Composite and PCB Based Implementations of a Solar Panel Design for SwampSat

Sharan Asundi, Matthew Mahin, Vivek Nagabhushan, Tzu Yu Lin
Graduate Students, University of Florida, Gainesville, Fl, 32611; 352-846-3020
asundi@ufl.edu, mmahin@ufl.edu, vivekn@ufl.edu, tyl@ufl.edu

Norman Fitz-Coy
Associate Professor, University of Florida, Gainesville, Fl, 32611; 352-846-3020
nfc@ufl.edu

Abstract

A multifunctional solar panel design is implemented as (i) carbon fiber composite panel and (ii) printed circuit board (PCB) for SwampSat, a University of Florida CubeSat. The solar panels structurally support SwampSat and accommodate embedded magnetic coils, a surface suitable for mounting solar cells, Sun sensor mounting and circuitry for sun sensors, solar cells, temperature sensors and magnetic coils. Wet layup technique, used for the development of carbon fiber composite panels with embedded magnetic coils and the vacuum bagging procedure to cure the panels are discussed. The implementation as a multi-layered PCB to accommodate 2oz per square foot copper traces as magnetic coils, copper deposits for mounting solar cells and circuitry and connectors for panel components is discussed. The paper discusses the design, development, lessons learned as well as the pros and cons of each implementation. Prototypes of fully functional panels are presented. Results of thermal-vacuum and vibration tests performed on the PCB panel are discussed.

I. Introduction

CubeSats, conceived as educational satellites,[1] have challenged the paradigm of traditional satellites and are being increasingly recognized for their utility. The CubeSat project[1] has evolved into a program and organizations, particularly universities, around the world are building pico- and nanosatellites adhering to the CubeSat form factor.[2] CubeSat form factors constraints the mass of a 1U CubeSat or picosatellite to be under 1.33 kg and the dimensions along and across the rails to be 10cm x 10cm x 10cm. In an effort to seek and provide standard attributes for CubeSats, the CubeSat program has posed many challenges for the developer. Solar panel design for 1U CubeSats has been one such challenge and has sought multiple functionalities in a single design. Although various design techniques have been implemented and successfully launched in space[3],[4] a design description and a technical analysis is lacking. The work presented, discusses two implementations of a solar panel design for SwampSat[5] and the advantages and limitations of each.

SwampSat is a University of Florida 1U CubeSat mission with the objective of demonstrating on orbit precision three axes attitude control using a pyramidal configuration of control moment gyroscopes. The satellite is designed around the CubeSat form factor and the architecture is subsystem based. A subsystem assembly shown in Fig. 1 identifies at large the components of SwampSat. The CMG based attitude control system (ACS) is designed to occupy the bottom half and the electrical power system, transceiver and flight computer occupy the top half of SwampSat. An aluminum frame and the solar panels structurally support SwampSat and isolate the CMG based attitude control system (ACS) and other satellite components from solar radiation. Additionally the solar panels address the requirements for a suitable surface for mounting solar cells, embedding magnetic coils for momentum management and the circuitry for Sun sensors and other peripheral components. The following section discusses the requirements in further detail.

II. Solar Panel Design

SwampSat solar panels are designed to satisfy requirements across subsystems and adhere to CubeSat form factor. SwampSat's solar panel design was primarily mo-

