Development of an Active Electrodynamic Glove Integrated Shield (AEGIS) for Lunar Dust Mitigation

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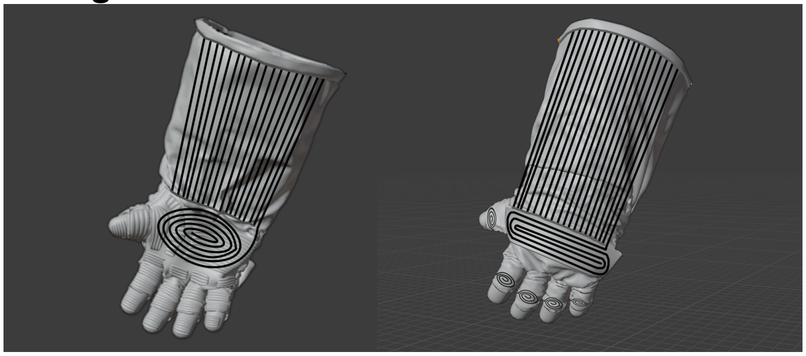
Objectives & Technical Approach:

- Mitigate dust accumulation on Artemis xEMU gloves by using electrodynamic dust shield (EDS) technology.
- Demonstrate flexibility and durability of carbon nanotube (CNT) electrodes
- Generate an active electric field to mitigate dust accumulation on the xEMU suit gloves by:
    1. Embedding CNT electrodes in the outer orthofabric layer
    2. Delivering multi-phase AC signal to electrodes to generate an electric field

Image:



Team:

- Adam Mladenetz – Project Manager
- Cade Ingram – Systems Engineer
- Ralph Quartiano – Lab Manager & Systems Engineer
- Drew Binkley – Thermals Team Lead
- Kade Carlson – Electronics Team Lead
- Noah Muthler – Electronics Team Lead
- Noah Chaffin – Software Team Lead
- Akhilesh Mulgund – Safety Team Lead
- Sonali Nagpal – Structures Team Lead

Schedule:

- Preliminary Design Review – End of February 2021
- Mid Project Report – May 20, 2021
- Critical Design Review – End of June 2021
- Technical Report – October 27, 2021

Following the systems engineering V-method of development, February through June will be system definition, design, and preliminary testing. June through October will be implementation, and testing.

Total Project Cost:

- **$151,327**

I. Summary Statement

As part of the 2021 NASA BIG Idea Challenge, the Penn State Student Space Programs Lab (SSPL) proposes the development of the Active Electrodynamic Glove Integrated Shield (AEGIS). AEGIS will use electrodynamic dust shield (EDS) technology to address lunar dust accumulation on the gloves of the Artemis xEMU spacesuits during use. Lunar dust consists of small, jagged particles, many of which are ionized by various forms of solar radiation. These particles stick to surfaces and can cause abrasion and erosion. These particles can cause irritation if inhaled and have the potential to cause bronchitis, lung cancer, and other long term health effects. EDS works by establishing an AC high-voltage signal on electrodes to generate an electric field. Both charged and neutral dust particles are then transported away by the alternating electric field. AEGIS will integrate electrodes made of carbon nanotubes (CNTs) into the fabric of these gloves, since CNTs are more flexible than traditional electrodes. Additionally, CNTs are more lightweight, durable, and conductive than traditional metal wires. AEGIS will protect xEMU gloves from dust accumulation with minimal power consumption while also maximizing astronaut range of motion. This will enable astronauts to perform extravehicular activities (EVAs) with minimal health risk and increased dexterity.

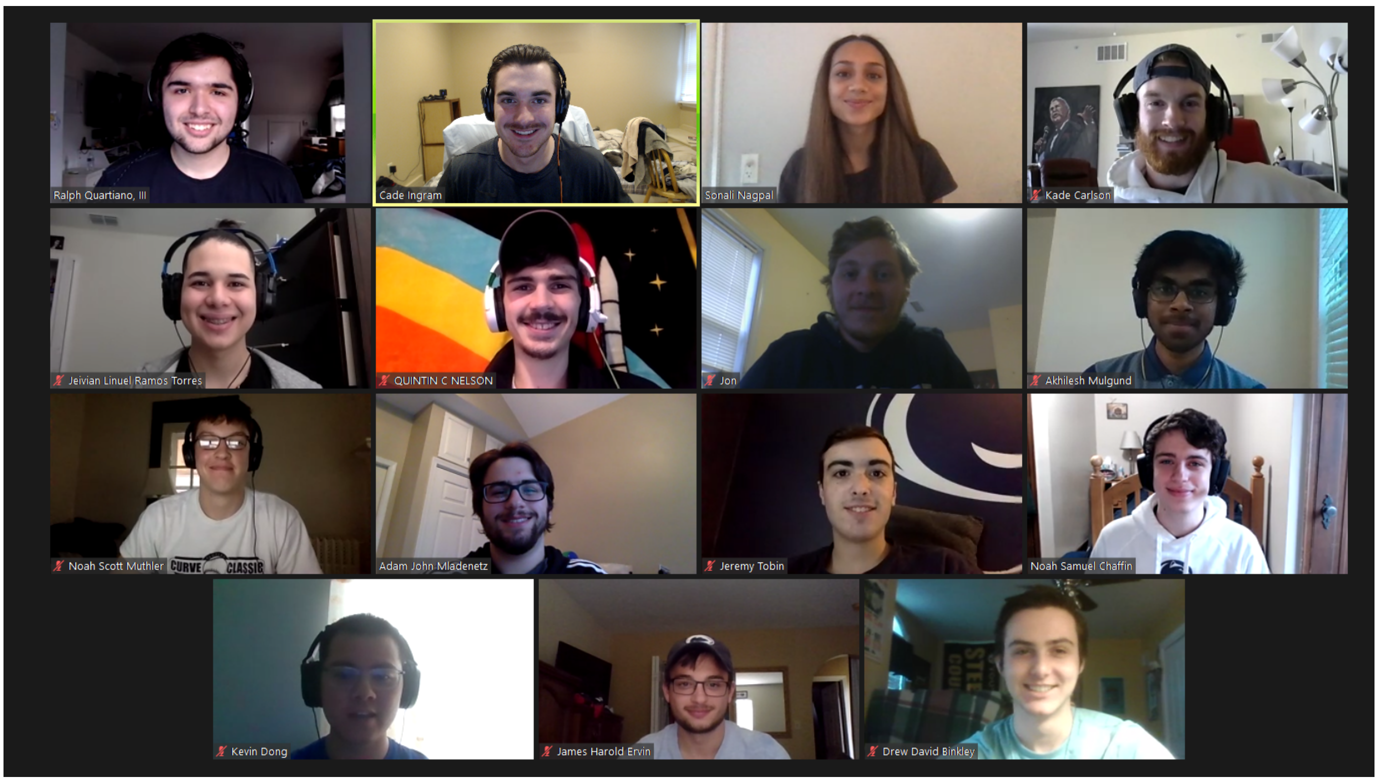


Fig. 1: The AEGIS Team.

II. Problem Statement

In the 2019 International Agency Working Group Dust Mitigation Gap Assessment Report, lunar regolith dust has been identified as the "principal limiting factor in returning to the lunar surface for missions of any extended duration" by NASA and several partnering international space agencies [1]. This report also overviews innovations in extravehicular activity (EVA) suit and life support dust mitigation technologies that are particularly critical to long-term lunar habitation.

