CUBESAT SYSTEM DESIGN FOR MARS EXPLORATORY BALLOON (MEB)

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ABSTRACT

Aerial vehicles, which have yet to fly on Mars, can provide a new method for exploring rugged terrain areas of Mars such as cliff and canyon walls that current surface vehicles are not capable of. Solar balloons use solar irradiation from the sun to heat up a lightweight envelope, which results in heating of the internal ambient air and generates lift. The Mars Exploratory Balloon (MEB) platform is stowed in a 12U CubeSat and piggybacks on a larger Martian Entry Descent and Landing (EDL) vehicle before initiating its own deployment sequence after acquiring a safe separation distance. Once deployed, the MEB uses a vent to control altitude and ride different wind patterns to collect high quality imagery and meteorological data from the Martian atmosphere. The present work gives an overview of the MEB platform, a concept of operations, and an analysis of several major subsystems.

1   INTRODUCTION

An important unsolved mystery on Mars is the observation of recurring slope lineae (RSL) that have formed at the edge of crater walls, canyons, cliffs, and slopes. Another is the seasonal observation of methane near the bottom of canyons and cliff walls. A combination of high-res imagery, stratigraphy, and core sample return of the Martian rock walls could help solve these mysteries. Autonomous aerial vehicles can enable access to high-priority extreme terrain science targets on Mars that previous robotic surface landers and rovers have been unable to reach.

With an extremely thin foldable envelope and need for a low-mass payload to maintain buoyancy the entire solar balloon and its gondolas will easily fit into a 12U CubeSat-deployment package. The 12U CubeSat can then piggyback on a larger Mars mission and deploy off a Mars EDL vehicle, eliminating the need for a dedicated heat shield. During descent, the solar balloon initiates its own deployment sequence before fully inflating and beginning to explore Mars. The envelope inflates to around the size of a passenger hot air balloon and carries a primary and venting gondola that occupy a 4U volume that can support up to a 10kg payload. This platform, from a stowed 12U configuration, to full inflation has been named, Mars Exploratory Balloons (MEBs), to pay homage to the Mars

Exploratory Rovers (MERs) that came before them. Fig. 1 shows the design concept of a MEB, fully deployed and exploring Mars.

From previous research, solar balloons for exploration on Mars prove to be feasible by using a lightweight envelope material with high absorptivity and low emissivity to capture radiation from the sun. By including a vent, the balloon is also able to control altitude. For longitudinal control, the balloon adjusts altitude to ride the wind, which is predicted to flow in different directions depending on altitude, like Earth. An ideal area for a solar balloon mission is the north pole during the summer; the balloon can maintain buoyancy for weeks at a time due to the extended period of sunlight.

2   RELATED WORKS

To date, exploration of Mars has been limited to surface landers, rovers, and reconnaissance orbiters. The first interplanetary rotorcraft, the Mars helicopter, will be launching with the Mars 2020 rover to test feasibility as well as perform as a multi-agent system to assist the rover with path planning [1]. Other aerial vehicles that have been proposed for Mars include solar balloons and lighter-than-air aerobots [2][3].

Balloons are not new to interplanetary missions. The first interplanetary balloon mission was the Soviet VEGA mission, which had the objective of collecting Venusian atmospheric data [4]. The mission was short, but successful, and has inspired proposals for future aerobot missions on several planets and moons. One of the most ambitious aerobot proposals is the Titan
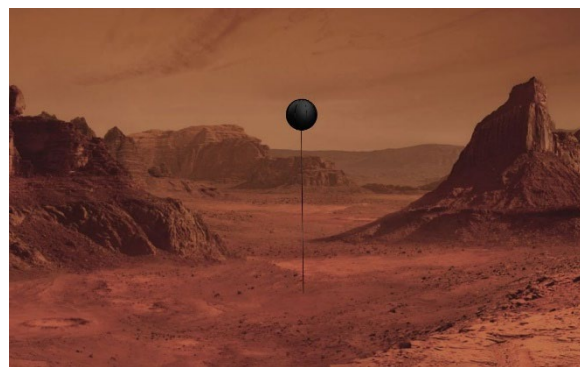
Figure 1 3D Model of a deployed MEB exploring Mars

airship explorer which would use a large helium balloon with an integrated propulsion system to explore Saturn's icy moon [5].

