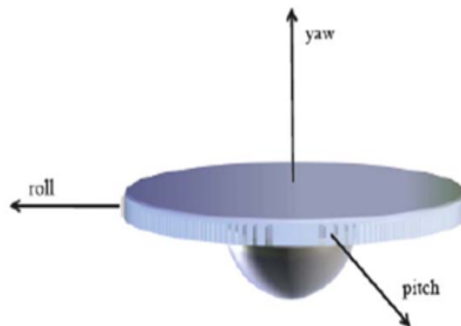


Figure 2. Visualization of tabletop testbed

3.1.2 The platform

The balance masses will be attached to the platform to align the center of mass with the center of rotation, and they will be located along three axes (X, Y, and Z). Each axis is placed at a different angle, measured from the center of the

platform. The X and Y axis balance mass assemblies are mounted 90 degrees from each other, and both are 135 degrees from the Z axis balance mass.

3.2.1 3D model

Platform/Bed

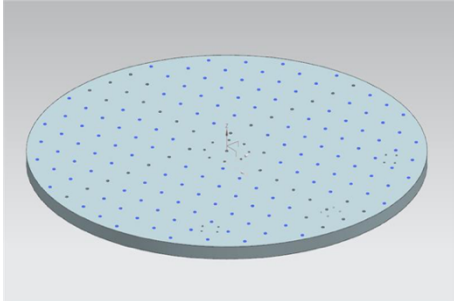


Figure 3. NX-Siemens 3D design of the Testbed's Platform

Stand

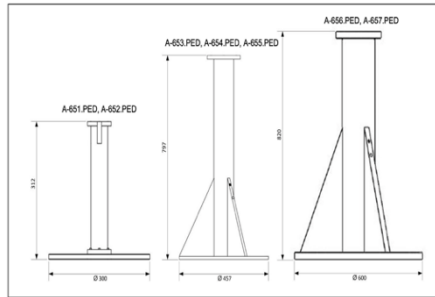


Figure 4. Dimensions of the PI Air bearing's stand.

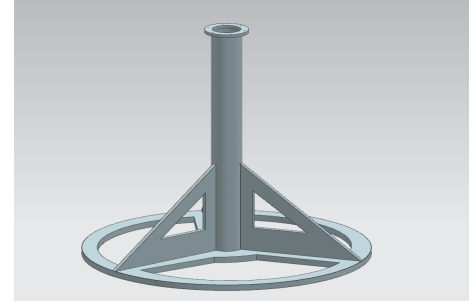


Figure 5. NX-Siemens 3D design of the Testbed's Pedestal.

Balancing Masses

The balancing mass consists of four components: the mass holder, slotting rod, L-bracket, and the main bracket.

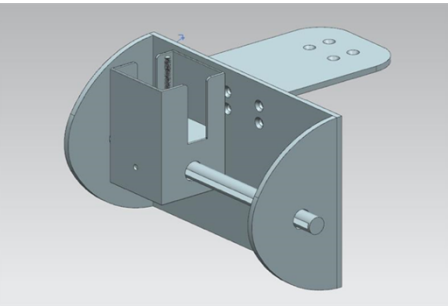


Figure 6. NX-Siemens 3D design of the platform's X and Y axes balancing masses.

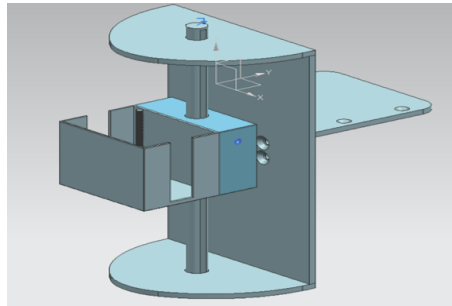


Figure 7. NX-Siemens 3D design of the platform's Z axis balancing mass.