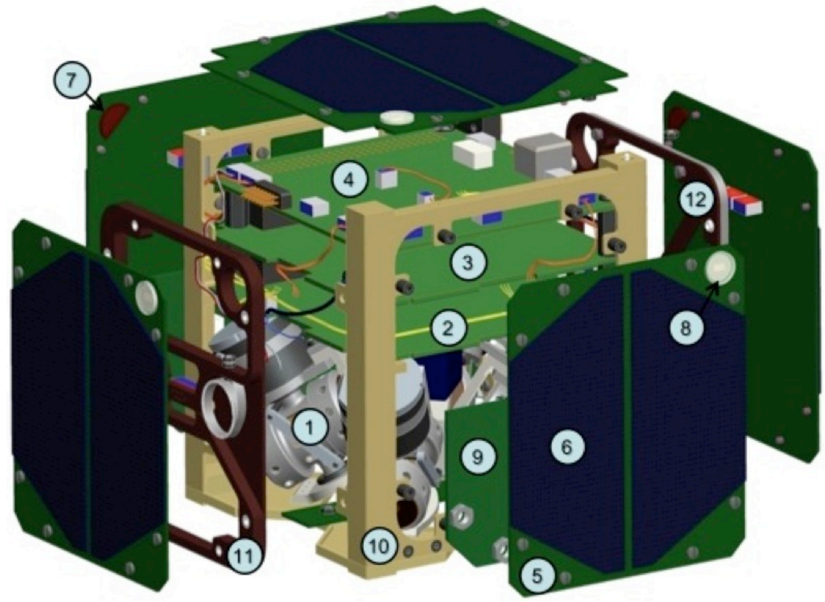


Figure 1. SwampSat Subsystem Assembly

tivated by the need to accommodate a surface suitable for mounting solar cells, embed magnetic coils for angular momentum management on SwampSat, provision for mounting Sun sensors, temperature sensors, bypass diodes and their respective electrical circuitry, and provide structural rigidity to the spacecraft. Solar cells used for CubeSat applications are designed to be light in mass and the cell-interconnect-cover (CIC) is susceptible to breakage. Failure of student designed CubeSats are attributed towards failure of solar panel components, specially solar cells.[3] A fine mounting surface is desired for favorable bonding between solar cells and panel surface. Coarse and uneven surface can lead to poor bonding which could eventually result in damage to the solar cells. Additionally the mass of the bonding material can significantly increase for coarse surfaces and adversely affect the satellite mass budget.

To accommodate SwampSat's angular momentum management requirements[6,7] the solar panels are designed to host embedded magnetic coils on at least 3 of the 5 panels of SwampSat. Momentum management is designed to be a timed operation with feedback from the IMU. Magnetic coils are energized for a specified period of time through ground control and the operation is autonomously terminated if the spacecraft angular velocity is estimated to be under a preset threshold. The allowable panel thickness and SwampSat power budget are the main factors driving the design of the magnetic coils. Each panel with magnetic coils is designed to host approximately 70-80 turns with the ability to be driven at 100mA. The embedded magnetic coils are designed to be accommodated in the area shown between the two dotted lines in Fig. 2.

SwampSat solar panels are required to accommodate peripheral components like sun sensors, temperature sensors and bypass diodes. Additionally delrin plates hosting the receive and transmit antenna systems are required to be accommodated between the solar panels and the CubeSat chassis. These requirements limit the options for placement of Sun sensors, temperature sensors and the corresponding circuitry. A side solar panel drawing is shown in Fig. 2 detailing the dimensions. Location of the peripheral components on the panel, viz., the Sun sensor, temperature sensor (LM135/335) and bypass diode (BAS40-04) are shown in Fig. 2. The provision for

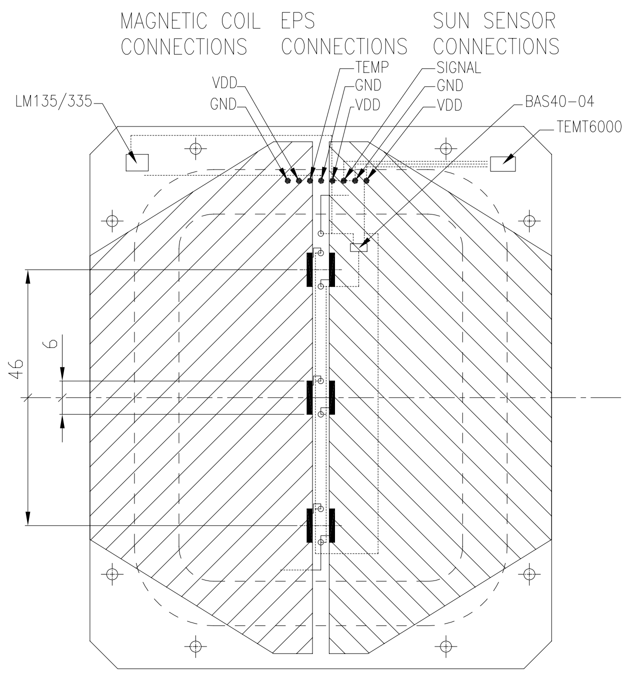
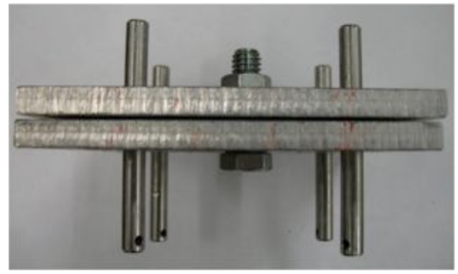


