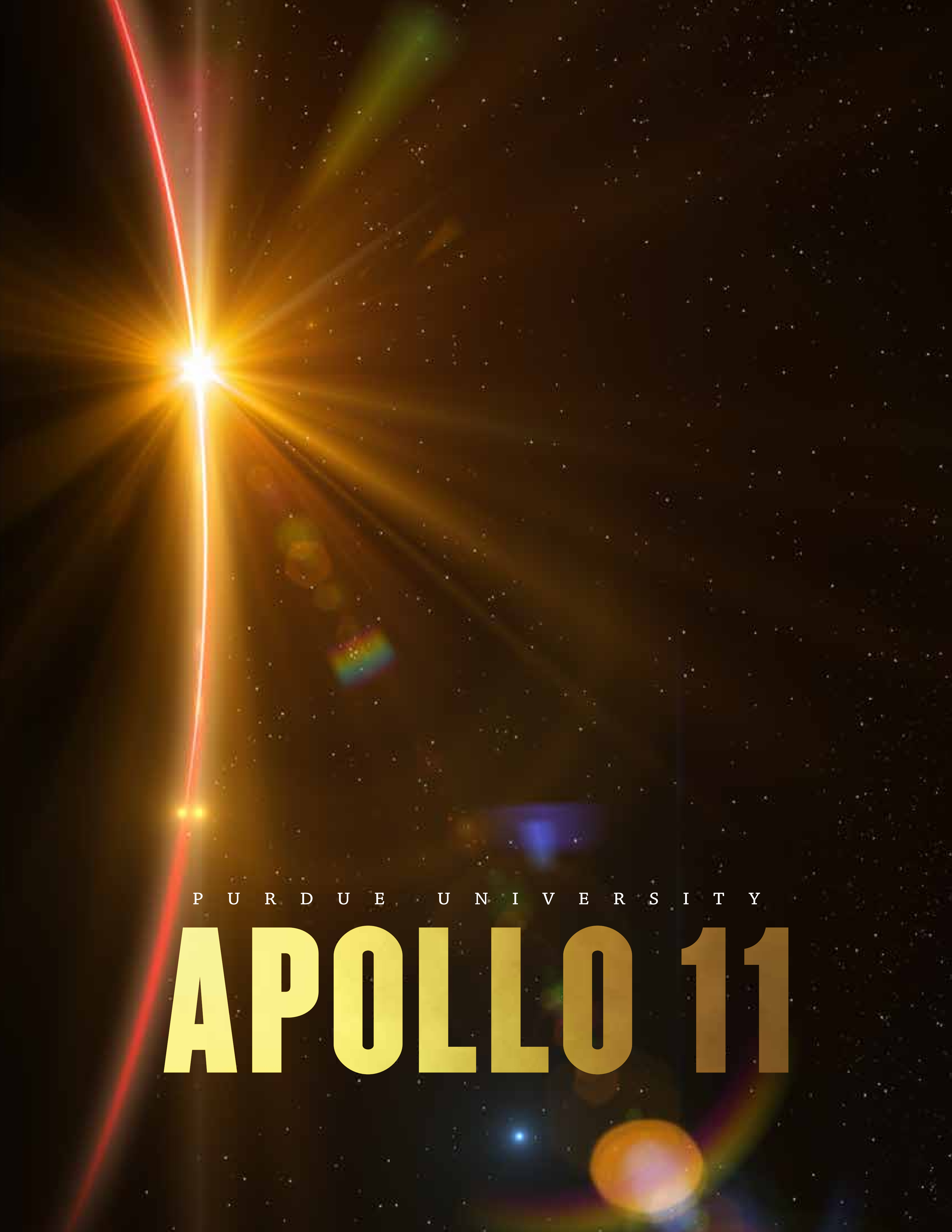


PURDUE UNIVERSITY

APOLLO 11

YESTERDAY AND TOMORROW

THE GOAL WAS AMBITIOUS. SOME THOUGHT IT IMPOSSIBLE.

President John F. Kennedy announced to Congress on May 25, 1961, that he wanted the United States to land a man on the Moon and safely return him to Earth by the end of the decade. He knew the prospective impact, saying, “No single space project in this period will be more impressive to mankind or more important for the long-range exploration of space, and none will be so difficult or expensive to accomplish.”

Three years earlier, the U.S. had initiated Project Mercury, the first human spaceflight program. It ultimately made six crewed flights from 1961 to 1963. Project Gemini began in 1961, sending 10 crews on missions in the two-man Gemini spacecraft in 1965 and 1966.

The Mercury program proved NASA could safely fly in space, and Gemini proved astronauts could spend days in space, work outside the spacecraft and connect to other spacecraft in orbit, before returning home.

