University of South Carolina's Path to Developing a Space Program

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The University of South Carolina (USC) has begun developing a space program through collaborations between the Molinaroli College of Engineering and Computing (MCEC) and its AIAA student branch. This space program primarily focuses on the development of CubeSat missions, and began with grassroots efforts associated with a senior design team. These grassroots effort led to acceptance into the University Nanosatellite Program Mission Concept (UNP-MC) phase, which supported the development of a CubeSat mission concept focused on proving the possibility of Fused Filament Fabrication (FFF) 3D printing in an isolated space environment. This mission concept will be detailed in this work, in addition to current efforts regarding the development of a Quantum Nitrogen-Vacancy in Diamond (Quantum N-V) magnetometry CubeSat. Future work and the development of a Space Projects committee within the USC student chapter of AIAA are also explored. Through these efforts, USC has built a basis for a space education program, and is now gaining momentum for this program through new projects focused on the development of space missions.

I. Introduction

The University of South Carolina (USC) is home to relatively new but rapidly expanding Aerospace Engineering programs that are continually growing in quality. The South Carolina aeronautical industry has been surging in recent years, which has led the aerospace programs to focus on preparing students to enter careers in the field of aeronautics as part of its plan to retain graduates in the state of South Carolina [1]. The aerospace program has been built around the aeronautical industry, which poses a challenge for students who want to pursue space-related engineering careers. Through a mix of grassroots efforts from both students, faculty, and staff, strides are being made to help swing the balance in favor of a more even mix of aeronautical and space-related options for students to pursue during their studies.

II. Senior Design and Grassroots Efforts

The beginning of the USC space program has roots in a senior design topic. This group sought to design the university's first CubeSat prototype and accompanying ground station in the span of thirteen weeks, with the specification that all testing would be performed on Earth due to the time and budget constraints placed on the project. In keeping with the tight time and financial limitations, the team sought to keep the project simple. Three different concepts, all featuring an identical external imaging payload, were proposed for the project. Designs one and three presented as very similar systems; both were designed to function in a 1U bus and make use of an omnidirectional antenna for communication as a means of accounting for their lack of attitude determination and control (ADCS) equipment. The primary difference between designs one and three were their solar panel configurations, with design one implementing five body mounted panels and design three making use of three body mounted and two deployable panels. Design two differed significantly from its counterparts, making use of a 2U bus and a unidirectional antenna, which introduced significantly more complicated pointing requirements. The complete system bore a significant resemblance to the initially proposed designs due to both the limited timeframe and the accuracies of the manufacturing methods used [2].

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Testing was successfully performed, validating the functionality of their system on Earth; while more simplistic than a CubeSat, this success had a landmark impact on the culture of the USC aerospace program. Specifically, its success made it clear that the university had the capability to produce students who could become successful space system engineers, promoting an increased interest in the astronautical component of aerospace engineering. The work of these senior design team members proved foundational for the formation of the space program at USC as it began to encapsulate some of the key system engineering and project leadership principles that are facilitating the development of the program in the modern day. Key examples of these skills include the development of system budgets and basic orbital simulations that would inform the development of later CubeSat concepting efforts that will inform the future development of the university's space program.

III. UNP-MC and the Gamecock Additive Manufacturing Exploration Satellite (GAMESAT)

In 2025, the USC Additive Manufacturing of Composites and Design Engineering (AMCODE) laboratory, located in the McNAIR Center for Aerospace Innovation and Research, was awarded an opportunity to participate in the University Nanosatellite Program Mission Concept (UNP-MC) Phase. This program, which provided a source of funding to support the beginning phases of the project, also provided three research assistants the opportunity to complete an internship program at the Albuquerque, New Mexico branch of the Space Dynamics Laboratory (SDL), one of the premier developers of small satellites. During this experience, development began on a cube satellite (CubeSat) mission concept for the Gamecock Additive Manufacturing Exploration Satellite (GAMESat) with support from SDL and Air Force Research Lab (AFRL) personnel.

