A Testbed for a three dimensional Pico–Sphere Satellite–Simulator(T3Dpilare)

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***Abstract*—This paper presents the mechanical design, assembly and construction of T3Dpilare. The principle target for this research was to design and built a three–axis floating–satellite simulator with six degree of freedom which is placed in a sphere for free movement. This three axis float–sat will be used to test the algorithms for three dimensional attitude control of satellites on earth. The simulator is named as 'T3Dpilare'. T3Dpilare is quite unique in its design, principle and mode of operation. It is a compact satellite simulator for the students and researchers. It offers a simple platform for on–ground testing of satellites and their subsystems in a quite frictionless environment to simulate the effect of zero gravity in the space.**

***Index Terms*—Aerospace, Avionics, Satellite Simulator, Attitude Determination and Control.**

I. Introduction

T3Dpilare is an air–bearing sphere, which is able to rotate freely in all three directions, internally rotation should be created by the virtue of the torque produced by the reaction wheels, same mechanism is also used in real satellites. The challenging situation for these kind of satellite simulator is the gravitational force of earth. If the centre of gravity of the sphere does not match with the physical geometric centre of the sphere then there would be a force arm which results in an unwanted torque, it is therefore required to shift the centre of the gravity of the sphere in the direction of its geometric centre. In order to full-fill this requirement there should be three moving masses in each direction (X,Y,Z), The position of the moving masses are controlled by the stepper motors. To determine the rotations a nine degree of freedom(DoF) IMU (Inertial Measurement Unit) should be used, it has a three dimensional rotation speed as well as a three dimensional acceleration sensor. The accelerometer shows us the direction of the gravitational vector and the position of the sphere, therefore it is necessary to determine the centre of of gravity of the sphere by using 6DoF IMU, where the the centre of gravity of the sphere is controlled by means of stepper motors and movable masses. The project had following requirements.

- The complete structure of T3Dpilare must reside in a hollow glass sphere of 30cm diameter.
- Structure should include three DC and three stepper motors.
- Each dc–motor should be able to rotate the float–sat in its particular axis so that the rotation in all 3–axis should be possible.
- The structure should be designed in such a manner that the stepper motor should be able to balance the centre of gravity by moving the attached masses .

In section two the state–of–the–art of the related projects are described. In section three the planning and the Computer Aided Design (CAD) of the simulator is presented which is followed by section four where the assembly and the integration of the different parts of the simulator are presented with explanation about the on–board electrical and electronics modules. In the last section the overall conclusion of the design and development of the T3dpilare is discussed with the recommendations for the future version of the simulator.

II. State–of–the–Art

In the field of Aerospace technology several projects are conducted to simulate the small satellites. In this section a brief description is provided about the similar efforts people have done for space research and development:

A. Floating Satellite (Float–Sat)

The Chair of Aerospace Information Technology at the University of Würzburg (Germany) has developed a Floating Satellite (Float–Sat) system. This system is used as a part of the exercises offered in the aerospace laboratory. It explains the approach for building small satellites to the students to learn and get familiar with basic satellite subsystems. It also provides a way to develop and test different control algorithms and strategies for different kind of space missions in an almost frictionless environment. The FloatSat system consists mainly of a mechanical structure that contains the basic satellite subsystems with one reaction wheel mounted at the centre of the horizontal plane of the structure. This reaction wheel is used to control the orientation of the satellite in one dimension. The detail of the FloatSat project can be found at [1].

B. Three Degree of Freedom (3DoF) test–bench for CubeSats

The University space centre of Montpellier and Nime, France has created a test–bench for CubeSats with three degree of freedom. In this test–bench a CubeSat is held in a frame with the hollow air–bearing, there is an external frame which is attached to a support and have an arm that is joined with an inner frame that contains hollow air–bearing pucks. When the sliding air–caps are attached to the bearing pucks the test-bench is able to rotate the CubeSat in all three axes [2].

C. Simsat: A Ground Based Platform For Demonstrating Satellite Attitude Dynamics And Control

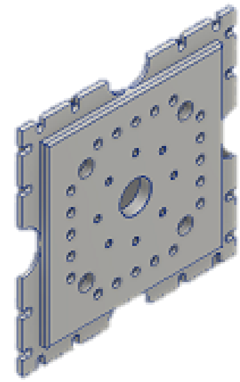
A simulation satellite is developed in the joint venture of United States Air Force Academy and Air Force Institute of Technology. Simsat was based on a spherical rotor which was placed on a air pedestal.The satellite's components were attached around the surface of the spherical rotor in such a manner that whole spacecraft was balanced [3]. This idea was presented almost twenty years ago. It provides an excellent opportunity to the students to practically learn the operations of a satellite in real time in a laboratory. Although the objective of Simsat and T3Dpilare were same but the T3Dpilare is also meant to be very simple, compact and small in size.

