Coordinating Development of the SWARM-EX CubeSat Swarm Across Multiple Institutions

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ABSTRACT

The Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) is a National Science Foundation (NSF) sponsored CubeSat mission distributed across six colleges and universities in the United States. The project has three primary goals: (1) contributing to aeronomy and space weather knowledge, (2) demonstrating novel engineering technology, and (3) advancing higher education. The scientific focus of SWARM-EX is to study the spatial and temporal variability of ion-neutral interactions in the equatorial Ionosphere-Thermosphere (I-T) region. Since the mission consists of three spacecraft operating in a swarm, SWARM-EX will take in-situ measurements of the neutral and ion composition on timescales of less than an orbital period to study the persistence and correlation between different phenomena in the I-T region. The engineering objectives of SWARM-EX are focused on advancing the state of the art in spacecraft formation flying. In addition to being the first passively safe, autonomous formation of more than two spacecraft, SWARM-EX will demonstrate several other key innovations. These include a novel hybrid propulsive/differential drag control scheme and the realization of a distributed aeronomy sensor. As a project selected by the NSF for its broader impacts as well as its intellectual merit, SWARM-EX aims to use CubeSat development as a vehicle for education. The six collaborating institutions have varying levels of CubeSat experience and involve students who range from first-year undergraduates to Ph.D. candidates. These differences in knowledge, as well as the distributed nature of the program, present a tremendous educational opportunity, but also raise challenges such as cross-institutional communication and coordination, document sharing and file management, and hardware development. By detailing its procedures for overcoming these challenges, the SWARM-EX team believes that it may serve as a case study for the coordination of a successful CubeSat program distributed across multiple institutions.

INTRODUCTION

The Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX), is a National Science Foundation (NSF) sponsored CubeSat mission distributed across six universities and colleges: The University of South Alabama (USA), Stanford University (Stanford), The University of Colorado Boulder (CU), Georgia Tech (GT), Olin College (Olin), and Western Michigan University (WMU).

This multi-university distribution poses unique opportunities, but also unique challenges. Facilitating collaboration and communication among team members separated by vast distances is a hurdle to building a single cohesive program. Furthermore, the introduction of physical hardware for system testing raises challenges in ensuring that all team members have the opportunity to participate in hardware integration and testing (I&T). This paper describes the methods (both planned and already implemented) that the SWARM-EX team uses to run a successful multi-university CubeSat mission, which may serve as a case study and template for the coordination of similar programs.

PROJECT GOALS

The project has three primary goals: (1) contributing to aeronomy and space weather knowledge, (2) demonstrating novel engineering technology, and (3) advancing higher education.

The engineering goal is to demonstrate novel CubeSat technologies. SWARM-EX consists of three 3U CubeSats that will demonstrate autonomous and reconfigurable formation flying with more than two spacecraft for the first time (such formation flying is colloquially called a spacecraft swarm). As such, SWARM-EX will demonstrate many technologies enabling swarm behavior, including: spacecraft crosslinks, relative state estimation, 3D printed cold gas propulsion, and autonomous configuration changes driven by differential drag.

SWARM-EX's swarm capabilities allow the mission to take unique measurements of the low Earth orbit (LEO) environment, which influenced how the science objectives were defined. With SWARM-EX being able to operate across variable (and large) along-track separation distances, each satellite will take in-situ measurements of atomic oxygen and ion density to observe changes in the atmosphere over timescales of less than one orbital period. These measurements cannot be made with a single orbiting spacecraft, so SWARM-EX will produce unique data for the scientific community.

By proving the efficacy of a reconfigurable swarm of CubeSats taking novel scientific measurements, SWARM-EX serves as a demonstration mission and experimental platform for novel technologies that can be scaled to support much larger CubeSat swarms (Figure 1). This, in turn, will open the door to small satellite networks capable of making high resolution scientific measurements. This paper will first expand on the project's science and engineering objectives to provide context for the mission, and will then explain how the project operates in the educational space as it works to achieve these objectives.

The educational goal is to provide valuable hands-on aerospace engineering experiences to students and faculty entering with varying levels of expertise. Students participating in this project range from first-year undergraduates to Ph.D. candidates and span many technical disciplines. Furthermore, some of the collaborating institutions have a rich history of CubeSat development, while others are in the early stages of developing their programs. These differences in skill and experience present a unique opportunity for educational growth for both individual students and entire CubeSat programs.

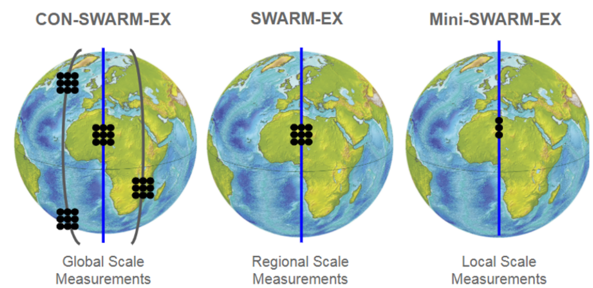

Figure 1: SWARM-EX is a scientific mission consisting of a trio of 3U CubeSats (rightmost image) that will demonstrate autonomous swarm technologies that can eventually be scaled to single swarms of larger sizes (center) and multiple swarms operating in different orbits (left).