The initial proposal for the GAMESat focused on integrating Fused Filament Fabrication (FFF) 3D printing technology with computer vision (CV) for event detection and response. The methodology for integrating these two technologies was conceptualized in a two phase process: first, the onboard-processing computer vision (CV) would detect space debris in close proximity to the satellite or hostile satellites. This information would then be passed on to the control architecture for the 3D printer payload and trigger the production of a small volume that would be kicked out of the spacecraft upon completion. The application of this technology is twofold: it can either be used to protect the vehicle from approaching debris, increasing its lifetime, or to inflict damage upon other space vehicles that have been deemed hostile. The main interest in this technology was as a form of debris management, since characterizing the impacts of an isolated space environment (e.g. a vacuum environment not easily accessible by humans) on the FFF printing process and understanding the adjustments needed to ensure the production of quality parts in said environment. The UNP-MC staff, upon analysis of this mission, noted significant challenges with its implementation; primary concerns involved the planned ejection of printed components out into the space environment and the use of the CV. The printed component concern was the simpler of the two, as ejecting printed parts into the space environment violated a rule that made the CubeSat ineligible for launch [2]. The response to this objection was rather simple, and resulted in the removal of the part ejection component from the mission, although the project team chose to keep the and repurpose the FFF printer payload for experimentation regarding how the space environment impacted the printing procedure.

Part of the process for establishing the experimental architecture was determining which variety of FFF printer should be used as a basis for the CubeSat payload. Trade studies were performed on common commercial-off-the shelf (COTS) architectures such as Core XY and Belt-Bed systems. A major consideration of the trade study was the ability of the printer to self-clear; a necessity derived from the volume constraints of the CubeSat. The importance of this consideration led to the selection of a Belt-Bed system as the basis for the hypothetical payload, a decision that would influence the development of the CubeSat's basic architecture. Future work was also influenced by this decision since power studies would need to be performed on existing Belt-Bed systems to develop a better idea of how miniaturization could influence the grade of electrical power system (EPS) that is needed to support the payload and experimentation.

The CV issue was considerably more complex; the technology, while theoretically applicable to the use case of observing space debris or hostile satellites, would need to have exceptionally quick capture capabilities and capture distance to successfully image the debris or satellites it encounters. Trade studies were performed in an attempt to identify cameras and processors that could meet these specifications during the early portions of mission concepting, but all considered options failed to meet the unrealistic demands necessary to enable this use of the technology. Following the results of this analysis, the team pivoted to considering the use of CV internal to the volume of the CubeSat as a means of performing print defect detection, resulting in more trade studies to select appropriate cameras, CV algorithms, and processors. Performing these studies resulted in an understanding that running a CV model in addition to the payload would introduce serious volume and power concerns on top of the technical complexity of designing such a system. Further consultation with UNP staff eventually resulted in the migration away from the use of CV for onboard processing of print quality, eliminating some of the volume and power concerns. This necessitated the use of ground analysis techniques to verify print quality, which introduced a new challenge of selecting how often the team wanted to check the prints – a major consideration for this selection was the delays it would introduce into the experimental process. The need for this consideration resulted from the additional power draw that would come from keeping the system ready during its "paused" phase while it waits for a command indicating it is ok to proceed to come in from vehicle operators. Implementing this paradigm increases the risk of a battery drain that would, at a minimum, cause the team to lose operation of the CubeSat until its battery is restored. Of particular concern is that the forced tumbling of the CubeSat would then make it harder for any solar cells it may feature to charge the battery, possibly preventing the CubeSat from regaining functionality at all. Ultimately, the after consulting with UNP-MC experts on the proper design of the experiment, it was concluded that a layer-by-layer analytical approach would be appropriate for proving the validity of FFF printing in an isolated space environment.

The analysis performed by the GAMESat team and the aid from the UNP-MC experts was instrumental in downscoping the mission to a more reasonable scale. This downscoping provided the GAMESat team enough context to develop a mission statement that captures the team's overall goal and mission objectives (MOs) that macroscopically define what the team must do to achieve what is laid out in their mission statement.

