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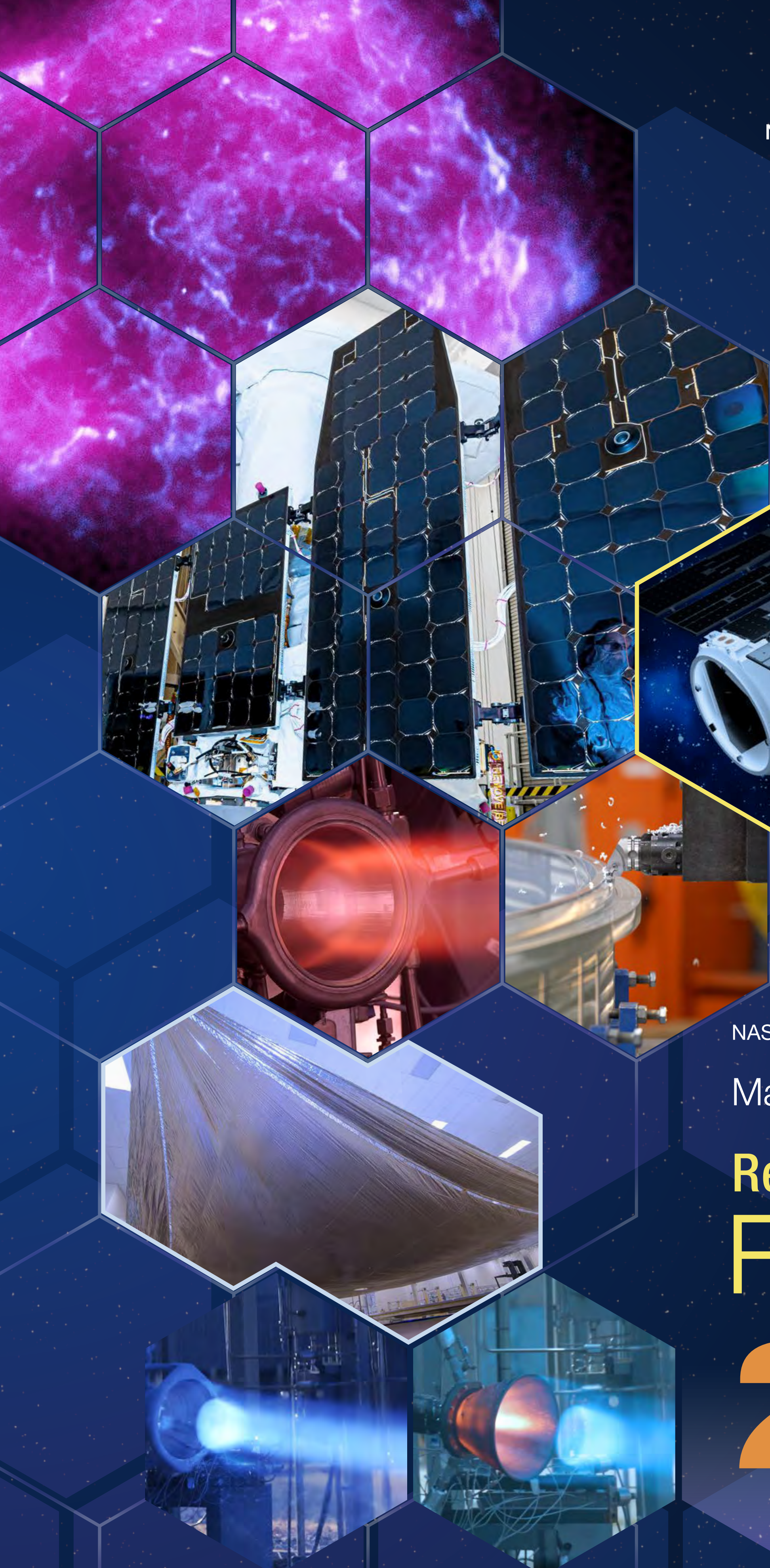

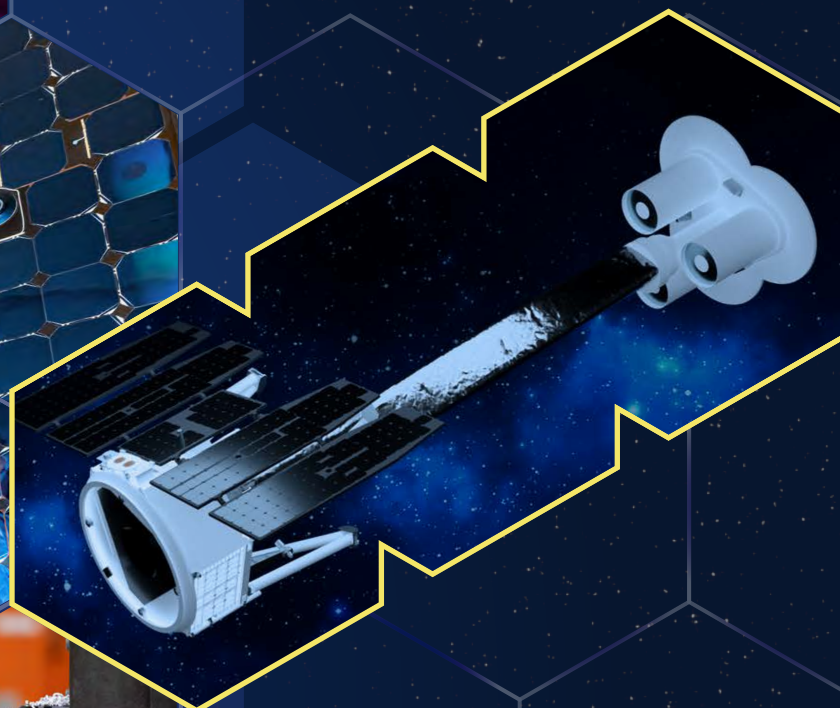

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Marshall Space Flight Center

Research & Technology REPORT 2021

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Research and Technology Report 2021

J.W. Dankanich and R.L. Frederick, Compilers
Marshall Space Flight Center, Huntsville, Alabama

ACKNOWLEDGMENTS

The points of contact and coordinator at Marshall Space Flight Center (MSFC) for this Technical Memorandum (TM) are John W. Dankanich and Rebekah Frederick. The MSFC Office of Center Chief Technologist recognizes Jason Shoemate, Kathleen Hotchkiss, and Kathy Jobczynski of the MSFC Scientific and Technical Information Group for assisting in the development of this report. The Center Chief Technologist, John Dankanich, and Technologist Rebekah Frederick provided the support, insights, and decisions required for the compilation of this TM.

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FOREWORD

This past year brought new challenges, but it also presented new opportunities and I'm proud to say the Marshall team excelled at every turn. Whether working from home or on-site, the team never stopped the innovation and dynamic technology development that is making all our exciting missions possible.

Everything we do here, from Artemis work to science to technology development is because we have a determined team of people making it happen. Returning humans to the Moon is the first step in exploring farther into space and it's our scientists and engineers that are developing the technologies to make those dreams a reality.

Our unique capabilities and facilities will enable these missions of discovery and exploration. Things like the Imaging X-Ray Polarimetry Explorer and the Near-Earth Asteroid Scout — these missions are happening right now thanks to our diverse and talented workforce of 7,000 strong.

Whether it's developing the habitation and life support systems to live and work in space or advancing the technologies that will allow us travel to deep space destinations, just knowing that Marshall will play a part in advancing our nation's space program makes me proud, humbled, and in awe of this team.

Thank you for all that you do.

Jody Singer

Center Director
Marshall Space Flight Center

INTRODUCTION

For MSFC, 2021 ended with the spectacular launch of the Imaging X-ray Polarimetry Explorer (IXPE). The mission uses advanced innovative instrumentation to gain understanding of some of the most extreme objects and events in our universe. This mission is a great microcosm of the MSFC 2021 Research and Technology (R&T) portfolio. It is not because IXPE is just an innovation that can impact our understanding of the laws of nature, but because it is a testament of achievements that are continued on schedule, and with impact, during the new evolving virtual work environment. Brief disruptions occurred in 2020, but the results have been accelerated adoption of collaborative tools, expansion of the technical reach and actually bringing teams closer together; by eliminating biases associated with physical proximity-based relationships.

Innovation is not and cannot be constrained by geographical locations. The MSFC 2021 R&T portfolio showcases an increase in collaborations and partnerships across the entire NASA enterprise, and also with universities and industry partners, small and large, to advance a wide range of new technologies that will not only enhance existing programs, but enable new architectures to achieve NASA objectives. I am humbled once again to share just a small portion of the great work at MSFC, with its research and technology activities, objectives and progress.

John W. Dankanich

Center Chief Technologist
Marshall Space Flight Center

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TA01:

Propulsion Systems

100mN ASCENT Thruster for Lunar Flashlight Propulsion System (LFPS)

OBJECTIVE: *To develop and deliver a first-of-its-kind thruster for a CubeSat mission architectures.*

PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center (MSFC) was responsible for the development of the Lunar Flashlight Propulsion System (LFPS). The LFPS project selected Plasma Processes LLC (PLASMA), to build, qualify, and deliver a number of 100mN thrusters for the Lunar Flashlight mission. PLASMA started this development effort through the Small Business Innovation Research (SBIR) program in 2017. PLASMA worked closely with MSFC on the definition of performance requirements and interfaces. That work continued under SBIR Phase IIE. PLASMA was selected to build thrusters for the LFPS in 2019. The project ordered twelve (12) units: ten (10) flight and two (2) qualification units.

APPROACH/INNOVATION

These thrusters use the Advanced Space Craft Energetic Non-Toxic (ASCENT) monopropellant formerly referred to as AF-M315E, developed by the Air Force Research Laboratory (AFRL). Synergy of strategic interests in small ASCENT thrusters led to MSFC and AFRL entering into an Interagency Agreement to share in development of these thrusters.

MSFC and AFRL both place high emphasis on (1) programmatic success for LFPS and (2) establishing a reliable commercial source for thrusters. MSFC worked with PLASMA to address Manufacturing Readiness Level (MRL) as well as Technology Readiness Level (TRL). MSFC assisted in PLASMA's efforts to establish their in-house manufacturing and testing capability.

PLASMA has a unique capability in near-net shape manufacturing of refractory metal components. This process, called El-Form®, is used to manufacture chambers and other components. PLASMA also leveraged this process to develop and manufacture a breakthrough, monolithic, metal-foam catalyst. This catalyst has demonstrated exceptional resilience in the extremely hot environment where the propellant is catalytically decomposed and combusted. The 100mN thruster is the first flight thruster to use this catalyst.

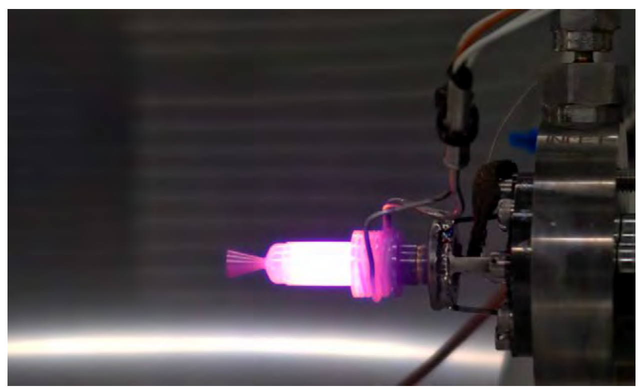


FIGURE 1. A 100mN thruster built by Plasma Processes LLC; uses ASCENT propellant (AF-M315E).

The LFPS project commissioned MSFC Engineering to perform a thruster-level thermal analysis anchored by PLASMA's test data. PLASMA provided the MSFC team access to thermal performance data and permitted MSFC to access specialized instrumentation necessary to provide those insights. The LFPS project also commissioned MSFC Engineering to perform a thruster-level structural analysis. This analysis effort takes thermal analysis data into account to assess the thruster's design margins at operating temperatures. The insights gained through the thermal and structural modelling effort provided great confidence in the performance margins of the various materials and assembly processes employed in the thruster's manufacturing and verified manufacturing requirements against NASA standards. Such a verification validates the thruster and will improve commercial market acceptance.

RESULTS/ACCOMPLISHMENTS

The first flight thrusters were delivered to MSFC in March 2021 and were integrated onto the LFPS in April 2021 by a PLASMA engineer. The 100mN thruster qualification program started in May 2021. The initial test plan matrix was developed by MSFC based on the mission needs for Lunar Flashlight. The thruster far exceeded the required performance and the team's expectations. The LFPS project extended the qualification program three times, hitting additional performance milestones including a 101-min-long continuous firing and a 94-min-long pulse train. Ultimately, the LFPS project suspended the qualificaion program after other tasks took priority. At the time the qualification program was suspended, the thruster had accumulated nearly six hours of total firing time and over 3.5 times the required propellant throughput. Perhaps more remarkable is that the thruster showed no sign of performance degradation at the time the program was suspended. The qualification thruster remains in good health and was stored for continued testing later.

PLASMA completed the acceptance testing of the remaining thrusters later in 2021. MSFC also placed a new order for three (3) additional thrusters for use on a new propulsion system.

SUMMARY

This activity was an excellent example of the power of the SBIR program in which the firm and an interested project can mutually benefit through collaboration and openness. Through SBIR Phase I, II, and IIE, MSFC and the firm were able to mature this thruster technology to a point that it achieved a space flight opportunity. Then, through SBIR Phase III, the firm built, acceptance tested, and qualified the thruster for the Lunar Flashlight mission. The LFPS effort led to AFRL engagement and several follow-on awards from both NASA and AFRL.

PRINCIPAL INVESTIGATORS: Daniel Cavender, Thomas Hasanof (PLASMA)

PARTNERS: Air Force Research Laboratory (AFRL); Plasma Processes, LLC

FUNDING ORGANIZATIONS: Advanced Exploration Systems (AES) Office, Small Business Innovation Research (SBIR)

FOR MORE INFORMATION:
https://www.plasmapros.com

22N Green Propulsion Thruster for Small Satellite Planetary Exploration Missions

OBJECTIVE: *To refurbish and test a modified 22N thruster with a coated Molybdenum alloy thrust chamber.*

PROJECT GOAL/DESCRIPTION

Bradford Space and ECAPS proposed the development and testing of a low-cost version of the ECAPS 22N High Performance Green Propulsion (HPGP®) thruster in collaboration with NASA Marshall Space Flight Center (MSFC). The proposed Cooperative Agreement between Bradford Space and NASA MSFC builds upon the implementing agreement (IA) in process between the Swedish National Space Agency and NASA to develop an engineering qualification model (EQM) of the 22N HPGP thruster.

The results of this project will: (1) aid maturation of green propulsion technology through testing under relevant environmental conditions; (2) characterize the molybdenum (Mo) alloy thrust chamber compatibility with high temperature environments; (3) provide a baseline for comparisons of Mo alloys versus iridium (Ir)-lined rhenium (Re), to determine any potential economic savings; and (4) help close technical gaps identified under the 2016 Green Propulsion Inter-Agency team that realize near-term priorities in chemical space propulsion.

APPROACH/INNOVATION

The Bradford ECAPS High Performance Green Propulsion (HPGP®) technology is based on storable ammonium dinitramide-based liquid monopropellant blends (i.e., LMP-103S and LMP-103S/LT (low temperature)) and the associated thruster technology. The test program will comprehensively test the thruster in a relevant environment to advance the technology readiness level (TRL) of the thruster.

To complement ongoing work, a low-cost version of the ECAPS 22N HPGP® thruster (named 22N GP thruster) will be refurbished and tested. The thruster is highly suitable for small spacecraft on planetary missions as well as other commercial and government small satellites in the 200–500 kg range. Storable liquid monopropellants LMP-103S and LMP-103S/LT offer higher combustion temperatures over monopropellant hydrazine, requiring that key components (e.g., the reactor bed, thrust chamber, nozzle) are made from refractory materials that can withstand increased temperatures. While typically Ir-lined Re is used for the thrust chamber, this proposal seeks to achieve and validate a lower-cost version of the 22N thruster using a coated molybdenum alloy for the same component.

The project objectives are:

(1) Verify manufacturability and performance of a lower cost 22N GP thruster.

(2) Provide direct access and full visibility to NASA to ease entry of the technology into the US market.

(3) Enable a direct comparison with a full qualification engine, which will be built and tested in parallel at ECAPS under the IA.

(4) Achieve qualification propellant throughput as deemed suitable by NASA MSFC for small planetary missions and within budgetary constraints of the project.

In parallel to the 22N HPGP® development, fabrication, and testing, the 22N GP thruster will provide further validation of technology maturation. Hot-fire testing will be performed at NASA MSFC with a test matrix deemed suitable for small planetary missions. Successful completion of the test program will shorten the path to technology implementation for such missions, provide testing

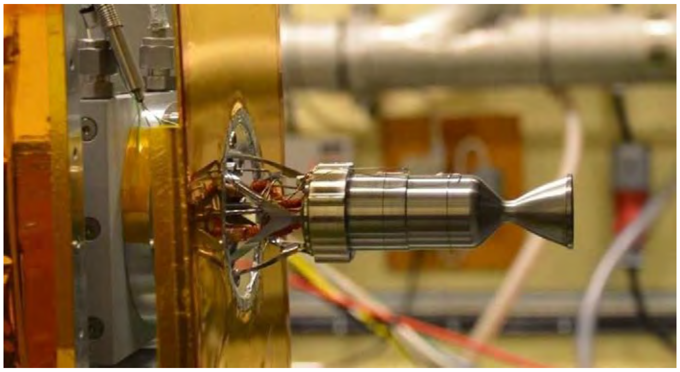


FIGURE 1. A 22N thruster built by Bradford ECAPS; uses LMP-103S propellant.

results from a relevant environment, and advance the 22N GP thruster to TRL 6.

RESULTS/ACCOMPLISHMENTS

The 22N HPGP® thruster has been returned to ECAPS for disassembly and refurbishment. The thruster has undergone functional checks (e.g., leakage, electrical checkouts, etc.) according to ECAPS internal procedures to ensure all flow control assembly is within specification. Presently, the thrust chamber assembly (TCA) is queued for a protective coating (against combustion gases) before reassembly of the new TCA, which will be followed by acceptance testing at ECAPS and return to NASA MSFC for the full hot-fire test program. The test matrix, which was developed under the premise of thruster use for small planetary missions, has been reviewed by both NASA MSFC and Bradford Space to ensure goals for technology validation are met. Presently, NASA MSFC has 28 kg (62 lbm) of LMP-103S and is actively procuring an additional 40 kg (88 lbm) for a total propellant throughput of 68 kg (150 lbm) to meet test objectives.

While awaiting thruster and propellant delivery, NASA MSFC's efforts in tandem have been planning and preparing the test site at the Component Development Area (CDA). The engineering team at MSFC has developed a test schematic for fluid handling, instrumentation, and flow control, and has procured relevant hardware. Present activities include cleaning and calibrating flow control hardware, providing a duplicate set of hardware for technicians to configure tube routing in tandem, preliminary testing of the thruster load cell and associated thrust stand, and maintaining equipment as necessary. CDA facility operations include system testing to ensure acceptable vacuum levels are attainable for test fires exceeding 30 min and determining contingency plans well prior to the scheduled test period; verifying access to appropriate power supplies; confirming optics comply with diagnostic imaging systems; and ensuring workflow for test setup (e.g., fabrication, passivation, calibration, and certification) in order to meet project schedule.

SUMMARY

The 22N GP thruster activity is actively making progress toward a test campaign to validate a low-cost version of the 22N HPGP® thruster. Results from this project will soon validate operation of the 22N GP thruster in a relevant space environment advancing it to TRL 6, which offers benefits to both commercial and governmental small space satellites as an alternative to monopropellant hydrazine and reduces a programmatic supply chain risk.

PRINCIPAL INVESTIGATORS: Daniel Cavender, Wilhem Dingertz (Bradford ECAPS)

PARTNERS: Bradford Space, ECAPS

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

FOR MORE INFORMATION: https://www.bradford-space.com

Spectre Propulsion System—Formulation and Development

OBJECTIVE: *To develop a multi-mode propulsion system for CubeSat missions.*

PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center (MSFC), through cooperation with small business and academia partnerships, has been developing the Spectre 'Multi-Mode' Propulsion System. This new propulsion system will have both chemical and electrospray (e-spray) thruster technology fed from a common propellant tank. This enables high thrust and high impulse in one package. A 4U-sized propulsion system on a 12U CubeSat could achieve >1 km/s Δv, with thrust up to 1 N, while offering great flexibility and capability for SmallSat missions (Moon, Mars, and beyond).

APPROACH/INNOVATION

The Spectre team leverages hardware and knowledge developed through the Lunar Flashlight Propulsion System (LFPS) project. The team also takes advantage of NASA and Air Force Small Business Innovation Research (SBIR) and Small Business Technology Transfer program awards (STTR), Cooperative Agreement Notices (CANs), Center Innovation Funds (CIFs), and other Internal Research and Development (IRaD) investment to develop many of the Spectre components.

Spectre is a 'dual-mode' propulsion system, with both chemical and electrospray thruster technology that feed from a common propellant tank. Dual-mode and multi-mode systems offer the best of both in one solution, with great flexibility for missions. Both high thrust chemical and high efficiency e-spray are enabling for cislunar, and other interplanetary SmallSat missions. Spectre is a pump-feed system that uses the Advanced Space Craft Energetic Non-Toxic (ASCENT) monopropellant formerly referred to as AF-M315E.

RESULTS/ACCOMPLISHMENTS

In August 2021, the Spectre team conducted the first integrated system-level 'FlatSat' test of a multi-mode propulsion system, demonstrating notional concept of operations (ConOps) functions. This test addressed important system-level design, integration, and operations questions. Highlights from the FlatSat testing include:

- Remote fill and refill of e-spray thrusters from a common tank.
- Use of electric pump to tailor pressure for chemical thruster inlet conditions.
- Concurrent refill of e-spray thruster while firing another (continuous operations).
- Technology Readiness Level (TRL) advancement from 2 to 4.
- Firing of a micro pump-fed chemical thruster.

SUMMARY

Spectre is managed by MSFC, with integration and test support from The Georgia Institute of Technology (Georgia Tech). The Spectre effort is jointly funded by the MSFC Chief Technologist, with support from the Air Force Research Laboratory and component contribution from both NASA and Air Force SBIR programs. Commercial partners include Espace Inc., Flight Works Inc., and Plasma Processes LLC. Academia partners include Georgia Tech and Massachusetts Intitue of Technology. The baseline system is intended for 12U CubeSat per NASA Standard. The project has entered the detailed design phase. MSFC will lead and manage the design, manufacturing, assembly, and testing of a dual-mode green propulsion system. A protoflight Spectre Propulsion System is planned to complete assembly and testing in early 2023.

PRINCIPAL INVESTIGATOR: Daniel Cavender

PARTNERS: Plasma Processes, LLC; Georgia Institute of Technology; Massachusetts Institute of Technology; Espace, Inc.

FUNDING ORGANIZATIONS: Cooperative Agreement Notice (CAN), Center Innovation Fund (CIF), Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR)

Advanced Design Tools for Electric Sail Propulsion Systems

OBJECTIVE: *To develop advanced computational tools for the design and optimization of electric sail spacecraft.*

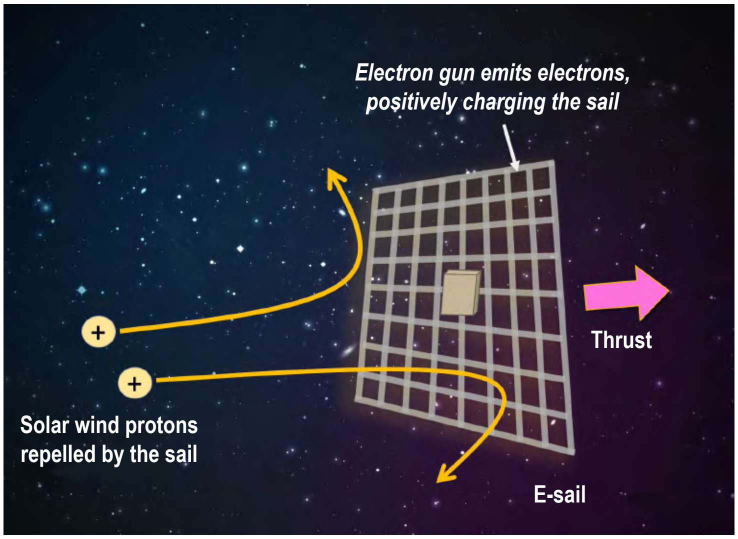


FIGURE 1. Schematic of an E-sail operation.

PROJECT GOAL/DESCRIPTION

The concept of electric solar wind sail, envisioned by Finnish space physicist Pekka Janhunen in 2004, is one of the few promising interplanetary propulsion technologies currently being explored at NASA. An electric sail, or E-sail, consists of an assembly of km-long, µm-thin metal tethers; photovoltaic elements providing electric power; and an electron gun. E-sails should be propelled exclusively by solar wind protons, which transfer their momentum to the spacecraft as they reflect off its tether mesh by a high positive potential created when electrons are emitted by the electron gun (fig. 1). Powered by the solar energy and driven by solar wind, E-sails have significant potential to become a high-priority space propulsion technology, as their cost is expected to be significantly lower and their lifetime is expected to be longer than those of competing propulsion systems. However, considerable challenges still stand between theory and deployment. With the focus on thruster propulsion, this work aims to overcome these challenges in order to provide a high-fidelity computational tool that will assist NASA scientists and engineers with the advancement of the technology from its current design stage to the operational prototype.

APPROACH/INNOVATION

Today's level of manufacturing technology provides a number of benefits, including the availability of µm-thin metal tethers; compact and energy efficient electron guns; and highly miniaturized advanced-risk machine computer systems, all offering the plausible path for E-sails to be prototyped and manufactured. For such a leap forward to be performed, however, one key element is missing: the reliable assessment of thruster performance during its in-flight operation.

The innovation of this project stems from the fact there is simply no available computational tool that can model the E-sail operation in a predictive manner. The key innovative elements that must be accounted for to successfully model an E-sail in flight are (i) positively-biased material immersed in a plasma, (ii) self-consistent modeling at a kinetic level, and (iii) multi-scale spatial and temporal nature of the problem at hand.

At the core of the computational tool being developed is the self-consistent 2D/3D particle-in-cell (PIC) approach to the solution of the plasmakinetic Boltzmann-Vlasov equations. It addresses a number of outstanding issues, such as external (source sheath) and internal (tether surface) boundary conditions;

spacecraft tether charging and floating potential; electron gun operation and a free-space cathode; and the development of a fluid electron model predictive of the full-scale plasma flow over an E-sail.

The primary development platform is Stanford University's PIC software Statistical Process Control (SPC), which will be leveraged by the Air Force multi-physics package Spacecraft Multi-Scale/Multi-Physics Universal Research Framework (SM/MURF), and our in-house experimental work that will supply thrust measurements under controlled and well-characterized laboratory conditions, and thus enable extensive validation of PIC models and algorithms.

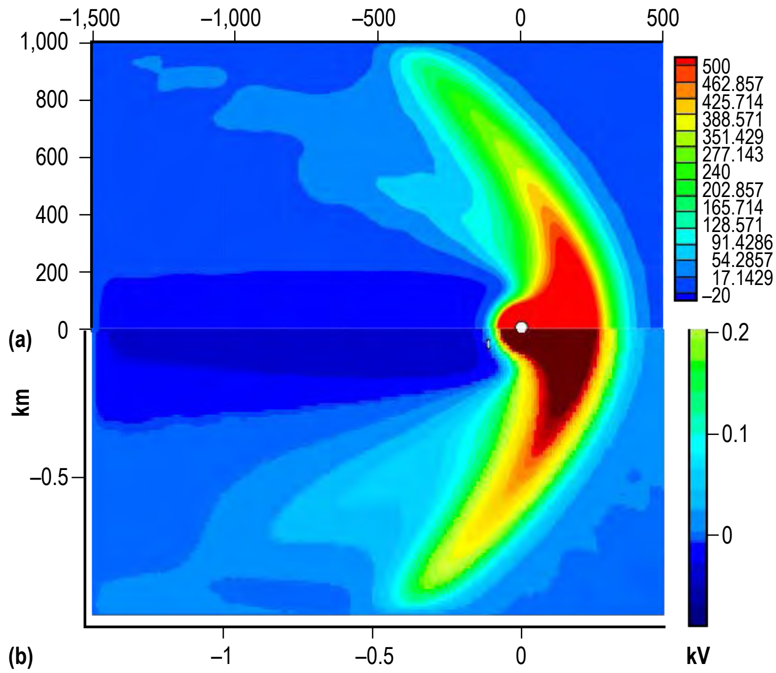


FIGURE 2. Potential fields over a tether; (a) our solution and (b) Janhunen's solution.

RESULTS/ACCOMPLISHMENTS

The first step of this work was the validation of the numerical models currently implemented in SPC and SM/MURF codes. The validation was focused on modeling of a well-studied, negatively biased cylindrical Langmuir probe immersed in an argon partially-ionized plasma and comparing computed probe currents with the Orbital Motion Limited (OML) theory and available experimental results. Good agreement was observed for full-PIC solutions with the OML theory for collisionless plasma, and with measurements for collisional cases. Conventional Boltzmann potential models have shown to predict the collisionless plasma well and predict the collisional plasma relatively poorly.

The second step was the implementation of Janhunen's 2015 electron model, which essentially provides the state-of-the-art E-sail thrust force assessment and replaces the self-consistent electron transport with a fluid model. Our results were shown to match very well the original Janhunen's results (fig. 2), but the model itself was found to qualitatively misrepresent the electron population inside the incident ion shock wave. These findings imply that the thrust force obtained by that model might significantly, up to an order of magnitude, underpredict the actual thrust force exerted by solar wind plasma on an E-sail spacecraft.

SUMMARY

Our computational study has shown that the state-of-the-art estimates of the thrust force on E-sails may, in fact, be drastically underpredicting the actual force. Based on these findings, the work now will focus on (i) the development of a high-fidelity plasma model that self-consistently accounts for the plasma-spacecraft interaction, and (ii) the validation of such a computational model using laboratory prototype experiments.

We expect the results of the work to have significant impact not only on the E-sail technology but also on future plasma-assisted spacecraft propulsion techniques. Collaboration with Air Force scientists is planned in these studies, as well as in other fields that rely on plasma physics, such as micro- and nanofabrication.

PRINCIPAL INVESTIGATORS: Sergey Gimelshein (Particle Matters Inc.), Ken Hara (Stanford University)

TECHNICAL MONITOR: Anthony M. DeStefano

FUNDING ORGANIZATION: Small Business Innovative Research (SBIR) Program

The Lunar Flashlight Propulsion System

OBJECTIVE: *To deliver a propulsion system for the Lunar Flashlight mission.*

PROJECT GOAL/DESCRIPTION

NASA's Marshall Space Flight Center (MSFC) and the Glenn Lightsey Research Group at The Georgia Institute of Technology (GT) co-developed the Lunar Flashlight Propulsion System (LFPS) for NASA's Jet Propulsion Laboratory (JPL) Lunar Flashlight mission. In less than 2 years, this team designed, built, and acceptance tested a novel, 'green' chemical propulsion system. That system was delivered to the Lunar Flashlight Project at JPL in May 2021. The LFPS will perform a lunar orbital insertion, where the spacecraft will begin its search for water-ice in the permanently shadowed lunar south pole craters.

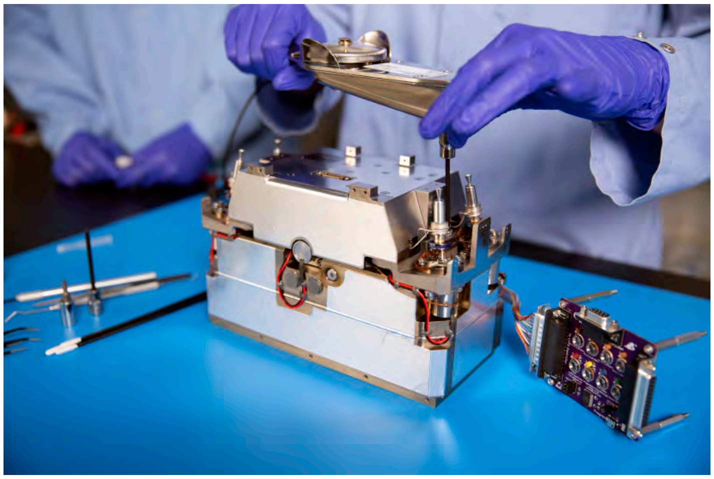


FIGURE 1. The Lunar Flashlight Propulsion System (LFPS) built by MSFC and Georgia Tech's Space Systems Design Lab (SSDL).

APPROACH/INNOVATION

The LFPS approach of using the Advanced Space Craft Energetic Non-Toxic (ASCENT) pump-feed monopropellant propulsion system significantly reduces hazards and enables the meeting of delivered-impulse requirements for the mission in the highly mass-, power-, and volume-constrained CubeSat configuration. ASCENT, formerly referred to as AF-M315E, provides relief from hazards via its reduced vapor pressure and enhances maneuver capability with increased energy density. Use of a pump, as opposed to the traditional pressure-fed approach, provides hazard relief by allowing the system to remain at a significantly reduced pressure during launch and deployment. It also enhances delivered performance with repeatable pulse performance. The use of ASCENT further provides hazard relief due to its low vapor pressure, low toxicity, and high stability. These features enable ease of handling during pre-flight operations. ASCENT propellant also enhances maneuver capability with increased energy density compared to other monopropellants (e.g., hydrazine).

RESULTS/ACCOMPLISHMENTS

MSFC delivered the propulsion system to JPL in early May 2021 to begin integration into the Lunar Flashlight spacecraft. The craft will return to MSFC for fueling before being transported to the launch vehicle. Once launched, the Lunar Flashlight will take roughly six months to reach the Moon using its propulsion system and insert the spacecraft into a polar orbit before beginning its two-month primary mission.

SUMMARY

The mission will demonstrate the ability to use powerful yet compact propulsive CubeSats for a variety of science missions on the Moon and across the solar system.

PRINCIPAL INVESTIGATOR: Daniel Cavender

PARTNERS: Plasma Processes, LLC; Flight Works, Inc.; Georgia Institute of Technology; Air Force Research Laboratory (AFRL)

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office

Additively Manufactured Propulsion E-pump Demonstrator (AMPed) Engine

OBJECTIVE: *The AMPed team aims to design, build, and test the first fully cryogenic electric pump-fed engine. The end goal is to demonstrate a battery-powered engine hot-fire.*

PROJECT GOAL/DESCRIPTION

Additively Manufactured Propulsion E-Pump Demonstrator (AMPed) is a 7500 lbf liquid oxygen (LOX)/liquid methane (LCH_4) electric pump-fed engine developed in-house at NASA Marshall Space Flight Center (MSFC). The effort includes several branches within the Engine/Propulsion (ER), Space Systems Engineering/Design (ES), and Testing (ET) departments and is currently funded by the Advanced Development Office (ADO). The engine utilizes high power electric motors powered by batteries to drive the propellant pumps. Recent improvements in battery technology have made electric cycle engines more competitive with traditional thermodynamic cycles at intermediate thrust classes (2,000–10,000 lbf) applicable to lander and small launch vehicle applications. The use of electric motors allows for direct pump speed control, which eliminates the need for turbines and complex engine throttling valves. AMPed also utilizes additive manufacturing processes for components such as the pump housings and thrust chamber assembly. The result is a simplified engine design with benefits to performance, cost, and development time.

APPROACH/INNOVATION

The AMPed team has been utilizing engine system modeling tools to determine engine performance and component requirements. The AMPed team has identified two primary areas in electric cycle engines that present the most significant challenges: cryogenic electric motors and high-performance batteries. These areas have been addressed by small, focused teams of NASA engineers working alongside industry partners to increase the Technology Readiness Level (TRL) of emerging technologies that fulfill the unique needs of this application.

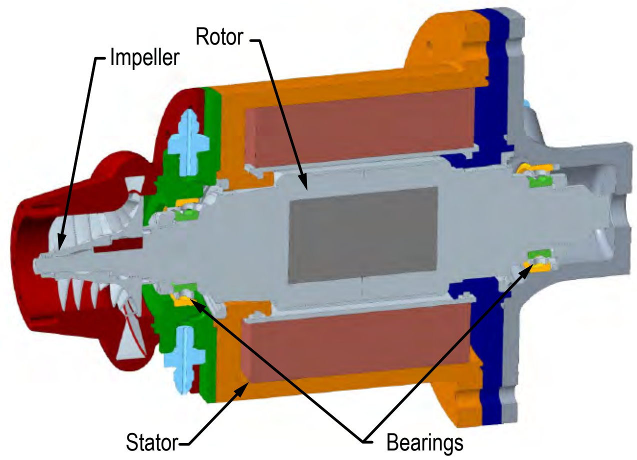


FIGURE 1. LOX pump cross-section.

ELECTRIC PUMPS AND CRYOGENIC MOTORS

The Propulsion System Department's Turbomachinery Group is consulting with internal and external electric motor experts to design high-efficiency electric pumps (epumps). Cryogenic epumps are rare, but those in operation usually cool bearings with the working fluid and ignore the efficiency gain in operating the motor at cryogenic temperatures. The engine will take advantage of LCH_4's cooling capacity to increase electric motor performance by optimizing secondary coolant flows. The team will mature this concept in FY22 by facing design challenges such as isolating the LOX pump environment, minimizing fluid in the motor airgap, and clocking with cryogenic commutation devices. The LOX and LCH_4 epump Preliminary Design Reviews (PDRs) will be key milestones of FY22. Future work will include

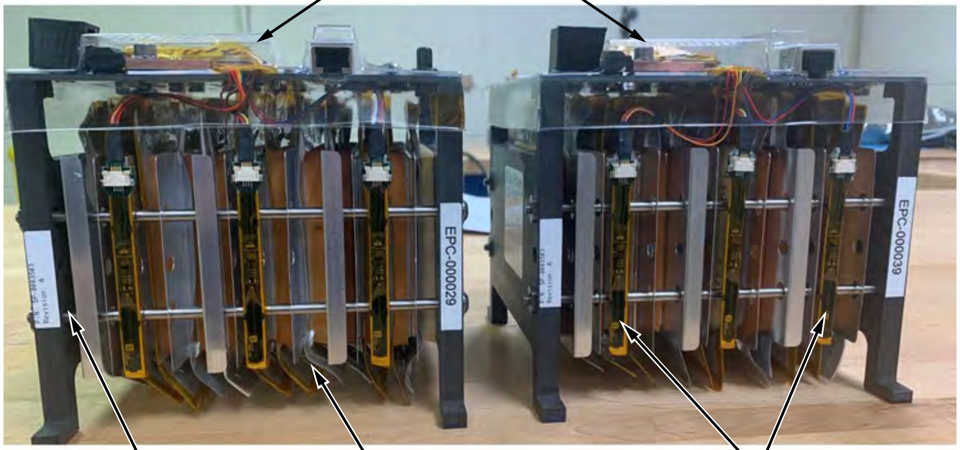


FIGURE 2. Sion Li-metal battery modules.

prototyping, critical analysis, manufacturing, and component-level motor and pump testing.

HIGH-PERFORMANCE BATTERIES

The battery is the largest driver of thrust-to-weight ratio in electric cycle engines. High discharge rates required for this application are driving the AMPed project to look beyond state-of-the-art lithium (Li)-ion batteries. The AMPed team worked with the Electrical Power Systems Branch (ES32) to procure and test Li-ion and novel Li-metal cells. Testing demonstrated that Li-metal cells offer a clear performance advantage over the Li-ion counterparts. The AMPed team is collaborating with industry partners to design and test a battery prototype with >90 kW power capabilities. Sion Power is developing rechargeable Li-metal cell technologies which provide numerous benefits compared to Li-ion cells. Li-metal cells have historically been single-use devices. This is because charging presented concerns for thermal runaway and dendrite growth. Dendrites are spike-shaped lithium deposits that grow on the anode surface during charging. These structures can pierce the separator and internally short the cell. Sion Power is developing the Licerion cell, an example of which is shown in figure 2, which uses novel electrolyte and anode materials to address these issues. Individual Licerion cells and small battery modules consisting of 12 cells were successfully tested at MSFC in 2021 and demonstrated excellent performance. Current estimates show that the battery mass could be cut by 50% compared to a Li-ion alternative. Rocket Lab, Aerojet Rocketdyne, and Dynetics have expressed interest in this battery work. The FY22 battery development objective is to build and test a >10 kW battery module integrated with a battery management system.

RESULTS/ACCOMPLISHMENTS

AMPed worked with ForeFront Engineering and Design to develop custom electric motors in 2020. The team traded many types of electric motors and picked 2-pole permanent magnet synchronous motors (PMSMs). The system's custom high-speed 30–50 kW electric motors (45,000 and 60,000 revolutions per minute (RPM)) were found to best operate at 240V by considering electric motor, inverter, and battery performance. Current models predict electric motor efficiency of 97%. It should be noted that these machines are relatively easy to scale for custom development. The Propulsion System Department's Turbomachinery Group designed a small 45,000 RPM LOX inducer and impeller under 2 in in diameter to achieve engine power balance requirements. Analysis of meanline and computational fluid dynamics data showed the design was so small that it fell out of certain 'rule of thumb' design correlations. These results have been anchored into new design software correlations and are being used in a redesign effort.

The AMPed team worked with the ES32 Power and Electrical Integration Branch to test several cell candidates at various discharge rates and temperatures in 2020. High current testing required a facility upgrade, so the AMPed project procured and installed a 200V/150A battery test system in MSFC's Bldg. 4487. The Licerion Li-metal candidate demonstrated a 450 Wh/kg specific energy compared to the 200–250 Wh/kg demonstrated by the Li-ion cells and was chosen as the primary candidate for the project. The Licerion battery module was tested at discharge rates as high as 120A and temperatures between 0 and 20 °C in a thermal chamber to characterize performance. AMPed obtained a full-scale battery pack concept that includes detailed integration hardware, a battery management system, and thermal management system interfaces. The data obtained were provided to interested parties at Johnson Space Center (JSC), Dynetics, and Rocket Lab.

SUMMARY

The design and operation of this type of engine is unprecedented for NASA. The AMPed team has made significant progress on component design, hardware testing, and engine cycle analysis during the past year. A physics-based thermo-fluid model of the engine system has been created to guide the engine development process. Collaborative efforts with industry partners have yielded useful sizing and performance data for components such as the motor, controller, and battery. The team has successfully completed the FY21 LOX pump design and battery test objectives. FY22 plans include LOX and LCH_4 pump PDR milestones and a fabrication of subscale battery modules that can be combined to create a full-scale battery.

PRINCIPAL INVESTIGATORS: Alber Douglawi and Zachary Standridge

PARTNERS: Sion Power Corporation, ForeFront Engineering and Design

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

OBJECTIVE: *To reduce design and production schedules while allowing for reduced parts, increased reliability, and significant mass reduction; creating a healthy American supply chain for large-scale, regeneratively-cooled liquid rocket engines.*

PROJECT GOAL/DESCRIPTION

The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project has developed and advanced large-scale and lightweight regeneratively-cooled liquid rocket engine components utilizing multimetallic freeform additive manufacturing (AM), composite overwrap techniques, and advancing AM analysis capabilities. All of these technologies combined are being implemented to significantly reduce design and fabrication cycles. RAMPT is reducing the design, fabrication, and assembly schedules while allowing for reduced parts, increased reliability, significant weight reduction and the creation of a healthy American supply chain.

The three primary goals of the RAMPT project are to: (1) develop additive and advanced manufacturing methods and design processes that enable new regeneratively-cooled thrust chamber assembly (TCA) technology, focused on large-scale TCAs; (2) identify and optimize additive manufacturing design and fabrication processes that lead to reduction of production lead times and analysis life cycle for large-scale TCAs; (3) engage manufacturing community organizations in the development effort and facilitate infusion of technology into the commercial industry through public-private partnership.

APPROACH/INNOVATION

The RAMPT project has advanced the following technical areas: (1) laser powder directed energy deposition (LP-DED) freeform AM techniques to fabricate an integrated regeneratively-cooled channel wall nozzle structure; (2) composite overwrap techniques to significantly reduce mass and provide structural capability for a large TCA; (3) bimetallic and multimetallic AM deposition processes, including copper-alloy to superalloy transitions to optimize material performance; (4) advanced modeling and simulations for large-scale deposition processes to obtain optimal property predictions and material designs, and to develop 'smart' tool-paths to reduce distortion and provide acceptable components; and (5) integrated regeneratively-cooled combustion chamber and nozzle design tool to significantly reduce design cycles and take full advantage of additive technologies.

NASA has engaged Auburn University under contract to develop and operate the RAMPT public-private partnership with over 13 specialty manufacturing vendors to enable a long-term supply chain available to the government and the commercial rocket industry. This allows for cost sharing from industry and rapid infusion of processes throughout the supply chain.

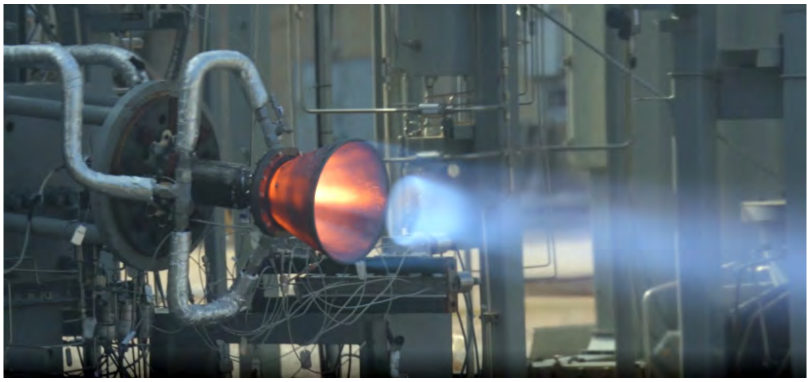


FIGURE 1. 7k-lbf AM GRCop–42 chamber with composite overwrap structural jacket completed testing at MSFC Test Stand 115.

RESULTS/ACCOMPLISHMENTS

In a few short years, the RAMPT project has matured manufacturing processes and integration of various scales of hardware through hot-fire testing. The progression of hardware scale allowed for incorporating early lessons learned into larger scale hardware with increasing chamber pressures as thermal and structural loads become more challenging. Hot-fire testing was completed on 2k-lbf and 7k-lbf thrust-class de-coupled hardware, which included composite overwrap chambers and an LP-DED nozzle with integral channels. This demonstrated feasibility with temperatures up to 450 °F on the composite overwrap. De-coupled hardware has been developed for the 40k-lbf thrust classes and will complete hot-fire testing in FY22. The 2k-lbf, 7k-lbf, and 40k-lbf coupled hardware are currently in work as of this report.

Selection of composite material systems and winding, overwrapping, and braiding strategies for the 7k-lbf and 40k-lbf thrust-class hardware have evolved under RAMPT. In addition, bimetallic AM material characterization studies are maturing to compare gas cold spray, LP-DED and laser hot wire DED cladding processes for manifolds, structural jackets, and coupled chambers/nozzles. These processes all have different advantages and disadvantages, including heat input, potential for distortion, ability to deposit on complex surfaces, material overspray/usage, bonding strength, supply chain, and feedstock availability.

Composite manufacturing throughout the RAMPT project has proceeded under a public-private partnership with Auburn University and commercial partners with the goal of maturing design and manufacturing technology within the industry. Throughout RAMPT, many lessons have been documented with respect to composite overwrap as a structural jacket for a TCA operating in harsh environments. Developments include processing techniques and resin advancements for filament winding and braiding.

FIGURE 2. Ultra-large DED nozzle (58 in × 72 in) with integrated cooling channels that is ≈65% scale of the SLS Core Stage RS-25 engine nozzle. Build time: 90 days.

A significant accomplishment of RAMPT has been the ability to demonstrate large regeneratively-cooled channel wall nozzle structures using LP-DED. The team produced one of the largest AM nozzles NASA has printed, measuring 58 in in diameter and standing 72 in tall, with fully integrated cooling channels. This nozzle (fig.2) was 65% scale of the Space Launch System (SLS) Core Stage RS-25 engine and was fabricated using NASA HR-1 in 90 days. A full-scale LP-DED nozzle liner (with no channels) was also fabricated measuring 96 in in diameter and standing 111 in tall. Additional development work is ongoing, which NASA is currently working with commercial space partners and the SLS program.

Simulation modeling played a key role in the deposition of the full-scale LP-DED nozzle liner to inform build strategies that control distortion during fabrication. As part of this development, computational modeling and validation to predict residual stresses and distortion in additive parts were compared across multiple simulation codes. Many of these simulations are limited to monolithic materials, although bimetallic is being studied. The bimetallic modeling will require additional future development efforts to fully evolve.

SUMMARY

RAMPT impacts all phases of the engine TCA life cycle by addressing the component in regeneratively-cooled rocket engines with the longest lead time, highest cost, and heaviest weight. The LP-DED process has completed a series of large-scale manufacturing demonstrators and successfully completed hot-fire test hardware. Various composite overwrap chamber configurations have evolved and 7k-lbf hardware has been tested. The bimetallic technology is advancing through processes development and mechanical testing, and computation modeling is aiding critical manufacturing process decisions.

PRINCIPAL INVESTIGATORS: Paul Gradl, Chris Protz

PROJECT MANAGER: John Fikes

PARTNER: Auburn University

FUNDING ORGANIZATION: Game Changing Development (GCD) Program

FOR MORE INFORMATION: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/RAMPT/
https://doi.org/10.2514/6.2021-3236
https://doi.org/10.2514/6.2021-3231
https://arc.aiaa.org/doi/10.2514/6.2021-3233
https://arc.aiaa.org/doi/10.2514/6.2021-3655

Liquid-Liquid Integrated Reaction Control System and Compressed Gas

OBJECTIVE: *The Liquid-Liquid Integrated Reaction Control System will demonstrate the feasibility of using a pump-fed recirculation loop to feed reaction control system thrusters, and the Compressed Gas System will demonstrate capturing, compressing, and storing boiloff propellant.*

PROJECT GOAL/DESCRIPTION

NASA's future exploration missions will require the use of cryogenic propellants to meet mission performance needs. While this need is driven primarily by the performance requirements of the main propulsion system, utilizing those same cryogenic fluids for auxiliary propulsion systems can have performance benefits and simplify design of the vehicle. The Integrated Reaction Control System (IRCS) and Compressed Gas System (CGS) will perform proof-of-concept tests to demonstrate the feasibility of the systems to provide these functions. The Liquid-Liquid IRCS system will demonstrate the ability to maintain liquid quality propellant at the thruster inlet by means of a pump-fed manifold, and the CGS will demonstrate capturing the boiloff from a cryogenic tank using a two-compressor system.

APPROACH/INNOVATION

The Liquid-Liquid IRCS system is novel in that it uses a pump-fed manifold controlled by a pressure regulating device to maintain liquid propellant at a fixed pressure within the manifold. Previous Integrated Reaction (IR) system concepts usually involve a gas or a two-phase propellant being delivered to the thruster inlet. The use of the pump-fed manifold enables a single-phase liquid to be supplied instead, allowing for higher mass flowrates to the thruster and more controlled inlet conditions.

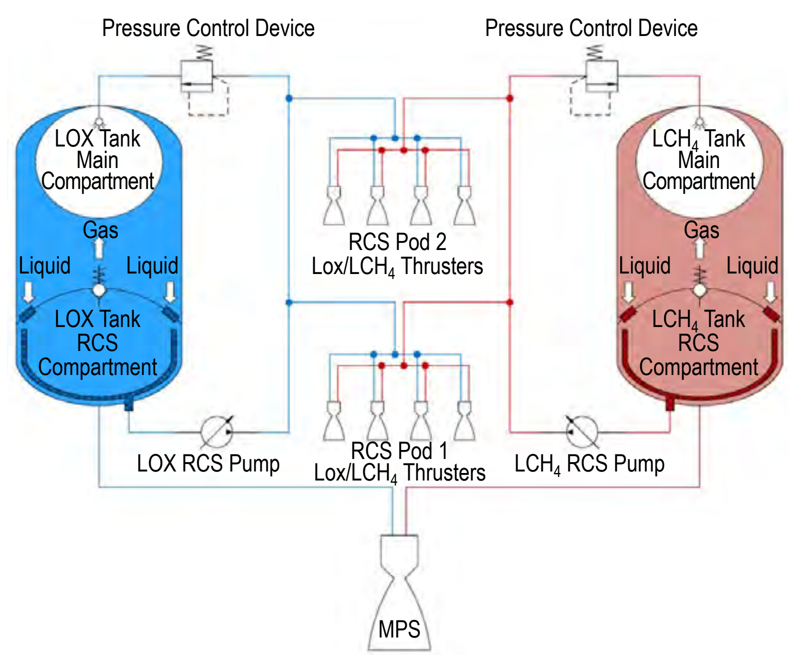


FIGURE 1. Concept Schematic of IRCS.

The CGS stores cryogenic boiloff to be used for pressurization, gas-phase reaction control thrusters, or other auxiliary fluid systems. By using the boiloff, additional mass for carrying auxiliary fluids can be eliminated. Other proposed systems involve heating liquid propellant to form a gas. This system, instead, relies on the natural production of gas from boiloff in main propulsion systems, removing a combustion device from the system.

RESULTS/ACCOMPLISHMENTS

In FY21, the IRCS and CGS team successfully built and tested both proof-of-concept systems. The IRCS testbed was used for over 20 tests, varying flowrates through the recirculation line, number of active thruster simulators, and duty cycle of pulsing thruster duty cycle. The system successfully maintained acceptable liquid inlet conditions in the inlet during periods of active operation. In addition, heat loads applied to the tank were less than expected, addressing a key technical hurdle for system feasibility. However, the system was not able to maintain chill-in for the thrusters between active use cases. Future designs will rework the cooling design to better maintain chill in the thruster.

FIGURE 2. IRCS Testbed simulating firing using liquid nitrogen during testing.

The CGS was able to meet the test objectives of taking cold, sub-atmospheric pressure gas from the vent of a cryogenic tank and compressing. While successful, the performance of the system was lower than expected, taking longer to compress, and reaching a lower final pressure.

In addition to demonstrating feasibility, the tests provided lessons learned for the component requirements necessary for these complex systems.

SUMMARY

The IRCS and CGS test programs demonstrated the feasibility of two novel fluid systems that would enable the use of cryogenic propellant for reaction control and auxiliary fluid system. Both systems met their primary test objectives, although the system performance was better than expected in some cases and worse in others. Lessons learned and data from this test series will be applied to new component developments that can enable these systems for future missions.