SCIENCE OBJECTIVES

The scientific focus of SWARM-EX is to study the spatial and temporal variability of ion-neutral interactions in the equatorial Ionosphere-Thermosphere (I-T) region using a CubeSat swarm to make in-situ measurements. There are two daytime phenomena in the I-T region that SWARM-EX will observe: the Equatorial Ionization Anomaly (EIA) and the Equatorial Thermospheric Anomaly (ETA). The EIA occurs in the equatorial ionosphere with two crests at $\pm 15°$ in magnetic latitude and a valley at the magnetic equator.[1] This feature is caused by the fountain effect resulting from the upward vertical drift associated with eastward electric fields produced by the ionospheric E-region dynamo. The ETA is a similar feature that occurs in the upper thermosphere with two crests $\pm 20 - 30°$ in magnetic latitude and a valley at the magnetic equator. There are competing theories as to how the ETA is formed and how it interacts with the EIA, and SWARM-EX will be a key component in gathering the data necessary to support and refute various claims. Figure 2 shows two plots depicting the EIA and ETA at 400 km altitude, which visually shows that the two features are magnetically aligned.

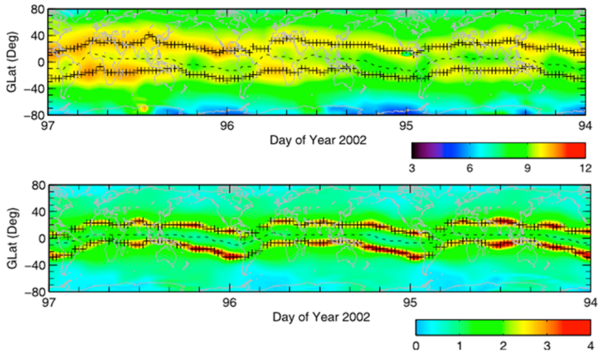

Figure 2: Neutral Mass Density (top) and Electron Density (bottom) showing the ETA and EIA respectively from data taken by the CHAMP satellite at 400 km altitude. Graphs taken from Lei et al.[1]

In LEO, specifically in the altitude range of 150-550 km, atomic oxygen (AO) is the dominant species and defines the neutral and ionospheric composition. Due to photoionization from the Sun's radiation, and other chemical processes, the atomic oxygen ion O^+ is the dominant ion in LEO. The AO and O^+ compositions in LEO are crucial to understand because those two species can affect spacecraft performance and radio communication. AO not only oxidizes materials with its reactive chemical composition, but also damages spacecraft when its atoms collide with ram-facing surfaces in LEO.[2] Since AO is the dominant neutral species, it is the main contributor to orbital drag, which is necessary for full orbital and decommissioning analyses. O^+ composition (and its concomitant electron density population) is also important to predict and understand because it affects spacecraft charging and GPS/radio signals. O^+ does not directly contribute to these effects, but since there is charge neutrality in LEO, the electron density is equal to the O^+ density. Electrons build up charge on a spacecraft, which can affect instruments sensitive to the spacecraft potential. This charge buildup can cause differential charge on a spacecraft that can arc and damage the spacecraft. The electron density in LEO can cause scintillation effects on GPS signals, preventing a GPS receiver from locking on a signal. These densities also dictate what radio frequency can pass through the region without being reflected back to the source. As a result of these effects, there are many organizations interested in knowing the neutral and ion composition in LEO. SWARM-EX focuses on the EIA and ETA features because those structures are composed of electrons and AO, respectively. To observe the ETA feature, SWARM-EX will measure the AO concentration using the Flux-Probe-EXperiment (FIPEX) developed by the University of Stuttgart Institute of Space Systems. To observe the EIA feature, SWARM-EX will take measurements of the O^+ concentration using a planar Langmuir Probe provided by ASTRA LLC.

The I-T region is dynamic, meaning that there are sub-daily changes, diurnal changes, seasonal changes, and variations depending on solar cycle and geomagnetic activity.[3] It is important to the scientific community to acquire temporally dense, and precise measurements to improve current empirical and physical models of the I-T region. To obtain these data, SWARM-EX divided its science goals into two primary science questions: 1) How persistent and correlated are the plasma density and neutral oxygen in EIA and ETA features? 2) Over what timescales, less than 90 minutes, do we observe changes in EIA/ETA properties due to non-migrating tides and geomagnetic activity?

