Structural Design, Integration of Micro Propulsion units and Thermal Analysis of UWE (University of Wurzburg's Experimental Satellites) Platform

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Abstract
Pico satellites have seen major technological advancements in recent years. The next UWE mission objective is to demonstrate orbit manoeuvring capabilities combined with precise attitude control using an electric propulsion system. This paper summarizes the thruster integration concepts, CAD design and analysis. Structural analysis is carried out using NX Nastran with the launch conditions and results being presented. Also, Orbital heating analysis was performed using NX Space Systems Thermal to study the thermal behaviour and results are validated against in-orbit data from predecessor UWE-3. Based on the results, generic design is qualified for launch and is expected to serve as a platform for future satellites.

1. Introduction

During recent years, we have seen the tremendous growth in the potentials of CubeSats and its applications. Universities are working towards CubeSat programs with advanced mission objectives and pushing the limits of the platform. Also, national space agencies are supporting diverse research ideas to validate the technical capabilities and look forward to utilize CubeSats as a cost effective platform. In the UWE program (University of Würzburg Experimental satellites), a roadmap was set to utilize a Picosatellite formation flying for Earth observation based on multi-point measurements [1]. UWE-1 launched in 2005, tested to optimize the telecommunication link using Internet Protocol parameters with respect to the challenging space environment [2]. UWE-2 launched in 2009 to test and demonstrate attitude and orbit determination. UWE-3 mission was successful in implementing a real-time miniature attitude determination and control system on-board the satellite [3]. The next UWE mission objective is to demonstrate orbit manoeuvring capabilities combined with the precise attitude control using a micro propulsion system.

2. UWE Platform design and development

UWE-3 introduced a robust and flexible pico-satellite architecture and intended to have a generic satellite platform for future UWE missions [4]. The subsystem design of UWE platform includes

1. OBDH (On-board Data Handling)
2. ADCS (Attitude Determination and Control system) with Wheel drive unit
3. Communication subsystem
4. Power subsystem (batteries, solar cells)
5. Propulsion subsystem (Thrusters and PPU)

The spacecraft's structures are usually classified into primary and secondary structures. Those which react to the overall bending, axial, shear, and torsional loads constitutes primary, whereas those elements which do not appreciably contribute to overall stiffness falls under secondary category. In UWE platform, the primary structure comprises of CubeSat rails, spacers, and bolts and the secondary structure comprises outer panels and other structural elements. The materials used for the rails are Aluminium 6061-T6 as specified in CubeSat design specification.

The On-board Data Handling subsystem is the core of every satellite and has control over all the other subsystems. The UWE platform on-board system currently features a two redundant ultra-low power 16 MHz micro-controllers designed to dynamically function in a Master-Slave configuration. The design features a toggle watchdog, power cycling unit and supporting electronics. It is also responsible for storing and transmitting the housekeeping data to the ground station. A detailed information about the hard- and software design aspects of OBDH system is given in [4].

The attitude determination system consists of three types of sensors: magnetometers, sun sensors, and gyroscopes. The primary set of magnetic sensors is single-axis hall sensor devices mounted on the ADCS board and the secondary set are mounted on the inner side of the each panel. Attitude control is mainly achieved through magnetorquers with the air coils wounded on the inside of outer panels. The sun sensors are located on each panel (six sides) and measures angle with a large FOV of 150° towards the brightest object in view and capable of determining the direction of incident light with an angular resolution of 2.7° and an accuracy of about 5°. The gyroscopes are single-axis MEMS devices mounted orthogonally to each other on the ADCS board. The satellite also carries a miniaturized reaction wheel intended for control manoeuvres which is mounted in between the ADCS and power board. It is controlled by a wheel drive unit attached as supplementary to the ADCS board.

The power board was designed with two Li-Po batteries with each having a storage capacity of 2600 mAh. It provides two default voltage levels (3.3 V and 5.0 V) to all subsystems with the power generated from the solar cells which have an efficiency of approx. 30 percent.

