n-LOTUSat: The Design of a Student-Driven Lean CubeSat Project

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Lean satellite concept is built on designing nonconventional and non-profit satellite with less cost and less time consuming than conventional satellite design. In this concept, taking risks is easier thanks to its budget and time advantages. This provides performing new and interesting experimental ideas. The idea of n-LOTUSat (Nano Lean satellite Of Technical University) is inspired by the lean satellite concept. It is a one-unit CubeSat project which is under development by undergraduate students of Istanbul Technical University (ITU) with the support of Space Systems Design and Test Laboratory (SSDTL). Missions of the satellite are testing a magnetometer –that is designed by the team- in space environment and measuring radiation at Low Earth Orbit (LEO) as well as using a camera as a horizon sensor. The primary mission is testing our magnetometer in space environment and comparing its measurements with a commercial-of-the-shelf (COTS) magnetometer. Moreover, we will use their magnetic field vector measurements in our attitude determination and control (ADC) algorithm. The secondary mission is measuring total ionizing doze (TID) radiation with a dosimeter at LEO. The tertiary mission is developing a horizon sensor algorithm and testing the algorithm on the camera's processor by using camera images.

Keyword: CubeSat, lean satellite, magnetometer, dosimeter, camera

1. Overview

n-LOTUSat is a 1U CubeSat that has three distinct payloads for three unique missions: a magnetometer, a dosimeter, and a camera. Objectives of the CubeSat are: To test a fluxgate magnetometer which has been designed and produced by the team, to collect data about the total ionizing radiation dose that the satellite is going to be exposed to at LEO, and finally develop a horizon sensor algorithm that utilizes on-board camera images. Passive control has been chosen since high pointing accuracy is not vital for the aforementioned missions. Moreover, solar power and data handling systems are crucial for providing energy to the systems and managing the satellite with help of the on-board computer. Additionally, as a mission achievement, space qualification for in-house-made electrical power system (EPS) and on-board computer (OBC) cards shall be achieved.

2. General Design

Besides consisting of three payloads, n-LOTUSat has subsystems such as attitude determination & control, command & data handling, communication, structure & analysis, and electrical power subsystems. Primary payload is the fluxgate magnetometer which is designed and produced by the team members. Moreover, the magnetometer will be tested in space by comparing data from the COTS magnetometer already existing in the satellite. The secondary payload is a COTS dosimeter which will collect data about the total ionizing radiation dose that the CubeSat is going to be exposed to at LEO and provide a real-life data for the future missions. The tertiary mission is to develop a horizon sensor algorithm by processing the images taken from the camera on the CubeSat. A passive attitude control system consisting of a permanent magnet and hysteresis rods will be used hence, it does not require a high-precision attitude control to orient the camera and communication system. Also, to use the power efficiently, images will be taken only when the correct attitude is provided according to the data from the attitude determination algorithm. A QUEST-based algorithm is being developed by the team to reduce the computational load and determine the attitude in the most optimal way. The vector information which is needed by the attitude determination algorithm are a sun vector, which is to be determined by sun sensors, and a magnetic field vector, which is to be determined by an additional COTS magnetometer. A total of ten solar cells, two on each surface except one surface which have a magnetometer boom, the EPS card and batteries are parts of the electrical power system. In addition to these subsystems, the communication system, consisting of antennas and communication modules, and the OBC, the brain of the satellite, are other subsystems.

3. Background

3.1. General Information About the Team

The n-LOTUSat is a CubeSat project team established in 2021 by the students of Istanbul Technical University with the support of Prof. Dr. Alim Rüstem Aslan, the founder and director of Space Systems Design and Test Laboratory (SSDTL). The team consists of 21 undergraduate students from different disciplines such as electronics and communication engineering, meteorological engineering, and computer engineering, essentially astronautical engineering. Space Systems Design and Test Laboratory (SSDTL), which received mentorship at every stage of the project, has successfully placed a total of 6 CubeSats into LEO, including ITUpSat-1, the first CubeSat of Türkiye and working on more. Moreover, the electrical power system (EPS) and the on-board computer (OBC) system are designed by researchers of SSDTL. The compatibility of the designed components with the satellite was ensured by the team. In addition, solar cells and manufacturing of the structure were provided by The Scientific and

Technological Research Council of Türkiye (TUBITAK), an important research and development center. The name chosen as n-LOTUSat (Nano Lean Satellite of Technical University) reflects the identity and mentality of the project in the simplest possible way. In addition to enabling satellite production to become widespread in institutions such as universities; lean satellite model that paves the way for space technologies by reaching more customers due to its low cost. Proceeding with this mentality, the research, the reports, and the scientific data to be obtained from the space environment will be shared as an open source throughout the project. In this way, it is aimed to contribute to the CubeSat technologies and space science literature in the most effective way.