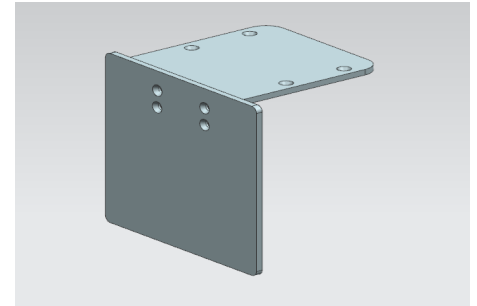


Figure 8. NX-Siemens 3D design of the platform's Arduino.

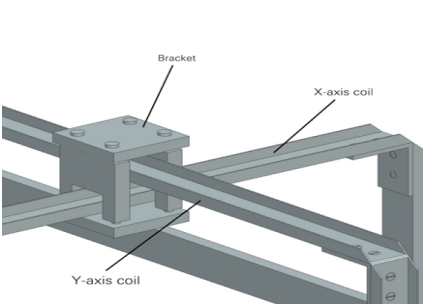


Figure 9. NX-Siemens 3D bracket assembly.

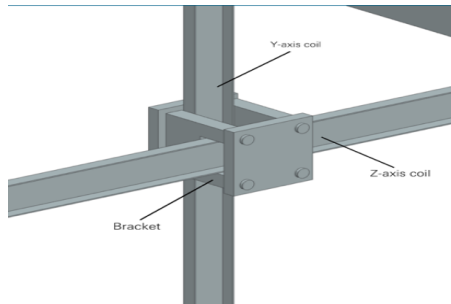


Figure 10. NX-Siemens 3D design of Z-Axis attachment point.

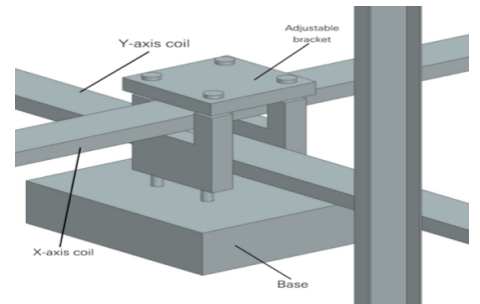


Figure 11. NX-Siemens 3D design of the base and bracket.

- The Y and Z axes will be joined by the same bracket, as seen in Figure 9.
- A base will support the cage to raise it above the floor to avoid any disturbances, and the base is attached to the bracket used to mount the X and Y axes together, as noticed in Figure 10.

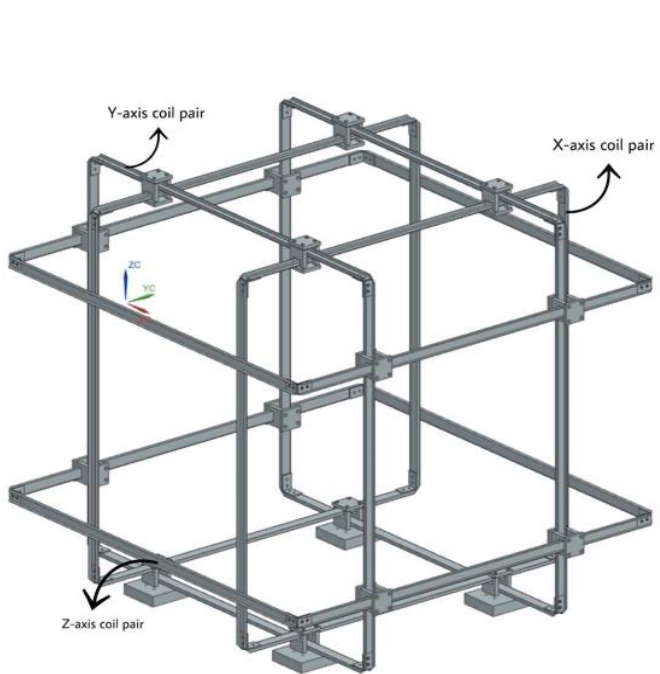


Figure 12. NX-Siemens 3D design of the assembled Helmholtz cage.