SWARM-EX's unique swarm configuration allows these science questions to be answered for the first time. Previous missions were typically composed of one satellite taking I-T measurements; therefore, at LEO, there can only be one measurement at the EIA/ETA feature each orbital period (which is approximately 90 minutes). This is a significant limitation because the satellite returns to the equatorial region with a change of 22.5° in longitude. Furthermore, traveling ionospheric disturbances and traveling atmospheric disturbances also cause perturbations that occur within 60 minutes or less during a solar maximum period.[4] In order to capture the neutral response to a plasma change in less than 90 minutes, and at the same longitudinal position, more than one satellite must take measurements. SWARM-EX will demonstrate how a multi-satellite swarm can determine the persistence and non-persistence of the EIA and ETA. With a configuration of three satellites, each spaced by a variable separation of up to 1,300 km in the along-track direction, SWARM-EX will use cross-correlation analysis between plasma and neutral measurements to determine the spatial structure of persistent features and response lag times of non-persistent features.

ENGINEERING OBJECTIVES

The SWARM-EX engineering objectives focus on advancing the state of the art in spacecraft formation flying, which is represented by the TanDEM-X, PRISMA, and CanX-4/5 missions.[5–9]

Spacecraft formation flying is the use of multiple spacecraft acting in concert to achieve shared objectives, which would ordinarily require a larger spacecraft. Spacecraft formations have significant advantages over monolithic spacecraft. These include the ability to create large, time-varying baselines between individual spacecraft and improve robustness to failure due to the inherent redundancy that comes with distributing payload tasks. However, the advantages that are afforded by spacecraft formation flying come at the cost of increased mission complexity, as well as challenging requirements for distributed guidance, navigation, and control (GNC). The complementary space and ground segments of the SWARM-EX GNC system are being developed by the Stanford Space Rendezvous Laboratory.

The SWARM-EX mission will advance the state of the art in several key ways: (1) it will be the first demonstration of passively safe, autonomous formation flying for more than two spacecraft, (2) it will utilize a novel hybrid propulsive/differential-drag control scheme, (3) it will achieve fuel balancing among the spacecraft in the formation using a virtual chief method, and (4) it will realize a distributed aeronomy sensor.

Autonomous Guidance, Navigation, and Control

To meet the diverse mission objectives of SWARM-EX without exceeding the limited resources available onboard, the GNC system must be fuel efficient, computationally simple, and able to ensure safety during proximity operations. To that end, each SWARM-EX spacecraft will host an identical GNC hardware/software subsystem. The hardware layer includes a dedicated microprocessor clocked at 1 GHz, an omni-directional UHF inter-satellite link (ISL), a Blue Canyon Technologies XACT-15 attitude determination and control system (ADCS), a 3D printed single-thruster cold-gas propulsion system, and a Novatel dual-frequency GNSS receiver. The software layer includes functions that perform relative orbit determination, relative orbit prediction, maneuver planning and execution, and collision avoidance. A block diagram of the GNC architecture is shown in Figure 3.

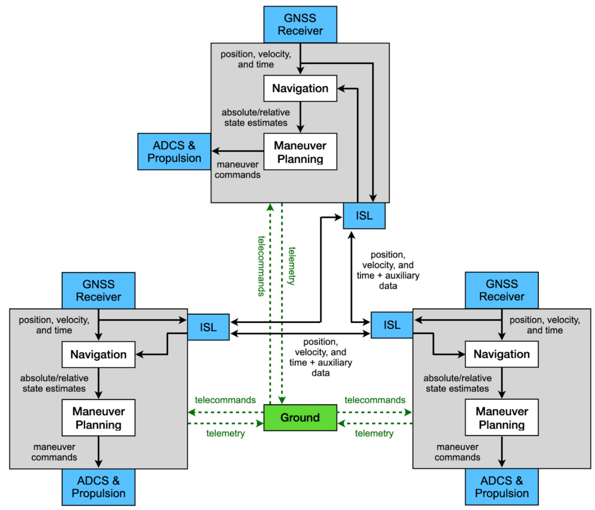

Figure 3: SWARM-EX onboard GNC architecture.

By exchanging position, velocity, and time (PVT) solutions output by their onboard GNSS receivers via the ISL, SWARM-EX spacecraft will estimate not only their own state but also their relative states with respect to the other spacecraft in the formation. Quasi-optimal relative orbit keeping and reconfiguration are performed through closed-form solution in ROE-space.[10] During proximity operations, the method of relative eccentricity/inclination vector separation will be used to ensure that the formation remains safe even in the presence of hard propulsion system failures, attitude safe modes, and overall uncertainties.[11,12]

In order to achieve the large along-track reconfigurations that are needed to meet the mission's science objectives, while considering the limited propellant available onboard, a hybrid of propulsion and differential drag-based control will be used.

Fuel balancing throughout the mission lifetime will be achieved using a virtual chief methodology. This method minimizes the delta-v cost of long-term formation maintenance through careful selection of a virtual spacecraft that serves as the relative motion reference of the swarm for control.[13] Since the SWARM-EX spacecraft have identical GNC capabilities, the role of the reference chief can also be assigned to any physical spacecraft as needed to achieve the mission goals.