Micro propulsion units and the supplementary power processing unit are combined to form the propulsion subsystem. Currently we have two thrusters in consideration which are Micro Vacuum Arc thrusters (μVAT) from University of Armed Forces in Munich (UniBW), Germany and NanoFEEP (highly miniaturized Field Emission Electric Propulsion) thrusters from TU Dresden, Germany. Both thrusters fall under the category of electrostatic thrusters, however, they operate on different principles. The details on the operational principle of μVAT, design and development of power processing unit are discussed in detail in [5]. For the NanoFEEP thruster, the design, development and testing of the thrust units are discussed in detail in [6].

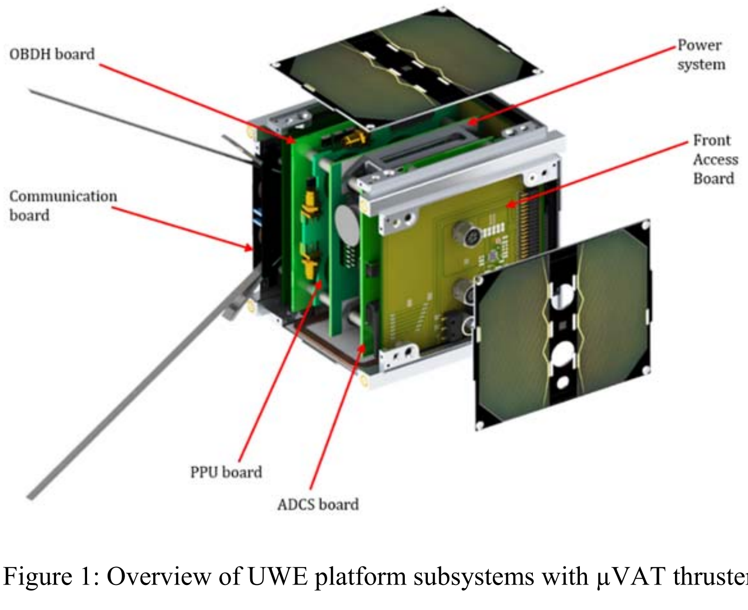


Figure 1: Overview of UWE platform subsystems with μVAT thruster

3. Thruster Integration – CAD concepts

To integrate the thrusters onto the CubeSat platform, mass and volume budget are the major constraints. Integrating a new subsystem into an already established platform leaves us with limited options. Different concepts were discussed initially to integrate the thrusters. They can be broadly classified into either attaching the thrusters on the side panels or attach on the inside of the CubeSat rails. Apart from the space constraints, it is also very important to provide enough rigid support to the thrusters for survival during the launch phase. So to provide structural integrity as well as to efficiently utilize the available space, it was decided to integrate the thrusters along the CubeSat rails. The inside portion of the corner frames have enough free space to accommodate the thrusters. This enables us to integrate four thrusters with one at every corner and therefore to deliver required torque and thrust combination during the mission. The arrangement of other subsystems are also modified to effectively distribute the mass and maintain the centre of gravity close to the geometric centre. We were able to achieve centre of gravity located within ±1.5 mm on all the axis from the geometric centre.

With the need to adhere CubeSat design specifications, the outer structures of the CubeSat rails are anodised to avoid cold welding with deployer rails. The CubeSat rails were custom designed specifically for the UWE platform, this allows vital modifications to accommodate the thrusters. With the two thrusters currently in study for integration, preliminary design concepts were developed to incorporate the thrusters. The concepts are shown below in Figure 3 and Figure **3**. To allow the integration along the rails the PCB on the inside need to be slightly modified to avoid interference.