NASA proposed and has conducted experiments to use solar Montgolfiers for soft landings on Mars. Rather than carrying a lighter-than-air gas, the balloons use heated atmospheric air generated from solar irradiation to achieve buoyancy [6]. There have also been several studies and models for vertical controllability of solar balloons and high altitude lighter-than-air balloons on both Earth and Mars [7-9]. Lighter-than-Air vehicles can also utilize different wind patterns at various altitudes to adjust their horizontal movement [10-12].

3   MISSION OBJETIVE

The MEBs have two major mission objectives. The first objective is to collect high-quality imagery of hard to reach areas of Mars such as canyon and cliff walls, as well as rugged terrain areas that rovers cannot explore. A major goal of the MEB platform is to capture high resolution imagery of Recurring Slope Lineae (RSL), one of the Red Planet's greatest mysteries. As a low altitude aerial platform, the MEBs can collect finer detailed imagery than any of the current orbiters. The MEBs can also provide a unique perspective that the current surface vehicles on Mars cannot obtain. The MEB will use the onboard cameras for visual terrain mapping, visual odometry, and selecting optimal landing sites.

The second major mission objective is to collect atmospheric data on Mars to develop better Martian meteorological models. Currently, atmospheric data collection on Mars has been limited to the surface vehicles and the MAVEN spacecraft which collects data on winds in the Martian upper atmosphere. The MEB can collect atmospheric data in a larger 3D area to help improve these weather and climate models. Wind speed data will also be critical for limited control of the MEBs. Through venting, the balloons can adjust their altitude to ride different wind currents and achieve limited horizontal control. Additionally, the balloons can temporarily land and wait for wind direction to change.

4   CONCEPT OF OPERATIONS (CONOPS)

Fig. 2 shows a proposed concept of operations for the MEB deployment sequence. The MEB will piggyback on a larger Mars EDL vehicle before carrying out its own deployment sequence. The stowed MEB jettisons sections of the 12U CubeSat throughout the descent to reduce weight, eventually resulting in two lightweight gondolas connected to the inflated MEB. The MEB's low mass envelope acts as both a parachute and balloon throughout the descent and because of its material properties, can achieve buoyancy before making contact with the Martian surface.

4.1 Piggyback Mission

The stowed MEB CubeSat will enter the Martian atmosphere on a larger EDL vehicle to avoid the cost of an entire mission as well as eliminate the need for a dedicated EDL vehicle. CubeSat landings for asteroids and the Moon have been proposed, but none have launched at this time [13][14]. Mars introduces the additional need for a heat shield during reentry to withstand the heat from high speed entry into the upper Martian atmosphere. Even with the thin atmosphere, a spacecraft entering Mars will heat up to over 1000 K. The MEB can fit inside of a 12U CubeSat in a stowed configuration, so rather than creating an EDL vehicle specifically for the MEB, to minimize size, we suggest piggybacking on the EDL vehicle of a larger Mars lander mission. A similar design has been proposed for an inflatable sailplane that deploys at a high altitude
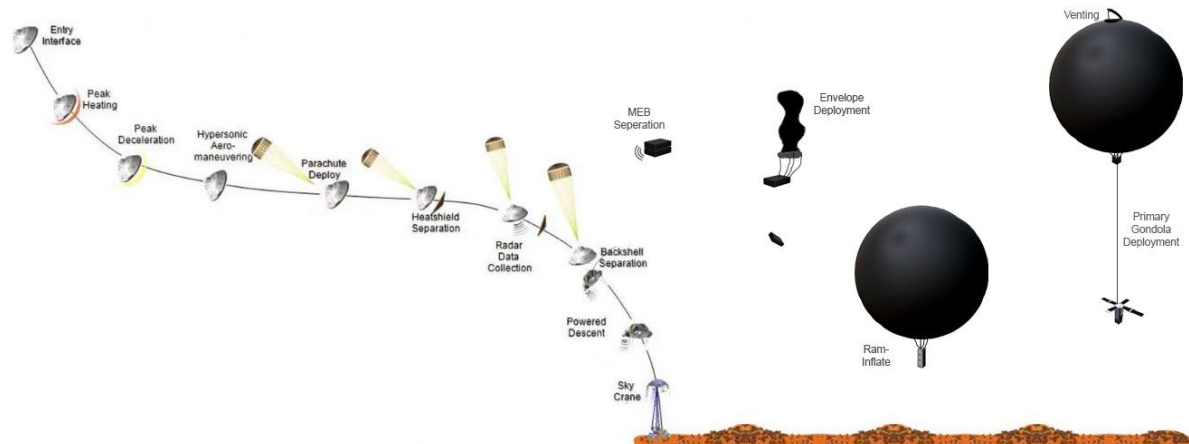

Figure 2 Concept of operations for deployment of a MEB on Mars

on Mars after piggybacking on another mission's EDL vehicle. [15].