Lunar dust from regolith limits astronaut mobility and dexterity, hindering their ability to interact with instruments and safely navigate their environment. The structural integrity of moving parts, such as suit joints and valves, are at high risk of degradation when abrasive dust accumulates in these areas. In addition to impacting EVAs, lunar regolith dust poses severe risk to life support systems when carried into habitation structures after EVAs.

Fig. 2: Gene Cernan of Apollo 17 wearing a regolith dust covered EVA suit inside the lunar module (NASA Image).

The structural integrity of the suit is at high risk when performing numerous, extended EVAs on the lunar surface. The lunar dust is composed of rough and jagged particles that readily embed into the fabric of the suit as shown in Figure 2, and act as an abrasive when accumulated in moving parts. Apollo 17 astronauts reported degradation of suit parts such as valves, joints, and gloves after only 22 hours of EVAs [2]. The build up of dust in sections of the suit that experience repeated motion leads to frictional forces degrading the structural integrity of the parts. Advances in the materials of the suit are required to extend the operable lifetime, but will likely require additional technologies to fully mitigate the abrasive nature of the dust.

Lunar regolith dust increases stress on life support systems, necessitating costly maintenance. Air filtration systems can fail to capture dust particles allowing them into cabin air breathed by astronauts, the performance of liquid- and solid-waste processing systems can be hindered by dust buildup, and crop yield can be reduced and/or contaminated. Dust mitigation is especially crucial to long-term lunar habitation because of the health risks posed by lunar regolith dust. There is evidence that the lunar dust is toxic, consisting of unsatisfied chemical bonds that make the surface particles reactive due to the near-vacuum state of the lunar environment [3].

Previous Apollo missions reported that the dust causes difficulty with breathing after the microscopic particulates were inhaled [3]. The accumulation of these particulates can leads to severe respiratory problems, including an increased risk of lung cancer [4], and non-respiratory issues such as prolonged eye and skin irritation. Dust mitigation technologies must be further developed in order to protect astronauts from these health risks for a safe and sustained lunar presence.

III. Background

Lunar dust particles are fine grains of lunar regolith less than 100 micrometers in size. The particles are primarily comprised of silicone dioxide, aluminum oxide, calcium oxide, magnesium oxide, titanium dioxide, and iron [5]. The particles vary in shape from spherical to extremely angular with jagged edges, making them extremely hazardous to lunar operations.

A significant amount of lunar dust on the Moon's surface becomes electrostatically charged due to the solar wind, cosmic rays, and solar radiation. In the regions of the Moon exposed to the Sun, dust particles can become positively charged to a potential of around 5 to 10 V. In contrast, in the Moon's permanently shadowed regions (PSRs), dust particles commonly become negatively charged. Electrostatic charge exacerbates the adhesion problem posed by the already jagged and abrasive dust. This issue has led to the development of multiple promising dust mitigation technologies, including the electrodynamic dust shield (EDS) concept.

EDS is an active dust-mitigation technology that uses a non-uniform electric field to repel dust particles from a surface. Figure 3 demonstrates the dust removal capabilities of EDS technology. The dielectric coating on the electrodes isolates them from the outside environment to prevent arc discharge. A traveling electric field is generated when a multiphase AC signal is run through the electrodes. The electric field induces a dipole moment in neutral dust particles, and directly acts on charged particles. The dielectrophoretic and electrostatic forces generated by the electric field moment moves the dust particles across and off the surface. EDS has been successfully tested in simulated lunar environments and showed promising dust mitigation capabilities [6].

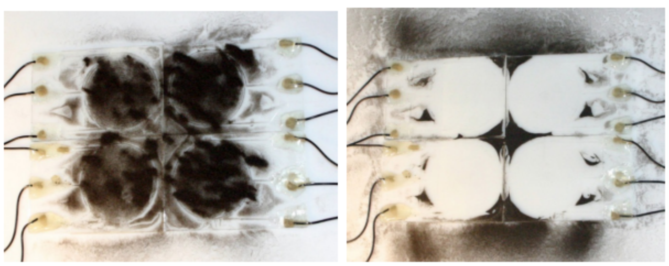


Fig. 3: Simulant dust removal with EDS at NASA Kennedy Space Center (NASA Image).

To date, EDS has primarily been applied to rigid objects, such as solar panels and habitat exteriors. For a space suit, an EDS system would embed an electrode grid in the multi-layer dielectric coating on the outer orthofabric layer [7]. Implementing EDS technology into space suits, especially the xEMU suit under development, is critical to reducing health risks and maintaining functionality limited by the accumulation of dust on these suits. As integration in space suits requires flexible electrodes, carbon nanotubes (CNTs) show promise as the electrode material due to their flexibility (see Figure 7). CNTs are small, flexible conductors, allowing them to be woven into the fabric of a space suit and generate an electric field efficiently. The average bending strength of multi-walled CNTs in recent studies was approximately 14 GPa; however, this ranged between 11 and 63 GPa [8]. CNTs are not only more durable than traditional alternatives, but are also up to 1000 times more conductive [9].

These properties of CNTs will allow the AEGIS system to reach optimal cleaning efficiency. The use of CNTs can reach 80–96% cleaning efficiency alone, whereas copper wires require mechanical vibration to achieve 80% cleaning efficiency. CNTs allow the astronaut full range of motion unlike copper, and are 30% stronger than copper wires [10]. Studies conducted by the Human Spaceflight Laboratory at the University of North Dakota, in conjunction with the Boeing Company, greatly informed the design of AEGIS. These studies focused on implementing multi-walled CNTs into the suit fabric as a form of active dust mitigation. The solution developed was the SPacesuit Integrated Carbon nanotube Dust Ejection/Removal (SPIcDER), which used suit-integrated CNTs to actively remove dust from a prototype lunar spacesuit knee joint. The SPIcDER system established the initial framework for the implementation of CNTs into the outer layer of orthofabric found on the exterior of the EVA suits [10].

The studies conducted by the University of North Dakota also indicated health and safety concerns that AEGIS aims to mitigate. Two of their primary concerns were exposure to frayed CNT material and electrical arcing between CNTs. The implementation of CNTs between layers of orthofabric prevents frayed particles from being inhaled by the astronaut while still allowing for EDS to remove the dust particles from the suit. Electrical arcing is the most prominent concern that will need to be addressed in future iterations of this technology. The SPIcDER suit used CNTs from DexMat, an innovative CNT fiber and film manufacturer, which AEGIS will utilize as well. Collaboration with DexMat is described in Section X [10].

While University of North Dakota research was instrumental to the design of AEGIS , the AEGIS system is intended to further development of CNT use in EDS applications. As seen in Figure 4, the system will be designed to meet the specifications for the Artemis xEMU suit and be implemented within the *gloves* of the suit, rather than a knee joint. By implementing CNTs into a region of the suit as complex as the glove, the AEGIS team will develop techniques for integration of CNTs into multiple types of joint that can be used throughout the entire xEMU suit. Designing a system with xEMU interfacing in mind will better prepare EDS technology for use in the Artemis Program. Additionally the AEGIS system seeks to mitigate the issue of electrical arcing by insulating the CNTs and allowing for voltage regulation by the user (see Section V).