The goals of all the simulators described above were quite same but their structure and Attitude Determination and Control System (ADCS) are different. In the paper [4] the author has described many more simulators people have invented for the simulations of an aerospace vehicle.

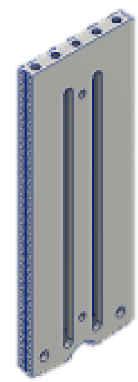
III. Planning

The T3Dpilare consists mainly of a mechanical structure that contains the basic satellite subsystems with three reaction wheels attached with a dc–motor mounted in alignment with the X, Y and Z axis. These reaction wheels are used to control the orientation of the satellite in three dimensions. In–line with each dc–motor there exist a stepper motor with a moving mass to adjust the centre of Mass (CoM) of the structure to balance it perfectly.

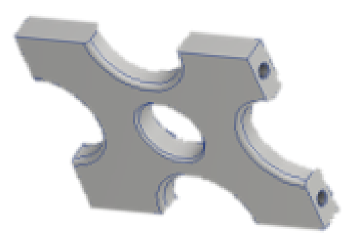
In order to facilitate a simple, compact and symmetrical design , computer aided design (CAD) tool Inventor^{TM} was used to develop the structure of the T3Dpilare. The mechanical parts were designed to create the housing for three DC motors and three stepper motors, DC motors housing was created to put the motor with the reaction wheel. The housing for the stepper motor was created to put the stepper motor with the moving mass. This moving mass approach was adopted to adjust the centre of gravity during the operation of the satellite. The design was conducted so that wiring remains simple. In the following two figures some of the CAD designs of the components of T3Dpilare are presented. The housing for the batteries was designed in such a way that they can be easily charge and replace. Each battery is one cell battery. There are four housing designs to accommodate three batteries in each housing. In total there are twelve batteries in T3Dpilare. In the following figure the fully assembled design is presented. The reaction wheels were facing towards the cube and the centre housing was reserved for the stack of the controlling boards which includes the micrcontroller, dc motor driver, stepper motor controller, battery charging circuit and also an IO–expansion board.



(a) Base Plate



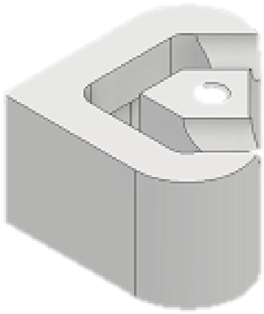
(b) Supporting–arm Plate



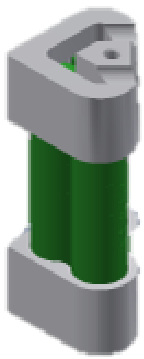
(c) End–stop

(d) Housing for dc and stepper motors

Fig. 1. Different Parts of the structure of the Simulator.



(a) Battery–holder



(b) Batteries in the housing.

Fig. 2. Mechanical Structure for the batteries.

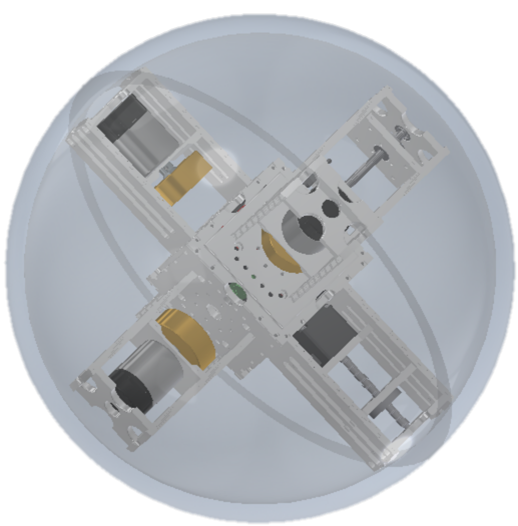


Fig. 3. Fully assembled CAD design of T3Dpilare

Diameter	3.5 cm
Thickness	0.8 cm
Weight	64.8 gm

Table I: Properties of reaction wheel.