Figure 2. Solar Panel Design

mounting solar cells, shown as a hatched planes, is designed to be in that orientation for accommodating a Sun sensor and a temperature sensor. Embedded electrical circuitry is thus required to connect the two cells in series. This circuitry includes a dual bypass diode to ensure that failure of one cell does not affect the power harnessing capability of the other.

SwampSat chassis accommodates 3 variations of the solar panel design shown in Fig. 2. As indicated in the figure the first type is in the shape of a rectangle with chamfered edges and 8 mounting holes. A second type, dimensionally identical to the first one, accommodates 4 mounting holes. To make provision for separation springs and a flight switch along the chassis rails as per the CubeSat form factor specifications[2] a third type of panel is designed in the shape of a rectangle with L corners. SwampSat antenna system is built around two delrin plates and the length of dipole elements are different for receive and transmit modules. The two delrin plates are unique in their configuration and shape and each plate is sandwiched between a solar panel and the SwampSat chassis. A provision is made to accommodate interface connectors between the solar panels and the subsystem boards through the delrin plates on two sides of the CubeSat. Connectors are designed to be hosted on the panels to interface solar cells and temperature sensors to the EPS board; the Sun sensors and the magnetic coils to SFC430.



(a) Fixture

(b) Finished Coil

Figure 3. Fabrication Fixture and Finished Coil

III. Solar Panel Design Implementations

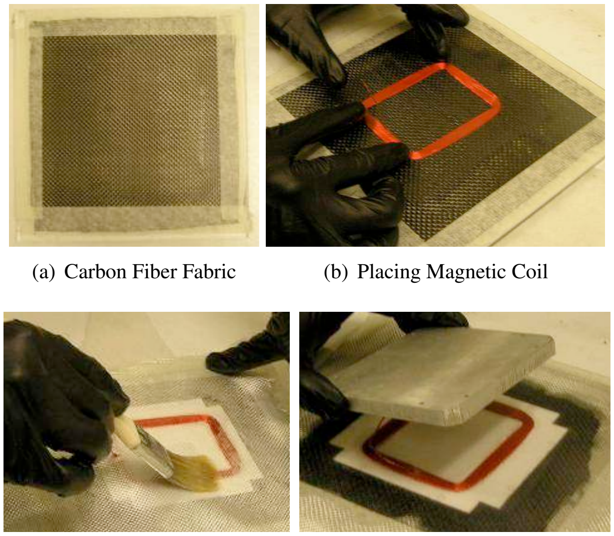
The solar panel design shown in Fig. 2 is implemented as a (i) carbon fiber composite solar panel and (ii) printed circuit board (PCB) solar panel. The two implementations are discussed in the following subsections.

A. Carbon Fiber Composite Solar Panel

Composite solar panel implementation process involves preparation of magnetic coils, laying out fiber composite and machining the product to achieve precise dimensions. Magnetic coils are prepared from enamel coated 30 AWG copper core wire and EPO-TEX 78-165 epoxy. Two metal plates with 4 through holes and a spacer sandwiched between them are held together in place by a nut and bolt as shown in Fig. 3(a). Metal rods are inserted into the through holes for guiding the path of the copper wire in the shape of a coil. Layers of magnetic coils are secured together in place by the epoxy resin and the fixture shown in Fig. 3(a) is cured for 10 minutes at 100^0C or 30 minutes at 80^0C. The latter option is observed to be favorable for flowing out the excess epoxy resin out of the magnetic coils. A finished magnetic coil fabricated using this process is shown in Fig. 3(b).