Mission Statement: Create a system that can test the capabilities of additive manufacturing in an un-controlled, isolated space environment to provide data for 3D printing in future missions.

MO-1: Demonstrate Additive Manufacturing in an Isolated Space Environment.
MO-2: Capture Printed Part Quality Data on a Layer-by-Layer Basis.

The definition of the mission statement and the mission objectives defined the mission at a high-level which enabled the team to develop success criteria to define what the CubeSat must be able to accomplish its goal of proving out additive manufacturing in an isolated space environment. The minimum success criteria (MSC) establish the idea of the minimum-viable product for the CubeSat, the full success criteria (FSC) indicate what objectives must be completed to fully satisfy the goals of the project team, and the stretch goals (SGs) detail the above-and-beyond objectives for the system to be performed once all other criteria are met. The success criteria are as follows:

1) MSC: Print 1 cm of filament to the bed and image the print.
2) FSC: Print 2 or more stacked layers of filament of dimensions 1 cm x 1 cm (Length x Width).
3) SG-1: Image multiple layers of the same print and downlink images for analysis.
4) SG-2: Print a supportless structure to understand filament deformation and advanced printer capabilities not achievable on Earth.
5) SG-3: Conduct mechanical testing (deflection, hardness) of 3D printed components in space.

From these mission objectives and mission success criteria, the team was then able to begin designing the overall experiment flow for the GAMESAT mission. This experimental procedure details both how the GAMESat will carry out its experiment on a day-by-day basis and the overall phased structure of the experiment as well. The experiment operates through a combination of operator-commanded and automatic transitions, with the system producing individual layers of the assigned print and then pausing for human analysis and a "go-ahead" command throughout phases 1-3. Phase 4 behaves differently, as by the time this portion of the experimentation has been reached, the team will have proven confidence in the capabilities of the GAMESat technology, allowing it to be operated as a printer would be on Earth, where the initial layer is monitored and occasional check-ins are performed instead of checking every layer.