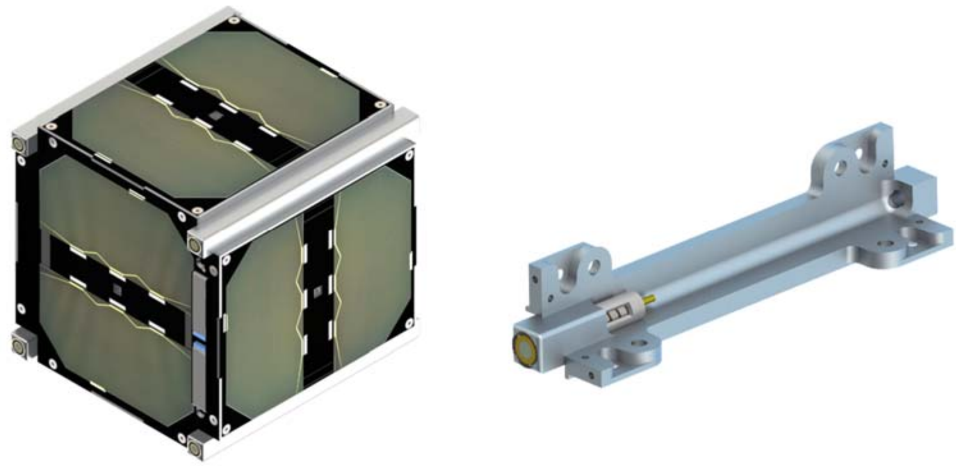


Figure 2: UWE platform concept with integrated µVAT from UniBW

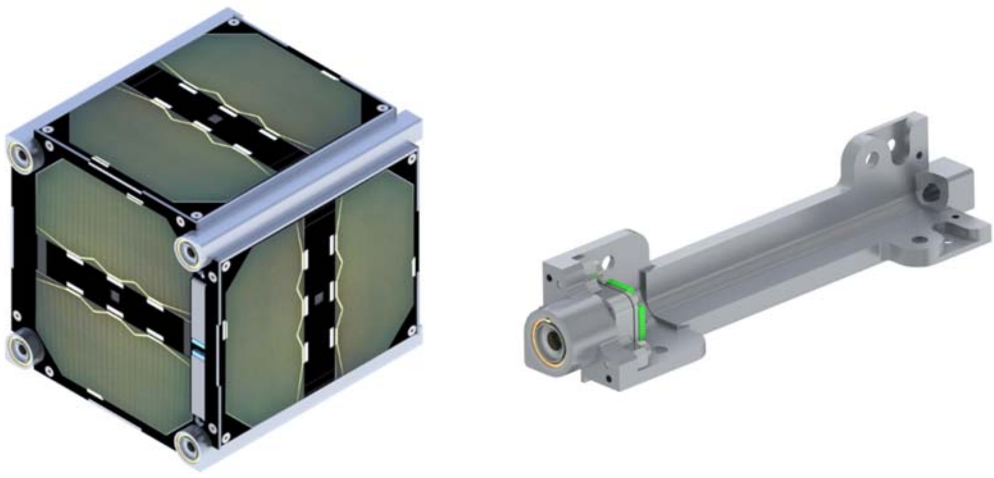


Figure 3: UWE platform concept with integrated NanoFEEP thrusters from TUDresden

4. Finite Element Modeling and Analysis

FEA was performed using Siemens NX CAE software. The main objective of the analysis is to study the structural and thermal behaviour under defined environment and boundary conditions. NX Nastran solver environment was used to simulate the structural analysis, whereas NX Space Systems Thermal suite was used to simulate the orbital thermal analysis. Orbital thermal analysis was performed very rarely in the Cubesat scale and also it is the first time performed in UWE-program.

Before FEA, the 3D CAD model were simplified and processed with the data such as material properties, loads, constraints as per the solver environment requirements. Meshing was done with greater care, such that the anticipated areas of stress will have high mesh density and this allows to get very accurate results. With proper preparation of finite element model, the computational time required for solving can be shortened to a greater extent.

4.1 Structural analysis

The structural simulation plays a vital role in validating the design and its robustness. This is achieved through static load analysis and Modal analysis [7]. Static loading analysis is mainly performed to study the structural deformation along with the displacement and to identify the regions of the maximum stress developed during the loading sequence. Modal analysis is performed to identify the natural frequency of the system and to verify with the natural frequency limitations provided by the launch provider.

4.1.1 Static Analysis

For the static load analysis, we need to simulate the actual loading conditions during the launch phase. Since the satellite's orientation is not known prior to launch, we have to assess the orientations based on the expected arrangements as specified in [8]. They are termed as horizontal and vertical arrangements.

To calculate the worst-case loads during acceleration period of the launch vehicle into orbit, the accelerations level are assumed to be approximately 10.5 g in the longitudinal direction and 3.5 g in the transverse directions. Also, the cubesat assumed to be placed at the bottom of a 3U rack and the weight of the other two satellites acts on the bottom CubeSat. In addition, the mass of the individual CubeSat is assumed to be 1.33kg max as stated in CubeSat design standards. With the above assumptions, the worst case loads of both arrangements are calculated.