IV. Project Description

This section discusses the AEGIS system design, verification, team structure, and project timeline, both for the competition's year-long development and potential path to flight.

To mitigate dust accumulation on the gloves of the Artemis xEMU suits, SSPL proposes the Active Electrodynamic Glove Integrated Shield, or AEGIS. AEGIS functions by using CNTs as electrodes in an EDS system on the glove's surface, serving as an active dust mitigation technology. When the astronaut steps out onto the lunar surface to perform an EVA, they will activate the AEGIS system. AEGIS then begins to remove and repel dust from the xEMU glove. AEGIS can remain active for the entire duration of the EVA, or can be turned on off at the astronaut's discretion. When the EVA is completed, the astronaut will shut off the AEGIS system and stow the xEMU suit as they normally would.

Fig. 4: Palm and back side of Artemis xEMU suit glove with AEGIS interface.

A. Suit Joints

The abrasive qualities of lunar dust are particularly dangerous in suit areas with moving parts and, specifically, joints. These areas require a certain amount of rotation and freedom, so as to not hinder the mobility of the astronauts or compromise the structural integrity of the suit. By implementing CNTs into the xEMU glove, the AEGIS team will be able to test several different joint types simultaneously. These tests will determine how the CNTs affect mobility and endurance of these joints. Additionally, the tests will provide data of how mobility and movement impact the durability of the CNTs. This data will provide valuable information about how this technology could be implemented in future iterations of space suits.

The numerous small joints and tight spacing within the glove provide an appropriate setting to test arcing as well as dust mitigation. The orientation of the CNTs will need to be configured in a manner such that will effectively remove dust without compromising the mobility and integrity of the suit. The optimal pattern for implementing the CNTs will be determined through analysis, simulation, and testing. These patterns will be designed to allow the joints to function normally, while also allowing for successful mitigation of dust.

B. Arcing and Electrical Issues

Electric arcing occurs when gas breaks down and produces an electric discharge. Although the Moon is a high-vacuum environment, outgassing (from gloves stored in habitation atmosphere) and accumulation of charged particles on surfaces can lead to arcing. Such arcing can potentially cause fire that can damage spacesuits and injure astronauts. Arcing may occur between the fingers, for example, where the CNTs are in close proximity to each other and electric fields are large. Electric arcing could also occur between the suit and other electrical equipment. If the user comes into contact with this electrical equipment, the circuit would short and the human body would experience electric shock. Among other safety measures, AEGIS will implement a kill switch that can immediately cut voltage supply in case of an emergency.

Additional concerns revolve around the electric field generated by the AEGIS system itself. Depending on the strength of the electric field and the relative distance, electromagnetic interference (EMI) can occur, which could disrupt certain electronics in the vicinity vital to the astronauts mission. We will characterize EMI from the AEGIS system during operation.

C. Artemis xEMU Suit

The new xEMU suits (see Figure 5) will contain various dust-tolerant features to mitigate the risks posed by inhalation of, or contamination from lunar regolith's glass-like shards [12]. The suit will contain a portable life support system to regulate toxic gasses, temperature, and monitor overall suit performance. Miniaturization of the electronics has allowed NASA to include duplicates of the system regulators to increase safety and EVA duration. The suit is also made of various materials that will protect against temperatures ranging from -157 to $+121$ °C. The suit provides proper pressure for the body, water to drink, and oxygen to breathe [12]. The suit is composed of the pressure garment, upper torso, lower torso, and cooling garment [11].

Fig. 5: Astronaut Kristine Davis, wearing the Artemis xEMU suit, high fives NASA Administrator Jim Bridenstine at NASA event (NASA image).

The pressure garment enables astronaut mobility and is made up of the upper torso, helmet, lower torso, and cooling garment [11]. The upper torso connects the necessary systems to the portable life support system, with a rear-entry hatch that allows astronauts to climb into the suit from the back. The lower section of the suit is comprised of the pants and boots, with a waist bearing that allows movement and turning of the hips. The lower torso also contains a body seal that connects the lower torso to the upper torso [12].

The xEMU torso has implemented updated shoulder pad placement and other shoulder enhancements that allow astronauts to reach across their body and pick things up easier. To provide this mobility, the new shoulders have cable pulleys that allow shoulders to move up and down but limit the ability to rotate the joint. Bearings were put into the suit to allow full mobility of the arm from shoulder to wrist. The xEMU lower torso has increased mobility at the hips, increased bending at the knees, and boots with more flexible soles as compared to the suits used in the Apollo missions. This mobility will allow the astronauts to walk on the Moon instead of doing the "bunny hop" that Apollo astronauts were forced to do [11].

The xEMU cooling garment is made of spandex and water tubes. There are 300 feet of water tubes woven into the clothing covering all body parts except for the hands, feet, and head. The water tubes regulate body temperature and remove extra heat by running chilled water close to the skin [12].

The primary transmission vector of dust into the lunar habitats is the EVA suits. By designing AEGIS with the xEMU suit in mind, dust contamination will be mitigated at its source and will aid in the success of the Artemis Program.

D. Sustained Lunar Presence

The Artemis program seeks to maintain a sustained presence on the Moon to further develop the technology necessary for future exploration of Mars. There are numerous challenges to be addressed as the program evolves and moves towards its goal. Specifically, dust is a major limiting factor for the possible length of EVAs and missions in the lunar environment. The AEGIS is a first line of defense against the accumulation of dust on the astronauts' suits, preventing mechanical deterioration of the suit itself and transmission of the dust into the lunar habitat. The implementation of a dust mitigation system such as AEGIS would decrease costs due to damaged suits and equipment along with increasing the data return of science missions.

As described in Section III, the lunar dust causes suit degradation by decreasing the overall durability of the suits, which, in turn, affects the long-term sustainability of future lunar missions. If the suits experience rapid degradation, they will require frequent replacements or repairs, which inhibits the long-term habitation goal of the Artemis program.

Dust accumulation can hinder an astronaut's ability to perform necessary tasks and can damage vital equipment. By implementing the AEGIS system into the xEMU gloves, astronauts accumulate less dust on their hands, therefore reducing the rate of decay of the suit's outer layer and, by extension, increasing the potential longevity of the EVA suits. The reduction of lunar dust on EVA suit gloves will also reduce accumulation of the harmful dust on equipment. By reducing the dust on their hands, it also has the potential to reduce the amount of dust that is spread by contact.

Through less dust build up on their hands, the astronauts reduce the spread of dust to any objects that they interact with directly or indirectly inside the lunar habitat. Bringing less dust into the landing craft or habitation unit addresses several concerns: it reduces the strain on the air filtration system, increases overall air quality, and reduces the amount of dust in contact with astronauts' skin and any interior electronics. Reducing the number of dust particles contaminating the habitation areas protects the astronauts' health and will allow them to safely continue any potential prolonged lunar excursions.

The AEGIS system will be inactive until the astronaut is on the lunar surface. When the astronaut steps out on to the lunar surface to begin an EVA, they will activate AEGIS through the user interface located on the glove (or other suitable user interface identified by spacesuit engineers). This will then engage the system to energize the CNTs to repel and remove the dust. Through the user interface, the astronaut will be able to control the power of the system to increase or decrease the supplied voltage depending on the surface activity. When the astronaut is preparing to enter the habitation unit, they will power off the AEGIS system for maximum safety.