Precise Relative Orbit Determination and Aeronomy

In addition to exchanging PVT solutions via the ISL, SWARM-EX spacecraft will downlink their raw GNSS measurements to the ground segment.

These raw measurements will then be processed in a state-of-the-art estimation framework, enabling centimeter-level relative navigation accuracy. This framework, the Distributed multi-GNSS Timing and Localization (DiGiTaL) system, uses error-canceling combinations of GNSS observables and performs integer ambiguity resolution (IAR) using a modified form of the well known LAMBDA method.[14, 15]

This precise orbit determination is crucial for the relative accelerometry experiment that will be performed by SWARM-EX. During this experiment, spacecraft will be commanded into a high-drag configuration, while others remain in a low-drag configuration. The differential ballistic coefficient is then modulated to maximize sensitivity of the relative motion to atmospheric drag. Combined with the precise relative state estimates provided by DiGiTaL, this is expected to lead to a better recovery of the atmospheric density.[16] Thus the spacecraft themselves become aeronomy sensors.

This novel experiment also opens the door to other groundbreaking techniques. By combining the advanced estimation architecture of DiGiTaL with suitable models and measurements taken by the FIPEX and Langmuir Probe sensors onboard, SWARM-EX has the potential to simultaneously estimate the absolute and relative spacecraft orbits and other scientific parameters of interest. Through this data-fusion technique, it would be possible to reconstruct the ionospheric and thermospheric environment with much greater precision than has been previously achieved through single spacecraft.[17]

PROJECT MANAGEMENT & SYSTEMS ENGINEERING

To assure mission objectives are being met and that the spacecraft design matures effectively, SWARM-EX follows a simplified version of the project life cycle outlined in the NASA Systems Engineering Handbook.[18] In accordance with the handbook's recommendations, the SWARM-EX team performed a mission concept review (MCR) in August 2020 and a preliminary design review (PDR) in February 2021. The mission is currently in phase C, final design and fabrication, and has a critical design review (CDR) tentatively scheduled for September 2021. Following the CDR, the team will complete hardware fabrication and acquisition and schedule a system integration review (SIR) prior to system assembly and testing. Key deliverables for the PDR included concept of operations timelines, system budgets (mass, volume, power, link, and data), system architecture diagrams, full baseline designs for each spacecraft subsystem, and a master equipment list. A render of the fully assembled spacecraft, which has been updated since PDR, is shown in Figure 4.

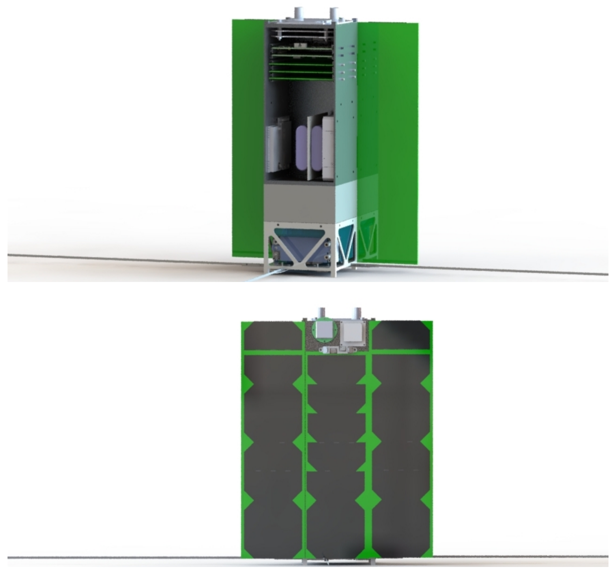

Figure 4: Renderings of an assembled SWARM-EX spacecraft as of May 2021.

Data collection requires that the spacecraft's sensors (FIPEX and Langmuir probe) point into a particle stream. The decision was therefore made to place the instruments on the small (1U) face of the 3U bus, which will roughly align with the direction of the spacecraft's primary velocity vector. The ability to collect multiple data points in the same region within a single 90-minute orbit requires the satellites to be spaced hundreds of kilometers apart from one another in the along-track direction, as shown in Figure 5.

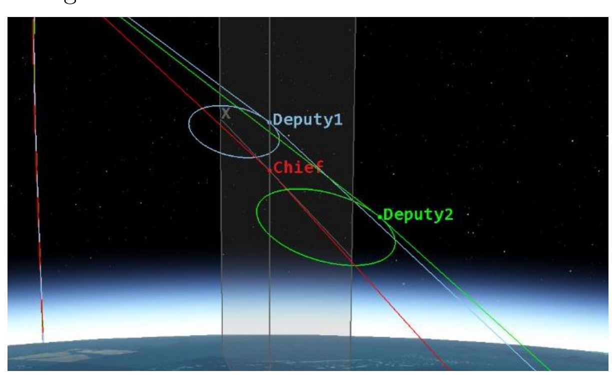

Figure 5: The SWARM-EX satellites will be spaced out in the along-track direction, which is aligned with the velocity vector. They will use cold gas propulsion and differential drag to vary separation from hundreds of meters to more than 1,000 kilometers.