After the heat shield of the EDL vehicle is jettisoned, the 12U CubeSat will launch off of the EDL vehicle using solid rock propellant as shown in Fig. 2. Heat shields for previous Mars surface missions have been jettisoned at heights of up to 12 km which would be the ideal separation height for the stowed CubeSat [16]. From simulations using models of the Martian atmosphere, Fig. 3 shows that the MEB could achieve buoyancy before contacting the ground with a large enough balloon volume-to-mass ratio as well as pre-heating of the envelope before being exposed to the atmosphere. Heating of the internal air could easily be achieved by using a rapid chemical combustion reaction. If, however the envelope is not preheated, or the volume-to-mass ratio is too small the MEB would instead crash into the Martian surface at of 5-15m/s before achieving lift. Therefore, the ideal landing site should be at a low elevation to maximize altitude over the Martian surface.

4.2 Initial MEB Deployment

The stowed MEB 12U requires its own propulsion system in order to achieve an adequate separation distance from the main vehicle. Typical Advanced CubeSat Ejector Systems (ACES) have ejection velocities of less than 5 cm/s for use in space. However, such a low ejection velocity will not provide the necessary separation distance of at least 500 m. To achieve this distance, the MEB will use an array of small, high-thrust solid rocket motors.

After separating, the stowed MEB will jettison the propulsion system and 12U chassis using a combination of explosive bolts and burn wires. A drogue shoot will then be deployed to partially unravel the folded MEB envelope. When the envelope is free, the hoop at the bottom of the balloon will naturally assume form.
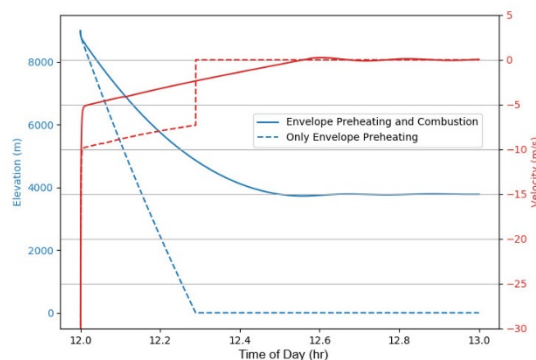

Figure 3 Landing profile for initial deployment with and without envelope preheating

Next, a timed chute deploy will fully release the envelope to begin natural ram-injection inflation while falling through the upper atmosphere. Ram-intake balloons dropped from high altitudes have been successfully deployed by NASA in a terrestrial setting, including with solar balloons [3][17].

In the drop tests, the solar balloons failed to inflate without a rigid hoop at the mouth opening. Therefore, solar balloons on Mars need a hoop that can be compressed to a small volume. The hoop will use either a lightweight shape memory alloy such as NiTiNOL, or a pressurized inflatable hoop.

4.3 Multi-Day Flight

A solar balloon flying on Mars would be an achievement, but the ideal goal is to have these balloons fly for weeks or months at a time. If the MEBs are restricted to flying near one of the Martian poles during the summer or winter, they can utilize the constant sunlight to remain buoyant for weeks at a time. Therefore, a polar mission is suggested for an initial solar balloon flight. For any other regions on Mars, the MEBs will safely land prior to sundown and a system for reinflating the balloons would need to be developed. Re-inflating a landed balloon for a subsequent flight presents one of biggest design challenges for the MEB platform.

Table 1 Stowed 12U MEB CubeSat Technical Margins

Component	Mass (kg)	Volume (cm^3)
12 U Structure	2	12000
Primary Gondola	5	3250
Vent Gondola	6	1000
Folded Envelope	11	1000
Propulsion Chamber	1.5	1000
System Margin	25%	25%
Total	27	7800

5   Stowed 12U CubeSat

Before the MEB is deployed on Mars, it will be stowed in a 12U package. Fig. 4 shows the stowed state of the CubeSat, which will include the stowed primary gondola, vent gondola, folded balloon envelope, and propulsion chamber. Additionally, Tab. 1 gives an estimate of the technical margins for the stowed configuration with the folded solar balloon envelope consuming about half of the mass budget.