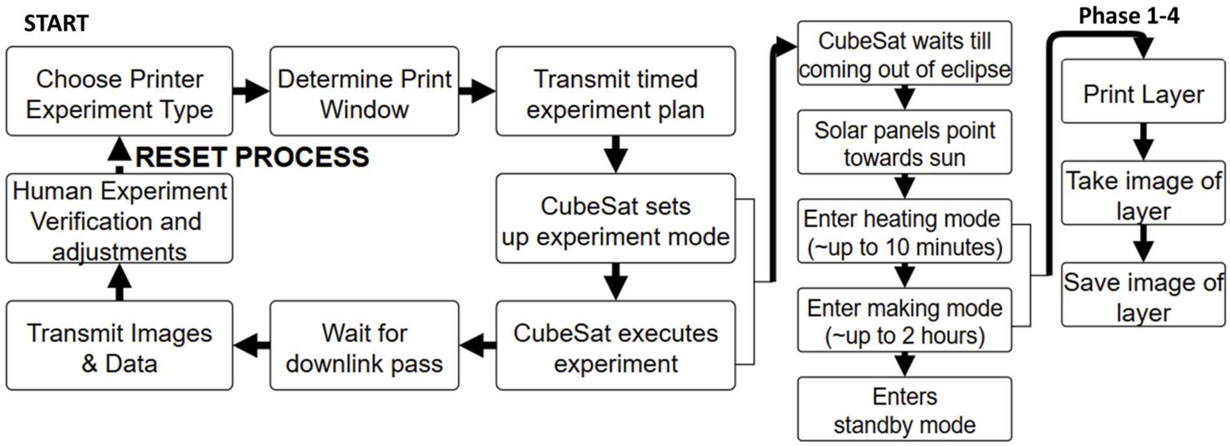

Fig. 1 GAMESat Experiment Procedure

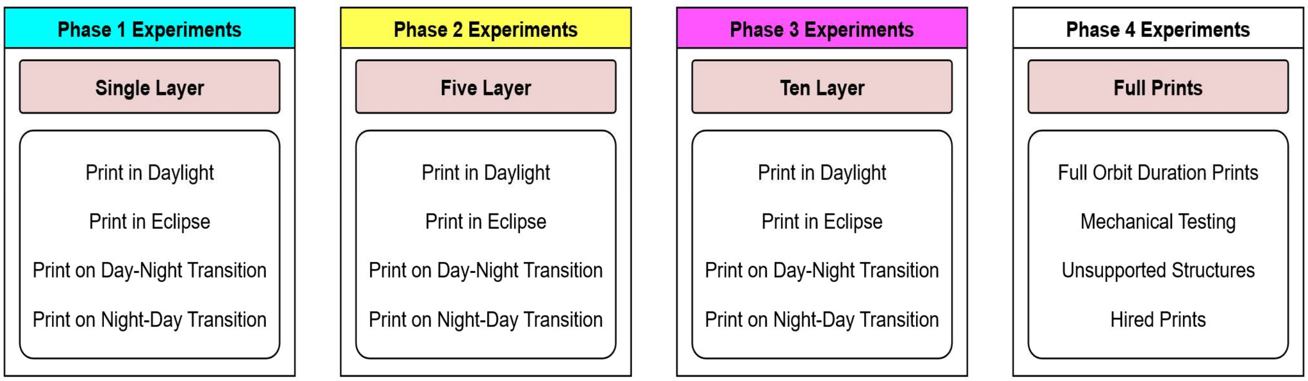

Fig. 2 GAMESat Experimental Phases

The progression of the experiment through its individual phases was designed to be controlled by the GAMESat team, with operators evaluating whether or not it has demonstrated the capability to consistently produce parts with the number of layers associated with the current phase. To allow for this evaluation, the experimental procedure has been structured in a way that allows for the project team to use the cameras onboard the CubeSat to image the individual layers of the prints.