PRINCIPAL INVESTIGATOR: Cameron Hines

FUNDING ORGANIZATION: Game Changing Development (GCD) Program

Nuclear Thermal Propulsion (NTP)

OBJECTIVE: *The development of a low enriched uranium (LEU) NTP system is the most promising advanced in-space propulsion option for a crewed missions to Mars. NTP offers a safe, affordable option for an in-space transportation architecture that enables faster trip times, safeguards astronaut health, and provides abort scenarios not available from other propulsion architectures. NTP is also being developed for Department of Defense applications.*

PROJECT GOAL/DESCRIPTION

NASA's history with nuclear thermal propulsion (NTP) technology began in the earliest days of the Agency in 1958. An NTP system offers significant advantages over other propulsion architectures for human Mars missions and in cislunar space. NTP could also enable highly advanced science and exploration missions, and power systems derived from NTP could enable a power-rich environment anywhere in the solar system (or beyond).

FIGURE 1. SNP stage.

The current Space Nuclear Propulsion (SNP) project objective is to develop a subscale NTP engine using low enriched uranium (LEU) fuel that is scalable to the Mars mission requirements for in-space propulsion. In support of this objective, additional tasks are underway to determine the best approach of accomplishing a system demonstration and to identify a mitigation path for compliance with testing and launch regulatory requirements. NTP concepts under consideration all readily meet the launch approval requirements set forth in National Security Presidential Memorandum (NSPM)-20 "Launch of Spacecraft Containing Space Nuclear Systems."

APPROACH/INNOVATION

The use of LEU offers potential advantages for a nuclear propulsion program that includes less burdensome security regulations, similar to those for a university research reactor. The use of LEU-based fuels also enables the development effort to partner with industry and academia. The project is focused on the technology maturation of a fuel composition that could be leveraged by a point-of-departure subscale engine reference design baseline. In concert with the in-house fuel development and engine design evolution, a competitive procurement for a reactor design and development activity has been completed.

One of the challenges to NTP development is maturing the technologies for fabrication and test of the fuel composition and element design that can tolerate the combined environments predicted in the NTP reactor core, which significantly exceeds those of commercial power reactors. The project is pursuing a multifaceted approach with government partners, industry, and universities to develop technologies for LEU NTP systems.

Tests of fuel samples are being performed in multiple test facilities that contribute unique separate- and combined-effects exposure to the samples, including the Marshall Space Flight Center (MSFC) Compact Fuel Element Tester (CFEET), the MSFC Nuclear Thermal Rocket Element Environment Simulator (NTREES), the Idaho National Labo-

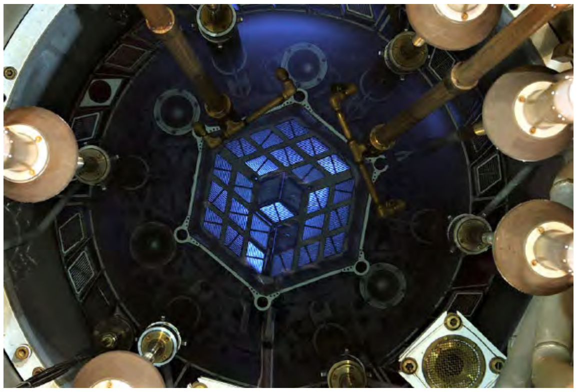


FIGURE 2. MIT NRL test facility.

ratory (INL) Transient Reactor Test (TREAT) Facility, and the Massachusetts Institute of Technology (MIT) Nuclear Reactor Laboratory (NRL).

RESULTS/ACCOMPLISHMENTS

The SNP project successfully completed test campaigns in the INL TREAT reactor and has begun detailed preparation for the more sophisticated Sirius 4 TREAT test in 2023 that will include flowing hydrogen within the test article. In concert with the Sirius tests, fuel element and material tests were conducted in the NTREES facility to verify material survivability and element design efficacy in a high-temperature hydrogen environment and to provide additional insight and data prior to nuclear testing. Fuel particle tests were conducted at the MIT NRL and work was initiated to provide additional test capability at MIT, taking advantage of the unique capabilities of the MIT reactor design. Research was initiated at several universities on high-performance NTP systems, with the goal of enabling round-trip human Mars mission times of less than 15 months while still allowing for a minimum stay time of 2 months in Mars' vicinity. Fuel and moderator development activities conducted by SNP were designed to provide immediate risk reduction contributions and to add to the collective body of knowledge that can be leveraged in development of any space fission system. In addition, significant progress has been made with system power balance and thermal modeling, NTP ground test options, and non-nuclear engine components, including irradiation tests of various non-metal materials. Finally, the SNP project successfully awarded three industry contracts to pursue NTP reactor designs in support of the eventual development of affordable, useful NTP systems.

SUMMARY

NTP is directly relevant to the Agency's vision, mission, and long-term goal of expanding human presence into the solar system and the surface of Mars. As missions aim for targets farther out into the solar system, nuclear propulsion may offer the only viable technological option for extending the reach of exploration, where solar panels can no longer provide sufficient energy and chemical propulsion

FIGURE 3. Sirius-2a cermet sample fabricated at MSFC.

would require a prohibitively high mass of propellant and/or prohibitively long trip times. NTP provides the fastest trip time of all currently-obtainable advanced propulsion systems. Fast trip times will safeguard astronaut health by reducing exposure to zero gravity and cosmic radiation. Reduced round-trip travel time also reduces risks associated with reliability uncertainties inherent in complex systems, as well as those associated with life-limited, mission-critical systems. NTP also enables mission abort options not available from other propulsion architectures for human Mars missions.

PROJECT MANAGER: Dayna Ise

PRINCIPAL INVESTIGATOR: Michael G. Houts

FUNDING ORGANIZATION: Technology Development Missions (TDM) Program

FOR MORE INFORMATION:
https://www.nasa.gov/mission_pages/tdm/main/index.html

Solar Cruiser

OBJECTIVE: *Solar Cruiser is a spaceflight mission to mature solar sail propulsion to enable near-term, high-priority science missions and at destinations as defined in the NASA Solar and Space Physics Decadal Survey.*

PROJECT GOAL/DESCRIPTION

Solar Cruiser is a pathfinder mission sponsored by the Heliophysics Division's Solar Terrestrial Probes Program that will enable near-term missions to address important science questions about the Sun, its interaction with Earth, and other elements of the heliosphere. Solar Cruiser will demonstrate how solar sail propulsion can enable spacecraft to collect observations from novel vantage points that are difficult to reach and sustain. Specifically, Solar Cruiser will maintain a position sunward of Lagrange point L1—the position where Earth's and the Sun's gravity are balanced along the Sun-Earth line. Solar Cruiser will also demonstrate technologies that will enable future missions to improve space-weather monitoring, prediction, and science.

Solar sails use large, highly reflective, lightweight material that reflects sunlight to propel a spacecraft. The continuous photon pressure from the Sun's rays provides thrust with no need for the heavy, expendable propellants employed by conventional chemical and electric propulsion systems that limit mission lifetime and observation locations. Solar Cruiser will demonstrate the ability of solar sails to enable missions to observe the solar environment from unique vantage points of interest to Heliophysics science, including sustained station-keeping sunward of L1. Monitoring the Sun at this orbital location is of interest not only to NASA scientists, but also to support human spaceflight crew safety and health; the National Oceanic and Atmospheric Administration (NOAA); and the Department of Defense. Solar Cruiser will also demonstrate the capability to obtain sustained in-situ Earth magnetotail measurements and the ability to achieve and maintain a high-inclination solar orbit—a capability which future missions to image the polar regions of the Sun will require.

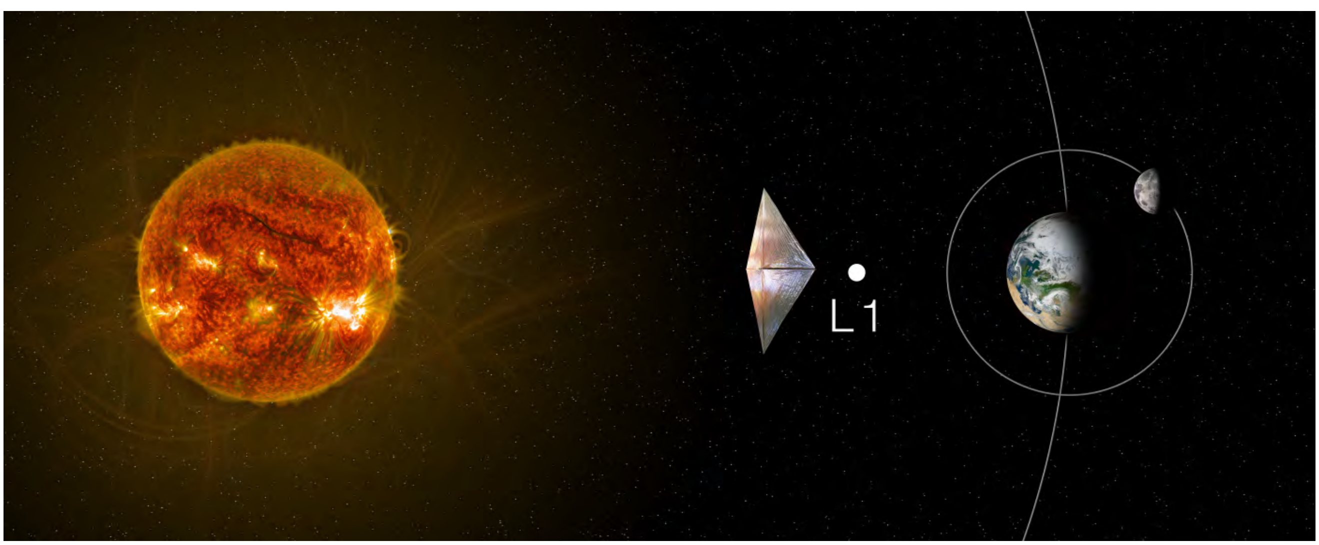


FIGURE 1. Solar Cruiser will use a solar sail to cruise past Sun-Earth L1 and demonstrate a solar sail's capability to fly a non-Keplerian trajectory.

APPROACH/INNOVATION

Solar Cruiser will fly a large, four-quadrant solar sail on a ten-month demonstration mission. Solar Cruiser includes the largest sail ever flown—a 1,653 m2, 2.5-µm-thick reflective sail that is thinner than a human hair. Solar Cruiser also includes four 29.5 m, lightweight, composite booms to deploy the sail; embedded thin film photovoltaics to demonstrate a new method of power generation; and embedded Reflective Control Devices (RCDs) that will help keep the sail stable. The sail membrane is manufactured using a thin-film polyimide (clear polymer 1, or CP1) coated with aluminum to make it reflective. The sail will be deployed and tensioned using composite Triangular, Rollable and Compressible (TRAC™) booms. These extremely long booms have a triangular cross-section that can be forced flat, enabling them to be rolled onto a spool for stowage.

Solar Cruiser will use an Active Mass Translation (AMT) device originally developed by MSFC for the NEA Scout mission to actively adjust the spacecraft center of (light) pressure relative to its center of mass to keep the sail stable and to support steering and navigation. In addition, RCDs, composed of a thin film that can be switched from reflective to transmissive with an applied voltage, will contribute to maintaining the sail's stability during flight. Solar Cruiser will also demonstrate the use of thin-film photovoltaic cells embedded in the sail to generate electrical power.

RESULTS/ACCOMPLISHMENTS

Key milestones achieved this year include a successful Systems Requirements Review and the start of fabrication of a full-scale quadrant engineering development unit. Prototype full-scale composite booms, sail deployer, and active mass translator, as well a functional photovoltaic and RCD membranes were fabricated and are being tested.

FIGURE 2. Four one-quarter scale composite booms were built and deployed from a prototype sail deployer.

SUMMARY

Solar Cruiser is scheduled for launch in 2025. Once it successfully demonstrates these technologies, solar sail propulsion using large, high-performance sails will be available for future science missions, providing a new capability for NASA and the nation.

PRINCIPAL INVESTIGATOR: Les Johnson

PARTNERS: Ball Aerospace; Roccor, Inc.

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Characterizing the Performance of Ultra-High Temperature Ceramic Fuels for Nuclear Thermal Propulsion Technology

OBJECTIVE: *To perform thermal and mechanical property measurements of cermet fuels.*

PROJECT GOAL/DESCRIPTION

The development and successful flight of a nuclear thermal propulsion (NTP) system is, in part, upon the characteristics of the nuclear fuel and its ability to survive the high temperature hydrogen environment of the engine. While there are many challenges to be addressed in regard to NTP, fuel development lies at its core. In order to develop and select the highest-performing fuel and the associated fabrication processes, various fuel forms (e.g., materials and their states) need to be characterized in regard to their behavior in a hot hydrogen environment. Nuclear, thermal, and fluid models all play a part in understanding the fuel behavior in the context of this characterization effort. However, there is a lack of material property data at NTP-relative temperatures (2,500 K to 3,000 K) due to the nature of the materials and the limitations of measurement equipment. The goal of this work is to empirically measure thermal and mechanical material properties at temperatures as close as possible, given equipment limitations, to the engine environment. This work is ongoing and the results to date are discussed below.

APPROACH/INNOVATION

The goal of this work is to gather thermal and mechanical properties of cermet nuclear fuels relevant to NTP. These properties include thermal diffusivity/conductivity, coefficient of thermal expansion, heat capacity, and four point flexure tests for mechanical testing at elevated temperatures. Material property measurement of these materials provides unique challenges given the requirements for contamination control. Additionally, the temperature range of relevance to NTP is extremely high (2,500 K to 3,000 K) and most equipment is not capable of reaching this temperature range due to material interactions of the equipment with the test specimen and other constraints. Data available for the properties of NTP-relevant nuclear fuels is limited in literature for these reasons. This work began with measurements of a surrogate material (MoWHfN) and will proceed with cermet fuel (MoWdUN) upon completion of machining, which has been delayed due to machining restrictions in regard to nuclear material. This work will contribute to the physical models and fabrication efforts underway to develop a nuclear thermal engine. Follow-on work will likely involve the measurement of material properties of other fuel forms of interest to NTP.

RESULTS/ACCOMPLISHMENTS

To date, thermal properties of MoWHfN have been measured. Billets of test material were prepared by direct current sintering and test geometries machined from sintered billets. The materials tested were 60% by volume cermet in a matrix of 30% by weight tungsten/70% by weight molybdenum.

Thermal diffusivity measurements were taken from 200 to 1,400 °C using the laser flash technique. Specimens were coated in carbon to improve laser absorption and emission. Although this improved the laser flash technique, evidence was seen of a carbide reaction layer formation, influencing results. These results can be seen in figure 1. Dilatometry measurements of the coefficient of thermal expansion were performed and are shown in figure 2. The average values fall between the typical values for the ceramic and metal matrix. Differential scanning calorimetry curves and four-point flexure bar tests and analysis of the surrogate material are ongoing. Material property measurement of the cermet fuel, MoWdUN, is expected to proceed first quarter of FY22, once machined specimens are completed at Idaho National Laboratories.

SUMMARY

This work seeks to provide the material properties through experimental measurements to temperatures as close as possible to NTP relevant levels needed to improve model predictions of engine operation, as well as to inform fabrication and fuel form decisions. Some initial data has been collected on surrogate fuel that will guide models of early surrogate fuel element tests. Follow-on cermet fuel property measurements, as well as future projects measuring material properties of other fuel forms, are critical to understanding fuel behavior, fabrication, design, and overall engine development.

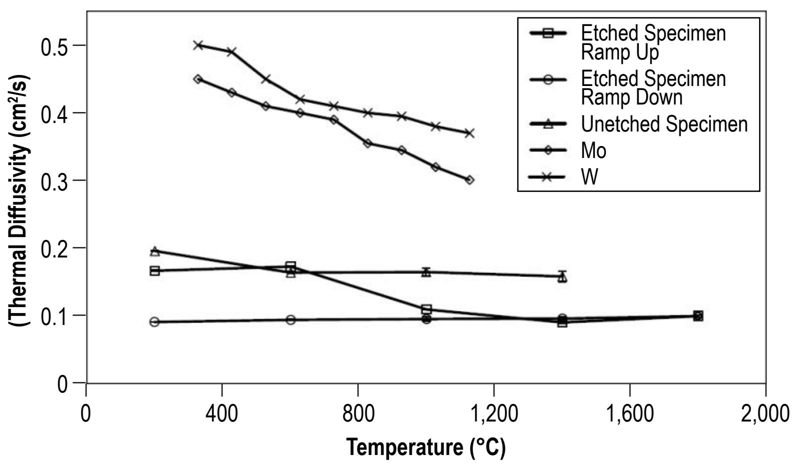


FIGURE 1. Laser flash thermal diffusivity measurements of MoWHfN.

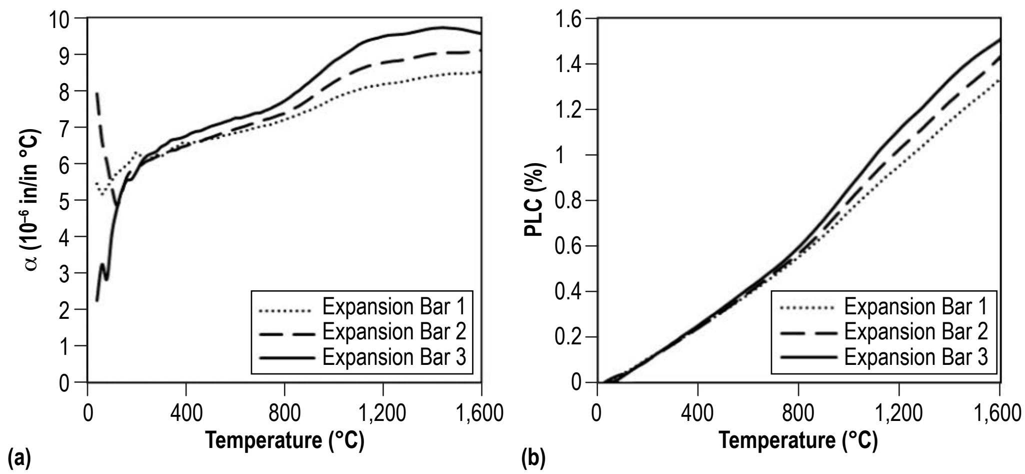


FIGURE 2. Coefficient of (a) thermal expansion and (b) percent linear change.

PRINCIPAL INVESTIGATORS: Dr. Joseph Graham (Missouri S&T), Brian Taylor (NASA)

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

TA02:

Flight Computing and Avionics

Wireless SmallSat Interface Technology

OBJECTIVE: *To develop wireless interface methods to support rapid mission integration and post-deployment reconfigurability.*

PROJECT GOAL/DESCRIPTION

Rowan University (RU) and NASA Marshall Space Flight Center (MSFC) partnered to develop wireless means for intra-satellite communication. The popularity of the small satellite (SmallSat) format has rapidly expanded over the past 20 years. Users range from NASA missions, to the private sector and educational institutions, including universities and K-12 students. One of the many challenges of SmallSat architectures is the interconnection of multiple subsystems, including power, communication, guidance/navigation/control, data handling, payload, and others. Each subsystem is connected using a combination of point-to-point and backplane wiring techniques. Advantages of direct wiring include low power consumption, low latency, and relative simplicity. However, disadvantages include wiring mass, wiring volume, connector volume, and often tedious assembly techniques that make later changes problematic and prone to maintenance-induced errors. Methods offering reduced interconnect complexity were sought to lower mass and simplify integration.

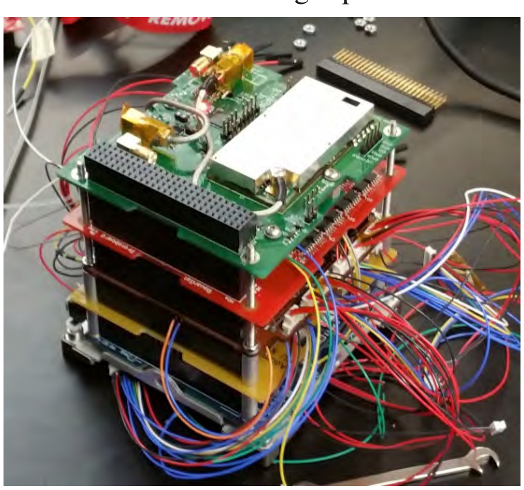


FIGURE 1. Example of current typical small satellite wiring.

The goal of the project was to evaluate wireless alternatives that could support substantial portions of the interconnect problem. Using a prior SmallSat design based largely on the Pumpkin Space Systems ensemble, wireless module-module communication alternatives were tested for data and control exchanges.

FIGURE 2. BLE intra-spacecraft prototype.

Power is still provided via hard wiring. Key performance metrics include delay, throughput, power, and error rate. The volume and cost of the approach was also evaluated. Demonstration at a TRL6 level was sought including testing in representative thermal/vacuum conditions. Future work will mature the technology to TRL9 and commercialize the resulting SmallSat wireless technique.

APPROACH/INNOVATION

Many wireless standards were available to evaluate including Bluetooth (BT), Bluetooth low-energy (BLE), Zigbee, WiFi, long-range wide area networks (LoRa WAN), and others. Among the key performance metrics that informed the down-select process to BLE are latency, throughput, power, and cost. The evalu-

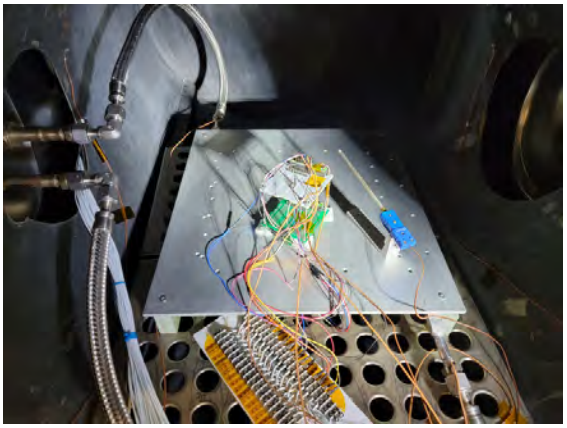


FIGURE 3. Intra-spacecraft wireless system in the thermal/vacuum test chamber.

ation process included measurements of latency, throughput, power, and packet error rate (PER). The evaluation began using commercial off-the-shelf (COTS) nRF52833 evaluation boards. Once initial test procedures were established and preliminary results achieved, custom modules were developed for the second phase of testing, which included use of MSFC testing facilities.

RESULTS/ACCOMPLISHMENTS

Latency was measured by using a 100 MB test file transferred between two nRF52833 targets at a transmit power level of –4 dBm with a separation distance of 10 cm. A BLE sniffer analyzed the packet stream to determine average latency, which was found to be 3.2 ms.

Throughput was determined by finding the average bit rate achieved during the transfer of the 100 MB test file. Using the distance and transmit power levels, a throughput of 1.2 Mbps was achieved.

Power consumption was determined using an available nRF52833 power profiler. Idle consumption was found to be 2.8 mW; power during active transmission was 48.2 mW.

PER was estimated by comparing the total number of packets sent to the received packets that had a valid cyclic redundancy check (CRC). For the same distance and transmit power levels, the PER was found to be 98.1%.

Each of these metrics was also completed in a thermal vacuum chamber to test the integrity and operability in an orbital-like environment. Initial analysis shows that there is no correlation between throughput and PER with the low pressure and varying temperature of a space environment. While in the thermal vacuum chamber, throughput varied from 1.223 Mbps to 1.336 Mbps and PER varied from 0% to 0.15%.

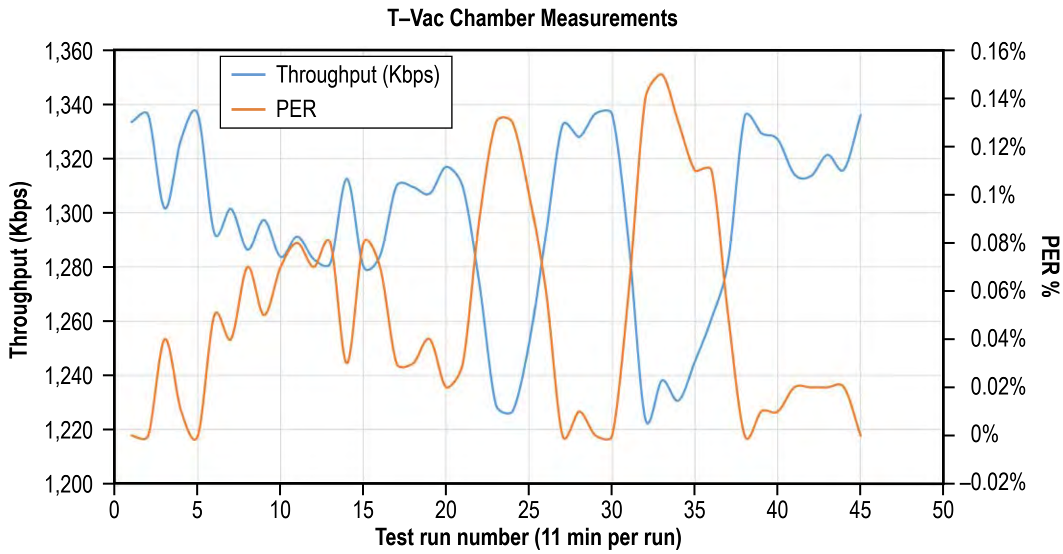


FIGURE 4. Thermal/Vacuum test data.

Final prototype design for the BLE integration board was designed to encompass the area on the boards that would normally be taken up with the PC104 header, 66.7 mm × 10.2 mm. The resulting height was reduced by almost half, from 10.85 mm to 5.75 mm, with room for further reductions in all dimensions. The result of this reduction allows for each subsystem board to have vertical movement of 5.75 mm, instead of the ridged spacing of the header system. This allows for more diverse board designs, orientations, and center of mass adjustments using board placement rather than adding balancing weights.

Major tasks completed include:

- Evaluated readily available wireless standards offering potential for wireless SmallSat application.
- Completed suite of evaluation tests for selected BLE technology.
- Provided final report detailing the methods and results.
- Created multiple prototype BLE modules with working data transfer software.

SUMMARY

The successful demonstration of wireless alternatives to conventional hard-wired interconnect suggests a number of advantages useful to future SmallSat design:

- Reduced integration time by simplifying module interconnection.
- Reduced interface mass and volume.
- Supports post-deployment reconfiguration.
- Facilitates integration of wireless sensors.
- May improve reliability by supporting bypass routing of failed modules.

PRINCIPAL INVESTIGATOR: Sangho Shin, RU

TECHNICAL LEAD: Darren Boyd

PARTNERS: Charles Vaughan, Marshall Space Flight Center; Triad RF Systems (Patrick Sherlock)

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

TA03:

Aerospace Power and Energy Storage

The Lightweight Integrated Solar Array and anTenna (LISA-T) Pathfinder Technology Demonstrator (PTD)

OBJECTIVE: *To demonstrate the deployment, operation, and environmental survivability of the LISA-T power generation and communication array in a representative operational environment.*

PROJECT GOAL/DESCRIPTION

Satellite miniaturization continues to create lower-cost, faster-paced, and higher-risk-tolerant options for space missions. Small spacecraft continue to grow in popularity and are becoming of interest to scientific, exploratory, and commercial missions alike. The large body of research and development within government, academia, and industry has greatly advanced small spacecraft technologies and, as a result, mission capabilities. However, electrical power systems have not commensurately increased in capability, creating a bottleneck in bus design and, ultimately, payload capability. This is driving the need for advanced power generation, storage, and distribution designs. The Lightweight Integrated Solar Array and anTenna (LISA-T) is being developed, in partnership with NeXolve Holding, LLC in Huntsville, AL, to fill the power generation technology gap.

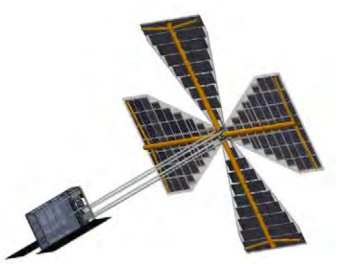
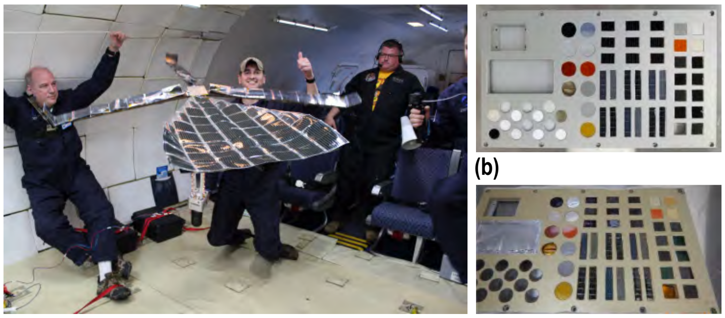


FIGURE 1. LISA-T PTD mission configuration. LISA-T array shown deployed from the 6U host CubeSat bus.

LISA-T provides a compact, lightweight, efficient, and affordable power generation system with an integrated antenna for small spacecraft missions. LISA-T generates >300% more power per mass and volume than state of the art options, vastly improving electrical power availability on small spacecraft. The technology will enable both highly capable, near-Earth small spacecraft missions, as well as the capability for small spacecraft to operate deeper into space than currently possible. Ultimately, this will usher in new, low-cost options for the nation to execute science applications such as space weather monitoring concepts, national defense applications such as on-demand battlefield monitoring, as well as small spacecraft flagship mission support such as communication relays or ancillary spacecraft to capture additional science during larger missions.

To date, LISA-T has been developed through technology readiness level (TRL) 6. Prototype arrays have been fabricated and tested in a comprehensive set of relevant space environments. Material and solar cell samples have been flown on the International Space Station, and mechanical deployments have been completed in simulated micro-gravity on parabolic aircraft flight (the so-called 'vomit comet'). To prepare the array for mission infusion and ubiquitous use, an in-space technology demonstration is currently being prepared. The LISA-T Pathfinder Technology Demonstration (PTD), seen in figure 1, is a payload comprising a LISA-T array along with supporting electronics, data collection systems, and other hardware that will fly on a 6U CubeSat as part of NASA's Small Spacecraft PTD series of rapid demonstration missions. LISA-T PTD will demonstrate the deployment, operation, and environmental survivability of LISA-T in a low Earth orbit. The mission will prove out the LISA-T technology, achieving TRL7, and ensuring the power generation array is ready for mission designers to take advantage of the >300% higher power generation for small spacecraft.



(a) (b) (c)

FIGURE 2. (a) LISA-T Zero-G successful simulated weightlessness deployment test. LISA-T shown deployed on final parabola, without gravity offloading, supporting itself in weightlessness. LISA-T Space Station space exposure plate; (b) pre and (c) post flight.

APPROACH/INNOVATION

To fill the technology gap, LISA-T utilizes thin-film materials to do more from less. The use of thin-film-based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option; however, the materials, cells, and deployment systems have not been available to make them a reality. Thinner materials yield both mass and volume savings, enabling more power to be generated from the same mass and volume allocation. Perhaps just as important for small spacecraft, the mechanical flexibility of thin-films lends itself well to stowage and deployment schemes; allowing novel folding of the array into the spacecraft for launch as well as unfolding of the array once in space. LISA-T is utilizing advanced solar cells being developed in industry (for example, inverted metamorphic multifunction cells) coupled with advanced, space-rated polyimide materials manufactured by our partner, NeXolve Holding, LLC, to form the basis of LISA-T. These cells and core materials are backed by a novel multifunction mechanical system, which provides both the structural backing as well as deployment forces for the array.

RESULTS/ACCOMPLISHMENTS

Several accomplishments have been made over the last two years to prepare the LISA-T technology for the PTD mission. Early in FY20, the LISA-T PTD array configuration was successfully tested under a simulated weightless environment utilizing a parabolic flight from the Zero-G Company in Dumfries, VA. The team flew ≈60 parabolas testing 4× deployments to ensure proper mechanical operation in a weightless environment. For thin-film, low mass systems, this testing is a necessity as the forces induced by gravity during ground based mechanical testing greatly affect the system results, hindering the ability to predict the mechanical performance of the array in the microgravity of space.

Also in FY20, samples of the LISA-T array, which spent ≈1 year exposed to the low-Earth orbit (LEO) space environment on the Materials on International Space Station Experiment Flight Facility (MISSE-FF), were successfully returned to Earth. Pre-measurements of the samples were taken before launch to International Space Station (ISS) early in FY19 and post-flight measurements were successfully completed in FY21. The data shows good potential for the materials, solar cells, and assemblies that comprise LISA-T to successfully survive the space environment for shorter-term missions that are typical of small spacecraft.

Lastly, the LISA-T PTD team successfully completed a Critical Design Review (CDR) in September 2021. The successful CDR shows a mature payload design to demonstrate LISA-T in-space and prepare the technology for mission uses. The NASA LISA-T team has begun design integration with Tyvak, the provider of the host small spacecraft (the PTD) that will demonstrate LISA-T. The LISA-T PTD payload is currently working toward an FY22 launch on the VOX Space 'USSF/STP S-28-B' launch.

SUMMARY

The LISA-T array will enable both highly capable, near-Earth small spacecraft as well as the capability for small spacecraft to operate deeper into space through both improved power generation and communication capabilities on the same deployable array. The LISA-T PTD mission will demonstrate this array, proving it out for future mission use. The deployment, operation, and environmental survivability of LISA-T will be tested. This mission, combined with ground based testing, the parabolic testing, and the MISSE-FF exposure modeling will enable LISA-T to provide >300% improved power generation to small spacecraft and usher in a new class of low-cost, fast-paced, risk-tolerant missions.

PRINCIPAL INVESTIGATORS: John Carr and Les Johnson

PARTNERS: NeXolve Holding, LLC; Tyvak

FUNDING ORGANIZATION: Space Technology Mission Directorate (STMD)

Flexible Ultracapacitor Energy Storage Devices for Wearable Crew Health Sensor Platforms

OBJECTIVE: *To develop flexible dielectric composites with an ultrahigh energy storage density to be used as wearable energy storage devices.*

PROJECT GOAL/DESCRIPTION

The goal of the project was designed to create flexible dielectrics with a high energy storage density (≈10 J/cm^3) that can be used to develop energy storage devices. Due to its flexibility, the energy storage devices fabricated using the dielectrics developed can be integrated into wearable electronics, such as wearable sensors for astronauts. Two approaches were investigated for the creation of flexible dielectrics: polymer-ceramic composites and polymer-coupling agent composites. The former takes advantage of newly developed spark plasma sintering (SPS) ceramics that exhibit a giant dielectric constant. The latter opened a new avenue for improving the energy storage performance of dielectric polymers. It was experimentally demonstrated that the dielectric constant of the dielectric polymer can be significantly enhanced by adding SPS ceramic nanoparticles into the polymer matrix, but the electric breakdown field is reduced as a result. It is experimentally found that the electric breakdown field of a dielectric polymer can be significantly enhanced and that the dielectric constant of the dielectric polymer is simultaneously increased by adding a small amount of coupling agent into the polymer matrix. This was validated by using different dielectric polymers and different coupling agents. Therefore, a high energy storage density (≈10 J/cm^3) was achieved in the polymer-coupling agent composites.

APPROACH/INNOVATION

The energy storage density (U) of a dielectric is determined by $U = \frac{1}{2}\, \varepsilon_0 \varepsilon_r E_b^2$, where ε_0 and ε_r are the permittivity of vacuum and the dielectric constant of the dielectric and E_b is the electric breakdown field of the dielectric. Therefore, it is highly desirable to have the dielectrics with a higher E_b and a larger ε_r for energy storage applications. In general, dielectric ceramics exhibit a larger ε_r, but a much lower E_b, while dielectric

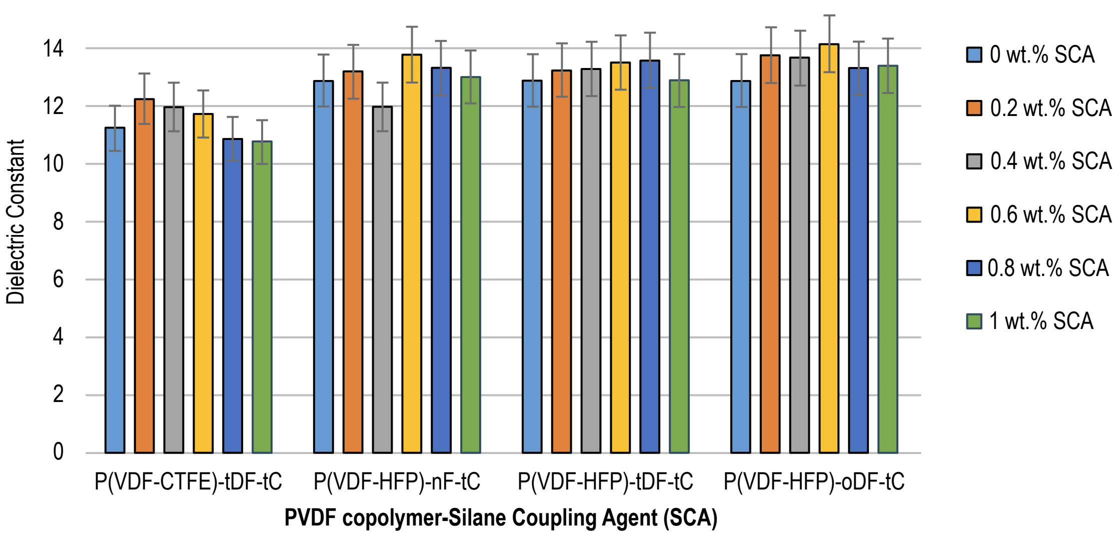


FIGURE 1. Dielectric constant measurements based on weight percent of various polymer-coupling agent composites.

polymers exhibit a much higher E_b, but a lower ε_r, which results in a higher U in polymers than in ceramics. Therefore, it is beneficial to develop polymer-ceramic composites. Various polymers and ceramic nanoparticles have been studied to develop high performance polymer-ceramic composites. We recently developed a new type of ceramics (i.e., SPS ceramics with a special nanostructure – barium titanate ($BaTiO_3$) nanoparticle coated with silica (SiO_2)) that exhibit a giant ε_r. Therefore, it is of interest to fabricate the polymer-ceramic composites using SPS ceramic nanoparticles. However, it should be noted that adding ceramic nanoparticles into a polymer matrix results in a reduced flexibility. It would be most beneficial if the U of the dielectric polymers can be improved while maintaining the flexibility of the polymers. Therefore, the polymer- coupling agent composites were investigated. In this project, Poly(vinylidene fluoride-co-hexafluoropropylene) (P(VDF-HFP)) was used as the polymer matrix for the development of polymer-based composites. At very beginning, the research was focused on the determination of the optimized thermal treatment condition of P(VDF-HFP) to achieve a high E_b. For the development of polymer-ceramic composites using SPS ceramic nanoparticles, the key was to fabricate the nanoparticles with a good uniformity from SPS ceramics. In this project, two different processes were used, and the process parameters were studied. The nanoparticles of SPS ceramics with a relative uniformity were fabricated. The polymer-ceramic composites were then prepared using solution cast and spin-coating processes. The dielectric properties and energy storage behavior of the composites were characterized. For the development of polymer-coupling agent composites, silane coupling agents (SCAs) with different molecular weights (tDF–tC, nF–tC, and oDF–tC) were used.

RESULTS/ACCOMPLISHMENTS

For the polymer-ceramic composites, it was experimentally found that the dielectric constant of P(VDF-HFP) was significantly enhanced by adding ceramic particles, as seen in figure 1. For the composites under the same electric field, the energy storage density increases with the ceramic content. Unfortunately, the E_b of the composites decreases with increasing ceramic content, which results in a lower energy storage density in the composites, as seen in figure 2. For the polymer-coupling agent composites, it was experimentally found that the E_b of polymer is significantly enhanced by

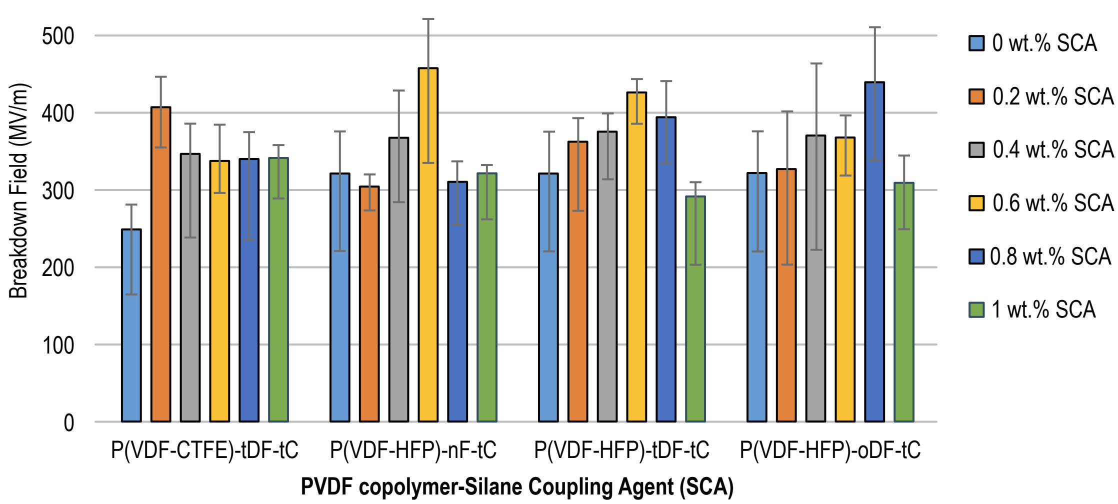


FIGURE 2. Electric breakdown field measurement based on weight percent of various polymer-coupling agent composites.

adding small amounts of coupling agent but decreases with further increasing content of the coupling agent, which results in a maximum E_b for the composites with a certain content (<1.0 wt.%) of the coupling agent. Additionally, it is experimentally found that the dielectric constant of the polymer can also be improved by a small amount of coupling agent. Therefore, the energy storage density of the polymer-coupling agent is significantly improved by adding a small amount of coupling agent. The polymer-ceramic composites have been extensively studied. The innovation of our project is the usage of a newly developed SPS ceramic that exhibits a giant dielectric constant. Coupling agents have been used in the development of polymer-ceramic composites for improving the wettability between the polymer matrix and ceramic particles. In this project, the coupling agent was used to improve the energy storage density of polymer. This is a novel approach for the development of polymer-based dielectrics for energy storage applications. The polymer-coupling agent composites have the following advantages over the polymer-ceramic composites:

(1) the composites maintain the flexibility of the polymer matrix, which makes them ideal for wearable electronics/devices;

(2) the composites have a better uniformity and are easy to be prepared/fabricated, which would reduce the cost of energy storage devices;

(3) the composites have a lower density, which results in the lighter energy storage devices; and

(4) the composites can be prepared with smaller thickness, which reduces the operating voltage of energy storage devices.

SUMMARY

In this project, two types of dielectric composites have been studied to develop the composites with a giant energy storage density. One is polymer-ceramic composites that have been extensively studied. The innovation of our approach is the usage of nanoparticles of SPS ceramics that exhibit a giant dielectric constant. With the composites under the same electric field, adding SPS ceramic nanoparticles significantly improves/enhances the energy storage density of the polymer matrix. A new avenue for developing high-performance dielectric composites and the polymer-coupling agent composites was explored in this project. It is experimentally demonstrated that adding a small amount of coupling agent into a dielectric polymer can significantly enhance/increase the energy storage density of the polymer matrix. The polymer-coupling agent composites have many advantages over the widely studied polymer-ceramic composites.

PRINCIPAL INVESTIGATOR: Terry D. Rolin

PARTNER: Zhongyang Cheng, Ph.D., Auburn University

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Improved Satellite Robustness Through Application of Erosion Resistant and High Emissivity Coatings

OBJECTIVE: *To develop erosion-resistant, lightweight, passive, high-electron-emission coatings for spacecraft surfaces such as solar arrays.*

PROJECT GOAL/DESCRIPTION

Ionizing radiation occurs because of space weather events like solar flares or cosmic rays. It has the potential to incur cascading spacecraft damage that could lead to loss of key services such as communications, remote sensing, and environmental monitoring. The application of a high-electron-emission coating could mitigate charging and erosion effects brought on by ionizing radiation. Thus, the overall goal of this Small Business Innovation Research (SBIR) project was to optimize, develop and transition a scalable, cost-effective process to apply an erosion-resistant, lightweight, passive, high-electron-emission composite coating onto spacecraft components like solar panels. This coating can enhance the components' lifetime and durability within low-Earth orbit (LEO) and geostationary equatorial orbit environments.

APPROACH/INNOVATION

Faraday Technology and Utah State University (USU) developed a scalable electrophoretic deposition (EPD) process to tune and controllably apply enhanced composite coating onto spacecraft components. The key innovation associated with the FARADAYIC® ElectroPhoretic Deposition process and associated apparatus (U.S. Patent Application Number: 63/231,923 filed 08/11/2021) for application of passively emitting/erosion resistant coatings is the ability to coat shaped surfaces and to selectively coat critical sections of surfaces. An example of the local application of the composite coating is seen in figure 1. The FARADAYIC ElectroPhoretic Deposition process/apparatus is scalable, non-line of sight, and amenable to a wide range of component shapes.

The specific objectives for the Phase I program were:

(1) Applying composite mixtures of hard solids and low work function ceramics onto viable spacecraft materials.

(2) Tuning the deposit composition for improved electron emission yield.

(3) Tuning deposit composition for improved ion erosion resistance.

(4) Demonstrating sustained electron emission yield through ion erosion.

(5) Demonstrating a transition and scale-up pathway for application to spacecraft components in Phase II.

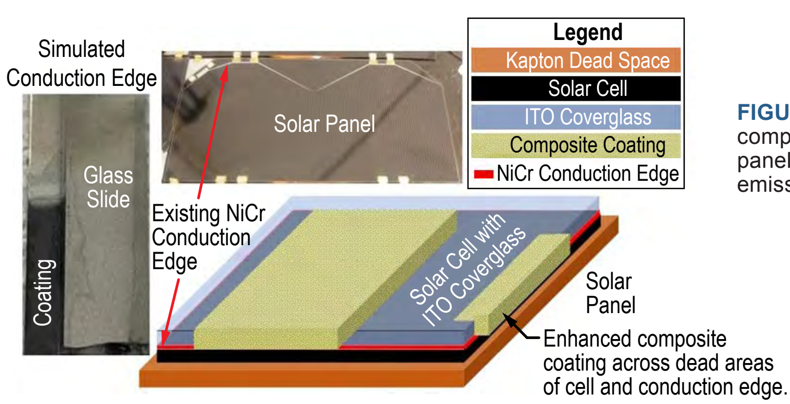


FIGURE 1. Local application of enhanced composite coating onto simulated solar panel for radiation resistance and electron emission yield.

TABLE 1. Electron emission data obtained on enhanced composite coating.

Sample ID	TEY Maximum	Energy Maximum (keV)	First Crossover E_1 (keV)	Second Crossover E_2 (keV)
A1 6061 Substrate	1.8 ± 0.03	300 ± 10	43 ± 2	1,050 ± 50
Grit Blasted Composite A1 6061 Substrate	1.5 ± 0.05	320 ± 20	26 ± 4	1,500 ± 50
Enhanced Composite Coating – Multi Layer	1.4 ± 0.2	750 ± 20	45 ± 5	1,900 ± 50
Enhanced Composite Coating – Multi Layer	3.15 ± 0.2	370 ± 20	45 ± 5	3,300 ± 50
Enhanced Composite Coating – Mixture	3.6 ± 0.2	520 ± 30	31 ± 5	6,000 ± 50

RESULTS/ACCOMPLISHMENTS

During Phase I of this SBIR, Faraday Technology and USU successfully developed a scalable manufacturing approach to produce an enhanced composite coating of hard conductive boron-doped diamond/graphene and low work function materials. They demonstrated the feasibility to tune the composition and density of composite coatings to enhance the electron emission yield and improve the ion erosion resistance. The coatings were tested in the USU Electron Emission Test (EET) Chamber. Test data is shown in table 1.

The results of the tests indicated a 140% increase in the maximum (∑max) total electron yield (TEY) over the noncoated A1 substrate sample, as well as substantially extending the range of electron yields between crossover energies above 1 kilo-electron volt (keV) by approximately 4 times. Improved erosion resistance of the coating was also demonstrated, with the nominal emission properties in modeled ISS plasma erosion conditions at a low density (106/cm^3), low temperature (≤1 eV electron temperature) plasma for 60 ± 1 min with an approximate 30% duty cycle. Furthermore, Faraday Technology was invited and partnered with NASA Marshall Space Flight Center to fly the most promising electrophoretic deposition samples as part of the Materials on International Space Station Experiment MISSE-16 and evaluate their performance after exposure to the LEO space environment.

SUMMARY

Faraday Technology and USU have developed a next-generation ion-erosion-resistant, high-electron-emission passive composite coating. When applied to key components such as solar cells, this coating will enhance the durability, effectiveness, and lifespan of spacecraft through space weather ionizing radiation events. Therefore, we envision the resulting product of this work could be applied to any spacecraft materials that could be subjected to such environmental challenges. Furthermore, it would be of interest to platforms including spacecraft skin, solar panels, circuit boards, and emitters. The proposed technology will encompass fundamental and applied research, and any number of unforeseen advances in commercial and military sectors may result. Industries producing satellites or devices in aggressive space environments will also benefit from the proposed technology.

PRINCIPAL INVESTIGATOR: Rajeswaran Radhakrishnan

PARTNER: Utah State University

FUNDING ORGANIZATION: Small Business Innovation Research (SBIR)

TA04:

Robotic Systems

In-Space Assembly and Manufacturing Using Synchronized Robotics

OBJECTIVE: *To make sheet metal forming, an established on-ground manufacturing process, more accessible to NASA for both ground-based and in-space applications.*

PROJECT GOAL/DESCRIPTION

Ground-based manufacturing processes are traditionally not designed with resource constraints and versatility in mind. Single-purpose, heavy machineries are commonly used to carry out a single operation in a long chain of operations. They are, for most part, not autonomous in that they do rely on skilled labor for continued operation and quality assurance. These are all luxuries that cannot be afforded in space. However, the know-how in these manufacturing processes and the processes themselves are essential to success of NASA in extending its presence into deep space. Sheet metal forming is one such process where, in its current form, it is not ready for deployment in space. Sheet metal parts are, however, extensively used in a multitude of applications, making their processing an enabler for deep space travel. The aim here is to take an established on-ground manufacturing process and make it more accessible to NASA for both its ground-based and in-space applications.

APPROACH/INNOVATION

This effort is aimed at using off-the-shelf, industrial robots for direct fabrication of sheet metal parts via the formative process without the need for any tooling. The technology involves two industrial robots forming and shaping a sheet of metal to a target design. The two robots, one acting as the forming robot and the other as the support robot, are programmed to synchronously trace a path on the metal and progressively form the metal to the desired shape. The technology makes use of the incremental sheet-forming process, a well-documented and researched metal forming process. At the same time, the technology is based on established and universally

(a)

(b)

FIGURE 1. (a) Rendering of the planned layout for Machina Labs' manufacturing factory consisting of multiple robotic sheet metal forming cells. (b) Examples of parts manufactured out of various alloys using Machina Labs' robotic sheet metal forming technology.

practiced sheet metal forming theories, which means that the know-how, theories, models, standards, and qualification procedures are already in place. Having said that, commercial uptake of the technology has been slow. This can be attributed to the fact that, with the added degrees of freedom offered by the process, more stringent process control protocols have to be put in place. Machina Labs has successfully set up an operational large-envelope, two-robot sheet metal forming cell at its facility in California and is currently in the process of commissioning and adding additional robotic cells (fig. 1). Selecting pressurized tanks as the target component, Machina Labs will be using its robotic cells to manufacture a range of tanks and demonstrate the viability of robotic sheet metal forming technology.

RESULTS/ACCOMPLISHMENTS

Through its Small Business Innovation Research (SBIR) Phase I effort, which was also supported through Machina Labs' own investment, the company demonstrated the viability of using a robotic sheet metal forming system for various applications. Work was specifically carried out in the following areas during the performance period:

- Hardware: Work on Machina Labs' two-robot sheet metal forming system with the aim of having the process automated.
- Planning and control: Testing of strategies that allow for adaptive control of the robotic sheet-forming process through feedbacks from the physical system.
- Metrology system: Testing of a cost-effective, light, and flexible metrology system that can be used to establish closed-loop control and act as in-situ quality control (QC) system.

During the performance period, the company also engaged in commercialization discussions with various enterprises in the automotive and aerospace domains. In the process, a large, prototype aluminum assembly was delivered to a potential customer. Lessons learned: Engage in commercial discussions early in the process to guide prioritization and planning.

SUMMARY

Machina Labs successfully set up an operational large-envelope, two-robot, sheet metal forming cell. The cell was used to demonstrate the viability of robotic sheet metal forming as a technology that can be utilized for NASA and non-NASA applications. Work was carried out on a number of different alloys, different geometries, and different part sizes to assess the flexibility and capability of the technology in manufacturing sheet metal parts. Commercial discussions with established and new companies have been very fruitful, highlighting the immediate need for an agile solution for manufacturing of sheet metal components. Targeting a specific application (i.e., tanks), work is planned to further demonstrate the viability of the technology.

PRINCIPAL INVESTIGATOR: Babak Raeisinia

FUNDING ORGANIZATION: Small Business Innovation Research (SBIR)

Near-Earth Asteroid (NEA) Scout

OBJECTIVE: *NEA Scout is an interplanetary spacecraft in a 6U CubeSat form factor launching on Artemis-1, which will use a solar sail to travel to, and a camera to characterize, a near-Earth asteroid.*

PPROJECT GOAL/DESCRIPTION

Near-Earth Asteroid (NEA) Scout, scheduled to launch on Artemis 1, will be America's first interplanetary mission using solar sail propulsion. Using photons from the Sun, the spacecraft will be propelled using its solar sail to flyby a near-Earth asteroid (2020 GE) upon which it will use a high-quality 20-MPx array optical science camera to image the target and address key strategic knowledge gaps. NEAs are of interest not only for human exploration, but also for science, in-situ resource utilization, and planetary defense.

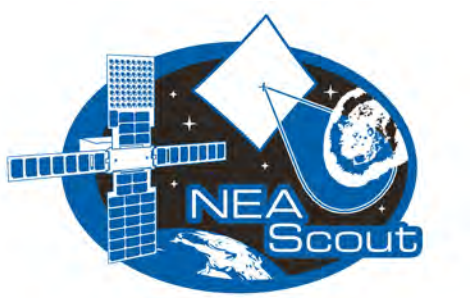


FIGURE 1. NEA Scout project logo.

APPROACH/INNOVATION

The following three key technologies that are detailed in this report are important and unique to the NEA Scout project: the controllable solar sail, the on-board science image processing technology, and the Dreadnought CubeSat Integration Support Hardware.