- Vertical arrangement: 274 N longitudinal direction; 45 N in transverse direction.
- Horizontal arrangement: 137 N in longitudinal direction; 45 N and 91 N in transverse direction.

With the above loads, we developed test cases to perform the simulation. For vertical arrangement, we developed four test cases with major loads of 274 N on Z+ axis, transverse loads on X+, Y+ axis. Similarly, four test cases for Z- axis. In total, eight test cases for vertical arrangement and 16 test cases for horizontal arrangement with major loads on X +/- and Y+/- axis were studied.

The static analysis test was performed with SOL103-Linear static analysis solver in NX. For the vertical arrangement, maximum displacement on the structure is found to be 0.184 mm and maximum von-mises stress developed is 55 MPa. Whereas in the horizontal arrangement, maximum displacement is 0.262 mm and maximum von-mises stress developed is 115.57 MPa. The displacement levels are within the acceptable limits for the structure. The stress levels are well within the ultimate tensile strength of 310 MPa and the yield strength of 276 MPa of Aluminium 6061-T6.

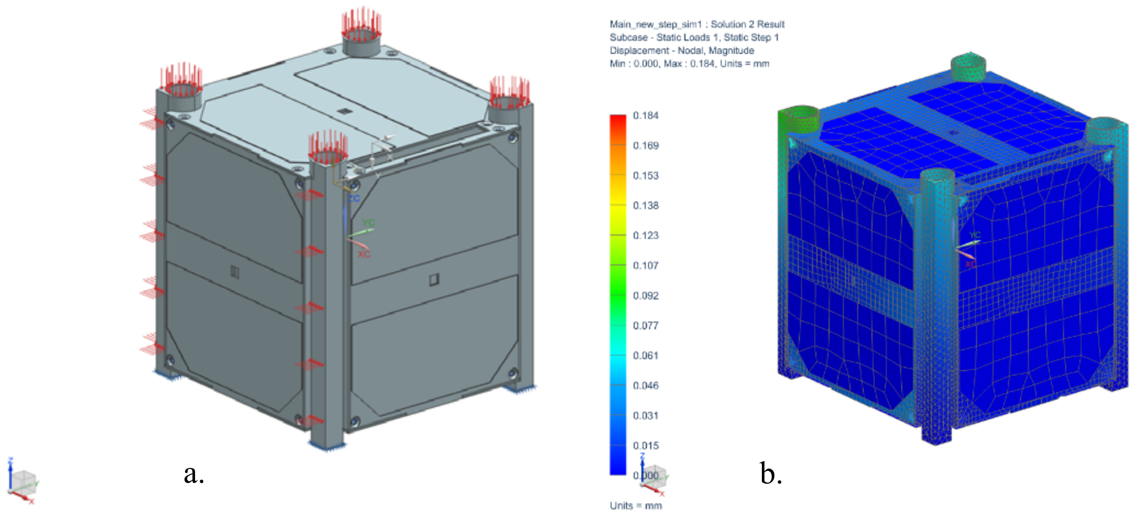
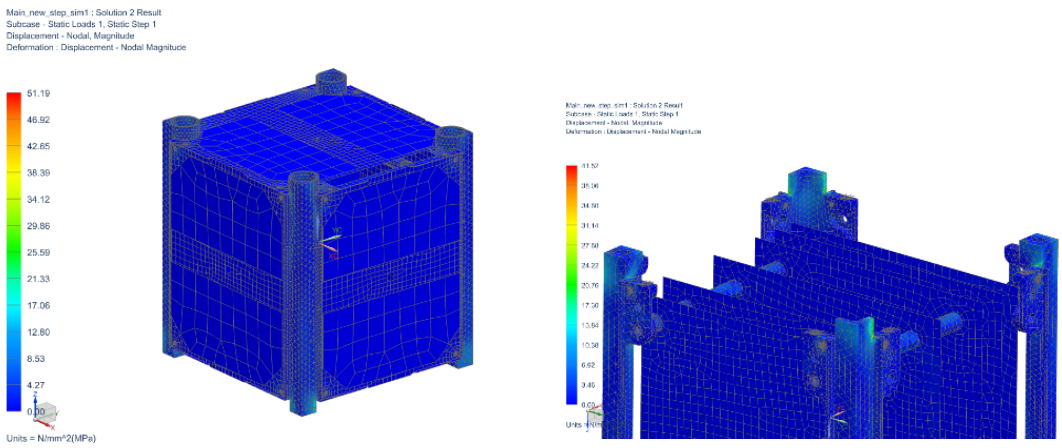


Figure 4: Static analysis (vertical arrangement) -- a.) Loading conditions b.) Displacement results



a. b.

