Modifications to the Exolance Probe Design to Conform to the 3U Cubesat Form Factor

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Abstract

The CubeSat satellite design was developed in order to allow access to space for small payloads. Conforming a payload's design to fit a CubeSat form factor allows for the device to be a low-cost and feasible addition to an existing mission. For this reason, it is important to consider how existing machinery can be modified to fit a CubeSat's form factor in order to allow more projects to gain access to space. This research focuses on the modification of the Exolance Mars surface probe design to fit a 3U cubesat form factor. The probe is a spear-like penetrator that contains a biosensor tip at its end and was the subject of this paper due to the push to explore the possible biological habitation of Mars. The probe differs from previous missions in that it aims to reach a depth of about one meter under the surface of Mars in order to test for life in an area less affected by the external conditions of Mars. This paper explores a telescoping design that allows for the probe to fit within the confines of the CubeSat as well as the power, mass, and volume budgets for the components that aid in general CubeSat functionality. Three unit (3U) CubeSat mass and size requirements were used to guide the design of the completed apparatus. Communication and control systems are also proposed. The results of this research are intended to enable the Exolance concept to become a low-cost mission that will communicate valuable data about life on Mars.

Background/ Introduction

The cost and material heavy task of sending missions to outer space led to the inception of the CubeSat program, a small satellite design that was developed by California Polytechnic State University, San Luis Obispo, and Stanford University's space systems development laboratories [1]. These satellites are designed to provide access to space for small payloads in standard form factors. The design allows the project to be economically feasible and thus more likely to be able to launch [2]. This flexibility in production costs has led to the creation of unique payloads by private and public entities. Cubesats have also gained popularity in light of NASA's recent launch of MarCo A and B alongside the InSight mission to Mars [3]. The mission will help to establish criteria for other missions that wish to collect data from Mars in a similar way and will open a new frontier for cost-effective space exploration.

The search for life on Mars has bloomed into a prodigious enterprise due to the proximity of Mars and the planet's similarity to Earth. This search for life began with NASA's Viking probes which launched in 1975. The space probes, Viking 1 and Viking 2, each had an orbiter that photographed the surface of Mars and a lander that studied the planet's surface. The orbiter helped pick up and transmit data so the information could be relayed back to Earth. The Viking mission indicated that water was most likely present on Mars but no longer flows at the surface. However, the biological experiments conducted on this mission were inconclusive [4]. The Mars Pathfinder mission [5], the Mars Global Surveyor [6], and the NASA Phoenix missions [7] all helped to collect data about the surface and chemistry of Mars. This information was collected in part due to its relevance in determining biological habitation of the planet. The Curiosity and Opportunity rovers also contributed to this body of research by searching for the organic and chemical conditions that would sustain life by performing sediment sampling [8] [9]. The rover concluded that the organic compounds needed to sustain life were present on Mars; however, actual life on the planet has still not been found. NASA proposes that life has not yet been found on Mars due to the radiation at the planet's surface which would inhibit microbial growth. Therefore, in order to find life, a probe must penetrate the Martian soil until it reaches a depth that is less affected by the external conditions of Mars. One such probe design for this type of mission is the Exolance, a spear-like penetrator probe that burrows itself into Mars's surface in order to relay data concerning microbial life to an orbiter [10]. It is based off the 1970s Viking landers and the Curiosity rover's technology but differs in that it attempts to penetrate the surface of Mars deeper than the few centimeters previous missions have been able to accomplish. Due to the high cost of exploring Mars, this idea remains a mission concept.

This research is intended to explore the feasibility of space probe modification to conform to a 3U Cubesat form factor in order to conserve resources and maximize an interplanetary mission's purpose. In order to narrow the scope of this goal, this research focuses on the modification of the exolance probe due to the renewed push to explore Mars and its ability to contain life. The CubeSat design was proposed to aid in the probe's launch due to its affordable and relatively low-maintenance functionality. These elements would allow the exolance probe design to be a low cost addition to an existing mission instead of the burdensome endeavor it would be if it was launched independently. This paper also explores the feasibility of compacting an exolance probe to fit the CubeSat form factor along with the other components of the CubeSat.