SOLAR SAIL

The NEA Scout spacecraft is housed in a 6U CubeSat form factor. A CubeSat is a small spacecraft built on a modular design architecture of 10 cm × 10 cm × 10 cm cubes. The previous year's innovations were the design, development, test of a solar sail system to provide the propulsion required for the mission. With this year's integration of the spacecraft into the launch vehicle, the team focused on the flight control system managing the sail's continuous low thrust throughout the flight. NEA Scout will be different from all previously flown solar sail systems. Its objective is to use the sail for controlled flight to affect a close flyby of the target asteroid. Given that the solar sail is a single sheet deployed on four booms from the center two units of the 6U, 3-axis controlled spacecraft, any asymmetries between the center of pressure (CP) of the sail with the spacecraft system center of mass (CM) will result in a torque on the system that must be carefully managed to maintain attitude and thrust control. To manage the CP/CM offset and other solar pressure induced torques, NEA Scout will use an active mass translation (AMT) device, reaction wheels, and incremental changes in velocity provided by an on-board cold gas thruster system. The technologies developed for NEA Scout, including the boom geometry, sail membrane, deployment system, AMT, and algorithms for managing the sail's momentum and attitude are being transitioned into a much larger and more capable sail system for the planned NASA Solar Cruiser mission (planned to fly in 2025).

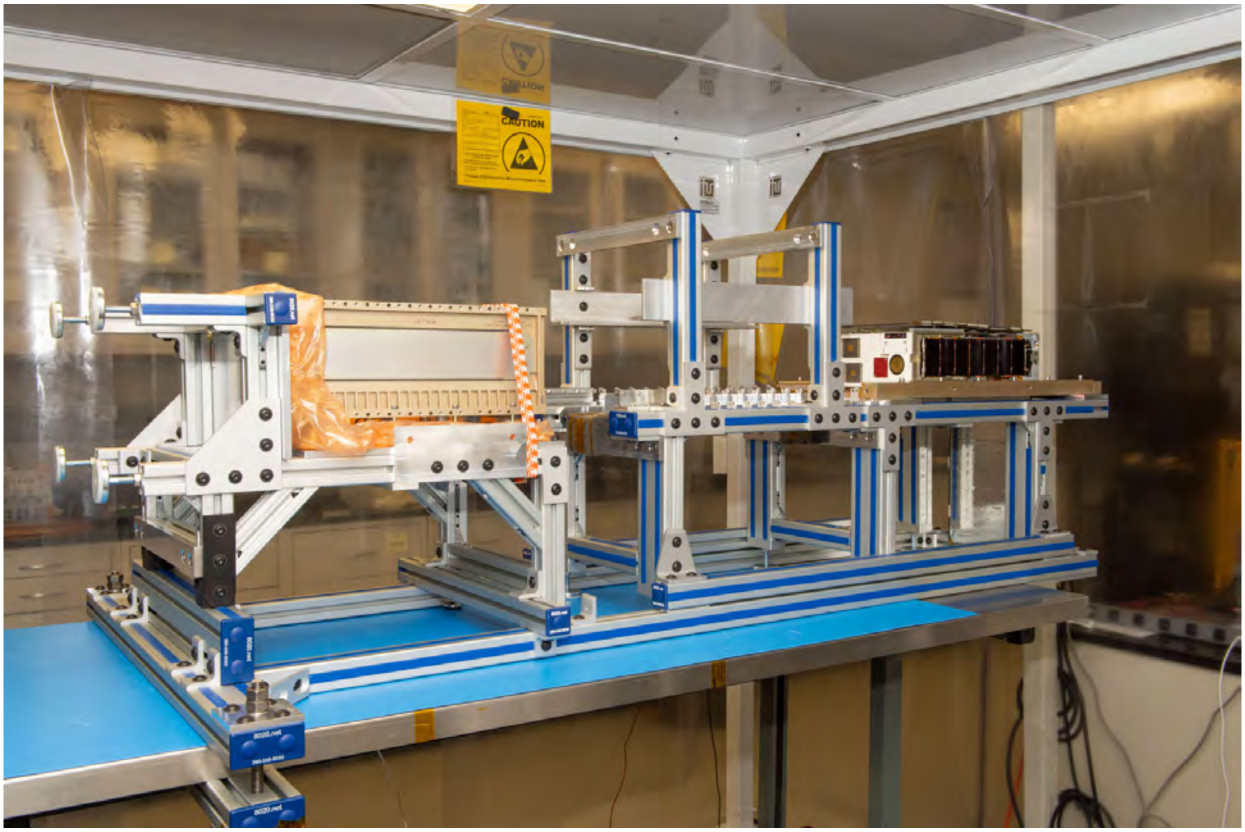


FIGURE 2. Dreadnought CubeSat Integrator.

SCIENCE IMAGE PROCESSING

The suite of onboard science processing commands developed for NEA Scout enables high-resolution imagers to capture large amounts of data and prioritize the most important aspects for downlink during bandwidth-constrained mission scenarios. This is accomplished through a collection of downsampling, cropping, and compression routines, which can be used together to significantly reduce the volume of data which is sent to Earth while not sacrificing resolution. Once a target region is identified, cropping can be commanded as either a specified region of the image or around the brightest object in the image. This produces high resolution cutouts around the target and relevant stars, which can be downlinked for a fraction of the bandwidth allocation when compared with the complete image. The onboard target detection technique allows trajectory verification and refinement; the detection of targets of opportunity; automated target tracking (in future missions); and target survey and classification (in future missions). This year, the NEA Scout team finalized the ground-based science software, including Planetary Data System format specification and creation for eventual archiving. This end-to-end pipeline can be easily adapted for different cameras.

DREADNOUGHT

Dreadnought was designed to support integration and test of NEA Scout after a failed fit check with flight dispenser. It supports a CubeSat safely, while providing maximum visual and physical access in and out of the dispenser simulator. The CubeSat can be translated horizontally into the desired position, dispenser, or fixture in a slow, controlled manner. Dreadnought also affords control while maneuvering the CubeSat into a vertical position. This support is necessary for CubeSats that are sensitive to bending, as was the case for NEA Scout. The elevated table provides full access to the 'upper' CubeSat surface and room to fully open upper and lower 3U-long solar panel wings. For NEA Scout, Dreadnought allowed custom fitting of the upper and lower solar panels into the dispenser, necessary due to out-of-plane condition of flight solar panels. When in the simulator, fit of the panels was easily observable and access was available for measuring clearances. This allowed correlation to the dynamic analysis models for better prediction of behavior in vibration testing.

RESULTS/ACCOMPLISHMENTS

The NEA Scout spacecraft has been fully integrated, tested, and qualified for flight. Following completion using the Dreadnought, the spacecraft was successfully integrated into the dispenser and subsequently loaded onto the Orion Stage Adapter (OSA) of Artemis I and is awaiting launch. The algorithms necessary to control the AMT, reaction wheels, and incremental ΔV provided by the on-board cold gas thruster system—all necessary for maintaining the sail attitude and managing its momentum (supporting mission design)—were developed at NASA Marshall Space Flight Center (MSFC) and are the primary innovations of the past year. The NEA Scout science software developed by NASA Jet Propulsion Laboratory (JPL) is a critical addition to NEA Scout. It allows the use of a high-quality science camera with a 20-megapixel array and it provides operational flexibility to platforms with limited bandwidth or resources. This distilling of scientific data returned to Earth enables increased focus of attention by human operations, reducing turnaround time for critical decision making.

SUMMARY

NEA Scout will demonstrate the feasibility of using a low-cost, solar sail-propelled CubeSat on an asteroid reconnaissance mission. It will be the U.S.A.'s first interplanetary mission propelled by a solar sail and a pathfinder for many potential missions using sail technology in the future. Onboard data analysis enables new mission profiles, which are not possible with traditional methods for analyzing science return. Altogether, the NEA Scout mission will be a pathfinder for a capability that can benefit a variety of future missions, big and small.

PROJECT MANAGER: James Stott

PARTNERS: Jet Propulsion Laboratory, Langley Research Center

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office

FOR MORE INFORMATION:
https://www.nasa.gov/marshall/news/releases/2021/nasa-solar-sail-asteroid-mission-readies-for-launch-on-artemis-i.html
https://www.nasa.gov/content/nea-scout

TA06:

Human Health, Life Support, and Habitation Systems

Investigating the Performance Characteristics of Auxetic Foams in Neuropathy Treatment Applications

OBJECTIVE: *To investigate the performance characteristics and efficacy of auxetic foams as a neuropathy aid in order to highlight and address postural and balance deficiencies in neuropathic victims and returning astronauts (due to adverse space conditions), while simultaneously fortifying spatial structures.*

PROJECT GOAL/DESCRIPTION

Technologies geared toward the health, muscular longevity, and Earth applications of returning astronauts are important, but currently scarce at NASA. Astronauts are exposed to 10 times more radiation in space than on Earth and are much more susceptible to degenerating muscular and nerve diseases and conditions, such as neuropathy and limited mobility. Moreover, 20 million people suffer from limited mobility and neuropathy (inclusive of returning astronauts). This project seeks to investigate the performance characteristics of auxetic foams and evaluate its efficacy as a neuropathy aid sufficient to mitigate the symptoms of neuropathy and limited mobility for neuropathic victims (inclusive of returning astronauts). Additionally, this project will explore the material characteristics of the auxetic foam for potential applications in astronauts' suits and structures deemed pivotal for deep space exploration systems.

FIGURE 1. Examples of the auxetic foam in action, showing the expansion of the foam in transverse direction after being stretched.

Auxetic foams are foams with negative Poisson's ratios. They expand when stretched and shrink when compressed. This is contrary to almost all naturally occurring or synthetic materials, whose Poisson's ratios are positive. Auxetic foams exhibit many desired properties that may aid in mitigating symptoms of neuropathy and limited mobility (i.e., significantly improved cushioning and pressure relief, superior shape conformity, optimal dynamics, enhanced toughness, shear resistance, bending stiffness, improved impact and indentation resistance, etc.).

APPROACH/INNOVATION

Innovative aspects of this project that will be developed include the neuropathic prototype sufficient for optimal circulation and the management of neuropathic symptoms, as well as the spatial structures that will be fortified as a result of incorporation of the auxetic material.

FIGURE 2. Phase I and II testing utilizing motion capture and force plate technologies.

Neuropathy is a symptom of many underlining causes and diseases and is not partial to age, race, or position. Therefore, returning astronauts, as well as U.S. soldiers, athletes, diabetics, cancer patients, victims of car accidents, victims of stroke, and others who suffer from neuropathy will all benefit from the technology. The neuropathic aid will be developed upon measuring the ground reaction forces of various neuropathic and limited mobility victims and integrating the data results with the auxetic material technology. Follow-on activities are anticipated upon completion of this project in order to engage in comparative analysis of a variety of materials, to engage industry, and to optimize the developed neuropathic aid.

RESULTS/ACCOMPLISHMENTS

This follow-on project has successfully completed its second phase of testing, providing insight into the impact of the different attributes of neuropathy and to the characteristics and mechanics needed for a sufficient neuropathic aid. Additionally, this project has successfully evaluated and analyzed the auxetic material for incorporation and fortification of spatial structures. Furthermore, this project has initiated the careers and enhanced the educational careers of a plethora of interns, enabling them to pursue doctoral degrees and obtain fellowships. Lastly, this project has successfully partnered with academia, opening up avenues for collaboration opportunities across the NASA agency.

SUMMARY

This project will not only help alleviate pain experienced amongst returning astronauts and other neuropathic victims, but it will fortify spatial structures that will enable deep space exploration and longer missions. This project will improve the quality of life of more than 20 million individuals by minimizing doctor visits, physical therapy treatments, and the symptoms and pains associated with neuropathy.

PRINCIPAL INVESTIGATOR: LaBreesha Batey

PARTNERS: Florida Agricultural Mechanical University (FAMU); Enrique Jackson, Angela Lovelady

FUNDING ORGANIZATION: Center Innovation Fund (CIF)

Development of Non-Platinum Group Metal (PGM) Catalysts for Hydrogen Resource Recovery (HRR)

OBJECTIVE: *To demonstrate at least 85% hydrogen recovery from a nominal Plasma Pyrolysis Assembly (PPA) by developing a non-platinum group metal catalyst utilized in a single-cell electrochemical separator.*

PROJECT GOAL/DESCRIPTION

Currently on the International Space Station (ISS), approximately 50% oxygen (O_2) is recovered from metabolic carbon dioxide (CO_2). NASA is currently targeting technologies that achieve 75–90% oxygen recovery. One approach to achieve additional recovery is to recycle hydrogen (H_2) by adding a methane (CH_4) postprocessor downstream of the Carbon dioxide Reduction Assembly (CRA) that is part of the Atmosphere Revitalization (AR) architecture on the ISS. NASA has been exploring the Plasma Pyrolysis Assembly (PPA) for this purpose. The PPA converts the CH_4 produced by the CRA into a mixed gas stream of mainly H_2 and acetylene (C_2H_2). Secondary reactions occur that result in a PPA effluent mixture containing H_2, unreacted CH_4, product C_2H_2, and trace quantities of water (H_2O), carbon monoxide (CO), ethylene (C_2H_4), ethane (C_2H_6), and solid carbon (C).

In order to recycle H_2 back to the CRA, the H_2 byproducts must be removed to prevent fouling of the Sabatier catalyst. NASA has been working with Skyre, Inc. to develop an electrochemical-based H_2 separation technology for this application. In 2018, two subscale electrochemical H_2 separation systems were delivered to NASA that employ alloyed platinum catalysts to preferentially separate H_2 from the PPA effluent. The platinum-alloyed catalyst showed improvements over traditional platinum in terms of lowering acetylene conversion; however, the resulting performance was not satisfactory to meet the requirements of a sustainable H_2 recovery/recycle solution. The focus of this project is to develop a non-platinum group metal (PGM) catalyst that is electrochemically active to the hydrogen oxidation reaction (HOR) to enable effective H_2 separation while catalytically preventing the acetylene hydrogenation reaction.

APPROACH/INNOVATION

A key aspect of this technology approach is the requirement to separate and purify H_2 from the PPA product stream while preventing C_2H_2 hydrogenation. This will achieve the desired H_2 recovery rates, which will increase O_2 recovery. During the H_2 separation process, the PPA effluent stream is fed to the cell anode. The H_2 is oxidized to protons, and electrons and the protons migrate across a proton exchange membrane (PEM) from the anode to the cathode due to the imposed electrical field. The electrons are pumped by a direct current (DC) power supply to the cathode where they combine to form gaseous H_2. The membrane only transports protons, leaving the remaining constituents in the anode exhaust stream. A schematic of the process is depicted in figure 1.

CO is present in the PPA effluent stream, which is a known poison to a platinum catalyst with low-temperature PEM cells. The subscale

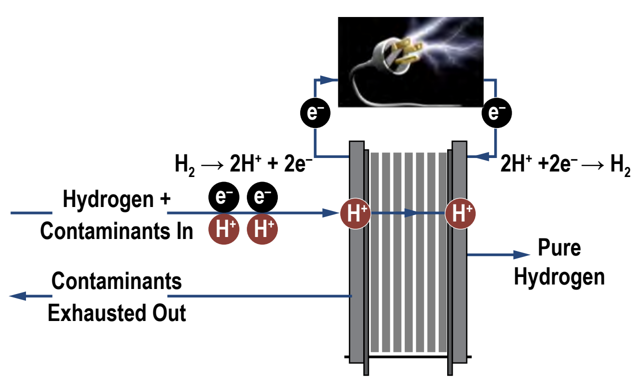


FIGURE 1. Electrochemical Hydrogen Separator.

units delivered to NASA were built with polybenzimidazole (PBI)-based membranes. PBI membranes allow high-temperature operation, which inhibit adsorption of CO. However, these membranes use phosphoric acid for proton conductivity that corrode cell hardware and can potentially migrate and negatively impact downstream hardware.

This project is focused on achieving the desired H_2 recovery rates through the development of non-PGM catalysts for the HOR that achieve high hydrogen recovery rates, that are tolerant to CO, and that reduce hydrogenation of C_2H_2. To ensure desired outcomes, three approaches have been implemented while investigating the use of non-PGM. The first is to prevent adsorption of acetylene onto the catalyst by providing inert surfaces; the second is to prevent the reaction of acetylene with H_2 by separating the different active sites for C_2H_2 and H_2 adsorption; and the third approach is to poison the active catalyst sites. Low-temperature PEMs were utilized rather than PBI-based materials to mitigate corrosion and acid migration issues identified in previous program activities. Future electrochemical development efforts will focus on scale-up from a single-cell hydrogen separator with the optimized non-PGM, to a three-cell unit, then to a full-scale separation unit that will be utilized to process gas at four-crew member rates.

RESULTS/ACCOMPLISHMENTS

In FY21, work was completed to advance the development of the electrochemical H_2 separator membrane technology. Three metal-based non-PGM catalyst system candidates (one metal oxide and two metal sulfide) were synthesized, characterized, and evaluated. Catalyst testing was limited to 5 cm^2 hardware to identify a viable catalyst system. The results indicate that the metal oxide catalyst outperforms the metal sulfide candidates and the baseline platinum-alloyed catalyst. The optimal catalyst selection was completed, and work has started on generating large batches of the catalyst for construction of the single-cell electrochemical unit. An expanded view of previous electrochemical cell hardware is pictured in figure 2.

FIGURE 2. Expanded view of the electrochemical cell hardware.

SUMMARY

It is imperative that a H_2 separation technology is identified for the use of the PPA. This is an attractive solution to increase O_2 recovery for long-duration manned missions. The use of an electrochemical separator is one of the H_2 separation methods that could prove viable to the success of the PPA technology. It was observed that the platinum-alloyed catalyst in previous builds of the separator contributed to degraded performance and performance could be increased by employing a non-PGM catalyst. In FY21, efforts focused on synthesizing, characterizing, and testing candidate catalysts to identify the optimal candidate for an electrochemical H_2 separator solution. Future work will involve synthesizing large bathes of the optimized catalyst, then fabricating a single-cell electrochemical separator.

PRINCIPAL INVESTIGATOR: Cara Black

PARTNERS: Skyre, Inc.; University of Connecticut

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Ionic Liquid-Assisted Extractive Distillation for the Removal of Dimethylsilanediol

OBJECTIVE: *To enable the recycling of water used in environmental control and life support systems (ECLSS) by developing an extractive distillation process using ionic liquids (ILs) to allow for the removal of dimethylsilanediol (DMSD) from water.*

PROJECT GOAL/DESCRIPTION

Due to launch mass restraints, the recycling of consumables, such as breathing air and water, used in environmental control and life support systems (ECLSS) is mandatory for any deep-space human exploration missions. While NASA has decades of experience in recycling water, the presence of unexpected contaminants can significantly degrade the performance of purification systems. One such contaminant, dimethylsilanediol (DMSD), is extremely difficult to remove from water due to its high hydrophilicity, and its presence has been shown to significantly increase the rate of replacement for the resins used in water purification system. While this impact is minimal on the International Space Station (ISS) with regular resupply missions being possible, deep-space exploration missions will not have the luxury of easy resupply. This project seeks to develop a new approach for the removal of DMSD from water using ionic liquids (ILs) in an extractive distillation process, thus removing the need for additional resupply mass.

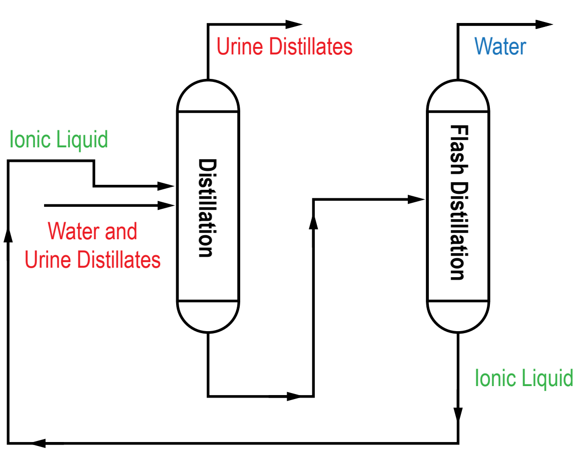


FIGURE 1. A process flow diagram for the separation of water and DMSD using IL-assisted extractive distillation.

APPROACH/INNOVATION

The key innovation in this project is the use of an IL to allow for the separation of water and DMSD through distillation. Under normal circumstances, distillation is not an effective separation technique due to the high affinity DMSD has for water; but the addition of an IL that has high water affinity and low DMSD affinity increases the relative volatility of the DMSD to the point where separation of the DMSD is possible. Additionally, as the IL is nonvolatile, once the DMSD is removed, a simple flash distillation will remove the water from the IL. No IL is consumed in this process, allowing the purification system to operate without any need for resupply.

The major technical challenge for this work is the identification of an IL with high affinity for water and low affinity for DMSD. Rather than using resource-expensive experimental screening, computational modeling was used to identify IL candidates. These ILs were then characterized experimentally to validate the computational results. The end products of this effort will be not only an IL that is a candidate for use in extractive distillation, but also improved computational models of ILs that will allow their use in other ECLSS applications and more.

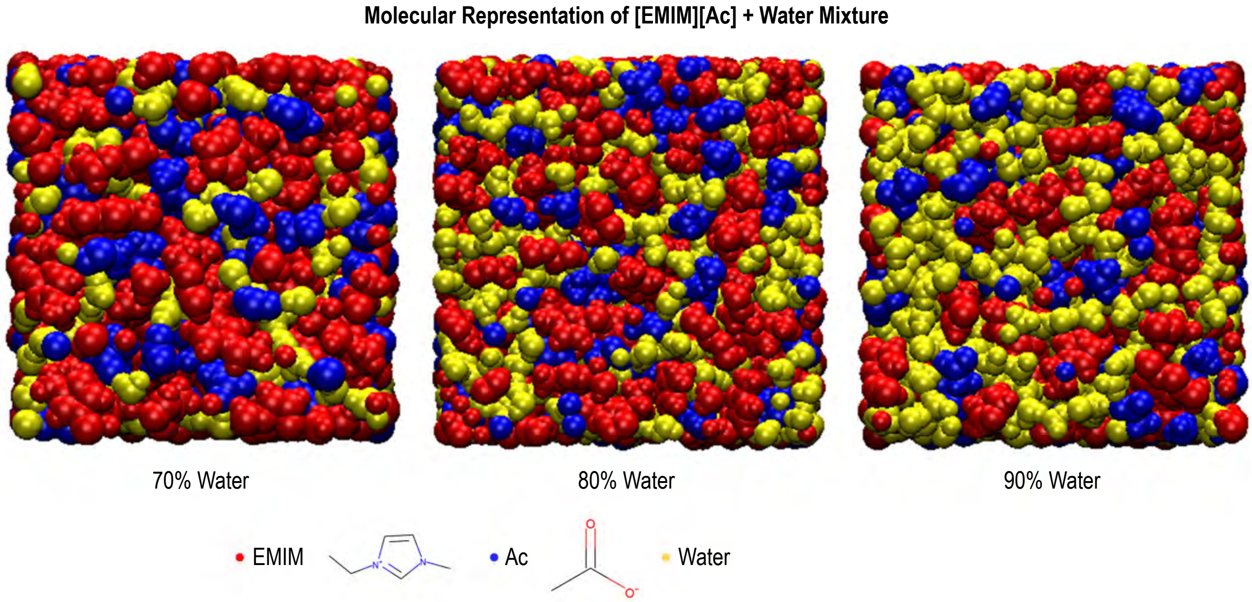


FIGURE 2. Molecular dynamics simulation results of IL-water mixtures.

RESULTS/ACCOMPLISHMENTS

Accomplishments over the last year include:

(1) Developing computational models for ILs and DMSD and verifying the predictions of these models through experimental work.

(2) Synthesizing and characterizing the physicochemical properties of candidate ILs.

(2) Measuring the activity coefficients of water and DMSD in candidate ILs as a function of composition and temperature.

SUMMARY

The recycling of water is a critical part of any ECLSS for long-term human space exploration missions. This effort has successfully demonstrated the use of IL-based extractive distillation as a means for removing one contaminant, DMSD, that can lead to significantly increased ECLSS consumable mass. Furthermore, the computational work developed should serve as a basis for identifying ILs that can be used to remove other contaminants in the water recycling system, as well as ILs for use in cabin air purification and many other applications.

PRINCIPAL INVESTIGATOR: Jindal Shah, Oklahoma State University

PARTNER: Oklahoma State University

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Development of Multifunctional Boron Nitride Nanotube-Reinforced Titanium-Based Metal Matrix Composites for Space Vehicles and Structures With Improved Wear Resistance and Radiation Shielding Property

OBJECTIVE:

To develop metal matrix composites with improved wear resistance and radiation shielding property.

PROJECT GOAL/DESCRIPTION

The gravity on the Moon is about 1/6 of that on Earth, which makes everything significantly 'lighter,' including lunar soil. Thus, the soil on the Moon tends to float and imposes an often-overlooked wear condition to the entire structure of space vehicles upon landing and during the mission. The floating lunar soil becomes a more significant challenge to moving parts of lunar vehicles as it serves as asperities and causes wear. There is a need to develop advanced wear-resistant, lightweight, and high-strength material for space vehicles and structures to address this challenge. Radiation, on the other hand, is another risk for space vehicles and structures. Galactic cosmic radiation, secondary neutrons, and solar flares pose significant threats to the electronics and materials on space vehicles and structures. Hence, the advanced materials for use on any space vehicles and structures should protect them not only from wear, but also from the harmful radiations in space. Boron nitride nanotube (BNNT) is a novel material that can solve three problems in this scenario, as shown in figure 1. Hence, this project aims to develop BNNT-Titanium (Ti) metal matrix composites (MMCs) into a multifunctional, advanced material system for future space vehicles and structures.

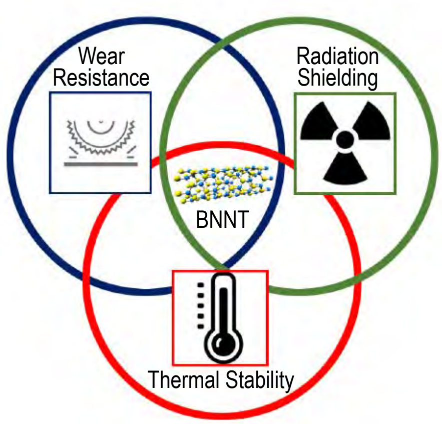


FIGURE 1. Versatility of BNNT.

APPROACH/INNOVATION

The proposed technology development approach seeks to achieve the following goals/deliverables:

(1) Synthesis of fully densified BNNT-Ti MMCs using spark plasma sintering (SPS) and ensuring the survival of BNNT after sintering.

(2) Identification of the optimum composition and architecture of BNNT in Ti-based MMCs for best wear resistance and radiation shielding properties.

Four milestones have been identified to achieve the proposed goals/deliverables.

(1) Identify BNNT morphology and dispersion techniques for use in Ti MMCs.

(2) Synthesize fully densified BNNT-Ti MMCs using SPS.

(3) Characterize the wear resistance and radiation shielding of BNNT-Ti MMCs.

(4) Optimize the architecture of BNNT-Ti MMCs for the best performance.

The Cooperative Agreement Notice (CAN) partner, Florida International University (FIU), has already filed a patent on integrating BNNT into Aluminum (Al) MMC with a unique sandwich structure. The elastic modulus of BNNT-Al MMC has improved 60% compared to original aluminum, while the tensile strength has improved 600%. Despite the great success in BNNT-Al MMCs, little progress has been made in BNNT-Ti MMCs. Titanium possesses better mechanical properties than aluminum, but it also has a much higher melting point that challenges the employment of BNNTs. However, a recent breakthrough at FIU demonstrated the synthesis of fully dense BNNT-Ti composite at a significantly low sintering temperature (650 °C), which enables the possibility of a BNNT-Ti MMCs with improved strength, wear resistance, and radiation shielding properties.

Post-sintering treatment will be the immediate step after this CAN project. Thermal and mechanical post-treatment like heat treatment and rolling would improve the BNNT-Ti MMCs in many aspects. Heat treatment can eliminate the residual stress in the composites after sintering and control the desired Ti phases. Rolling of these MMCs can mechanically align the BNNT within the matrix that leads to improved mechanical properties. A systematic study is being carried out on post-treatment effects on the mechanical, tribological, and radiation shielding properties of BNNT-Ti MMCs.

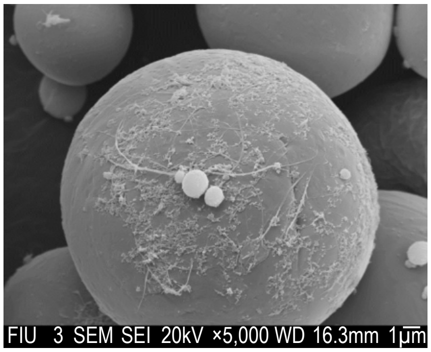


FIGURE 2. BNNT dispersion on Ti_6Al_4V powder.

RESULTS/ACCOMPLISHMENTS

Significant accomplishments of the CAN project are summarized below:

(1) Uniform dispersion of BNNTs in Ti powder matrix has been achieved (fig. 2).

(2) Fully densified BNNT-Ti MMCs have been achieved by SPS (fig. 3).

(3) The wear performance of BNNT-Ti MMCs has been evaluated in the presence of various lunar regolith simulants.

(4) 1 wt.% of BNNT addition has shown the most significant improvement in wear and coefficient of friction (COF).

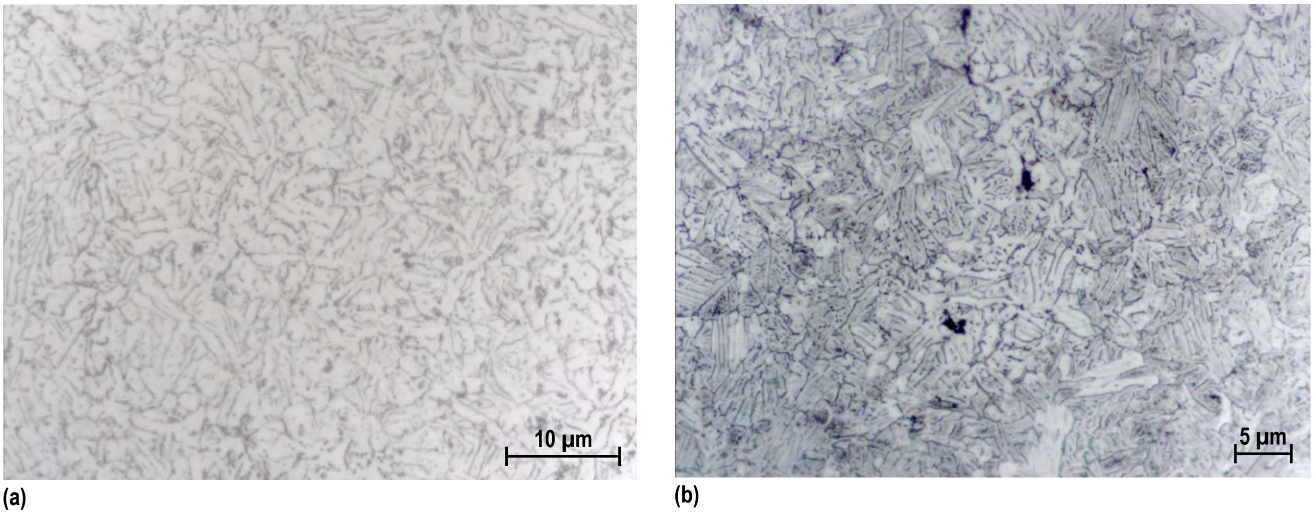


FIGURE 3. Dense microstructure of (a) SPS pure Ti6Al4V and (b) Ti6Al4V—1 wt.% BNNT.

The commercially available BNNTs typically contain contaminations, such as free boron, so a purification process was developed. As received, BNNTs were heated to 750 °C for 24 hours. The color change from brown to pure white indicated the purification process had been completed. The purified BNNTs were then immersed into isopropyl alcohol (IPA) and subjected to ultrasonication for 45 min to break down any agglomerations. Ti powders were added to the solution to prepare BNNT-Ti powder mixtures. The dried powder mixtures were sintered using SPS with a temperature of 950 °C and a pressure of 60 MPa. The dwell time for sintering is 15 mins to achieve fully densified BNNT-Ti MMCs.

Wear tests were carried out using a ball-on-disc tribometer. A 3 mm aluminum oxide ball was selected as a counter surface. A load of 5 N was applied to the specimens. The wear track was 3 mm in diameter with a rotating speed of 50 rpm. The test duration was 30 mins. Compared to pure Ti, BNNT-Ti showed a 10% improvement in wear resistance and a 9.7% reduction in COF. Three lunar regolith simulants were used as abrasives to evaluate wear resistance of BNNT-Ti MMCs against the lunar surface environment: Zircon, Greenland Anorthosite (GA), and JSC-1A. The results suggested that the addition of BNNT provided significant protection against Zircon simulant, as a 25% reduction in wear volume and 3% reduction in COF was observed. However, no significant improvements have been observed in the case of GA and JSC-1A, which suggests the BNNT additions are more effective in improving wear resistance against large lunar dust (>100 µm).

Sintered samples have been rolled at NASA Langley Research Center to observe the effect of plastic deformation on the mechanical properties of Ti_6Al_4V-BNNT composites. Radiation shielding properties of BNNT-Ti MMCs are currently under investigation by NASA Langley Research Center.

The 26-mm diameter samples have been sintered for radiation shielding. The results from rolled samples and radiation shielding tests will be updated once available.

SUMMARY

This Cooperative Agreement Notice (CAN) project develops novel, multifunctional BNNT-Ti MMCs for space vehicles and structures with improved wear resistance and radiation shielding properties. During this project, challenges like purification of BNNTs, uniform dispersion of BNNT in Ti powder matrix, and full densification of BNNT-Ti MMCs are overcome. The wear resistance of BNNT-Ti MMCs is evaluated with and without lunar regolith simulants. The addition of BNNTs showed improvement in wear resistance in both cases compared to the pure Ti metal. However, the increase in wear resistance became negligible in the case of simulants with fine particle size less than 100 µm. An additional layer of protective coating is recommended. Post-treatment of sintered BNNT-Ti MMCs will be the immediate step after this CAN project. Heat treatment and rolling of the sintered specimens are expected to improve the mechanical and tribological properties further. Radiation shielding property assessment is still ongoing. The results will be shared once they are available.

PRINCIPAL INVESTIGATOR: Arvind Agarwal

PARTNERS: Florida International University (FIU); NASA Langley Research Center (LaRC)

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

FOR MORE INFORMATION:
https://pfl.fiu.edu

Development and Testing of Adsorbent for Treating Wastewater on the International Space Station

OBJECTIVE: *To develop and test a deep eutectic solvent-coated graphitic biochar adsorbent as water filtration media for treating dimethyl sulfone-contaminated wastewater on the International Space Station.*

PROJECT GOAL/DESCRIPTION

The main goal of the project is to develop a deep eutectic solvent (DES)-impregnated graphitic biochar adsorbent to treat wastewater contaminated with dimethyl sulfone ($DMSO_2$). The key tasks of the project include: (a) identifying specific hydrophobic DESs by varying hydrogen bond donors (HBD) and hydrogen bond acceptors (HBA) and their molar ratio for the extraction of $DMSO_2$, (b) synthesizing a high surface area graphitic biochar, (c) synthesizing and immobilizing a task-specilic DESs on the graphitic biochar, and (d) performing treatability studies using DES-impregnated graphitic biochar for the removal of $DMSO_2$ in water.

APPROACH/INNOVATION

Screening of more than 45 different hydrophobic DESs composed of different combinations and molar ratio of HBA and HBD was performed utilizing a conductor-like screening model for realistic solvents (COSMO-RS). In COSMO-RS, the thermodynamic properties of the test fluid and solutions are calculated based on quantum mechanical data. This is an innovative approach to thoroughly process large batches of DES combinations within a model without having to spend valuable resources for benchtop testing. The model's results capture selectivity, capacity, and performance indices for each DES towards $DMSO_2$ affinity, and thus, a top-five ranking of the 45+ DESs for empirical assessments can be made. This modeling has also been used in other similar test environments and conditions that led to successful empirical verifications.

Once selected for high affinity of $DMSO_2$ removal from water, the DESs were immobilized onto a solid support. In this effort, the solid support is comprised of specific type of biochar, a graphitic carbon framework providing a diverse range of ion exchange properties. The base materials for biochar synthesis can be sourced from readily available, natural products (e.g., walnut shell). In fact, walnut shell is considered a naturally inert plant-based biosorbent used in hazardous material removal applications.[1, 2] DESs and graphitic biochar were synthesized in-house and further tested for performance matrices on $DMSO_2$ through small-scale batch and filtration column testing.

RESULTS/ACCOMPLISHMENTS

Forty-eight (48) DESs had been chosen as potential candidates for extraction of $DMSO_2$ from water for analysis through the COSMO-RS modeling. The selected DESs consist of a mixture of an ionic liquid (one part of cation and one part of anion, HBA) and two parts of an HBD. Results from the modeling identified three (3) viable candidates available for purchase/synthesis and characterization.

Benchtop batch testing of $DMSO_2$ removal was completed for two of the three DES candidates. Results indicated one of the two DESs provided 49% removal of $DMSO_2$, the highest of this test series. This DES was identified as 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide + octanoic acid [EMIM]NTf2. The [EMIM]NTf2 was later immobilized onto walnut biochar

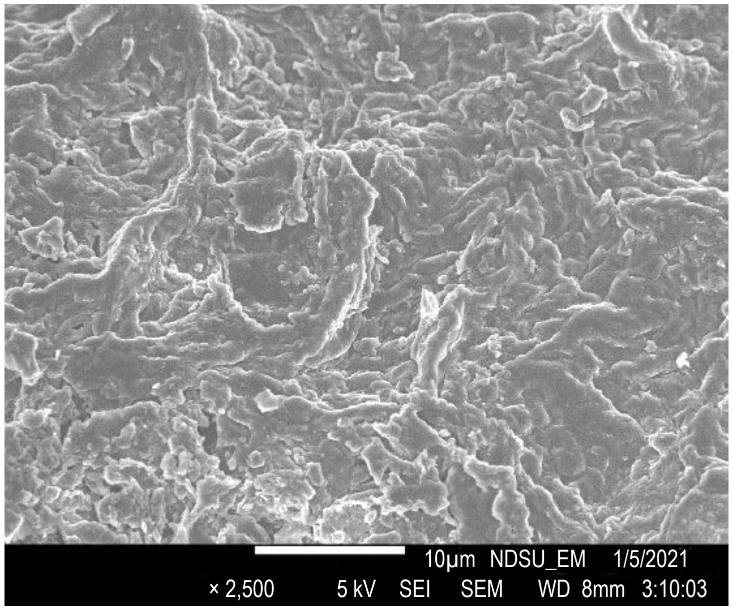


FIGURE 1. Electron microscopy images of biochar surface.

(fig. 1) to understand $DMSO_2$ adsorption kinetics and capacity. Experimental batch tests within closed glass vials containing 0.02 g [[EMIM]NTf2 + biochar] and 10 mL of a targeted $DMSO_2$ concentration (110 µg/L) were conducted. The tests included effects of competitive species [dimethylsilanediol (DMSD) and ethanol] and pH (3–11). Overall, the sorbent media performed with complete $DMSO_2$ removal in all conditions except for pH of 3. This acidic condition decreased the efficiency of the $DMSO_2$ removal to only 64%.

Based on its excellent performance, walnut-based biochar with [EMIM]NTf2 sorbent media has been selected for column filtration assessments, mimicking the relevant flow-through environment intended for this technology. Final results are expected to be completed in November 2021; however, early indications report the first 0.110 mg of $DMSO_2$ processed on the column filled with ≈10 g of sorbent media had 100% removal.

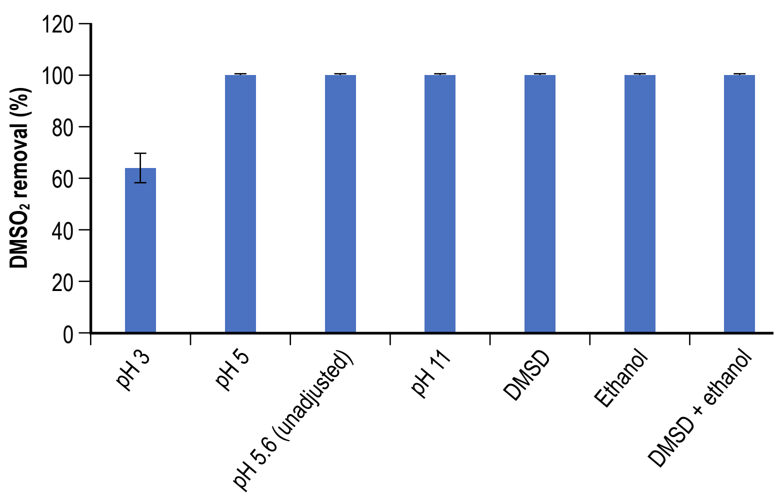


FIGURE 2. Results of testing $DMSO_2$ removal by DES-coated biochar.

SUMMARY

Deep eutectic solvents immobilized on graphitic biochar has shown early success at effective removal of $DMSO_2$ from water. A modeling process of COSMO-RS early on in this effort has demonstrated an efficient down-selection process among more than 45 DESs ahead of costly benchtop resource utilizations. Based on highest activity coefficients, selectivity, and capacity rates estimated from COMSO-RS, three DESs were selected to further empirical testing. This led to the final selection of [EMIM]NTf2 for the DES to be immobilized on a walnut-based graphitic biochar.

Benchtop testing and preliminary flow-through column testing continue to support success for $DMSO_2$ removal from water. Further understanding of pH effects have shown that pH <5 will be a challenge but still acceptable within the intended technology integrations within the Environmental Control and Life Support Systems (ECLSS) Water Recovery System (WRS). Continued testing is still in work to fully realize the viability of this DES with graphitic biochar and will be completed by the end of 2021.

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PRINCIPAL INVESTIGATOR: Eakalak Khan

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Metallic Environmentally Resistant Coating Rapid Innovation Initiative (MERCRII)

OBJECTIVE: *To develop wear-resistant coatings to enhance wear and abrasion resistance for lightweight alloys in extreme space environments.*

PROJECT GOAL/DESCRIPTION

Lightweight alloys such as aluminum and titanium are often specified for space systems to minimize mass. However, such alloys have poor tribological response (high friction and wear). To address this weakness, we propose to develop advanced wear- and radiation-resistant coatings for lightweight parts for use in lunar and Martian architectures, and to design unique wear characterization techniques comparing different lunar simulants. The materials will include aluminum and titanium alloys as substrates and cold-sprayed and plasma-sprayed boron nitride (BN)-based and nickel-titanium (NiTi) metallic coatings.

APPROACH/INNOVATION

Two coating types will be developed for the ubiquitous core spacecraft materials Al and Ti: BN-based coatings and NiTi-based coatings. Both coating types exhibit high wear resistance and the BN-based coatings are expected to provide radiation shielding improvement. BN-nanomaterials are well known for their excellent mechanical and thermal properties, high impact resistance, low friction coefficient, chemical inertness, corrosion resistance, and good interfacial adhesion with Al and Ti metals. It has been observed that coatings that perform best in sliding are not always the hardest but rather those with a high hardness/elastic modulus ratio. NiTi-based materials offer a unique combination of high hardness, low modulus, and extensive elastic deformation range resulting in superior static indentation load capability. Based upon laboratory static load tests performed at NASA Glenn Research Center (GRC), bearings made with NiTi alloys provide up to ten times higher tolerance to denting damage compared to conventional steel bearings. This novel bearing material has the potential to be highly resistant to damage caused by lunar and Martian dust. The coatings will be applied through two process technologies: plasma spray and

FIGURE 1. Three-body abrasion test on hBN-Al6061 coating using JSC-1A lunar simulant.

cold spray. Plasma spray is a well-known process in which powders are melted in a high temperature inert gas stream (a plasma) that is electrically heated. This process represents a lower risk path to successfully deposit the developed coatings. Cold spray is a more novel process in which powders are accelerated through a supersonic nozzle in a gas stream to extremely high speeds and impinge on the target (the sample to be coated). The goal for next year is to expose the coating to thermal cycle and radiation environments and perform tribological tests in the presence of lunar dust after exposure, to confirm the survival of the coatings in extreme environments similar to those experienced in space. The coating technology will be demonstrated to enable the use of both conventionally manufactured (CM) as well as additively manufactured (AM) mechanisms. Both manufacturing techniques are likely to be used in the Artemis and Moon to Mars architectures. The coatings will be applied to three mechanisms of action: joint, torsional, and blasting, which will be fabricated from Al and Ti. These mechanisms of action are of high interest (value) to the Human Landing System (HLS), In-Space Manufacturing (ISM), and surface operations teams. These mechanisms of action encompass commonly utilized mechanisms and will enable this technology development effort to create optimized advanced wear coating options that will protect an array of future mechanisms for the Moon, Mars, and beyond.

RESULTS/ACCOMPLISHMENTS

Initial 51NiTi plasma-sprayed coatings achieved high hardness and greater than 99% density. However, wear testing and analysis shows higher wear and friction than expected. More recent studies on plasma-sprayed 60NiTi coatings showed much higher wear resistance in pin-on-disk testing than the initial lower nickel-content samples. 60NiTi shows very encouraging results and work will continue with it. An overlay of a solid lubricant coating is a possibility and is being discussed with a possible vendor.

Initial pin-on-disk wear tests performed on hexagonal boron nitride (hBN)-Al6061 showed low wear resistance. In more recent testing, it has shown high wear resistance in the presence of the three-body abrasive Zircon; this was unexpected because this simulant is known to be especially abrasive (it was chosen for wear tests, in part, because of its high abrasivity). This will be studied further.

Another regolith simulant, JSC-1A, was used to characterize three-body abrasive pin-on-disk wear in a more typical lunar regolith environment; these tests are on-going. Plasma Processes, an industry project partner, attempted to cold spray 60NiTi, but they were not able to do so. This material is very spring-like (high elastic deformation under load) at room temperature. Any impact energy that goes into the particle in a collision during deposition is stored and nearly fully released elastically, making it difficult to produce a coating of any thickness without the introduction of high temperature.

Cold spray coatings of hBN-Al were also deposited at Plasma Processes with 95% density, but with very low hardness and poor wear performance. Based on its poor performance, this hBN-Al coating has been eliminated as a possible coating for this Early Career Initiative (ECI) project. Further analysis and testing are planned as we seek to determine how wear resistance can be improved. hBN-Al coatings have shown problems with hBN break-down during plasma spray with helium. Plasma Processes has delivered some coupons to MSFC of hBN-Al coatings plasma sprayed with nitrogen (allowing for lower temperatures) in an attempt to preserve hBN during plasma spray. MSFC performed wear testing with and without regolith and used scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS) to characterize these new coatings. Better wear performance was observed if compared with plasma spray samples with helium; however, the wear performance is still below expectation. The ECI project is discussing dust mitigation work with ten different projects at multiple centers around NASA (including MSFC, Langley Research Center, Jet Propulsion Laboratory, NASA Headquarters, and Kennedy Space Center) and at universities to learn and to look for collaboration opportunities.

SUMMARY

Economical and durable NiTi- and BN-Al-based metallic coatings for prolonged use on the lunar and Martian rovers will be developed using cold spray and plasma spray techniques. Additionally, additively manufactured (AM) aluminum and titanium alloys will be tested. Wear tests will include three-body abrasion, and surface erosion (e.g., simulating Mars storms). Test results will also demonstrate differences in wear for different lunar simulant types and will demonstrate the effects of particle radiation on material wear resistance. Finally, the coatings will be demonstrated on simulated space environments applied on mechanisms relevant to HLS and ISM.

PRINCIPAL INVESTIGATOR: Sara Rengifo

PARTNERS: Langley Research Center (LaRC); Glenn Research Center (GRC); Florida International University (FIU); Plasma Processes, LLC

FUNDING ORGANIZATIONS: Space Technology Mission Directorate (STMD)

FOR MORE INFORMATION:
https://nasa.sharepoint.com/sites/STO_jamboree/SitePages/Development-of-Coated-Additively.aspx

Spacecraft Oxygen Recovery

OBJECTIVE: *To develop hardware that increases oxygen (O_2) recovery from metabolic carbon dioxide (CO_2) to greater than 50%.*

PROJECT GOAL/DESCRIPTION

The state-of-the-art process reactor (Sabatier) processes less than 50% of available metabolic carbon dioxide (CO_2) because hydrogen (H_2) is limited to that produced by the Oxygen Generation Assembly (OGA); about half the reacted H_2 within the Sabatier is lost as methane and is not converted to water. To increase oxygen (O_2) recovery necessary for long duration missions, the Spacecraft Oxygen Recovery (SCOR) project is developing two different technologies that are capable of recovering up to 100% of the oxygen from metabolic CO_2: a Continuous Bosch Reactor (C-Bosch) brassboard developed by Umpqua Research Company (URC) and a Hydrogen Recovery by Carbon Vapor Deposition (CVD) brassboard developed by Honeywell.

APPROACH/INNOVATION

The C-Bosch replaces the Sabatier and eliminates the need for a postprocessor. The reactor is fed H_2 from the OGA and CO_2 captured by the CO_2 removal system, producing particulate carbon and water. Theoretically, the Bosch process can recover 100% of the O_2 from CO_2.

A delta Critical Design Review was held March 2–3, 2021, for the C-Bosch technology. The review resulted in several findings: (1) significant progress was made in many technical areas; (2) the collaboration toward development of an initial kinetic model was considered noteworthy; (3) too much risk remained in the design to warrant exercising the contract option for hardware fabrication; (4) the kinetic model should be completed as a deliverable to our Advanced Exploration Systems (AES) customer. The existing contract with URC was allowed to close and a new, reduced-scope, limited-duration effort to perform additional test series was negotiated with URC to complete the kinetics model in cooperation with NASA systems analysts. The contract was signed on July 22, 2021, and included additional focus on humidified kinetic studies, temperature effects, and catalyst usage. The data will be used to complete the kinetic model, which will be delivered to the AES Life Support Systems (LSS) project.

The Hydrogen Recovery by CVD technology receives methane (CH_4) from the Sabatier and reduces it to H_2 and solid carbon at very high temperatures (≈1,200 °C). The H_2 is recycled back to the Sabatier to allow for increased O_2 recovery via water production, while the carbon is deposited within preformed carbon fiber substrates, eliminating soot and particulate carbon typical of O_2 recovery systems. Multiple preforms are loaded into a cartridge that fits into the reactor. The system requires two reactors in order for it to run continuously. As one reactor is processing CH_4, the other is undergoing substrate cartridge removal and replacement. The filled substrates are hard and soot-free, and can be handled without transfer of carbon particulates. This is an advantage over other carbon-forming O_2 recovery systems. Figure 1 shows a fresh, unused carbon fiber substrate.

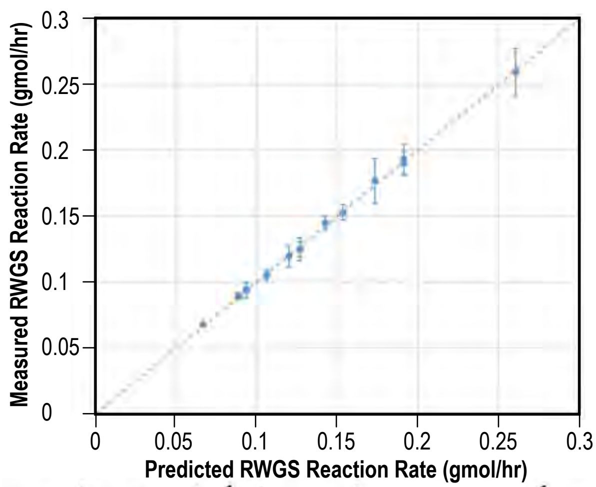
FIGURE 1. Shows a fresh, unused carbon fiber substrate.

The CVD brassboard will be delivered with high temperature HAYNES®-alloy metallic reactors. The CVD operating temperatures are very close to the documented temperature limits of the alloy used and a vacuum jacket was added to reduce delta pressure stresses on the reactor wall, in order to mitigate possible thermal deformation (creep) of the metal. Metallurgical characterization of samples of the advanced high-temperature alloys used in manufacture of the metal reactors is being performed. This characterization will give insights into how the integrity of the reactors may hold up during planned testing and on overall operational life, which is expected to be sufficient for test operations but not for flight utilization. The Advanced Exploration Systems/Life Support Systems (AES/LSS) project has funded a contract with Honeywell to design new reactors using ceramics or composites, which are expected to be more reliable under such high temperatures for long durations. The use of these advanced materials will result in a significant mass reduction and elimination of the vacuum jacket, therefore reducing the mass of the total system.

Early on, the Honeywell CVD project identified a potential risk to the Sabatier catalyst from the CVD recycle product gas. In addition to hydrogen, the product gas stream will contain unpyrolyzed methane and traces of other compounds including acetylene and benzene. To understand the effects and provide a mitigation strategy, the project purchased a quantity of Sabatier catalyst from Collins to be tested at MSFC using the Carbon Dioxide Reduction Catalyst Test Stand (COR-CaTS) shown in figure 2. Testing was performed using three gas mixes as determined by Honeywell's model that predicts the product gas of the CVD reaction at different levels of conversion efficiency. The dry gas testing was completed in 2019. Humidified gas testing was completed June 2021. Data analysis showed slightly decreased performance of the Sabatier catalyst, but the team was unable to determine the significance of the decrease. The data was sent to NASA Johnson Space Center where a statistician is reviewing it. In addition, samples of the spent catalyst for each gas run were sent to the MSFC Materials Lab for analyses. Results are pending.

RESULTS/ACCOMPLISHMENTS

The URC Continuous Bosch reactor kinetics model is expected to be completed in March 2022 and will provide valuable information regarding the Bosch process. For instance, the Series Bosch system is currently in development under the AES/LSS project at NASA Marshall Space Flight Center (MSFC). This system is different from the Continuous Bosch Reactor as it employs two reactors instead of one. The kinetics model could be modified to support the Series Bosch development and possibly a continuation of development for the Continuous Bosch Reactor.



$$r_{RWGS} = k_{RWGS} S_V \left[P_{CO_2} P_{H_2} - \left(\frac{1}{K_{RWGS}} \right) P_{CO} P_{H_2O} \right] \frac{1}{(P_{CO_2})^{0.33} (P_{H_2})^{0.21} (P_{CO})^{0.23} (P_{H_2O})^{0.1}}$$

FIGURE 2. Kinetics data for the Reverse Water Gas Reaction to be used to increase accuracy of the Continuous Bosch Reactor.

The Honeywell CVD brassboard includes 2 reactor assemblies mounted on a skid with the balance of plant (BOP) including control and safety systems as shown in figure 3. All critical components of the BOP have been ordered and received and assembly is underway. In addition, the LabView-based control system has been updated and is currently being integrated with sensor components, flow meters and other electrical systems, which will be followed by a full check-out.