Figure 5: Static analysis a.) Von-mises stress b.) Region of maximum stress

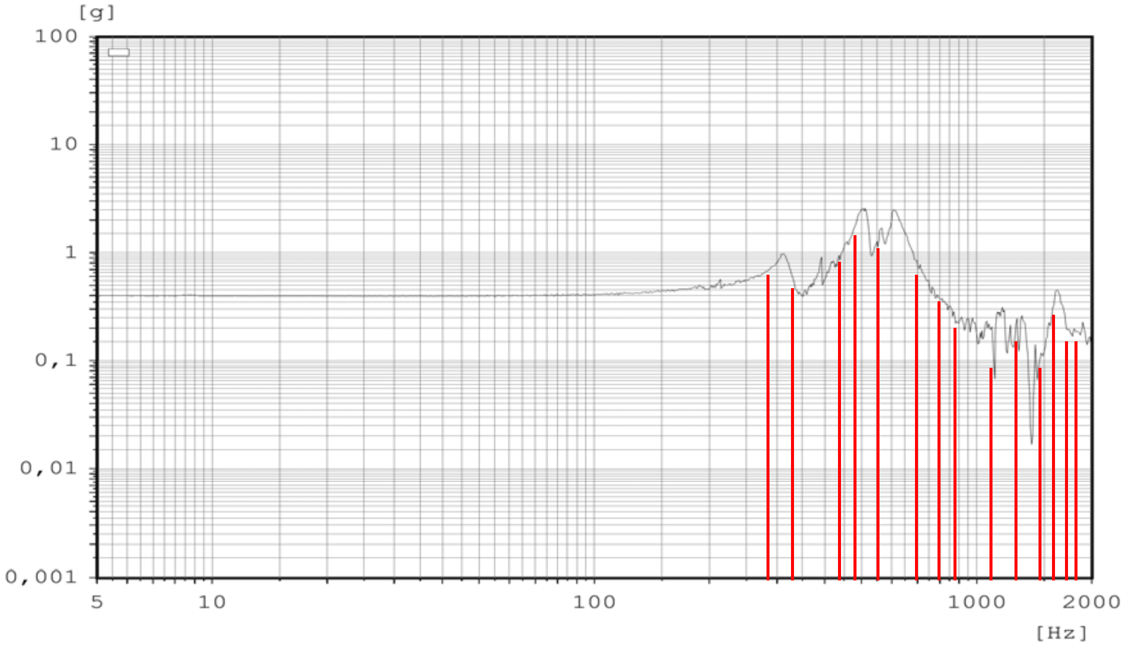
4.1.2 Modal Analysis

Modal analysis was performed to study the natural frequency of the future UWE platform with the new subsystems integrated. The analysis was performed using SOL111 – Modal frequency response environment in NX. The analysis was performed over the frequency range of 5 – 2000 Hz. Based on the launch vehicle user guide, the payload mounted within the launch vehicle should be designed with a natural frequency of more than 20 Hz in the longitudinal direction and 10Hz in the lateral direction. This is mainly to avoid the direct coupling of the payload with the launch vehicle interface. Also, it is stated that the fundamental frequency for the flight model of payload has to be greater than 20 Hz.

Table 1: Natural frequencies of the structure over 5 – 2000 Hz range

Mode	Natural Frequency [Hz]	Mode	Natural Frequency [Hz]
1	286.9	11	879.1
2	336.1	12	1088.4
3	442.3	13	1256.3
4	449.3	14	1459.7
5	488.5	15	1541.1
6	556.3	16	1547.8
7	701.8	17	1602.3
8	799.3	18	1717.9
9	805.6	19	1744.3
10	820.6	20	1821.2

The above list of natural frequencies are then verified with real-time vibration test results performed for UWE-3. The comparison results are provided below in Figure **6**. The plot shows frequency range of 5-2000Hz in the x-axis and the g-force in the Y-axis direction. The red lines indicates the frequency data obtained from simulation. The simulation results are very much intact with the actual data performed for UWE-3 and this suggests the structures are qualified for launch.