The total delta-v of the onboard cold-gas propulsion system is severely limited by the volume available for propellant storage. To enable reconfiguration without the use of propellant, SWARM-EX will use differential drag. Because of the mission's relatively low altitude (approximately 450 km), each spacecraft will experience atmospheric drag. Differential drag is a technique by which the amount of drag a spacecraft experiences is varied by adjusting its ballistic coefficient, resulting in a controllable net drag force. This ballistic coefficient is controlled by varying the cross-sectional surface area of the spacecraft relative to the velocity vector, which requires a sufficiently large planar surface for the cross-sectional area to be significantly varied. Deployable solar panels, which form a flat panel of approximately 900 cm^2 after deployment, allow the SWARM-EX satellites' cross-sectional areas to be adjusted simply by changing their orientation. Attitude control is performed by a commercial ADCS with significant flight heritage.

COLLABORATING INSTITUTIONS

Of the six collaborating institutions, three universities have significant CubeSat experience (Stanford, CU, GT) and three have nascent CubeSat programs that have not yet launched a satellite (USA, Olin, WMU). To build experience across all institutions, each school is leading the development of at least one subsystem, and many subsystem teams have membership from two or more institutions. For example, SWARM-EX members from CU act as mentors for Olin team members in structures and systems engineering and also provide guidance to USA team members on communication and electrical power system (EPS) design. GT team members serve a similar role with regard to the propulsion system, mentoring students on the WMU team. With its significant specialization in GNC, Stanford acts as a resource for all the other institutions with regard to formation flying and relative orbit control.

This collaboration supports cross-institutional mentoring activities for all team members, including undergraduate students, graduate students, staff, and faculty; this achievement is the primary educational objective of the SWARM-EX project. Through communication, outreach, and future collaborative efforts, it is hoped that such action will proliferate in institutions outside of SWARM-EX, thereby engendering the creation of long-term, project-based learning environments across the nation.

While all six of the institutions involved in SWARM-EX are critical in designing the satellite bus, it is infeasible to ship CubeSat hardware to each institution for distributed development. Therefore, due to the abundance of CU's laboratory facilities and experience with small satellite I&T, the CubeSats will be constructed and tested at CU. This necessary localization of the physical satellites away from most team members is a prime example of the challenges the SWARM-EX team faces by being distributed across six different institutions. Consequently, team communication is especially crucial to SWARM-EX's success, and the team is utilizing a variety of communication strategies to launch its satellites according to schedule.

REMOTE COLLABORATION

Because the SWARM-EX team is distributed across six schools, four meeting strategies and two digital communication tools (video conferencing and Slack, an instant messaging platform) have been used to facilitate remote collaboration. These meeting strategies include biweekly all-hands and subsystem meetings, weekly meetings internal to each school, and an optional and more casual seminar series.

Biweekly All-Hands Meeting (cross-university)

Every two weeks, a video conference is held with all students from all schools. Each subsystem team (which may be distributed across multiple schools) brings a "quad chart" slide to this meeting, which has four primary sections: (1) *accomplishments*, in which the subsystem team reports on what actions/analyses have been performed over the past two weeks, (2) *plan for the next two weeks*, in which the subsystem team outlines the actions they plan on accomplishing in the next two weeks, (3) *pending action items*, which is a small table listing project deliverables the subsystem team has been assigned and planned delivery dates for those artifacts, and (4) *issues impeding progress*, in which the subsystem team has an opportunity to discuss items they are missing or struggling with prior to being able to complete their actions. Raising issues impeding progress in the all-hands meeting presents the opportunity for each team to easily ask any other team for information they may be missing and gives them the ability to flag new risks for faculty and team leads. There is also a fifth section on each slide, which simply includes the names of students who attended the previous subsystem meeting, providing an easy way for other subsystem teams to know who to contact about questions regarding that subsystem's current state. An example quad chart slide is shown in Figure 6.

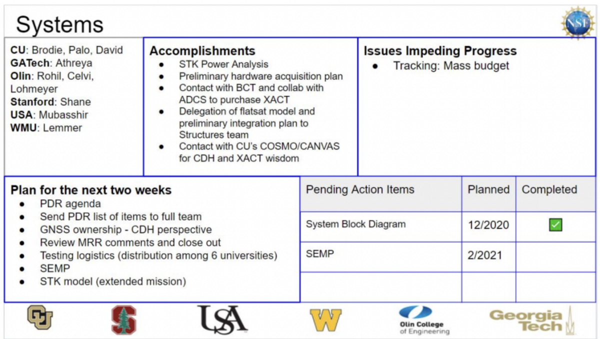

Figure 6: An example "quad chart" slide brought to the biweekly all-hands meeting. Each subsystem team notes their accomplishments from the past two weeks, describes their plans for the next two weeks, provides visibility into what deliverables they are currently working on, and flags issues that are impeding their progress.