E. Design Constraints and Assumptions

The AEGIS system will adhere to 2021 NASA BIG Idea Challenge Constraints. By adhering to these constraints, listed below, AEGIS will be able to operate with other systems designed as part of the competition, and to fit within NASA's overall lunar presence architecture.

- Able to manage and mitigate abrasive dust
- Able to mitigate small particles ($\sim$0.5–50 μm)
- Minimal barriers to NASA adoption (e.g., low mass, small size, low power, etc.)
- Cost-effective solution
- Nonflammable
- Able to work in harsh lunar south pole environments it is intended for
  - Lunar noon (up to -49 °C)
  - Lunar night (down to -232 °C)
  - Multiple day/night cycles
  - In permanently shadowed regions (down to -243 °C)
- Technologies should reach a minimum technology readiness level (TRL) of 4

To satisfy the 2021 BIG Idea Challenge criteria, the AEGIS system needs to be be capable of removing small dust particles from accumulating on the gloves of the xEMU suit. As specified by NASA in the *SBIR 2016 Phase I Solicitation*, the system should be capable of operating for 8 hours of EVA sorties, and have a total operational lifetime of 2300 hours or more. Durability testing will determine the reliability of CNTs, and the power system will be designed to maintain operation for 16 hours (which is double the recommended amount [13]). Successful laboratory testing of a proof-of-concept system in an operational setting will increase the technology readiness to level 4 (TRL 4).

For AEGIS to achieve TRL 5, environmental tests will need to be conducted. Optimizing the hardware requires testing the system in a thermal environment similar to that of the Moon, and will be done through a thermal–vacuum (TVAC) test described in Section VI. The effectiveness of dust repulsion is related to the gravitational environment of the system. On Earth, high efficiencies (80–96%) can still be achieved by EDS systems despite the high-gravity environment relative to that of the Moon [10]. The microgravity environment of the Moon and Mars would aid in the effectiveness of dust repulsion, and further testing of the system in microgravity environments would be required for TRL 5.

V. System Description

The AEGIS system is comprised of three main components, a control unit, glove interface, and CNT electrodes (see Figure 6). The control unit houses a main power system, a Teensy 3.2 (EDS controller), and a three-phase inverter circuit. The glove is made up of integrated CNTs and a user interface that allows the astronaut to control supplied voltage. A battery is connected to the power system, which distributes power to components at

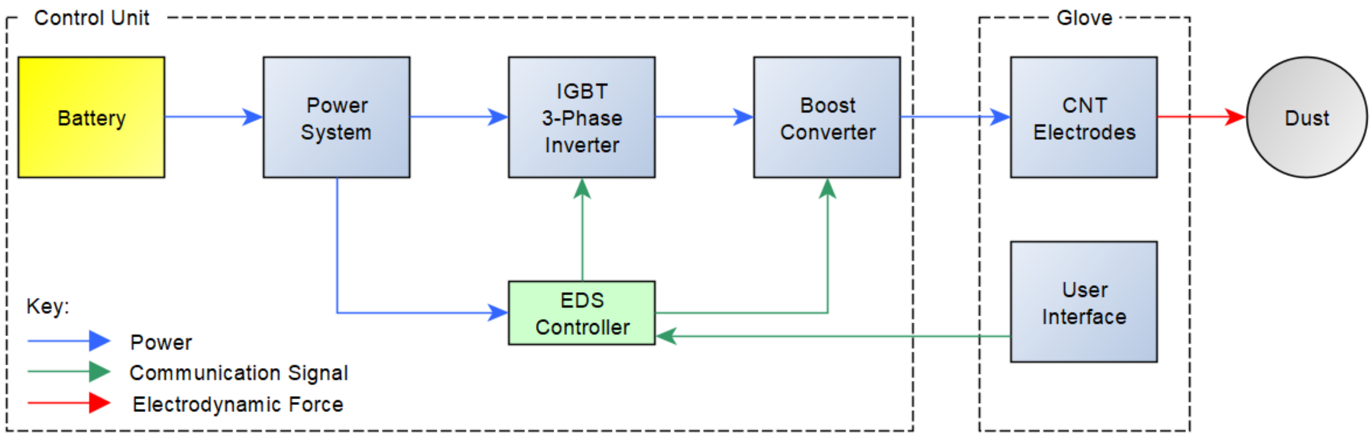


Fig. 6: System block diagram for the AEGIS instrument.

the appropriate voltages. Power is sent to the switch used to regulate the amount of power sent to the CNT electrodes. The EDS Controller receives a signal from the User Interface dictating what voltage the system will supply to the CNT electrodes, in turn, varying the electric field strength.

A. *Structures*

The control unit for the system will be housed in a small aluminum box, designed to be integrated in the back of the suit. It will house the power system, control computer, and heating elements. The AEGIS team plans on obtaining orthofabric to be used for the construction of the outer layer of the glove. The user interface of the glove will be on the wrist for easy access. It will consist of buttons to control the power setting and an on/off switch. The glove will have CNTs integrated in different patterns, some will be longitudinal, and others will be spirals to ensure flexibility (See Figure 4). The exact pattern of the CNTs will be determined through testing and electric field simulations to find the most efficient configuration [14]. The AEGIS team will sew CNTs into the fabric, since automated systems are currently not available for sewing CNTs [10]. This will be done with the help of industry and faculty collaborators discussed in Section X.

B. *Electronics*

Generation of the EDS field requires a high-voltage three-phase AC signal at very low currents (in the order of nano- to microamperes) [10]. Initial design assumptions presume the xEMU suit power-delivery system will supply a standard 28 V DC if AEGIS is implemented into the final xEMU design [15]. It follows that, for this project, an independent power source in the form of an external battery will be included in the design for the proof-of-concept. The power system will use a three-phase inverter circuit to create three, 120° phase-shifted outputs. To generate a three-phase AC signal, insulated-gate bipolar transistors (IGBTs) will be used. IGBTs are selected over conventional MOSFETs for their increased breakdown voltage, which is required to pass the high-voltage signal for the EDS system. The inverter circuit will step up the phase-shifted voltages to the operating voltage of the EDS system through a boost converter. Further research and design considerations will be required to dictate the degree of control the user has over the field strength and may reveal that varying the field strength is not necessary. The EDS field requires a voltage of 600–1200 V AC with a frequency of 5 or 10 Hz to effectively remove dust. Configuration testing with the CNTs will determine the ideal voltage and frequency to be designed to, and is expanded upon in Section VI-A. The preliminary testing of the EDS with the CNTs will inform the degree of control required for optimal functioning. Adjustment of the field strength may be necessary for limiting power consumption during certain periods, increasing field strength when working in extremely dusty environments (i.e., when taking samples or moving large quantities of regolith), or lowering field strength when interacting with sensitive equipment. A low-power mode will be implemented for emergency situations in which xEMU suit power needs to be conserved, and can be activated at the discretion of the user or designed to the power constraints of the suit. A Teensy 3.2 microcontroller will be used to control the EDS system with three field-strength presets: low, normal, and high. The user will have access to an on/off switch and can select the preset relevant to the current operational environment through a user interface embedded into the glove. The field-strength presets will dictate the voltage sent to the the EDS system, and will be defined through the preliminary testing of the CNTs.