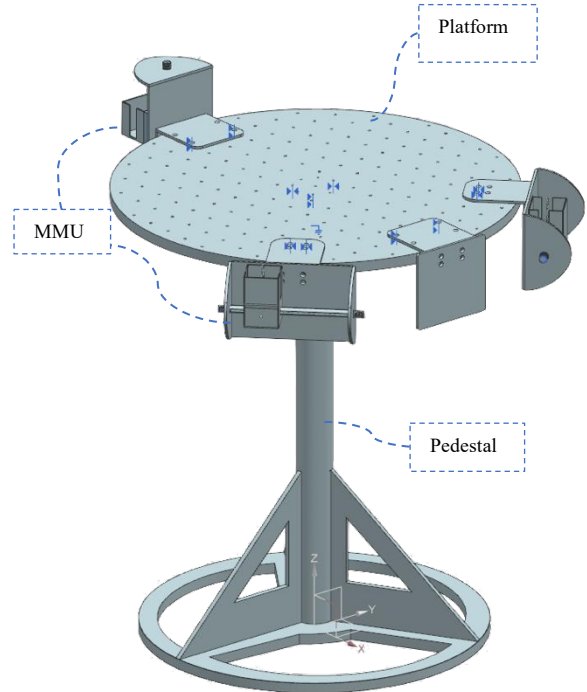


Figure 13. NX-Siemens 3D design of the assembled Testbed.

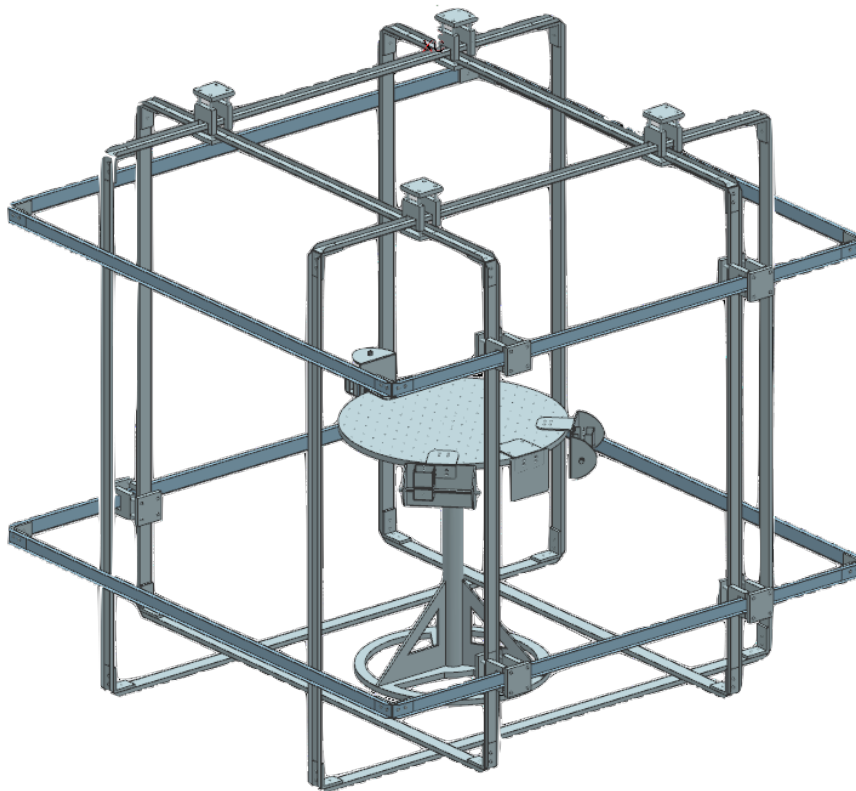


Figure 14. NX-Siemens 3D design of the assembled Testbed System.