6   Balloon Envelope

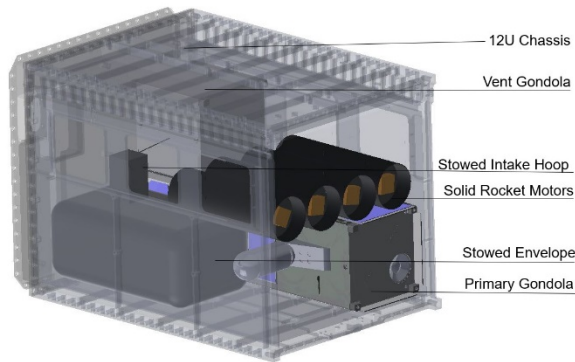The MEB envelope properties assumed for the baseline model in Tab. 2 are from a material developed by

Figure 4 Stowed view of the MEB inside a 12U Chassis

JPL for their solar balloon experiments in the late 1990's [3]. The material is a lightweight 3.5-micron Mylar with 55 denier Kevlar mesh with a germanium alloy coating. The coating has an absorptivity of 0.6 and IR emissivity of 0.03, which is ideal for collecting solar radiation. Alternative coatings with similar properties include tarnished copper and Dark Mirror coating [18].

A vent will be installed at the top of the balloon that can either be a parachute vent like on hot air balloons or a lightweight butterfly valve. Either design requires the need for a vent gondola near the balloon envelope to control the vent. Additionally, the bottom of the envelope will include a rigid hoop as mentioned in the CONOPS sections. The balloon's gores will be attached together via a thin lightweight thermoplastic adhesive.

7   Gondola Subsystems

The following section gives an overview of the major subsystems onboard both the primary gondola and the

Table 2 Assumptions for Baseline MEB Model

Dynamic Viscosity	$1.130 * 10^{-5}\ (N/m^2)$
Thermal Conductivity	$10.024 * 10^{-3}\ (W/m°K)$
Prandtl Number	0.76
Diameter	20 (m)
Volume	$\approx 3000\ (m^3)$
Payload Mass	10 (kg)
Envelope Density	$.009\ (kg/m^2)$
Envelope Thickness	3 (μm)
Envelope Emissivity	.03
Envelope Absorptivity	.6
Envelope Specific Heat Capacity	$320\ J/kg°K)$
Mars Surface Temperature	225 ºK
Mars Ground Emissivity	.95
Mars Albedo	.17

vent gondola. Tab. 3 gives an estimate of the technical margins for the combined weight, power, and volume of the primary and vent gondolas. Additionally, Fig. 6 shows a 3D model of the deployed gondolas.

7.1 EPS and Solar Power Performance

The MEB will use solar panels as the main source of power. Solar panels are more desirable than radioisotope thermoelectric generators (RTGs) for several reasons. RTGs weigh significantly more than solar panels designed for CubeSats and are also much more cost effective. While RTGs do provide significantly more power than solar panels, they rely on propellant, while solar panels simply utilize sunlight, and the power an RTG outputs is far more than the MEB requires to operate.

For the MEB primary gondola, Endurosat solar panels were selected due to their customizable features (optimal voltage, current, sensors, etc.), as well as the high solar cell efficiency, max power output (8.43 W) and deployable burnwire assembly. The MEB will have 4 Endurosat 3U solar panels on the CubeSat; each panel equipped with 7 Triple Junction CESI Solar Cells CTJ30 and a solar cell efficiency of 29.5%.