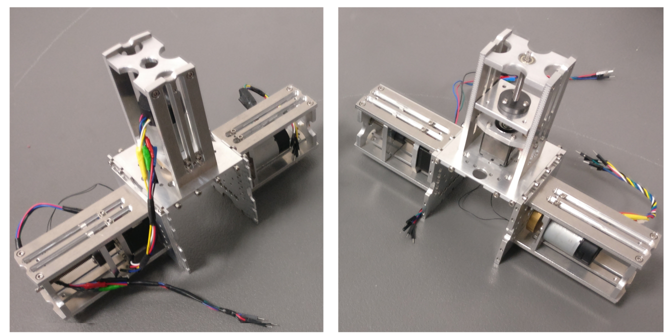


Fig. 4. Partially assembled structure of T3Dpilare

IV. Execution

After designing, all the parts of the structure were manufactured with Aluminium with the CNC machine. Aluminium was chosen because of the stability requirement. The reaction wheel that is meant to produce the torque to create angular momentum in each direction is made of brass. The density of this type of brass is 8620 $\frac{Kg}{m^3}$. This reaction wheel has following characteristics. As the design was conducted in a symmetrical fashion the assembly and the integration was also followed in the same way as shown below: The centre housing of the T3Dpilare was assigned for the microcontroller, driver boards for motors, IMU , IO–expansion and also the battery. The wiring of the components is conducted in a very careful way to avoid any loose wire that potentially creates the noise, endangers the electronics and also disturbs the operation of the T3Dpilare.

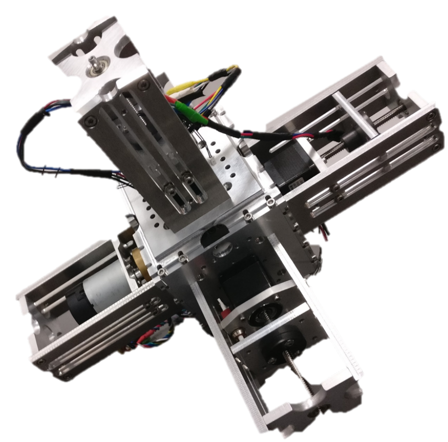


Fig. 5. Fully assembled structure of T3Dpilare

Fig. 6. Floating sphere

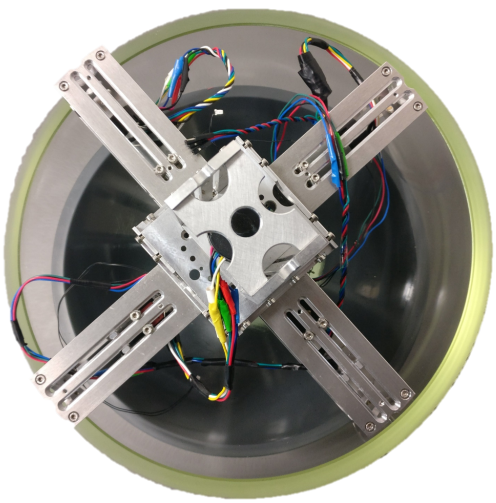


Fig. 7. Aerial view of T3Dpilare in the sphere on a floating platform

A. Floating Sphere

The T3Dpilare's structure presented in the above section is placed in a hollow sphere of the glass. The glass sphere is chosen over the plastic because the metal structure was heavy and it was not possible to properly operate with the plastic sphere. During the testing some non–uniformity was found on the surface of the glass then it was scratched to make it uniform.

Inner Diameter	30 cm
Thickness	12 cm

Table II: Properties of sphere

B. Vacuum Generation

In order to perform the proper operation of the T3Dpilare the vacuum is created in the sphere with a Deck Purge Box from the company Global Ocean Design^{TM} [5]. This box in combination with a purge port removes all the air and moisture from the sphere and creates vacuum inside to resemble the space environment around the concealed structure of T3Dpilare.

