Lunar High Quality Terrain Scanning Mission Using LIDAR Technology

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ABSTRACT

As interest in exploring the moon grows, this study suggests a mission plan that involves using a CubeSat fitted with a LiDAR sensor (SALi) to survey large sections of the lunar landscape and gather precise information on its ruggedness and altitude. By making use of available components and an advanced Guidance, Navigation and Control (GNC) system featuring star trackers, IMUs and maintaining a circular polar orbit at 125 km above the moon's surface the CubeSat will implement the Lambert Method for efficient orbital insertion around the moon and employ reaction wheels along with ion thrusters for accurate imaging. Communication will rely on the 400 MHz UHF band. Utilize the CubeSat Space Protocol (CSP) for secure data transmission while enhancing signal strength through a deployable mesh reflector antenna. The KubOS flight software will oversee onboard functions with data being transmitted via Amazon Web Services (AWS) ground stations. This mission concept presents a strategy, for gathering detailed topographical data of the lunar surface by capitalizing on a CubeSats cost effectiveness paired with LiDAR technology.

INTRODUCTION

In the past few years, lunar exploration interest increased exponentially and with it, new challenges have arisen. The moon environment itself is not very much explored enough, and for every mission that serves a purpose on the moon it must go through multiple steps. Some of the missions that have failed due to lunar environmental can occur more often without proper mission planning like Surveyor 4 in 1967. Surveyor 4 was an unmanned spacecraft launched by NASA with the goal of soft landing on the moon and performing scientific investigations. However, during its descent to the lunar surface, communication was lost just moments before touchdown.[1] The exact cause of the failure remains unknown, but it is believed to be related to an anomaly in the spacecraft's attitude control system. The spacecraft likely crashed into the lunar surface. While terrain wasn't explicitly cited as the cause, issues with spacecraft systems during descent can be exacerbated by the lunar terrain's unevenness. Another recent example is Following the crash of the Beresheet spacecraft on the lunar surface, subsequent analysis of imagery captured by NASA's Lunar Reconnaissance Orbiter (LRO) in Figure 1 revealed evidence of lateral displacement or skidding at the crash site.[2]

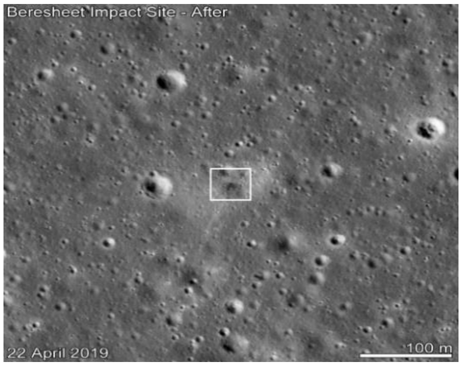


Figure 1: The terrain around the Beresheet Spacecraft[2]

This observation suggests that the spacecraft did not maintain a stable, upright position upon impact but instead experienced a degree of lateral movement or "tipping over." The presence of a dark, elongated smudge or debris trail extending from the impact site indicates that the spacecraft likely slid or skidded across the lunar surface following the initial contact. This lateral motion can be attributed to the high velocity and angle of impact, which resulted in the loss of stability and the dynamic behavior of the spacecraft upon landing. This paper will propose a mission plan utilizing CubeSat's affordability and availability and integrate LiDAR sensors to scan a wide area of the moon's surface and provide accurate data about surface unevenness and elevation.

STRUCTURE AND PAYLOAD

The selection of the CubeSat structure comes with a variety of options; therefore, a decision matrix was used to compare between two options: 1-Commercial-off-the-shelf 2-Custom Machined Structures.

Table 1: Comparison between COTS and Custom Machined Structures

Criteria	Commercial-off-the-shelf (COTS)	Custom Machined Structures
Complexity	3	5
Structural Flexibility	3	5
Cost	4	3
Internal Volume	3	5
Time to Manufacture	5	2
Weight	4	3
Reliability	5	2

Rating from 1-5, 1 being the lowest 5 is the highest.

With the ready-made solution provided by COTS, it eliminates the need for design and fabrication and thus allocates time and resources to other aspects of the project such as the specific payload on the mission. Also, it provides higher reliability as these structures are manufactured repeatedly within industry standards and used regularly by space companies.