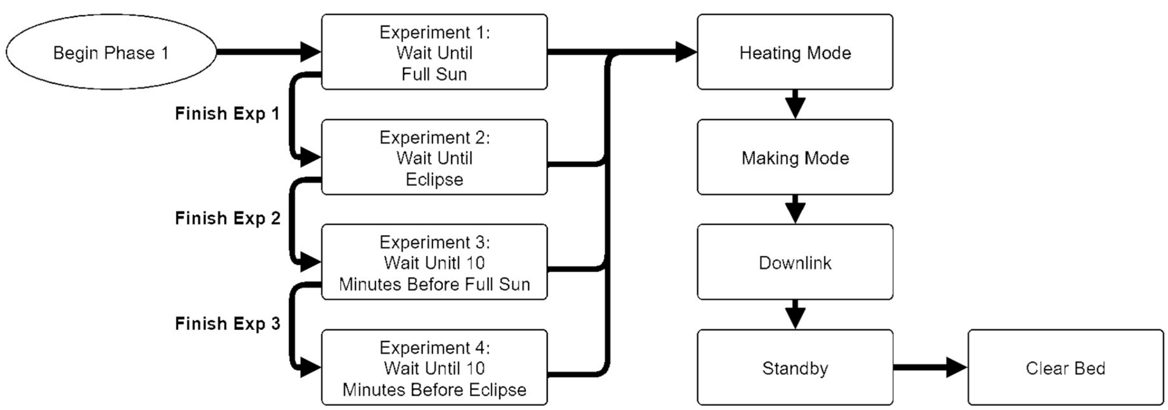

Fig. 3 Phased Experimental Procedure

An important part of the GAMESat experiment was deemed to be understanding the impact that transitioning between levels of solar exposure (e.g. full sun, eclipse) had on the print process. This results in the need for precise timing of the mission, as each phase will be split into four parts: a full sun print, a full eclipse print, an eclipse-full sun transition print, and a print during the transition between full-sun and eclipse. The transition prints are scheduled to begin 10 minutes before their full-sun or eclipse respectively; this is because the control architecture limits the heating mode to a nominal maximum of ten minutes as can be seen in the process flow shown in the Fig. 3. Each phase of the experiment that the GAMESat conducts will proceed through these four different conditions so the team can make note of how the orbital timing impacts the progressively more complicated prints. Phase 4 is the only exception to this since prints will be complex enough to require full orbits to be completed, as shown in the phase layout that is Fig. 2. The experimental phases also play a role in defining the Concept of Operations (CONOPS) for the GAMESat Mission, as it is structured to consider the orbital parameters needed for to achieve the correct timings for sun transitions, downlinks, and analysis as detailed in the CONOPS shown in Fig. 4.

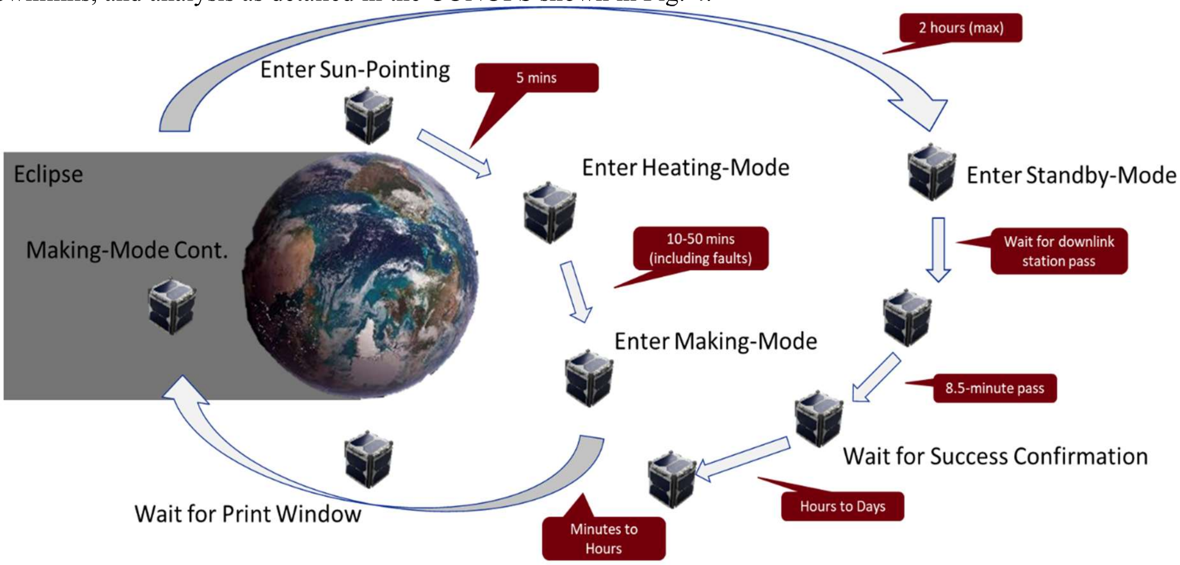

Fig. 4 GAMESat Concept of Operations

A key part of the mission concepting process, beyond establishing the overall scope and procedure for the mission, was understanding what will serve as the primary technical limitations for the CubeSat. The nature of an FFF 3D printer introduces significant constraints on power and thermal management, as resistive heaters require a considerable amount of energy and benefit from convection cooling on Earth. The lack of a medium to allow convection makes it challenging to maintain a suitable temperature for the CubeSat and to provide enough power to prevent the system from fully discharging its battery. These factors resulted in a special degree of consideration being applied to the UNP-MC provided power budget, as shown in Fig. 5.