Wet lay up technique using a carbon fiber fabric is chosen for implementing the solar panel design as a composite. As a rule of thumb equal weights of the carbon fabric and epoxy resin are used. Two layers of approximately 12"x12" carbon fiber fabric are placed on a cleaned glass plate and a mixture of one portion of 105 epoxy resin and one portion 205 hardener is uniformly applied onto the fabric. Magnetic coil prepared using the process described is placed on the wetted portion of the fabric with the exposed leads pointing upwards. Two additional layers of the carbon fiber fabric are placed on top of the coil and the leads are passed through the fibers. The epoxy mixture is uniformly applied onto the top layer. To minimize formation of air pockets excess epoxy is carefully removed after each application. An aluminum mold with groves is placed on top and pressure is applied gently to secure the coils in the grove. The composite preparation along with the aluminum mold is vacuum bagged, held under load and allowed to set for 3-4 hours at room temperature. While the mold ensures the magnetic coils reside in the groove, the clean glass plate on the other side ensures a surface finish suitable for mounting solar cells is obtained. Once the composite pane is set it is trimmed to a convenient dimension identified by the imprint of the mold. The aluminum mold is designed to be used as a fixture for sanding the pane to precise dimensions and drilling mounting holes. A composite pane under development is shown in Fig. 4.

The precisely dimensioned composite pane is functionally transformed into a multifunctional composite panel by mounting solar cells and laying out electrical traces, bypass diodes and temperature sensors. A combination



(a) Carbon Fiber Fabric (b) Placing Magnetic Coil

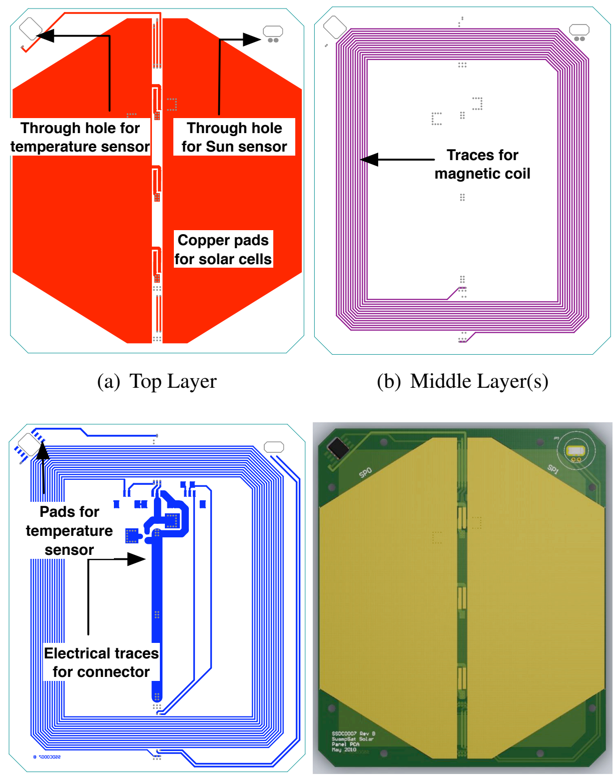
(c) Applying Epoxy Mixture (d) Placing Aluminum Mold

Figure 4. A Composite Pane Under Development

of the EPO-TEK 78-165 conductive epoxy from Epoxy Technology, conductive pen and metal foil tape from 3M with high temperature resistant adhesive is used for laying out electrical traces. To account for the loss of a single solar cell on any panel, bypass diodes are soldered appropriately along the path of the electrical traces. Space grade epoxy from NuSil Technology, CV-2566 CV Silicone Elastomer, and custom designed disposable stencils are used for mounting solar cells on the surface obtained from the glass plate. A temperature sensor is mechanical glued at the corner of the panel and electrically interfaced to the traces on the other side of the pane via the through holes. The composite panel is designed to accommodate a Sun sensor on another corner.