CubeSats

Size and Scope of Research

CubeSats are designed to be compact in order to minimize the space needed to be designated to the project. They are required to conform to certain control factors: shape, size, and mass. Specific

CubeSat design specifications vary upon the size and the configuration of the satellite. The size and mass limitations are in place in order to prevent the unit from taking a toll on the original mission's functionality. The CubeSat's ability to sustain its machinery without impacting the larger mission is an integral part of the concept's success and are the primary guidelines that influence payload design. Common dimensions for these nanosatellites are defined in Table 1 below [11]. The size and mass requirements all represent the maximum values permitted for the satellites.

Table 1.

CubeSat Designation	Size	Mass
1 Unit (1U)	10 cm x 10 cm x 10 cm	1-2 kg
2 Unit (2U)	10 cm x 10 cm x 20 cm	2-3 kg
3 Unit (3U)	10 cm x 10 cm x 30 cm	3-4 kg
6 Unit (6U)	10 cm x 20 cm x 30 cm	4-5 kg

By compacting the exolance probe into a 3U form factor instead of the 6U size and mass specifications, more of the units can be carried alongside the mission which will allow for a greater scope of data after the probes deploy. The 3U dimensions are still large enough to contain the exolance design.

The launch vehicle on which the CubeSat will be attached (via a dispenser that ensures the protection of the CubeSat during travel) varies. Dispensers themselves also vary upon the form factor of the CubeSat. In order to allow for a broader application of this research, a 3U form factor was used due to the intermediate size of the conventionally used Poly-Picosatellite Orbital Deployer (P-POD) dispenser that encases the satellite. Many launch vehicles would be able to accomodate the P-POD dispenser and this dispenser has already been integrated on a number of launch vehicles [11]. This would make this research applicable and feasible over across a wide scope.

Outer CubeSat Components

In order for a CubeSat to be able to fulfill its mission while sustaining itself, it must have the following components while still fitting under the size and mass constraints that are defined in Table 1.

3U Chassis

The internal components of the satellite are encased in a chassis that is usually made out of Aluminum 7075 or 6061-T6 due to the thermal energy that is expended on the CubeSat and the possibility of the material cold welding [11]. According to the specifications of Cal Poly/Stanford launch personnel, the components of the CubeSat must also be encased in a shell and the dispenser should not constrain deployable hardware. This chassis ensures that the hardware of the satellite is efficiently compacted. The primary structure mass of this component on marketed CubeSat frames is about 242.8 grams [12].

Fig. 1 3U Chassis

Solar Panels and Power Dispension

The electrical power system of the proposed CubeSat design consists of solar panels, which would be the second component of the nanosatellite's external skeleton. Due to the accessible resource of solar energy in space, solar panels are the primary source of power for a mission. This design does not utilize batteries due to the volume and mass heavy nature of these cells. This space needs to be used instead for the exolance probe design, which would preferably be as large as possible in order to ensure proper launching. The more mechanical alterations the payload must undergo will lessen the degree of the probe's release success. In order to fulfill the CubeSat's power needs, 5 solar panels that are each 10 cm by 30 cm will be deployed. In the case of misalignment, three half-length solar panels can generate up to 2.34 watts (Note: This calculation considers Mars's proximity to the sun). These half solar panels will be located on the sides of the CubeSat as shown in *Figure 2*.

