SSC20-WP1-13

"Development of Electrodynamic Tethers for Propellantless Propulsion in Low-Earth Orbit"

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ABSTRACT

The Miniature Tether Electrodynamic Experiment-1 (MiTEE-1) is a University of Michigan faculty research project, backed by student research and leadership, consisting of a 3U CubeSat with a short rigid boom electrodynamic tether (EDT) connecting a picosatellite providing enhanced current collection. It is the first of two satellite missions working towards a technology demonstration and increased knowledge of CubeSat spacecraft charging dynamics. This will thus allow for increased refinement and full operation of an EDT spacecraft system capable of station keeping activities on MiTEE-2. The mission of the MiTEE organization is to demonstrate and refine the technology needed to successfully use electrodynamic tethers on CubeSat and smaller platforms. With a final goal of producing a pico (100g-1000g) to femto (<100g) sized pair of satellites capable of complex station keeping activities further advancing the ability to create low cost, long term, and controllable satellite constellations. The following paper describes the MiTEE-1 spacecraft, proposed operations, and the hardware needed to demonstrate a miniature EDT housed in a 3U body.

INTRODUCTION

The Miniature Tether Electrodynamics Experiment (MiTEE) is a faculty research project providing an educational experience and a technology demonstration. The mission uses a 3U CubeSat architecture to investigate the use of miniaturized (~10-30 m), low-power electrodynamic tethers (EDTs).

In the past three years MiTEE-1 has matured from its initial design phase to the fabrication of a fully functional 3U CubeSat. In the past year, specifically, the final assembly of the flight spacecraft was completed, flight software was refined, and launch vehicle integration compliance testing was completed. MiTEE-1 will launch as a NASA sponsored mission on ELaNa 20, riding on Virgin Orbit's LauncherOne vehicle in 2020.

Electrodynamic Tethers

Electrodynamic tethers (EDTs) are long conductive wires that conduct current between two locations with the express goal of interacting with the local magnetic field. They directly interact through the basic Lorenz magnetic force equation:

$$F = IL\ x\ B \tag{1}$$

The direction of current flow through the EDT with respect to the magnetic field vector governs the direction in which the force acts, thereby enabling a multitude of potential operational modes. Enhanced station keeping capabilities are obtained by the spacecraft when operating in one of two operating modes: applying an external bias to the induced motional EMF generated or allowing for current to flow naturally due to the induced motional EMF. These operations enable a spacecraft operating an EDT to either increase or decrease its own velocity by directly interacting with the Earth's magnetic field. This is especially intriguing for the operation of CubeSat, and smaller spacecrafts, because it does not require any stored propellent potentially increasing the life of the mission and saving crucial onboard volume [1]. This is compounded by the fact that small satellites have a reduced mass verses surface area ratio, and thus deorbit in time frames much shorter than traditionally sized spacecrafts. Equally important is the ability of an EDT to induce a 'magnetic drag-force' on its vehicle during periods of non-active reverse biasing of the system. This potentially allows for a robust, passive system to dramatically attenuate orbital velocity, and subsequently decrease the amount of time between satellite deactivation and atmosphere reentry, thus reducing space debris.

Space Tether Uses in the Past

There are many examples of past use of space tethers. Tethered Satellite System (TSS) of 1992. The goal of the TSS was to demonstrate the feasibility of deploying and controlling an electrodynamic tethered system in orbit. The satellite was tethered to the space shuttle and dragged through the ionosphere to generate an electromotive force for power generation [2].

Also of notable interest is the Plasma Motor Generator (PMG) of 1993 which was a demonstration of the ability to use the naturally occurring EMF potential differences to conduct current in an EDT between two spacecraft. This mission showcased the reversibility of the current within the tether, proving that the EDT can be used to either boost or de-boost the spacecraft to achieve its desired position. It also verified the notion of using EDTs to counteract the atmospheric drag forces and enforce the spacecraft with station keeping capability using magnetic propulsion [3].

MITEE-1 SYSTEM DESIGN

MiTEE-1 is divided into five different functional subsystems in order to maximize the working knowledge of the multidisciplinary students involved in the project and offer clear distinctions of responsibilities.