Although COTS are standardized in many aspects, they provide flexibility in mounting configurations and the integration of additional which can be helpful to satisfy the mission's requirement.

Materials

The properties of the materials selected for the frame contribute to the CubeSat's endurance to mechanical and thermal stress during different phases of the mission. For our mission materials, there are several criteria needed for the lunar environment which include temperature fluctuations ranging between -200°C to +130°C and a low thermal expansion coefficient (less than $20*10^{-6}$/C).[3]

As mentioned earlier, because COTS will be used in the mission, it provides options for selecting the material of the structure, therefore, an Aluminum 7075 & 6061 can satisfy the requirements for the materials.

Payload

The SALi in Figure 2 combines designs of current systems for CubeSat laser communication and integrated detector cooler assembly providing the ability of real-time range and velocity measurements during landing.[4]

Moreover, SALis versatility extends to its ability to work with many types of spacecraft designs and mission plans. Whether used on its own or as part of a set of instruments SALi can meet a variety of mission needs and goals. Its modular structure allows for integration with different spacecraft models, including CubeSats, small satellites and larger spacecraft. This adaptability allows SALi to assist in a range of scientific studies from exploring the moon's surface to missions involving asteroids. Additionally, SALis strong performance in challenging space conditions ensures that it functions reliably throughout stages of a mission, from launch and travel to activities on the surface. This makes it a versatile tool, for space exploration projects.

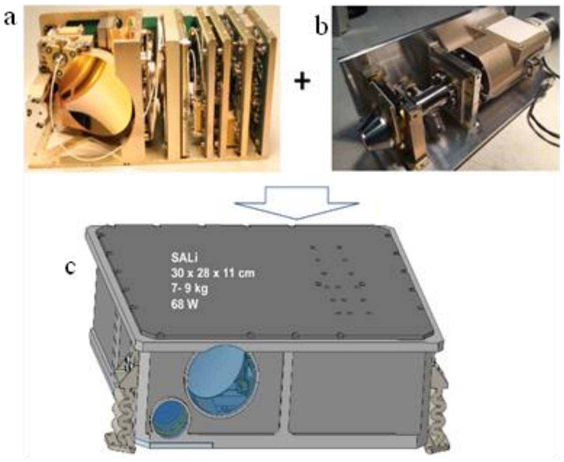


Figure 2: The conceptual design of the SALi. (a) CubeSat Laser Communication Terminal (10 x 10 x 20 cm). (b) CubeSat 2x8 pixel HgCdTe APD Array IDCA (7 x 7 x 20 cm). (c) a and b are combined to build the SALi instrument (30 x 28 x 11 cm)[4]

The advanced electrical bus (ALBus) in Figure 3 is suggested for the deployment. ALBus is developed to reduce mechanisms risk from the deployment of solar arrays.[5]

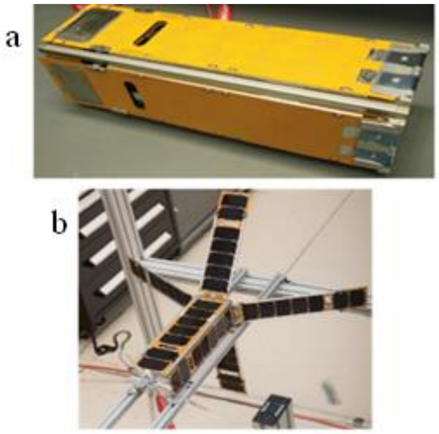


Figure 3: Flight ALBus CubeSat. (a) Flight ALBus CubeSat Stowed Configuration. (b) Flight ALBus CubeSat Deployed Configuration[5]

NAVIGATION AND CONTROL'S ROLE IN HIGH QUALITY TERRAIN SCANNING

Integration of a sophisticated Guidance, Navigation, and Control (GNC) systems in CubeSats can dramatically improve the success rate of a lunar high quality terrain scanning mission. To successfully map the lunar surface with high resolution and accurate topological data, orbital stability must be achieved through GNC systems. Furthermore, these systems will assist in reaching and continuously maintaining the desired orbital element for this mission. This section will focus on orbital dynamics and the ingenious use of GNC technology.