Those missions set the stage for Apollo, a program with an ultimate goal to land an American on the Moon and bring him safely back to Earth.

Photos by Rebecca Wilcox, John Underwood and iStock

ON JULY 20, 1969, THAT MISSION WAS ACCOMPLISHED. NEIL ARMSTRONG BECAME THE FIRST HUMAN TO STEP FOOT ON THE LUNAR SURFACE.

Armstrong left his indelible footprint 14 years after he graduated with a degree in aeronautical engineering from Purdue, a university that provided the technical education he needed to achieve his giant leap and the socially enriching environment that led him to cherish his years at Purdue and give his enthusiastic support for the University until his death in 2012.

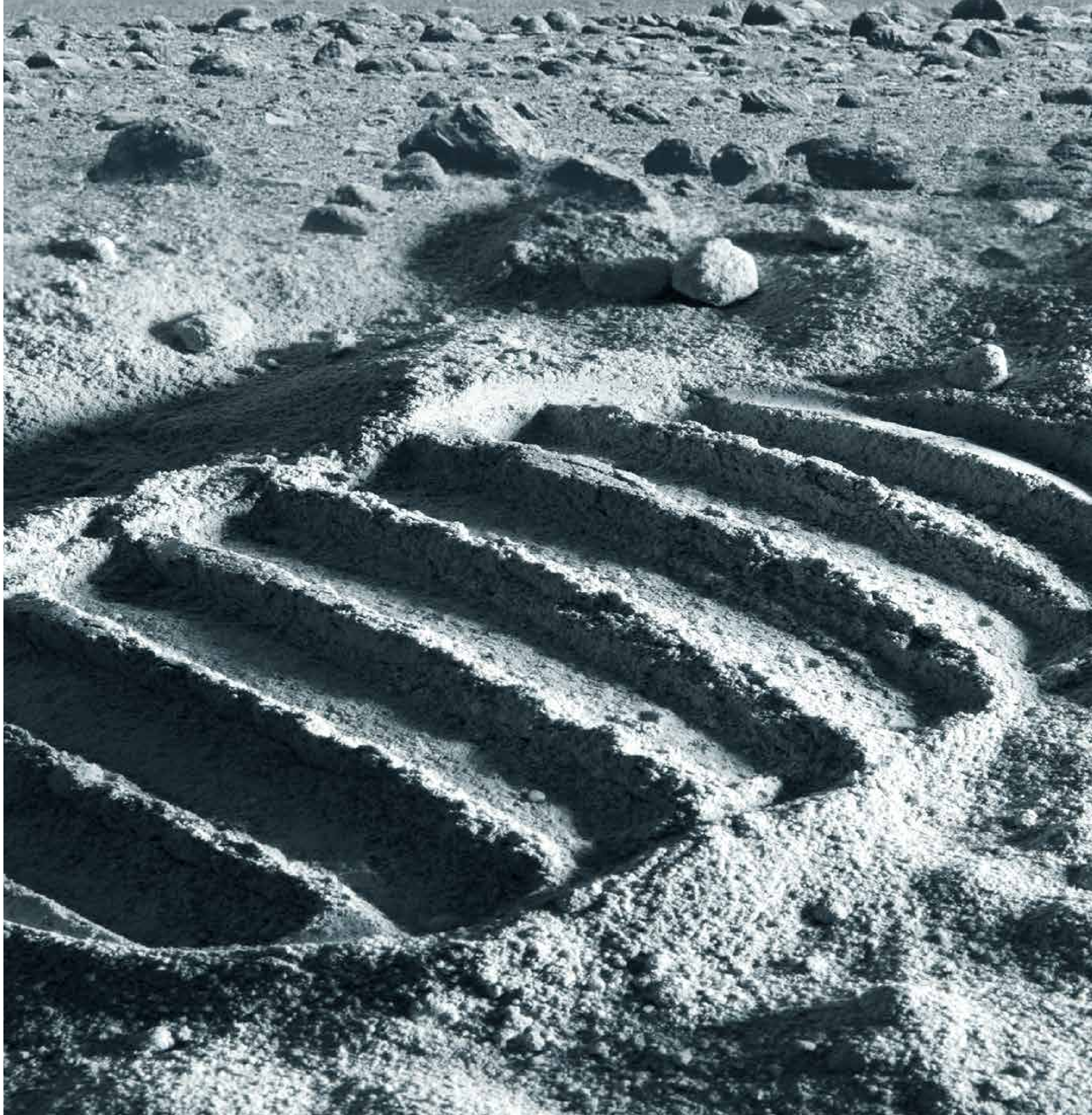
In 2019, Purdue celebrated the 50th anniversary of Apollo 11, Armstrong's considerable role in the mission, and the permanent mark he made on Purdue.