3.2. Mission Selection

At first when the team came together, the project was initiated by researching satellite systems. While researching satellite systems by exchanging ideas with our professors, the team's attention began to turn to PocketQubes. After a few months of researching PocketQubes and the space missions that can be designed with them, it was decided that making a CubeSat instead of a PocketQube would be a better choice for the project's goals. The first of the main reasons for this choice was that due to the small volume of the PocketQubes, the number of missions that could be fitted to it and missions' capabilities were insufficient for the project's goals. Secondly, if a PocketQube is to be designed, electronic cards with dimensions of 5cm x 5cm should be used, but the low production of these cards and the extra expensiveness of the produced ones did not suit our mentality. In case that this option was chosen, almost all cards would have to be produced by the team or would have to be bought at a relatively more expensive. Since the majority of the project consisted of astronautical engineering students, the main focus was on the systems engineering of space systems rather than electronic design. For this reason, it was thought that it would be more useful both for concentrating on the missions more and for the process of learning astronautical engineering, and it was decided to build a CubeSat project.

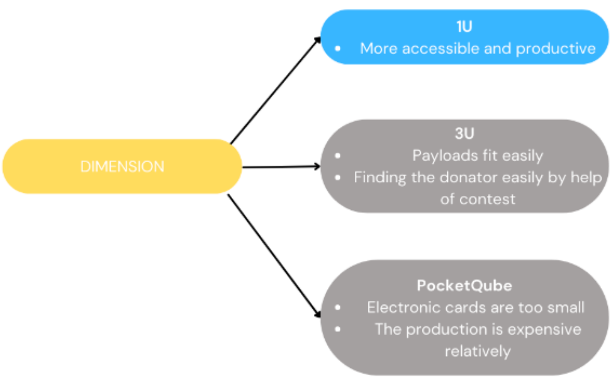

Fig. 1. Dimension Selection Trade-Off

When it comes to the CubeSat size selection, many CubeSat projects and missions have been researched, primarily university projects. In this research process, extra efforts were made to put the functionality and contribution to the scientific literature at the base of the project. While doing researches on the experimental approach in CubeSats, various CubeSat design competitions were encountered, but unfortunately it was seen that the application deadline for these competitions was missed and the competition option was eliminated because the team did not want to wait for close to a year to participate in the competitions. The trade-off on dimension selection of the satellite up to this time of the project is as shown in the Figure 1 above. Spectrometers were the first payload to be studied for a long time during the research process. The main reason the spectrometers were eliminated was that they were too large. In the beginning, it seemed logical to design a 3U satellite to easily use larger sensors such as spectrometers, but as the process progressed, considering the economic conditions of the country, it was agreed that there would be problems in finding sponsorship for such a project as undergraduate students. Thus, at this stage of the project, the size of the satellite, 1U, was decided. Subsequent research was directed to payloads with a smaller volume, but which would not deviate the project from the scientific mentality. Thermal cameras and CubeSat missions with thermal cameras have begun to be searched in order to contribute to the detection of increasing forest fires in the Mediterranean region and the observation of changes in water bodies that are accelerating as a result of climate change. However, both the large amount of data to be downloaded in these missions, the need for highly accurate attitude control, and the fact that the data to be obtained from a single camera on a single satellite would not be sufficient; were the reasons for the elimination of this option. After these processes, the selected missions are in order of priority; designing and manufacturing magnetometer, measuring TID with dosimeter, using camera as a horizon sensor and downloading photos of the Earth. Important parameters affecting the decision for the mission selection process can be seen in Figure 2 below.

The primary and main payload of the project, the magnetometer, will consist entirely of circuits and sensors to be designed by the team. The sensor, which will be produced as a desktop model beforehand regardless of sizing, will be reproduced in accordance with 1U CubeSat standards at the last stage. While choosing this mission, although the team were aware that a new product, which is not easily available in the market and has not been produced by our mentors before, will force the team; the work has started with the motivation of working on magnetometers theoretically before and being in a long-term project. The most important mission of the satellite is to provide flight heritage to a sensor, all of which will be produced by the team, to test it in space and to compare the data to be obtained from it with the data obtained from the Commercial Off-The-Shelf (COTS) magnetometer.