Frequency data from simulation; data from UWE-3 vibration test; X – frequency; Y – g-force

Figure 6: Natural frequency results comparison with UWE-3 test data

4.2 Orbital thermal analysis

Most of the UWE CubeSats will be launched into the sun-synchronous orbit at an altitude of 700~800 km with the ascending node varying from 11hr to 15hr where this allow the CubeSat to have a minimum eclipse duration of 15-20 min for every orbit. The main objective behind the orbital thermal analysis is to visualize and validate the thermal performance of the system in the orbit. It was performed using the NX space systems thermal suite.

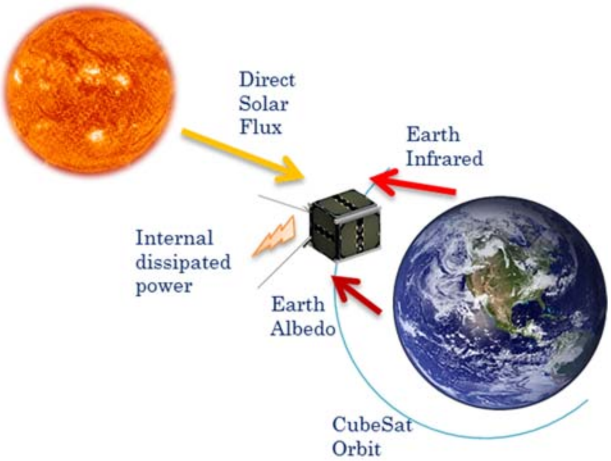


Figure 7: Major heat sources of CubeSat in orbit

In order to perform orbital simulation, orbital parameters need to be provided as input. So in order to verify the test results, it was decided to simulate the orbital characteristics of UWE-3 satellite. Two line element data taken from NORAD are considered, parameters are derived from the two line elements and provided as input to the system. Other required simulation objects are selected based on the analysis requirements. Hemicube algorithm with the medium view factor accuracy of 128 x 128 was chosen to compute the view factor. This was mainly selected over its advantage of having calculation time linear with elemental count.