4. Results and Discussion

4.1 Stress calculation (analysis calculation)

$$\text{margin of safety} = \frac{\text{max yield stress of your material}}{\text{maximum stress of your design} \times \text{safety factor}} - 1 \quad (1)$$

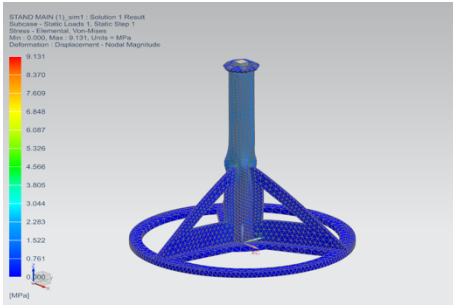


Figure 15. Stand Stress Elemental Analysis.

$$\text{margin of safety} = \frac{276}{9.131 \times 1.5} - 1$$

Margin of safety=19.15>1, considered safe

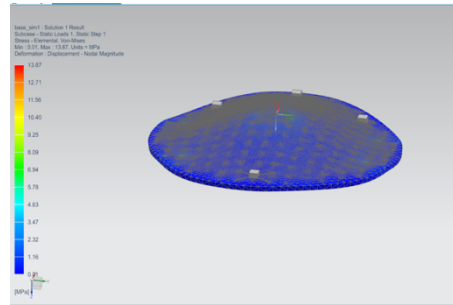


Figure 16. Bed Stress Elemental Analysis.

$$\text{margin of safety} = \frac{276}{12.87 \times 1.5} - 1$$

Margin of safety=12.266>1, considered safe

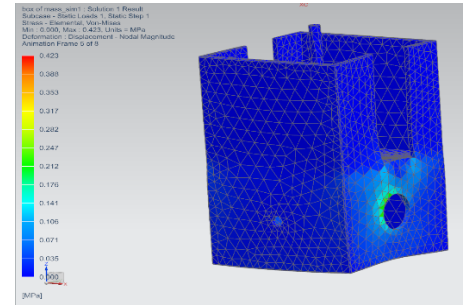


Figure 17. Mass holder stress Elemental Analysis.

$$\text{margin of safety} = \frac{276}{0.423 \times 1.5} - 1$$

Margin of safety=433.98>1, considered safe

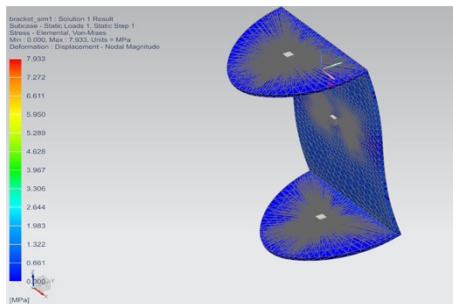


Figure 18. Mass Bracket stress Elemental Analysis.

$$\text{margin of safety} = \frac{276}{7.933 \times 1.5} - 1$$

Margin of safety=22.194>1, considered safe

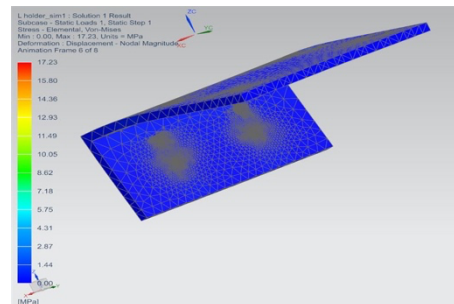


Figure 19. Mass L-bracket stress Elemental Analysis.

$$\text{margin of safety} = \frac{276}{17.23 \times 1.5} - 1$$

Margin of safety=9.679>1, considered safe

4.2 Discussion

NX-Siemens is used to test the testbed design. The design has undergone stress analysis. The circumstances of each sub-component in the testbed are determined differently. In Fig. 15, the stand is tested by putting a force of up to 800 N on the top of the stand, which is the mass of the fixture, the satellite, the mass balancing system, and the electrical component. By calculating the safety margin, the stand is considered safe as the margin of safety is greater than one. Then the main part of the testbed, which is the platform, is tested by distributing the forces as shown in Fig. 16, which are from the mass balancing system and the fixture. Also, the safety margin of the stress analysis of the platform is

considered safe. Figs. 17, 18, and 19 are parts of the mass balancing system; they are considered safe as long as the safety margin exceeds one. Conclude that the design of the testbed will be capable of holding up to a 12U CubeSat.