Integration of GNC and Imaging Technologies in Lunar Orbit Dynamics

To secure precise navigation and control, the CubeSat will utilize a collection of advanced star trackers and inertial measurements units (IMU's). Star trackers will provide accurate orientation data by referencing the position of stars and moving with the same rate as the stars. This is necessary in navigating in space where Global Positioning System (GPS) is not available. In regard to the IMU's, it is a device that provides measurements for the acceleration and angular rate along with attitude determination and stabilization. In addition, the IMU continuously tracks and provides real-time data and updates about the CubeSat's movement and orientation allowing for correcting any deviations in orbit or trajectory. The integration of GNS systems is vital for aiding the CubeSat's advanced mapping technologies, which consists of multispectral cameras used to scan the terrain of the moon surface make use of state-of-the-art imaging technologies, such as charge coupled devices (CCDs) or complementary metal oxide semiconductor (CMOS) sensors paired with filter arrays to take images in bands at the same time. These cameras can utilize imaging methods for in depth analysis as well. Through calibration a precise measurement can be achieved, allowing scientists to examine the terrain attributes and composition properties with high accuracy and high-resolution LiDAR systems. These sensors are tasked with capturing meticulous lunar surface features and topographical data but require careful stabilization and alignment.

Orbital Dynamics

For continuous high-quality mapping of the lunar surface, a circular orbit with an altitude of 125 KM and inclination of 90 degrees was chosen. This orbit allows for a stable and consistent view of the moon surface as well as it is critical for detailed topographical mapping and surface analysis. The orbit inclination will allow for comprehensive mapping of the surface of the moon over time due to its rotation around itself.

$$V_{orb} = \sqrt{\frac{GM}{R}} \tag{1}$$

Where G is the value of the universal gravitational constant 6.67430×10-11 m3 Kg-1 s-2, M is the mass of the moon which is 7.35×1022 Kg, and R is the radius from the center of the moon to the CubeSat with a value of 1,862.5 km.

A circular orbit at this altitude will have an orbital velocity of 1.623 km/s. This will result in an orbital period of 2 hours, scanning the same area about 12 times per day, consequently leading to more detailed imaging and topographical data.

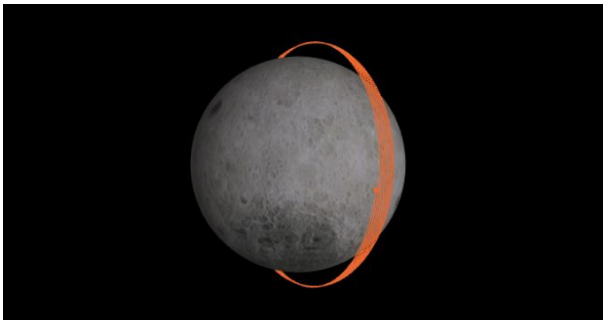


Figure 4: Orbit of 125 km around the moon

Guidance Systems

The guidance systems of a CubeSat Determines the most efficient trajectory from Earth to the Moon and Subsequent lunar orbit intersection. The system computes the CubeSat's path, employing algorithms such as Lambert Method to navigate the complexities of lunar transfer.[6] Lambert Method is a mathematical approach to figure out a spacecraft's location and velocity vectors at one point in time while it is in orbit around a central body from its position vectors at another as in Figure 5.

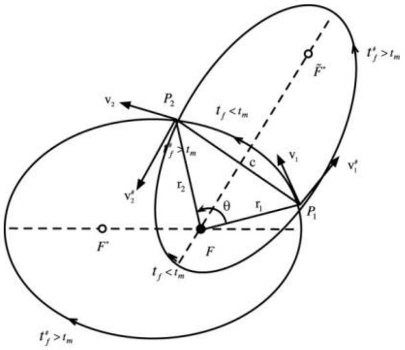


Figure 5: Lambert's method graph[6]

$$\Delta t = \sqrt{\frac{a^3}{\mu}}(\alpha - \beta - (sin\,\alpha - sin\beta)) \tag{2}$$

Where

$$\sin\frac{\alpha}{2} = \sqrt{\frac{s}{2a}} \tag{3}$$

$$\sin\frac{\beta}{2} = \sqrt{\frac{s-c}{2a}} \tag{4}$$

$$c = \|\vec{r}_2 - \vec{r}_1\| \tag{5}$$

$$s = \frac{c + r_1 + r_2}{2} \tag{6}$$

a is the semi-major axis of the orbit, Δt the time it takes for an object to move from one point to another in space under the influence of gravity, μ is the gravitational parameter, α and β are angles related to the geometry of the orbit. c is the cord and s is the semi-perimeter.