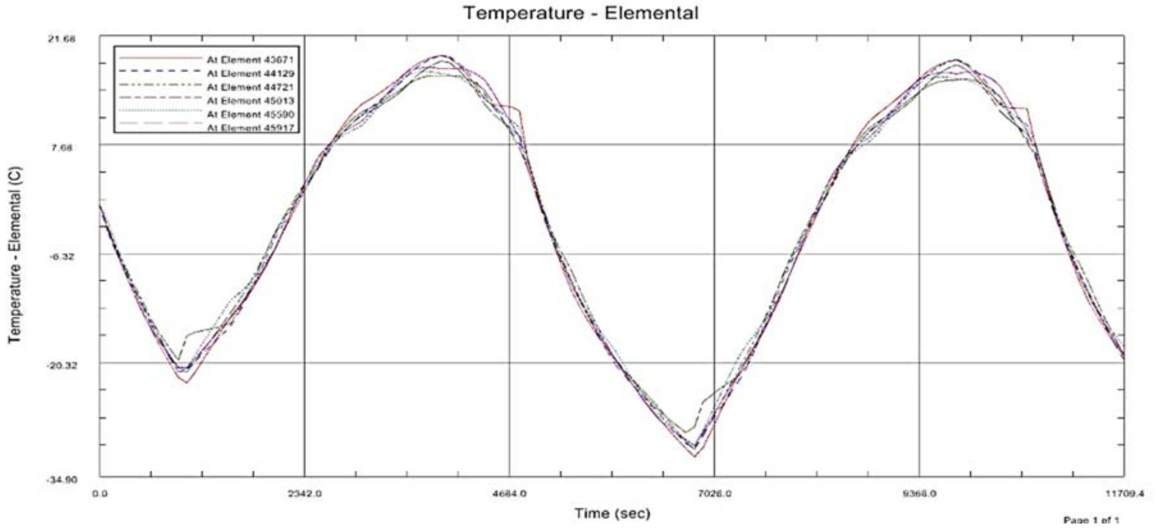


Figure 8: UWE-4 panel temperatures from orbital simulation

The data presented above was obtained from the simulation over a period of two orbits. The finite elements situated near to the temperature sensors on the outer panels were selected for the above plot. It is evident from the results shown in Figure **8** that the temperatures of the panels vary from 21º C to -29º C over the course of one orbit. The above results are verified against the in-orbit temperature sensor data from the outer panels on UWE-3 shown in Figure **9**. The simulation results are very much intact with the in-orbit data and this will enable us to characterize the system's performance in future.

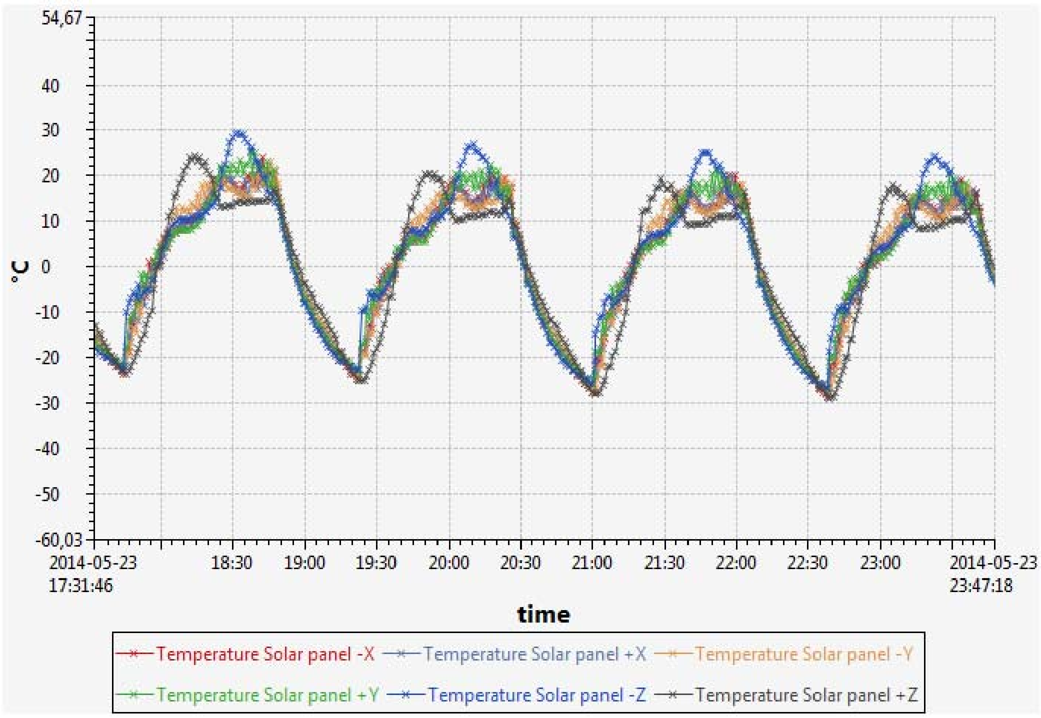


Figure 9: UWE-3 in-orbit temperature sensor data

5. Conclusions

The next UWE satellite will carry an electric propulsion system for attitude and orbit control. For the integration of thrusters, several concepts were discussed and finally opted to attach it into the CubeSat rails. This design integration provides the best possible solution for adding micro propulsion system into the UWE- platform. The mass of the platform is well distributed and the satellite's centre of gravity was maintained close to geometric centre with ±1.5 mm on all the axis. This provides great advantage over the design and control perspective. The results from the finite element analysis verify that the structure satisfies the generalised launch vehicle payload requirements. Orbital thermal analysis was carried out to characterize the system's performance while in orbit. The data from the simulation are very much intact and validated against in-orbit sensor data from UWE-3. Any new additional subsystem integration in future will require modification to accommodate it into structure. Integration of the thrusters will provide a sustainable platform for future missions. This will serve as base for any future UWE satellites and as platform for the pico-satellite formation flying mission [9].

Acknowledgements

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