C. *Software*

The software subsystem will control a three-phase AC signal that will be amplified to a voltage range of 600–1200 V AC running through the CNT electrodes. Presets will be compiled into the EDS controller that will allow for a variation of electric field strengths emitted from glove electrodes. The EDS controller will then take inputs from a user interface integrated into AEGIS, allowing for the user to switch between these presets. The presets will be defined by preliminary testing, and will determine the voltage delivered to the EDS system. COMSOL Multiphysics simulation software will be used to visualize the establishment and temporal nature of the electric fields across the glove's surface. These simulations will help determine which configurations work best for dust mitigation and will reveal any other issues to address in AEGIS's electrode configuration. Additionally, a robotic hand apparatus will be used in testing to bend the glove to assess the flexibility and durability of CNT wires. This test will also determine if moving the glove effects the dust mitigation capabilities of AEGIS. Therefore, the software subsystem will be responsible for managing this bending apparatus and creating controlled testing environments for AEGIS.

D. *Safety*

The safety of astronauts and electrical equipment is a primary design constraint of the AEGIS system. Arcing and CNT toxicity are concerns that will be addressed during the testing phase. There are several electronic systems within the xEMU suits, including life support systems and communications, that could be affected by AEGIS. Electrical arcing and crossing of the electrodes are also of concern. To prevent this, the team will identify a minimum distance between electrodes. Furthermore, measures to prevent the moving of electrodes within the glove's fabric will be taken.

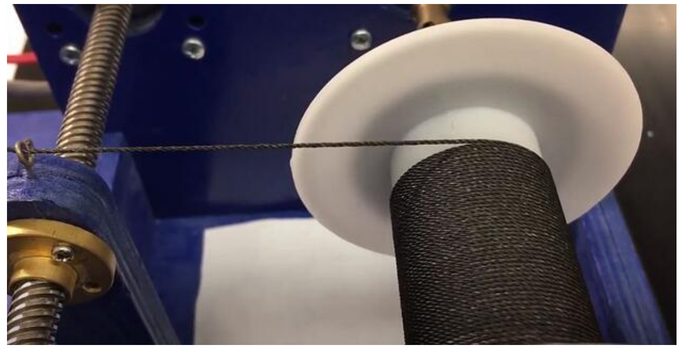


Fig. 7: DexMat carbon nanotube yarn (DexMat Image).

The use of CNTs also raises concerns about human health. A study done on mice by the Division of Environmental Chemistry found that constant exposure to CNTs can cause inflammation, fibrosis, lung cancer following long-term inhalation, and gene damage in the lung. It can also potentially cause reproductive difficulties [16]. Since the CNTs are embedded into the glove, this is not a major concern, but precautions such as insulating the CNTs will be made to ensure that this is not an issue.

VI. Proof of Concept

A. *Preliminary Testing*

Preliminary CNT testing will guide the design of the AEGIS system. Previous experimental implementations of EDS systems have conducted limited research into the spacing of the electrodes, frequency, voltage, and pattern configuration. A voltage range of 600 to 1200 V AC with a parallel, longitudinal configuration of the CNTs has been identified for effective dust removal and repulsion [10]. However, additional information is needed on the implementation of various CNT configurations for specific high-mobility areas such as joints and the variation of the field strength in response to the operational environment. In addition, we plan extensive modeling of the electric field to ensure there are no blind spots. To design a system that can safely and reliably operate in various environments, the AEGIS team will expand the knowledge base of EDS before the implementation phase through preliminary testing.

Various orientations and configurations of the EDS system will be tested. Specifically, orientations other than longitudinal can be useful for extending the mechanical durability of the system, and possibly increase the electric field area of effect. For EDS purposes, the CNTs can be oriented in a longitudinal, spiral, or square configurations, shown in Figure 8. The spiral or square configurations may be better suited for implementation on the knuckles of the glove, as they will experience the greatest mechanical stress and will also allow the electric field to extend down the sides of the knuckle. Several diameters of CNT yarn will also be tested to identify the ideal diameter for efficiency and mechanical durability. Smaller diameter yarn could also be better suited for spiral or square EDS configurations due to the ability to concentrate a greater amount of CNTs in a smaller area. An electrode diameter of 200 μm and an electrode spacing of 1–1.2 mm have been identified as satisfactory configurations in the studies from the University of North Dakota [10]. When altering the diameter and supply voltage of the electrodes, the optimal spacing will be directly affected and will have to be experimented with for each configuration.

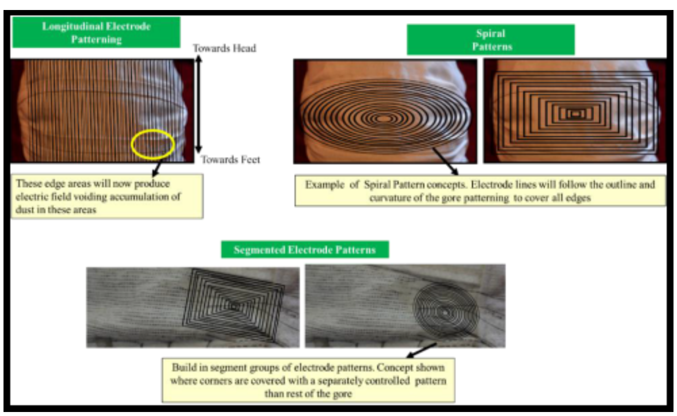


Fig. 8: Possible orientations of CNT electrodes (from [17]).

In conjunction with configuration testing, the AEGIS team will be testing various voltage levels and their effectiveness at removing regolith dust. A voltage of 1000 V has been identified in previous EDS implementations as an acceptable input for high cleaning efficiency [10]. When interacting with sensitive equipment around the lunar staging area, the electric field emitted by the AEGIS system may have adverse effects on the electronics at normal field strengths. During these periods it may be beneficial to maintain a low field strength to repel the smaller dust particles that are harder to remove once embedded in the xEMU fabric. Likewise, if the astronaut is operating in extremely dusty environments, such as when in a lunar roving vehicle or moving large quantities of regolith, it may be beneficial to temporarily maintain a higher field strength. These tests seek to identify the proper voltages for implementing the low field strength, default field strength, and high field strength presets mentioned above. CNT configurations will be temporarily implemented on the outer layer of small orthofabric “coupons” and will be powered by a laboratory test bench. This will allow the team to test a voltage range of 600–1200 V AC and record the cleaning efficiency when simulant regolith is applied to the test samples.

B. Pattern and Arcing Tests

Testing the occurrence of electrical arcing will be essential to ensuring safety. Different electrode patterns will be tested at a range of operating voltages and frequencies to identify configurations with intention of mitigating the concerns of arcing. Spacing between the electrodes will also be tested at various different suit positions in order to ensure no arcing is present in any posture.

C. Durability Testing

To test the durability of the system and to study the rate of its mechanical decline, a robotic hand will be created to test the repeated bending of the glove prototype. The purpose of this apparatus is to simulate the effects that many repeated EVAs will have on the CNTs within the glove. Data on conductivity changes and fraying from these tests will be recorded to determine how the CNTs are affected by long term use and could potentially result in a change in the pattern or location of the CNTs themselves. These data will be compared against the operational lifetime constraints for EVA suit devices, outlined in the *SBIR 2016 Phase I Solicitation* [13], which specifies an operational lifetime of 2300 hours or more.