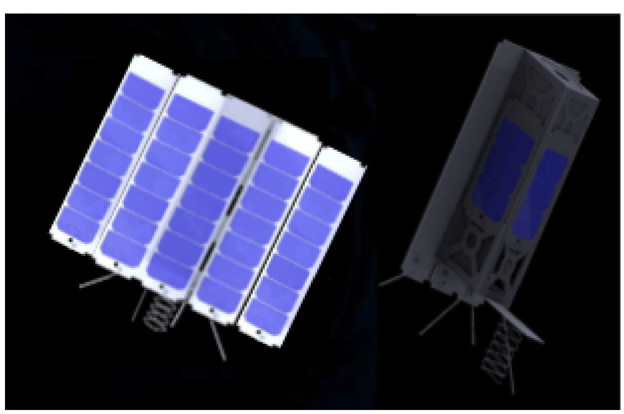

Fig. 2 Solar Panel Array

In order to maximize the surface area that the solar panels will cover, and therefore maximize the amount of power that will be available to the CubeSat, the solar panels will be deployable. The suggested deploying mechanism for the solar panels is the Jet Propulsion Laboratory's burn wire release mechanism that uses a nichrome burn wire that activates upon heating [13]. It cuts through a cable that allows the solar panels to expand. Due to the variable success of the deploying mechanism (due to either failing to heat or overheating the wire), multiple CubeSats will be deployed with the mothership so that if one fails, other probes will still function and be able to relay their data about the surface of Mars. The number of CubeSats to be launched will be dependent on mission constraints.

A 3U cubesat would generally have an array of seven triple junction solar cells that are laid out on a circuit board. Each panel is 30 cm by 10 cm, the length of one of the longer cubesat sides. The actual cells only cover about 90% of the panel surface area due to their configuration on the circuit board. For this study's purpose, only one faces of the CubeSat will be covered by solar panels. This will allow for the deployment of the probe and the location of the antennae. When taking into account inconsistent charging time and performance degradation, the most efficient vendor (SpectroLab) is able to generate about 24.55 watts for five panels per each period the satellite passes the sun (Note: This calculation factors in Mars's proximity to the Sun) [14].

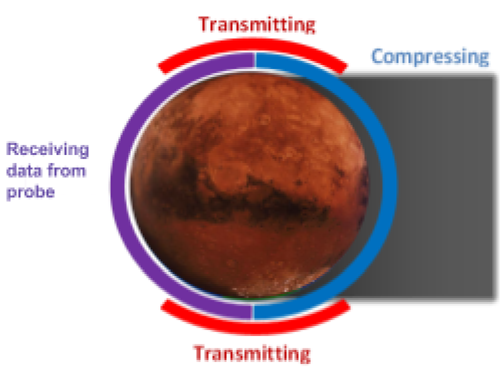

Fig. 3 Power Management

In order to conserve energy that would be used to propel the CubeSat, manage power, transmit the data from the probe on the surface of Mars, etc. it would be most practical to only activate the communication units when the CubeSat is in contact with the mothership. This could be done through mission planning and timing. This coordination is demonstrated in *Figure 3.* The CubeSat itself should also stagger its functions based upon its orbit and proximity to the sun. The sun sensor could aid in this configuration.

Inner CubeSat Components For this Specified Mission

Other general components of a CubeSat include a communications system, electrical power system, attitude determination & control system, and the command & data handling system. A CubeSat will also carry a payload that dramatically varies and is dependent on the type of mission that is being carried out. It should be noted that different missions will have different demands for the components that are inside of the satellite. The primary purpose of this proposed mission is to have a probe land on the surface of Mars and relay data to the CubeSat, which acts as an orbiter. The CubeSat then relays this data back to the mothership, which would relay the data back to Earth. This system of communication will enable the antenna of the probe to be minimized due to the intermediate communicator between the mothership and probe. This research factors in the volume, mass, and energy costs of the following components that are integral to fulfilling this mission's purpose in the table below. Note: Budgets often vary upon the provider and these values are all averages or are derived from a primary provider's data. The current to wattage conversion factor in the voltage bus.