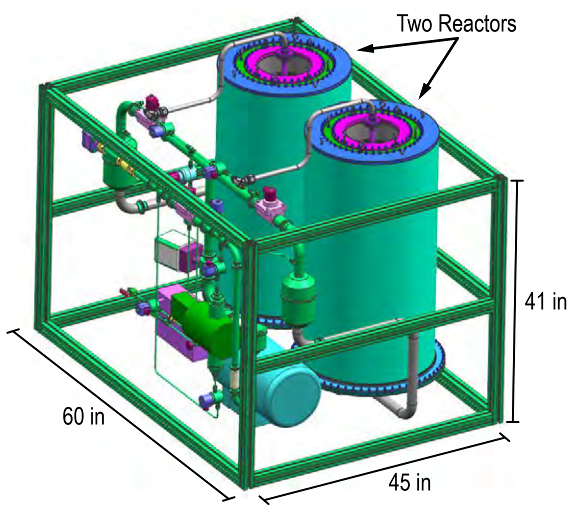


FIGURE 3. NASA MP brassboard skid layout.

Delayed by COVID, the final shipment of the high temperature advanced alloy stock for reactor fabrication was received May 21, 2021. Machining is underway. Fabrication of the reactors involves a critical series of steps, including transfer between facilities for machining, welding, x-ray verification, and coating with a Platinum-Aluminum alloy. Completion of fabrication of the reactors is expected by early February 2022, at which time Honeywell will integrate the reactors into the skid and test the system prior to delivery to MSFC.

Receipt of the CVD brassboard by the AES/LSS project at MSFC is expected at the end of June 2022. Under AES/LSS, both standalone and integrated testing is planned. The stand-alone testing will provide confirmation that the system works as expected and allow the test operators to become familiar with the system. The CVD brassboard will then be integrated with Precision Combustion's Sabatier as a risk mitigation step prior to possible integration with the flightlike Collins Sabatier and operation of the EDU.

SUMMARY

The SCOR project technologies are in the final stages of completion. The Honeywell Hydrogen Recovery by CVD brassboard and Umpqua's work on the model are expected to be completed during FY22. The AES/LSS project will take ownership of these deliverables. Testing of the Honeywell Hydrogen Recovery by CVD is expected to begin once MSFC receives it. The AES/LSS contract with Honeywell to design advanced material reactors will continue through to August 2022, at which time a decision will be made on whether or not to continue into the next year.

PRINCIPAL INVESTIGATORS: Christine Stanley; Steven Yates, Honeywell; John Thompson, URC

PARTNERS: Honeywell and Umpqua Research Company

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office, Game Changing Development (GCD) Program

TA07:

Exploration Destination Systems

Screening, Identification and Development of Task-Specific Acidic Ionic Liquids for the Dissolution and Recovery of Metals and Silica from Regolith

OBJECTIVE: *To use computational modeling to enable the recovery of oxygen and metals from regolith by using ionic liquid solvents.*

PROJECT GOAL/DESCRIPTION

NASA's plans for future long-term, deep-space exploration missions will require the use of in situ resources to reduce the total launch mass, and thus cost, required for these missions. Lunar and Martian regolith are a valuable resource, containing both oxygen and a variety of metals, such as iron, aluminum, and magnesium. Oxygen is useful for both breathing air and as a propellant for rocket engines, while the metals are potential feedstocks for in-space additive manufacturing. However, extracting these materials from regolith is technically challenging, as terrestrial processing techniques are not suitable for use in a space environment. As such, NASA has been pursuing a number of novel regolith processing technologies.

One such technology uses a class of novel materials known as ionic liquids (ILs) to dissolve the regolith, allowing for the electrochemical recovery of metals and oxygen. Initial experimental work has produced promising results, but these experiments are time- and material-intensive. As such, the goal of this project is to use computational modeling to improve the understanding of how ILs dissolve regolith and to allow for the design and selection of ILs with improved regolith processing performance, thus increasing the efficiency of metals and oxygen recovery from regolith.

FIGURE 1. Mojave Mars Simulant 2 (MMS-2) Martian regolith simulant.

APPROACH/INNOVATION

The key innovation in this work is the use of ILs to dissolve regolith. The use of ILs allows for the process to occur at or near room temperature, compared to other approaches which require elevated (>900 °C) temperatures. Lower operational temperatures require significantly reduced power inputs, reducing the amount of infrastructure needed to support regolith processing.

The major technical challenge for the work is developing appropriate computational models for both the ILs and the regolith being dissolved. The interactions between these species during the dissolution process are complex, and well-designed models are critical for ensuring that the data produced by simulations accurately reflect experimental results.

Computational efforts were thus focused on designing appropriate force field models for ILs, studying their interaction with select mineral components found in regolith (e.g., alumina or silica), and comparing the computational results to experimental values. Once these values agree, future work can use this modeling to design or select ILs that perform well at dissolving regolith, saving the significant time and expense of screening ILs via solely experimental work.

RESULTS/ACCOMPLISHMENTS

This effort has produced a number of accomplishments, including:

(1) A new molecular simulation was developed based on the conductor-like screening model for realistic solvation, which was found to be a promising approach for the identification of ILs for regolith dissolution.

(2) A new IL solvent, 1-ethyl-3-methylpyrrolidinium hydrogen sulfate, was identified as a promising candidate for regolith digestion via simulation and the performance of this IL at processing regolith was verified experimentally. This new IL also demonstrated improved extraction capability as compared to prior ILs, specifically in its ability to extract calcium from regolith simulant.

(3) An alternative non-aqueous solvent, ethylene carbonate, was identified for use as a cosolvent with ILs to enhance regolith digestion.

SUMMARY

The use of in situ resources for life support, manufacturing, and construction is a vital part of any future deep-space exploration missions. The simulations developed in this project will enable the utilization of these resources by enabling the high throughput screening of ILs for use in the extraction of metals and oxygen from regolith. Such screening will result in superior performance of the extraction process which will reduce mass, energy, and volume requirements for processing hardware.

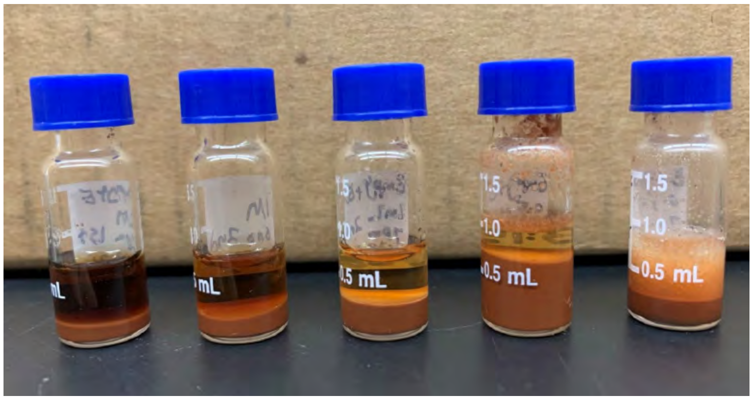


FIGURE 2. MMS-2 simulant being digested by solutions of IL and cosolvents.

PRINCIPAL INVESTIGATOR: Eakalak Khan, University of Nevada Las Vegas

PARTNER: University of Nevada Las Vegas

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Developing a Novel Method to Bond Planetary Regolith to Form Rigid Structures for Space-Based Habitats

OBJECTIVE: *To investigate and explore the possibility of using ionic liquids to form structural tiles comprised of Martian regolith for use in for deep space autonomous construction technologies.*

PROJECT GOAL/DESCRIPTION

Future manned exploration missions to Mars will require the construction of infrastructure, including landing pads, berms, and habitats, on the Martian surface. The mass of materials needed for this work is large, which precludes their supply from Earth due to the high cost of launch. As such, these structures will need to be fabricated from in situ resources. Martian regolith is a promising material for use in construction, but new manufacturing techniques using regolith need to be developed as terrestrial construction techniques are not well suited for in-space use. This project explored the use of ionic liquids (ILs) to enable the low-temperature sintering of Martian regolith to allow for the fabrication of structural tiles.

FIGURE 1. Martian regolith simulant after sintering with ILs.

APPROACH/INNOVATION

The innovative feature of this work is the use of novel acidic ILs to sinter the regolith. The use of these ILs allows for the regolith processes to be performed at or near room temperature, which greatly reduces the energy required compared to traditional sintering processes. Furthermore, the ILs used are fully recovered, allowing for the processing of a theoretically infinite amount of regolith without any additional launch mass, which could greatly reduce the cost of constructing infrastructure on the Martian surface in support of long-term exploration missions.

The goal of this project was to evaluate the performance of select ILs at sintering Martian regolith simulant. This was done experimentally, focusing on sintering conditions (e.g., time, temperature, compression) and the mechanical properties of sintered simulant, as well as computational efforts to better understand the interaction of ILs and simulant. Together, these data will allow for the development and refinement of an IL-based sintering process and the future preparation of large-scale structural components for in-space construction.

RESULTS/ACCOMPLISHMENTS

A joint computational and experimental effort to optimize the selection of ILs for regolith processing has been completed. Eleven ILs (one from commercial sources and ten from in-house synthesis) were evaluated for their ability to sinter Martian regolith simulant. Coupons for testing the mechanical properties of the sintered simulant were prepared, although actual testing was delayed due to COVID-19 impact.

Computation efforts focused on performing molecular dynamics simulations on two of the best performing ILs with select terrestrial analogues of the mineral components found in Martian regolith. Alumina, hematite, and silica were chosen as the analogues to be studied, and the simulations offered insight into how the ILs dissolve said minerals. Both ILs were found to have favorable interactions with hematite and alumina, which are both metal oxides; and showed less favorable interactions with silica. Such interaction behavior could explain the formation of the white precipitates in figure 2 and suggests that beneficiating Martian regolith to have higher mineral oxide concentrations could lead to superior sintering performance.

FIGURE 2. White precipitates indicative of silicates found on the surface of Martian regolith simulant after sintering with ILs.

SUMMARY

The use of in situ resources for in-space construction is a vital component for any long-term mission to Mars. The IL-based regolith sintering processes developed through this work is a promising method to enable the fabrication of construction components while also minimizing launch mass requirements as well as process energy inputs. The work performed by this study will serve as a foundation for scale-up of the sintering process, allowing for the construction of large structural items such as landing pads, berms, and habitats; allowing for the establishment of a human presence on Mars and beyond.

PRINCIPAL INVESTIGATOR: Hunain Alkhateb, University of Mississippi

PARTNER: University of Mississippi

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

MSFC Autonomous Systems and Operations (ASO)

OBJECTIVE: *To develop and demonstrate autonomous systems technology, including: automated planning and scheduling systems, plan execution technology, fault management, and crew decision support technology for future exploration missions.*

PROJECT GOAL/DESCRIPTION

Autonomous operations of spacecraft will be essential to mitigate the effects of time delay for future human exploration missions. Autonomy encompasses both crew decision support to enable astronauts to operate spacecraft systems without the assistance of Earth-based mission control, and vehicle systems automation to reduce crew workload and operate dormant spacecraft when crew are not present. The NASA Marshall Space Flight Center (MSFC) Autonomous Systems and Operations (ASO) team is maturing technology by demonstration onboard the International Space Station (ISS) and analog testbeds for infusion into future exploration missions.

APPROACH/INNOVATION

Autonomous Mission and Operations-EXpedite the PRocessing of Experiments to Space Station Rack-2.5 (AMO-EXPRESS-2.5) is a software-only payload designed to evaluate crew self-scheduling and activity monitoring for future exploration missions. It will be deployed onboard ISS, partly on the Operations LAN (OpsLAN) and partly in the Payload Multiplexer Demultiplexer (PLMDM). The software allows ISS crew to schedule and execute a simulated EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Rack power-on and power-off activity. AMO-EXPRESS-2.5 uses a simulated EXPRESS Rack, specifically a simulation of EXPRESS Rack 7 (ER7), to reduce ISS risk and increase flexibility, making it easier to achieve the demonstration objectives. Both the simulation of ER7 and the automation controlling it are implemented as Timeliner bundles that run on the PLMDM.

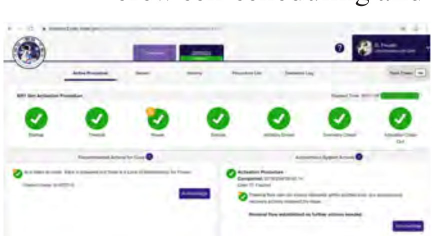


FIGURE 1. UI EXPRESS tab for AMO-EXPRESS-2.5.

AMO-EXPRESS-2.5 will demonstrate the crew's ability to change their daily schedule and will subsequently execute and monitor a complex system power-up and configuration task, demonstrating both crew autonomy and vehicle automation. AMO-EXPRESS-2.5 demonstrates a transfer of authority from Mission Control to the crew. AMO-EXPRESS-2.5 builds on prior executed crew autonomy experiments and demonstrations onboard ISS. In earlier demonstrations, the exact time of the power-up and configuration was previously planned, which is common practice. In the current work, however, the crew must schedule the activity on their own within their daily timeline and perform the activity later on the same day. Numerous simulated fault conditions are introduced, requiring the crew to understand the state of the activity and perhaps take action to respond.

FIGURE 2. UI Overview tab with Modify Timeline pop-up for AMO-EXPRESS-2.5.

AMO-EXPRESS-2.5 will evaluate crew self-scheduling and system awareness activities, as well as monitoring capabilities. This demonstration will have the crew self-schedule a simulated ER7 powerup and configuration activity. The crew will later initiate and monitor this activity. Each simulated activity will exercise one of several different simulated ER7 scenarios, including a variety of off-nominal conditions requiring different responses. The crew will evaluate and react to each scenario and replan their activities as needed. The demonstration is to select a day in advance that allows the crew time to schedule and execute the activity, but let the crew perform all other steps: to select when to perform the powerup; to initiate and monitor the activity; and to respond as needed. Mission Control will only be on hand to ensure the demonstration goes smoothly. This demonstration will prove the crew's ability to autonomously manage spacecraft systems without assistance from Mission Control. The successful demonstration will validate the ability of the crew to choose when to perform activities, as well as monitor their execution and to require the crew to respond to off-nominal situations.

This work represents a significant increase in demonstrated autonomy capability compared to previous work. This demonstration uses systems with rich electronic command and telemetry interfaces, and demonstrates how crews can autonomously respond to off-nominal scenarios. AMO-EXPRESS-2.5 integrates the automation used in payload autonomous operations directly into our technology for use by the crew. Unlike previous work, the current demonstration integrates scheduling and procedure tools in a single application, and features a complete end-to-end integration of scheduling, procedure display, and system automation. Also, unlike previous work, the AMO-EXPESS-2.5 demonstration differs in its concept of operations, allowing the crew to schedule and perform activities on the same day. It is this realtime flexibility in manipulating the daily activity plan that is a critical enabler of crew autonomy not previously demonstrated in space.

RESULTS/ACCOMPLISHMENTS

Autonomous science operations onboard the ISS to this point have been tremendously successful; however, these activities are still planned and initiated by flight controllers. The previous AMO-EXPRESS demonstrations have been particularly noteworthy accomplishments, but they have demonstrated only a subset of autonomy capability needed for future exploration missions. While AMO-EXPRESS-2.5 will not operate until early 2022, the results from the demonstration are expected to validate the crew's ability to autonomously manage a spacecraft without assistance from the ground. The crew will be able to autonomously operate systems, self-schedule activities, respond to off-nominal situations, perform fault recovery, and replan their activities as needed.

SUMMARY

Great strides have been made with respect to enabling crew autonomy, reducing the workload of ground controllers, assisting the crew, and increasing operational reliability. The natural progression would be to increase all levels of automated intelligence and to eventually allow for fully automated vehicles and payloads with real-time replanning. With Artemis flights and Gateway on the horizon, the hope is that the steady stream of autonomous science payloads will grow. The requirements for automation for future missions beyond low-Earth orbit will help the crew enable autonomy to perform all aspects normally allocated to the ground controllers.

PRINCIPAL INVESTIGATOR: Jeremy Frank, Ames Research Center (ARC)

CO-PRINCIPAL INVESTIGATOR: A. Haddock, Marshall Space Flight Center (MSFC)

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office

FOR MORE INFORMATION:
https://techport.nasa.gov/view/32946

Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project

OBJECTIVE: *To develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure elements on the lunar surface via construction of landing pads, habitats, shelters, roadways, and blast shields using lunar regolith-based materials.*

PROJECT GOAL/DESCRIPTION

NASA needs the capability to consolidate and stabilize regolith on large scales, including microwaves and additive manufacturing-based construction or additive construction (AC), to mitigate dust via in-situ manufacturing and repair. This capability will sustain a long-term human presence on, and the utilization of, the Moon. It also provides a thermal heater for volatile extraction from regolith, a heating source, and ultimately radiation protection structures for habitats. This capability currently does not exist. The goal of the Moon to Mars Planetary Autonomous Construction Technology (MMPACT) project is to develop the tools that will create the capability to construct this necessary infrastructure on the lunar surface.

APPROACH/INNOVATION

The Lunar Surface Innovation Initiative (LSII) Formulation Planning Guidance for Lunar Construction identified the following capability needs that are addressed within the MMPACT project.

- Material and construction requirements and standards. MMPACT is partnered with Space Exploration Architecture (SEArch+, the 3D Printed Habitat Challenge Design Award Winner in two Phases), BIG, Ionospheric Connection Explorer (ICON) (who is using AC to build the only permitted, seismic-compliant housing in the United States and Mexico), and other members of industry and academia to support construction requirements and standards development. MMPACT also partners with materials experts within NASA, industry, and academia to support material requirements and standards development.
- Increased autonomy of operation. MMPACT is partnering with the Defense Innovation Unit (DIU); the Air Force Civil Engineering Center (AFCEC); the Texas Air National Guard (TANG); and ICON to increase autonomy of operations and remote operations capabilities for construction systems.
- Scale of construction activities. MMPACT is leveraging current technology elements at ICON and NASA Marshall Space Flight Center (MSFC), as well as maturing microwave processing protocols and thermal design to a Technology Readiness Level of six. The team plans for early demonstrations of subscale planar construction capabilities. The team will also develop lunar Job Site Mobility Systems (JSMs) and Materials Deposition System (MDS) prototypes. The team is targeting a MDS proof of concept lunar surface technology demonstration in 2026 on a Commercial Lunar Payload Services (CLPS) lander.
- Hardware operation and manufacturing under lunar environmental conditions. The MDS and JSM candidates will be evaluated, downselected, and performance tested in a thermal vacuum (TVAC) chamber. The prototype microwave system will also be TVAC tested. Resulting materials will be characterized for properties used in structural models. This portion of the effort leverages (1) MSFC's expertise and experience in microwave and additive manufacturing construc-

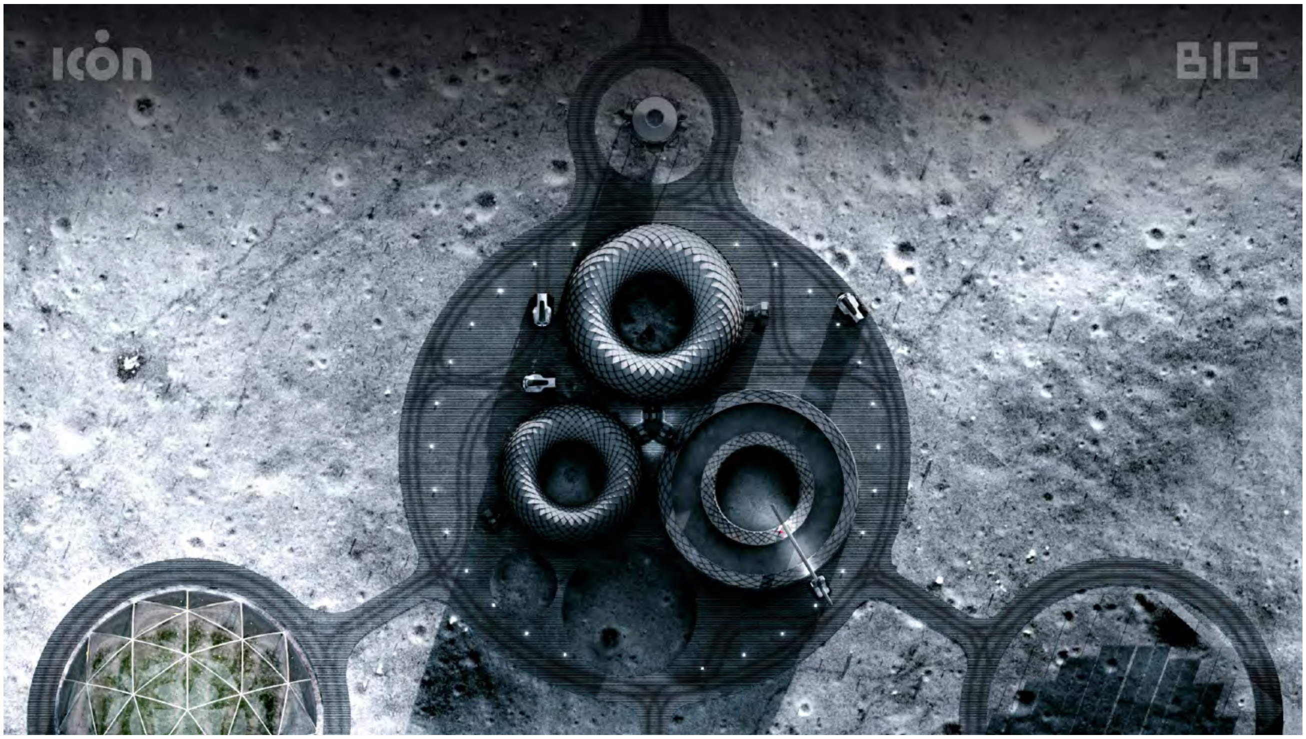


FIGURE 1. IIllustration of construction activities near the south pole of the Moon. Image used with permission from MMPACT partners ICON and the Bjarke Ingels Group (BIG).

tion materials and technologies, (2) industry advances made from the 3D Printed Habitat Centennial Challenge, and (3) extensive partnering with the Air Force.

- Long-duration operation of mechanisms and parts. The MMPACT payload will be designed for dust mitigation, leveraging LSII programmatic element linkages/interfaces and a dust mitigation technology survey completed by yet2. The materials will be selected based on their ability to operate in lunar environmental conditions. The technology will be designed for robustness, and robotic field reparability, and assessed for vulnerabilities in the lunar environment.

RESULTS/ACCOMPLISHMENTS

The MMPACT team developed a lunar construction roadmap that identifies the path through two demonstration missions and two qualification missions to establish a full construction capability on the lunar surface. The first lunar Demonstration Mission, DM-1, is planned for late 2026. The team defined technology gaps and closure plans in support of the Space Technology Mission Directorate (STMD) Strategic Implementation Plan and incorporated them into the MMPACT demonstration and qualification mission goals. Towards those goals, the three primary elements of MMPACT have multiple accomplishments to report:

- Olympus Construction Technology. The Lucy Student Pipeline Accelerator and Competency Enabler (L'SPACE) student-designed Lunar Plume Alleviation Device (LunarPAD), printed by ICON in October 2020, was hot-fire tested at Camp Swift in Bastrop, TX in March 2021. The PAD design successfully diverted the engine plume and prevented disturbance of the surrounding soil. Samples of cementitious materials have been cast and cured at different atmospheric pressures to quantify the effect of water vapor pressure on porosity of cement/regolith simulant blends.

- Construction Materials Development. The Construction Materials team is acquiring data on materials to identify the most promising AC material for DM-1. Lunar regolith simulants have been acquired and characterized via multiple techniques. Mississippi State, via a Cooperative Agreement Notice contract, produced In-Situ Resource Utilization (ISRU)-based ductile iron ingots for use as printed electronic inks. Their process utilizes simulated extracted metals from simulant and carbon from the Environmental Control and Life Support System Bosch process. Penn State will fly a geopolymer experiment to the International Space Station (ISS) in early 2022.
- Microwave Structure Construction Capability. Multiple organizations conducted testing to define high temperature (750 °C) bakeout for simulant JSC-1A to remove non-lunar-like materials (e.g., terrestrial weathering products). Previously, only adsorbed water was removed at 200 °C. The team initiated large-scale microwave sintering in a manner that could be performed on the Moon. Previous work was small scale and took advantage of microwave reflections from the experiment setup, or a non-lunar-like microwave applicator. The team accomplished sintering in air and in a dirty thermal vacuum chamber (DTVAC). Microwave sintering processing protocols are being refined.

SUMMARY

The MMPACT project has made significant strides in both strategic planning and accomplishing specific work in FY21. The project is on track to meet all requirements for a successful lunar DM-1 in 2026.

PRINCIPAL INVESTIGATOR: Raymond G. "Corky" Clinton, Jr.

PARTNERS: ICON, BIG, SEArch+, Jet Propulsion Laboratory, Kennedy Space Center, Langley Research Center, Jacobs Space Exploration Group, Blue Origin, Pennsylvania State University, Mississippi State, University of Mississippi, Drake State, Crown College, University of Nevada in Las Vegas, Colorado School of Mines, University of Alabama in Huntsville, Georgia Institute of Technology, Clarkson University, Dr. Holly Shulman, RW Bruce Associates LLC, Microwave Properties North, Radiance Technologies, Southern Research, Branch Technology, Canvas, Kappler, Southeastern Universities Research Association, JP Gerling, United States Air Force, AFCEC, TANG, DIU, Logical Innovations, Aerie Aerospace, MTS, and Space Resource Extraction Technologies

FUNDING ORGANIZATION: Space Technology Mission Directorate (STMD)

FOR MORE INFORMATION:
https://www.nasa.gov/oem/surfaceconstruction

TA08:

Sensors and Instruments

LargE Area Burst Polarimeter (LEAP)

OBJECTIVE: *To provide a new dimension to the understanding of astrophysical jets and black hole environments.*

PROJECT GOAL/DESCRIPTION

The LargE Area burst Polarimeter (LEAP) is a mission concept currently under review by NASA that will radically improve the understanding of some of the most energetic phenomena in the Universe by exposing the underlying physics that governs astrophysical jets and the extreme environment surrounding newborn compact objects. LEAP will do this by making the highest-fidelity polarization measurements to date of the prompt gamma-ray emission from a large sample of Gamma-Ray Bursts (GRBs). The LEAP science objectives are met with a single instrument—a wide field of view (FOV) Compton polarimeter that measures GRB polarization over the energy range from 50–500 keV and performs GRB spectroscopy from 20 keV to 5 MeV.[1]

APPROACH/INNOVATION

The LEAP instrument is mounted as an external payload on the International Space Station (ISS). The instrument is based on standard, well-proven technologies with few technical challenges. The large FOV, derived from the random distribution of GRBs in both space and time, means that there is no preferred pointing direction on the celestial sphere. This feature, combined with the resources and well-understood operations of the International Space Station (ISS), provide the foundation for a straightforward mission design.

The primary innovation is the novel configuration of the ≈1,000 LEAP detector elements and the use of ISS to support

FIGURE 1. LEAP project logo and illustrative design.

the large detector volume needed to achieve the required sensitivity, rather than the technology itself. The full instrument consists of seven independent LEAP Polarimeter Modules (LPMs), a Passive Shielding Assembly (PSA), a star tracker, a Global Positioning System (GPS) receiver, and associated electronics. Each LPM includes a 12 × 12 array of independent scintillation detectors designed to measure Compton scattered photons, which provide a measure of polarization. The array is pointed toward deep space and attached to an external ISS site.

RESULTS/ACCOMPLISHMENTS

LEAP recently completed Phase A of its lifecycle with the submission of a detailed Concept Study Report (CSR). The mission is currently under consideration for continuation to Phase B. The CSR provides details of the instrument and mission concept and includes a schedule and cost estimate. If selected, LEAP would launch in 2025 and its baseline mission would last for three years, with the possibility to extend.

In preparation for continued instrument development, a prototype LPM was fabricated, assembled, and tested at the University of New Hampshire, which is the lead institution for LEAP. Results from the prototype validated the simulated response, indicating positive proof-of-concept. This prototype LPM has a reduced number of independent detector elements, 25 as opposed to 144, and uses benchtop readout electronics. Polarimetry and spectroscopic performance were assessed and reported in Oñate Melacio et al. in 2021.[2]

SUMMARY

LEAP is a Compton scattering polarimeter that uses low-risk technologies assembled in a unique way to maximize its sensitivity and to make optimal use of ISS infrastructure and resources. High-sensitivity polarization measurements of the prompt GRB emission result in a number of insights regarding the nature of GRB jets that will allow LEAP to:

- examine the formative stages of the most extreme relativistic jets;
- quantify the sharing of energy between matter and magnetic fields in GRB jets;
- identify the nature of prompt GRB radiation;
- provide the first simultaneous polarization and spectroscopy measurements for a large sample of prompt GRB emissions to enable detailed comparison with theoretical models.

LEAP's science goal to improve the understanding of astrophysical jets and the environment around newborn black holes and neutron stars directly addresses questions raised by the 2010 Astrophysics Decadal Survey: (1) "How do black holes grow, radiate, and influence their surroundings?" The need for x-ray polarimeters was called out as a needed new facility; and (2) How does "... magnetism affect the evolution of stars?" Even after 10 years, these questions remain largely unanswered and are even more important now with the recent discovery of gravitational waves. The 2013 NASA astrophysics roadmap (Enduring Quests/ Daring Visions) suggested possible topics for focused small-scale missions. LEAP embodies two of the suggested missions: (1) monitoring energetic transients with x- and gamma-ray telescopes; and (2) measuring x- and gamma-ray polarization.

REFERENCES:

1. Mark L. McConnell, et al., "The LargE Area burst Polarimeter (LEAP) a NASA mission of opportunity for the ISS," Proc. SPIE 11821, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXII, 118210P (24 August 2021); doi: 10.1117/12.259473.

2. Karla Oñate Melecio, et al., "Evaluation of a prototype detector for the LargE Area burst Polarimeter (LEAP)," Proc. SPIE 11821, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXII, 118210Q (24 August 2021); https://doi.org/10.1117/12.2594568.

PRINCIPAL INVESTIGATOR: Mark L. McConnell, University of New Hampshire

DEPUTY PRINICIPAL INVESTIGATOR: Jessica Gaskin

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Small Form Factor Optical Technologies for Future Satellite-based Lightning Detectors

OBJECTIVE: *To design a high-resolution lightning detector that can be used in small satellite missions.*

PROJECT GOAL/DESCRIPTION

The need for satellite-based observations of lightning is increasing, as this data can provide key insights into Earth's thunderstorms and the hazards they pose, including their response and effects during a changing climate. To detect lightning from space, lightning mappers require very fast cameras and lens systems that can confine light into a very narrow window of wavelengths. This project utilizes advancements in camera sensor and optics technologies made since the early 1990s (when existing lightning mappers were designed) to design a smaller, lighter-weight, and higher-resolution lightning detector for future small satellite missions.

APPROACH/INNOVATION

Automated optical detection of lightning from the vantage point of space requires a very fast camera capable of taking pictures of clouds every 0.5–2.0 ms in various lighting conditions. Additionally, higher-resolution sensors are needed to detect small lightning flashes that frequently occur in severe storms but tend to evade current satellite-based lightning detectors. The sensor must be sensitive enough to detect the relatively lower number of lightning flash photons emanating from thick clouds, as well as have sufficient dynamic range so the photons from the brightest clouds and flashes do not saturate the sensor's pixels. Achieving such high frame rates at high resolution is a technical challenge for charged coupled device (CCD) sensors, which offer great light sensitivity and dynamic range and as such have been used in space-based lightning detectors.

The capabilities and availability of complementary metal-oxide-semiconductor (CMOS) sensors have improved dramatically since the 1990s, such that they are now more ideal than CCDs for space-based lightning detection applications. In this project, we surveyed the existing CMOS sensor trade space and identified three candidates that meet the minimum resolution, frame rate, and radiometric performance requirements for a new 1–2 km resolution lightning mapper. This lightning mapper is being designed to detect small and faint lightning flashes, which are often prevalent in severe storms but largely missed by existing lightning mappers relied upon by operational weather agencies such as the National Oceanic and Atmospheric Administration's National Weather Service.

The largest component of satellite-based lightning detectors is the optical assembly, which holds the lens system. Existing lightning detectors use several refractive lens elements to collimate light through the filter, which makes the optical assembly rather long. The primary challenges to reduce the size of the optical assembly used by existing lightning detectors results from the requirements for a wide field of view (80° × 80°) and an ultranarrow bandwidth filter (<1.5 nm). Advancements in the fabrication and design of freeform optics, which are surfaces capable of more efficiently bending light over smaller distances than traditional spherical or aspherical lens elements. Incorporating freeform optics into these assemblies would potentially allow for a smaller and lighter optical imaging system. Hence, we considered the feasibility of using freeform optics in designing a more compact and lightweight optical assembly for future lightning detectors. Since a wide field of view can be a challenge in designing a reflective system, we revisited the refractive lens design used by existing lightning imagers and focused on reducing its length.

We plan to use the new optical imaging system design from this project to build a multispectral lightning detector with transformative capabilities that is small enough to be hosted on a CubeSat. In particular, the system is being developed for a future proposal to an Earth Venture-class mission concept called CubeSpark, which will use a constellation of small satellites to obtain novel 3D observations of lightning on a global scale.

RESULTS/ACCOMPLISHMENTS

The three commercially available CMOS sensors considered in our detector trade study consist of very small pixels, which is common of high-resolution CMOS sensors. Hence, pixel binning is required to achieve acceptable signal-to-noise ratios (SNRs). The Lince5M sensor produced by Teledyne e2v scores highest, providing greatest SNR ratio at the lowest event detection threshold required, as seen in figure 1. We plan to integrate this CMOS sensor into a camera system capable of acquiring 12-bit images every 1 ms, and then perform a series of tests to verify our performance simulations.

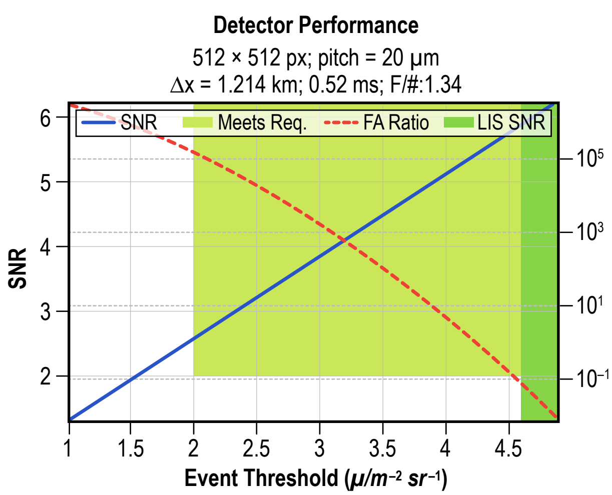


FIGURE 1. Simulated detector performance shows that weak lightning events can be detected by the e2v CMOS sensor with an SNR >2.

Through a collaboration with Goddard Space Flight Center's Optical Design Laboratory, we deemed that freeform reflective optics will not achieve a wide enough field of view needed to observe the convective pulses of a thunderstorm from low Earth orbit using a single camera system. Since space is of the essence on a CubeSat, a multicamera system to image a single wavelength is not ideal; hence, a refractive system will be required. To reduce the size and complexity of the traditional refractive optics design, which is used in most lightning mappers, a single hemispheric lens coated with a narrowband filter was designed to limit the angle of incident light that enters the aperture. The design for this lens is seen in figure 2. However, controlling the coating thickness on a highly curved surface remains a challenge that requires further development. If possible, the length of lightning detector's optical assembly could be reduced by a factor of six and its fabrication costs also significantly reduced.

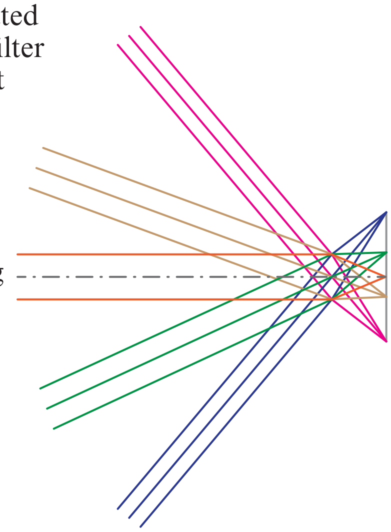


FIGURE 2. A revolutionary new optical design where the entrance pupil resides at the center of curvature of a single hemispheric lens that is coated to meet filter requirements.

SUMMARY

Future satellite-based lightning mappers will need CMOS sensors to detect small lightning flashes often prevalent in very intense thunderclouds. Additionally, the size of current lightning mappers precludes their use in affordable constellations of low-Earth orbiting satellites. This project identified a new CMOS sensor candidate to obtain higher resolution images of lightning and designed a new camera lens system that offers a significant reduction in size, weight, and costs for future high-resolution lightning mappers.

PRINCIPAL INVESTIGATOR: Patrick N. Gatlin

PARTNERS: University of Alabama in Huntsville, Goddard Space Flight Center (GSFC)

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Advanced Microwave Precipitation Radiometer (AMPR)

OBJECTIVE: *To provide calibrated measurements of the Earth's atmospheric and surface characteristics from an airborne platform.*

PROJECT GOAL/DESCRIPTION

The Advanced Microwave Precipitation Radiometer (AMPR) is an airborne, polarimetric, passive microwave radiometer producing brightness temperatures at 10.7, 19.35, 37.1, and 85.5 GHz. These frequencies are sensitive to the emission and scattering of precipitation-size ice, liquid water, and water vapor. AMPR is thus able to provide information on surface and atmospheric parameters, including precipitation over ocean and land surfaces; cloud liquid water and atmospheric water vapor over the ocean; sea surface temperature and near-surface wind speed; soil moisture; and sea ice. AMPR is a cross-track scanning radiometer and its polarization basis varies as a function of scan angle. In order to retrieve geophysical information, the calibrated horizontally (H) and vertically (V) polarized microwave brightness temperature values need to be determined. This is accomplished by deconvolution of polarization-variable measurements from two orthogonal channels per frequency.

APPROACH/INNOVATION

During FY21, the instrument was prepped for a second deployment of a field campaign called Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS). The planned January/February 2021 deployment was postponed due to COVID-19. Thus, additional prep work and instrument development occurred in advance of the planned January/February 2022 IMPACTS campaign. This work involved significant maintenance on the instrument, particularly focused on mitigating radio frequency interference (RFI) observed on one of AMPR's 37.1-GHz channels during IMPACTS 2020. In addition, development was advanced on AMPR's new data system, called Marshall Space Flight Center (MSFC) Instrument Data Architecture for Science (MIDAS), as well as on a new power distribution unit (PDU) for AMPR. Lab and sky-focused testing of the instrument occurred throughout in support of this maintenance and instrument development.

RESULTS/ACCOMPLISHMENTS

Mitigation of the 37.1-GHz RFI primarily focused on three major tasks: cleaning of the problem channel's waveguide system, improving mounting stability for the waveguide to reduce vibration, and installing isolators on each 37.1-GHz channel. The RFI was difficult to replicate on the ground, so the extent to which these actions will mitigate the observed in-flight RFI is not fully known. If the fix is not successful, analysis confirmed our ability to eliminate the RFI in post-flight data processing, at the cost of some spatial resolution for the channel.

The MIDAS data system successfully flew and operated during the return transit flight from IMPACTS 2020. Since then, the AMPR team has made a series of updates to MIDAS to improve its capabilities, and thus promoted it to be the planned primary data system in IMPACTS 2022. These updates included new scanning capabilities, including nadir staring. In addition, network time protocol and the ability to downlink near-realtime AMPR data from the ER-2 were enabled.

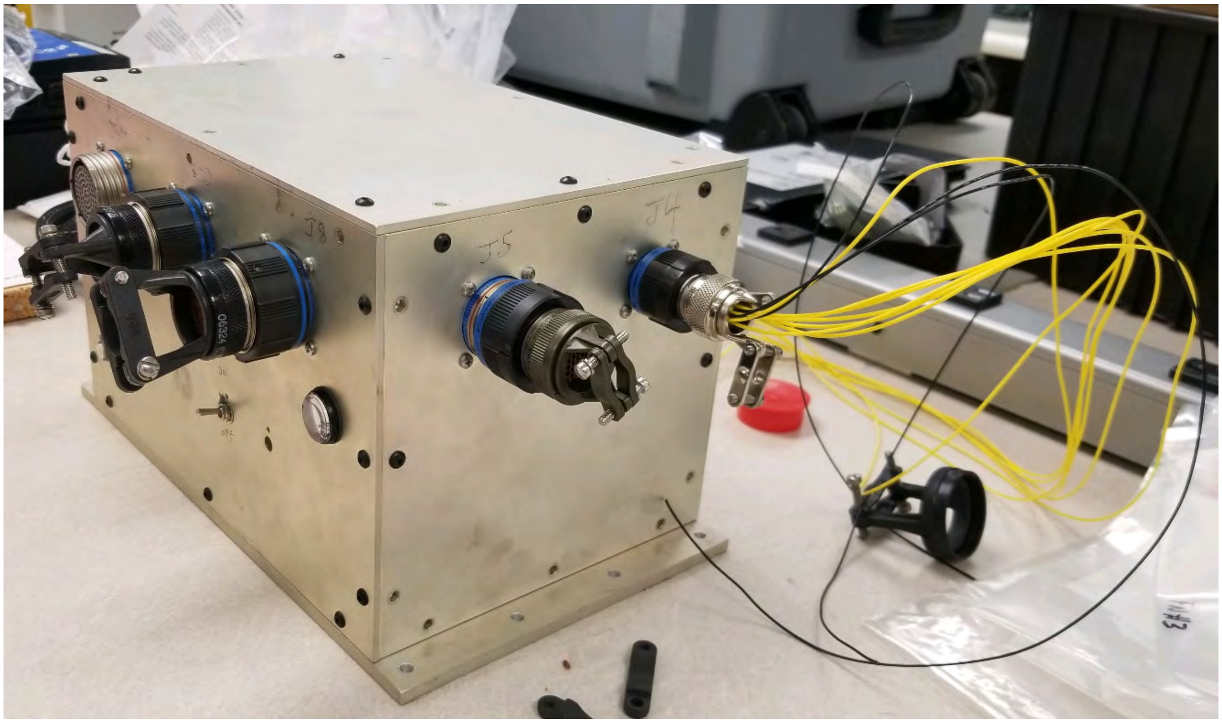


FIGURE 1. Photograph of the new AMPR PDU in development.

The new PDU (fig. 1) was constructed and underwent significant electrical, vibrational, and thermal testing during FY21. This PDU will deliver significantly cleaner power using modern electronics, and will eventually serve as the primary PDU for AMPR, replacing its legacy data system. The new PDU is still undergoing rigorous evaluation before mating with the rest of the instrument, and so for IMPACTS 2022 it will only serve as an emergency spare.

SUMMARY

In FY21, COVID-19 prevented AMPR's deployment due to postponement of the second IMPACTS campaign. However, significant maintenance and instrument development work nonetheless occurred. This work should mitigate RFI contamination of one 37.1-GHz channel. In addition, the continued instrument development led to the new MIDAS data system being ready for its first fully operational deployment in IMPACTS 2022. Finally, a new PDU is in development and testing and should be available as an emergency spare if needed in IMPACTS 2022.

PRINCIPAL INVESTIGATOR: Timothy J. Lang

PARTNERS: University of Alabama in Huntsville, Aerospace Corporation, University of Utah, Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC)

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION:
https://weather.msfc.nasa.gov/ampr/

Imaging X-ray Polarimetry Explorer (IXPE)

OBJECTIVE: *IXPE will perform x-ray polarimetric imaging of cosmic sources, adding polarization degree and orientation to the properties (time, energy, and position) observed in x-ray astronomy. In doing so, it will extend the understanding of x-ray sources and processes for various types of neutron stars, stellar-mass black holes, supernova remnants (SNR), and active galactic nuclei (AGN).*

PROJECT GOAL/DESCRIPTION

Led by NASA Marshall Space Flight Center (MSFC) Principal Investigator, Dr. Martin C. Weisskopf, IXPE is a NASA Small Explorer (SMEX) mission, in partnership with the Italian space agency (Agenzia Spaziale Italiana, ASI) and with prime contractor Ball Aerospace. The IXPE Observatory launched in December 2021 into an equatorial, 600-km circular orbit. Following a one-month orbital commissioning, IXPE began its 2-year baseline mission to measure the x-ray polarization of several dozen cosmic sources. IXPE includes three identical x-ray telescopes, each comprising a nested grazing-incidence Mirror Module Assembly (MMA) and a polarization-sensitive (imaging) detector unit (DU), separated by a deployable boom to establish the telescopes' 4-m focal length. The IXPE Observatory includes the telescopes and the spacecraft, which provides typical subsystems—mechanical, structural, thermal, power, electrical, telecommunications, aspect determination and control, and command and data handling.

The Observatory will transmit data to the primary (Malindi, Kenya) or secondary (Singapore) ground station, to be relayed to the Mission Operations Center (MOC) in Boulder, CO and then to the Science Operations Center (SOC) in Huntsville, AL. All scientific data will be publicly available through NASA's High-Energy Astrophysics Science Archive Research Center (HEASARC) at Goddard Space Flight Center (GSFC). If approved by NASA, the IXPE mission will continue beyond 25 months, initiating a HEASARC-administered general observer (GO) program.

APPROACH/INNOVATION

The enabling technological innovation for IXPE is the polarization-sensitive Gas Pixel Detector (GPD), developed by the Italian Instrument Team. This device images the ionization track of the photoelectron ejected during absorption of an x-ray photon in a gas, by drifting the track onto a pixelated application specific integrated circuit (ASIC), after amplifying it with a Gas Electron Multiplier (GEM). Each ionization track contains information on the photoelectron's energy, absorption location, and initial ejection direction, which is correlated with the polarization orientation (fig. 1).

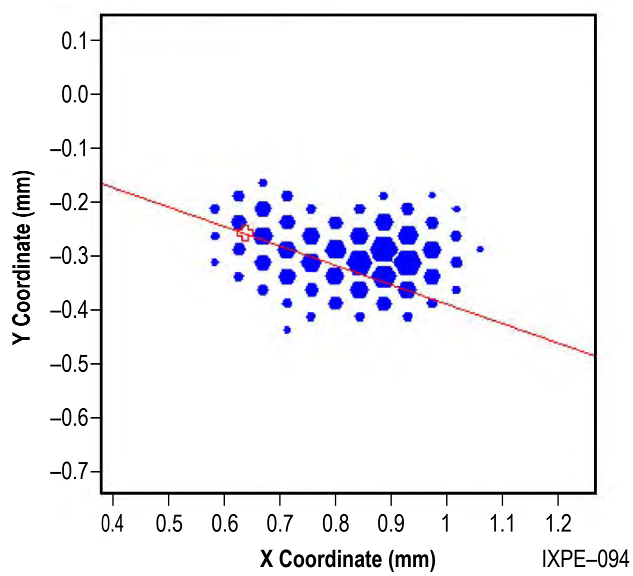


FIGURE 1. The blue dots show the image of the track of electrons produced by a single X-ray absorbed in the Italian-provided IXPE polarization-sensitive detectors. The size of a dot represents the number of electrons imaged at that position, the larger the size, the more electrons. The red line, the results of analyzing the track, shows the direction of the primary photoelectron that started the process and is in the direction of the polarization of the incident X-ray.

Over the past two years, IXPE researchers at Stanford University developed innovative neural-network software to analyze these ionization tracks. By more accurately reconstructing the initial ejection direction of the photoelectron, this software will improve the polarization sensitivity of IXPE by an amount comparable to what would be achieved by adding a fourth telescope.

RESULTS/ACCOMPLISHMENTS

There were significant accomplishments in all elements of the IXPE project in 2021. Ball Aerospace completed assembly, integration, and testing of the IXPE Observatory (fig. 2). The Ground System completed the Malindi and Singapore radio-frequency (RF) compatibility tests with the spacecraft, interface testing of the network, mission scenario tests and mission rehearsals. The SOC has developed a suite of tools for on-ground processing of the telemetered Science

PHOTO CREDIT: BALL AEROSPACE

FIGURE 2. IXPE fully deployed in a test chamber at Ball Aerospace.

and Housekeeping data, including improving the image quality of the aspect solution using x-ray images.

Finally, the IXPE Project successfully completed several major milestone reviews including the Observatory Pre-Environmental Review. After a successful Operations Readiness Review and Pre-Ship Review in October 2021, the IXPE Observatory was shipped to NASA Kennedy Space Center (KSC) in November 2021. The IXPE Observatory was integrated into the SpaceX Falcon-9 launch vehicle and launched from LC-39A in December 2021. The mission patch (fig. 3) exemplifies the international partnership that has made IXPE possible.

FIGURE 3. IXPE mission patch.

All these tasks were accomplished despite the extraordinary challenge of the COVID-19 pandemic. As an international project, the IXPE team has members in Italy, Japan, and throughout the United States. The difficulties have not been so much technical as logistical—e.g., how to integrate and test hardware with some critical teammates supporting remotely. With flexibility and adaptability, Team IXPE found a way to accomplish these critical activities, completing the IXPE Observatory and opening a new window into the x-ray universe.

SUMMARY

In December 2021, the IXPE Observatory launched on a Falcon 9 from LC-39A at KSC and, after commissioning activities, began its Science mission. First light is anticipated in January 2021, after which IXPE data will be available to astrophysicists around the world. Initial results will give insight into NASA's Astrophysics first objective: "Discover how the Universe works".

PRINCIPAL INVESTIGATOR: Martin Weisskopf

PARTNERS: Italian space agency; Agenzia Spaziale Italiana (ASI); Istituto di Astrofisica e Planetologia Spaziali/Istituto Nazionale di Astrofisica (IAPS/INAF); Istituto Nazionale Fisica Nucleare (INFN); OHB-Italia; Ball Aerospace and Technologies Corp.; University of Colorado, Boulder/Laboratory for Atmospheric and Space Physics (LASP); Nagoya University, Japan; Università Roma Tre, Italy; Stanford University; Massachusetts Institute of Technology (MIT)

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION:
https://ixpe.msfc.nasa.gov/

TA09:

Entry, Descent, and Landing

Stereo Cameras for Lunar Plume-Surface Studies

OBJECTIVE: *To study the effects of retrorocket plumes on the lunar surface.*

PROJECT GOAL/DESCRIPTION

There is currently a dearth of information regarding the effects of rocket exhaust plume impingement onto granular surfaces, like those found on the Moon or Mars. From previous flights, it is known that this phenomenon, plume-surface interaction (PSI), generates craters at the landing site and the plume entrains surface particles in its high-velocity flow. This eroding landing surface can lead to instability during the final stages of descent and landing. Additionally, the high-velocity particles can have a sandblasting effect, potentially damaging lander hardware and nearby surface assets. A better understand of PSI allows for smarter and safer lander designs. The Stereo CAmeras for Lunar Plume-Surface Studies (SCALPSS) project is a stereo descent imaging system and flight payload that will be used to study the lunar surface erosion caused by retrorockets on a lunar lander. The goal of SCALPSS is to capture high-resolution images during descent and after landing. These images will allow researchers to reconstruct the 3D topography of the plume-altered landing site; characterize the dynamics of the ejecta sheet's global features; and determine the altitude at which PSI onset occurs.

APPROACH/INNOVATION

To transform the 2D images that SCALPSS returns into 3D digital elevation maps (DEM), photogrammetry will be utilized. Photogrammetry is commonly used on Earth for terrain surveying, but its application for understanding the effects of PSI is a novel one. This difference in application has provided the opportunity to venture into the unknown and push the boundaries of what is known about the uses of photogrammetry. Not only will SCALPSS be used to generate a post-landing surface topography, but the images during descent will be used to develop DEMs prior to touch down, providing transient landing site topographies. This methodology works by taking two or more images with overlapping views and using phototriangulation to generate a 3D coordinate system and stereo models. These stereo models are then viewed in 3D and used to generate a DEM. SCALPSS will consist of four cameras mounted along the base of Intuitive Machines' Nova-C lunar lander, which is scheduled to launch in the first quarter of 2022. The cameras will be oriented in such a way that maximizes overlap to increase stereo coverage of the altered landing site. The images that SCALPSS captures will then be used to generate DEMs of the landing site under the Nova-C.

A similar approach has been used to reconstruct the landing site of the InSight Mars lander, but this approach only used one camera on a robotic arm and it only captured photos after landing. This resulted in less stereo coverage and higher uncertainty for erosion calculations. The SCALPSS cameras have been selected specifically for this reconstruction task, and since it was optimized to maximize stereo coverage and it will begin imaging when PSI onset occurs, improvement in coverage and certainty is expected. Further, SCALPSS 1.1 is currently in work and will continue into next year. This improved iteration of SCALPSS will include two additional cameras possessing lenses with longer focal length. These lenses provide a more zoomed in field of view that will allow for images to be captured at higher altitudes during the lander's descent, prior to PSI onset. These images will be used to generate a 'before' DEM to which the altered site DEM can be compared, further reducing uncertainty.

RESULTS/ACCOMPLISHMENTS

The team at NASA Marshall Space Flight Center (MSFC) has worked to characterize the accuracy of the imaging system. This was done in three phases. First, two-camera testing was done to down-select which camera and lens combination SCALPSS would use. A dowel board, a 2 × 2 ft board comprised of dowels of various heights and diameters, was used as a target for the cameras to image. An accuracy and stereo coverage analysis yielded a high-resolution monochrome camera and a 3.37 mm focal length lens (both with flight heritage). Second, additional two-camera testing was performed with the dowel board. In this case, camera separation distances and convergence angles were adjusted to see their effects on accuracy. Third, a more comprehensive test was performed at MSFC's Flat Floor Robotics Laboratory. This test utilized four cameras mounted to a lander base mock-up in the flight configuration. A lunar crater mock-up was used as the imaging target with a solar simulator to provide more representative lighting conditions. The camera configurations were also varied to obtain more data for off-nominal cases. This data continues to be analyzed, but preliminary results show a root-mean-square error (RMSE) of 1.78 mm. An example of two images from this Flat Floor testing can be found in figure 1. The accuracy work performed at MSFC was delivered to NASA Langley Research Center (LaRC), where the project is led, and it aided in the determination of the flight camera configuration. Part of this configuration is the angles at which the cameras will be mounted, which is reflected in the camera mounting brackets seen in figure 2. The brackets were manufactured at LaRC and the flight unit of SCALPSS was delivered to Intuitive Machines in October 2020.

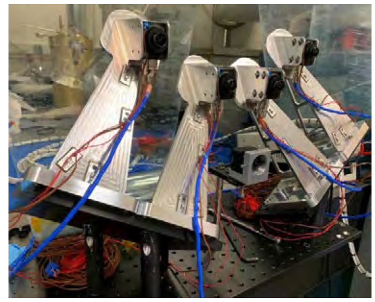


FIGURE 2. Flight cameras in mounting brackets.

SUMMARY

SCALPSS improves upon prior attempts at characterizing PSI and looks to make further improvements on iterations in the future. The project has created a great opportunity for collaborations between centers that will continue in the years to come. A payload like SCALPSS is vital for understanding the effects of PSI. With NASA looking to return to the moon in 2024, SCALPSS will provide timely data regarding PSI on the lunar surface, increasing safety for future astronauts and decreasing mission risk.

FIGURE 1. Two flight-configuration images from Flat Floor testing.