Choosing the dosimeter as a secondary payload was an ideal decision because it aligned with the aim of reducing the size to 1U and still having a scientific purpose for the CubeSat. The selected dosimeter has ideal features for our satellite in terms of power consumption, weight and dimensioning. The most interesting part about this mission is that the planned launch date coincides with the solar maximum, the peak point of the Sun's 11-year cycle. Moreover, the planned orbit, the ISS's (International Space Station) orbit, is one of the important orbits for total ionizing dose measurement.

As the tertiary payload, a camera had been chosen, the purpose what was originally planned was simply to take photos of the Earth and download the captured photos to the ground station. However, as the project progressed, the increasing level of knowledge of the team members encouraged using the camera as a horizon sensor. After determining the priority function of the camera as the horizon sensor, changes were made to the pre-selected mission requirements and therefore to the selected lens. The captured photo will be used in the data attitude determination algorithm after the camera's own microprocessor is processed in the algorithm.

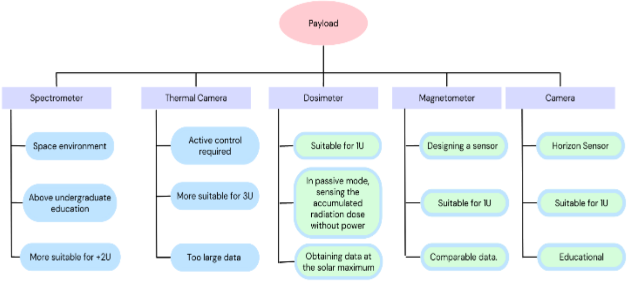

Fig. 2. Payload Selection Trade-Off

During the months of mission design, the only common idea was to develop an innovative and useful project. The entire mission design was shaped on this concept under the leadership of our consultant, and it still continues to evolve with more micro-developments.

4. Current Status and Plans of Payloads and Subsystems

A satellite is a device that has to work in extreme conditions due to the space environment such as huge temperature differences, vacuum and high radiation levels. Also, unfortunately, it is not possible to replace defective parts in the most cases. Therefore, a component that is expected to operate in space must be chosen punctiliously so that components must bear the conditions above. Although ground tests predict that the components will work in the space environment, flight heritage is the most assured way to predict that the components will operate in space without any malfunction. Thus, common parameters for the components are considered as: size, mass, power consumption, accessibility, ease of combining with other components and flight heritage.

4.1. Magnetometer

The primary mission is to design and manufacture a fluxgate magnetometer by the team and test it in space. Since all the team members are undergraduate students, at first, the team members had to acquire necessary knowledge of electronics and magnetometers. Vital information about how does fluxgate magnetometers work, what are the magnetic field and magnetic hysteresis have been learned. Extending the team's knowledge on these issues, a virtual electrical circuit was designed to generate waves, the key signal for measuring magnetic fields with fluxgate magnetometers. At present, the virtual circuit that produces the waves is being tested on a breadboard physically. In short, to make a desktop model of the fluxgate magnetometer is being tried. Thanks to these models, it is expected to understand the sensor and the circuit in a better way. The future plan is to improve the desktop model, in order to fit it to the CubeSat.

4.2. Dosimeter

While planning the launch date of CubeSat, it has been seen that the mission coincides with solar maximum of Schwabe cycle. Therefore, one of the missions has been chosen as measuring the TID which the CubeSat will be exposed to at LEO. Moreover, the collected TID data will be shared as open source. While searching the market and selecting a proper dosimeter, parameters that have to be taken into consideration had been conferred with MSc. Sahip Kızıltaş, an esteemed researcher of ITU Nuclear Energy Research Institute. For that purpose, a dosimeter with a high sensing range, from 1 cGy to 1 kGy, has been chosen. Another important parameter of the dosimeter selection was the power budget of the CubeSat. Since the mission required to detect TID, there was no option to not measuring the TID at any time in the orbit. Also, it was pondered that there may be times when the EPS can only provide energy to the vital components such as OBC and communication components, due to limited energy storage capacity. So, the inability of the dosimeter to measure during energy shortages was considered risky for the mission. Therefore, a dosimeter which can keep accumulating the TID data in passive mode with no power consumption has been chosen. Recently, funding to buy the dosimeter is being searched then, calibration tests will be conducted in the future.