B. Printed Circuit Board Solar Panel

The solar panel design discussed previously is also implemented as a 6-layer 1mm thick printed circuit board with FR-4 cores, 2oz per square foot copper, dual side solder mask with fully insulated vias, and an immersion gold over electroplated nickel finish. The implementation has embedded magnetic coils, pads for mounting solar cells and electrical traces for interfacing them to the SwampSat EPS. Additionally the PCB panel implementation makes provision for mounting a Sun sensor, temperature sensor and surface mount dual bypass diode. Pads are laid on the top layer for mounting solar cells with solder paste as shown in Fig. 5(a). Magnetic coils, summing to 71 turns, are laid out on 4 inner layers and the bottom layer of the PCB as shown in Fig. 5(b) and Fig. 5(c) and interconnected by vias. A temperature sensor, bypass diode and connectors are mounted on pads on the bottom layer and electrically interfaced through PCB traces. Temperature sensor and Sun sensor leads are routed from outside of the coils to the inner region via vertical traces on the top layer between the solar cell pads. Solar cell leads on the top layer are connected to the traces on the bottom layer through vias and electrically interfaced to the EPS board through a connector. High current traces for the solar cells and magnetic coils utilize multiple parallel vias. Mounting holes for the PCB panels are machine drilled, and through holes for the sensors, allowing flushing with the top surface, are machine milled. The Sun sensor utilizes a carrier PCB to provide front-looking mounting pads flush with the back surface. The PCB design for three different types of layers and a complete panel are shown in Fig. 5.



(a) Top Layer (b) Middle Layer(s)

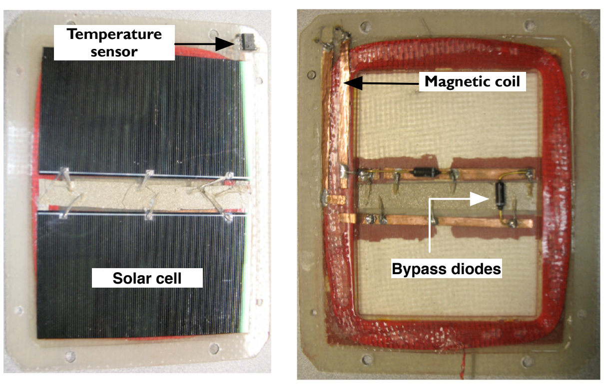
(c) Bottom Layer (d) Layers Overlayed

Figure 5. A Multifunctional PCB Solar Panel

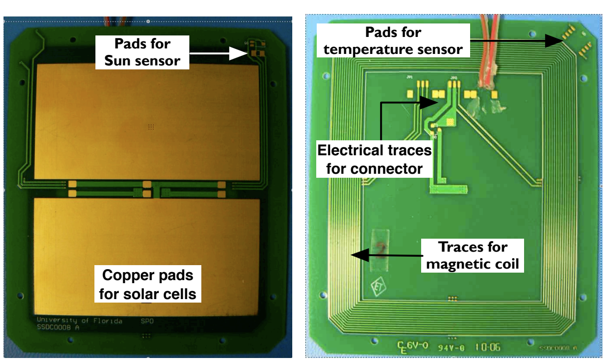
C. Results and Comparison

Prototype panels implemented using the above techniques are shown in Fig. 6. The prototype panels host solar cells which have a different form factor than the ones described in the design. While composite panels are fabricated in house, the PCB panels are designed specifically for SwampSat and fabricated from a professional PCB manufacturer. Additionally the prototype panels are evaluated and based on the feedback obtained, the design is modified and presented. Bypass diodes shown in the composite panel implementation are not surface mount type but a specific part of the type is identified for final implementation.