Guidance capabilities are crucial not only for reaching the intended lunar orbit but also for maneuvering the satellite to maintain the orbit against perturbative forces like solar radiation pressure and uneven lunar gravity.

Navigation Systems

A combination of star trackers and IMUs are used to ensure accurate navigation through space. The star tracker provides precise orientation data by referencing the position of stars. This method will ensure the necessary accuracy for space navigation. Additionally, the IMU continuously tracks and provides real-time data and updates about the CubeSat's movement and orientation allowing for correcting any deviations in orbit or trajectory. This approach will allow for precise orbital and attitude maintenance, which is highly important for the success of the mission.

Control Systems

The control system of the CubeSat utilizes a set of reaction wheels and ion thrusters. The Thrusters will provide a high level of impulse and thrust making it a suitable fit, for a high quality lunar terrain scanning mission that needs precise movements and efficient propulsion to maintain and adjust the CubeSat's orientation and position. Reaction wheels will allow for fine-tuned adjustments in the CubeSat's attitude, which is important for the alignment of imaging equipment. For broader orbital maneuvers and adjustments, the ion thrusters will be utilized.

SIGNALS AND DATA CONNECTION

The CubeSat’s communication system, particularly vital for lunar missions, is tailored to overcome the significant challenges of long-distance space communication. Its RF subsystem must be highly efficient, given the constraints on data rates, power, and mass, dictated by the extended lunar distances. Key objectives include ensuring CubeSat survival post-launch, collecting telemetry data for mission operation and control, and adhering to communication protocol standards. The system's design must account for signal delays and requires robust components to maintain signal integrity in the harsh space environment.

Frequency Band Selection

A comprehensive analysis of suitable frequency bands for lunar communications is essential, considering the unique challenges posed by long-range space missions. Key factors influencing the choice of frequency include the substantial free space path loss associated with the extended distances, atmospheric interference from Earth's ionosphere and troposphere, and the data transmission rates required by the mission.

For our CubeSat project, informed by the mission-specific requirements and the SALi LiDAR system's bit interval with a Code Period of Ts = 65,024µs .[8] We have selected the Ultra-High Frequency (UHF) band at approximately 400 MHz. This decision was based on several technical considerations:

- The bit rate of the mission's communication system was used as a baseline to determine the necessary frequency based on eq6, subsequently adjusted above the Nyquist frequency and bandwidth to prevent aliasing by using eq7 and eq8.

$$R = \frac{R_b}{T_s} \tag{6}$$

$$f_{Nyquist} = 2B \tag{7}$$

$$B \geq \frac{R}{\log_2(1 + SNR)} \tag{8}$$

- The UHF band is compliant with the Federal Communications Commission (FCC) regulations, ensuring legality and operational feasibility.
- The chosen frequency band strikes a balance between minimizing atmospheric losses, which are prevalent above 300 MHz due to moisture and other particulates and avoiding ionospheric disturbances common below 30 MHz.

Despite the maturity of lower frequency bands (up to S-band) for small satellite operations, these are often overcrowded and pose significant licensing challenges. Conversely, while higher frequencies can provide greater gain relative to antenna aperture size, they also suffer increased atmospheric attenuation and require more precise transmission directionality due to their proportionally higher free space loss and narrower beam widths.

Ultimately, the UHF band at 400 MHz was deemed the most suitable for our application. It offers an optimal compromise between bandwidth availability, regulatory compliance, and technical feasibility, particularly considering the atmospheric and ionospheric conditions expected during the mission. The precise design of our antenna system will ensure maximal gain and alignment accuracy, further enhancing communication reliability and efficiency.