PRINCIPAL INVESTIGATOR: Michelle Munk, Langley Research Center

MSFC LEADS: Michael Manginelli (TL), Manish Mehta (Co-I)

PARTNERS: Langley Research Center (LaRC); Johnson Space Center (JSC); and Cardinal Systems, LLC.

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Hydrogen Gas Generator for Hypersonic Inflatable Aerodynamic Decelerators (H_2G^2)

OBJECTIVE: *To conduct a series of ground-based environmental tests of a zero-gravity hydrogen gas generator.*

PROJECT GOAL/DESCRIPTION

Large, inflatable heat shields will be needed for future crewed missions to Mars. Anasphere, Inc. is developing a pyrotechnic hydrogen gas generator that would be used as the inflation system for these heat shields. This project involved conducting a series of ground-based tests on the Anasphere hydrogen gas generator that simulated the space environment. The results of these tests will be used to improve the design of these devices before they are submitted for final flight qualification tests.

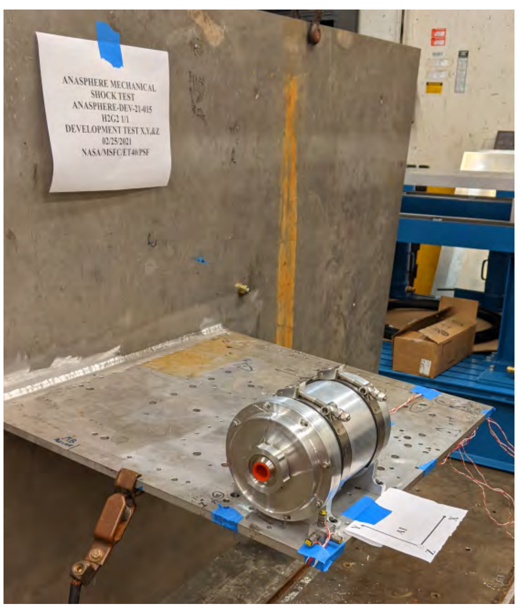


FIGURE 1. The small gas generator in the test rig for the shock test.

APPROACH/INNOVATION

The gas generator underwent shock and vibration testing and a thermal vacuum test. Before and after each test, the gas generator was given an x-ray computed tomography (CT) scan. These scans were used to gauge the health of the generator after each test.

Several organizations at NASA Marshall Space Flight Center (MSFC) collaborated to complete all of the testing for this project. These organizations included MSFC Shipping and Receiving, Safety and Mission Assurance, and several teams within MSFC's Test Laboratory. Each organization coordinated well together, ensuring the safe transfer of the test article between test sites.

FIGURE 2. The large gas generator being unboxed at MSFC following shipment from Anasphere, Inc.

FIGURE 3. The large gas generator being unboxed at MSFC following shipment from Anasphere, Inc.

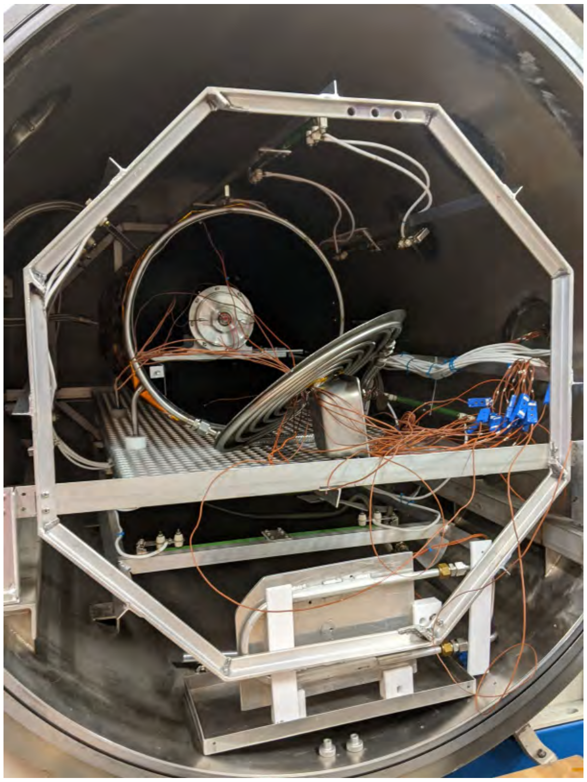


FIGURE 4. The small gas generator inside a thermal vacuum chamber at MSFC.

RESULTS/ACCOMPLISHMENTS

The CT scans showed damage to the interior of the gas generator following shock and vibration testing. The generator was sent back to Anasphere for disassembly and forensic inspection.

A second gas generator provided by Anasphere was connected to an inflatable torus and installed in a vacuum chamber. The gas generator was activated and partially inflated the torii, but a deflation occurred due to a problem with the gas generator. The second gas generator will also be dissembled and inspected by Anasphere.

SUMMARY

Multiple teams at MSFC collaborated with Anasphere on this project, paving the way for future collaborations in the future. While the inflation test did not completely inflate the torii, the team gathered a significant amount of relevant test data across all of the ground tests. The data from these tests will be used by Anasphere to improve the design of future gas generators.

PRINCIPAL INVESTIGATOR: Adrian Soler-Luna

PARTNER: Anasphere, Inc. (Manhattan, Montana)

FUNDING ORGANIZATION: Space Technology Mission Directorate (STMD)

FOR MORE INFORMATION:
https://www.nasa.gov/mission_pages/tdm/main/index.html

TA10:

Autonomous Systems

Project Polaris: Data Planning and Control Tool

OBJECTIVE: *To automate nominal spaceflight operations by integrating planning products, operations procedures, and commanding/telemetry tools using artificial intelligence and machine learning technology.*

PROJECT GOAL/DESCRIPTION

As NASA missions and technologies evolve, ground operations will move away from 24/7 manual support. NASA has a need for autonomy within ground operations to support NASA long-term goals. The Data Planning And Control (DPAC) tool will automate planning by merging telemetry, flight control, and procedures into a seamless operational interface for the Data Systems Ground Operators. DPAC will reduce workload, lower the risk for human errors, and provide multi-project modularity in programs to include Gateway; Lunar Surface Ops; and On-Orbit Servicing, Assembly, and Manufacturing (OSAM)-supported projects. Upon completion of the follow-on Huntsville Operations Support Center (HOSC) implementation effort at NASA Marshall Space Flight Center (MSFC), the tool has the potential to reduce International Space Station (ISS) console operator support by a 6.0 work-year equivalent (WYE) and increase the overall technology readiness level (TRL).

FIGURE 1. A member of the Data Planning and Control (DPAC) team at work.

APPROACH/INNOVATION

The DPAC tool is essentially an improvement in automation of the real-time planning and execution of complex mission operations activities, such as those related to the ISS. Previously, the user relied on pre-generated mission plans to identify commanding activities. At the scheduled activity window, the user would read the plan, determine the necessary commands to accomplish the plan, identify the correct procedure to execute the command, then execute the procedure by manually entering the command data and then sending the command. The primary weakness of this process is it does not allow for real-time adjustments to planned activities as the process relies on a pre-generated activity plan. The user must manually replan activities if changes occur. A second weakness is that the existing process requires the user to manually transcribe information from one application to another, introducing potential error and requiring operator resources. The third weakness is that the existing process relies on highly technical operators to make real-time reconfigurations of systems. For systems in remote locations, for example at the Moon or Mars, it is impractical to have onsite technical experts or wait for assistance from ground-based experts. By creating a system that can automatically reconfigure complex systems to accommodate planned events and common plan changes, an organization can make significant reductions in flight operations support, freeing experts to focus on more challenging problems.

The DPAC tool relies on several existing software tools built and maintained by the MSFC Payload Mission Operations Division, as shown in figure 2. The Data Systems Routing and Configuration

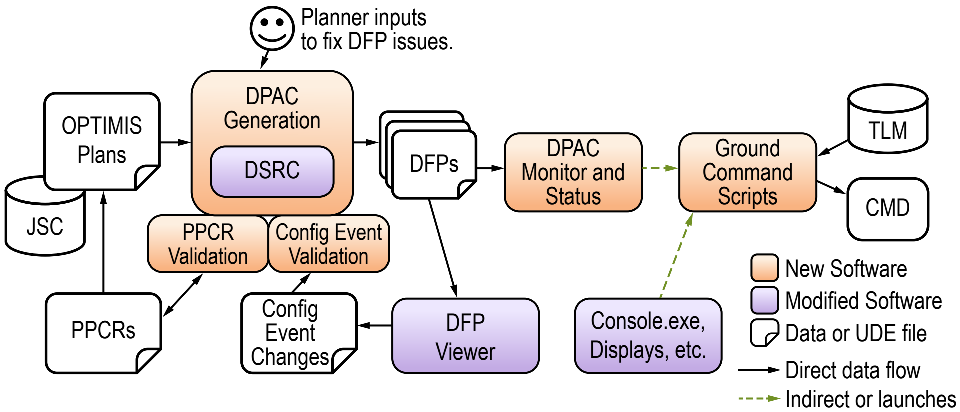


FIGURE 2. DPAC Tool Architecture.

(DSRC) tool is a program that pre-generates activity plans called Data Flow Plans (DFPs). The DFP Viewer allows the operator to view the plan and the Enhanced PC suite of applications enables commanding and telemetry services for mission operations. The DPAC tool also relies on existing ground command procedure documentation generated by the flight operations teams. The DPAC tool will provide a user interface that allows the user input modifications to the planning products, to monitor and control the execution of activities, and perform general monitoring of the DPAC tool status. Behind the scenes, the DPAC tool will be reading planning products and making updates based on user-input; reading and assessing telemetry; translating activities into command procedures and command activities; auto-populating the commands with data from the plan; and automatically sending the plans after any required operator review. The integration of these tools and building the intelligence to drive them will be our primary challenge.

Part of the integration and ‘smarts’ of the DPAC tool will be achieved through the incorporation of artificial intelligence (AI) and/or machine learning (ML). The DPAC tool must understand several complex information sources encountered during mission operations. For example, it must know when telemetry indicates it is correct to send a particular command, when it is safe to move an activity, what changes will impact the system, and how to read the ground command procedures the users already operate from. We hope to apply the capabilities of AI and ML towards these tasks, identify the limits of these capabilities, and implement robust intelligent solutions into the DPAC tool. We may not be able to completely automate flight operations, but we can certainly make the operator’s job easier.

RESULTS/ACCOMPLISHMENTS

The Advanced Explorations Systems’ Project Polaris selected ten proposals for funding in the summer of 2021. The DPAC tool was one of them, and we began work in September. Our team of engineers, developers, and operators from several different organizations and two different centers has finally formed, is completing training on the HOSC operations philosophy and environment, and has begun work on finalizing the tool’s concept of operations and requirements. As our systems engineering and planning products are being finalized, our team will get to work on implementation and into the hard part of designing and implementing this new technology. Testing and deployment to operations is expected to follow in 2023. Our team is excited about this effort and looking forward to knocking out some major milestones in FY22.

SUMMARY

Our newly formed team is very excited about the potential impacts of the DPAC tool on the operations community, and very much looking forward to applying advanced intelligences to our tools. We cannot continue forever using our existing operations concepts, especially when we get into deep space. There are ways in which technology can free our expert operators from the routine tasks of their job, and we aim to develop a tool which will enable that freedom. Integrating smarter planning systems with intelligent commanding processes and existing vehicle telemetry will allow operations teams to focus on mission critical communication and coordination. The Polaris DPAC team knows this effort will be challenging, but we know it is achievable and we are eager to see it through.

PRINCIPAL INVESTIGATOR: Mason Hall

PARTNERS: Marshall Space Flight Center (MSFC), Langley Research Center (LaRC)

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office

TA11:

Software, Modeling, Simulation, and Information Processing

Short-Term Prediction Research and Transition (SPoRT)

OBJECTIVE: *To transition unique satellite observations and research capabilities to the operational weather community to improve short-term, regional forecasts.*

PROJECT GOAL/DESCRIPTION

SPoRT is an end-to-end research-to-operations/operations-to-research (R2O/O2R) activity focused on accelerating the use of satellites, nowcasting tools, and advanced modeling and data assimilation techniques to improve short-term weather forecasts. SPoRT partners with universities and other government agencies to obtain near real-time (NRT) data, develop new products, and obtain operational perspective to increase the likelihood of adoption by the operational weather community.

APPROACH/INNOVATION

SPoRT incorporates the end user throughout an iterative R2O/O2R feedback process (fig. 1) by identifying a forecast challenge, incorporating a potential solution into the user's decision support system (DSS), providing training on use of the product, and assessing the product's impact on their decision-making process. Product iterations continue until a solution is used in regular forecast operations. Collaborative relationships between SPoRT enable honest feedback on product and training value resulting in lasting operational impact of new data products. Often, this feedback includes suggested product changes that lead to significant improvements, increased use of the product, and additional opportunities for research and development. Assessment reports published for the broader community communicate successful product transitions.

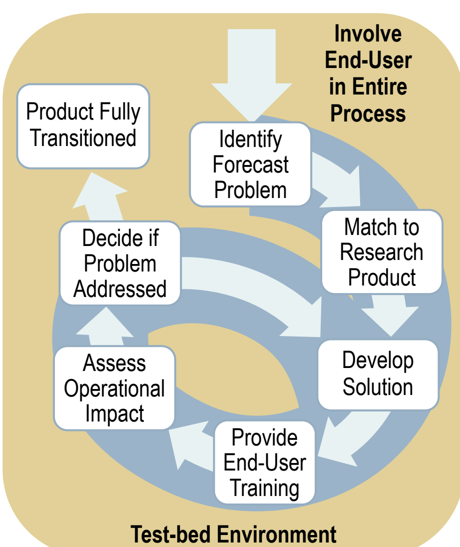


FIGURE 1. Graphical representation of the SPoRT unique R2O/O2R paradigm.

RESULTS/ACCOMPLISHMENTS

SPoRT has been part of a collaborative effort within the National Oceanic and Atmospheric Administration (NOAA) Joint Polar Satellite System (JPSS) Proving Ground and Risk Reduction (PGRR) Program to develop gridded satellite sounding retrievals for the operational weather forecasting community. The NOAA Unique Combined Atmospheric Processing System (NUCAPS) retrieves vertical profiles of temperature, water vapor, trace gases, and cloud properties derived from infrared and microwave sounder measurements. A new, optimized method for deriving NUCAPS level 2 horizontally- and vertically-gridded products is described here. This work represents the development of approaches to better synthesize remote sensing observations that ultimately increase the availability and usability of NUCAPS observations. This approach, known as 'Gridded NUCAPS', was developed to more effectively visualize NUCAPS observations to aid in the quick identification of thermodynamic spatial gradients. Gridded NUCAPS development was based on O2R feedback and is now part of the operational National Weather Service display system.

SPoRT is using hyperspectral infrared satellite sounding retrievals to examine thermodynamic changes in the tropical cyclone (TC) environment associated with the diurnal cycle of radiation. Vertical profiles of temperature and moisture are retrieved from the Suomi National Polar-orbiting Partnership (S-NPP) satellite system, NOAA-20, and the Meteorological Operational (MetOp) A/B satellite system, leveraging both infrared and microwave sounding technologies. Vertical profiles are binned radially based on distance from the storm center and composited at 4-hr intervals to reveal the evolution of the diurnal cycle. For the three cases examined — Hurricane Dorian (2019), Hurricane Florence (2018), and Hurricane Irma (2017) — a marked diurnal signal is evident that extends through a deep layer of the troposphere. Statistically significant differences at the 95% level are observed in temperature, moisture, and lapse rate profiles, indicating a moistening and destabilization of the mid- to upper troposphere that is more pronounced near the inner core of the TC at night. Observations support a favorable environment for the formation of deep convection caused by diurnal differences in radiative heating tendencies, which could explain why new diurnal pulses tend to form around sunset. These findings demonstrate that the diurnal cycle of radiation affects TC thermodynamics through a deep layer of the troposphere and suggest that hyperspectral infrared satellite sounding retrievals are valuable assets in detecting thermodynamic variations in TCs.

Airborne dust has broad adverse effects on human activity, including aviation, human health, and agriculture. Remote sensing observations are used to detect dust and aerosols in the atmosphere using long-established techniques. False color Red-Green-Blue (RGB) imagery using band differences sensitive to dust absorption (Dust RGB) is currently used operationally to assist forecasters and decision-makers in identifying dust at night and can aid process studies of dust events. However, there are still limitations, subjectivity, and nuances to image interpretation making night-time dust identification difficult even for experts. This study applies machine learning to the problem of night-time dust detection with a simple random forest (RF) model using NASA/NOAA Geostationary Operational Environmental Satellite-16 (GOES-16) Advanced Baseline Imager (ABI) infrared imagery, band differences sensitive to dust absorption, and Dust RGB color components as inputs to the model. For images with dust present, the model correctly labels 85% of dust pixels and 99.96% of no-dust pixels for all dust images in the validation data set. The addition of a single null case to the training data set drastically reduces error in labeling no-dust pixels as dust from 45% to 14.5%. Application of the machine learning model to the April 13–14, 2019 dust event demonstrates the ability of the model to identify dust during night-time hours when visual dust detection is limited by the cooling ground surface characteristics.

SUMMARY

SPoRT is a highly successful project that conducts world-class research and transition activities, with a model that is both sustainable and able to grow with new opportunities. Through collaboration with university and government partners, SPoRT has successfully transitioned value-added observations and capabilities from recently launched satellites to weather forecasters. These accomplishments further SPoRT's vision to be a 'go-to' project in the applied research community to accelerate the use of next-generation satellite datasets into the operational weather community.

PRINCIPAL INVESTIGATOR: Christopher Hain

PARTNERS: National Oceanic and Atmospheric Administration, National Weather Service

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Multiple SmallSats Cross-Correlation Localization Technique

OBJECTIVE: *To develop an open-source, modern-analysis toolkit to perform localization of gamma-ray bursts using data from multiple gamma-ray SmallSats in different orbits.*

PROJECT GOAL/DESCRIPTION

The project goal is to develop and distribute GammaLoc, an open-source, modern-analysis toolkit that can utilize multiple SmallSats' data to localize gamma-ray bursts (GRBs). GRBs are extremely bright stellar explosions whose gamma-ray durations can last from milliseconds to hundreds of seconds, followed by longer emissions from x-rays to radio. By combining the data from gamma-ray instruments in different orbits, the project will enable concurrent missions to operate as a network with enhanced capability to detect and localize GRBs, thereby increasing the overall science return and enabling precise follow-up observations in other wavelengths. It will also enable future mission planning with a standardized toolkit for sensitivity study and evaluation. The localization output will be in the modern Hierarchical Equal Area isoLatitude Pixelization (HEALPix) format. This format is commonly used by both space-based and ground-based observatories, as well as multimessenger observatories in gravitational waves and neutrinos, such as LIGO/Virgo and IceCube. This software is written in Python, which has been adopted by the astronomy community for analysis. It is co-developed with our Universities Space Research Association (USRA) collaborators supported by their internal research fund and will be made available to the public via NASA github.

APPROACH/INNOVATION

The signal cross-correlation method has been in use by the Interplanetary Network (IPN) for GRBs since the 1970s, with the latest iteration of the network in operation since 1990. It uses the signal arrival time difference between two instruments separated by a known distance in space to triangulate the arrival direction. However, the IPN triangulation software is not publicly available, though the method is documented. GammaLoc will be a modernized, publicly-accessible version with support for varying instrument characteristics, such as sensitivity and baseline, GRB signal strengths, and temporal morphologies.

After this first year of initial development of the GammaLoc toolkit, we will be proposing to NASA's Astrophysics Research and Analysis Program to expand the toolkit further to include additional algorithms that can strengthen the signal cross correlation and plugins for specific gamma-ray missions.

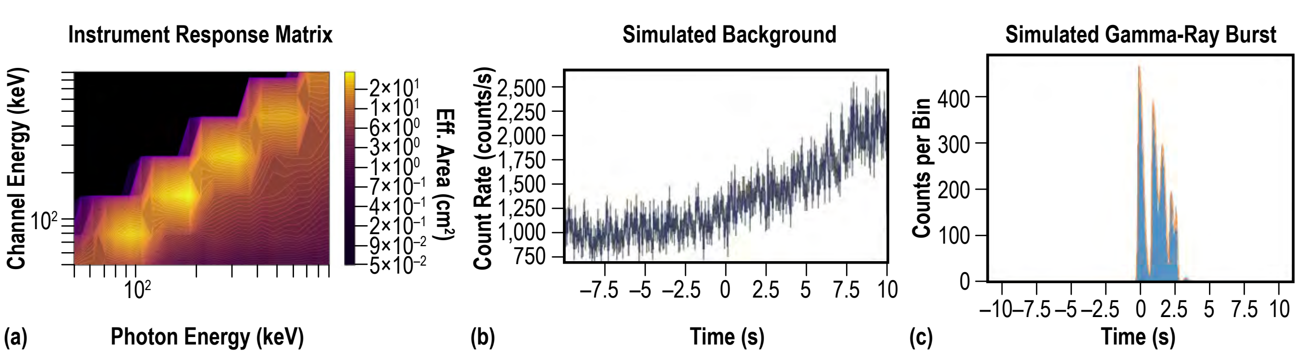


FIGURE 1. Simulated instrument response, background rate, and GRB signal from the GammaLoc modules.

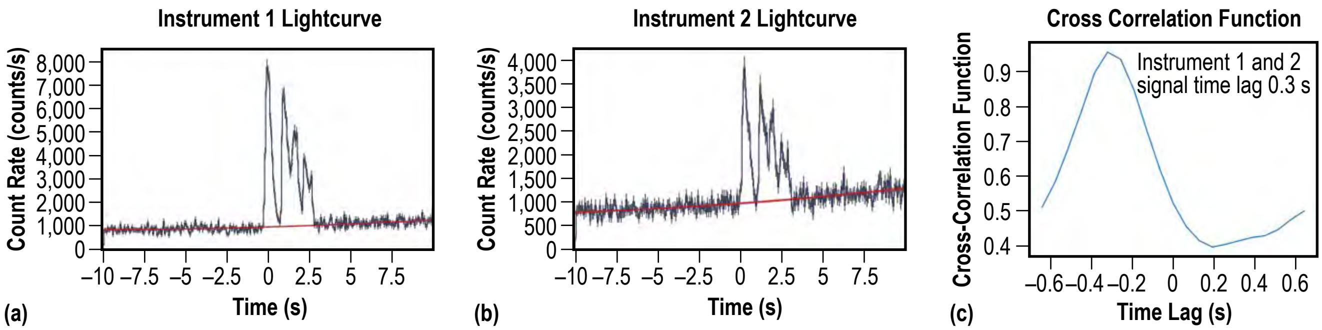


FIGURE 2. Lightcurves from simulated instruments 1 and 2 and time lag identified by cross correlation.

RESULTS/ACCOMPLISHMENTS

GammaLoc contains five modules developed by each team member and utilizes the Fermi Gamma-Ray Burst Monitor (GBM) Data Tools suite of simulation functions. Figures 1 and 2 highlight the simulation output from the different modules listed below.

(1) The response module provides the response matrix of the instrument, which includes the effective area for a range of photon energies from a particular sky location and spacecraft orientation. Users are also able to resample the response data and visualize the response matrix in several plotting parameters. Example preliminary response files are included for the mission concepts StarBurst and MoonBEAM.

(2) The lightcurve module provides the signal lightcurve with either single or multiple pulses, in varying amplitudes and combination/summation.

(3) The background module provides the background rate that can be constant or time-varying with a polynomial function.

(4) The spacecraft location module provides an elliptical or circular orbit in an Earth-centered coordinate frame.

(5) The cross-correlation module utilizes the output from the previously described modules to match the signals from two instruments and produce the final localization.

Additionally, our USRA collaborators have procured a new high-speed computer for simulations.

SUMMARY

The first year of development on GammaLoc produced a simple toolkit that uses the IPN technique to determine the GRB location with generic input parameters and examples. Additional algorithm and functional development for the individual modules are being assessed for the next expansion stage to be proposed to the NASA's Astrophysics Research and Analysis Program. Documentation and tutorials are being prepared for public release.

PRINCIPAL INVESTIGATOR: C. Michelle Hui

PARTNERS: University of Alabama in Huntsville, Universities Space Research Association

FUNDING ORGANIZATION: Center Innovation Fund (CIF)

Commercial Smallsat Data Acquisiton (CSDA) Program

OBJECTIVE: *To bring commercial data to researchers.*

PROJECT GOAL/DESCRIPTION

The Commercial Smallsat Data Acquisition (CSDA) Program was established to identify, evaluate, and acquire data from commercial sources that support NASA's Earth science research and application goals. NASA's Earth Science Division (ESD) recognizes the potential impact commercial small-satellite (SmallSat) constellations may have in encouraging/enabling efficient approaches to advancing Earth system science and developing applications for societal benefit. A data team has been established at NASA Marshall Space Flight Center (MSFC) to develop scalable, efficient, and repeatable data management capabilities as well as to provide end user services for all data acquired by the CSDA Program.

APPROACH/INNOVATION

The CSDA Program data team seeks to develop scalable, repeatable, and efficient processes for the management of commercial data. Data management includes not only the archiving and distribution of data, but data information curation and development of services to support end users of the data. The CSDA data team has developed a cloud-based native data system to support the CSDA Program goals. Three distinct phases have been defined and broadly describe where the data are within the data system, the applicable services, and responsibilities of the data team. These are an Evaluation Phase, Transition Phase, and Long-term Sustained Use Phase. In the Evaluation Phase, the data team coordinates with commercial data vendors to obtain data and documentation while learning about each acquired product. During the Transition Phase, all acquired commercial data becomes available to a broader group of end users based on respective end user license agreements, with the data team providing user data access approval and data distribution through temporary services. Furthermore, all data are made discoverable such that the science community may identify potential useful data as well as the means for becoming an approved user. Finally, in the Long-Term Sustained Use Phase, data acquired through the CSDA Program are formally published and archived in NASA Earth Observing System Data and Information System (EOSDIS) alongside all other NASA Earth science data.

RESULTS/ACCOMPLISHMENTS

The CSDA Program negotiated the uplift in end user license agreements with two commercial vendors from which it is currently acquiring data: Planet, which provides optical imagery data, and Spire Global, Inc., which provides global navigation satellite system (GNSS) data. Under the old agreements, data access and sharing were limited to NASA-funded investigators for science use. With these license agreement uplifts, CSDA Program-acquired data are available to the broader US Government research communities. The revised agreements and data details can be found on the CSDA Program website (https://earthdata.nasa.gov/esds/csdap#data). Following the announcement of this increased availability in July, the CSDA data team saw a significant increase in data access requests; five times more requests were received in the two months following the announcement compared to the prior two years of CSDA operations. Collection of user information required for verification, management of this information, and timely responses to requests were made possible with a web application form released in January 2021.

The CSDA Program data team has developed the Smallsat Data Explorer (SDX) to support the search, discovery, and distribution of data while it is in the Transition Phase (fig. 1). The SDX has supported the discovery of Planet imagery data since 2020, but has recently been extended to include the GNSS data. In order to make these data discoverable, the CSDA team coordinated with Spire Global, Inc. to enhance the GNSS metadata, notably to include spatial representations of their data such that spatial search of these data could be provided. Ten data products were integrated into the SDX, with two other additional data products available upon request from the data team. Furthermore, to support the large number of files requested by users of these data, the bulk download capabilities were improved to decrease download times and download tracking was added for easier restart in the event of network interruptions. Integration of additional data products from Spire Global, Inc., as well as other vendor data products, are planned.

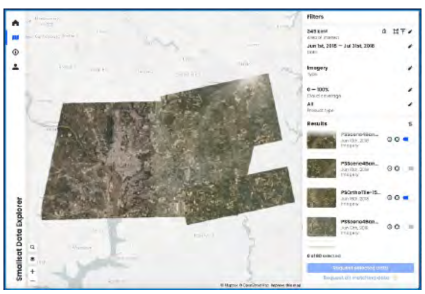


FIGURE 1. PlanetScope true color quick view imagery over the Washington D.C. area in the CSDA SDX. We acknowledge the use of imagery from the SDX application (https://csdap.earthdata.nasa.gov), part of the NASA CSDA Program.

In order to provide long-term preservation of data and make commercial data discoverable alongside all other NASA Earth science data, the CSDA data team is tasked with publishing data in the NASA EOSDIS system. In September 2021, the CSDA data team completed the Production Readiness Review, a formal evaluation by CSDA and EOSDIS management to assess the readiness of the data team and system for publishing data in the operational environment. To complete this review, the CSDA data team deployed its data publication pipeline in a user testing environment (fig. 2) and demonstrated the ability to ingest and distribute data with the required authentication; provided formal documentation, including a comprehensive data management plan; and developed internal operational procedures. The CSDA Program will be formally publishing Planet imagery in the EOSDIS system beginning in the fall of 2021.

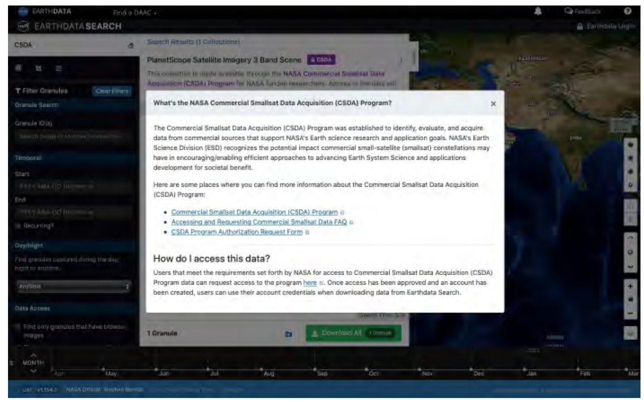


FIGURE 2. CSDA data search results with informational pop-out in the EOSDIS user testing environment of the Earthdata Search Client..

SUMMARY

The CSDA Program data team has developed a cloud native data system for the scalable and efficient management of all commercial data acquired by the Program. The team has developed and is integrating data into its SDX, a cloud-based data search, discovery, and distribution tool providing temporary data services while conducting more formal publication in the EOSDIS system. These development and operational activities all support a broader audience of data users. The CSDA Program continues to acquire new data and new data products through existing vendor agreements and by establishing purchase agreements with new commercial data vendors.

PRINCIPAL INVESTIGATOR: Aaron Kaulfus

PARTNERS: University of Alabama in Huntsville, Development Seed

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION: https://earthdata.nasa.gov/esds/csda

Field Campaign eXplorer (FCX)

OBJECTIVE: *To develop a cloud-native web-based visual explorer tool for Earth science field campaign datasets.*

PROJECT GOAL/DESCRIPTION

Field campaigns offer a wealth of observational data from ground-, airborne-, and satellite-based instruments. Such campaigns, focusing on specific phenomena, can provide observational data that would typically be otherwise unavailable. These data come in a variety of spatial and temporal scales; often provide three-dimensional observations; and can have complex navigational metadata that must be represented accurately. This variety of observations is also a weakness for using these data in subsequent analyses. Options are limited for showing three-dimensional data from multiple platforms at a coincident time and location.

The Field Campaign eXplorer (FCX) was created with the intent to address the various challenges when attempting to use datasets derived from Earth science field campaigns. The FCX system has been designed from the ground up to focus specifically on incorporating visualization and analysis of airborne data coincidentally with ground- and satellite-based observations. FCX improves the data management and discoverability of these datasets to quickly visualize and analyze these heterogeneous atmospheric data. With FCX, users can reenact mission flights and generate on-the-fly dataset visualizations.

APPROACH/INNOVATION

FCX uses a cloud-based infrastructure. This enables users to discover, explore, and visualize these data without having to download the FCX software and datasets to a local server, enabling science in the cloud. FCX uses a number of cloud-native and cloud-optimized resources to enable visualizations including Terracotta tiling and Cesium for dynamic visualization of data. The FCX system also provides access to all data, including mission reports, to enable users to further explore the context of the missions.

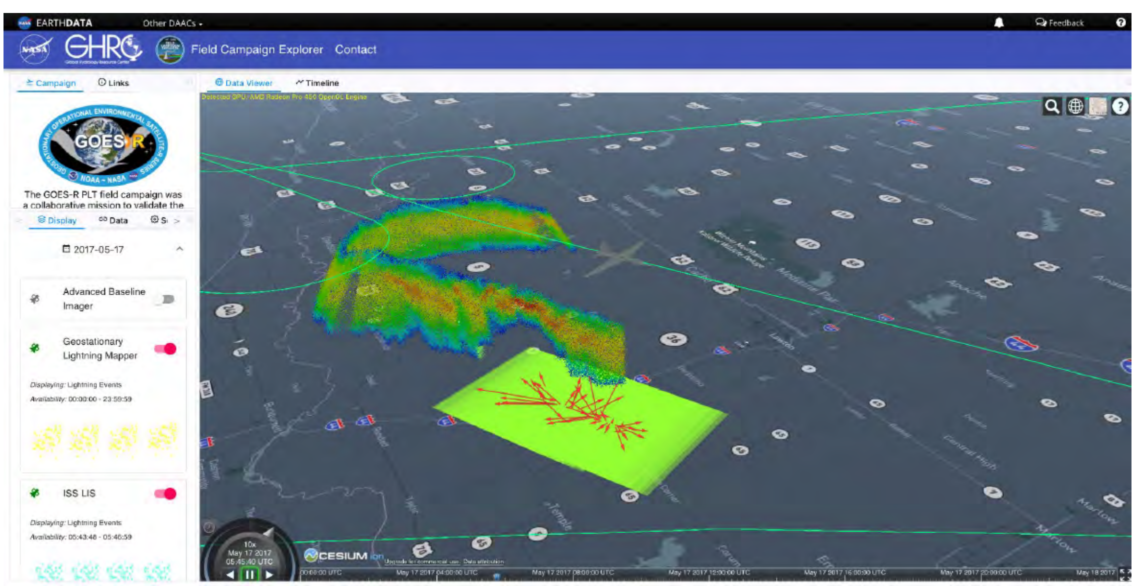


FIGURE 1. FCX Homepage.

RESULTS/ACCOMPLISHMENTS

There have been several notable accomplishments for FCX, enabling the system to achieve the objectives and goals previously described. These accomplishments have been focused on establishing FCX as a cloud-native system to enable users to work with available data without having to download FCX or the data to be visualized and analyzed. FCX is enabled by the Global Hydrometeorology Resource Center Distributed Active Archive Center (GHRC DAAC) having transitioned its holdings to the cloud. This has allowed for robust testing of FCX's capabilities and sets the stage for FCX to work with other cloud-based datasets. The cloud work has required FCX to operate with a serverless architecture, which has been achieved. Another defining trait for FCX is the ability to work with three-dimensional datasets. This is particularly critical with airborne datasets. Lastly, FCX has been deployed in NASA's cloud-native environment, the NASA-compliant General Application Platform (NGAP). The live FCX page is available at: https://ghrc.earthdata.nasa.gov/fcx/index.html.

The image shown in figure 1 shows an example of the coincident FCX display taken from the Geostationary Operational Environmental Satellite-R Series (GOES-R) Post Launch Test field campaign archived at GHRC DAAC. Here, users can search for more information on the parent field campaign and other supporting products in the upper-left. This includes the campaign's landing page, description, list of instruments and details, as well as related micro articles. The remainder of the left side provides user controls to select a particular flight day and to toggle individual instrument and observations on or off. The scene shown in this image comes from May 17, 2017, at 0545 UTC. The green line shows the ER-2's flight path while the ER-2 icon shows the location of the ER-2 at this time, due south of Lawton, Oklahoma. The green boxes show the flash density observations from the Fly's Eye Geostationary Lightning Mapper (GLM) event Simulator (FEGS) while the red arrows show the direction and intensity of the electric field from the Lightning Instrument Package (LIP). The final display extending below and behind the ER-2, using a 10-min time frame, is the nadir point Cloud Radar System (CRS) radar reflectivity observations. Combined, these observations allow for an analysis of the nature and intensity of the convective storms being flown over by the ER-2.

SUMMARY

The Field Campaign eXplorer (FCX) is a cloud-native tool serving as a data discovery, visualization, and analysis system for coincident Earth science observations. It has been specifically designed to address the difficulties in effectively working with field campaign Earth observations that use data from a variety of instruments on ground-, airborne-, and satellite-based observations. By using a cloud-native format and accessing datasets in the cloud, FCX enables users to interact with a variety of coincident datasets in three dimensions without needing to download the FCX system or data. Furthermore, FCX enables users to further explore the data with access to the campaign and instrument descriptions, as well as links to the data to download or to access user guides. These capabilities promote more effective use of field campaign datasets, which have a wealth of information about the targeted phenomena investigated by the specific field campaign. Looking ahead, GHRC DAAC is incorporating several new features. First, with the initial version of FCX going live last year, GHRC DAAC is expanding the number of campaigns available within FCX. FCX is also in the final stages of open-source acceptance, which will enable users to build their own display and analysis components into the FCX system. Lastly, a three-dimensional data sub-setter is being produced to allow users to select a three-dimensional volume and download all data within this volume.

PRINCIPAL INVESTIGATOR: Manil Maskey

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION:
https://ghrc.earthdata.nasa.gov/fcx/index.html

Automated Marine Debris Detection

OBJECTIVE: *To detect marine debris from high-resolution satellite imagery using deep learning.*

PROJECT GOAL/DESCRIPTION

Marine debris poses threats to the marine ecosystem and navigation. Detection of such debris can aid efforts in cleaning ocean plastic pollution and avoiding navigational hazards. The high temporal resolution and broad coverage of small satellite imagery makes it uniquely advantageous for the dynamics of marine debris detection, where targets can be influenced by many shifting variables such as currents, fronts, weather, and anthropogenic activities across multiple geographic scales. The advantage to using small satellite imagery is that the spatial resolution is comparatively high relative to imagery from most open access satellites, which have primarily served as the focus for marine plastic detection in recent years.

We use deep learning on high-resolution commercial satellite data to automatically detect the marine debris. Deep learning, the current state of the art in machine learning and pattern recognition, is a multilayer neural network consisting of several layers of simple computational units. It learns discriminative features without relying on a human expert to identify which features are important.

APPROACH/INNOVATION

We developed a deep learning-based marine debris detection model using commercial small satellite imagery with a 3-m spatial resolution and daily temporal resolution. The accomplishments include: a novel geo-tagged marine debris dataset encompassing multiple international hotspot locations, which is ready to use for object detection modeling with small satellite imagery; an object detection model that infers locations of suspected marine debris aggregates within optical small satellite imagery; and evaluation metrics to assess the performance of our model.

ACCOMPLISHMENTS/RESULTS

We curated and annotated a dataset of visible marine debris using the ImageLabeler tool on scenes from the PlanetScope satellite. This dataset consists of 1,370 bounding boxes of marine debris which were validated using peer-reviewed studies. An object detection deep learning model was trained on our curated dataset and initial results on PlanetScope's optical imagery were obtained, achieving a F1 performance score of 0.74 on the test dataset. The images in figure 1 display two examples of the detections from the model. The percentages represent a likelihood accuracy of the detection belonging to the class of marine debris.

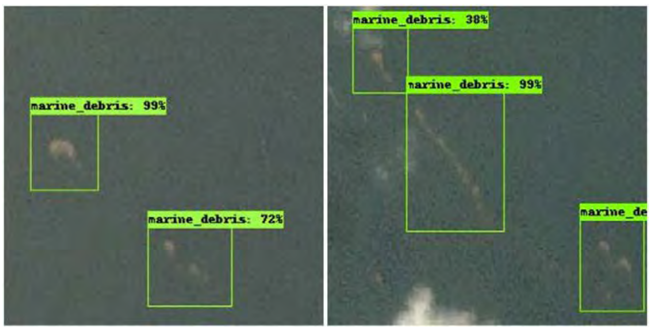


FIGURE 1. Detections geo-registered and vectorized to GeoJSON format.

We have performed experiments to assess the model's performance in generalizing over relevant geographies that differ from those included in the training dataset. The detections from these experiments have been evaluated, quality assured, and incorporated into an expanded training dataset that was used to develop a second model tasked with learning from a more geo-diverse distribution. The newest model was tested and proved to be more performant regarding generalization relative to the first model. We are currently working on extracting plastic signatures from the optical imagery-derived detections using spectral unmixing. To do this, we are leveraging the Near Infrared and Short-Wave Infrared channels from co-registered Sentinel 2 imagery to compute targeted spectral indices. The goal is to isolate plastic signatures from the detections to aid efforts to clean ocean plastic pollution.

We have submitted and received confirmation on open-source publication of the training dataset via Radiant Earth MLhub so that others can build advanced algorithms to detect marine debris. The project's code repository has been made public.

SUMMARY/CONCLUSION

Detection of marine debris was investigated using deep learning and commercial small satellite imagery. The resulting model is designed for application to optical imagery from the PlanetScope sensor captured over coastal areas burdened by significant debris pollution. PlanetScope benefits from daily global coverage of coastlines, and as such, enables rapid and scalable detection of marine debris incidents in the immediate aftermath of major pollution events, as cloud coverage permits. The dataset and models are being openly shared.

PRINCIPAL INVESTIGATOR: Manil Maskey

PARTNERS: University of Alabama in Huntsville, Development Seed

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION:
https://github.com/NASA-IMPACT/marine_debris_ML

Algorithm Publication Tool (APT)

OBJECTIVE: *To enable open science by making it easier to write and find Algorithm Theoretical Basis Documents (ATBDs), a key scientific document for understanding Earth observation data.*

PROJECT GOAL/DESCRIPTION

The Algorithm Publication Tool (APT) is a web-based application developed by the Interagency Implementation and Advanced Concepts Team (IMPACT) to streamline the authoring, management, and discovery of Algorithm Theoretical Basis Documents (ATBDs) for NASA's Earth Science Division. ATBDs describe the physical theory, mathematical procedures, and assumptions made for developing scientific algorithms that convert radiances received by remote sensing instruments into geophysical quantities. ATBDs enable open science by providing clear documentation about the methods used to create data products. They are required for every NASA Earth Observing System (EOS) instrument data product.

APPROACH/INNOVATION

The APT optimizes the ATBD process by providing a standardized template that makes it easy for scientists to create compliant and complete ATBDs. The ATBD content is stored as metadata, making it completely machine readable, searchable, and usable in other tools and services. In addition, as a centralized location, the APT simplifies collaboration among writing teams. The APT also makes it easy to format text and add equations, tables, figures and references using a rich text editor, LaTex tools and the Bibtex citation manager. Finally, the APT enables a streamlined ATBD journal submission process to the American Geophysical Union (AGU)'s Earth and Space Science (ESS), a gold open access journal.

The APT also acts as a centralized repository for NASA's Earth observation ATBDs. ATBDs may be discovered within the tool and may be previewed as either an HTML page or as a PDF document. In addition, the tool offers the option to save the ATBDs as PDF for future reference.

RESULTS/ACCOMPLISHMENTS

The IMPACT team released the first version of the APT and published it under https://impact.earthdata.nasa.gov/apt, including a landing page to highlight the features of the application as shown in figure 1. In addition to writing, submitting, and discovering ATBDs, the tool allows users to collaborate with other authors and to send their ATBDs through a review process. Having released the application, the team requested an initial group of science users to write several ATBDs for operational products on the APT. Based on the feedback received from these science users, the development team made improvements to the application.

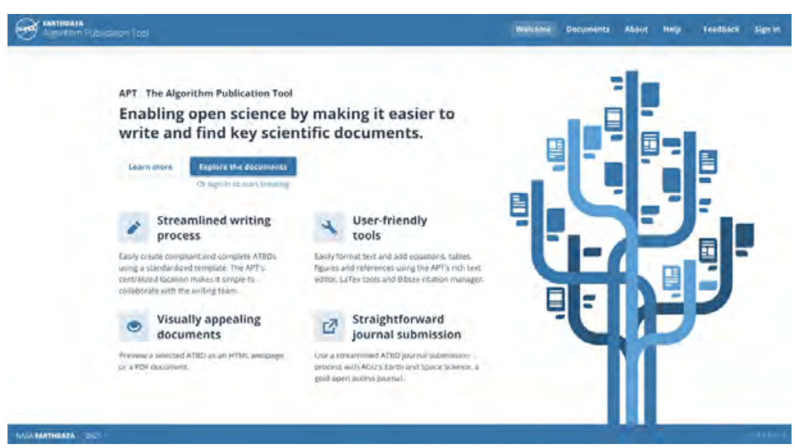


FIGURE 1. APT homepage.

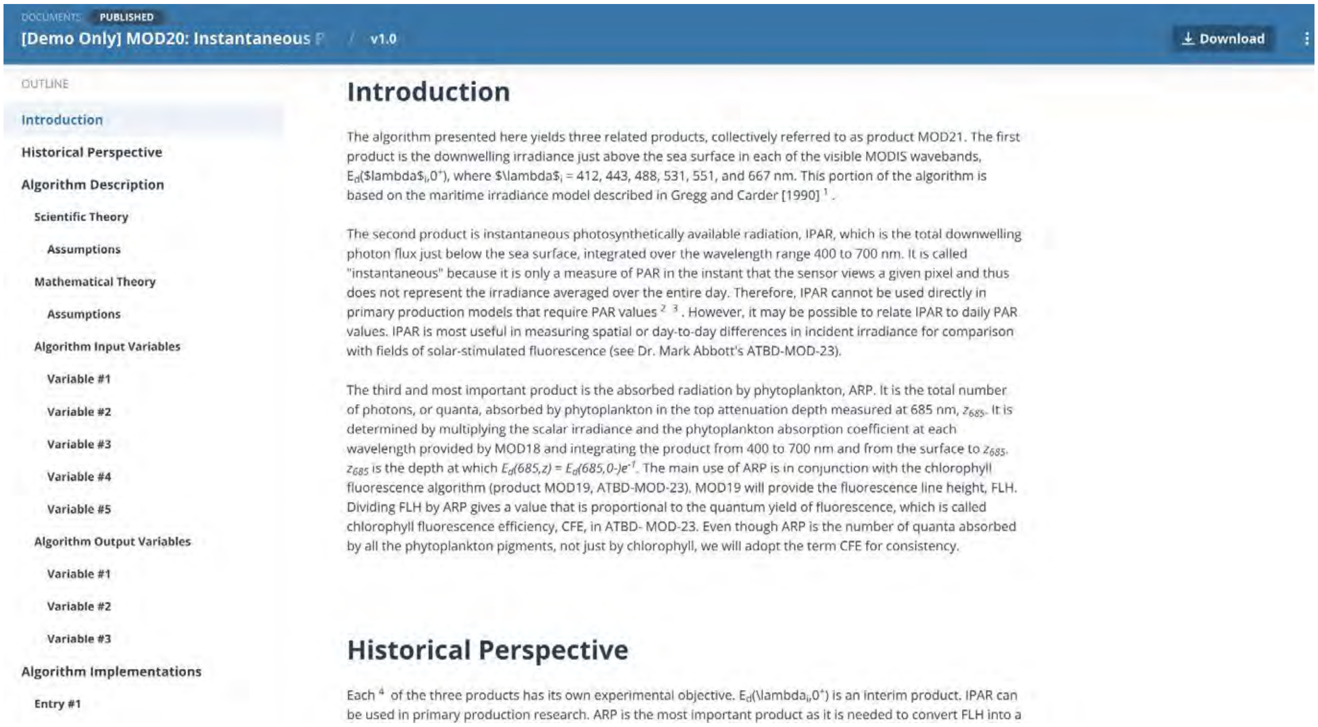


FIGURE 2. Example of ATBD.

The application includes a comprehensive framework for roles and permissions in order to guide the governance process for an ATBD during its lifecycle. Previously, the ATBD review process was handled in an ad hoc manner. The APT now provides a common and transparent process for reviewing ATBDs. Moreover, as seen in figure 2, the tool supports separate dashboards for authors, curators, reviewers, and admins to help streamline the journey of an ATBD from draft to review to publication.

In addition to this, the APT is collaborating with AGU's ESS journal to offer authors the option to publish an ATBD in a gold open access journal. A pipeline is under development to support streamlined integration between the APT and the ESS journal. As the first step in this pipeline, APT has developed a feature to export a journal-review-ready PDF document within the application.

SUMMARY

The Algorithm Publication Tool (APT) enables open science by making it easier to write and find Algorithm Theoretical Basis Documents (ATBDs), a key scientific document for understanding Earth observation data. Providing a centralized location to write, review and discover ATBDs is beneficial to the Earth science community. Providing a standardized template makes it easier for scientists to write comprehensive and complete ATBDs while offering a centralized ATBD discovery portal helps data users better understand Earth observation data products.

PRINCIPAL INVESTIGATOR: Rahul Ramachandran

PARTNERS: University of Alabama in Huntsville, Development Seed

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION:
https://impact.earthdata.nasa.gov/apt/

Catalog of Archived Suborbital Earth Science Investigations (CASEI)

OBJECTIVE: *To provide users a discovery tool for NASA Airborne and Field Campaigns that functions as a 1-stop knowledge and data center.*

PROJECT GOAL/DESCRIPTION

The web-based Catalog of Archived Suborbital Earth Science Investigations (CASEI) has been developed by the NASA Airborne Data Management Group (ADMG), which is part of the Interagency Implementation and Advanced Concepts Team (IMPACT) within NASA Marshall Space Flight Center (MSFC). CASEI was constructed to facilitate quick access for users to find detailed information about previous and current NASA airborne and field investigations and to locate any associated data products archived at NASA Distributed Active Archive Centers (DAACs). For decades, airborne and field data have been difficult to locate and obtain due to various reasons, including their distributed storage throughout various NASA Earth science locales or because they have incomplete or poor-quality descriptive metadata. CASEI now enables users to access airborne and field investigation details, including platform and instrument details, funding information, investigation scientific objectives, and significant events noted during the study. The information is highly interlinked and allows users to explore across all campaigns, platforms and instruments in order to identify the information and data in a fairly intuitive manner. Figure 1 displays an example of the user interface of the CASEI website.

FIGURE 1. Snapshot of a portion of the CASEI user interface's homepage.

APPROACH/INNOVATION

CASEI currently contains curated metadata for approximately 60 airborne and field investigations with plans for adding another 40 or more campaigns in FY22. CASEI utilizes a detailed PostgreSQL database constructed to specifically handle the many campaign-, platform-, and instrument-specific metadata previously not available together in one place. The metadata curation is performed by a team of scientists and students who gather the information. Successful construction of CASEI depends upon several important features and tools: (1) a list of carefully written definitions for all aspects of airborne and field campaigns; (2) a set of decision trees for producing consistent determinations for how to incorporate information from an existing campaign into the metadata scheme; and (3) a carefully designed Maintenance Interface (MI) using Django. All curated information is verified and checked by 3 separate team members to ensure the accuracy and completeness of all information entered into the database. The MI functionality continues to be refined to speed the metadata curation in response to ADMG's needs.

RESULTS/ACCOMPLISHMENTS

The CASEI web-based user portal was launched at the end of June 2021 and is available at https://impact.earthdata.nasa.gov/casei/. The rich, interconnected metadata fill a campaign landing page, as shown in figure 2. These landing pages provide a high-level snapshot of the campaign including deployment specifics, season, region, funding, key personnel, and easy access to platform and instrument details, to name a few. Users can directly access published data product landing pages by clicking on the Digital Object Identifiers (DOIs) for each data product associated with the campaign. Video demonstrations and user help is provided from within the tool for easy access. Public APIs are available for computer access to the inventory database content. The API documentation provides users with information about each metadata item.

FIGURE 2. Example campaign page within the CASEI user interface.

An IMPACT blog post and tweet announced the release of CASEI and Stephanie Wingo (CASEI Development Lead) and Deborah Smith (ADMG Lead) presented CASEI at various meetings and functions during the following summer months. CASEI was widely advertised at several professional venues, including the 2020 American Geophysical Union (AGU) Fall Meeting (Dec 2020), the 2021 American Meterological Society (AMS) Annual Meeting (Jan 2021), the 2021 MSFC Science and Technology Jamboree (June 2021), and a NASA Earth Science Data Systems Technology Spotlight (July 2021). Abstracts have been submitted for presenting CASEI to scientists at both the upcoming AGU Fall Meeting (Dec 2021) and the AMS Annual Meeting (Jan 2022).

SUMMARY

CASEI has been built by the NASA Airborne Data Management Group to provide users with easy access to important information and data access for NASA airborne and field campaigns. The complex and heterogeneous data products resulting from these types of campaigns require an understanding of the full contextual environment in which the data was collected for best use of the data products. CASEI ensures the vital information is preserved and available for users, both now and in the future.

PRINCIPAL INVESTIGATOR: Rahul Ramachandran

PARTNERS: University of Alabama in Huntsville, Development Seed

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION: https://impact.earthdata.nasa.gov/casei/

pyQuARC Open Source Library for Earth Observation Metadata Quality Assessment

OBJECTIVE: *To automate quality checks for metadata records that catalog NASA's Earth observation data products.*

PROJECT GOAL/DESCRIPTION

The Analysis and Review of the Common Metadata Repository (ARC) team within the Interagency Implementation and Advanced Concepts Team (IMPACT) has developed an open source, Python-based library called pyQuARC. The ARC team conducts quality assessments of NASA's metadata records in the Common Metadata Repository (CMR), which is a centralized database that catalogs all of NASA's Earth observation data products. The ARC team assesses CMR metadata against a set of quality criteria focused on correctness, completeness, and consistency, and pyQuARC packages the quality checks that the team has automated. Metadata quality assessments conducted by the ARC team are shared with NASA Earth science data providers who work to improve the metadata quality over time.

FIGURE 1. Conceptual diagram of pyQuARC. The Python-based library is designed to read and evaluate descriptive metadata used to catalog Earth observation data products and files.

APPROACH/INNOVATION

In addition to basic validation checks (i.e., adherence to the metadata schema, controlled vocabularies, and link checking), pyQuARC flags opportunities to improve or add contextual metadata information in order to help the user connect to, access, and better understand relevant Earth observation data products. A conceptual illustration of the pyQuARC interface is shown in figure 1.

pyQuARC also ensures that information common to both data product and file-level metadata are consistent and compatible. As open-source software, pyQuARC can be adapted and customized by a data provider to allow for quality checks that evolve with their needs, including the ability to check metadata not included in the CMR.

RESULTS/ACCOMPLISHMENTS

To date, the ARC team has verified a 58.12% improvement in the total number of metadata errors detected, and further improvements are ongoing. pyQuARC helps streamline the quality assessment process, allowing the team to save time and focus on any assessments that require a manual approach. The pyQuARC checks are currently being integrated into a tool called the CMR Metadata Curation Dashboard, which the ARC team uses to facilitate the generation and sharing of metadata quality reports with data providers.

SUMMARY

The ARC team, which is responsible for conducting quality assessments of NASA metadata records in the CMR, has developed a Python library called pyQuARC which packages the team's automated metadata quality checks. This Python library is open source and can be reused and customized to meet individual needs.