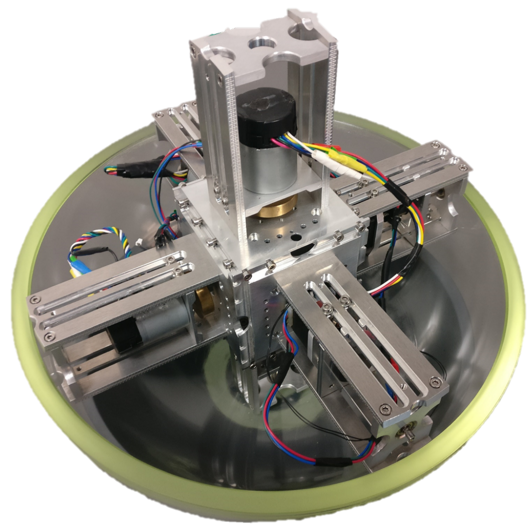


Fig. 8. Side view of T3Dpilare in the sphere on a floating platform

Fig. 9. Spherical Air Bearing Unit

C. Floating Platform

T3Dpilare's structure is placed into an Acrylic glass hemi–sphere shell that it is floating inside a Spherical Air Bearing Unit (SABU). The air bearing unit requires pressurized air input with a flow rate that may vary, depending on the mass of the floating unit. The pressurized air is fed in between the bearing surfaces through very small holes that are distributed on the unit's surface and discharge in the atmosphere through the edges of the bearing. This unit is made from Polyvinyl Chloride (PVC) material and it was designed to have a uniform distribution of the air flow and the pressure throughout the lubricating film between the unit and the hemisphere shell as shown in the figure 9. At the time of assembly it was observed that all the specifications of the mechanical designs were meeting the operating conditions, as shown in figure 10

D. Electrical Specification

There are four most important electrical components in the project, The dc motor interfacing, stepper motor interfacing,

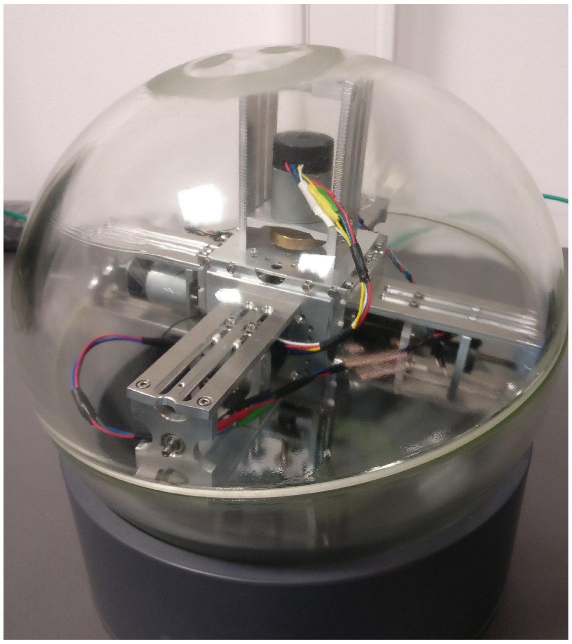


Fig. 10. T3Dpilare in operation

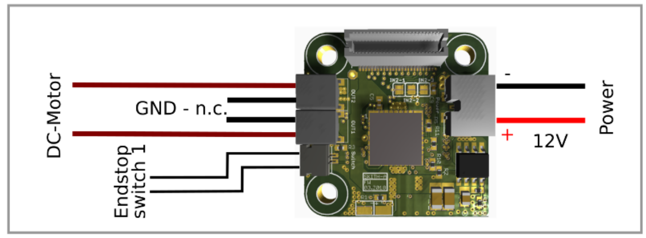


Fig. 11. DC motor driving board

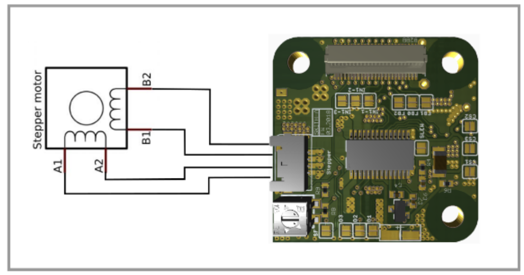


Fig. 12. Stepper motor Driving board

IMU and the power supply to the satellite. Each dc motor provides the rotation in a particular direction. These rotations are used to control the different modes of operation of the satellite. The IMU used in this project is LSM9DS1 from STMicroelectronics™, it has a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer in a single chip therefore it is able to provide nine degree of freedom in motion sensing [6].

1) On–Board Computer:: The on–board computer of this T3Dpilare is based on stm32f407 micrcontroller from STMicroelectronics™, it has a Cortex–M4 core [7]. Department of Aerospace Information Technology in the University of Wuerzburg has developed a very compact and customized state–of–the–art development kit based on this microcontroller for these kind of nano and CubeSat projects. This kit is developed in the form of stack. There is a unique possibility to add several extension boards on this kit. The first module contains the main board then there is an extension board which contains the driver for stepper motor and dc motor, then comes the extension board the IMU with the WIFI module and at last there is a IO–expansion board. The distance between two boards in the stack is 5mm. The thickness of each board is 1.6 mm.