D. Thermal Simulation

A thermal simulation of a glove and embedded CNT system will be performed via COMSOL Multiphysics. This simulation will verify the passive system’s ability to emit heat and insulate the glove from thermal damages. These COMSOL Multiphysics simulations will serve as a preliminary basis to determine if the initial design is sufficient to mitigate thermal damage to the suit. Future testing will be needed to verify the simulations and determine if any further action needs to be taken.

E. Thermal Vacuum Chamber Test

To test the ability of the system to function properly in a lunar environment, a thermal vacuum chamber (TVAC) test will be performed. This test will not only provide an opportunity to test the safety and feasibility of our CNT system in a near-lunar environment, but also allows for a test of the passive thermal system. This will ensure that heat loss from the CNTs will be effectively mitigated to prevent thermal damage to the glove. If needed, an active heating solution for the power system will be built to keep all electronic components in their operable temperature range.

VII. Team Structure

The AEGIS team is comprised of five major subsystems, all of which work in close interaction with one another. The five subsystems are: Electronics, Software, Structures, Thermals, and Safety.

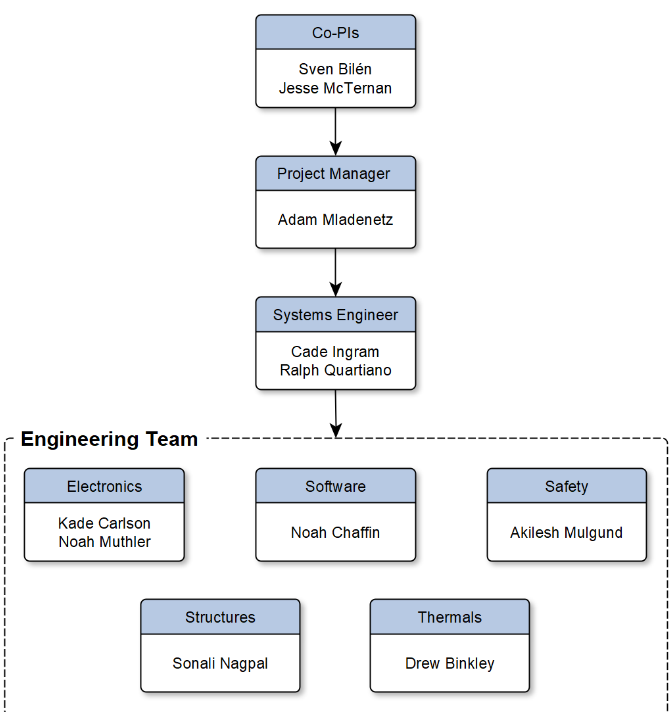


Fig. 9: AEGIS Org Chart.

The implementation of subsystems allows the members of AEGIS to focus and specialize in areas in which they have interest or experience. Each subsystem will have a dedicated lead who will report to the systems engineer. The team leads will have close interaction and communication with one another, which will allow them to work more efficiently. This structure is shown in Figure 9.

The electronics subsystem will work with both the structures and the software subsystems to implement the hardware necessary for powering the system. Electronics will be responsible for the power supply that will supply the optimal electric field strength for the most cleaning efficiency. Electronics will also be responsible for monitoring voltage and current through the CNTs. They will also create any necessary schematics and system block diagrams that explain how each piece of hardware interacts with the other.

The software subsystem will be closely integrated with the electronics subsystems to ensure proper functioning of AEGIS. Software will focus on writing code for the EDS controller and glove interface.

The structures subsystem will work closely with the electronics subsystem in order to integrate the CNTs into the suit's system. They will be responsible for creating the housing for the required power supply. The subsystem will also create the physical glove to be used in testing. Additionally, the structures subsystem will create any necessary computer aided design (CAD) models.

The thermals subsystem will work with both the structures and the electronics hardware branch to mitigate thermal risks posed by the system. They will work with the structures subsystem to ensure that the power supply and all its components maintain an operable temperature in the lunar vacuum environment. Additionally, they will work with structures to interface the CNTs into the suit and prevent any thermal damage from occurring to the suit itself.

In addition to the aforementioned subsystems, there will also be a subsystem dedicated to adressing health and safety concerns. This subsystem works with the previous four in evaluating the impact the designs would have on the astronauts' health or on the safety of the proposed missions. If this subsystem finds that a design is unsafe it will work with the other subsystems to modify the design.

VIII. Path to Flight

A. Scalability

As part of path to flight, the development of the AEGIS technology will expand ways in which the system can be scaled up to cover a larger portion of the suit. Based on the results of the electrode configuration and electric field efficiency testing, optimal CNT configurations will be identified for placement on the different geometries of the xEMU suit. Specifically, electrode configurations around joints and high-mobility areas will be recorded in detail for future expansion of the technology. In addition, electric field strength tests with various voltage and frequency inputs will identify the best power delivery configurations for dust removal efficiency and electric field power. The electric field modeling performed via COMSOL Multiphysics will develop the modeling practices needed to ensure uniform coverage of the EDS, preventing "blind spots" where dust could penetrate and accumulate. The power delivery system for AEGIS will conform to the International Space Power System Interoperability Standards to make integration with existing space power architecture seamless. Although AEGIS is designed specifically for the glove portion of the xEMU suit, it is meant to demonstrate the effective integration of EDS technology in one of the most complex parts of the xEMU suit. Scaling the EDS to the entire spacesuit is necessary for the overarching goal of complete dust mitigation, and the AEGIS system proof of concept will be an important cornerstone in the future implementation of this technology.

B. Interfacing with Suit Electronics

When implementing AEGIS into the xEMU suit, serial communication will be needed. This will enable the suit to take full control over AEGIS and send commands to switch between the presets modes. In addition, there may be reason to collect data from the AEGIS system, therefore requiring the use of a single-board computer to enable data collection.