PRINCIPAL INVESTIGATOR: Rahul Ramachandran

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

FOR MORE INFORMATION: https://github.com/NASA-IMPACT/pyQuARC

Optimization of a Dynamic Lightning Safety Algorithm for MSFC and the Public

OBJECTIVE: *To use the physical properties of clouds to determine when they can no longer support lightning to improve lightning safety protocols for Marshall Space Flight Center activities and, ultimately, the public.*

PROJECT GOAL/DESCRIPTION

The goal of this project is to use multiple remote sensing datasets (satellite, lightning, radar) and machine learning techniques to develop an algorithm to identify when clouds can no longer support lightning. This analysis has led to the development of a prototype dynamic lightning safety algorithm during FY20 by the NASA Short-Term Prediction and Research Transition Center (SPoRT) team, funded by the Center Innovation Fund (CIF). The algorithm is intended for future use by Marshall Space Flight Center (MSFC)'s Emergency Operations Center (EOC) and other personnel once it has been vetted against current EOC lightning safety practices. This work is innovative because its overarching goal is to shift lightning safety standards from hard rules (e.g., 30 min since last flash) to a dynamic algorithm that identifies exactly when the threat of lightning has ceased, mitigating overwarning and reducing downtime. Conservative estimates indicate that MSFC could save upwards of $1 million due to lost time from the perceived threat of lightning if the proposed work could develop a reliable algorithm to end the stand down period 10 min or more ahead of the standard 30-min rule used by the National Oceanic and Atmospheric Administration and MSFC.

APPROACH/INNOVATION

The innovation of this lightning safety algorithm is in the utilization of data synthesis techniques which merge multiple observations to a single, physically-based evaluation to the real-time threat of lightning for MSFC. The novel way that the algorithm aligns the strengths of radar, lightning, and satellite datasets to provide integrated decision support services to MSFC (and eventually the commercial and public sector) is not matched anywhere else in our field. The other main unique feature is the machine learning-generated model to indicate the location of flash initiation potential. This is the backbone of the algorithm and is solely in the possession of the team. The model output generates physically-based assessment of lightning potential using all of the cloud property information available, then calculates the likelihood that lightning will impact MSFC within 5 to 15 min.

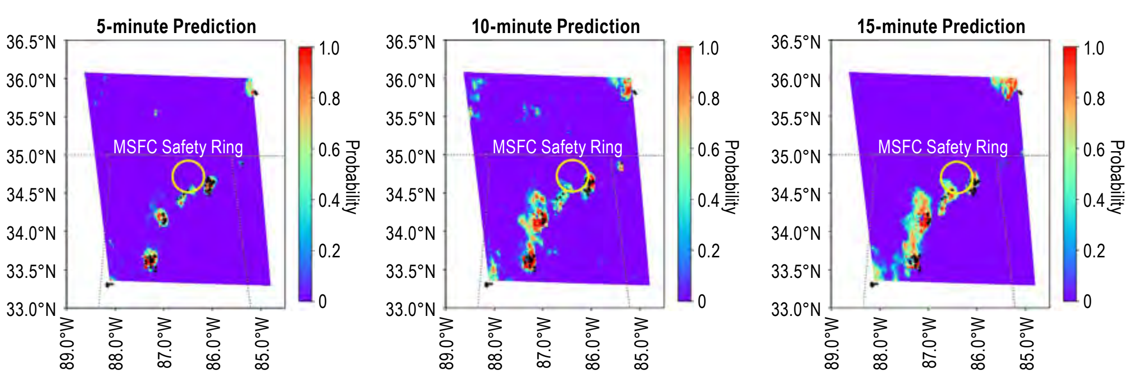


FIGURE 1. 5-, 10-, and 15-min lightning prediction probabilities near MSFC on 7 April 2019. The yellow ring indicates the 16 km safety buffer the MSFC Emergency Operations Center (EOC) uses to stand down due to lightning.

In 2021, the SPoRT team adapted the 2020 CIF-funded dynamic lightning safety algorithm to an Amazon Web Services (AWS) framework. This adaptation allows for heavy amounts of live data processing on Amazon's web framework to determine lightning threats anywhere in the country, and eventually around the world. The AWS implementation of the model provides an efficient on-demand data distribution system and separates data selection, preprocessing, and model execution routines, which enables the user to divide the processing workload between instances on a method-by-method basis before aggregating all datasets and executing the model on a designated machine. This construct is especially useful for algorithms with methods that take a long time to execute and multiprocessed methods that can't be efficiently run in parallel with other methods on one instance. This raised the project's Technology Readiness Level (TRL) from 5 to 6 during FY21 using Science Mission Directorate funding.

RESULTS/ACCOMPLISHMENTS

In 2020, lightning data from the previous two years was used in the initial development of the dynamic lightning safety algorithm. There were 222 days in 2018 and 2019 where lightning was observed within 150 km of Huntsville. 2018 data were used to develop a training dataset, and then 2019 data were used to test a machine learning model for skill score evaluation. Initial results for 5-, 10-, and 15-min predictions were strong, with the 5-min prediction performing best at ≈85% probability of detection (POD) and 20% false alarm ratio (FAR) using a 2 km × 2 km pixel verification method. The 10-min prediction remains similar in POD, but FAR increases to 40%. Much of this increase is due to the advection of storms with time, where the prediction lagged the storm motion.

In 2021, the team has taken steps to operationalize the algorithm utilizing tools to speed up processing and generation of visualizations in the end user's operational framework. Using the AWS architecture, the total runtime of the lightning machine learning model was reduced by more than 50% relative to the original algorithm's execution time on the NASA SPoRT's computing cluster. These efficiency improvements enable the program to consistently run under a 5-min threshold, which is mandatory in order for the 5-min predictive outlook to be useful in a live data context by our operational end users.

SUMMARY

A prototype dynamic lightning safety algorithm was developed by the NASA SPoRT team to provide 5- to 15-min predictions on lightning occurrence to improve lightning safety and reduce down time after a lightning threat is no longer possible. Initial results are strong with an 85% POD and 20% FAR for a 5-min prediction. Additional improvements are required to strengthen POD while decreasing FAR skill scores to increase accuracy, including accounting for thunderstorm advection, flash propagation, and application of this algorithm to understand impacts to lead time and reduction in additional downtime within MSFC's EOC protocols. This algorithm has grown from a TRL of 5 to a TRL of 6 during the FY21 year, and a near-term future goal is to provide this algorithm output to partners in real-time for operational assessment.

PRINCIPAL INVESTIGATOR: Christopher J. Schultz

PARTNERS: MSFC Emergency Operations Center, University of Alabama in Huntsville, National Weather Service, U.S. Forest Service

FUNDING ORGANIZATIONS: Space Technology Mission Directorate (STMD), Science Mission Directorate (SMD)

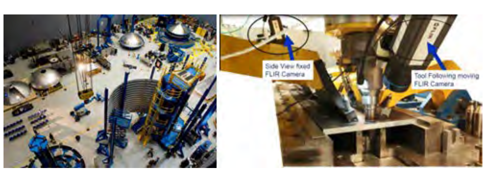
FOR MORE INFORMATION:
weather.msfc.nasa.gov/sport/

Computational Fluid Dynamics (CFD) Modeling of Lightweight Alloy Self-Reacting Friction Stir Welding (SR-FSW) to Correlate Thermal, Mechanical, and Viscoplastic Flow Phenomena With Weld Quality and Hardness

OBJECTIVE: *To develop high-fidelity solid-state friction stir welding (FSW) weld modeling software capable of simulations of Space Launch System (SLS)/Artemis-relevant alloys-based welding.*

PROJECT GOAL/DESCRIPTION

There is a recognized need for better analytical tools to support advanced manufacturing of metallic structures, "with a special emphasis on understanding friction stir weld processes and lightweight alloys." CFD Research Corporation, Inc. (CFDRC) in partnership with NASA Marshall Space Flight Center (MSFC) Metal Processes and Manufacturing Branch (EM32) has been working to mature, to further validate with experimental data, and to deliver an accurate self-reacting friction stir welding (SR-FSW), modeling and simulation software tool. This tool will allow researchers to predict the effects of process parameters, pin tool design, and welded material with a particular focus on Space Launch System (SLS)-relevant alloys such as AA2219 and AA2050.



(a) (b)

FIGURE 1. (a) MSFC South High Bay 4755 overhead view. In order to pre-production test welds, the use of (b) process development small-scale welding tools is also available. This validates the weld schedule(s) prior to actual (a) full-scale welding.

APPROACH/INNOVATION

The challenges faced by MSFC EM32 when developing SR-FSW weld schedules during transitions between working materials are one motivating factor for developing predictive models of the process. The nature of friction in stir welding provides another impetus for modeling, since the mechanically affected zone of the starting material that becomes the weld 'nugget' is not accessible for real-time monitoring during welding. In addition to working material changes, other challenges faced by EM32 include accelerating process learning and tool development on the benchtop scale, then transferring the process learning from benchtop-scale to joining sections of full-scale components.

The modeling approach utilized by the team builds on our prior work and complementary efforts in academia for predicting the outcome of similar friction stir welding processes. The process effects on workpiece temperature history and mixing are captured by a computational fluid dynamics (CFD)-based approach with a rigid-viscoplastic constitutive model for the effective viscosity of the workpiece when it experiences heating and strain rates sufficient for yielding. The predicted thermal and strain rate history experienced at multiple points across the weld are extracted from the model results and provide inputs for metallurgical process models to predict mechanical properties of the weld. Within this modeling framework, the principal challenges are: (1) obtaining adequate workpiece properties at elevated temperatures and high strain

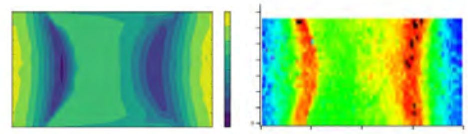


FIGURE 3. Comparison of (a) modeling and (b) measured (redacted ITAR), predicted Vickers Hardness transverse weld section profile from alloy precipitates Shercliff thermal dissolution master curve, natural ageing, and temperature history experienced in weld. Natural ageing only increases hardness. Advancing side on left, receding on right. Yield-based shoulder velocity stick-slip boundary condition.

rates; (2) predicting the contact condition at the tool-workpiece interface; and (3) adequately predicting the effects of the evolving microstructure on the resulting weld properties.

Next steps include continued application in support of MSFC EM32 (including tool design); application and validation for additional alloys; and parameterization of a more predictive process model.

RESULTS/ACCOMPLISHMENTS

The team has made significant progress in addressing each of the above challenges during the execution of this effort. The necessary workpiece properties have been obtained through a combination of measurements at MSFC (during prior efforts); prediction from CALPHAD and related theoretical approaches; and parameterization of experimental data obtained from ongoing literature searches.

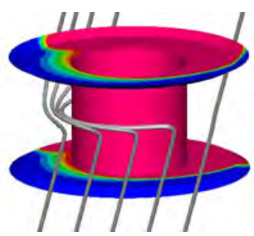


FIGURE 2. Focus-on-weld-region: angular velocity of workpiece material at the tool surface resulting from yield-based slip-stick model for the viscoplastic material flow. Some flow lines and a (redacted) SR-FSW pin-tool are visualized. Calculated are velocities, flow temperatures, strain rates, precipitates thermal dissolution and recovery…the ingredients contributing to as-welded bulk mechanical properties. Boundary condition not shown include the FSW weld head and machine, fixturing and chill bars, and weld work-piece thermal 'mass'.

The key advancement for the thermal and visco-plastic flow models during this project has been the development of a sub-model for the tool-workpiece contact condition. The contact condition, particularly in CFD-based models for FSW, is typically expressed as a single value for relative sticking (or slipping) at the interface or a semi-empirical correlation with some spatial variation. The developed contact condition is based on the relative magnitudes of the frictional stress at the interface (including effects of tool clamping forces) and the temperature-dependent shear yield stress of the workpiece material. The shear yield stress is determined from the local temperature at each location on the workpiece surface, and the workpiece is set to either stick to the tool if the frictional stress is greater than the shear yield stress or slip if the friction force is less than the yield stress. The only adjustable parameter of our implementation is a single value for numerically smoothing the transition from slip to stick. A representative workpiece angular velocity distribution at the tool surface, seen in figure 2, shows that this sub-model results in increased slip of the workpiece relative to the tool on the advancing side and leading edge with the workpiece material sticking to the tool on the receding side and trailing edge. Similar slip-stick distributions have been imposed through semiempirical models by others and were demonstrated to better capture the material transport.

To enable prediction of weld mechanical properties, postprocessing routines were developed to extract the temperature and strain rate history at multiple locations across the weld cross-section. This data is then passed to a metallurgical process model for prediction of the mechanical properties. In our earlier work, the process model was based on a simple correlation for the maximum temperature-compensated strain rate experienced by the material, essentially assuming that dynamic recrystallization effects on the strengthening precipitate size distribution dominate the weld properties in the mechanically affected zone. During this effort, we have implemented a semiempirical model for thermally-driven precipitate dissolution and regrowth that predicts the measured microhardness distribution across the weld for alloy 2219. The model is based on experimentally-measured softening kinetics for 2xxxx-series alloys, captured by a semiempirical curve fit and copper solute diffusivity variation with temperature, and measured hardness recovery after heat treatment.

SUMMARY

CFDRC has made significant advances in the state of the art of computational modeling of SR-FSW-welded alloys viscoplastic material flow and even the chemical evolution of alloy precipitates as driven by thermomechanical effects experienced during friction stir welding. In addition to these advances, CFDRC has performed numerous simulations of real SLS welding parameter conditions with actual tooling modeling (not shown), and has performed tooling geometry and weld parameter optimization studies for the relevant alloys.

PRINCIPAL INVESTIGATORS: Fredrick Michael, James Vernon Cole

PARTNERS: CFD Research Corporation (CFDRC) Inc.

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

TA12:

Materials, Structures, Mechanical Systems, and Manufacturing

Cavitation Effects on the Structural Dynamics of Turbomachinery Components: Modeling and Experiment

OBJECTIVE: *To create and experimentally validate a computational modeling tool for predicting the effects of cavitation on the structural dynamic properties of turbopump inducer and impeller blades.*

PROJECT GOAL/DESCRIPTION

Although rotating machinery in dense fluids is an inherent part of many systems, including rocket engine turbomachinery, naval propulsion, and water turbines, the dynamic characteristics of the structures in these systems (natural frequencies, mode shapes, and damping) have not been studied sufficiently. One of the most complicated aspects of this type of machinery is the cavitation phenomena, in which bubbles form on the structure during operation, as shown in figure 1. A cooperative research program is underway between NASA Marshall Space Flight Center (MSFC) and the University of Georgia (UGA) to induce cavitation on a pump-like structure in UGA's Dynamic Solutions high-speed water flow facility and use the results to validate a numerical model that can be extended to realistic pump structures (fig. 2). The development of this experimentally validated tool to characterize the structural dynamic characteristics of flow-path components in the presence of cavitation will significantly reduce MSFC's rocket engine design cycle costs by enabling analytical prediction of these critical parameters, rather than relying on the expensive and long process of trial-and-error testing and redesign.

FIGURE 1. Inducer cavitation in water tunnel.

APPROACH/INNOVATION

MSFC will develop a computationally inexpensive alternative to full-order fluid-structure interaction (FSI) simulations of cavitating flows. This will be accomplished by validating the recently developed Nonlinear Fluid Modal Method (NFMM) with experimental data of a cavitating flow case. MSFC will use FSI simulations of a representative 'unwrapped' inducer test article to construct the NFMM model; this can then be used in place of traditional computational fluid dynamics to predict the structural dynamic behavior, thereby increasing simulation speed by orders of magnitude. In parallel, UGA will fabricate and instrument the test article, mount it in a state-of-the-art high-speed water tunnel, run test flow cases with induced cavitation, and measure the structural dynamic response. UGA will also reduce the data and report it to MSFC for code validation.

The deliverables from UGA include a detailed test description, including instrumentation; test parameters and conditions; results summary; and digital copies of all test data. MSFC personnel will deliver a computationally efficient,

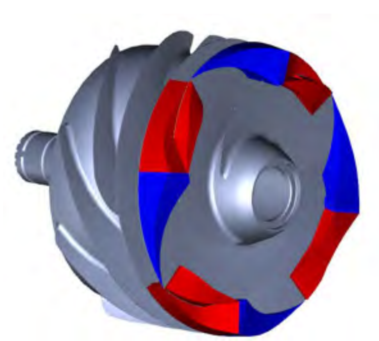


FIGURE 2. Finite element fluid/structure model showing regions of varying cavitation.

test-validated modeling tool that can be used in the development and analysis of liquid engines for NASA and its commercial space partners.

RESULTS/ACCOMPLISHMENTS

UGA has been testing a variety of configurations to determine the best combination of cavitation and measurable response. Plates with different leading-edge surface treatments, angles-of-attack, and water-tunnel depressurization have all shown to be effective in generating cavitation at the flow velocities achievable in the flow facility (fig. 3).

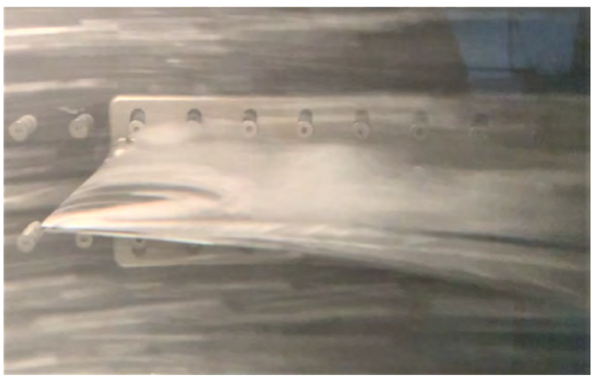


FIGURE 3. Cavitation sheet on UGA plate.

A number of other difficult issues have been successfully addressed, including flexibility of the test tunnel, and successful video and quantifiable measurement of the cavitation sheet. Damping measurements have been made for a variety of flow conditions with different pressures and flow velocities, although further optimization of these parameters is ongoing (fig. 4).

MSFC has made continual upgrades to the numerical tool as well as ease-of-use refinements to the analysis procedure. Although data are still being collected on the final test article, good agreement between numerical predictions and the preliminary data shared by UGA has been demonstrated. Additionally, while waiting for further cavitating data from UGA, MSFC has verified and validated the numerical tool against a larger set of non-cavitating experimental measurements.

SUMMARY

A Cooperative Agreement Notice technology development program is in progress between MSFC and the University of Georgia Research Foundation to study the effect of cavitation on fluid hydroelastic damping and natural frequency of pump structures. The data, which are being collected at UGA's water-flow dynamics facility, will be used to validate a numerical code being developed by MSFC personnel. Determination of natural frequency and damping is critical for successful operation of inducers and other turbopump structures. This is the first study of its kind, and initial results indicate that measurable levels of dynamic response and cavitation have been achieved. Further testing is ongoing to find the optimal combination of test parameters to fulfill the project goals.

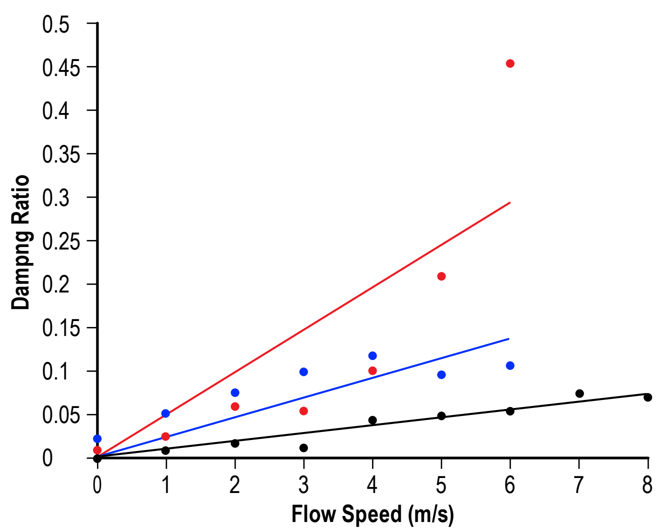


FIGURE 4. Damping vs. flow speed from UGA test.

PRINCIPAL INVESTIGATORS: Timothy Wray, Andrew Brown

PARTNERS: University of Georgia Research Foundation, Dr. R. Benjamin Davis

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Development of Laser-Assisted Manufacturing Processes for Spaceflight Applications

OBJECTIVE: *To carry out an advanced concept study to investigate the design requirements and potential capabilities of an on-orbit laser welding robot.*

PROJECT GOAL/DESCRIPTION

This project was a partnership between the NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) and MSFC's Materials and Processes Laboratory (MPL). The collaboration was a 2-month study that pulled on current state of the art for on-Earth laser-based manufacturing technologies and on-orbit satellite technologies with a focus on generating a design concept for a multipurpose on-orbit laser welding and manufacturing robot. The design of the robot was centered around being flexible for multiple different on-orbit manufacturing needs, but the study used the construction of an on-orbit habitat as the concept of operations (Con-Ops). This project aimed to address the future needs of NASA for on-orbit servicing, assembly, and manufacturing (OSAM) by developing an early concept for a robotic satellite that could be utilized for both assembly and manufacturing of on-orbit infrastructure. Examples of such infrastructure include other satellites, crewed habitats, and crewed vehicles for deep space missions. The design that was developed can now be used as a guide for a higher fidelity model aimed for flight missions by laying out the system requirements and gathering the pertinent component capabilities needed for each subsystem of the satellite.

APPROACH/INNOVATION

The study utilized experts in satellite subsystems; advanced laser processing components; and previous knowledge gained from NASA's heritage flight data from Skylab and KC-135 flight experiments focused on welding in space.

The MPL team investigated commercially-available fiber laser welding power supplies to determine the requirements of the welding system and to estimate the capabilities of the on-orbit welding robot. These welding power supply system requirements were used to bound the study and determine the requirements of the satellite subsystems. A few other assumptions were made that helped baseline the on-orbit robotic welder: that the robot would be welding 3-mm-thick stainless steel and that material would be delivered via a vehicle with an open-to-vacuum cargo bay.

After setting these ground rules and assumptions, the advanced concepts team determined what currently-available satellite subsystem technology would be required for the successful operation of this robotic welding system. These subsystems were used to create a baseline design concept and the Con-Ops of constructing the shell of a habitat module that would be outfitted by a crew for long-term habitation.

At the time of this study, most OSAM-related satellites were investigating single-point solutions like operating on a specific satellite or constructing additional features of a single satellite. This project looked at designing a concept that could be used for several different applications, from space station maintenance and habitat construction to working on deep space vehicles and other satellites. The next step for this program is to develop units for system and subsystem testing in-flight conditions. Ideally, an on-orbit experiment would generate the best data, but a suborbital flight could be used to simulate the microgravity environment.

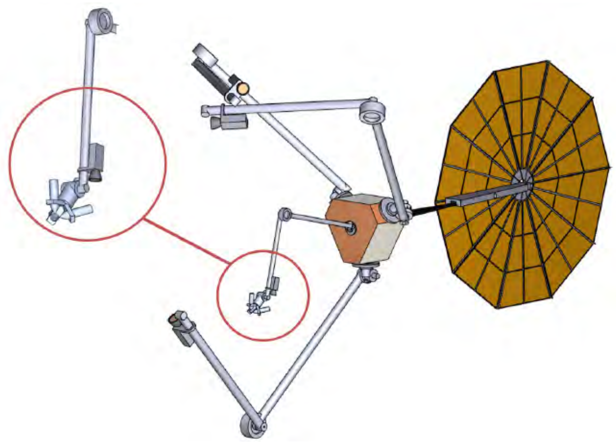


FIGURE 1. Diagram of ACO's notional design for welding robot satellite. The laser welding end effector is circled in red.

RESULTS/ACCOMPLISHMENTS

The welding robot satellite design required mobility, power generation, thermal management systems, and additional stability and control of the welding end effector (the part of the robot that would make the weld). The ACO's notional design is shown in figure 1. The benefits to using a fiber laser welding system is that the end effector can be decoupled from the power supply, meaning the robotic system could have an independent arm to operate the weld system. Keeping this in mind, the ACO team decided to utilize a multiarmed positioning and travel system for the welding robot. The final design concept has three main arms for gripping components to be welded and a smaller arm with finer movement control to hold the laser welding end effector. Additional reaction control system thrusters were added to the arms to aid in the event the robot became detached from its working environment. Additional thrusters or an umbilical may be needed to allow for orientation of the robotic system and to support larger, longer range movements, such as to a different satellite or a different nearby structure.

The power subsystems were designed on another set of assumptions regarding the welding system: that the welding operation would occur intermittently and there would be some cooldown time for the thermal management system to do its job. This was set to be 10 min of welding time and 120 min of cooldown time per weld cycle. These numbers were arbitrarily chosen to help with component sizing and selection. The team expects that these times would need to be revisited on a higher-fidelity design to truly narrow down how long the system could weld before overheating or damaging other subsystems. The satellite and welding robot would be powered by a solar array that would have a power regulation bus that would distribute power to a 480 V Lithium-ion battery and the remainder of the satellite's sub systems. A box diagram of the power supply design is shown in figure 2. The solar array would be sized such that it can charge the 480 V battery at 850 W for the 120-min cool down time and continuously power the rest of the space craft. The commercially available power electronics systems and the solar array would be taken from Orion spacecraft and International Space Station heritage designs. The thermal management systems would involve one large radiator subsystem, which would be

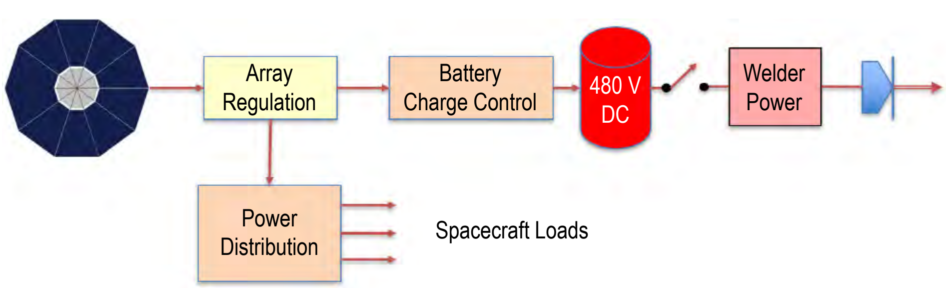


FIGURE 2. Box diagram of solar power supply designed to support the welding robot satellite.

capable of cooling all the satellite's subsystems, as well as the cooling circuit required by the laser welding power supply. This thermal management system would utilize previously space-qualified hardware and would meet the state of practice for current satellite systems.

The Con-Ops for this version of the robotic laser welding satellite was selected to be construction of a habitat structure that would then be outfitted and utilized by a crew. The robotic system would be transported on a space vehicle like an Orion spacecraft or Dragon capsule. The material would then be transported with the robot in the cargo bay of the spacecraft, which would act as the airlock and docking station for habitat. The satellite could then utilize its multiple arms to grab material from the cargo hold, position the pieces of material, and move the welding end effector to create seam welds joining these pieces of material until a final structure has been formed. In addition to manipulating the material, the robot could utilize its arms to change its position in order to reach different joint angles during this process. See figure 3 for the robotic system mid-operation.

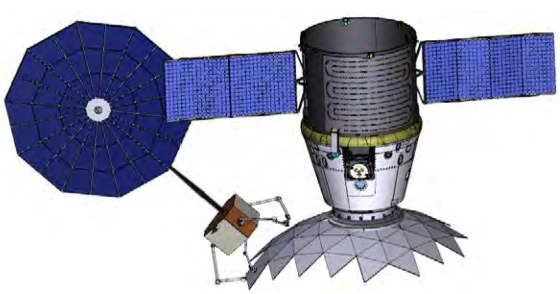


FIGURE 3. Illustration of welding robot satellite in operation.

SUMMARY

The results of this study show that a laser welding robotic satellite can feasibly be manufactured from components that are readily utilized by current-age satellites and spacecraft. The multiarmed design proved to be the simplest method for both positioning and moving the robot along a structure that was under construction. With a basic design in hand, a future team of engineers can work toward a higher-fidelity model that can be built and tested in an on-orbit environment. It is worth noting that significant research is needed with respect to the welding process itself in the environment of space before it is used to construct spacefaring infrastructure. Welding in space has previously been explored in heritage experiments by NASA and the Soviet Union, to varying degrees of success. The consensus from those experiments is that welding can be done in space; however, some processes are more favorable than others. Further understanding is needed to fully determine the best welding process for future projects. A system such as the one designed in this study could be a baseline for such experimentation.

PRINCIPAL INVESTIGATORS: William Evans, Zachary Courtright

FUNDING ORGANIZATION: Center Innovation Fund (CIF)

Composite Technology for Exploration (CTE)

OBJECTIVE: *To advance composite technologies with a focus on weight-saving, performance-enhancing bonded joint innovations for heavy-lift launch vehicle-scale applications to support future NASA exploration missions.*

PROJECT GOAL/DESCRIPTION

The Composite Technology for Exploration (CTE) project has developed and demonstrated critical composite technologies for future NASA exploration missions with a focus on composite joint technologies for Space Launch System (SLS)-scale composite hardware. The project supported SLS payload adapters and fittings by maturing composite bonded joint technology and analytical tools to enable risk reduction. (SLS payload adapter baselined the composite longitudinal bonded joint.) The CTE project has demonstrated weight-saving and performance-enhancing composite bonded joint technologies through completing materials characterization studies; developing advanced analysis tools; and designing, manufacturing, and testing various concepts for lightweight composite bonded joints. CTE has developed and validated high- fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints. By applying this comprehensive approach, the CTE project has matured the composite technology and improved bonded joint failure load and mode predictions. This has led to an increase of overall confidence in bonded joint composite structures.

APPROACH/INNOVATION

When properly designed, composite structures have many potential benefits over traditional metallic structures, including lower mass, better fatigue resistance, lower part count, and reduced life-cycle cost. NASA is advancing composite technologies that provide lightweight structures to support future exploration missions. Due to the large diameter of a heavy-lift-type launch vehicle and the unavailability of large autoclaves for curing composite structures, individual large composite panels must be manufactured separately and then joined together. The state-of-the-art method for joining launch vehicle composite panels and structures is metallic joints that are both weight- and labor-intensive. The CTE project has allowed NASA to gain experience with lightweight composite joints and analysis techniques specifically applicable to large-scale composite structures. CTE has designed, fabricated, and tested a lightweight bonded joint concept for the SLS Payload Adapter. The project has also developed and validated high-fidelity analysis tools and modeling, as well as analysis standards for the prediction of failure and residual strength of composite bonded joints.

RESULTS/ACCOMPLISHMENTS

LONGITUDINAL BONDED JOINTS

After demonstrating an out-of-oven manufacturing process for longitudinal bonded joints on the SLS Manufacturing Demonstration Article (MDA), longitudinal bonded joints were baselined by the SLS Payload Adapter to reduce weight and manufacturing time. The project has continued to support the payload adapter team and improve the high-fidelity analysis tools, modeling and the analysis standards of composite bonded joints.

CIRCUMFERENTIAL BONDED JOINTS

The last two years of the CTE project were focused on maturing lightweight three dimensional (3D)-woven composites for circumferential bonded joints (C-joints). A lightweight C-joint end ring point design was developed to mature

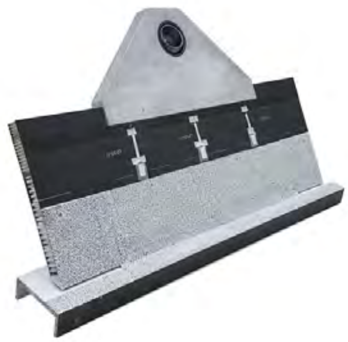


FIGURE 1. C-joint scale-up test article.

technology to replace current state-of-the-art metallic bolted end rings. The C-joint point design employs a 3D-woven composite C-channel and and a Pi preform that are bonded together to a composite sandwich panel. Figure 1 shows the scale-up test article that depicts a section of the C-joint. The CTE project focused on coupon testing, sub-element testing, and scale-up testing. Data gained from testing were used to develop and validate improved analysis techniques and models.

For the scale-up test design shown in figure 2, the CTE team performed extensive design, analysis, and test setup to ensure appropriate load introduction of the payload adapter and vehicle axial loads, while using a simplified flat (not curved) test article. The team developed 3D pretest analysis models including geometric and material nonlinearity; bolted interfaces; and load introduction kinematics.

In July 2021, The CTE project successfully completed testing on the scale-up test article loaded under various combinations of tensile and compressive loads to mimic the SLS payload and vehicle loads. The test demonstrated 3D-woven composite bonded C-joint manufacturing scaled-up from 6 in to 35 in. Modeling was performed to verify the scale-up test design by showing positive margin on load reaction hardware and test article. To prove joint viability, testing was conducted under four load combinations. All tests completed without failure, even going above 2.0 times the design limit load.

The CTE C-joint scale-up testing demonstrated 3D-woven joint manufacturing, load carrying capability, and predictive capability of associated structural models. The test team collected data that will enable future advancements. This work increased the understanding of damage in 3D-woven composites, specifically the complex geometry related to C-channels, including failure initiation and propagation. The development of the manufacturing process and testing increased the overall confidence of bonded joint composite structures.

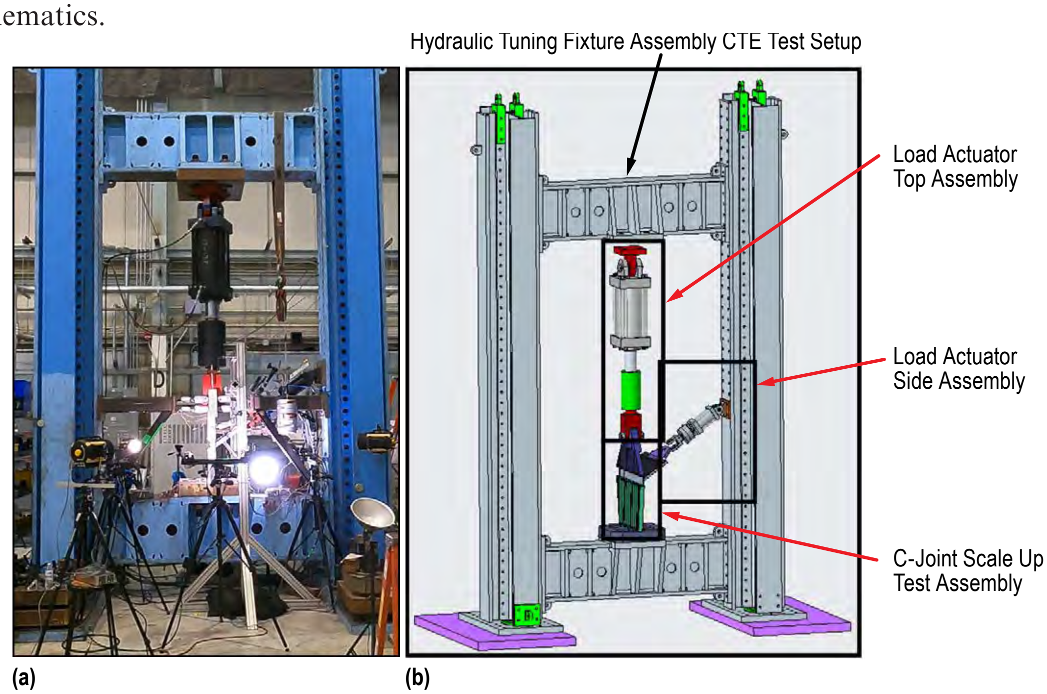


FIGURE 2. Test setup of large-scale circumferential joint test article.

SUMMARY

There are many potential benefits of composite structures/joints compared to metallic structures/joints, such as weight savings, cost savings, and performance improvement with increased reliability. The CTE project has enabled the infusion of lightweight composite joints technology into future exploration missions, including composite bonded longitudinal joints baselined by the SLS payload adapter. CTE has worked over the last few years to achieve these potential benefits by developing and validating high-fidelity analytical tools and standards for predicting failure and the residual strength of composite bonded joints. This work has provided an increased understanding of composite discontinuities, a path toward certification, and a reduction of risks while increasing confidence in composite joint technologies.

PRINCIPAL INVESTIGATORS: John Fikes, Mallory Johnston

PARTNERS: SLS Payload Adapter Team, Langley Research Center (LaRC), Goddard Space Flight Center (GSFC), Glenn Research Center (GRC)

FUNDING ORGANIZATION: Game Changing Development (GCD) Program

FOR MORE INFORMATION:
https://gameon.nasa.gov/projects/composite-technology-for-exploration-cte/

Design and Testing of Advanced Composites and Coatings for Radiation Environment Shielding (ACCRES) Applicable to Crew Vehicles, Habitats, and Avionics

OBJECTIVE: *To develop new, innovative, multifunctional materials for space systems to reduce weight while providing protections from the harsh space environment.*

PROJECT GOAL/DESCRIPTION

The lunar surface is always exposed to the direct bombardment of galactic cosmic rays (GCRs). In addition, the GCR flux generates a nuclear cascade in the lunar soil, resulting in production of albedo neutrons. Astronauts and critical hardware must be adequately protected from this radiation. Geoplasma, a partnership between Geocent and Plasma Processes, developed lightweight, multifunctional materials for structural applications and radiation shielding with some passive thermal control. University of Tennessee-Knoxville provided modeling of radiation transport through these shielding materials, and NASA Marshall Space Flight Center (MSFC) provided ultraviolet radiation exposures and x-ray exposure to compare the shielding to known materials, as well as optical property measurements.

APPROACH/INNOVATION

Geoplasma optimized the surface treatment of carbon fabric to enhance the bonding strength of various coatings and create a multi-layer material with polyethylene. Carbon (C) fabric sheets were vacuum plasma spray (VPS)-coated with boron (B) seen in figure 1, or boron nitride (BN). In addition, VPS of tungsten (W) coating on C fabric was also optimized to provide thermal protection and shielding against x-rays and gamma-rays. University of Tennessee-Knoxville performed transport simulations for both high-strength polyethylene- and polypropylene-fabric-based composite architectures to evaluate shielding effectiveness. These samples were then exposed to a simulated space environment at MSFC.

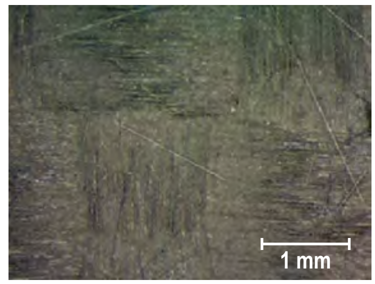


FIGURE 1. Scanning electron microscopy characterization of boron (B) coating on carbon (C) fabric.

RESULTS/ACCOMPLISHMENTS

Based on fundamental physics and transport simulation, a composite architecture was designed and fabricated to address a multitude of space radiation shielding challenges including charged particles, secondary neutrons, x-rays, and ultraviolet radiation. The composite architecture consisted of a polyethylene core sandwiched between C fabric coated with B-based compounds for neutron attenuation, or refractory metals such as W for attenuation of x-rays or electromagnetic pulses. The coating uniformity and thickness were optimized by adjusting the parameters of the vacuum plasma spray coating method. The final composite architecture was fabricated by overlaying the different materials in a specific sequence with polyethylene binder between the layers and bonding the layers using a pressure- and temperature-assisted molding process. When exposed to up to 1000 equivalent Sun hours of an ultraviolet source, the difference in the ratio of solar absorptance to solar emittance and the change in mass was negligible.

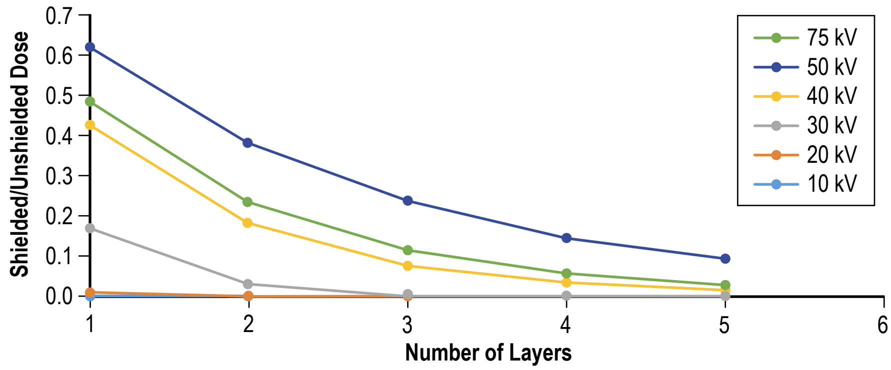


FIGURE 2. Shielding efficiency as a function of incident x-ray energy and composite layer. Each layer is approximately 0.127 cm thick.

SUMMARY

VPS of B, BN, and W on C fabric was successful, as was testing of these materials in simulated space environment. These multilayer, multifunctional materials show promise for use as structural components, radiation shielding, and passive thermal control. X-ray testing at energy levels of 50 to 320 keV showed that the W coating could provide attenuation between 96% to 69%, respectively. Table 1 shows the shielded/unshielded ratio measurements for various materials tested alongside the W coating. Figure 2 displays the increase in efficiency by using multiple composite layers.

TABLE 1. Measured shielded/unshielded ratio of different materials.

Sample	Measured Shielded/Unshielded Ratio		
	50 KeV	160 keV	320 keV
Geoplasm, W-coated side up, foam block	0.04	0.14	0.31
Al, 0.06 in thick	0.06	0.18	0.4
Al, 0.125 in thick	0.01	0.11	0.31
Tantalum, 0.01 in thick	0	0.02	0.12

PRINCIPAL INVESTIGATOR: Subhayu Sen, Geocent

PARTNERS: Geocent; Plasma Processes, LLC; University of Tennessee-Knoxville

FUNDING ORGANIZATION: Center Strategic Development Steering Group (CSDSG)

Additive Manufacturing Interface Mixing of Copper- and Nickel-Based Alloys and Their Influence on Repeatability and Reliability

OBJECTIVE: *To advance the use of additive manufacturing for liquid rocket engine components, factors that control the reliability of gradient or bimetallic combinations must be understood to meet the operational needs within high heat flux environments.*

PROJECT GOAL/DESCRIPTION

Additive manufacturing (AM) is being advanced for liquid rocket engine component applications to reduce cost and associated production schedules of launch vehicles, landers, and in-space propulsion. The demanding technical requirements for metal alloys in these extreme environments of high heat fluxes can be met with gradient or bimetallic combinations as illustrated in figure 1(a). This allows for optimized designs using a high conductivity alloy where needed and a higher strength/weight alloy for structural features. An example of this is a combustion chamber using a copper alloy liner to actively cool the chamber and outer structural jacket to react the loads. To fully realize the benefits of AM in this one-piece component, it is imperative that engineers understand the material properties and limitations associated with the fabrication method. Continued study and experimentation will further mature these complex designs using multimaterials with metal AM deposition shown in figure 1(b). This study benefits NASA and industry efforts in developing specifications and standards for the procurement of bimetallic AM components to ensure that consistent and reliable hardware is procured from commercial vendors.

APPROACH/INNOVATION

This study utilized specimens obtained from industry vendors using Laser Powder-Directed Energy Deposition (LP-DED) to create bimetallic joints of copper alloy C18150 and nickel alloy INCONEL 625 (IN 625). To evaluate the thermal profile from the thin walls in combustion chambers, subscale specimens, shown in figure 2, were machined and mechanically tested. Results from the tensile tests were correlated with metallographic images of the interface.

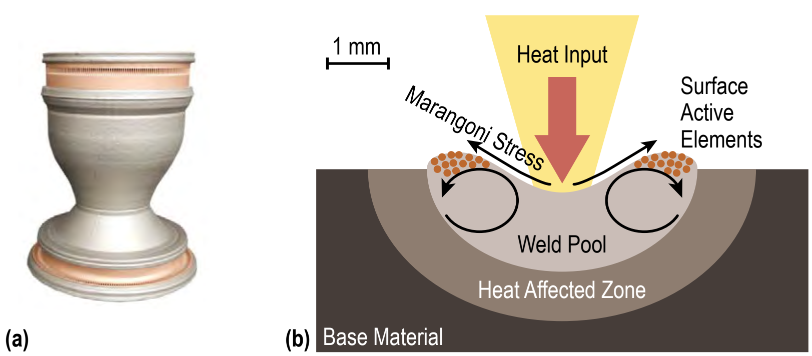


FIGURE 1. (a) Overview of bimetallic liquid rocket engine chamber and (b) use of metal AM for directed energy deposition (DED) of materials in the one-piece build.

FIGURE 2. Subscale AM specimen built for tensile tests.

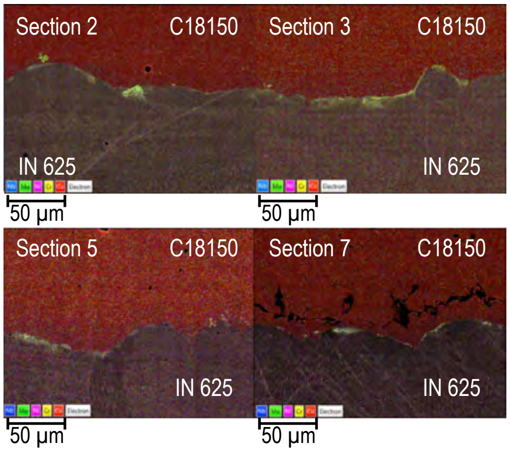


FIGURE 3. Elemental mapping of the interface as heat input was varied, decreasing from section 2 to 7.

RESULTS/ACCOMPLISHMENTS

Figure 3 shows the elemental distribution mapping for sections of the bimetallic build in which the heat profile changes. At the hottest region (Section 2), a globular segregation of niobium and molybdenum is observed in green. As the heat input is reduced, this segregation changes to a linear, continuous film in section 3. Finally, as the heat input is further reduced in sections 5 and 7, failure along the copper alloy is observed.

The tensile test results in table 1 show the yield strength and ultimate tensile strength (UTS) values at fracture are close to the value of the parent copper alloy, although there is a decrease as the heat input is reduced.

SUMMARY

A process using miniature tensile specimens of bimetallic joints fabricated with AM was demonstrated to mature these complex joints for combustion chambers. All miniature tensile specimens broke within the lower strength copper alloy, indicating a strong interfacial bond was obtained using LP-DED processing. A difference in elemental segregation along the interface was correlated with heat input due to geometry changes, with a critical amount associated with delamination events. Quantifying the critical heat input is pivotal to ensuring robust and repeatable hardware fabrication.

TABLE 1. Summary of tensile values for miniature tensile specimens.

Sample	Yield Strength (MPa)	UTS (MPa)	Elongation (%)
2-T	384 ± 15.3	421 ± 16.5	2.74 ± 0.89
3	329± 11.3	372 ± 14.7	3.58 ± 0.2
5	317 ± 14.3	367 ± 15.4	3.99 ± 0.23
7	315 ± 31.6	352 ± 31.5	3.37 ± 0.45
Parent C18150	403 ± 2.34	444 ± 1.52	13.9 ± 0.23
LP-DED IN 625	483 ± 22.1	758± 54.5	N/A

PRINCIPAL INVESTIGATORS: Judy Schneider, University of Alabama in Huntsville; Paul Gradl, Robin Osborne

PARTNER: Connecticut Center for Advanced Technology (CCAT)

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Evaluation of Alternative Nickel-Based Superalloys for Additive Manufacturing of Liquid Rocket Engine Components

OBJECTIVE: *Use of additive manufacturing opens the opportunity for re-evaluation of alloys and fabrication processes most suitable for design application.*

PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center (MSFC) is evaluating various additive manufacturing (AM) processes for reduction of costs associated with fabrication of launch vehicles and in-space propulsion. Although AM is revolutionary with regards to fabrication of one-piece, complex designs and shows promise in reducing costs, it is imperative that the engineer select the best AM process and postprocessing methods. As AM of the entire part may not be the most economical choice, methods to integrate AM into the fabrication cycle must also be considered. This study considers the interface between AM depositions, such as in the formation of complex fin geometry on a wrought hub during the fabrication of a simulated turbopump inducer.

APPROACH/INNOVATION

In this study, an AM process called Laser Powder-Directed Energy Deposition (LP-DED) was used with Special Metals Corporation's nickel alloy INCONEL 718 to build the blades onto a wrought INCONEL 718 hub for a turbopump inducer shown in figure 1. While AM can reduce the fabrication costs, further cost savings can be realized by using AM in combination with standard wrought forms as the build platform. However, this raises concerns regarding the microstructural evolution of the part in subsequent heat treatments to obtain the desired mechanical properties. To establish the AM process parameters, including heat treatments, flat panels were fabricated in form of boxes as shown in figure 2. Due to the repeated heating and cooling gradients, the AM material requires additional heat treatment stages to mitigate the resulting residual stresses and to homogenize the AM material prior to aging in order to achieve the desired properties. Therefore, the effect of postprocessing heat treatments on the already homogenized wrought material must also be evaluated to ensure the desired mechanical properties are realized in the final form.

FIGURE 1. Overview of inductors fabricated.

FIGURE 2. Flat panels fabricated.

For the study, a heat treatment schedule developed previously for Laser Powder Bed Fusion (L-PBF) of INCONEL 718, according to the ASTM F3301 Standard for Additive Manufacturing, was used. The effectiveness of the heat treatment was verified using flat panel LP-DED samples. Once the heat treatment schedule was verified, it was used for heat treatment of the AM-wrought hybrid samples. After each heat treatment step, the resulting structure and hardness across the interface was evaluated by both observation and hardness testing.

RESULTS/ACCOMPLISHMENTS

This study focused on the critical heat treatments to achieve a homogenized microstructure and achieve subsequent strengthening of INCONEL 718, a precipitation-strengthened alloy; the heat treatments focused on a homogenization cycle. After a full heat treatment of stress relief, homogenization, solutionizing and aging, figure 3 shows the resulting interface between the wrought INCONEL 718 hub and LP-DED material. No indications of delamination were observed, although there is a slight difference in grain morphology.

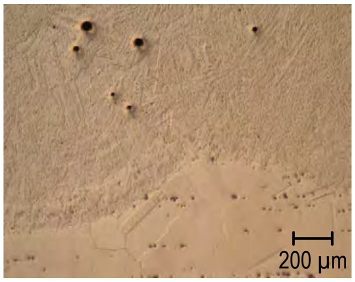


FIGURE 3. Close-up of interface.

Hardness measurements were used to evaluate the strength transition across the interface. Figure 4 summarizes the hardness results with the dashed red line indicating the interface. In the as-built condition, the LP-DED material is softer than the wrought hub. After subsequent heat treatments, the LP-DED material increases in strength. After the full heat treatment schedule, the difference in hardness between the two materials was found to be negligible. This is critical to the performance of the component as it alleviates potential stress concentrations that could result in premature failure of the part.

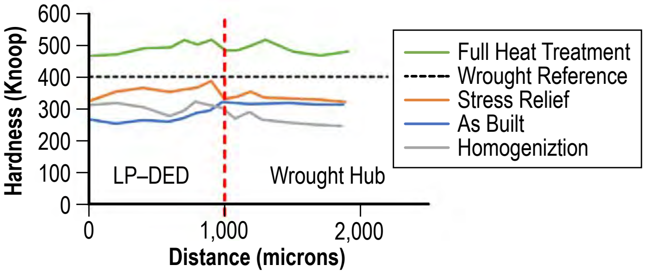


FIGURE 4. Hardness mapping across interface.

SUMMARY

This study evaluated and verified that the heat treatment schedule developed previously for L-PBF of INCONEL 718, according to the ASTM F3301 Standard for Additive Manufacturing, was also effective for the LP-DED material without detrimental effect on the wrought material. Results from this study are critical in demonstrating the use of hybrid AM and wrought processes to optimize manufacturing and reduce fabrication cost of components for liquid rocket engines.

PRINCIPAL INVESTIGATORS: Judy Schneider, University of Alabama in Huntsville; Paul Gradl

PARTNER: Connecticut Center for Advanced Technology (CCAT)

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

FOR MORE INFORMATION:
https://www.sciencedirect.com/science/article/pii/S2214860417306218,
https://link.springer.com/article/10.1007/s11837-020-04021-x

Large Scale Additive Manufacturing of Laser Powder Bed Fusion GRCop–42

OBJECTIVE: *To advance the current additive production using additively manufactured GRCop–42 and extend these applications to large scale liquid rocket engine hardware developed in the commercial supply chains.*

PROJECT GOAL/DESCRIPTION

Additive manufacturing (AM) of liquid rocket engine hardware represents a significant step towards affordability for launch vehicles and space exploration. AM provides the ability to produce liquid rocket engine components, such as combustion chambers, both cost-effectively and rapidly. This is because complex and integrated structures such as coolant channels can be produced in a single process step rather than requiring multiple manufacturing and assembly steps, which often require long lead times. For combustion chambers, a high conductivity material such as GRCop–42 is desired for active cooling applications. GRCop–42 (Cu-4 at.% Cr-2 at.% Nb) is a particular copper (Cu)-chromium (Cr)-niobium (Nb) alloy that has been advanced at NASA and is being matured in the commercial supply chain. GRCop–42 allows for increased conductivity over the previously developed GRCop-84 while maintaining excellent mechanical properties.

This Small Business Innovation Research (SBIR) Phase III effort was established between NASA Marshall Space Flight Center (MSFC) and Elementum 3D. The intention was to develop the printing process parameters, powder evaluations, and supply chain infusion needed to successfully AM Laser Powder Bed Fusion (L-PBF) GRCop–42 components using a large platform. Features such as surface roughness, part density, and various thermophysical and mechanical properties have been characterized under this development effort. A specific focus of this effort was to understand the challenges in adapting the GRCop–42 L-PBF process to a large-scale machine capable of building parts up to 400 mm in diameter. The end goal of the project was to extend production readiness of the GRCop–42 material for the commercial space supply chain.

APPROACH/INNOVATION

This work was established to infuse the GRCop–42 L-PBF printing technology into the commercial supply chain for ongoing AM production of high conductivity copper alloys. One key technical challenge with high conductance alloys includes the establishment of limitations in the production of specific features in the AM L-PBF process. Specific processing parameters and interaction with powder feedstock must be established for minimum angles, gap widths, wall thicknesses, and orifice diameters. This task developed the specific processing parameters, sample L-PBF builds, and full-scale hardware builds to understand and establish the design rules for practical use during L-PBF. A database was also developed for thermophysical and mechanical properties for the large L-PBF platform specific to GRCop–42. Specifics of print parameters have been found to heavily dictate what the surface roughness of critical interfaces would be. An integrated approach was developed to establish the powder feedstock, interaction with print parameters and resulting microstructure and liquid rocket engine component development on the large-scale L-PBF platform. An example of a full-scale GRCop–42 chamber and witness bars is shown in figure 1.

(a)

(b)

FIGURE 1. (a) L-PBF of full-scale combustion chamber and (b) witness specimens.

Several GRCop–42 AM L-PBF chambers have been produced utilizing the results of this work and successfully demonstrated at hot-fire test conditions. A single 7k-lbf chamber was demonstrated at multiple throttle points ranging from 100% power down to a 6.7:1 power level. These values equated to 750 psi in the chamber and 114 psi in the chamber at mixture ratios of liquid oxygen and methane between 2.3 and 3.2. The chamber was successfully throttled multiple times for a cumulative duration of 85 seconds. This test chamber is shown in figure 2.