Component	**Current Required**	**Voltage Bus**	**Wattage**	**Mass (grams)**	**Volume**
Flight Computer	.166 amp	3.3 V	.5478 W	94 g	96 x 90 x 12.4 mm
Sun Sensor (2)	.01 amp	5 V	.05 W	<5 g	33 x 11 x 6 mm
Reaction Wheel [15]	.45 amp	12 V	5.4 W	90g	33 x 33 x 38.4 mm
Data Transmitter [16]	.85 amp	12V	10.2 watts	270g	100 x 100 x 30 mm
UHF (Receive) Transceiver [17]	.178 amp	3.3V	1.7 W (Transmitter on) 0-.3 W (off)	94g	96 x 90 x 15 mm
Thruster (Pulsed Plasma) [18] [19]	.625 watts	12 V	7.5 W	150 g	90 x 90 x 25 mm

Star Tracker [20]	.7 amp	3.3 V	2.31 W	282 g	50 x 50 x 47 mm
Angular Rate Sensing Gyroscope	2.7 mA	3.3 V	.00891 W	150 g (est.)	9 x 9.5 x 3.44 mm
Totals	-	-	26.02 W-27.72 W	1.135 kg (1.504 kg including chassis and panels)*	901.0223 cm^3 **

*This allows for a maximum of 2.496 kg for the probe

** This allows about two units for the probe

Communication

The communications systems on CubeSats are limited by the amount of power that is able to be harnessed. The CubeSat generally has access to about 21.35- 24.55 W of power during each revolution around the planet using the solar panel design that is demonstrated in *Figure Two*. This calculation was made by multiplying the earth orbit prediction for the solar cell output times the square of the distance between the Sun and Earth. This value was divided by the square of the distance between the Sun and Mars. This accounts for the spherical radiation of the Sun's energy and the reduced output that is expected in Martian orbit. Due to the limited amount of wattage available for the spacecraft and the power requirements for other components of the satellite, communication systems must be significantly altered. The system usually consists of an antenna which deploys upon going to orbit. Nanoavionic's UHF antenna design is proposed for this CubeSat design [22].The UHF band will be utilized. This design allows for communication with the exolance probe and the mothership, which will be able to then transmit this data back to Earth for analysis.

Control

The attitude determination and control system (ACDS) needs to be put into place in order to stabilize and orient the CubeSat. Attitude determination itself is the process of combining sensor inputs and spacecraft dynamics to provide for an accurate and stable state for the spacecraft [23]. In order to function correctly and obtain specific location knowledge or pointing accuracy, most CubeSats need to remain stable and can not tumble freely. The ACDS system for this CubeSat design remains minimal due to the basic functions that are required of it and the power and volume constraints of the project. However, the methods that can be used to carry out the basic function of control vary and the ACDS system may be replaced with an alternative system. The components of the base design for this system include reaction wheels, a propulsion system, star trackers, a Sun sensor, and angular rate sensors [24].

Reaction wheels help keep the CubeSat in proper attitude and was incorporated into this design in order to ensure that the receiving antennae would be able to pick up the data from the probe on the surface of Mars during the CubeSat's orbit around the planet.

A propulsion system also aids in the mobility of the CubeSat and helps with orbit modifications and attitude control. Examples of thrusters for CubeSats include cold gas, resistojets, electrospray, and vacuum arc thrusters. Due to the lack of other positioning devices like magnetometers, this research proposes the use of a pulsed plasma thruster due to their high efficiency and low required wattage. Pulsed plasma thrusters operate by created pulsed high-current discharge across the surface of an insulator that serves as a propellant. The propellant material accelerates to a high speed. This pulse is driven by a capacitor in a setup that is shown below. The advantages to using such a thruster is the ability for the pulsed plasma to allow for precision maneuvering and its design simplicity [25]. This thruster was considered for this research; however, other thruster designs can be incorporated into the design if the provider desires.