4.3. Camera

Developing a horizon sensor algorithm and testing it in space has been selected as a mission of n-LOTUSat. Yet, it was decided to use COTS camera and lens therefore, the developing process is just limited to the algorithm and coding. Due to that reason, trade-off tables for candidate cameras and lenses are prepared to find a good pair that is capable of satisfying mission requirements. While selecting the camera and the lens, it has been taken into account that these components are not going to be used just as a horizon sensor. They are also going to be used to capture and download Earth images. These two missions require different camera properties: High resolution for taking Earth photographs and wide field of view (FOV) for horizon sensor. On the market search, it has been seen that high resolution cameras generally have a narrow FOV. An optimal camera with a relatively low resolution but a relatively high FOV has been chosen and the FOV is planned to be improved by a lens. After selecting the camera and the lens, several algorithms have been combined to develop a robust algorithm which can be tested on a computer. Thanks to those tests, an idea about results of the algorithm has been arisen. However, the algorithm will be rewritten smoothly in Micro Python, since the camera computer uses that language, to reduce errors. Then, the rewritten algorithm will continue to be tested and developed.

4.4. Command and Data Handling

The command and data handling subsystem have three main occupations: Data handling which includes mission and housekeeping data, command processing which is about control of the satellite systems and automation which is responsible for automatic tasks of the satellite such as electrical power modes regarding the battery level. Also, the subsystem is responsible for meeting these requirements both in hardware and software. The OBC will be tailored for the mission requirements of the CubeSat e.g., the original design of the OBC does not have a magnetometer implemented on PCB yet, there will be implement COTS magnetometer on the PCB, which is going to be used in the CubeSat, due to ADCS requirements. Also, FreeRTOS operating system is going to be used in the CubeSat. Which makes small and low-power edge devices easy to program, deploy and connect with each other.

4.5. Communication

The communication system has three major targets: Self-introduction of the CubeSat with Carrier Wave (CW) Morse, transmission of the commands to the CubeSat and transmission of data the from satellite to the ground station. There targets are going to be achieved by using antennas, radio equipment (transceiver and receiver), ground station and a private radio frequency to the CubeSat at the Ultra High Frequency (UHF)/ Very High Frequency (VHF) band. Since that radio frequency is going to be private in order to avoid interferences, a permission has to be taken from the local authorities and negotiations are being conducted on that subject. A UHF monopole antenna is going to be manufactured and tuned by the team as a part of the communication mission.

4.6. Electrical Power System (EPS)

After months of learning and reviewing many electrical power systems, the EPS card was designed by a graduate student and re-designed its properties by the team, such as increasing low voltage buses instead of high ones, for 1U CubeSat. The Lynx EPS card is currently in production, when received, vibration and thermal tests will be carried out. About the battery, is planned to design and manufacture a nickel-cadmium battery, but there is also the possibility of using a mission-appropriate, space-qualified lithium-polymer (Li-Po) battery as a reliable additional plan. Subsequently, the battery selection and solar cell analysis were completed, and the power budget began to be prepared. However, while preparing the power budget, attention was paid to dividing it into three sections: power generation, power requirements, and power consumption according to different modes. Different modes have been arranged so that certain systems such as OBC, EPS, and beacon are not going to be powerless throughout the orbit. In case sufficient energy cannot be stored in the battery during the solar eclipse and operating three different payloads at different times: Launch and Early Orbit Phase (LEOP), Stabilizer Mode, Normal Mode, Safety Modes are defined for essential possibilities and the total consumption of each mode was calculated separately in a single table.

4.7. Attitude Determination and Control System (ADCS)

The process started with the review and comparison of attitude determination algorithms which are solutions to the Wahba's Problem like SVD, TRIAD, q-Method, QUEST, ESOQ and their variants. Each of these methods come up with their advantages and disadvantages. Considering the needs and limitations for a 1U CubeSat, main criteria was minimizing the work load of on-board computer while having adequate accuracy, resulted in the selection of QUEST algorithm. Earth's magnetic field and Sun direction models have been chosen as reference direction models because of their sufficient accuracy and low cost of their sensors and contacted with many companies to get the ideal sensors for the mission. Initial orbit model created by ISS's two-line element set (TLE) data and then orbit propagation simulated considering aerodynamic drag and Earth's oblateness. Currently the team is working on magnetic reference model utilizing International Geomagnetic Reference Field (IGRF) and meanwhile deciding between magnetometers and sun sensor alternatives. Upcoming missions are designing of passive magnetic attitude control system and performing detailed orbit and attitude simulations.