Biweekly Subsystem Meetings (cross-university)

A single subsystem team may contain students from multiple schools. As a result, each subsystem schedules a video conference with all members of their team, which is open for members of other subsystem teams to attend. These meetings are held every two weeks and complement the biweekly all-hands meeting, providing an opportunity for each subsystem to address the plans, action items, and issues that they raised in the all-hands meeting. At these subsystem meetings, subsystem teams create and assign specific plans and action items to individual students. If the meeting agenda is short, this meeting may occasionally be used as a working session.

Weekly Internal Meetings (intra-university)

At the discretion of each institution, a weekly meeting may be held with students from that particular school. These meetings may serve as tag-up or work sessions and often include discussion among student leads and other students on the project. They also provide an opportunity for students across multiple subsystem teams but within the same institution to collaborate and communicate both with each other and with the faculty lead at their school. Prior to COVID-19 restrictions being put in place, these meetings could be held in person, strengthening the relationship between students and professors at each institution.

Biweekly Seminar Series (cross-university)

It is a goal of the SWARM-EX program to expose the involved students and professors to a variety of research topics and engineering disciplines. To that end, SWARM-EX holds a biweekly seminar in which any team member may present on a topic of interest to them, irrespective of the relevance to the SWARM-EX mission. Examples include professors speaking on their fields of scientific interest, graduate students presenting on their research topics, and undergraduates sharing insights into their subsystem or other research projects in which they are engaged. These seminars typically begin with a presentation and end with a lengthy Q&A session, providing an opportunity for students to ask questions and learn from other team members. These seminars serve to strengthen the relationships between team members across various locations and between students and professors, building a more cohesive team and also opening up the possibility of mentorships for undergraduates who are curious about other disciplines or their own path to graduate school.

Digital Communication Tools

Each school provides direct access for their students to a particular video conferencing platform (Zoom or WebEx) so that they have the agency to schedule working meetings and discussions independently of the planned weekly and bi-weekly meetings. Additionally, all students and professors participating in SWARM-EX are part of the team's Slack workspace, a popular instant messaging service that allows teams to form "channels" or group chats centered around a particular topic. Each subsystem on SWARM-EX has its own channel and any team member can write messages to any channel. Students can also send direct messages to each other and any professor on the project. This allows students to directly communicate with their peers at other institutions in real time, independent of email.

TEAM POLICIES AND PROCEDURES

A distributed team like SWARM-EX encounters challenges with file sharing, file storage, and export control compliance. These obstacles are further complicated by differing rules and regulations among the involved institutions, as well as the necessity of granting team members access to the internal network of an institution of which they are not a member. To address these issues and ensure that all team members have access to project files, SWARM-EX uses a combination of a shared Google Drive and GitLab as repositories for file storage. The file management process is documented in the SWARM-EX Systems Engineering Management Plan and is distributed to all team members.

The primary file storage system employed by the SWARM-EX team is Google Drive, a popular cloud-based storage solution that allows users to save files online and access them from any device with an internet connection. SWARM-EX utilizes a shared drive hosted by CU Boulder. When a new member joins the SWARM-EX team, they are granted access to SWARM-EX's shared Google Drive through a Gmail (Google Email) account. Access management is performed by student project managers, faculty leads, and the Principal Investigator (PI).

The SWARM-EX team has found that Google products are valuable collaboration tools. Google Docs, Google Sheets, and Google Slides (among others) allow SWARM-EX team members to work simultaneously on a document that updates live as edits are made; when used in conjunction with video calls, SWARM-EX team members located across the country are able to collaborate almost as though they are in the same room.

Although Google Drive is a powerful tool for collaboration, it has a number of disadvantages. For one, Google has announced that by July 2022, they will no longer be providing unlimited storage space to the academic community. Second, Google Drive does not support version control well. With the ability to constantly make changes, it is often difficult to determine when a change has been made to a document, who has made that change, and for what reason. For file types like Google Docs, Sheets, and Slides, the SWARM-EX team has combated this issue by instituting a document release procedure, which calls for users to export Google documents to non-editable PDFs prior to major technical reviews. These released files are preserved at key points in the mission and serve as critical references for all team members. This document release process, however, does not translate well to all parts of the mission, such as flight software (FSW) development, board design, and computer-aided design (CAD) modeling, for which both version control and the ability to make changes rapidly are critical.

This, in turn, prompts the second file storage system utilized by SWARM-EX: GitLab, an open-source collaboration platform that provides features like agile planning, version control, and code review, as well as built-in security. A GitLab project for SWARM-EX is hosted on a server at CU called PaloLab (named after SWARM-EX's principal investigator). Running on a Network Attached Storage (NAS) device, GitLab serves as a Git repository that team members can clone onto their local machine. They can then establish a branch to which they can commit edits to repository files, and if granted the proper privileges, they can merge their edits with the master branch. GitLab automatically collates a history for each file in the repository. It tracks all changes that are made to a file, the user who made those changes, and the time when the changes were made. It also requires users to provide a comment explaining the changes, which helps with documentation.