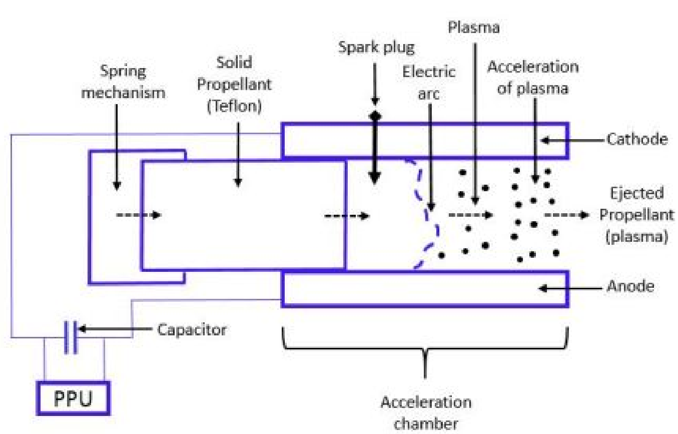

Fig. 4 Pulsed Plasma Design

Star tracking furthers the precision of attitude determination and functions by measuring the positions of stars in order to stabilize a spacecraft [26]. It was used in this CubeSat design to further the accuracy of pointing which is a vital part of the mission due to the function of the antennae.

A Cubesat Sun sensor determines the spacecraft body angles in respect to the sun. It is extremely light and is able to achieve high measurement accuracy for its size. More than one hundred CubeSat Sun sensors have been delivered to international satellite programmes [27]. It has been incorporated into the design due to its efficiency.

Angular rate sensors are gyroscopes that measure angular rate or how quickly the object turns. This was incorporated into this CubeSat design in order to be able to pick up deviations from the designated angular rate [28].

Due to the insignificant Martian magnetosphere, neither a magnetometer or a magnetorquer was included in the design as these systems both interact with a magnetic field in order to stabilize the spacecraft [29].

Computing

In order to manage data, a CubeSat must contain its own command and data handling system (CDHS) which is able to process, analyze, and compress data. The on-board command system aids in transmitting data, changing settings, commanding power on and off, data collection from the gyroscope, etc. The processing core of this unit is able to interpret commands and schedule action to ensure that the Cubesat is responding to its mission requirements and external stimuli [30].

Exolance Probe

The previous section of the paper discussed the components of the first Cubesat 10 x 10 x 10 cm unit in order to cover the functionality and mechanics that help to sustain the CubeSat for this designated mission. This section discusses modifying the exolance probe design in order to fill the remaining two 10 x 10 x 10 cm units.

Background on Design

The Exolance probe is an innovative project design that is intended to carry life-detection equipment that will function upon landing into Martian soil. The design remains a mission concept.

However, after the launch of CubeSats MarCo A and B, further CubeSat missions will be considered and this modification could be proposed to be launched as a cost-effective addition to a mission. This part of the paper explores the feasibility of making probe as affordable and compact as possible.

The concept consists of an impact penetrator that is intended to weigh a few kilograms. This specific value is undefined due; however, there is a maximum of 2.496 kgs left for the probe in the CubeSat design. In this concept, the penetrator releases from the CubeSat in low Mars orbit. The penetrator then burrows under the surface of Mars where it performs a metabolic test that detects chemical reactions that are created by microorganisms that live one or two meter below the surface. The tip of this detection equipment is proposed to have a self-sterilizing surface technology that will prevent inaccurate results. The one meter length that the probe is expected to reach is optimal when retaining information about life due to this region being less affected by the external conditions of the Martian climate. The rear-end of the penetrator remains on the surface and contains an antennae that stands erect to allow for communication with the orbiting CubeSat. The existing concept for the design by the Explore Mars inc. group is shown in *Figure 5* below.