Outgassing test was performed by on the PCB panels in a vacuum chamber and difference in mass observed before and after the outgassing cycle was negligible. The vacuum chamber was pumped down to $\sim 7.8 \times 10^{-7} torr$ and maintained at this level for 19 hours. A maximum of 0.0236% decrease in mass was observed in the PCB panels. Additionally, a PCB panel with mounted solar cells, temperature sensor and embedded magnetic coils was also tested for its functionality and structural integrity by subjecting it to random vibration loads conforming to the PSD table in the CubeSat to PPOD interface control document.[8] The panel was subjected to vibration loads along each axis and the solar cell functionality was verified before and after the vibration test by measuring the voltage output under a sun simulator. The structural integrity of the panels was inspected and the continuity of the traces for temperature sensor and magnetic coils was verified before and after the vibration test. The PCB panel assembly was found to be functional and no visual signs of damage were observed from the vibration tests. The setup used for performing the vibration test is shown in Fig. 7 and the profile captured by the computer system commanding and monitoring the shaker is shown in Fig. 8.



(a) Composite Solar Panel



(b) PCB Solar Panel

Figure 6. Composite and PCB Solar Panel Implementations

The setup shown in Fig. 9(a) is used for evaluation the performance of the embedded magnetic coils in each of the panels. Each solar panel is designed to accommodate approximately 70-80 turns in its embedded magnetic coil and sustain a current load of at least 100mA. With the intent of producing the same magnetic field and accommodating the same number of turns the coil in the composite panel is evaluated to have better performance than that in the PCB. Power consumed as a function of supply current is used as a criteria for evaluating the performance. A DC power supply unit with the capability to vary voltage and current is used for energizing the magnetic coils embedded in each panel. Starting with an initial supply current of 100mA the voltage to the magnetic coils is varied to increment the current in steps of 10mA. Precise voltage and current measurements captured during the experiment are used to compute the power consumption. A plot of power consumption as a function of supply current, shown in Fig. 9(b), evaluates the performance of the coils. Although the magnetic coils in each panel cannot be accommodated in the same thickness the ability to fabricate a variable thickness composite panel enables it to be better suited for accommodating efficient magnetic coils.

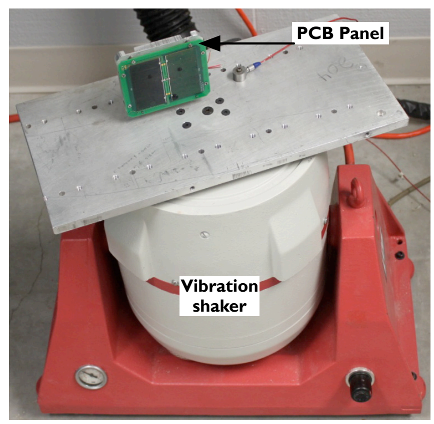


Figure 7. PCB Panel Vibration Test Setup

Magnetic coils embedded in the composite panel are evaluated to perform better than those in the PCB panel but the power budget for SwampSat is capable of accommodating either type of coils and the circuitry for driving them. Although composite panels are lighter in mass the wet layup fabrication technique is capable of introducing air pockets. In comparison, the manufacturing technique for PCB panels enables them to consume lesser volume, make them better suited for space environment and hosting surface mount components and connectors. The epoxy mixture and the technique used for mounting solar cells on composite panels can lead to outgassing issues. In comparison, solder paste and solder flux are used for mounting solar cells on the PCB panels and the combination is observed to be relatively free of air pockets. PCB panels are better suited to accommodate delrin plates for hosting the receive and transmit antenna modules for SwampSat. Electrical connections are manually laid for composite panel but the traces for PCB panels are ma-