The PaloLab server must be accessed via CU's internal Virtual Private Network (VPN), which only CU students have access to. Faculty leads at CU have provided a process by which non-CU team members can become a CU person of interest, a network status that provides them with the necessary credentials to log in and access the CU VPN.

The SWARM-EX NAS is physically located in a designated Export Control Room (ECR) at CU Boulder. This allows SWARM-EX team members to securely store and share export-controlled files through PaloLab. The team GitLab has a specified folder to which only team members who are U.S. persons have access. All SWARM-EX team members are provided training on how to handle export-controlled documentation; team members know to never download sensitive documents onto their personal hard drives.

TESTING PLANS

Distributed Testing Strategy

As the project progresses toward the later stages of satellite design and approaches the CDR in September 2021, substantial testing of physical hardware must be completed. It is a goal of the SWARM-EX leadership for all members of the team to gain educational experience with developing and testing physical hardware, regardless of the institution to which they belong. However, there are some significant factors impeding this objective. For one, the participating institutions have different situations in terms of facilities, equipment, and staffing. Additionally, like many academic programs, SWARM-EX has tight budgetary constraints. This means that much of the testing must be done on flight hardware, rather than on engineering development units. Shipping hardware between institutions during different phases of I&T increases program costs and introduces significant risk of damaging hardware.

Consequently, the team has developed a testing distribution plan that helps strike a balance between our goals and the challenges that have been identified. Since CU has a relatively high number of students working on the project over the summer, along with the necessary facilities and equipment for testing and eventually integration, it has been chosen as the location where the majority of testing will be done.

Some functional testing will be performed at the institutions managing the respective subsystems. This includes testing GNC algorithms at Stanford on non-SWARM-EX testbeds, testing the propulsion system at GT prior to shipment and at WMU after delivery, conducting electronic loads testing on the electrical power system circuit boards at USA, and testing secondary ground stations located at Olin and USA. This distribution allows for students at each institution to be involved with the hands-on aspects of testing while working within their insitution's capabilities and minimizing the costs and risks associated with shipping components. Furthermore, to ensure that the different institutional teams have continued ownership and visibility even if the physical testing of their subsystems will take place at CU, each institution will be responsible for developing the testing plans for their subsystems. They will then support the implementation of their plans remotely or, if logistics allow, by traveling to CU to do so in person.

FlatSat Design and Assembly

As an example of this distributed testing strategy in action, development of the flight system testbed (colloquially called a FlatSat) is led by Olin and CU students, and will serve as the first integrated testing platform for components developed at the various institutions. The first phase of development is designing the FlatSat in CAD modeling software, which is shown in Figure 7. The development of this high fidelity CAD model and its associated assembly plans is primarily led and coordinated by Olin students. Off-the-shelf and custom components were selected for inclusion in the FlatSat in collaboration with team members at Olin, CU, WMU, and USA. As the FlatSat design matures, ownership will transition to CU students for the physical assembly, testing, and integration of components onto the testbed in the summer of 2021, while the assembly and test procedures for those components will be written by the respective subsystem teams at all institutions.[19, 20]

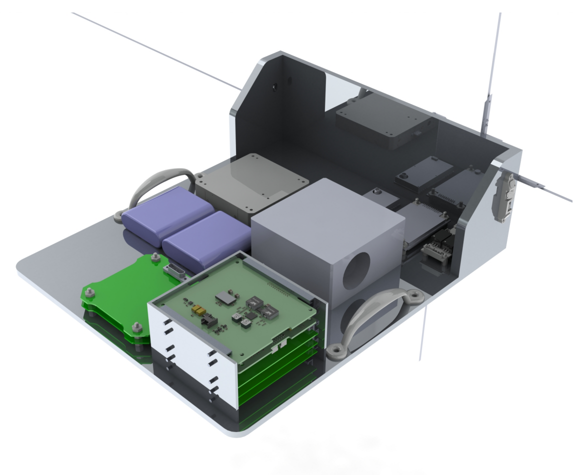

Figure 7: Rendering of assembled SWARM-EX FlatSat as of May 2021.

Presently, Olin students are creating CAD files for parts that will be manufactured in house, mainly utilizing the software SolidWorks. GrabCAD is the software tool used for CAD file sharing across universities and distributed team members. The command and data handling (CDH) and electrical ground support equipment (EGSE) boards will be designed in-house at CU with manufacturing outsourced to professional companies. For parts that can be fabricated in-house, SWARM-EX team members will utilize the facilities and staff of the CU laboratories and machine shops, traveling to Boulder as necessary.