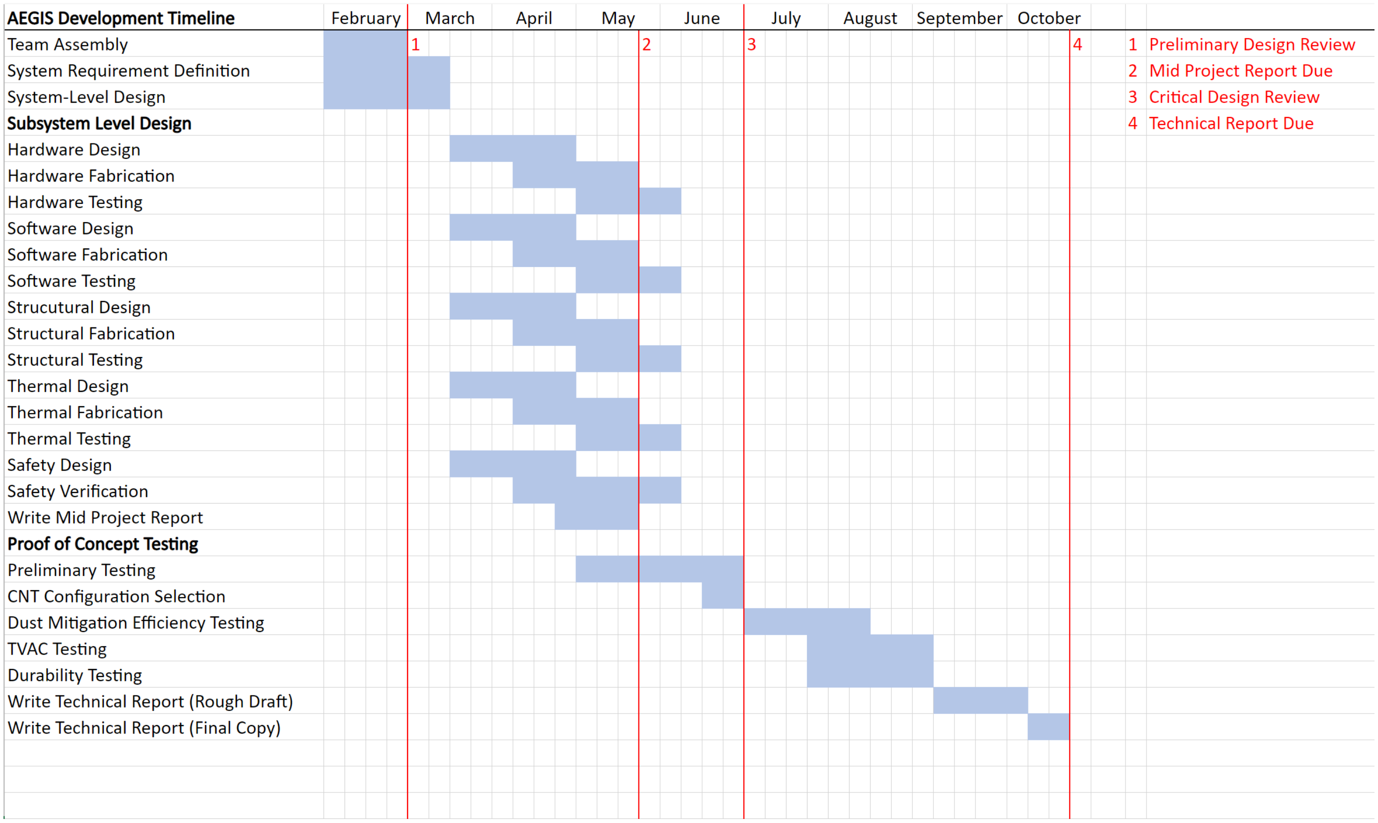
Presently, the power draw of the EDS system has not been characterized. Through research on previous EDS systems, the AEGIS team has identified testing ranges of 600–1200 V with a low current draw on the order of micro- to nanoamperes. Operation voltage is expected to be approximately 1000 V. Preliminary testing will reveal the actual power draw for extended use of the system. AEGIS will be designed with an external power source included in the form of a battery. The power delivery system will be designed in house. Further research into the power constraints of the xEMU suit will dictate whether an external power source will have to be included in path to flight.

C. Future Enhancements

It is recognized that the ideal AEGIS system would be fully autonomous, requiring no interaction from the astronaut that could increase their cognitive load during the already stressful EVA. As such, we will explore several pathways for enhancements.

First, we will engage UI/UX experts to develop an interface that minimizes cognitive loading. Second, building on advisor Dr. Bilén's research expertise (e.g., [18] [19]), we will investigate automated methods for determining if arcing is occurring such that the system can be automatically shut down.

IX. Project Timeline



Detailed Budget

Budget categories:	**01/01/2021-06/30/2021**	**01/01/2021-06/30/2021**	**Total**
1. Salaries and Stipends			
a. Lead Faculty Advisor- Dr. Sven Bilen	$2,669	$2,735	$5,404
b. Project Advisor- Dr. Jesse McTernan	$1,822	$1,872	$3,694
c. Student Stipends (10 students)	$28,000	$50,000	$78,000
2. Fringe Benefits	$1,567	$1,607	$3,174
3. Lab Supplies	$1,177	$3,823	$5,000
4. Capital Equipment	$30,000	$0	$30,000
Fabrication of Brassboard System			
5. Travel to the BIG Idea Forum			
a. Faculty Advisor		$1,000	$1,000
b. Students		$14,000	$14,000
6. Indirect Cost (F&A)	$4,377	$6,678	$11,055
TOTALS	**$69,612**	**$81,715**	**$151,327**

BUDGET JUSTIFICATION
The Pennsylvania State University

Personnel – The principal investigator is budgeted at the percentage of time shown using his/her actual salary in the calculation. The principal investigator's time includes both technical and project management functions. Any other individuals/positions shown are budgeted at the percentage of time shown and actual salaries used. For project time occurring after July 1 of any given year, the salaries have been adjusted at the University approved rate of 2.5%.

Senior Personnel:

- **Sven Bilen, Faculty Advisor** – 8.33% effort over 3 months (0.25 summer month). Project PI and interface with Penn State administration, faculty director of SSPL, provide direction and student training.

- **Jesse McTernan, Faculty Advisor** - 15% effort over 3 months (0.45 summer month). Project co-PI, associate director of SSPL, engage with students during design, fabrication, and testing.

Fringe Benefits – Fringe benefits are computed using the fixed rates of **34.88%** applicable to Category I Salaries, 12.35% applicable to Category II Graduate Assistants, 7.94% applicable to Category III Salaries and Wages, 0.31% applicable to Category IV Student Wages, and 23.88% for Category V, Postdoctoral Scholars and Fellows, for fiscal year 2021 (July 1, 2020, through June 30, 2021). If this proposal is funded, the rates quoted above shall, at the time of funding, be subject to adjustment for any period subsequent to June 30, 2021, if superseding Government approved rates have been established. Fringe benefit rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency.

Student Stipends/Participant Support - budgeted @ $78,000. To support Spring and Summer 2021 stipends for 16 students (10 @ $6000 each, 6 @3000).

Materials and Supplies - budgeted @ $5,000. To support early-stage prototyping, lab costs to support testing effort.

Equipment – budgeted @ $30,000.

Part	**Estimated Cost**
EVA Glove analogue	$7000
DexMat CNTs	3000
Power System	4000
Cables & Connectors	2000
Housing - Aluminum & Machining	2000
Thermal System Components	2000
Control Unit Components	5000
Contingency	5000
Total	$30,000

Travel - budgeted @ $15,000, $1,000 for a faculty advisor and $14,000 for student team. All travel will be in accordance with University travel regulations and mileage will be charged at the current rate on the date of travel. Travel estimates are based on costs that were incurred on previous projects of a similar nature for federal and state agencies. To attend the BIG Idea Forum for 10 students. Assumes 4-night hotel stay and a registration fee of $500 per attendee.

Facilities and Administrative Costs – F&A rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency. Penn State's current provisional on-campus rate for research is 60.50% of MTDC from July 1, 2020, through June 30, 2021. New awards and new competitive segments with an effective date of July 1, 2021, or later shall be subject to adjustment when superseding Government approved rates are established. Per 2 CFR 200 (Appendix III, Section C.7), the actual F&A rates used will be fixed at the time of the initial award for the duration of the competitive segment.

X. Capabilities Statement

Penn State's SSPL is a student-led, faculty-directed space research lab founded in 2006 by Dr. Sven Bilén. Dr. Bilén's research within aerospace applications include spacecraft systems design, spacecraft–plasma interactions, high-voltage systems, software defined radio, and electrodynamic tethers. Dr. Sven Bilén is a leading expert on high-voltage systems and arcing as well, which will be particularly helpful to the design of AEGIS. His deep technical knowledge of electrical and aerospace engineering, vast experience in the design of electrical space systems, and mastery of systems engineering practice are invaluable for all SSPL projects, including AEGIS.