Fig. 5 compares the power generated from the four panels mounted in different configurations on the primary gondola. The configuration with the least power output is the XY configuration, in which the solar panels are flat on the sides of the CubeSat. In this configuration, the solar panels only produce about 12 W-hr a day, which is not sufficient to power the MEB. The Z configuration positions the solar panels normal to the sides of the CubeSat, as shown in Fig. 6. This configuration produces about 77 W-hr over the course of a day and does not add extra weight to the MEB. The X-Y-Z configuration uses solar panels in an L-shaped form, where part of the panel extrudes outward and the other section is mounted to the side of the CubeSat,
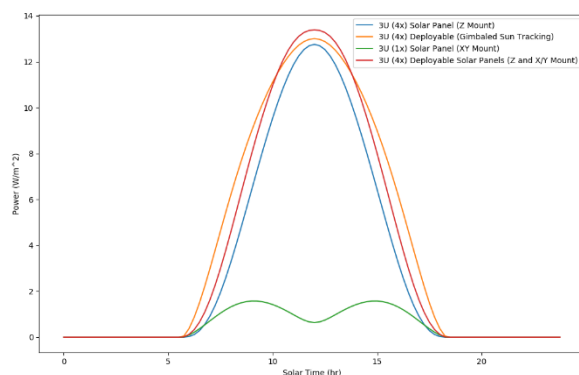

Figure 5 MEB Solar Power Performance for Different Mounting Configurations

acting as a combination of the previous two configurations.

In addition, these solar panels produce a high-power output (89 W-hr) but add more weight to the MEB. If desired, the angle of the solar panels can be adjusted using the sun sensor (photodiode), which acts as a solar tracking system. The sun sensor enables the panels to move in the north and south directions and coupled with the balloon's ability to rotate, the panels will be able to follow the sun from sunrise to sunset. As the solar panels are tracking the position of the sun, they can be positioned to maximize the effective solar cell area, thus producing the maximum possible power for the MEB. The solar-tracking case, as calculated in Fig. 5, can adjust the solar panel angles to be normal to sunlight and produces and extra 20 W. While the MEB gains some additional power in both the X-Y-Z and sun tracking configurations, these configurations would also add extra weight and complexity. More weight would also result in more power draw for the tether system. Thus, the MEB will feature the Z-configuration which produces a high-power output (76 W-hr) while minimizing weight.

7.2 Telecommunications

Due to mass and power constraints, the solar balloon will not be able to communicate directly with the Deep Space Network (DSN). Like other surface vehicles on Mars, the gondola will be equipped with an omnidirectional UHF antenna and transceiver to provide communication with the Mars Reconnaissance Orbiter (MRO), MAVEN, or any future satellites carrying NASA's Electra telecommunications platforms. The Mars orbiters then use X-Band to relay the data to the DSG. Electra and Electra-LiTe (ELT) serve as a constellation of Mars network nodes that relay high rate

Figure 6 Labeled 3D Model of the Deployed MEB's Primary and Vent Gondolas

in-situ mission science and engineering data [19]. The ELT is a smaller less power-hungry version of the Electra, has already been successfully deployed on the Mars Science Laboratory, and has been proposed for both the Mars 2020 rover and the Titan Explorer [5][19][20].

Table 3 MEB Gondola Technical Margins

Component	Mass (g)	Volume (cm^3)	Average Power (W)	Peak Power (W)
PRIMARY GONDOLA				
3U Structure	300	3000	-	-
3U Solar Panels (4x)	520	40	-	-
OBC	100	100	.4	.4
EPS	360	240	.2	.2
UHF Antenna	85	25	-	-
UHF Transceiver	95	200	.08	1
Zigbee Transceiver	100	10	.015	.75
Monopole Antenna	50	1	-	-
Primary Camera	250	200	.3	1
Observing Cameras (4x)	100	4	.2	1.5
NAV Camera	50	5	.1	.1
Star Tracker	350	275	.4	7
IMU	15	10	.185	.185
REMS	150	275	.4	7
Primary Tether + Spool	160	100	-	-
High Torque Servo	125	100	3	50
VENT GONDOLA				
1U Structure	100	1000	-	-
High Speed Servo	50	45	.015	.75
Flight Control Box	300	20	.5	.5
EPS	270	150	-	-
Monopole Antenna	10	2	-	-
Observing Cameras (x2)	50	2	.1	1
Vent Tether + Spool	20	30	-	-
System Margin	25%	25%	25%	25%
Total	6kg	2400cm³	7W	83W

The baseline balloon model cannot fit the ELT in a CubeSat volume along with all other necessary components. The ELT is the ideal telecommunications package for a larger gondola that can support a heavier payload and generate more power.