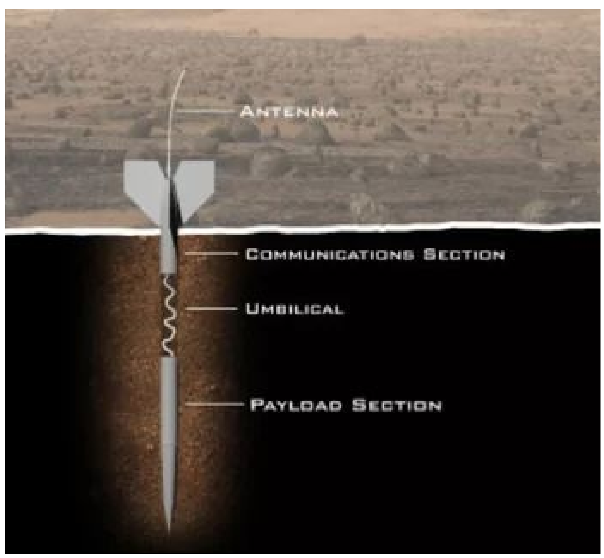

Fig. 5 Existing Exolance Probe Design

Modified Payload Design

A telescoping design was proposed in order to modify the probe design to make it compact to fit the requirements for the CubeSat. This section of the paper will describe the dimensions of the modified probe starting from the antenna and going to life probe. The entire probe has the ability to fill two free CubeSat units that are each 10 x 10 x 10 cm.

Suggestions for the material of the probe are discussed as follows. These materials should be tested in order determine each material's ability to withstand the heat caused by the descent and the pressure caused by impact. Bunker buster military technology has been used to reference the first two materials. The 2267.96 kg BLU-113 bomb is designed to penetrate about 6 meters of solid concrete or 30.5 meters of earth. This probe weighs about 100 times less than the bomb and can be predicted to penetrate the Martian soil to a lesser extent [31]. The material for this bomb is designed to withstand high pressure while retaining a deep penetration depth. M-Steel [32] or ES-1 Steel [33] could be considered for the probe material due to their strength. This would ensure that the nose of the penetrator, which would carry the biosensor chip, would not be damaged. Due to the high weight of steel, carbon nanotubes can also be considered due to their high tensile strength and strength. This material is about 100 times the strength of steel and is only ⅙ the weight. However, the difficulty in working with this material limits its practicality [34]. It has been difficult to develop larger materials using the carbon nanotubes.

Due to the intense heating of entry the probe will undergo during its descent, the outer material of the probe will be composed a blend of cork wood, binder, and silica glass spheres in order to dissipate the heat that is generated by atmospheric friction. This combination was employed on the Viking Mars lander and effectively shielded the instrumentation from the heat. US manned space missions Mercury, Gemini, and Apollo also used this a technology similar to this. The material is able to chemically react with the Martian atmosphere and deflect the heat to the back of the vehicle. This process also slows the kinetic energy of the vehicle due to its heat loss [35].The lack of parachutes, thrusters, and other modes of slowing the vehicle allow for the probe to be able to penetrate the Martian soil without being significantly damaged.

In order to find the length of the antenna, it was assumed that the UHF band will be utilized and it would be operating at 450 MHz. This band is used in current Mars missions between landers, rovers, and orbiting spacecraft and is also supported by the chosen antenna for the CubeSat. The data rates for this link is up to 2 Mb/s. This high-data-rate link was used due to its ability to not interfere with direct-to-Earth links for existing and future Mars spacecraft [36]. With this operating frequency, the antenna would be 32.5 centimeters when it is unfolded [37]. Only 20 cm is available for this portion of the probe when it is compacted. For this reason, a telescoping design was proposed where the antenna would telescope into two components and lock into place upon expansion. The expansion of the antenna would be facilitated by the air resistance that pushes upwards during the downwards descent of the probe.

The antenna is secured on a platform that is 5 cm long. This platform is included to provide stability for the antenna and allows for the attachment of fins that are folded in order to conserve space. These fins make the probe more aerodynamic when they are undergoing descent. The platform is relatively hollow inside and has a strong protective shell (either the steel proposed above or carbon nanotubes) in order to prevent shattering. The umbilical cord of the probe is partially contained in this portion while the rest of the cord is stored in another component below it. The umbilical cord helps to relay data from the biosensor tip at the end of the probe to the antenna at the top. The umbilical cord is also able to be stored in a spiralized fashion that allows for greater length upon the probe's expansion in the Martian soil. The umbilical cord is designed to be 40 cm.