5. Conclusions

This paper attempts to show how we can test an Attitude Determination and Control System (ADCS). Since the vision of the UAE has been to explore space more, we need to help develop testing systems for such components. Our main goal in the project is to test the attitude determination and control systems of up to 12U CubeSats. The frictionless and magnetic field space environment required for the CubeSat must be simulated in order to test the ADCS. Based on the expected results from the paper, the outcomes to be delivered upon the successful completion of this paper would be Literature reviews were conducted on previous ADCS testbeds and the Helmholtz cage, identifying the hardware requirements, software requirements, and mechanical constraints for the system. As part of the design process, the component combination that best meets the needs of the targeted application was selected (the mass balance, sensors, etc). A detailed 3D and 2D design of the system was provided. As well as design stress analysis using NX.

Acknowledgements

This project would not have been possible without our extensive support from the National Space Science and Technology Center at United Arab Emirates University Their support, knowledge, and patience have been insightful in that they allowed us to apply what we have learned over the years as aerospace engineers into the workforce. And this work is supported by the startup grant funded by UAEU-MBRCS student research program, the grant code is (G00004025). Finally, we would like to thank our family members for their unending support and help throughout our study.

References

- [1] *NASA*. (n.d.). Retrieved November 7, 2022, from https://www.nasa.gov/sites/default/files/atoms/files/nasa_csl_i_cubesat_101_508.pdf
- [2] M. E. Rudd and J. R. Craig, "Optimum Spacing of Square and Circular Coil Pairs," 1968.
- [3] R. Galliath, "Design of a CubeSat Testbed," thesis, 2020.
- [4] J. A. Olsen, "Attitude Determination and Control System Testbed for Hardware and Software Testing and Verification for Small Satellites," thesis, 2021.
- [5] "ADCS Test Facility," *Hawaii Space Flight Laboratory*. [Online]. Available: <https://www.hsfl.hawaii.edu/facilities/adcs/>. [Accessed: 1-Oct-2022].
- [6] Irina Gavrilovich. Development of a robotic system for CubeSat Attitude Determination and Control System ground tests. Automatic. Université Montpellier, 2016. English. NNT : 2016MONTT329 .
- [7] K. J. J and A. B. N, "Automatic Mass Balancing of Air-Bearing based Three-Axis Rotational Spacecraft Simulator," *Guidance, Control, and Dynamics*, vol. 32, pp. 1–14, 2009.

[8] D. M. Meissner, “A THREE DEGREES OF FREEDOM TEST BED FOR NANOSATELLITE AND CUBESAT ATTITUDE DYNAMICS, DETERMINATION, AND CONTROL,” thesis, MASTER OF SCIENCE IN MECHANICAL ENGINEERING, California, 2009.

[9] IEEE code of Ethics. IEEE. (n.d.). Retrieved November 7, 2022, from <https://www.ieee.org/about/corporate/governance/p7-8.html>

[10] Attitude Control for satellites flying in VLEO using aerodynamic surfaces. (n.d.). Retrieved November 7, 2022, from https://www.researchgate.net/profile/Valentin-Canas/publication/338573033_Attitude_control_for_satellites_flying_in_VLEO_using_aerodynamic_surfaces/links/5e1da91992851c1dcd387e32/Attitude-control-for-satellites-flying-in-VLEO-using-aerodynamic-surfaces.pdf

[11] Helmholtz Cage. (n.d.). Retrieved November 7, 2022, from <https://uccubecats.github.io/HelmholtzCage.html>