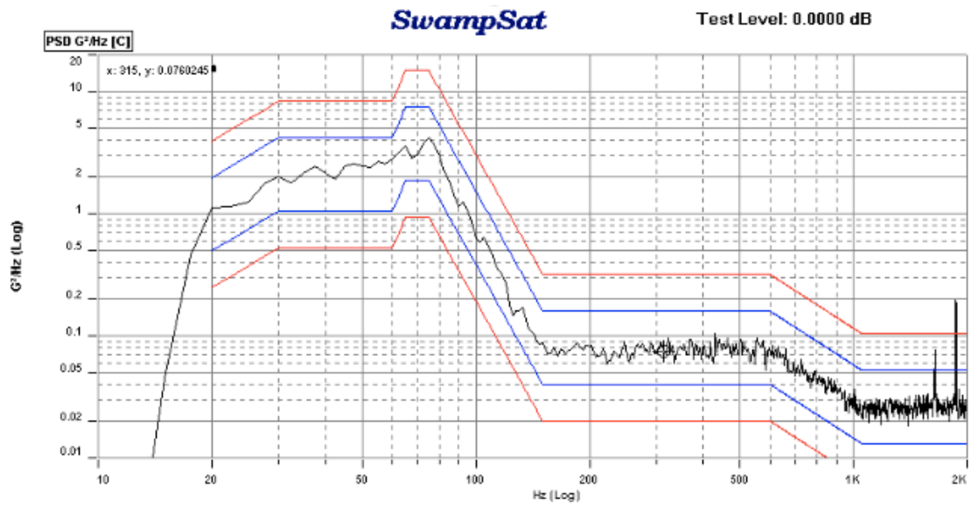
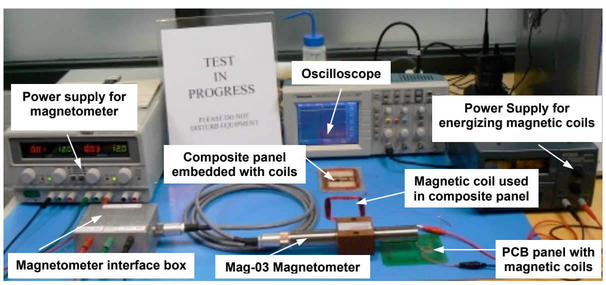
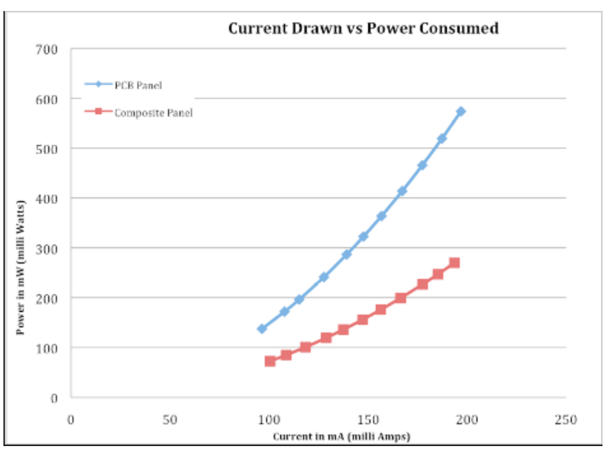


Figure 8. Vibration Test Profile

chine fabricated and are more reliable.



(a) Setup for Characterizing Magnetic Coils



(b) Plot of Supply Current vs Power Consumed

Figure 9. Magnetic Coil Characterization

IV. Conclusion and Future Work

PCB panels are selected for SwampSat mission for reliability and compact packaging. Within the limiting thickness of around 1*mm*, due to CubeSat form factor and SwampSat mission, the panel is efficiently designed to suit the requirements. Copper tabs for mounting temperature sensor on each panel are laid out on the bottom surface but the design makes provision for the sensing element to flush with the top surface. A similar provision is made for accommodating a Sun sensor on each panel.

Efforts are on to precisely determine the magnetic field output by composite and PCB panels and evaluate the capability of the magnetic coils to manage the angular momentum of SwampSat. The panels are designed to be scalable to more than 6 layers or accommodate additional turns of embedded magnetic coils for missions requiring the capability. Thermal analysis and heat dissipation are being evaluated for better characterization of the panels. Accommodating different orientations of the solar cells, alternate PCB material and mounting technique are also under evaluation.

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