Instead, the MEB main gondola will be equipped with a lighter weight UHF transceiver and omnidirectional antenna. We propose the Endurosat UHF antenna, which weighs less than 100g and can be configured to transmit data at rates up to 100 kbps. The transceiver uses around 80mW of power in receive mode. The MEB will also use the complimentary UHF Endurosat omni-directional antenna which has a gain of about 0dBi and a max RF output power of 3.5W. The antenna uses a burnwire to deploy radiation rods, which will occur in the final stages of the deployment sequence. A system link budget analysis was performed between the proposed MEB radio and the MRO's Electra and results in 15+dB.

Additionally, the MEB's will be equipped with Zigbee radios for short-range communication, like the Mars helicopter launching with the 2020 rover [1]. The Zigbee radio operates in the 900 MHz range and can relay data up to 250 Kbps over up to 1000 m. Both the primary gondola and vent gondola will use this Zigbee pair as well as 2 small deployable monopole antennas. The Zigbee radios could also be used to communicate with other close-range surface vehicles, such as the Mars 2020 Rover or helicopter.

7.3 Tether System

A unique functionality contained within the MEB platform is a tether system that allows for greater freedom in sensing, mobility and possible sample acquisition. Due to the thickness and mass of powered tethers, the vent gondola will instead be attached to the primary gondola with a lightweight Kevlar® thread. The tether system consists of a thin, lightweight Kevlar® thread, reel, and high torque continuous rotation servo. The tether connects the vent gondola to the primary gondola and allows the primary gondola to adjust the vertical distance from the balloon by being reeled into the spool located in the primary gondola. The vent gondola uses a similar system for opening and closing the vent at the top of the balloon but uses a miniaturized version of the primary gondola's tether system, with a low torque servo, smaller spool, and thinner kevlar thread.

From basic calculations, the tether must be able to withstand 60 Newtons of force to carry the 10kg payload and withstand wind gusts. The tether selected, Aramid 1414, is made from Kevlar with a thickness of 0.35 mm and can withstand 240 Newtons of force. Because the Zigbee communication range between the primary gondola and vent gondola is limited to a maximum range of 1 km, the proposed tether distance is also 1 km.

The estimated time to fully reel in 1 km of tether would be a maximum of about 120 minutes when the primary gondola is reeling during flight. However, this time can be reduced to less than 90 minutes, if instead the primary gondola rests on the ground and reels in the balloon during venting maneuvers. This would eliminate most of the load on the servo.

7.4 Sensing

The MEB platform has the unique advantage of having the capability to measure atmospheric properties at different altitudes, up to 5 km, over a much wider longitudinal area than current surface vehicles. The current design will use the same Rover Environmental Monitoring Stations (REMS) that is installed on the Curiosity and Mars 2020 Rovers. The REMS collect data on 3-dimensional wind speed, air temperature, humidity, atmospheric pressure, and ultraviolet radiation levels [21]. Ideally, a miniaturized version of the REMS would be designed for the MEB because it is 15 cm long, but for this preliminary design, the REMS was selected due to its flight heritage. The REMS unit has 2 booms to collect 3D wind data, but because the MEB is free to spin while floating, the additional boom pole shouldn't be required and instead the additional sensors on it can be added to the single boom.

Another unique capability of the MEB is to have an Astrotube™ for both sensing and gripping. The Astrotube™ is a lightweight rigid boom that can compact down into a smaller footprint to install on micro satellites. The same technology has been used for the initial deployment of solar sails [22]. The main function of the Astrotube™ will be to closely examine cliff and crater walls with a small camera attached to the end as well as potentially probe canyon walls to collect additional science data such as temperature and composition.

The gondolas will house several cameras for collecting imagery. The primary gondola will use the MSSS ECAM-C30, for its primary source of aerial imagery; this camera is currently used on the Mars Rovers. Additionally, the MEB will use several cameras with flight heritage or that have been tested for thermal and radiation survivability. Several smaller cameras will be installed on each of the gondolas to check statuses and collect imagery on Astrotube™ deployment, envelope deployment, and venting status. These

observation cameras will be a Sony IMX 214 with a Bayer color filter array mated with an O-Film optics module. Additionally, the primary gondola will use a downward facing nadir pointed grayscale low resolution pixel sensor (Omnivision OV7251) mounted to a Sunny Optics module with a much larger FOV. The navigation camera will be used for visual terrain mapping as well as visual odometry estimates. Finally, the primary Gondola will also include a Blue Canyon NST star tracker to assist with navigation estimates. The star tracker will be useful for multi-day missions, but would not be required for a polar mission, as the constant sunlight would prevent seeing the night sky. The star tracker will also be useful for the end of life mission stage to determine final position of the landed MEB and the primary gondola can still collect meteorological data without the balloon flying.