4.8. Structure

Firstly, the team began with long readings and literature reviews about CubeSat protocols that are specified by the space authorities. These rules had numerous restrictions at millimetre or even smaller scales, so a lengthy period spent on carefully understanding the limitations before starting the design process. After clarifying where to start, the team began focusing on the structure design. Many sample designs were viewed, contacted with different companies to learn the price for available models and production costs for a customized structure. After long ponderings, the team decided that buying an available model will not worth the price and will not be beneficial for learning. This decision led team to contact even more companies around the world and meanwhile kept investigation of sample designs and finally finished the structure. Currently, the team is working on the interior design which includes how the mass would be distributed inside the satellite in most efficient way. The following plan is designing of solar panels and the mechanisms for the deployable instruments.

4.9. Analysis

First step into analysis was determining the orbit lifetime and the orbital data considering given launch date. The solar cells that are going to be used for the satellite decided. TUBITAK undertook the cost and installation of Azur Space branded solar cells and performed the efficiency tests. Finally, the solar cell power analyses were performed using the previously obtained orbital and attitudinal data. Co-operating with the ADCS team, a more precise orbit simulation was performed by considering the deployment velocity of 1 m/s and 45° from the nadir in the ISS body coordinate system from JAXA's (Japan Aerospace Exploration Agency) J-SSOD (Japanese Experiment Module-Small Satellite Orbital Deployer) mechanism. Since the deviation from the original ISS orbit was too small, the results were also almost identical. Next is to perform thermal analyses to ensure that the thermal balance inside the satellite will not cause any problem and structural analyses to ensure that the satellite can withstand all vibrations and stresses.

5. Learning Outcomes

Undoubtedly, this project was started with the aim of contributing to the literature and gaining practical training in addition to the engineering education received at the undergraduate level, besides, led us to gain very crucial experiences in the project. It was deemed appropriate to include this section in order to enable the experiences gained to guide on student-driven CubeSat projects.

First of all, the most essential point of managing a project, especially consisting of undergraduate students, is the adjustment of the project schedule, for the reason that team members devote a lot of time to their education in addition to the project. Accordingly, while determining the project calendar, the academic calendar of the students should be considered, as well as the project schedule should not be delayed.

Afterward, passing through the learning process to the technical design, the recommendations developed in that direction, such as the simulation, drawing, and analysis programs used should have the same versions and updates by the whole team. For instance, concerning design teams, structural and interior design can undergo many evolutions upon the requests of other subsystems. Due to this situation, arranging and storing the update of each file in the most systematic and time-tagged way is imperative.

To summarize the critical parts of the overall statements, it is emphasized that the literature review is very important, it is necessary to communicate more with the companies when purchasing materials, and the importance of the fundamentals of theoretical information.

6. Conclusion

In conclusion, in this report, the adventure of an undergraduate CubeSat team from its establishment to the stage of making a physical model -although not yet concluded- is conveyed. In general, the birth of the idea of a CubeSat project, forming a motivated multidisciplinary team, finding a mentor that can guide and then determining the payloads to this CubeSat with a literature review were determined as the first steps. Afterwards, time planning was made and what should be done and when should be done was discussed. Past experiences, current developments and targets were mentioned, and then learning outcomes from each of the separate multidisciplinary teams for separate subsystems were collected and presented.

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8. Abbreviation and Acronyms

ADCS	Attitude Determination and Control System
COTS	Commercial Off-The-Shelf
CW	Carrier Wave
EPS	Electrical Power System
FOV	Field of View
IGRF	International Geomagnetic Reference Field
ISS	International Space Station
ITU	Istanbul Technical University
JAXA	Japan Aerospace Exploration Agency
J-SSOD	Japanese Experiment Module-Small Satellite Orbital Deployer
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
Li-Po	Lithium-Polymer
METU	Middle-East Technical University
n-LOTUSat	Nano Lean Satellite of Technical University
OBC	On-Board Computer
PCB	Printed Circuit Board
SSDTL	Space Systems Design and Test Laboratory
TID	Total Ionizing Dose
TLE	Two Line Elements
TUBITAK	Scientific and Technological Research Council of Türkiye
UHF	Ultra High Frequency
VHF	Very High Frequency

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