Remote access to the integrated FlatSat testbed is available in a limited capacity to students outside of the physical lab space. This includes Remote Desktop access to testbed computers (both for CU students and students at other universities, via VPN) and remote access to programmable power supplies. The team believes that this strategy will allow SWARM-EX to successfully transition from distributed design work to shared hardware development and testing.

EDUCATION AND PUBLIC OUTREACH

As part of the project, the SWARM-EX team established an Education and Public Outreach (EPO) team with three primary goals. First, this project seeks to provide a unique opportunity for cross-institutional mentoring activities for all its members and is continuing to advance its efforts in creating more opportunities. The EPO team has also been developing a CubeSat questions Slack channel, which acts as a repository for CubeSat knowledge and expertise. Lastly, the team has been working to create a set of surveys to learn more about the team members who are participating in the project, including what prior knowledge and experience they may have.

Cross-Institutional Mentoring

Because SWARM-EX is composed of institutions with various levels of experience developing CubeSats, team members from schools with more experience naturally serve as mentors for those with less experience. Teaching, training, and learning are advanced through the inclusion of students at all academic levels; each institution is leading the development of at least one subsystem, and many subsystem teams have membership from two or more universities.

Consequently, institutions with well-established CubeSat programs are integral to the startup of new programs, greatly accelerating the development of these new programs. Furthermore, the experience and practices of these well-established institutions immediately become founding principles in the new programs, propagating those experiences and practices across the growing field of small satellite development.

CubeSat Questions Slack Channel

A Slack channel for asking questions about CubeSats, eponymously named the CubeSat Questions Slack channel, was introduced to students at partnering institutions to give them access to content experts and experienced CubeSat teams. Since its creation, it has grown to include experts from many institutions beyond those involved in SWARM-EX and become a discussion board where new CubeSat teams can go to learn and find specific information or advice on CubeSat topics. These topics can include tips for building and designing CubeSats, information on hardware/software, guidance for acquiring mentorships, and advice on building relationships between developed CubeSat teams and new teams. Currently, the channel has secured the membership of a variety of content experts in all areas of CubeSat development, including launch, operations, I&T, EPS, structures, communications, propulsion, and GNC. Unlike current CubeSat resources, the CubeSat Questions channel provides a more personalized experience where a detailed, direct answer can be received from a context expert. The team has recently begun opening the channel to CubeSat programs at other institutions so that members of these programs have a resource where they can find information and get questions answered about the various CubeSat subsystems, testing, and on-orbit operations. The channel also acts as a potential tool for organizing and advertising academic activities such as lectures or webinars on successful CubeSat programs. The channel has 110 total members as of May 2021, including both students and experts from 16+ universities around the world, and remains open for new members to join in on discussions. Any student teams interested in joining this channel are invited to do so by having a faculty mentor contact Dr. Kristina Lemmer from WMU's Department of Mechanical and Aerospace Engineering.

Team Member Surveys

As an additional part of SWARM-EX's educational goals, a set of surveys will be completed by members of the project. These surveys include a demographics survey, an entry survey, an annual survey, and an exit survey. These surveys will allow the team to determine the demographics, subsystem interest, familiarity with CubeSat design tools, and quality of preparation for future goals provided by the cross-institutional mentoring program. When a student joins SWARM-EX, they will be asked to take the entry survey to allow the SWARM-EX team to gain a better understanding of what skills they possess. The exit and annual surveys have questions similar to the entry survey but include additional questions that gather information about participants' experiences, involvement, and skills they have gained while participating in SWARM-EX. Overall, these surveys will allow the team to gain insight into the effectiveness of the SWARM-EX program in training and teaching its members on a cross-institutional level.

LOOKING AHEAD

As the team prepares for the CDR, progress must be made in a number of adjacent areas to support hardware testing. The team will be closing contracts for a variety of components so that individual component and system testing can begin. The team will also fabricate multiple versions of the CubeSat structure through iterative design. Initial versions will be 3D printed and more mature versions will be machined out of aluminum. These will allow the team to perform fit checks and learn machining best practices.

After the CDR, the SWARM-EX team will complete all I&T, with a Pre-I&T Review (PITR), a Pre-Environmental Review (PER), and a Pre-Shipment Review (PSR) scheduled for 2022 and early 2023. After these milestones have been completed, the team will be ready for launch, which is scheduled for sometime between mid-2023 and early 2024.

The distributed nature of the SWARM-EX program has vastly expanded the academic networks of its participating members and has paved the way for future collaborative efforts. An example of this can already be seen in SpectrumX, a multi-institution proposal for the NSF-sponsored Spectrum Innovation Initiative: National Center for Wireless Spectrum Research (SII-Center), submitted in April 2021, which includes the SWARM-EX faculty leads from CU and Olin.[21,22] The SWARM-EX team will apply the lessons learned from coordinating the SWARM-EX program to SpectrumX and hopes to apply its distributed mission model to future projects across collaborating networks in order to produce impactful technical progress and facilitate positive educational outcomes.

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