Mode	Power Draw (W)	Power Generated (W)	Mode Power Status
Safe	13.25	22.50	9.25
Standby	23.09	135.00	111.92
Heating Mode	140.50	135.00	-5.50
Maker Mode	113.00	135.00	22.00

Variables		
Timestep	1	min
Max battery capacit	136.32	Wh
Eclipse	37.8	%
Orbit Period	94.61	min

Key
Derived value
Value to Enter

Fig. 5 GAMESat Power Budget

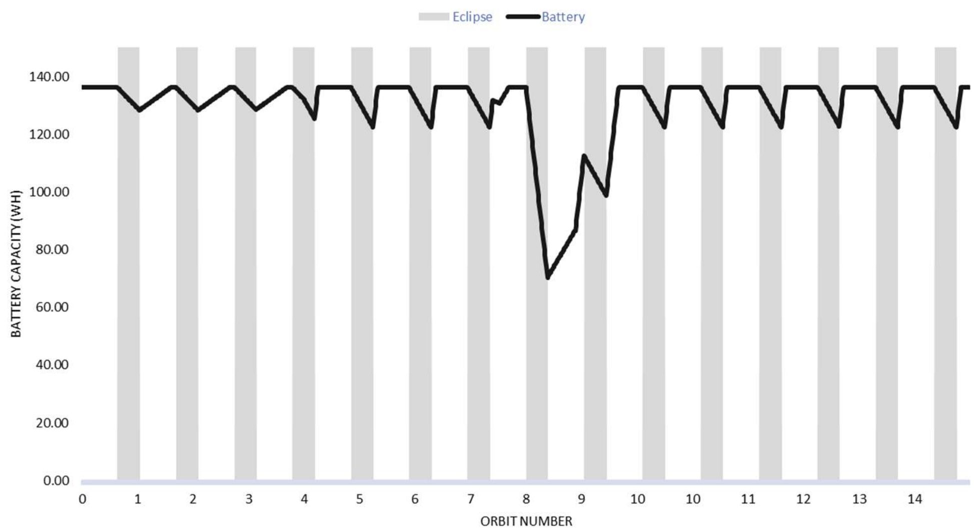

Fig. 6 GAMESat Energy Balance: Battery Capacity in One Day

Consideration of the power budget indicates that the GAMESat maintains a power positive state in all phases, with the exception of the heating phase; this is due to the high demand of the resistive heaters as can be seen through the power negative nature of the phase shown in Fig. 5. Compensating for the high power draw of the system requires the implementation of a large-capacity battery, as the team wanted to keep a ~50% battery capacity minimum to extend the life of the system; a battery with capacity exceeding 135 Watt-hours is necessary for this, as printing in eclipse depletes the reserves of the satellite as shown in Fig. 6.

With the stability of the satellite established, the team began developing requirements for the GAMESat; of particular interest for this project are the requirements for the payload, power management, and thermal management systems since analyses performed with the aid of the UNP-MC experts yielded these components as being both the most impactful on the success of the mission and the most complicated to manage. Investigations of thermal managements systems are currently ongoing, but limited progress is possible without a better understanding of true thermal output characteristics of a miniaturized FFF printer. Future work has been expected to provide the thermal profiling needed to continue this investigation and further refine the thermal management system requirements for the GAMESat mission.

IV. Operationalization of an FFF 3D Printer Towards Payload Development

Following the developments from the Mission Concept program, the AMCODE lab was committed to continuing the development of the GAMESat platform. A better understanding of payload behavior was necessary to enable further work since a more complete power profile was deemed important in properly sizing the systems for the CubeSat. In pursuit of this, lab researchers carried out a study using the Creality CR-30 Belt Bed 3D printer to understand the power consumption of a full-scale printer when producing typical testing volumes such as calibration cubes. While power analysis is still ongoing, printer experimentation did yield an understanding that mechanical optimizations were needed to maximize printer functionality.

The primary mechanical optimization that was performed to the CR-30 was the installation of a direct-drive conversion mount, removing the Bowden tube installation that comes with the printer. The motivation for this conversion procedure was twofold, as installing the direct drive mount helped reduce the overall volume of the printer while also increasing the reliability of the system by helping mitigate common sources of defects such as cracking by decreasing the length the filament has to travel prior to extrusion.