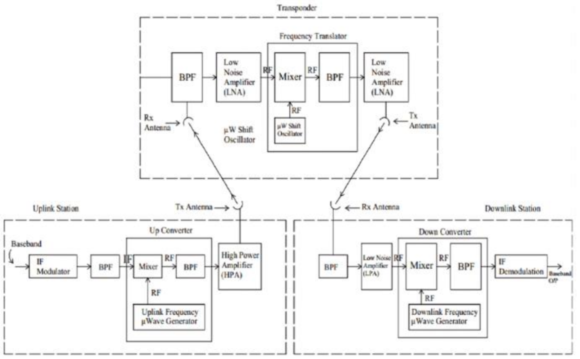


Figure 6: Transmit and receive block diagram

Telecommunication Protocol Selection

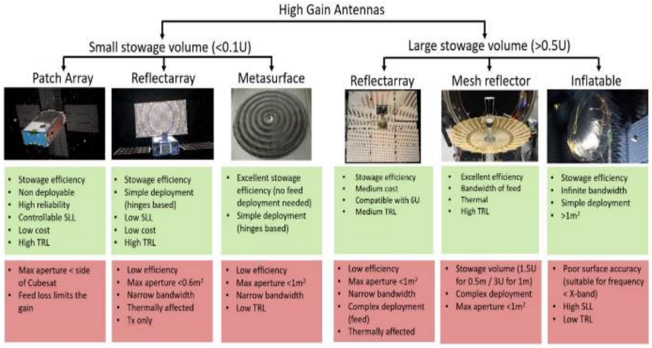
When it comes to implementing the communication protocol within the CubeSat, a major property to consider is the ability to maintain a reliable connection given the space environment and limited antenna capabilities. The reliability factor is of massive necessity especially with the mission objective of residing in lunar orbit. The selection of the communication protocol streamlines to either the Consultative Committee for Space Data Systems (CCSDS), the CubeSat Space Protocol (CSP), or the AX.25 protocol.

The CCSDS protocol's high-power consumption makes it ineffective for our CubeSat's implementation. CSP and AX.25 offer the best implementation for CubeSat systems. However, CSP is more reliable than AX.25 as it implements the Cyclic Redundancy Checksum (CRC) for error detection in comparison to the retransmission policy as error detection in the AX.25 protocol.[9] Thus, the telecommunication protocol of choice for lunar CubeSats is the CSP.

Antenna Design Selection

In the design of our CubeSat's communication system, the antenna plays a pivotal role, given its influence on the overall system performance. Considering the CubeSat's volume limitations, our design approach has focused on optimizing key technical specifications such as gain, polarization, and radiation patterns within the allowable dimensions.

It is acknowledged that increasing the antenna aperture enhances the link margin, facilitating higher data rates or the possibility of reducing transmission power—a critical factor for energy efficiency in space. After a detailed comparative analysis of various antenna types, as shown in Figure 7, our selection criteria were directed towards achieving high directivity and gain without exceeding the spatial constraints of our CubeSat.



	Patch Array	Reflectarray	Metasurface	Reflectarray	Mesh reflector	Inflatable
Advantages	Stowage efficiency Non deployable High reliability Controllable SLL Low cost High TRL	Stowage efficiency Simple deployment (hinges based) Low SLL Low cost High TRL	Excellent stowage efficiency (no feed deployment needed) Simple deployment (hinges based)	Stowage efficiency Medium cost Compatible with 6U Medium TRL	Excellent efficiency Bandwidth of feed Thermal High TRL	Stowage efficiency Infinite bandwidth Simple deployment >1m²
Drawbacks	Max aperture < side of Cubesat Feed loss limits the gain	Low efficiency Max aperture <0.6m² Narrow bandwidth Thermally affected Tx only	Low efficiency Max aperture <1m² Narrow bandwidth Low TRL	Low efficiency Max aperture <1m² Narrow bandwidth Complex deployment (feed) Thermally affected	Stowage volume (1.5U for 0.5m / 3U for 1m) Complex deployment Max aperture <1m²	Poor surface accuracy (suitable for frequency < X-band) High SLL Low TRL

Figure 7: High gain antenna selection guidelines for X- or Ka-band application for CubeSats

While the NanoCom ANT430 is a well-regarded antenna for CubeSats in Low Earth Orbit (LEO) missions due to its compact size and reliability, it does not meet the ambitious specifications required for our mission profile as it clearly shown in the antenna specifications.[10] Instead, we have chosen a deployable Mesh Reflector Antenna which promises superior performance characteristics suitable for our higher mission aspirations.[10]