As discussed earlier, the MEB can 'fly' to regions inaccessible by current rovers and landers. This includes crater walls, ridges, canyons, and even skylights. To successfully navigate this rugged terrain the MEB must maintain slow lateral motion and potentially anchor or grip to a cliff face, the ground, or skylight entrance. Since the MEB gondola design is modular, additional sections can be added for specific mission goals. Options for this include carrying a toolkit containing tethers, conventional grippers, soft-robotic end-effectors, or spiny grippers, which have shown to be effective in latching onto rocks and anchors.

There is great interest in exploring cliff-walls, ridges, canyons and skylights to observe the exposed stratigraphy and identify geologic changes, particularly when there was a thicker atmosphere and flowing water on Mars. Exploring such stratigraphy on Earth has given insight into past climate change as well as major

Figure 7 MEB performing 3D LIDAR Mapping and mineral spectroscopy of an exposed canyon wall

geologic/climate cataclysms including volcanic eruptions, flooding, tsunamis, evidence for past life and extinction events. Exploring these rugged walls will also give much better insight into the mystery of recurrent slope linaes (RSL) and apparent orbital images of seasonal water-flow. Some instruments required to observe the stratigraphy include high-resolution imagers, 3D LIDAR, stereo-imagers, and hand-lens imagers. Additional devices to core and return samples are desired for performing gas-chromatography, atomic-dating, and mineral spectroscopy.

Fig. 7 shows the MEB positioned parallel to a cliff wall to perform 3D LIDAR mapping (red), imaging and mineral spectroscopy (green) of the exposed rock stratigraphy providing insight into past geologic and climatic events on Mars. Using a corer, samples could be obtained for gas chromatography and detailed observation under a high-power microscope. These samples could be analyzed to determine past habitability and available resources to support life.

8   CONCLUSIONS

This work demonstrates the preliminary feasibility of deploying a solar balloon on Mars to collect high resolution imagery, collect meteorological data, as well as prove that balloons are a viable method for aerial exploration on another planet. Using COTS components, the entire MEB platform can fit in a stowed configuration in a 12U structure prior to deployment. After deployment, the MEB then sheds the propulsion system and 12U chassis and inflates to the size of a passenger hot air balloon.

The MEB platform is also highly customizable to carry out various science objectives. The system margins are sufficient to house additional sensors and payloads that could be carried or dropped from the MEB. The balloon and gondola mass and size can also be adjusted to carry different payloads. A minimalist design could have an MEB envelope that is half the size of the baseline model.

9   FUTURE WORKS

Future work for this project includes performing more detailed analysis of all the major subsystems. The current subsystems serve as a baseline estimate, but many can be improved and miniaturized. Additionally, we would like to run CFD experiments to test various vent designs as well as determine the ideal throat size for the intake hoop at the bottom of the solar balloon. We plan to design an Earth version of the MEB platform to test portions of the deployment sequence empirically, as well as conduct GPS-denied autonomous navigation algorithms using only venting maneuvers.
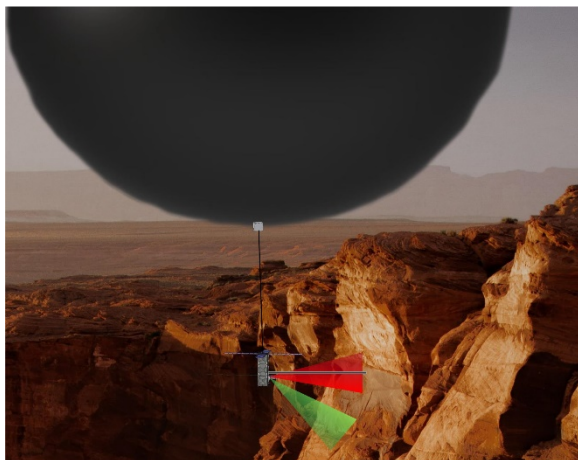
Acknowledgement

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