Further experimentation with the CR-30 is expected to provide an understanding of how unique print process parameters, such as printhead acceleration, can impact the power consumption of the system and the quality of parts produced by the system. The knowledge gained from experimenting with these parameters is expected to be used to construct an ideal set of process parameters that can be applied to GAMESat space printing operations and further refined on-orbit to account for the nature of the space environment and the impacts it has on the FFF printing process.

V. Quantum-NV CubeSat Mission Concept Development

USC's MCEC is currently in the process of expanding its research base, breaking into fields such as battery development and quantum sensing through a collaboration between some of its faculty and Physics department instructors in the McCausland College of Arts and Sciences (MCAS). The MCAS Physics faculty have managed to construct a quantum nitrogen-vacancy in diamond magnetometer, a high precision sensor that has received increased attention in recent years. The focus of the collaborative products is the continued development of this sensor technology and its applications to informing the power grid of solar events and magnetic fluctuations in the ionosphere.

The potential application of this sensor technology to protecting the South Carolina power grid has to do with the fact that extraterrestrial magnetic fluctuations, such as coronal mass ejections, can cause Earth's magnetic field to react in a way that produced ground-induced currents (GICs) [3]. GICs pose a risk to the power grid because they have the capability to flow through the gridlines and cause damage to the infrastructure that supports the transit of electricity [3]. The project aims to miniaturize the sensor for use as CubeSat payload, and mission concepting for this CubeSat is in its early stages. The goal of the CubeSat component of the project is to build on the success of the OscarQube mission, which validated the technology on onboard the International Space Station (ISS). Culmination of this project will result in the completion of key mission concepting deliverables such as a mission design document, technical requirements for the CubeSat, budgets outlining the technical feasibility of the CubeSat, and other key documentation.

VI. AIAA Space Projects Committee and Future Work

To play its part in the expansion of space offerings at USC, the student chapter of AIAA is working to stand up a Space Projects committee to offer students opportunities to gain technical experience outside of the annual Design-Build-Fly (DBF) competition. This is especially important as the DBF competition becomes increasingly competitive. The initial objective of the space projects committee was to serve as a student workforce for CubeSat project development under the guidance of lab research assistants who have more expertise from programs such as UNP-MC. An additional component of the committee was intended to be the beginning of a Solar Sail program in collaboration with introductory mechanical and aerospace engineering instructors, but internal restructuring has stalled these efforts. To continue with the development of the committee, it is currently undergoing restructuring efforts. To enable the committee to more effectively impact the USC campus and the students who make it up, it will become both an event planning and learning tool for students. As an event planning body, it will work to organize space-related technical events across multiple disciplines; one example is a planned collaboration with computer science organizations within the MCEC to bring a NASA hackathon to campus for students to participate in. An additional component of the committee will also be the production of education materials, in which student members will aid lab research assistants and branch leadership in producing short-form content to give students a digestible way to become familiar with the principles of space systems engineering.

VII. Conclusion

USC began with an aeronautics-dominated aerospace program, largely in line with the structure of South Carolina's industrial base as part of its goal to keep graduates in South Carolina. Space systems engineering was first introduced into the program through the efforts of an impassioned senior design team who chose to develop a CubeSat and ground station prototype for their project. The next milestone came with USC's acceptance into the UNP-MC phase, which supported the development of a mission concept for the GAMESat that aims to prove out the viability of FFF 3D printing in an isolated space environment. To supplement the work carried out during this program, the USC student chapter of AIAA became involved through the creation of a dedicated Space Projects committee to provide its members with hands-on space systems engineering experience. Through these efforts, USC has become involved in research and development projects focused on space missions and is now building up momentum to continue expanding the program into the future.

Acknowledgments

I would like to acknowledge the contributions of Mr. Patrick Bailey and Ms. Shruti Jadhav to this work and their contributions to the USC space program. As the members of the senior design team that spawned an interest in CubeSats within the MCEC, they are foundational to the state of the aerospace program today.

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