SSPL provides undergraduate students the opportunity to design, fabricate, and integrate practical space systems, enabling hands-on experiences through the various projects in which students can apply classroom knowledge in a real-world setting, and is comprised of a diverse group of primarily undergraduate students. Many engineering and science majors are represented, forming a team with diverse backgrounds and skill sets for designing space systems. While working within SSPL, students use systems engineering methodology to design, manufacture, and verify space systems—gaining not only technical knowledge, but also a practical understanding of how industry aerospace projects are run. Students take leadership positions on these projects, yielding real-world experiences that develop the next generation of engineering leaders.

SSPL developed the Polar Atmospheric Student Sounding (PAWSS) sounding rocket payload as a part of the Grand Challenge–Cusp initiative [20]. This Grand Challenge was an international collaboration between the US, Norwegian, and Japanese universities intended to study the northern magnetic cusp through sounding rocket payloads. Penn State developed the PAWSS payload, which flew on the G-CHASER student sounding rocket launched in January of 2019 from Andøya Space Center[21]. On-board this payload was a radio receiver (both analog and SDR-based) for total electron count measurements and a LIDAR that measured neutral density, data from both of which was used to further understand the coupling between neutrals and charged particles in the mesosphere during a polar mesosphere winter echo (PMWE).

SSPL is developing the Oasis instrument as part of the 2020 NASA BIG Idea Challenge (see Figure 10). This instrument will perform laser-induced breakdown spectroscopy (LIBS) to survey for water in permanently shadowed regions (PSRs) near the Moon's southern pole. Identifying the concentrations of water at various locations for *in-situ* resource utilization will be crucial to future long-term lunar habitation. Oasis aids the Artemis program in the identification of this vital resource by supplying reliable and accurate data on where water can be found and in what concentrations. The design, manufacturing, and testing of Oasis performed over the past year will be presented at the 2020 NASA BIG Idea Forum in January 2021.

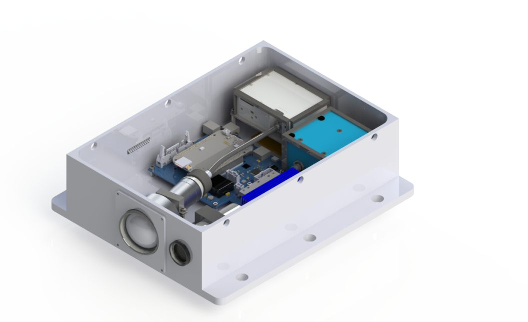


Fig. 10: Oasis payload shown without lid to expose components.

The engineering students on the Oasis team have gained valuable experience throughout that project. The team of predominantly sophomore undergraduate engineering students now have technical experience in CAD, design for manufacturing, thermal analysis and simulation, control systems, command and data handling, and PCB design and manufacture, among other areas. These skills have been cultivated over a year of working within a systems-engineering environment. Industry-standard project management practices were followed, including subsystem-based team organization, design reviews with external experts, lean management, unit testing, and requirements documentation. A combination of new and returning members, SSPL is prepared to expand upon the lessons learned from Oasis to develop the AEGIS system.

While the knowledge gained during the ongoing OASIS project will benefit the development of AEGIS, the experience gained throughout AEGIS development also has potential to aid Oasis. As a primarily optical system, lunar dust poses risk to the operation of Oasis, since regolith accumulation on optical surfaces can prevent laser ablation and/or emission capture. Furthermore, thick regolith buildup on the outer walls of the payload would reduce thermal system efficiency, potentially increasing power draw and/or damaging components. Experience gained in the development of an EDS system for AEGIS could be utilized in the development of one for Oasis as well. The symbiotic relationship between the two SSPL projects can advance both of them to a greater TRL.

The Penn State Learning factory, a college-run machine shop and makerspace on campus, gives SSPL members access to cutting edge manufacturing technologies and training in order to safely and effectively use them. This allows SSPL to create many of the structural parts required by projects.

SSPL's in-house environmental testing consists of a Lesker vacuum chamber and a TestEquity 1007C thermal chamber. The vacuum chamber is capable of going down to 10 μTorr and the thermal chamber operates between -73 and 125 °C. The vacuum chamber will be used for operational testing of the payload in a vacuum environment, outgassing verification, and thermal performance, whereas the thermal chamber can be used to test the thermal effects of the AEGIS system. In cooperation with the Applied Research Lab (ARL), SSPL also has access to a high-performance shake/vibration table. This was used previously to test the durability of pre-built components for the PAWSS payload, and can be used to verify resistance to vibrations experienced during launch.

As part of the proposal phase of this project, the AEGIS team has identified and communicated with key industry and faculty collaborators. ILC Dover, NASA spacesuit supplier since the days of Apollo, and DexMat, an innovative carbon nanotube manufacturer, support AEGIS and have expressed great interest in collaborating with us on the project.

ILC Dover, based in Frederica, Delaware, has been pushing the boundaries of aerospace engineering and materials science for over 50 years. Originally manufacturing high altitude flight suits for the US Navy and Air Force, the company was contracted by NASA in 1965 to build space suits for the Apollo missions, which were worn by Neil Armstrong and Buzz Aldrin during their spacewalks. Since then, ILC Dover has continued spacesuit development as well as other projects with NASA including the airbags used by the Pathfinder rover. ILC Dover has not only offered their expertise to assist the AEGIS team in integrating an EDS system into xEMU gloves, but have also indicated the ability to supply the team with materials to be used in testing, including the outermost layer of an xEMU glove model.

Utilizing CNT manufacturing techniques originally developed at Rice University, DexMat has been innovating CNT technology since its incorporation in 2015. DexMat's Galvorn product line consists of strong and conductive CNT fibers and tapes, that have been used in multiple aerospace applications. One such application was the groundbreaking University of North Dakota study cited extensively in this proposal. By supplying the CNTs used in that study, DexMat aided North Dakota in significantly raising the TRL of CNT-based EDS systems for use in spacesuits. DexMat has offered to supply CNTs for this project as well, in addition their immense knowledge of how to use the material. Having access to world-class CNT products, as well as the expertise behind them, will be invaluable to AEGIS going forward.

Dr. Felicia Davis, Associate Professor of Architecture, and Dr. Namiko Yamamoto, Associate Professor of Aerospace Engineering, at Penn State will be collaborators in the AEGIS project. Dr. Davis has an extensive body of work surrounding the integration of electronics into fabrics for the purposes of communications and heating. Thus, her expertise will inform the integration of EDS electrodes into xEMU glove fabric. Dr. Yamamoto has done extensive research on the mechanical properties of CNTs, which will be extremely beneficial in the design of the CNT-based EDS system. Dr. Yamamoto also manufactures CNTs as part of her research, samples of which could used for testing. The counsel of these faculty experts will be extremely valuable and will inform the design and integration of the AEGIS system.

With diverse technical experience, access to a wide range of facilities, and expert industry and faculty collaborators. SSPL is well equipped to train the future generation of space systems engineers and to develop the AEGIS system.

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