The final component of the probe is the area that contains the biosensor tip which will carry out the biological experiments for the experiment. This area has been segmented into three units and its total length is 40 cm. The specific lengths for each component has remained ambiguous due to the lack of a defined value for the length of the biosensor tip. This ambiguity also allows for a degree of flexibility in the design.

In order to allow for adequate telescoping and to ensure that all of the parts are able to seperate, each component was allowed .375 cm of a width gap in relation to the component above it. Although it can be assumed that the acceleration of the probe during its fall would aid in expanding the probe and the force expended on the probe would cause it to unfold completely upon impact, these gaps are created in order to aid in this process and ensure a smooth expansion. The segments of the probe would lock into place in a similar manner to a telescoping cane.

Due to the relatively unknown nature of the biosensor probe at the tip, the power requirements for this device can not be defined. For this reason, it can only be proposed that the power for the probe will come from a battery that can be stored in one of the expandable units. The biosensor design can vary depending on the provider. Biosensors generally are designed to detect the presence of nucleic acids such as DNA or RNA. Other biosensors mix water with the soil and look for ionic compounds associated with amino acids. An example of a biosensor that NASA has developed with the intention of detecting biohazards helps to demonstrate the efficiency of these devices. The biosensor uses sensitive carbon nanotubes, which detect biohazards. If a biohazard is present, the sensor generates an electrical signal. This technology is able to fit on a small biosensor chip [38]. Another biosensor that is able to monitor glucose, lactate, oxygen, carbon dioxide, glutamate, etc. fits within a chip that is .5 by .5 by 5 mm [39]. The variability in this probe design led to the length of the design remaining ambiguous; however, the small size of these biosensors ensures that they probe is able to accomodate a single, or multiple chips.

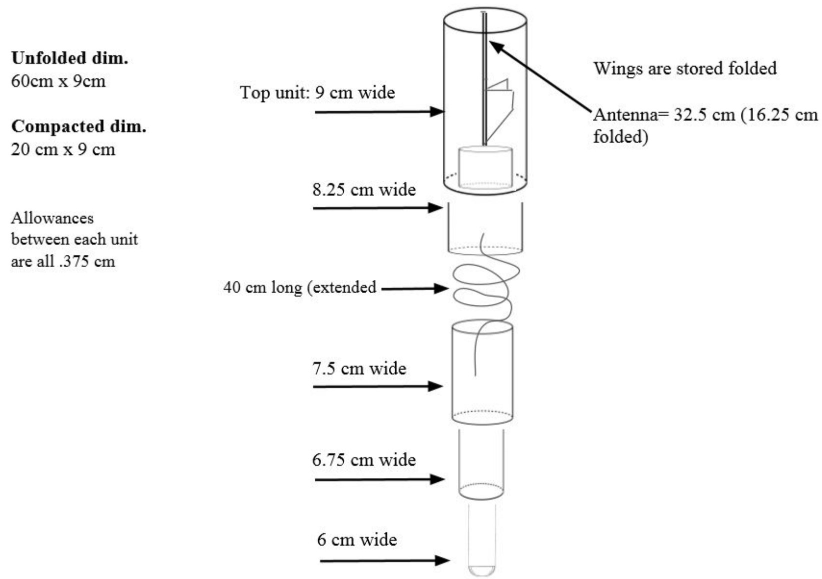

Fig. 6 Modified Payload Design

Conclusion

It can be concluded that the basic exolance probe design is able to be modified to fit the 3U CubeSat facto, which will allow for the mission's efficiency and low cost. This can be accomplished through the telescoping of the probe design. This paper has also factored in the other components of the CubeSat in order to ensure the satellite can both function correctly and be able to house the probe.

Further Research

Due to the relatively undeveloped design of the exolance, further research could expand on the specifics of the probe's design and discuss the efficiency of various elements for the probe's design. Other methods of probe deployment could also be considered. As stated before, this research provides a basis for the modification process to space probes and the components that should be included in a CubeSat that is designed to fulfill a similar mission's purpose. Other research could use this general CubeSat model and change it in order to satisfy the requirements for their missions.

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