Plasma-Electrodynamics

The Plasma-Electrodynamics subsystem is responsible for defining the mission driving science requirements of MiTEE-1, interpreting the mission data, and helping develop the overall electrical requirements of the EDT. Specifically, plasma directly deals with the picosat, boom, cathode, and Langmuir probe components. Shown in figure 2 is the electrical circuit used to drive the miniature EDT equipped on MiTEE-1.

The deployable endbody picosat, which is a 6cm x 6cm x 2cm metal planar picosatellite, collects electrons from the surrounding plasma enhancing our current collection capabilities. The cathode itself is a thermionic emitter provided by E-Beam Inc. The Langmuir probe sensor provides plasma diagnostics data including electron temperature, plasma density, and when using in conjunction with information provided by external systems general spacecraft charging information. The Langmuir probe used on the MiTEE-1 mission is an adaptation of the Langmuir Probe system developed by the University of Michigan Space Physics Research Laboratory (SPRL) work on the Pro-Seds mission developed by SPRL specifically for use on small satellite payloads.

Orbits, Attitude Determination, and Control System

The Orbits, Attitude Determination, and Control Systems (OADCS) is responsible for running relevant mission simulations, characterizing system dynamics, and implementing an active attitude control system for the detumbling and nominal attitude adjustments. Magnetorquers are selected for active control and were manufactured and characterized in-house. Photodiode pyramid sun sensors and magnetometers are used for attitude determination throughout the mission.

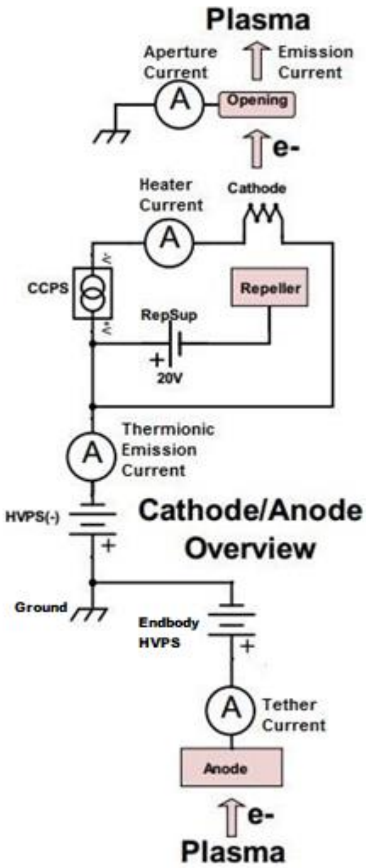

Figure 1: Electro-Dynamic Tether System Electrical Schematic Of MiTEE-1

Electrical Power Systems

The Electrical Power Systems (EPS) safely powers and charges all the major systems of the spacecraft. This is achieved using various components, such as the EPS board, which powers the entire satellite and charges the battery system, and the solar board, which provides power to the general EPS board to charge the batteries. This board was designed by SPRL for their QB50 mission and was mildly altered for use on the MiTEE missions. The HVPS board implements two high voltage power supplies to provide proper bias to the EDT and Cathode system, and the CCPS board implements two constant current power supplies which drive the filaments expelling electrons via thermionic emission as prescribed in the EDT electrical system.