2) Battery:: Battery was selected on the basis of the power requirement as well as on the basis of the geometry of the T3Dpilare. There are twelve Lithium Ion 18650 Cell (2600mAh) Batteries.

3) DC–Motor Interface: : There are three dc–motors present in the structure therefore it was required to design a dc motor driver. The dc motor driver was based on a MC33926 full H–bridge, which can be operated in the range of 5 Volt to 28 Volt and it can provide almost 3 Ampere current(with 5A peak to peak value) [8]. Power to the dc–motor is controlled via the pulse width modulation (PWM) generated by the internal timer circuit of the microcontroller, the PWM output is passed to the H–bridge board which controls the motor operation.

4) Stepper Motor Interface:: In order to balance the structure in all three directions there is a stepper motor attached in–line with each dc motor. A moving mass is attached with each stepper motor. The control software of the T3Dpilare should be able to rotate each stepper motor such that the attached mass is moved to a specific position so that structure does not vibrate and remains stable. The stepper motor carrier board is based on L6470 dSPIN motor driver from STMicroelectronics™. It can be operated in the range of 8 to 45 V and it can provide upto 7.0 ampere of current. The driver has an SPI interface [9].

5) Circuit Diagram:: The most important part of the electrical circuit of T3Dpilare is the battery charging circuit. The battery setup of the project was providing 14.8 Volt but each board in the stack is required to be operated on 12V. Therefore a step–down voltage regulator is used to reduce the voltage from 14.8 volt to 12 volt with 15 ampere of current. A power switch is connected between the voltage regulator and the charging circuit which allows the battery to be charged in isolation i.e without being connected with the rest of the circuit. The driver boards for the dc and stepper motors, board with debugging port, IO–expansion board as well as the main board with microcontrollers are designed discretely in such a manner that they can be connected together on top of each other to form a stack. This kind of setup has improved the harness efficiency by eliminating the use of many individual wires and this stacking of boards was also necessary to place all the boards in the centre housing of the T3Dpilare.

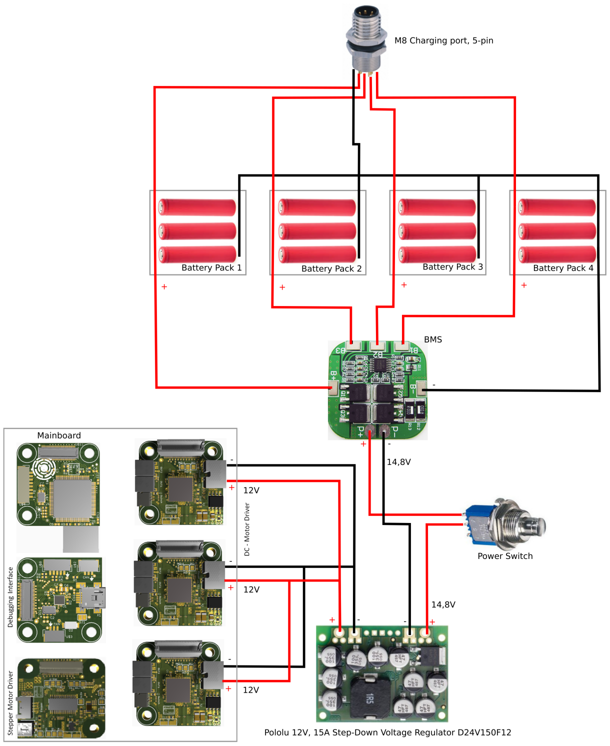


Fig. 13. Electrical Circuit diagram of T3Dpilare

V. Conclusion and Future Work

This research has produced a ground–based platform to understand the sub–systems and components of a space vehicle. It provides means to experiment, check and validate different control algorithm for the ADCS of satellites. The whole target of this project was to develop the structure of a pico–satellite with six degree of freedom . Additionally the electronics for the motors, batteries and sensors was also developed. The T3Dpilare is an state of the art satellite simulator which is designed and built to support research and education. The pitch, roll and yaw of the simulator can be controlled for the different modes of operations of the satellites. The structure is enclosed in a hollow–sphere where the vacuum is created with the vacuum generator and the structure is being floated on a hemispherical air–bearing unit which is providing a frictionless platform for the simulator to be operated in an environment which is similar to the space where the gravity is zero. The future work for this project is related to the development of the control algorithms for the autonomous operation of ADCS and also the testing of different machine learning and evolutionary algorithms for the ADCS.

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