FIGURE 2. Hot-fire testing of a 7k-lbf GRCop–42 L-PBF thrust chamber tested at NASA MSFC Test Stand 115.

RESULTS/ACCOMPLISHMENTS

Major milestones included process parameter development for various witness samples, build geometry evaluations, microstructure and material property evaluations, demonstration hardware builds, and fabrication of full-scale hardware through all post-processing. Multiple chambers were produced at thrust classes from 7k-lbf to 40k-lbf as primary deliverables of this effort. In addition, production capabilities for the commercial space industry have been established with an understanding of the process from feedstock through end part. Material properties and print parameter development were key deliverables toward extending production capabilities for commercial space and industry customers. The anticipated next step after completion of this work is full production and flight infusion of GRCop–42 material using the large-scale L-PBF process.

SUMMARY

This work focused on the process development of large-scale AM L-PBF GRCop–42 for production of liquid rocket engine hardware. Following integrated feedstock and process parameter development, a mechanical and thermophysical database was developed for various properties of GRCop–42. Full scale 7k-lbf and 40k-lbf hardware was produced, postprocessed and delivered to NASA for hot-fire test validation. Testing successfully demonstrated the feasibility to scale the AM L-PBF GRCop–42 process for use in the application of large-scale liquid rocket hardware.

PRINCIPAL INVESTIGATORS: Paul Gradl, Tom Teasley, Jeremy Iten (Elementum 3D)

PARTNER: Elementum 3D

FUNDING ORGANIZATION: Space Technology Mission Directorate (STMD)

FOR MORE INFORMATION:
https://doi.org/10.2514/6.2019-4228

Metal Digital Direct Manufacturing (MDDM) for Close-Out of Combustion Chambers and Nozzle Fabrications

OBJECTIVE: *The maturation of automated, wire-fed, additive manufacturing methods for producing regeneratively-cooled large rocket engine nozzles including Arc-Wire Directed Energy Deposition (AW-DED) methods for depositing the nozzle liner and Laser Wire Direct Closeout (LWDC) methods for closing out the coolant channels without the use of fillers and demonstrating the technology readiness levels needed for commercialization beyond government requirements.*

PROJECT GOAL/DESCRIPTION

This NASA-sponsored, sequential Phase II Small Business Technology Transfer (STTR) project matured two additive manufacturing (AM) processes: Arc-Wire Directed Energy Deposition (AW-DED) and Laser Wire Direct Closeout (LWDC). The aim for maturing these AM processes is to advance the Technology Readiness Level (TRL) and commercial infusion for liquid rocket engine (LRE) combustion chambers and nozzles. This project focused on various iron (Fe)-based superalloys including JBK-75 and NASA HR-1, with these processes producing a mechanical property database and a series of manufacturing demonstrator nozzles through scale-up and hot-fire testing. This project demonstrated the processes through TRL 6 for commercialization in both government and industry requirements.

The project sought to achieve the following goals:

- Demonstrate AM processes for producing LRE nozzle liners and closing out the coolant channels using localized deposition methods that do not require filler materials.
- Demonstrate commercially viable, automated methods for producing regeneratively-cooled LRE nozzle liners and the closeout of the coolant channels using the JBK-75 alloy.
- Conduct initial metallurgical and mechanical property characterization of the JBK-75 and HR-1 alloys produced by utilizing cored-metal wire in the AW-DED process.

FIGURE 1. All-AM subscale nozzle with manifolds prepared for hot-fire testing.

APPROACH/INNOVATION

This project advanced manufacturing readiness focusing on the following areas:

- Completed AM of an intermediate scale (40k-lbf) regeneratively-cooled nozzle produced utilizing cored-metal JBK-75 wire feedstock for hot-fire testing at NASA Marshall Space Flight Center (MSFC).
- Demonstrated the technologies necessary to scale the AW-DED process for producing nozzle liners using cored-metal wire for subsequent machining and LWDC of the coolant channels using solid wire feedstock.
- Demonstrated the capability for closing out the coolant channels using automated, LWDC processing with localized preheating to enable close-out with adequate microstructures.
- Demonstrated automated methods for depositing high-quality JBK-75 material with mechanical properties capable of meeting engineering requirements.
- NASA MSFC has engaged Keystone Synergistic Enterprises along with their STTR partner, the University of Alabama in Huntsville (UAH), to mature and demonstrate the manufacturing processes required to AM regeneratively-cooled LRE nozzles.

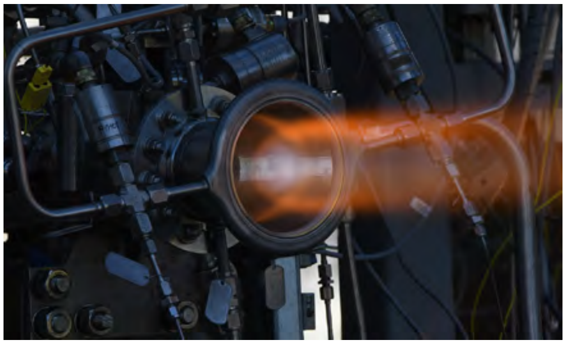


FIGURE 2. Nozzle produced using AW-DED and LWDC undergoing hot-fire testing at MSFC Test Stand 115.

RESULTS/ACCOMPLISHMENTS

This project matured AM processes at several hardware scales to enable integration of lessons learned from subscale to large-scale components. Hot-fire testing was successfully completed on 2k-lbf thrust-class regeneratively-cooled nozzles utilizing conventional alloys such as INCONEL 625, HAYNES® 230®, and JBK-75. Scaling to intermediate scale nozzles (35k-lbf) was also successfully demonstrated through delivery of an INCONEL 625, Haynes 230, and JBK-75 alloy nozzles to MSFC for hot-fire testing. Focusing on the JBK-75 alloy proved to be challenging, as this alloy is susceptible to microcracking during AM of the liner and the closeout of the coolant channels. A significant effort was required to overcome this material processing challenge and demonstrate full-scale processing methods with high quality. Closed-loop control methods were successfully demonstrated to enable deposition of large-scale nozzles maintaining positional tolerances within ±0.010 in with nozzle diametrical eccentricities exceeding ¼ in. Automated, localized preheating methods were also demonstrated to enable ±25 °F sustainment of the preheat temperature required to avoid microcracking of the JBK-75 alloy while successfully closing out the coolant channel transitions. Metallurgical analysis verified the ability to perform this type of complex nozzle closeout processing while maintaining a high-quality closeout layer for the coolant channels without the use of fillers.

In addition, utilizing supplementary Small Business Innovation Research (SBIR) Phase III funding from NASA MSFC, tensile and fatigue properties for the JBK-75 and HR-1 alloys were produced from material deposited by the AW-DED process. This was demonstrated with cored-metal wire (avoiding very long lead times associated with conventional wire manufacturing) and the products were thermally processed using a heat treatment schedule developed by MSFC. This allowed for microstructural characteristics and avoided potential embrittling phases associated with these alloys using AM processes.

SUMMARY

This project successfully completed demonstration of a series of manufacturing capabilities to additively manufacture regeneratively-cooled LRE nozzles and successfully delivered various scale nozzles for hot-fire testing. Additionally, the project produced JBK-75 and HR-1 alloy wires using cored-metal manufacturing methods; deposited blocks of the alloy for subsequent heat treatment to produce tensile and fatigue properties for the two alloys; and characterized the alloys through mechanical testing. The project also successfully demonstrated automated methods for AM of large-scale nozzles with the JBK-75 alloy while maintaining a high-quality microstructure with engineering properties required to sustain mechanical and thermal loading encountered by full-scale nozzles.

FIGURE 3. Demonstrated versatile methodology for automated closeout of large rocket engine nozzles.

PRINCIPAL INVESTIGATORS: Paul Gradl, Bryant Walker (Keystone Synergistic), Judy Schneider (University of Alabama in Huntsville)

PARTNERS: Keystone Synergistic, University of Alabama in Huntsville

FUNDING ORGANIZATION: Space Technology Mission Directorate (STMD)

FOR MORE INFORMATION:
US Patent Numbers: 10,471,542 and 9,835,114
https://technology.nasa.gov/patent/MFS-TOPS-81
https://doi.org/10.2514/6.2018-4860
https://doi.org/10.2514/6.2019-4361

Size Effects on Microstructure and Mechanical Properties of Additively Manufactured GRCop–42

OBJECTIVE: *To investigate the effects of varying thicknesses on as-built and hot isostatically pressed additively manufactured Laser Powder Bed Fusion GRCop–42.*

PROJECT GOAL/DESCRIPTION

Due to the copper (Cu)-chromium (Cr)-niobium (Nb) alloy GRCop–42 (Cu-4 at.% Cr-2 at.% Nb) having exceptional thermal conductivity and superior strength at elevated temperatures, it is a material of choice for several applications containing thin-walled structures, including liquid rocket engine combustion chambers. However, when a thin-walled structure is produced using additive manufacturing (AM) processes, the solidification rate is affected, thereby leading to different microstructure and different mechanical properties relative to bulk materials. Therefore, it is necessary to understand how decreasing the part thickness affects the overall material behavior.

This Cooperative Agreement Notice (CAN) project was designed to verify variations in porosity, microstructure, surface roughness, and quasi-static response at different thicknesses produced using the same build process parameters. Specimens were fabricated vertically on a build plate through Laser Powder Bed Fusion (L-PBF) in the shape of standard tensile samples with equal dimensions but varying thicknesses. Additionally, the responses of the specimens to heat treatment were investigated by characterizing and testing the specimens both as-built and after undergoing a type of heat treatment called hot isostatic pressing (HIP).

APPROACH/INNOVATION

The quantification of size effects in L-PBF GRCop–42 was done by performing quasi-static tension tests on variations of ASTM E8 samples. Prior to performing the mechanical testing, microstructural features including porosity, pore size distribution, grain morphology, and grain orientation of the samples were investigated using x-ray micro-computed tomography (μCT) and electron backscatter diffraction (EBSD), respectively. Additionally, a digital profilometer was used to measure the surface roughness on each specimen.

This work produced publishable data which can be used by industry, academia, and government to further improve processes or develop new fabrication techniques, in addition to the scientific contribution that is understanding the underlying mechanisms responsible for size effect. The principal investigators have been developing a systematic approach to measure the effective load bearing area for AM thin-walled structures. Future work will focus on cyclic loading conditions and characterizing the key microstructural features governing the macroscopic response. Additionally, alternative methods for predicting the effective cross-sectional area are being explored as μCT is both expensive and time consuming.

RESULTS/ACCOMPLISHMENTS

A clear variation in tensile strength was observed during tensile tests for both as-built and HIP-processed specimens. Figure 1 shows the stress-strain curves for as-built and HIP-processed specimens of different thicknesses. Test results show a greater than 20% decrease in ultimate tensile strength (UTS) for both as-built and HIP-processed specimens as thickness is decreased from 2.0 mm to 0.7 mm. A difference in ductility is also observed, displaying nearly 50% reduction in ductility as specimen thickness is decreased from 2.0 mm to 0.7 mm.

Additional variation on stress levels was observed when measuring the effective cross-sectional area through calipers,

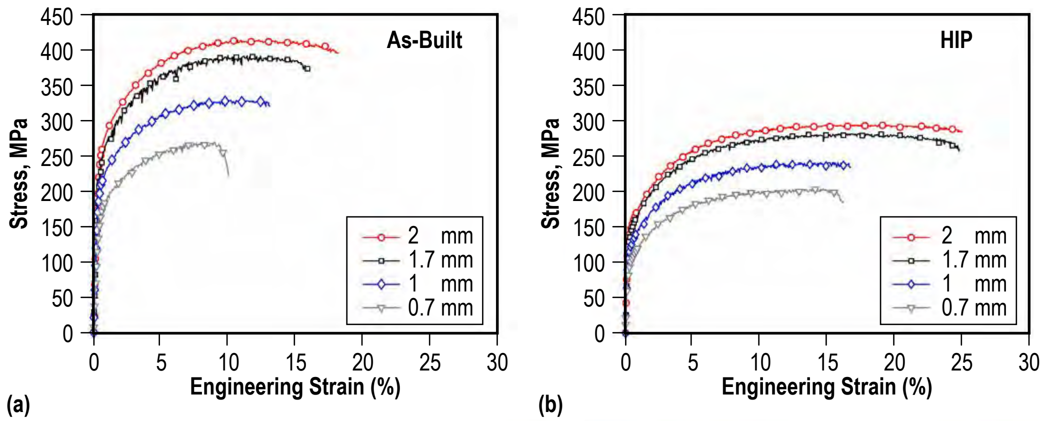


FIGURE 1. Stress-strain showing the tensile strength of (a) as-built and (b) HIP-processed specimens.

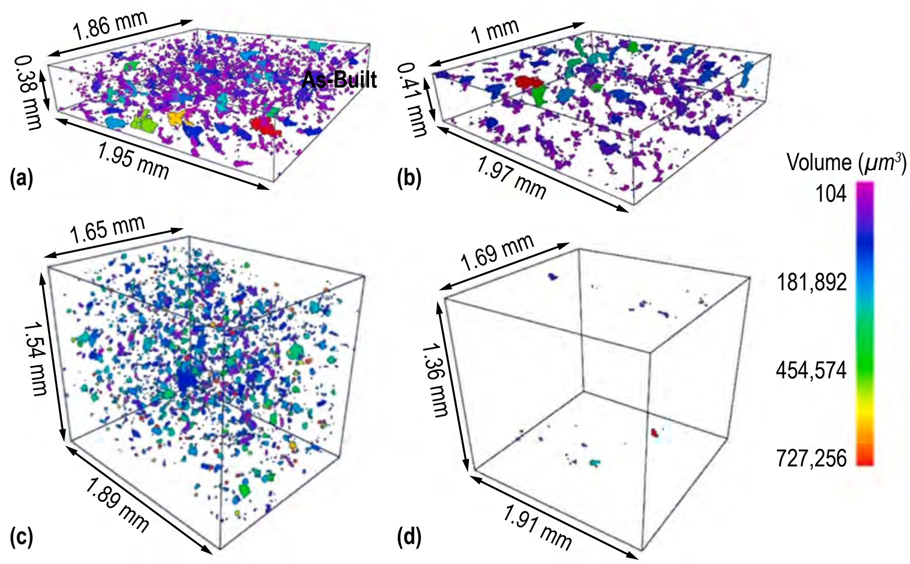


FIGURE 2. Internal porosity measured through μCT for 0.7mm and 2mm specimens: (a) and (c) show the as-built specimens; (b) and (d) show the HIP-processed specimens.

optically, and through μCT. There is an apparent decrease in UTS between 2.0 mm and 0.7 mm as-built specimens equal to 35%, 9%, and 29% when the load bearing area is measured with calipers, optically, and with μCT, respectively. A similar trend is observed in the HIP-processed specimens; however, the percentage reduction in elastic modulus, yield strength, and UTS is greater in as-built specimens than in HIP-processed specimens, meaning that HIP reduces the magnitude of the mechanical property decrease with decreasing thickness. These results confirm that the measurement method greatly influences the calculated stress.

SUMMARY

Through the investigation performed, the investigators were able to demonstrate the size effects on varying thicknesses of additively manufactured GRCop–42 fabricated using L-PBF. No significant microstructural variations trends with regard to surface roughness were observed with either thickness or heat treatment. However, since surface roughness was similar in all specimen thicknesses, it accounts for a larger percentage reduction in the load bearing area. Porosity showed a large variation with thickness, with thinner samples having a larger void volume ratio than thicker samples. Furthermore, HIP was found to be effective at reducing the total porosity, with increased relative effectiveness on thicker specimens.

PRINCIPAL INVESTIGATORS: Jason Mayeur (University of Alabama in Huntsville), Kavan Hazeli (University of Arizona), Paul Gradl

PARTNERS: The University of Alabama in Huntsville, University of Arizona

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

FOR MORE INFORMATION:
https://www.sciencedirect.com/science/article/pii/S0921509321007802

Surface Finishing of Additively Manufactured Superalloy Components

OBJECTIVE: *To develop a surface finishing process for additively manufactured nickel- and iron-nickel-based superalloys capable of removing surface material from surfaces uniformly while producing surface roughness lower than 0.8 μm, allowing improvements to mechanical and corrosion resistance properties.*

PROJECT GOAL/DESCRIPTION

Metal additive manufacturing (AM) processes allow for complex parts to be built, but often result in higher than desired surface roughness. A common method to remediate surface roughness is postprocess machining, but machining is not often feasible due to the complexity of the shapes. Surface enhancements, such as polishing processes, can be used on AM components to improve roughness (and resulting mechanical properties) as well as giving the product higher corrosion resistance. These surface enhancement methods must be capable of finishing complex geometries and controllably reducing features/wall thickness (not otherwise printable due to current printing technology limitations) to obtain desired final geometries. Finally, the surface enhancements must be applicable to INCONEL 625 and similar nickel (Ni)- and iron (Fe)-Ni-based superalloys. Development of these surface enhancements allows for a variety of liquid rocket engine components to be fabricated using AM processes such as Laser Powder Bed Fusion (L-PBF) and Laser Powder Directed Energy Deposition (LP-DED). The surface enhancement allows for AM components built with these processes to potentially meet requirements for thin-wall geometry and mechanical properties, which would otherwise not be achievable with AM.

FIGURE 1. INCONEL 718 samples processed using CP/CMP surface enhancement from Phase I and II SBIR.

APPROACH/INNOVATION

Under a Phase I and II Small Business Innovation Research (SBIR) award, an optimal finishing process was sought for INCONEL 625, JBK-75, INCONEL 718, and NASA HR-1 that could achieve significant surface material removal with a high degree of geometric accuracy (minimal shape alteration) while reducing surface roughness/texture and increasing fatigue life. After completion of all testing, a combination approach of chemical polishing (CP) and chemical-mechanical polishing (CMP) was selected as the optimal surface enhancement process.

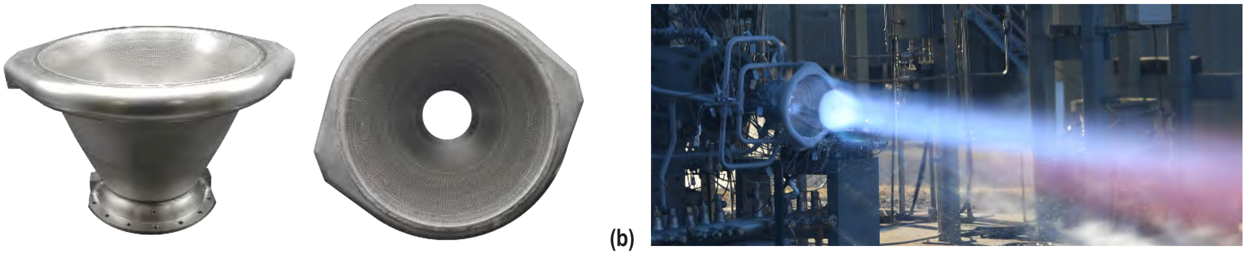
The optimal process steps to enhance the surface of the material were as follows:

(1) Reducing the AM surface roughness to a 0.8 μm root mean square.

(2) Removing 0.50 – 1.25 mm of material uniformly from external surfaces.

(3) Eliminating surface defects that would otherwise result in reduced tensile and/or fatigue properties.

(4) Having the potential for being automated, scalable, and needing minimal operator interaction.



(a) (b)

FIGURE 2. (a) NASA HR-1 additive nozzle processed using CP/CMP and (b) tested at NASA MSFC.

The CP/CMP processes required development of alloy-matching formulations capable of achieving a high degree of roughness/texture reduction at a controlled rate and uniformity across the surface. The CP step improves the surface roughness of as-built components while removing near-surface defects without altering component geometry. The CMP step, with its planarization capability, removes the remaining surface roughness, waviness, and texture, thereby producing an extremely smooth surface. These processes were developed across a series of samples and rocket engine components. The samples and components completed mechanical testing and endured hot-fire testing in actual conditions to demonstrate feasibility.

RESULTS/ACCOMPLISHMENTS

The CP/CMP process was advanced with new formulations and processing techniques for various alloys in the L-PBF and LP-DED processes. The alloys advanced were INCONEL 625, JBK-75, NASA HR-1, and INCONEL 718. A series of mechanical tensile test samples, fatigue samples, and test components were manufactured and processed for testing. Additional development under the SBIR Phase II allowed for scale-up of the process to accommodate rocket engine components with diameters up to 30 in. The tensile and fatigue sample specimens were mechanically tested via tensile strain, high cycle fatigue, and low cycle fatigue tests. Results from the mechanical tests showed that the specimens met all performance expectations; the CP/CMP process greatly improved fatigue life and reduced roughness. Test components, including combustion chambers and regeneratively-cooled nozzles at the 1.2k-lbf, 7k-lbf, and 35k-lbf thrust classes, were then processed using this CP/CMP process and hot-fire tested at NASA Marshall Space Flight Center (MSFC). Additional lessons were learned involving the specific chemistry differences from different printers and parameters, showing sensitivity to the surface finishing process. The chemistry of the CP/CMP process was subsequently refined based on the results of earlier tests, allowing it to be agnostic to printer or heat treatment. Corrosion-resistance experiments of the L-PBF INCONEL 625 samples were also performed, showing significant improvement after the CP/CMP surface enhancement.

SUMMARY

A production viable surface enhancement process has been developed using a combination of CP and CMP for various nickel and iron-nickel based superalloys. The process demonstrated significant improvements to the mechanical and corrosion resistance properties of these alloys. This process has been scaled up to allow for components with diameters up to 30 in and produced various components that were hot-fire tested at NASA. Significant commercial interest has arisen for the surface enhancement technique for commercial space and industrial applications. Further scaling of the technology to laccommodate arger components and further optimization of chemical formulations is of interest for the future.

PRINCIPAL INVESTIGATORS: Paul Gradl; Justin Michaud and Agustin Diaz, REM Surface Engineering

PARTNERS: Small Business Innovation Research (SBIR) Program, REM Surface Engineering

FUNDING ORGANIZATION: Space Technology Mission Directorate (STMD)

FOR MORE INFORMATION:
https://www.metal-am.com/articles/advancing-rocket-propulsion-through-3d-printing-novel-surface-finishing-technologies-and-public-private-partnerships/,
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https://doi.org/10.2514/6.2021-3236

Investigating Autonomous Healing of Cracks in Lightweight, Aerospace-grade Materials Systems

OBJECTIVE: *To fabricate and study a UV-curable shape memory polymer matrix reinforced by hybrid shape memory alloy (Flexinol) wires, glass fibers and carbon fibers for the autonomous healing of cracks in lightweight, aerospace-grade materials systems.*

PROJECT GOAL/DESCRIPTION

It has been well known that laminated composites are vulnerable to out-of-plane impact damage, where even low velocity impact events could undermine the materials. Various types of damages can result due to a low velocity impact event, the most common of which is delamination. If the delamination is not healed, in-plane mechanical properties will be significantly reduced. Z-pins have been widely used to help in resisting delamination. While this method can mitigate delamination, it cannot fully eliminate it. Therefore, the self-healing of delamination damage is highly desired.

Based on the biomimetic close-then-heal (CTH) strategy patented by the investigators, this project is studying the use of sinusoidal shape memory alloy (SMA) z-pins to assist in delamination closing and use of a multifunctional thermoset polymer developed by the investigators as the polymer matrix in effecting the self-healing. This polymer has high strength, high stiffness, and excellent shape memory effect. The polymer is ultraviolet (UV) curable, self-healable, recyclable, and 3D printable.

The role played by the sinusoidal SMA z-pins are threefold:

(1) Limiting of delamination;

(2) Closure of delamination by shape memory effect; and

(3) Heating of the laminate via electricity during the healing process.

The goal is that combination of the sinusoidal SMA z-pins and the multifunctional polymer will achieve the enumerated objectives. The success of this project will benefit specific NASA objectives for space exploration by providing lightweight structures with damage self-healing capability. Furthermore, this work will benefit the research mission of Southern University and further the value of existing intellectual property, including issued and pending U.S. patents covering self-healing of polymer composites structures. It will also enhance the education mission of Southern University by directly involving minority graduate and undergraduate students in related research.

APPROACH/INNOVATION

The approach is to use UV-curable shape memory vitrimer combined with sinusoidal SMA z-pins to fabricate out-of-autoclave-curing composite laminate. The major innovation is that the pre-tensioned SMA z-pins will not only reduce delamination, but also assist in delamination closure through constrained shape recovery; with the self-healable vitrimer as the matrix, the matrix-controlled failure, i.e., delamination, can be healed repeatedly.

RESULTS/ACCOMPLISHMENTS

Highlighted in figure 1 are the key steps in the vitrimer-matrix hybrid composite fabrication process. The laminate was cured by ultraviolet light, and the healing was achieved via electricity. The following experimental work has been carried out:

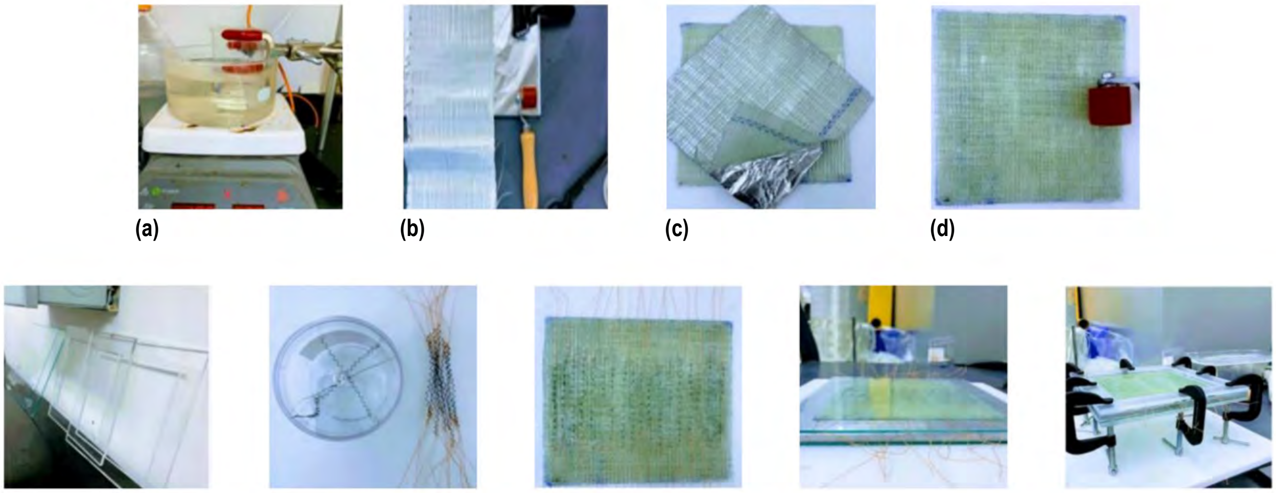

FIGURE 1. Composite Fabrication Procedure: (a) vitrimer preparation, (b) laying of Saertex unidirectional glass fiber, (c) rolling of sandwiched vitrimer-wetted glass fiber in thin sheets of aluminum foil to enhance surface finish, (d) rolled out laminate with good surface finish and orderly-aligned plies. (e) sinusoidal SMA z-pins and copper wire connections to be embedded in laminate, (f) sinusoidal SMA z-pins embedded in laminate, (g) glass sheet and frame to hold laminate for curing, (h) laminate sandwiched in aluminum mold with glass ware covering, (i) C-clamps used to exert pressure on laminate.

(1) Instron® Dynatup 8250 HV impact tester was used to carry out low velocity impact tests on the laminates according to ASTM standard D3763-18.

(2) Healing efficiency of the laminates with the SMA sinusoidal z-pins is compared with that of laminates manufactured with straight SMA z-pins and the control laminates without SMA z-pins.

(3) In addition to the crack initiation energy of the composite laminate as a basis for computing the healing efficiency, the crack propagation energy and the critical buckling loads recorded during compression after impact (CAI) test, were also used to ascertain the healing efficiency.

The investigators are in the process of analyzing the test results and will include them in the final report.

SUMMARY

The Southern University research team has developed a new laminated composite with enhanced impact tolerance and self-healing capability. The laminate was manufactured by using vitrimer as matrix; continuous glass fiber as reinforcement; and sinusoidal SMA z-pins as transverse reinforcement, delamination closing device, and conductor for joule heating. The laminate was cured by ultraviolet light and the self-healing effect was activated with electricity. Overall, the CAI strength of the sinusoidal SMA z-pinned composite laminate is better than the control laminate without SMA z-pins.

PRINCIPAL INVESTIGATORS: Patrick F. Mensah, Samuel Ibekwe, and Guoqiang Li

PARTNER: Southern University and A&M College

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Viability Assessment of Printed Powerless Sensor Structures for Aerospace Environment

OBJECTIVE: *To deliver preliminary results of the evaluation of hypervelocity impact to mimic the sensor system in a space environment.*

PROJECT GOAL/DESCRIPTION

The project aims to establish a preliminary investigation of the sensor system's optimal impact velocity and behavior in a space environment. The Florida A&M University (FAMU) team has printed the required samples for the preliminary investigation of the hypervelocity test. We printed four each of 0.5-in- and 1-in-thick samples, as shown in figure 1. The FAMU Team will be testing with NASA to establish a testing configuration to build the final sensor system, which is the 3D printed carbon fiber-reinforced acrylonitrile-butadiene-styrene (ABS) composite with an embedded indirect time-of-flight (ITOF) sensor. Previous objectives supported the success of printing the material with the embedment of an ITOF sensor. The next step will be to study the response and survivability of the sensor system to withstand a temperature range of –120 to 150 °C and other extreme environmental conditions. The hypervelocity impact study on preliminary matrix samples will be conducted at NASA's Marshall Space Flight Center (MSFC).

APPROACH/INNOVATION

This work investigates additive manufacturing technologies and the viability assessment of printed powerless sensor structures for the aerospace environment. The project is divided into two steps. Step 1 of the project related to the 3D printing of embedded ITOF sensors for structural health monitoring (SHM) and performance assessment. Step 2 of the project will now be to evaluate the performance of the printed sensor under environmental conditions (i.e., near-space). Additive manufacturing is an innovative approach to industrial production that allows the formation of lighter, resilient parts and systems. The 3D printed embedded powerless ITOF sensor structures can help address the NASA MSFC need for sensors with reduced mass, increased performance, improve the capability to detect, characterize, and track space objects.

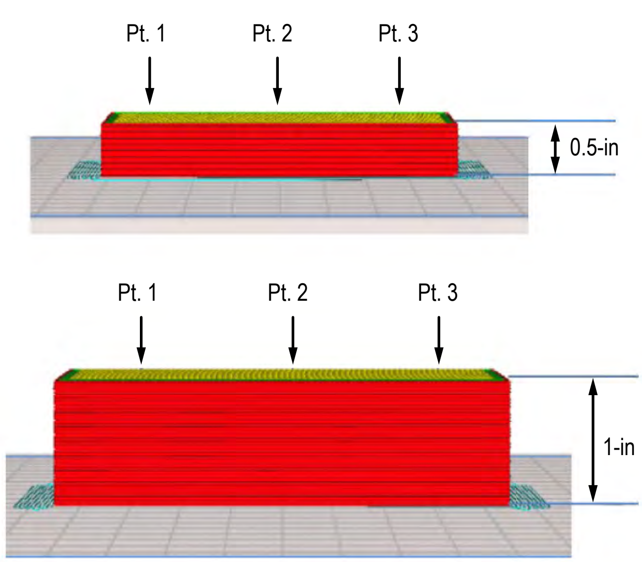

FIGURE 1. Schematics of the cross-sectional view of the printed composite with varying thicknesses.

The research plan for this project includes the following steps:

(1) Scale up samples to 0.5-in and 1-in thick to be shot with nylon bead projectiles. Figure 1 displays the schematics of the cross-section of the printed composites.

(2) Adjust printing parameters to deliver top-quality prints.

(3) Assess sample viability when struck with projectiles and investigate the degree of damage as a function of thickness.

RESULTS/ACCOMPLISHMENTS

The 0.5-in- and 1-in-thick 3D printed carbon fiber ABS matrix samples were produced and delivered to NASA for a preliminary hypervelocity impact test. Figure 2 presents a photograph of the printed composite with dimensions. The FAMU team is currently working with NASA to establish the impact test process parameters.

The current key challenges the FAMU team faces during the project are as follows:

- Establishing the degree of damage by the nylon beads projectile as a function of the sample thickness. The team notes note that previous samples were too thin to withstand a high-velocity impact. The samples have been scaled up to the dimensions (1) 3.27 × 1.61 × 0.39 in and (2) 3.45 × 1.73 × 0.87 in, which correlate to 0.5-in and 1-in thickness to withstand impact.
- The team encountered several issues with printing the composites due to the malfunctioning of the Ender 3 printer.

SUMMARY

0.5-in- and 1-in-thick carbon fiber ABS matrix samples were printed to investigate the process parameters for determining the optimum hypervelocity impact. The FAMU team will work with NASA personnel to meticulously examine the degree of the projectile damage as a function of thickness.

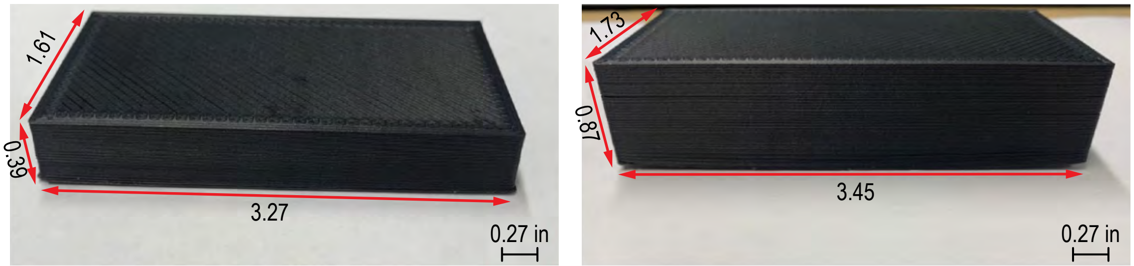

FIGURE 2. Preliminary carbon fiber-reinforced ABS matrix. Scale bar is 0.27 in.

PRINCIPAL INVESTIGATOR: Okenwa Okoli

PARTNERS: NASA, Florida A&M University

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Polymer Coatings with Glass Bubbles for Thermal Radiation Control in Space

OBJECTIVE: *To develop a lightweight, flexible, and scalable polymer composite coating for thermal radiation control in space by integrating hierarchical hollow glass microspheres and surface texture.*

PROJECT GOAL/DESCRIPTION

The main goal of this project is to develop a lightweight, flexible, and scalable polymer composite coating, which serves as a selective emitter for thermal radiation control in space, by integrating hierarchical hollow glass microspheres, or glass bubbles, and microscale pyramidal texture. An example diagram of this polymer coating can be seen in figure 1. Glass bubbles allow a higher degree of structural hierarchy, substantially lower weight, and larger interface density compared to other designs such as solid spheres, and the large interface density is important for selective optical control. The pyramidal texture further improves the optical properties through geometrically induced interference and confinement effects. A polymer matrix based on polydimethylsiloxane (PDMS) not only provides flexibility and conformal coating capabilities, but also provides compatibility with a cast molding process to create microscale texture in a scalable manner.

APPROACH/INNOVATION

The samples are prepared by integrating a controlled volume fraction of microscale glass bubbles from 3M™ within a PDMS matrix by mixing silicone elastomer and curing agent. After stirring and degassing, the PDMS film is applied to a textured mold and put into a vacuum oven for heated drying. After a full dry, the PDMS film is peeled off from the mold. Following sample preparation, the optical properties are characterized by ultraviolet (UV)-visible (VIS)-near-infrared (NIR) spectroscopy in wavelengths of 0.4–2.5 µm and Fourier-transform-infrared (FTIR) spectroscopy in wavelengths of 2.5–16 µm. Surface texture effects on optical properties are investigated using rigorous coupled-wave analysis (RCWA) and finite-difference time-domain (FDTD) simulations. The geometric parameters of the surface structures, mainly the aspect ratio (height/pitch), are varied to optimize the current design.

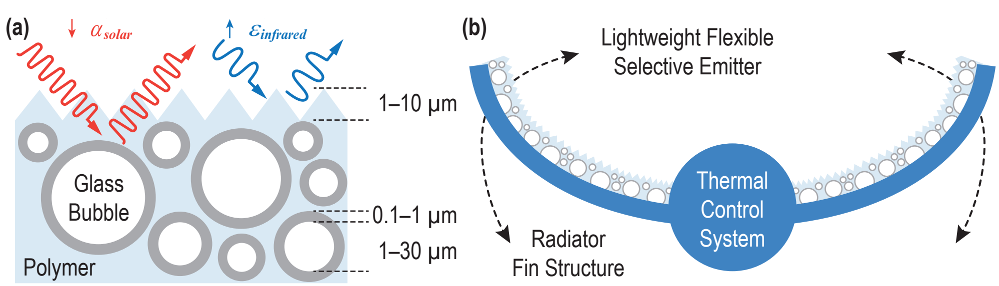

FIGURE 1. Proposed material and concept system designs. (a) The combination of glass bubbles and surface texture allows selective optical control that minimizes solar absorption and maximizes infrared emission; (b) The lightweight flexible selective emitter could be integrated with radiator fin or inflatable habitat structures and enable breakthroughs in thermal control of deployable and flexible systems.

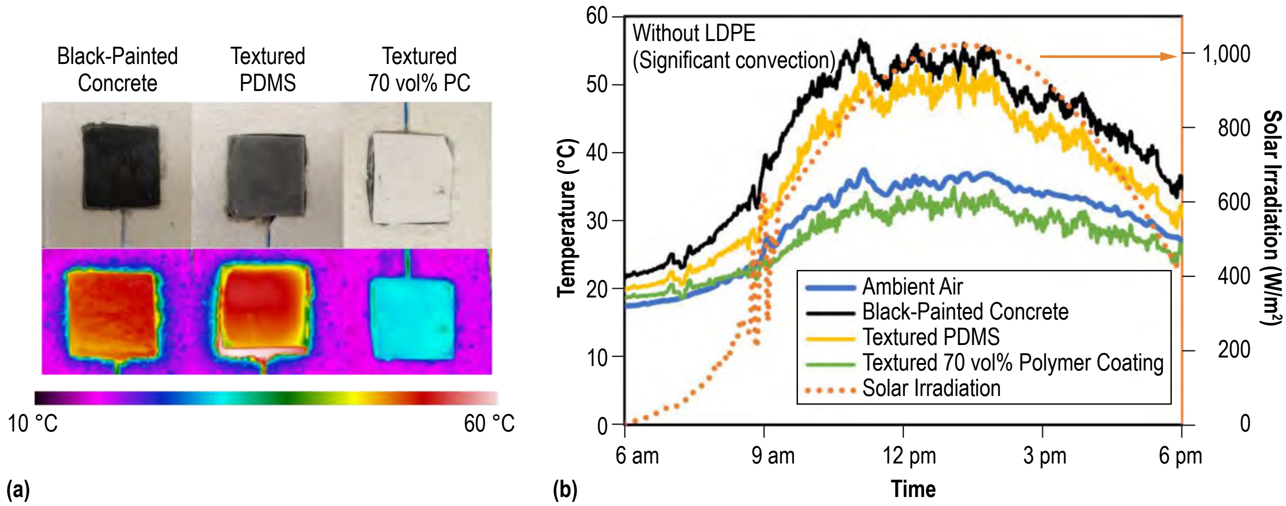

FIGURE 2. Thermal characterization of polymer coatings (PCs). (a) Optical and infrared images of black-painted concrete, textured PDMS on black-painted concrete, and textured polymer coating with 70 vol% glass bubbles on black-painted concrete. (b) Outdoor temperature measurements (without low-density polyethylene (LDPE)) of black-painted concrete (black curve), textured PDMS on black-painted concrete (yellow curve) and textured polymer coating with 70 vol% glass bubbles on black-painted concrete (green curve). Ambient air temperature (blue curve) and solar irradiation (orange dotted line) are plotted for comparison.

The predicted optical properties are used to generate theoretical temperature profiles for the textured and flat samples under ambient temperature and various heat transfer boundary conditions. The computational results are validated by experimental data obtained through established outdoor temperature measurements. The project also uses Mie theory and FDTD computations to investigate and understand the driving mechanism for optical properties of solar reflectors or selective emitters composed of hollow microspheres with uniform and varying diameters.

RESULTS/ACCOMPLISHMENTS

The optical measurements of the samples showed that as the volume fraction of glass bubbles increases from 0% to 70%, the average reflectivity in the visible region and NIR region is enhanced from 0.14 to 0.94 and from 0.13 to 0.84, respectively. The investigative team then studied the optical properties of glass bubbles in polymer composites and identified ideal design parameters. Outdoor measurements revealed that textured polymer coating enabled an additional 1.8 °C reduction in temperature compared to the flat variants when coated on common building material surface under limited convection and 0.63 °C reduction with significant convection at peak solar intensity, as shown in figure 2. Compared to polymer coatings with no glass bubbles, the textured polymer coating with 70 vol% glass bubbles show a significant temperature reduction on a concrete surface even when it is directly exposed to a peak solar intensity of around 1000 W/m^2. The results indicate the cooling performance of textured polymer coatings with glass bubbles is promising for spacecraft and building surfaces.

SUMMARY

Lightweight, low-cost, and scalable polymer coatings for thermal radiation control have successfully been prepared by integrating 70% volume fraction of glass bubbles within a PDMS film with surface texture. It has been demonstrated that this coating has a high solar reflectivity of 0.92 and high mid-IR emissivity of 0.85. The measurement results suggest that the polymer coatings can achieve a sub-ambient cooling and reduce the temperature significantly. The solar reflectivity of solid and hollow microspheres within a PDMS matrix has also been studied using Mie theory and FDTD simulation. The results show that hollow microspheres with a thinner shell are more effective in scattering light and lead to a higher solar reflectivity. The high scattering efficiency, owing to the refractive-index contrast and large interface density, in hollow microspheres allows low-refractive-index materials such as silica (SiO_2) to have a high solar reflectivity of 0.77, when the thickness of the film is 100 µm. The study found that the randomly distributed 0.5–1 µm SiO_2 hollow microspheres provide the largest solar reflectivity of 0.84 among all studied designs and the effect of varying diameters is supported by the backscattering ratio. It has also been identified that materials with a low extinction coefficient in the solar spectrum, such as yttria (Y_2O_3),are promising for solar reflection. The investigative team has further demonstrated that surface texture enhances emissivity in infrared wavelengths and greater cooling capabilities compared to flat polymer coatings.

PRINCIPAL INVESTIGATOR: Jaeho Lee (University of California, Irvine)

PARTNER: University of California, Irvine

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

FOR MORE INFORMATION: https://lee.eng.uci.edu

Software Tools for Effective Use of Additive Manufacturing In Situ Diagnostic Data During Process Development and Prototype Fabrication

OBJECTIVE: *To develop a robust software solution for automated analysis and anomaly detection in additive manufacturing (AM) in-situ process monitoring data.*

PROJECT GOAL/DESCRIPTION

CFD Research Corporation (CFDRC) in Huntsville, Alabama is developing software tools for automated analysis and postprocessing of additive manufacturing (AM) in-situ process monitoring data, linking the diagnostic data to potential defects or flaws in as-built parts. Currently, time-intensive manual review of in-situ monitoring data is required to assess the potential impact on part quality. As a result, the in-situ diagnostic data are not being fully leveraged to diagnose process outcomes and direct postbuild analysis. CFDRC is leveraging their experience in image analysis to identify process anomalies. Machine learning will be used to automate the identification of process disturbances that impact material quality by linking the data to nondestructive evaluation (NDE) results.

The machine learning meets an immediate existing need to process the large volumes of in-situ monitoring data that are generated with each AM build. It complements other efforts to enable the use of in-situ monitoring data for defect detection and part certification. Large, complex AM parts may not be inspectable using computed tomography (CT) or other NDE methods, so there is an urgent need to assess the effectiveness of in-situ monitoring as a tool for quantifying part quality and enabling certification.

APPROACH/INNOVATION

CFDRC began with a literature review to contextualize the state-of-the-art and promising approaches for processing in-situ monitoring data. A supervised convolutional, neural network is a common approach, but requires a substantial library of trained (labeled) images to draw from. Any supervised learning approach requires identifying defect locations and labeling them to build a training set. These are the types of approaches CFDRC has used in the past for detecting changes in remote imagery. Unsupervised learning can learn and recognize structure and patterns in raw data without labeled information. One major obstacle to overcome in the analysis of in-situ monitoring data is the presence of features that will appear as anomalies between build layers, but are an expected feature of the build process, such as the change in orientation of laser pass overlaps due to the chosen scan strategy. There are also variations in thermal emission that occur during a build that do not result in any detriment to the part. Using CT scan data to determine locations where a defect was formed is a useful way to identify in-situ monitoring signatures that affect build quality.

Edge detection and object extraction enabled individual analysis of multiple parts in an AM build and removal of background noise. Histogram analysis of the isolated build objects revealed major outliers, such as dead pixels and empty space around the parts, that needed to be corrected. The analysis led to the idea to generate synthetic nominal build data to use as a baseline for comparison. Partial synthetic data sets were generated from three build objects, and the true data from another build object were used as a test set for an autoencoder approach. This neural network consists of encoder and decoder layers that reconstruct the image to highlight outliers. Two additional postprocessing steps have been

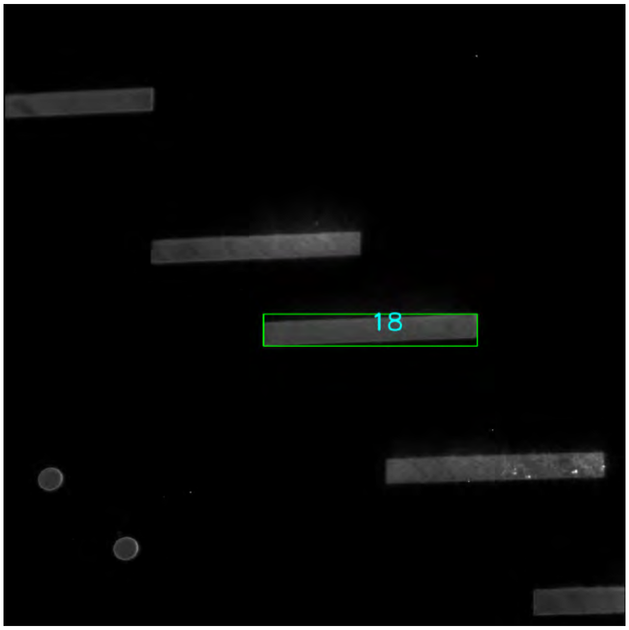

FIGURE 1. Automated object extraction script used on thermal imaging data from an AM build.

employed to reduce noise: an exponentially-weighted moving average filter to remove single-layer indications, and a median pooling filter to remove smaller spatial artifacts. Different statistical thresholding approaches were considered and tested, but in the end a 3-sigma threshold effectively highlights the areas of interest when combined with the postprocessing filters.

RESULTS/ACCOMPLISHMENTS

CFDRC has written an image segmentation algorithm in Python that is adaptable to different data sets. The algorithm is useful for isolating build objects for individual analysis and reducing data volume. This script has been delivered to NASA Marshall Space Flight Center (MSFC) and tested on different data sets with different object shapes and sizes with good results. The algorithm could be implemented to reduce data volumes or to facilitate image analysis.

CFDRC has also completed the phase of testing different image analysis methods and settled on an effective approach. Adding filters has improved results for reliable detection of defects with reduction of noise. CFDRC will continue to refine and improve this approach by testing it on build data and will prepare to deliver user-friendly scripts for implementation at MSFC. Beta image analysis scripts in Python have been delivered to MSFC for testing. In addition to the script that crops the image data (fig. 1), generates a three dimensional (3D) volume (fig. 2), and trains the variational autoencoder, there is another script that processes the data, as well as a script to visualize indications (fig. 3).

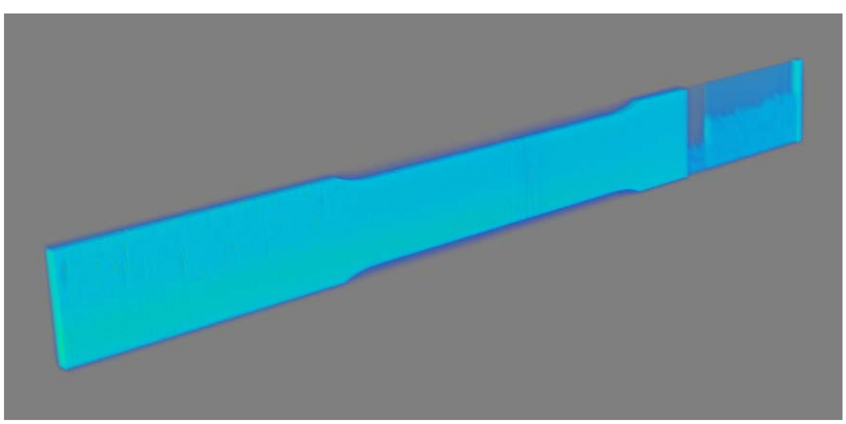

FIGURE 2. 3D reconstruction through image stacking of extracted thermal data.

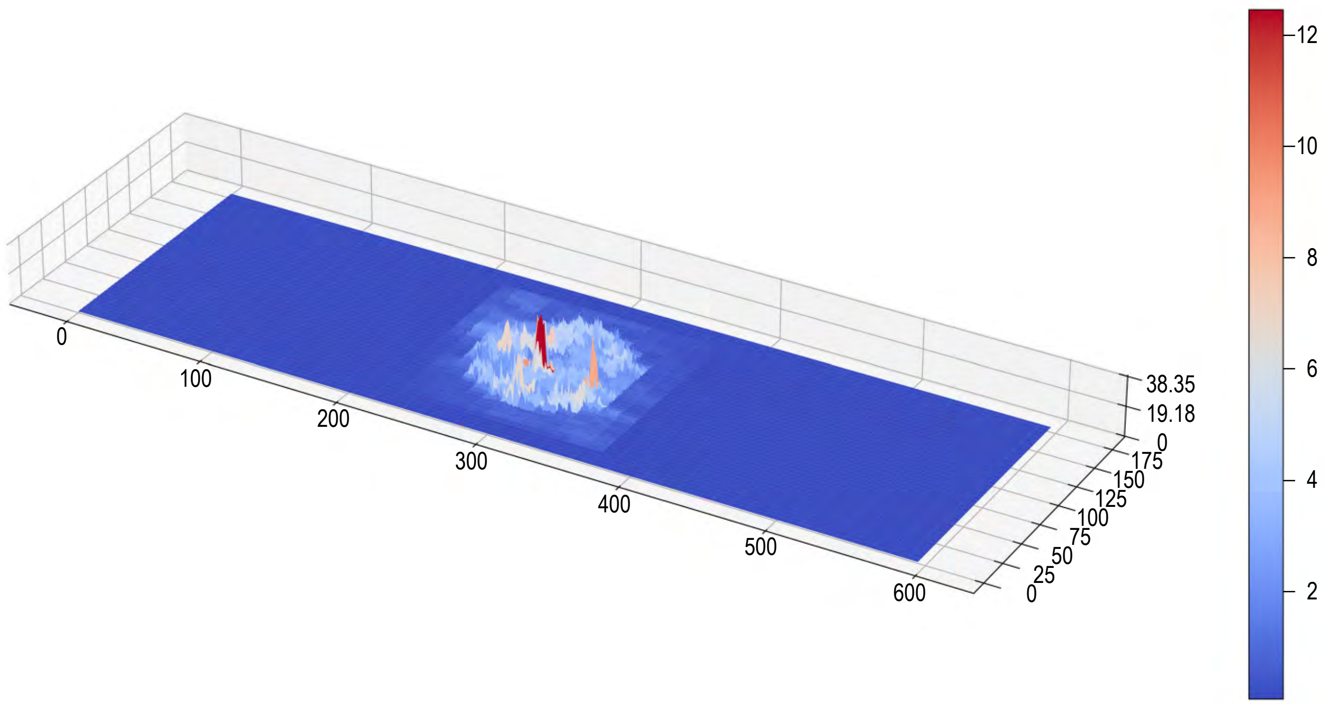

FIGURE 3. Indications of image anomalies in a single AM build layer. Seeded defects using no laser power were programmed into the AM process at these locations.

Another accomplishment has been the registration of CT data to in-situ monitoring data. These disparate data sets have differences in resolution and orientation that need to be reconciled before they can be compared side-by-side. The data sets have been rotated to align within 0.1 degree, and different approaches for registration are being tested now.

SUMMARY

This project is complementary to other efforts in analysis and interpretation of in-situ monitoring images. The goal of this project is a turnkey software solution for processing in-situ monitoring data. At the end of this effort, the final image analysis scripts will be delivered to MSFC. The scripts can be used on the data once it has been copied to another computer and exported as image files. Integration in-line with the AM equipment manufacturer's in-situ monitoring software and sensors could be a potential area of future work.

PRINCIPAL INVESTIGATOR: Vernon Cole, CFD Research Corporation

PARTNER: CFD Research Corporation (CFDRC)

FUNDING ORGANIZATIONS: Center Strategic Development Steering Group (CSDSG), Cooperative Agreement Notice (CAN)

Realizing Spatially-Resolved, Realtime Temperature Measurements in Friction Stir Welding (FSW) Using Ultrasonic Thermometry

OBJECTIVE: *To demonstrate the use of ultrasonic thermometry to remotely obtain real time, spatially resolved temperature profiles within the FSW zones with a newly developed 'Smart Tool.'*

PROJECT GOAL/DESCRIPTION

Friction stir welding (FSW) is a solid-state joining technique patented in the 1990s and first implemented at NASA Marshall Space Flight Center (MSFC) in 1995. It was successfully used in the joining of heavily alloyed aluminum panels on the external fuel tank for the space shuttle main engine (SSME) and has been baselined for the Space Launch System (SLS) as shown in figure 1(a). While the fuel tanks for the SSME used thinner workpieces since they did not provide structural support, the fuel tanks on the SLS provide structural support and therefore require thicker workpieces. As the workpiece increases in thickness, maintaining a constant temperature throughout the weldment is challenging. As with any joining process, knowing and controlling the temperature is fundamental to quality control and production of robust, high-quality joints. Thus, having a method to monitor, and ultimately control, the realtime temperature during FSW, shown in figure 1(b), becomes critical. However, in FSW, the temperature is not directly controlled but rather empirically correlated with the process control parameters of tool rotation and travel.

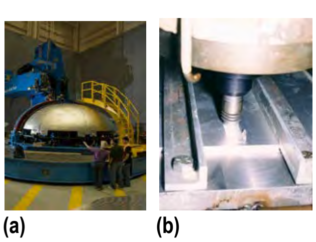

FIGURE 1. (a) FSW of dome for launch vehicle fuel tank with (b) close up image of FSW process.