The deployable Mesh Reflector Antenna offers a synergy between the desired large antenna aperture and the CubeSat's size restrictions.[10] This synergy is achieved through a deployable mechanism, elaborated in Figure 8, which allows the antenna to be stowed compactly during launch and then expand to its full operational size once in orbit.[10] The deployment process, while consuming power, utilizes a mechanical configuration system to transition into its final functional position

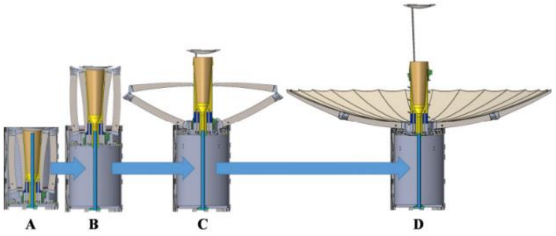


Figure 8: KaPDA Deployment Sequence[10]

Flight Software Selection

To facilitate the critical module of CubeSat, namely the command and data handling, our CubeSat will adopt the KubOS flight software to be running on the OBC. The selection of this software resulted after careful investigation on the preferable CubeSat software to use given the lunar orbital mission. According to Olman & Quiros.[12] the following comparison table has been created in aiding the selection of the flight software.

Table 2: Comparison between the popular flight software used in small satellites

NASA Core Flight Software	KubOS	F Prime
Modularized Components	Modularized Components	Modularized Components
Built for a wide range of applications, general	Built specifically for CubeSats	Built for complex scientific missions
Requires external OS	Comes with a KubOS Linux OS	Requires external OS
High learning curve	Low learning curve	High learning curve
Open Source	Open Source	Licensing fees apply

In addition, having software written in the Rust programming language gives maximum advantage in memory management, especially as the resources are limited and efficient memory utilization is necessary.[13] Consequently, the command and data handling in the KubOS implementation is conducted in a producer-consumer mechanism, where there exists a message bus that producers (modules generating certain data) push their data to it, while consumers (modules requesting or in need of certain data) subscribe to the message bus for incoming data. Overall, this mechanism provides a robust communication infrastructure, enabling efficient and flexible command and data handling within the CubeSat.

Connected Ground Station Development

As for the ground station development, our approach will utilize Amazon's distributed network of ground stations across the globe, namely Amazon's Web Server (AWS) Ground stations. These ground stations are effective in downlinking telemetry data quickly, in addition to the cloud computing benefits of AWS products, which range from advanced databases to store the huge amount of telemetry data, to compute power that allows for big data processing.[14] This approach greatly reduces the overhead of developing a ground station, and only requires paying for ground station antenna access time. This automation maximizes efficiency in downlink operations and the dynamic environment of these ground stations ensures mission-critical data gets through without delay.

CUBESAT'S COMPUTER ARCHITECTURE

As discussed at the outset of this paper, the proposed design employs Commercial Off-The-Shelf (COTS) components. These components, however, require a dedicated on-board computer system for control, data communication management, and operation initiation. There are several approaches to designing this system, such as using a single computer to manage all component operations. However, this approach may not always be practical in terms of scalability and effectiveness, particularly when dealing with numerous components. Therefore, a more efficient approach is to partition the computer system into different subsystems based on each system's functionality. Furthermore, each system will have its own control unit. This approach reduces overall development costs and enhances system flexibility in terms of adding more functionalities and improvements.[15] Consequently, the computer system in this paper will be divided into three subsystems as indicated in Figure 9: the Guidance, Navigation, and Control (GNC) system, the Data Connection and Signal System, and the Main Computer System. Each system will have its own control unit, which will ultimately connect to the main system. Table 3 lists all the COTS components used in the CubeSat, excluding the control units, and their respective systems. Since the functionalities of each system, apart from the main system, were discussed in previous sections, the following discussion will focus on the control units.