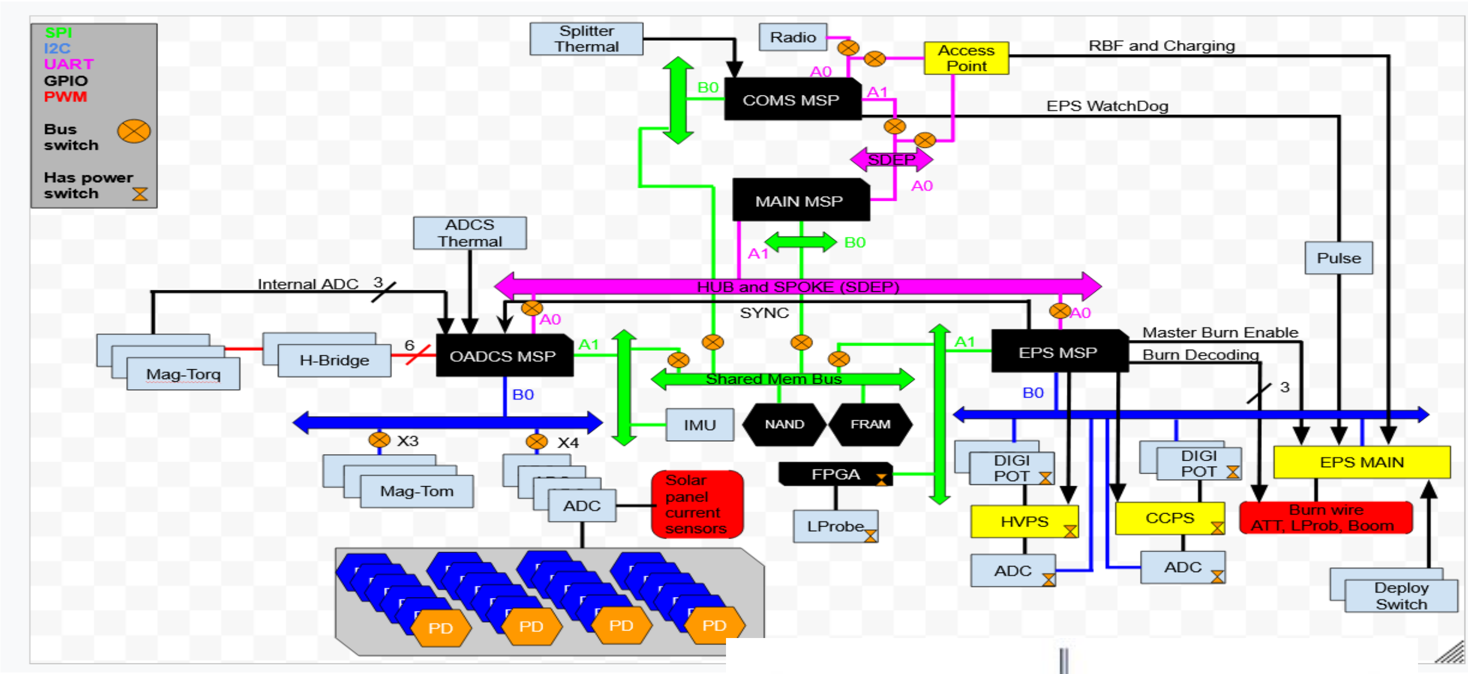

Figure 2: Computational Architecture Of MiTEE-1

Command and Data Handling

The Command and Data Handling subsystem controls all aspects of the electrical interfaces needed to control the MiTEE-1 spacecraft. It follows a modular design providing each major subsystem with its own low power microcontroller, MSP430's from Texas Instruments were used in MiTEE-1, allowing for reduced computational load on each processor and simultaneous control of sensors required to complete the science objectives. This unique system bus design includes a common flash memory device that allows for all processors to save and read from a common device. Allowing for interprocessor data acquisition in a standardize format that is seamlessly transmitted back to ground resulting is lowered data processing overhead and simplified ground activity interpreting all raw data produced by the MiTEE-1 system.

Structures

The structures subsystem designed all structural aspects of the MiTEE-1 mainSat and implemented the deployable boom and picosat design. The 1m long rigid boom used on MiTEE-1 was provided by the private company LoadPath. Unique to MiTEE-1's design is the implementation of a "backplane" design instead of the classically seen "stackup" systems observed in CubeSats.