APPROACH/INNOVATION

By making use of ultrasonic wave propagation, transducers can be installed remotely and used to monitor the workpiece material through temperature-dependent changes in time-of-flight of the signal. Preliminary data was obtained using ultrasonic transducers (UTs) mounted to a floating anvil shown in figure 2(a). In order to accommodate a wider range of FSW equipment, the transducers have been relocated to the backside of the tool as shown in figure 2(b). The remote attachment does not influence the thermal transport in the weld zone, nor subject the transducers to a harsh thermal environment. Use of this methodology will assist in understanding the occurrence of random variations in the properties of FSW weldments, especially with varying material alloys, with their corresponding process parameters. Ultimately, this proposed methodology would support various feedback control schemes to maintain constant temperature in the FSW zone and ensure the production of repeatable, robust, high quality weld joints, thereby maximizing the capability of the FSW process.

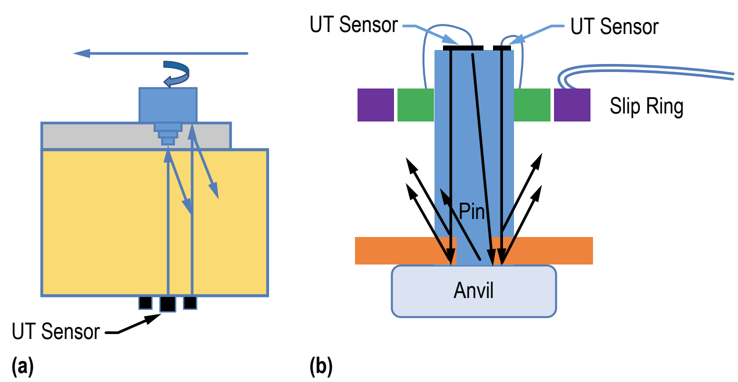

FIGURE 2. Installation of ultrasonic transducers (a) on a floating backing anvil and (b) on the backside of the FSW tool.

RESULTS/ACCOMPLISHMENTS

Temperature measurements made using the UT senor attachment, or 'Smart Tool,' during FSW of 6 mm-thick 2219 aluminum alloy panels are summarized in table 1. Empirical data for FSWing estimates the temperature to be in the range of 0.7 to 0.9 the homologous temperature. For aluminum alloys, this would correspond to temperatures in the range of 380 to 567 °C. From the literature, the temperature is expected to be highest near the shoulder (step 1), decreasing toward the backing anvil (step 3). Also, the temperature is strongly dependent on the tool rotation, increasing as the rotation is increased. Thus, table 1 shows the spatially-resolved temperature to track the expected trends.

TABLE 1. FSW Temperature (°C) in 6 mm-thick 2219 panels.

	Step 1	Step 2	Step 3	Average
275 RPM 6 IPM	560 ± 3.6	500 ± 17.7	376 ± 3.7	485 ± 8.3
300 RPM 6 IPM	584 ± 15.6	479 ± 3.0	395 ± 8.8	494 ± 9.4
350 RPM 6 IPM	621 ± 13.2	487 ± 16.7	405 ± 27.7	514 ± 10.8

SUMMARY

Preliminary data obtained using the 'Smart Tool' shows a strong correlation with published trends in the literature. Additional tests are being conducted to explore varying material thickness and aluminum alloys. The ability to directly extract the real time temperature is key in maintaining quality control to ensure repeatable, consistent, robust weldments with ultimate implementation of feedback controls.

PRINCIPAL INVESTIGATOR: Judith Schneider, University of Alabama in Huntsville

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Advanced Tooling Demonstration for Friction Stir Welding of Heat-Resistant Materials

OBJECTIVE: *To Improve the reliability and robustness of solid-state friction stir weldments, advanced materials are being investigated for the tooling. This not only supports the current joining efforts for the Space Launch System (SLS)/Artemis aluminum alloys, but also for future joining of materials that retain their strength at elevated temperatures such as INCONEL, titanium alloys, and steels.*

PROJECT GOAL/DESCRIPTION

Development of advanced high-strength and high-temperature solid-state friction stir welding (FSW) tool materials are required to support not only the large-scale FSW processing for the Space Launch System (SLS) and Artemis programs, but also for various commercial and industrial applications. Due to the large scale and long durations of these welds, tools that are fatigue- and wear-resistant are required to ensure high quality FSW. Thus, the development of advanced FSW tool materials is equally as important as the advancement of the FSW process. The tool must be able to survive the temperatures experienced in the FSW weldment under the high mechanical loading. Improving the durability of FSW tool materials is critical to producing robust weldments, not only in the current aluminum (Al) alloys, but also in materials that retain their strength at elevated temperatures such as INCONEL, titanium (Ti) alloys, and steels.

APPROACH/INNOVATION

Table 1 summarizes current materials used for FSW tooling. Empirically obtained temperatures for the weldment in the FSW process are in the range of 0.7 to 0.9 the homologous temperature. Thus, while tool steel is suitable for joining aluminum alloys, other materials with higher melting temperatures require more advanced tooling. These options are either brittle ceramics (i.e., polycrystalline cubic boron nitride (PCBN)) or tungsten (W)-based refractory alloys.

TABLE 1. Candidate FSW tool materials.

	Operation Temperature Limit (°C)	Machinable	Room Temperature Hardness (HRC)
MP159	600	Yes	56
PCBN	950	No	60–62
W–25%Re–2%HfC	1,050	Yes	48–50
W–25%Re–4%HfC	1,050	Yes	53–55

As noted in table 1, the refractory alloy W-25%Re with HfC is able to operate at the highest temperature in addition to being machinable. Using the processing methods developed under an earlier CAN, the addition of 4% HfC was shown to be optimal in terms of the resulting metallurgy. The tools, previously produced using spark plasma sintering (SPS), demonstrated a reduced cost of roughly $1,000 per tool. This is in contrast to the $10,000 to $50,000 price for the brittle PCBN tooling. The current CAN is demonstrating their ability to survive under FSW conditions in metals such as steel and titanium alloys.

RESULTS/ACCOMPLISHMENTS

To date, the W-25%Re-4%HfC tool that was produced for this research project has FSWed a length of 35 cm in 1018 steel without auxiliary heating. Images from an optical comparator captured the pin profiles before and after the weldments. No appreciable tool wear was noted, and the pin appeared clean and lacked any signs of erosion due to wear. A segment of the FSW underwent radiographic x-ray inspection, which showed a fully consolidated weldment without any inclusions that might arise from tool wear.

SUMMARY

Using previously developed processing parameters, additional tooling was made to support this study to reduce risk. To date, 35 cm of weldment has been completed in 1018 steel. Post-weld inspection verified that there was no significant wear of the pin tool. Radiographic x-ray inspection verified a clean weldment with evidence of voids or inclusions present from pin tool wear. Metallurgical specimens were also prepared to ensure the weldments were fully consolidated.

PRINCIPAL INVESTIGATOR: Judith Schneider, University of Alabama in Huntsville

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Enhanced Equipment Isolation in Extreme Vibratory Environments Using Rotational Inertial Devices

OBJECTIVE: *To develop a vibration mitigation device (VMD) that combines passive isolation and damping (rotational inertial device) into a single VMD.*

PROJECT GOAL/DESCRIPTION

NASA hardware is subject to extreme vibratory environments. These environments can cause damage to avionics boxes and other equipment that is difficult to mitigate. This problem is of particular importance when using legacy hardware in new systems with higher predicted environments, such as the Space Launch System and Orion spacecraft. A traditional solution to these vibration concerns are low-stiffness isolation mounts. The isolated system's low stiffness, and thus the low isolation frequency, effectively controls the acceleration response of the equipment it is attached to when considering a broadband loading; however, this decreased stiffness and low isolator natural frequency would cause the equipment to be subjected to excessive displacement and acceleration response at low frequencies due to transient excitation.

The objective of this collaborative project between the University of Tennessee and NASA Marshall Space Flight Center (MSFC) is to provide a proof of concept for, and assess the feasibility of, an equipment vibration isolation system for NASA hardware that features rotational inertial devices.

An archetype isolation system considering the needs of MSFC will be established. As this project is an intermediate step towards further development, only loading and response in one direction will be considered in this archetype system. Analytical and numerical modeling and optimization will be performed to model the behavior of different configurations of a rotational inertial device. Simulated flight hardware with an isolation system featuring rotational inertial devices will be designed, fabricated, and experimentally tested.

APPROACH/INNOVATION

This work seeks to leverage recently-developed rotational inertial devices and combine them with isolation systems. While these rotational inertial devices have taken various forms, their common feature is a mechanical device called an inerter. The inerter is a two-terminal mechanical device that produces a rotational inertial mass proportional to the relative acceleration between its two terminals. Figure 1 shows two common realizations of this device. Through the transformation of linear motion to rotational motion, the inerter can provide a large mass amplification, thus producing an effective large inertial mass through a physically small flywheel mass.

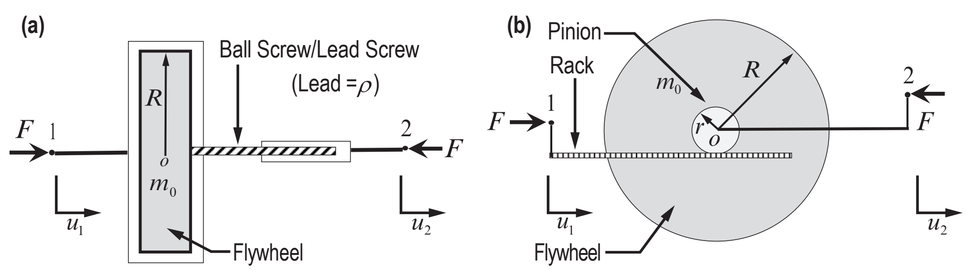

FIGURE 1. Common realizations used for inerters (a): ball screw/lead screw (b): rack and pinion.

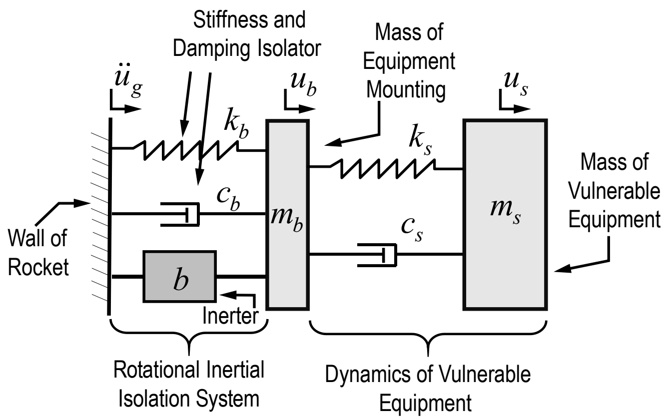

FIGURE 2. Dynamic model of equipment with rotational inertial isolation.

An example of an inerter-based isolation system is shown in figure 2. In general, studies on inerter-based isolation systems have found that they are capable of significantly reducing the displacement response of the isolated system without increasing their acceleration response. While previous studies of inerter-based isolation systems have shown promise in leveraging these mass effects for the vibration control of civil systems, these studies have largely not considered the unique demands of aerospace applications.

RESULTS/ACCOMPLISHMENTS

In the past year, significant progress has been made on this project with the most recent advances being made experimentally. An experimental testbed for assessing the rotational inertia devices as part of isolation systems has been designed and manufactured, as seen in figure 3.

FIGURE 3. Experimental vibration isolation test bed attached to a shake table for dynamic testing. The rotational inertial device can be seen in the bottom middle of the test bed.

In order to simplify the test environment, this test bed is designed to allow for vertical motion only. This system, without the rotational inertial component, is designed as a two degree-of-freedom (DOF) system with a single DOF system that is placed on an isolation layer. The primary stiffness elements in the test bed are beam springs that can be modified to provide a large range of different stiffnesses. The rotational inertia device rotates when the vertical motion of the first story makes a lead screw move through a lead screw nut. The device's flywheel is reconfigurable to provide a large range of mass effects.

This testbed is currently on the shake table at the University of Tennessee, where preliminary tests are underway. Through design, manufacturing, and preliminary testing, the research group has learned many lessons on the physical manifestation of rotational inertial devices. These lessons include the importance of tolerance, alignment, and lubrication. Additionally, the group has learned about the practical limitations of the geometric attributes of the lead screw that can allow back driving of the screw (a vertical force being used to create rotation in the flywheel). Some of these practical issues with the test bed have been resolved and some are in the process of being resolved. Once these issues are all resolved, testing of the efficacy of the device will begin in earnest.

SUMMARY

This project seeks to provide a proof of concept for an equipment vibration isolation system for NASA hardware that features a rotational inertial device. Simulated flight hardware with an isolation system featuring a rotational inertial device has been manufactured and preliminary experimental testing of this hardware is underway at the University of Tennessee shake table facility. Data from this project, including the experimental tests, will serve to evaluate the efficacy of the rotational inertial device as part of an isolation system. Additionally, the results of this study will be used to develop research questions that drive subsequent investigations of this device.

This project has been active for 14 months and will conclude in January 2022.

PRINCIPAL INVESTIGATOR: Nicholas Wierschem

PARTNER: University of Tennessee Knoxville

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Pinned Joints of Composite Honeycomb Sandwich Panels

OBJECTIVE: *To develop an effective methodology to predict the pin-bearing capacity of carbon/epoxy composite laminates to assist the design of the payload adaptor used for the Space Launch System.*

PROJECT GOAL/DESCRIPTION

A composite payload adaptor (PLA) is being designed and fabricated at NASA Marshall Space Flight Center (MSFC) for the Space Launch System (SLS). Functioning as the primary structural interface between the payload and the body of the launch vehicle, the PLA is connected to the payload and the body of the launch vehicle by metal clevis fittings via pin connections. The objective of this research is to develop an effective methodology to predict the pin-bearing capacity of composite laminated plates to assist the design of the PLA. The method developed includes material damage and failure models and the progressive damage models using the finite element method. This can also be applied to other composites applications where stress concentrations occur and the classical composites failure criteria are not suitable to estimate the load-carrying capacity of the composite structures.

APPROACH/INNOVATION

It can be found from the literature that the constitutive models representing the behavior of a composite material developed in the past take a quick departure when defining the degradation and failure response of the material. Several researchers derived multiple models in which the material response was dependent on the loading condition. Different models modified failure criteria, and constant stiffness degradation coefficients were utilized to calculate the stiffness loss of the composite materials. These models can be rendered as inaccurate because the data gathered from previous experiments show that fiber-reinforced composite materials do not always have an instant failure response or a constant degradation of their stiffness properties, especially in response to shear loading. Experimental data shows that the stiffness of fiber-reinforced composite materials degrades as a function of applied loading.

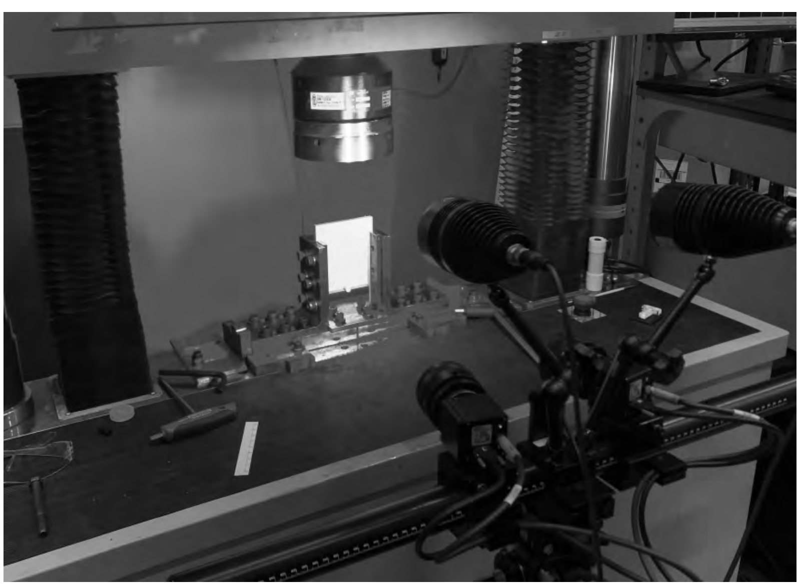

FIGURE 1. Pin-bearing test setup.

In the current study, material models were developed for the unidirectional and eight-harness satin-weave fabric of a carbon/epoxy composite material. These models include the failure criteria; the damage initiation criteria; and the relationships between stiffness degradation and extent of damage in the fiber direction, transverse direction, and shear. These damage models were applied to the progressive damage models of finite element analysis. A non-linear finite element analysis using the commercial finite element software package ABAQUS was performed along with user-defined FORTRAN material subroutines, which allowed controlling the stiffness of the composite material as dictated by the progressive damage model that was developed. This approach was adopted in the current Cooperative Agreement Notice (CAN) project to predict the damage initiation and progression of pinned joints of composite laminates. It also has a great potential for other composites applications.

RESULTS/ACCOMPLISHMENTS

Material models for unidirectional and eight-harness satin-weave carbon fabric/epoxy composite laminates have been developed and validated via experiment, as seen in figure 1. These material models include the failure, damage initiation, and damage progression in the fiber and matrix directions. They have been successfully incorporated into finite element models using the commercial software ABAQUS via user-defined FORTRAN subroutines to simulate the pinned joints of composite laminates. The pin-bearing capacities of composite laminates of two pin sizes and eight different layup sequences were simulated using the finite element method with the progressive damage model. Good correlations were observed between the results from the models and experiments.

SUMMARY

Two-dimensional progressive damage analysis methodology for pinned joints of composite plates was developed in this study. Through comparison to experiments, the methodology developed has shown to be effective in determining the approximate maximum bearing capacity and in-plane deformations of pinned joints of composite plates. Nonetheless, the model capabilities are limited to in-plane loading conditions. It is believed that the developed material model and methodology have shown an increase in accuracy when analyzing composite structures due to the consideration of damage accumulation and further damage progression. The developed damage modes played crucial roles in determining the bearing capacity of a pinned joint of composite plates.

It has been identified that the material models could be developed further. Experimental data show that out-of-plane loading conditions would affect the behavior of the composite plates. In summary, a three-dimensional extension accounting for delamination and out-of-plane displacements could be further developed to improve the capabilities of the material models presented. While additional development of this methodology could further improve the accuracy of failure load predictions for pin-bearing in composite laminates, in its current state, it can assist engineers in comparing the pin-bearing capacities of joints with different numbers of plies and layup sequences. The same methodology could very possibly be applied to composite laminates under different loading conditions. Further investigation would benefit the composites industry greatly.

PRINCIPAL INVESTIGATOR: Charles Yang, Wichita State University

PARTNER: Wichita State University

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

In-Space Manufacturing (ISM)

OBJECTIVE: *To develop and enable the technologies, materials, and processes required to provide affordable, sustainable on-demand manufacturing, recycling, and repair during exploration missions.*

PROJECT GOAL/DESCRIPTION

The NASA In-Space Manufacturing (ISM) portfolio provides a solution towards sustainable, flexible missions through on-demand fabrication, replacement, and recycling capabilities to support critical systems, habitats, and mission logistics and maintenance. These capabilities can provide tangible cost savings by reducing launch mass; reducing risk by decreasing dependence on spares; enabling design systems for maintainability; and enabling crew to respond to unanticipated scenarios.

FIGURE 1. ISM logo.

APPROACH/INNOVATION

Logistics support is a significant challenge for extended human operations in space, especially for missions beyond low-Earth orbit (LEO) where timely resupply or abort in the event of emergency would not be possible. The current logistics model is heavily dependent upon orbital replacement units (ORUs) for system-based repair and maintenance and is not logistically sustainable for long-duration exploration missions, which would require recycling, reuse, and in-situ resource utilization. The ISM portfolio includes three projects funded by the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program:

(1) On-Demand Manufacturing Of Metals (ODMM),

(2) On-Demand Manufacturing of Electronics (ODME), and

(3) Recycling and Reuse (RnR).

These three projects will significantly reduce mission risk and logistical requirements while enabling Earth-independent human spaceflight. Capabilities are being developed by leveraging new terrestrial technologies and adapting them for operations in pressurized and reduced-gravity or microgravity environments. To develop these technologies, the ISM projects are using the opportunity to test on the International Space Station (ISS), which serves as a one-of-a-kind test bed on the ISM technology development roadmap.

RESULTS/ACCOMPLISHMENTS

ON-DEMAND MANUFACTURING OF METALS

The ODMM project is pursuing the commercial development of hybrid (additive-subtractive) manufacturing prototype units for demonstration aboard the ISS. Two distinct approaches are being considered. Techshot, Inc. has developed a fully integrated, ground-based prototype system using bound metal deposition (BMD), known as the Fabrication Laboratory (FabLab), which can produce titanium parts. Redwire, Inc. is developing a wire-arc additive manufacturing (WAAM) system, called Vulcan, to produce aluminum components. Both approaches have the potential to expand material processing capabilities to other metals as well as polymers, with the vision of providing multimaterial capabilities for future missions.

During the final part of the Phase A FabLab project, Techshot completed a preliminary design review; completed and demonstrated their prototype FabLab hardware by successfully manufacturing five parts specified as ‘challenge builds’ by NASA (i.e., candidates for on-demand manufacturing on space missions); and delivered their Phase A final report on their two-year development effort. Currently, the ISM project and Techshot are working to mature the furnace design and electronics manufacturing capabilities of the system.

The Vulcan effort from Redwire focused this year on demonstrating subsystems and building out an engineering development unit, which integrates multiple heads for metal three-dimensional (3D) printing, polymer 3D printing, and subtractive manufacturing. Redwire has successfully demonstrated the following subsystems for Vulcan: the weldhead for WAAM; polymer 3D printing; subtractive manufacturing; automated machine tool changeout; an environmental control unit for chip capture; an in-process monitoring system to assess weld quality following deposition of a layer; and an iris clamp and robotic gripper for part fixturing and machining. A zero-g flight will provide data concerning the chip capture system and give insight into how the welding process will be affected by microgravity.

ON-DEMAND MANUFACTURING OF ELECTRONICS

The ODME project is developing a range of new on-demand printed sensors for monitoring environmental conditions; monitoring the health and condition of structures and vehicles; and monitoring astronaut crew health. In 2021, ODME started new projects to develop a cabon dioxide (CO_2) sensor, a printed radiation sensor, multiple structural health monitoring sensors, printed sensors for food spoilage, printed wearable biosensors for cortisol to monitor crew stress, and a printed bone density sensor.

The ODME project is also developing leading-edge technologies for harvesting and storing energy for electronics and sensor networks that can one day be demonstrated in space. ODME is working with a number of universities on these innovative technologies, which include a printed antenna array to harvest power from Radio Frequency Identification (RFID) or Wi-Fi electromagnetic networks; a printed thermoelectric device that will harvest power from small temperature differences in space environments; and several printed supercapacitor technologies to store the energy harvested by the above methods and use it for electronic circuits and sensor networks. In addition to the development of a cortisol biosensor to monitor astronaut stress, ODME is also working with the Stanford Linear Accelerator Center (SLAC) team as part of their COVID-19 Response Program to develop a silicon chip capable of detecting the SARS-CoV-2 antigen that can be produced inexpensively in high volumes.

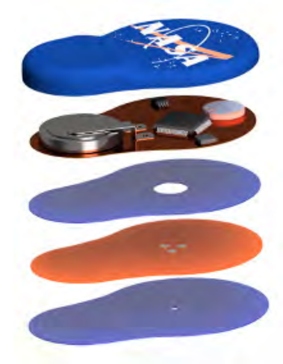

FIGURE 2. Cross-section of AstroSense printed sensor.

RECYCLING AND REUSE

Multiple waste streams that are not conducive to long-duration missions exist in the current ISS logistics model. The RnR project is focused on recycling and reuse of packaging materials, such as films and foams, due to their ubiquity and the large volume needed for stowage. Previous efforts under a Small Business Innovation Research (SBIR) agreement with Cornerstone Research Group (CRG) evaluated a limited subset of existing launch packaging materials. In early 2020, an in-house team consisting of polymer experts from NASA Marshall Space Flight Center's (MSFC) Materials and Processes Laboratory expanded the evaluation of existing packaging materials to include the 101 polymers listed in the Cargo Missions Manifest. Following this analysis, which took into account the impact of viscosity, material form, safety concerns, and thermal properties on printing and recycling, the team concluded that none of these materials were high-potential candidates worthy of further investigation. Instead, it was recommended that materials be developed with the intention of being recycled. This analysis will inform future efforts within the RnR project.

The Redwire Regolith Print (RRP) ISS Technology Demonstration project, a part of RnR, completed its mission of 3D printing a mixture of lunar regolith simulant and a thermoplastic material in the microgravity environment of the ISS. The RRP proof of concept shows the viability of printing with regolith composite material in a reduced gravity environment; it is a fundamental example of in-situ resource utilization and is applicable to lunar and Martian surface missions (Artemis and Moon to Mars). Using the data and knowledge gained from the mission, potential future missions with Redwire, previously Made In Space (MIS), will continue to refine and enhance the capabilities of 3D regolith printing.

PORTFOLIO MANAGER: James Stott

PARTNERS: Techshot, Inc.; Redwire Space (formerly Made In Space, Inc.)

FUNDING ORGANIZATIONS: Advanced Exploration Systems (AES) Office, Game Changing Development (GCD) Program

FOR MORE INFORMATION:
https://www.nasa.gov/oem/inspacemanufacturing

TA13:

Ground, Test, and Surface Systems

Ultra High Definition (UHD) Upgrade for NASA Imagery Experts Program (NIEP) Support

OBJECTIVE: *As NASA moves toward adopting new higher-resolution video for NASA TV and internal video purposes, the NASA Imagery Experts Program (NIEP) moved to upgrade the NASA TV infrastructure, the NIEP lab, and the NIEP flypack to support the new capability.*

PROJECT GOAL/DESCRIPTION

With an Agency goal of providing live ultra high definition (UHD) video distribution in time for the Artemis 1 launch, the NASA Imagery Experts Program (NIEP) upgraded assets under its direct control to support more demanding content formats. This included a full overhaul of the NIEP laboratory in Huntsville, Alabama; buildout and production use of a more compact, easier-to-ship video production package; and an upgrade to the NASA TV infrastructure at the Encompass facility to support NASA TV distribution of live UHD content.

APPROACH/INNOVATION

The NIEP supports the infrastructure for NASA TV, the primary conduit for broadcast video content both direct to the public and to media outlets, especially live event content. Though NASA TV supports a UHD channel on satellite, it is only for pre-recorded content. As NASA has matured in supporting UHD and higher-resolution video, the infrastructure has been upgraded in pieces, resulting in a mixture of technology at various levels of sophistication and capability. In 2021, NIEP was able to 'clean up its own house' by upgrading components to UHD-native systems in the following areas.

- NIEP put together a UHD fly-away production package, or flypack, that can be packed and shipped anywhere in the world.
- UHD equipment was installed at the NIEP Lab in Huntsville, Alabama, used to evaluate video quality and function of various video equipment.
- The existing UHD channel equipment at NASA's satellite uplink partner was updated to support satellite and internet distribution of live UHD content, instead of being limited to pre-recorded content.

RESULTS/ACCOMPLISHMENTS

The UHD flypack took advantage of advancing video technology to replace the older setup that started with HD technology. The upgraded technology also had the benefit of reducing both the weight and volume of the flypack, a clear win for portability. The first full field use of the new kit was for the Vice President's visit to NASA Langley Research Center (LaRC) in February 2020. It was used to cover the Demo-2 crew return to Johnson Space Center in July 2020; to capture the OSIRIS-REx asteroid sample pickup in Oct. 2020; and to support the Green Run tests of the Space Launch System at Stennis Space Center in January and March 2021, as seen in figure 1.

The NIEP Lab, located in the Huntsville Operations Support Center (HOSC) facility at NASA Marshall Space Flight Center (MSFC), supports interconnection and testing of cameras, video capture devices, displays, and other video technologies in both baseband

FIGURE 1. NASA Imagery Experts Program (NIEP) flypack for Stennis Space Center Green Run test.

and compressed video formats. Through IT Investment Funding (ITIF), the lab was upgraded with a video router and patch panels capable of supporting 12G Serial Digital Interface (SDI) switching, enabling transmission of 4K/UHD signals over a single coaxial input. This is an upgrade from the previous 3G-capable switch, which required four coaxial cables to support a UHD signal. High speed Internet Protocol (IP) video switching (up to 25 Gbps per signal) capability was added. This is a relatively new technology to the video industry that is rapidly being implemented. The IP system, known in the industry as Society of Motion Picture and Television Engineers (SMPTE)-2110 standard, will serve as a test bed and proving ground for new IP equipment as it is introduced.

NIEP also funded and delivered UHD-capable encoders, decoders, closed caption inserters, bug inserters, and a video router to the Encompass facility in Atlanta, as well as delivering UHD encoders and decoders to key NASA centers to enable support of live UHD broadcast to NASA TV UHD via satellite and streaming to the internet. The ability to add closed captions to a UHD broadcast is a new technology just now rolling out commercially.

SUMMARY

A series of upgrades in the NASA TV infrastructure, the supporting NIEP lab at MSFC, and the NIEP-managed UHD production flypack readies NASA to share our mission to the public in full ultra-high-resolution video from anywhere on Earth, and soon from off the Earth as the International Space Station rolls out UHD capability.

PRINCIPAL INVESTIGATOR: Rodney Grubbs

PARTNERS: Office of Communications (OCOMM); Office of the Chief Information Officer (OCIO)

FUNDING ORGANIZATION: Advanced Exploration Systems (AES) Office

FOR MORE INFORMATION:
https://www.nasa.gov/multimedia/nasatv/

TA14:

Thermal Management Systems

Lunar TheRMiS—Lunar Thermal Regulation for Mission Sustainability

OBJECTIVE: *To leverage both MSFC and partner capabilities to develop the Lunar TheRMiS—a validated collection of design and technology information for spacecraft and payload designers of systems that need to survive extreme lunar environmentst.*

PROJECT GOAL/DESCRIPTION

In recent years, there has been a push to return a human presence to the Moon, with an increased focus on sustainability. Part of this sustainability will be reusable and long-duration vehicles as Apollo-style, single-use vehicles are too expensive and impractical. Numerous engineering challenges exist when developing such vehicles, one of which is designing a thermal control system (TCS) that can survive the extreme cold of the lunar night. Currently, the state of the art is to use radioisotope heating; however, this is difficult to sustain for multiple reasons. Nuclear material has large cost, sociopolitical concerns, and integration challenges, making its use impractical for many missions. The Lunar TheRMiS team is developing an advanced TCS solution using non-nuclear components that will allow a 50–500 kg-class lander to survive the lunar night. This capability will enable scientific missions to close gaps in strategic knowledge for future human exploration of the Moon, as well as building sustainable lunar presence architectures that depend on survivability through the lunar night. The team is collaborating with Astrobotic, an innovator in commercial lunar landers, who will be providing their Peregrine lander as a testbed for analysis and eventual flights to the Moon. This effort will advance the TCS technology through system-level thermal vacuum testing and culminate in the delivery of flight-ready hardware to Astrobotic for a demonstration of the system during their second mission to the Moon. In addition, the effort will result in a validated toolbox of thermal modeling techniques, which can provide a set of TCS solutions for broad application to lunar landers and future thermal challenges faced by NASA and its commercial partners. The logo for the Lunar TheRMiS project can be seen in figure 1.

FIGURE 1.
Lunar TheRMis project logo.

APPROACH/INNOVATION

To solve this problem, the Lunar TheRMiS team is leveraging individual thermal control technologies—using heritage components at Technology Readiness Level (TRL) 9, as well as mid-TRL (TRL4 to TRL6) components—to develop an innovative non-nuclear solution. The team is utilizing advanced thermal control hardware such as variable conductance heat pipes (VCHPs), loop heat pipes (LHPs), embedded heat pipe plates (EHPPs), thermoelectric coolers (TECs), phase change materials (PCMs), thermal switches and the like; each with their own unique characteristics that allow them to solve pieces of the puzzle. It is important to point out that a TCS for the lunar night/day is a complicated system with complex interactions between the thermal control devices. It is unlikely that an integration of all commercial off-the-shelf (COTS) hardware will be sufficient. This is driving the need for the combination and optimization of a TCS comprised of both

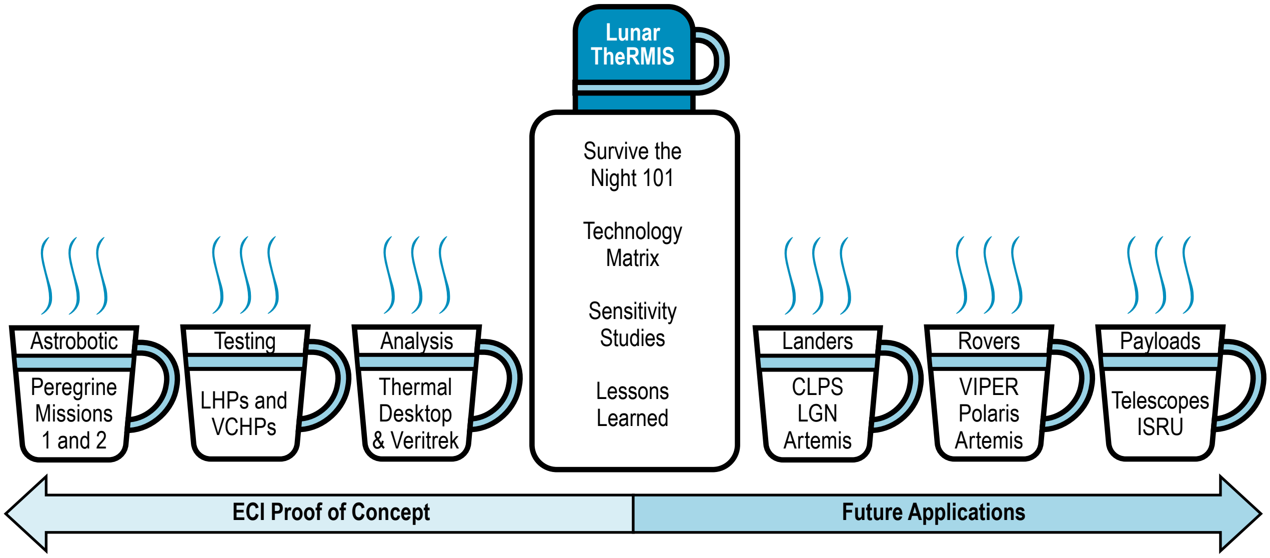

FIGURE 2. Diagram of a high-level overview of the Lunar TheRMiS project from proof of concept to projected future applications.

heritage/COTS parts as well as advanced, mid-TRL components. The challenge here is leveraging the strengths and weaknesses of each technology, while balancing the combination of heritage and next-generation components to advance the TCS technology toward the lunar night solution.

The Lunar TheRMiS project has three main objectives. To complete Objective 1, the team created a matrix of thermal control options, categorizing them by type and sorting by TRL. These options were qualitatively compared to highlight their strengths and weaknesses for surviving the lunar night. For Objective 2, potential solutions will be crafted from the matrix produced in Objective 1, with prototyping and testing to further narrow and mature the Lunar TheRMiS project to TRL6. Lastly, Objective 3 will produce a flight demonstration unit that will be integrated and delivered to Astrobotic for TRL7 technology demonstration on the lunar surface. The solution space defined by the proposed TCS, as well as the model validation and verification, will be useful to the greater NASA and commercial community as it provides a toolset for successfully implementing advanced TCS designs onto a broad range of lunar missions and beyond.

RESULTS/ACCOMPLISHMENTS

During the past year, the Lunar TheRMiS team has continued refining the technology matrix as relevant technologies are explored. This has involved analysis utilizing industry-standard tools such as Thermal Desktop, as well as newer tools that aim to rapidly produce results. The team procured an analysis tool that allows for parametric studies to be set up and performed at a speed unfeasible with the traditional methods.

In addition to analysis, the team has also been involved with a significant amount of testing. Systems involving both loop heat pipes (LHPs) and variable conduction heat pipes (VCHPs) have been tested. The heat pipes tested all have various advanced features that set them apart from traditional examples and provided specific benefits towards surviving in extreme lunar environments. One of the biggest accomplishments this year was the team taking delivery and testing of a flight VCHP. This heat pipe was tested by the team and will fly on Astrobotic's first lunar landing mission. Figure 2 provides a high-level overview of the Lunar TheRMiS project highlighting important components studied thus far, as well as projected future applications of this TCS solution.

SUMMARY

The Lunar TheRMiS team has continued developing the methodology and toolkit necessary to survive the lunar night. The TCS technologies are analyzed and tested to ensure they are fully understood as part of a complete system. The team has been involved with several testing campaigns, furthering their understanding of advanced heat pipes. The culmination of the year's efforts was in taking delivery of a flight VCHP and testing it, with the expectation of flight in 2022.

PRINCIPAL INVESTIGATOR: Will Johnson

PARTNER: Astrobotic

FUNDING ORGANIZATIONS: Early Career Initiative, Space Technology Mission Directorate (STMD)

TA17:

Guidance, Navigation, and Control

Lunar Node 1

OBJECTIVE: *To demonstrate autonomous navigation technologies to support lunar ascent, descent, surface, and orbital operations.*

PROJECT GOAL/DESCRIPTION

Lunar Node 1 (LN-1) is an S-band navigation beacon for lunar applications that was recently designed, built, and tested at NASA Marshall Space Flight Center (MSFC). As part of NASA's Commercial Lunar Payload Service initiative, this beacon, shown in figure 1, will be delivered to the Moon's surface on Intuitive Machines' NOVA-C lunar lander in early 2022.

FIGURE 1. LN-1 flight payload.

During this mission, LN-1 has the goal of demonstrating navigation technologies that can support local surface and orbital operations around the Moon, enabling a new autonomy capability that would decrease dependency on heavily utilized Earth-based assets like the Deep Space Network (DSN). An additional goal is to demonstrate and raise understanding of constraints, issues, and operational approaches to the management of lunar navigation aids from Earth.

To reach these goals, LN-1's design leverages CubeSat components as well as the Multi-spacecraft Autonomous Positioning System (MAPS) algorithms, which enable the autonomous spacecraft positioning through communication-integrated navigation measurements. In addition to demonstrating the MAPS payload, the radio will also be used in pseudo-noise (PN)-based one-way non-coherent ranging and Doppler tracking to provide alternate approaches and comparisons for navigation performance. LN-1 will represent a single node in a potentially greater MAPS network of assets aiding the development of lunar architectures. A representation of this network can be seen in figure 2.

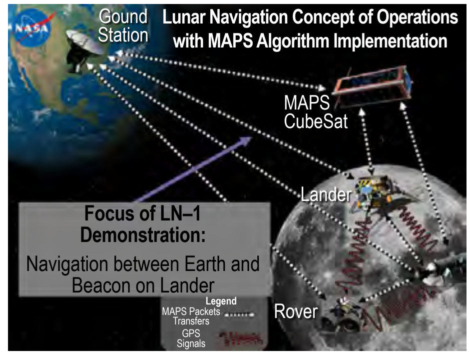

FIGURE 2. Lunar navigation concept of operations with MAPS algorithm implementation.

APPROACH/INNOVATION

LN-1 will need to demonstrate that its packets can be successfully received and processed to determine the payload state. To do this, over the course of the 7-day trans-lunar cruise and 13.5-day lunar surface operations, LN-1 will broadcast out its state and timing information back to Earth for several observation passes to the DSN. Upon reception of this data, high accuracy packet reception timestamps will be used (along with atmospheric data for induced delays) to assess a ranging observation. This data will be captured across multiple passes to compute a navigation state of the payload over the mission. In addition to demonstrating the MAPS payload, the radio will also be used in PN-based one-way non-coherent ranging and Doppler tracking to provide an alternate approach for navigation performance. In anticipation of next year's landing on the lunar surface, the team is also working to develop potential collaborations including cross-link demonstrations with potential Very Long Baseline Interferometry (VLBI) Earth-based observations. Further, the team is also working to bring additional ground stations online to get raw radio frequency (RF) observations to aid in development of one-way PN receivers.

An innovative aspect of LN-1 is that it provides a modular design made with commercial off-the-shelf (COTS) components that could be integrated into a variety of host vehicles and, with adequate power generation/storage, be able to offer long-term operation. Future host vehicles can include satellites, rovers, and landers that are part of a greater lunar architecture. In figure 1, which shows the flight payload, the compact size of the spacecraft can be identified. In terms of dimensions, the primary structure is approximately 175 × 220 × 300 cm in volume and ≈2.8 kg in mass. The dominating factor of the design is the large top surface, which is the spacecraft's radiator. To provide a clean interface with the host vehicle, LN-1 has designed a radiator to allow for heat dumping during operation. This is needed due to the hot environment on the lunar surface combined with the heat generated by the power draw of the radio while transmitting.

FIGURE 3. Evan Anzalone, LN-1's Principal Investigator (PI), performing the DSN – LN-1 compatibility testing.

RESULTS/ACCOMPLISHMENTS

After design and fabrication, LN-1 successfully completed all required environmental testing in 2021 at MSFC. This included electromagnetic interference testing, thermal vacuum testing, and vibration testing (qualification and acceptance). The completed payload was then delivered to Intuitive Machines in Houston, TX for integration into the NOVA-C lander and subsequent integrated environmental testing in late 2021.

With the payload delivered, the team also completed a variety of testing to ensure ground operations would be successful. First, there was the DSN – LN-1 RF compatibility testing performed at DSN's Development and Test Facility (DTF-21) in early 2021. These tests successfully verified RF compatibility between DSN and the LN-1 payload. Specifically, it was verified that DSN can receive S-band telecommunication signals in all the planned operational modes required to process telemetry and ranging data from LN-1. Downlink tests comprised of telemetry threshold data and ranging delay measurements. As part of this effort, engineers at DSN were able to implement a new capability to received one-way ranging signals using existing two-way ranging equipment that could lead to future enhanced DSN capabilities. This is the focus of the PN ranging approach of LN-1. Secondly, the team also completed data flow testing between DSN and MSFC's Huntsville Operations Support Center (HOSC). These tests verify this end-to-end data flow connectivity between the DSN and HOSC by testing firewalls and authentication methods with all three DSN locations. This ensures the LN-1 payload can be operated and data received by the LN-1 team at MSFC.

SUMMARY

Leveraging MAPS algorithms and COTS components, LN-1 will demonstrate innovative navigation autonomy on the lunar surface in a platform that is easily evolvable to future host vehicles. After a busy 2021 completing the required environmental and operational testing, the LN-1 team looks forward to demonstrating this platform in early 2022. This mission will allow the team to not only demonstrate the technology, but gather lessons learned to incorporate in future missions to build this growing architecture.

PRINCIPAL INVESTIGATOR: Evan Anzalone

PARTNER: Intuitive Machines

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Quantum Limits of Inertial Sensors

OBJECTIVE: *To improve the signal-to-noise ratio of optical gyroscopes and accelerometers by using a pair of ultrashort pulses circulating in a laser cavity, inreasing the sensitivity by introducing resonators in the laser cavity, and reducing the phase noise beyond the quantum limit applying quantum mechanical squeezing techniques.*

PROJECT GOAL/DESCRIPTION

Figure 1 illustrates a basic fiber (polarization-maintaining) accelerometer consisting of a linear cavity in which two pulses circulate. The device of figure 1 is an Optical Parametric Oscillator (OPO) pumped synchronously by a split frequency comb (green arrow, green loop) to create gain through the nonlinearity of the fiber for the two orthogonally polarized pulses (in red and green in the figure). Two frequency combs are extracted from the cavity (red curved lines) and made to interfere on detector Db. The combs have different optical frequencies, because they see different cavity lengths. The beat frequency Δv is equal to the product of the optical frequency v by the cavity length difference ΔL relative to the whole cavity length $\Delta v = v\Delta L/L$. We have demonstrated with a discrete components version of this OPO an uncertainty due to noise on Δv of less than 0.1 Hz, which translates into a sensitivity to displacement of less than 1 femtometer ($\Delta L = L\Delta v/v$). This extreme sensitivity, achieved without any electronic stabilization, was possible because the two frequency combs interfering on detector Db are correlated, being issued from the same gain medium and same cavity. The 0.1-Hz uncertainty in beat frequency is close to the quantum limit. Because in this device the two pulses evolve without coupling (as would be caused by scattering of one pulse into the other), it is possible to enhance the sensitivity without affecting the noise floor by using a Gires-Tournois resonator as end cavity mirror. Another approach sought is to reduce the phase noise (at the expense of the photon noise) by using squeezing techniques.

Our approach to the optical gyroscope is the same as that to the accelerometer, except that the OPO cavity is a ring instead of linear. The main difference

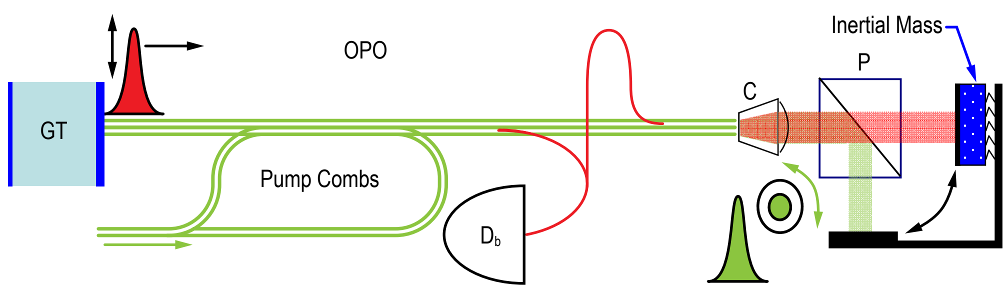

FIGURE 1. Accelerometer configuration with polarization preserving fibers. Two pulses (green and red) are circulated in the cavity. The horizontally polarized pulse (red) circulates in the straight cavity terminated by an inertial mass. The green pulse vertically polarized is deflected towards a reference mirror by the polarizing beam split- ter P. Because of the small difference in length (smaller than the wavelength) between the two cavities, the two pulse trains (frequency combs) emitted have slightly different frequencies, a difference detected as a "beat note" in detector Db upon which the pulses are made to interfere. C is a collimator. The device is an Optical Parametric Oscillator, pumped synchronously in either direction by a frequency comb (green arrow and green loop). GT is a Gires-Tournois interferometer (Fabry-Perot in reflection) used to enhance the response.

is that in the gyroscope, the beat note is due to the Sagnac phase shift/round-trip, which is proportional to the ring area. The fiber gyroscope can be expanded over a large area without a large increase in weight/volume. By contrast, the accelerometer response is inversely proportional to the dimension L, as shown above, and will therefore benefit from miniaturization.

APPROACH/INNOVATION

The innovations that we are bringing at this stage are:

- Demonstration of larger signal enhancement than noise increase through intracavity resonant dispersion, and the absence of coupling thanks to the use of ultrashort pulses.
- Detection sensitivity at the quantum limit.
- Detection sensitivity beyond the quantum limit through squeezing.

One main challenge is to identify and mitigate the sources of noise in the fiber OPO, in order to duplicate the performances of the discrete components OPO. A technical difficulty is the accurate control of fiber length without introducing mechanical delays outside of the fiber (synchronization pump-OPO; detection interferometer). In order to achieve signal enhancement by dispersion, the mode spacing of the resonant structure should by an exact multiple of the mode spacing of the cavity.

Squeezing techniques will first be applied on the model discrete component OPO which is closer to the quantum noise limit, while in parallel eliminating the classical noise limits of the fiber accelerometer and gyroscope.

There have been attempts to exploit so-called ‘exceptional points’ (EPs) to enhance the response of continuous-wave optical gyroscopes. Recent papers, including our own, have shown that the enhancement is dwarfed by the noise increase if the EP at the dead-band edge is used.

RESULTS/ACCOMPLISHMENTS

A discrete components Ti:sapphire pumped OPO was developed as a model laser to investigate the physics of signal enhancement and noise squeezing. The findings will be applied to a fiber OPO gyroscope that was also developed. One lesson learned in developing fiber lasers mode-locked with saturable absorbers is that the lifetime of the carbon nanotubes is not limited by the number of hours in operation, but by the number of times the laser is turned off/on.

SUMMARY

We have demonstrated that optical accelerometers and gyroscopes can be constructed with sources of dual, correlated frequency combs. The benefits of the short pulse operation is the absence of coupling between the pulses circulating in the cavity (no dead band), which implies also the possibility of beat note enhancement by resonant dispersion without a concomitant noise increase. It has further been demonstrated that the lessons learned with the model laser can be transposed to fiber technology. Fiber OPO’s have been constructed, and noise characteristics are being investigated.

PRINCIPAL INVESTIGATORS: Jean-Claude Diels, University of New Mexico; David D. Smith, Marshall Space Flight Center (MSFC)

PARTNER: University of New Mexico

FUNDING ORGANIZATION: Cooperative Agreement Notice (CAN)

Smart Video Guidance Sensor (SVGS)

OBJECTIVE: *A low volume, low power camera-based vision sensor that produces the relative position and orientation between an image acquisition subsystem and a known target for CubeSat-class missions.*

PROJECT GOAL/DESCRIPTION

Smart Video Guidance Sensor (SVGS) will be a low power, low mass camera-based vision sensor that produces the relative position and orientation between a camera and a known target configuration for CubeSat-class missions. SVGS comprises two subsystems – an image acquisition subsystem and a target subsystem. The target consists of LED markers in a specific configuration that is known to the image acquisition subsystem. The image acquisition subsystem images the target, performs image processing, and then feeds the image to the core photogrammetry engine. Since the target configuration is known, photogrammetry can be used to produce the relative position to the target as well as the relative orientation between the two systems. A camera-based vision sensor is applicable to a variety of use cases including Rendezvous, Proximity Operations, and Docking (RPOD); Entry, Descent, and Landing (EDL); lunar surface navigation, and Global Positioning System (GPS)-denied terrestrial navigation. SVGS is funded through the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program for FY21–22. The GCD development period seeks to increase the SVGS technology maturity level primarily for the RPOD use case.

The concept of operations for an RPOD application involves mounting the image acquisition on a 'chaser' spacecraft and the target subsystem on the target spacecraft. As the chaser spacecraft approaches the target spacecraft, the image acquisition subsystem images the target spacecraft and produces the relative position and orientation between the two spacecraft. This is then fed to the guidance and control system (external to SVGS), which will use the relative pose information to orient and position the two systems as dictated by the mission (e.g., perform a close approach for docking). The process by which SVGS determines the relative position and orientation between the chaser spacecraft and the target spacecraft is detailed in figure 1.

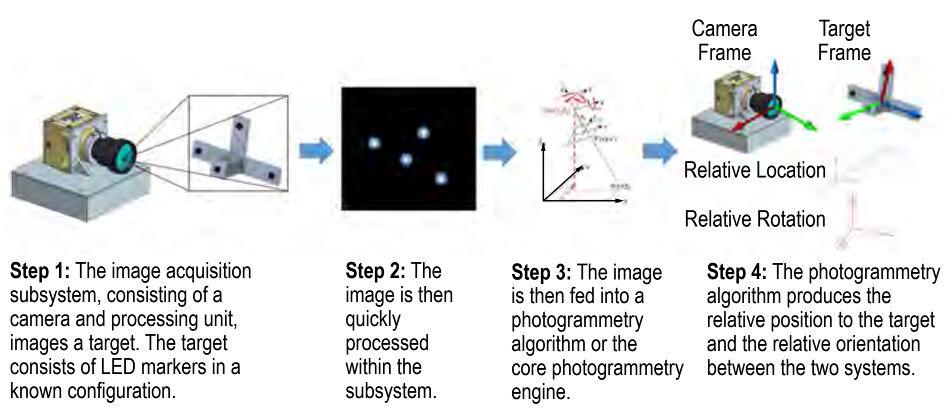

FIGURE 1. Diagram of Smart Video Guidance Sensor (SVGS) detailing the process by which it produces relative position and orientation between two spacecraft.

APPROACH/INNOVATION

The novelty in SVGS is the miniaturization and power reduction of existing video guidance sensor technology while maintaining accuracy requirements to meet mission needs. The project will mature this technology by developing an engineering development unit (EDU) produced with commercial off-the-shelf (COTS)/non-flight hardware and high-fidelity ground development unit (HF GDU) with robust, space-qualifiable hardware. The SVGS project will:

- Define the system architecture and requirements that support meeting performance requirements within power, mass, and volume allocations for operations in a space-like environment.
- Develop the image acquisition and correction subsystem through identification of key components for the camera and support equipment; design and implementation of camera software interfaces with main software; development of lens correction algorithm in software; integration and calibration of lens and camera; and test of lens correction algorithm with main software and hardware.
- Develop the processing subsystem through design of the advanced single board computer (SBC); fabrication of the SBC; and test of the SBC.
- Develop target subsystem through design and fabrication of the target hardware; design, fabrication, and test of the target processing board; development and integration of target functionality; and test of target subsystem.
- Perform functional testing of an integrated EDU to verify the algorithm and basic form, fit, and function. Identify requirements changes for the HF GDU.
- Implement design changes into the HF GDU. The HF GDU will utilize space-qualifiable hardware for critical components (e.g. camera, lens, etc). Perform functional testing of the HF GDU to increase maturity to a TRL 6.

RESULTS/ACCOMPLISHMENTS

A New Technology Report (NTR) was submitted for the SVGS technology. The NTR provides a means to capture technology improvements and innovations so that NASA can disseminate it appropriately.

The SVGS project has completed development of the SVGS software for use on the SBC using FreeRTOS, a real-time operating system. A breadboard unit has been developed and tested that utilizes the SVGS software, COTS lens, and SpectraCAM camera/vision system. The EDU SBC has been designed, fabricated, and assembled. The EDU SBC is undergoing troubleshooting and development testing. Design and fabrication of the target system is near completion. A lens correction algorithm has been developed and implemented with the EDU. Limited functional testing with the EDU is expected to occur during Q1-Q2 of FY22. Environmental test requirements have been developed and will influence the capabilities of the HF GDU.

SUMMARY

For FY21–22, SVGS will be maturing the technology for low-Earth orbit (LEO) and lunar/earth orbit Rendezvous, Proximity Operations, and Docking (RPOD) applications. Future applications include Entry, Descent, and Landing (EDL) and surface navigation between known targets (or systems) on the lunar surface. This technology could be adapted for deep space and the Martian surface. The SVGS technology is ideal for resource-constrained applications.

PROJECT MANAGER: Mallory Johnston

PRINCIPAL INVESTIGATOR: Ivan Bertaska

FUNDING ORGANIZATION: Game Changing Development (GCD) Program

INDEX BY FUNDING SOURCE

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Center Innovation Fund (CIF)

Center Strategic Development Steering Group (CSDSG)

Cooperative Agreement Notice (CAN)

Early Career Initiative (STMD)

Game Changing Development (GCD) Program

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14. ABSTRACT
Many of NASA's missions would not be possible if it were not for the investments made in research advancements and technology development efforts. The technologies developed at Marshall Space Flight Center contribute to NASA's strategic array of missions through technology development and accomplishments. This annual Research and Technology Report features brief write-ups from the scientists, researchers, and technologists of Marshall Space Flight Center who are working these enabling technology efforts, which are facilitating NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery.

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