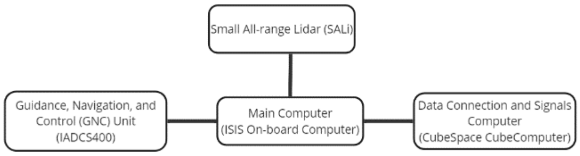


Figure 9: The CubeSat Computer System Architecture

Table 3: CubeSat Components

Component	Purpose	System
HG4930 MEMS Inertial Measurement Unit	Determine the altitude, acceleration, and position of the CubeSat	Guidance, Navigation, and Control (GNC) system
Sinclair Interplanetary ST200 Star Tracker	Determining spacecraft orientation relative to stars	Guidance, Navigation, and Control (GNC) system
RW400 Reaction Wheels	Altering the satellite's angular momentum for precise instrument targeting	Guidance, Navigation, and Control (GNC) system
Gen-2 BIT-3 Ion Propulsion System	provide propulsion for orbital maneuvers, station keeping, and trajectory adjustments	Guidance, Navigation, and Control (GNC) system
EnduroSat UHF TRANSCEIVER II	Increases the power of the transmitted signal to ensure it reaches the Earth-based receivers.	Data Connections and Signals
ISIS Deployable Antenna System	For transmitting and receiving radio waves	Data Connections and Signals
GomSpace AX100	Modulates outgoing signals and demodulates incoming signals to encode and decode data transmissions.	Data Connections and Signals
Small All-range LiDAR (SALi)	scan a wide area of the moon's surface and provide accurate data of that	Main system

Guidance, Navigation, and Control system

The control unit of this system has two primary functions. The first is to determine the CubeSat's current orientation in space relative to a specific reference using sensors such as the HG4930 MEMS Inertial Measurement Unit and the Sinclair Interplanetary ST200 Star Tracker. For this paper, the reference for these sensors will be the moon. The second function is to control the CubeSat's attitude by executing commands that utilize the available actuators to achieve the desired orientation in space. In this context, it is sufficient to use the Gen-2 BIT-3 Ion Propulsion System and the RW400 reaction wheels. The control unit used to perform these functions is the Attitude Determination Control System (ADCS). In this paper, we propose the use of the AAC Clyde Space IADCS400 ADCS.[16] This ADCS is specifically designed for CubeSats and includes the essential units needed for attitude determination, namely the RW400 reaction wheels and the ST200 star tracker. Therefore, there is no need for external reaction wheels or star trackers when using this unit.

Data connection and signals control system

Unfortunately , there is no direct equivalent to the ADCS that can be used as a control unit for the Data Connection and Signal System. This system's design largely depends on the mission itself and the required functionality from this system. Therefore, it is more practical to use an on-board computer to control this system's execution and its communication with the other systems in CubeSat or with the ground station. As shown in Table 3, this system uses many components. After a careful examination of each component's requirements, such as connection interfaces, we suggest using the CubeSpace on-board computer, named "CubeComputer".[17]

Main Computer System

This system integrates the control units used in the Guidance, Navigation, and Control (GNC) system, the Data Connection and Signal System, and the Small All-range LiDAR (SALi) sensor. Although each system will function individually with its own control unit, there is a need for an integrating unit that controls the subsystems and enables their communication when necessary. Regarding the LiDAR sensor, there is no need to create a specific subsystem to control it since it has its own control unit. As mentioned in the Command and Data Handling Subsystem section, the KubOS flight software will be used to handle the command and the data. Therefore, the main board that will be used must be compatible with the KubOS flight software. We suggest using one of the best on-board computers designed specifically for CubeSats, the ISIS On-board computer.[18] According to the KubOS documentation, this is one of the few on-board computers that support their flight software.[19] When it comes to needing an antenna, various scientific tools and the focus on using available components it suggests that a 3U CubeSat (around 10 x 10 x 30 cm) is the best size for this lunar LiDAR mapping project. While the exact weight is still uncertain it should fit within the limit (4 kg or 8.8 lbs), by utilizing COTS parts. However, adding the antenna and multiple instruments could potentially bring the weight closer to that threshold.

CONCLUSION

In the increasing scientific requirement of exploring the moon there is a growing need for approaches to overcome the unique challenges of outer space environments. Discussions have highlighted a plan that harnesses CubeSat technology to tackle these obstacles effectively. At the core of our proposal lies the incorporation of LiDAR sensors into CubeSat platforms marking a shift in how we scan the terrain. This combination aims to reduce risks associated with surface unevenness and environmental factors that have historically hindered lunar missions. Thorough examination of CubeSat structures, materials and payload choices emphasizes the role of planning in mission design. By utilizing COTS and advanced payloads like range LiDAR (SALi) we strive to enhance reliability and functionality while keeping time and costs in check.

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