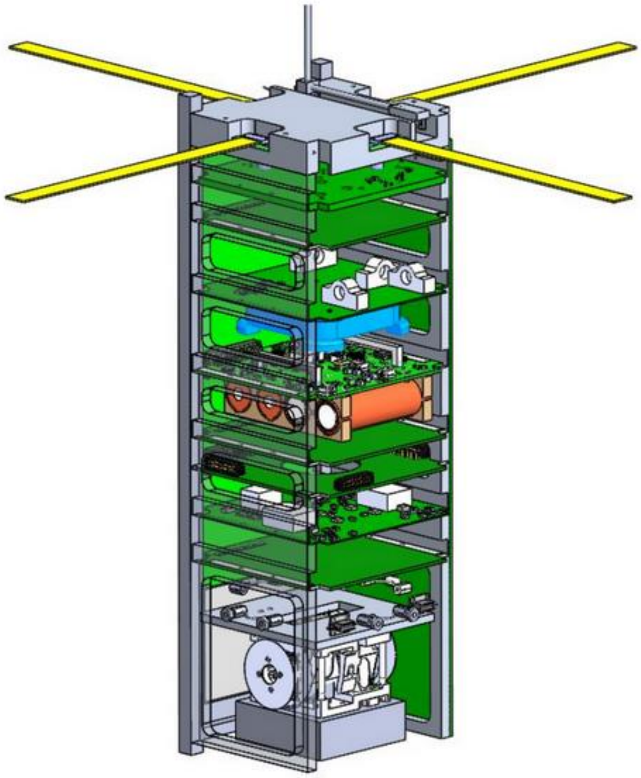

Figure 3: MiTEE-1 Structural Design Exemplifying Backplane Construction

MITEE-2 & BEYOND

MiTEE-1's successor, MiTEE-2, will provide validation of results from the MiTEE-1 mission with the implementation of a full EDT propulsion system. This system is currently under development and is projected to utilize a 30-meter long tether connecting a 3U main body to a smaller picosat endbody identically to the MiTEE-1 endbody. This will enable the spacecraft to perform on-orbit maneuvers without the use of traditional propellants, thus minimizing the wet mass of the spacecraft while extending the possible lifetime of the mission. There also exists a theoretical possibility for the tether to be used as a communications capable antenna. Future iterations of MiTEE spacecrafts may see progressively smaller endbodies and longer tethers to maximize the propulsive impact of the EDT on the spacecraft. Our team's end goal is to enable the capability of launching a constellation of coordinated, small EDT spacecraft able execute operations as a cohesive fleet with far more capabilities than a single spacecraft.

MiTEE-2 Current Status

Currently, design changes for tailoring the MiTEE-2 mission to accommodate a 30-meter long tether are underway. Changes to the orientation of the satellite to improve controlling capability were proposed between the configuration in Figure 7 versus a parallel orientation (dart configuration). This configuration choice will directly determine the layout of all the other components and deployables. The deployables for MiTEE-2 are a duel Langmuir probe system, a tethered picosatellite endybody, and antenna's. Another design choice is determining the direction of the dual Langmuir probe (LP) mechanism and antenna. The requirement is that the dual Langmuir probes must be installed orthogonal to the RAM direction of velocity and must not be parallel to the antenna or they risk causing electromagnetic interference. If the dual Langmuir probe design does not meet the volume constraints as required by NASA guidelines, there is also discussion about using a new technology called an isolated potential probe along with one LP and LP board.

Additionally, there is debate over changing orbit control features, namely magnetorquers versus reaction wheels. These decisions will all impact the EPS and CDH teams who would like to simplify the architecture and increase processing power. Implementing a field emitter array rather than a thermionic cathode is also a under question despite field emitter array technology being limitedly available commercially and having limited in-space testing.

CONCLUSION

MiTEE-1 will fly in 2020 and will be the proving ground mission for its successor, MiTEE-2. The MiTEE program is a demonstration of electrodynamic tethers as a non-expendable propulsion system for small, low mass satellites. Additionally, electrodynamic tethers provide unique benefits such as passive gravity gradient stabilization and the possible use as a high gain communications antenna. The system operates under the principle of in-situ electron collection from the ionosphere's ambient plasma environment to drive an electric current through the tether. The electromagnetic interaction of the tether with Earth's magnetic field will thus induce a Lorentz force to counteract atmospheric drag. The collected electrons are then emitted back into the ionosphere from the non-collecting body to complete a closed-loop electrical circuit. If successful, the demonstration will raise the technology readiness level for EDTs as a small spacecraft propulsion system. Future iterations of the MiTEE program will aim to further reduce the size of the tethered spacecrafts and begin to organize coordinated fleets of EDT satellite constellations. Fleets of this variety will be able to deliver a cost-effective solution to simultaneous measurements of a large geographic area or highly frequent measurements of a specific geographic area.

Acknowledgments

The MiTEE student team would like to express our gratitude to those who have made this mission possible. We thank our faculty advisor and principal investigator Prof. Brian Gilchrist for his essential work throughout the creation and formation of MiTEE. We also thank our two PhD candidate advisors, Omar Leon and Grant Mairs, who have worked diligently to address any obstacles that arose along with Dr. Iverson Bell whose PhD thesis inspired the MiTEE mission.

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