Purdue and the School of Aeronautics and Astronautics played key, behind-the-scenes roles in the initial Moon landing — an auspicious beginning.

Today we also celebrate the considerable role AAE must play in the future of space exploration. Our faculty and students are ambitiously pursuing groundbreaking research to help in NASA's mission to return humans to the Moon by 2024, and contribute to missions well beyond. They are world renowned in small satellite engineering, propulsion, mission design, materials, navigation and control, space situational awareness, autonomy, remote sensing and system-of-systems, leveraging unique laboratories and test facilities.

Our alumni populate the most innovative commercial companies, executing on dreams first dreamed in our school. They have established a significant presence at NASA in some of highest positions and in all areas of aerospace engineering.

As President Kennedy so aptly said in 1962 during a speech at Rice University in Houston, we all are serving "to organize and measure the best of our energies and skills" to achieve future missions that are chosen "because they are hard."



T-MINUS 15

ALINA ALEXEENKO
Professor of
Aeronautics and Astronautics

THE BIG CHALLENGE TO BE SMALL

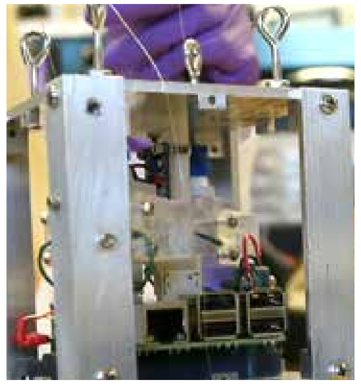
As spacecraft become ubiquitous, smaller and are used in large constellations — or in swarms of tens to hundreds of satellites — they will need to maintain precise orientation and be maneuverable. Precise pointing and maneuverability of satellites, especially the small ones that have very restricted volume and power, is the goal of our work.

Typically, we add maneuverability to a spacecraft with a propulsion system that provides momentum or delta-V. Various types of in-space propulsion technologies have been developed over time for larger satellites, but there are fundamental limits on how small one can make them without losing efficiency. Contamination can be a severe problem for small satellites, requiring careful propellant selection to avoid damaging the spacecraft. We are currently working on a new micropropulsion technology that exploits unconventional small-scale physics and uses water, a very common and benign propellant.

We know we cannot solve this issue by scaling down existing propulsion technologies. Just making good things smaller typically creates problems, or makes them stop working altogether. Our research team is examining beneficial effects of miniaturization and we have brainstormed a few concepts with Professor Stephen Heister. One of those interesting technologies is a thermal inkjet printer, which manipulates surface tension by local superheating of liquid to produce small, precise droplets of ink. Inkjet printers, of course, wouldn't work in a vacuum and would be difficult to pack in a CubeSat, but it was an inspiration.

We have begun to develop Film-Evaporation Mems Tunable Array (FEMTA) micropropulsion technology for picosats. FEMTA combines microscale physics of surface tension and solid/liquid/vapor heat transfer and flow into vacuum and microfabrication techniques originally developed for semiconductor manufacturing. First, we worked on a mesoscale proof-of-concept experiment using antifreeze and a wire heater and tested it in rough vacuum. We then teamed up with engineers from NASA's Goddard Space Flight Center and got funding from the NASA SmallSat Technology Partnership to develop microthrusters with ultra-pure water as the propellant.

We've learned a lot from working with the team at Goddard and have developed the first MEMS process for FEMTA thrusters. We also developed a tunable thrust demonstration on a micro-Newton thrust stand in high vacuum and an integrated compact system with four thrusters on a 1U CubeSat. Currently, we are working on a spaceflight test after being selected for a suborbital flight opportunity through the 2018 NASA REDDI. We are involving a lot of bright undergraduate students as a means of solving this issue. AAE and computer science undergrads have been contributing to the development of FEMTA technology every semester, and many of them are now working on spacecraft technologies in graduate school, NASA and industry.



Film-Evaporation MEMS Tunable Array is a concept that combines microscale physics of surface tension and solid/liquid/vapor heat transfer and microfabrication techniques that have been developed for semiconductor manufacturing. (Erin Easterling/Purdue University)

T-MINUS 14

APOLLO 11

STEVEN COLLICOTT
Professor of
Aeronautics and Astronautics

THE QUEST FOR A SATELLITE GAS GAUGE

How much liquid rocket fuel remains in the fuel tank of a communications satellite orbiting 23,000 miles above the Earth? Answering that question is far more challenging than placing an inexpensive device inside a fuel tank, as we do with automobiles — especially with the precision desired by satellite owners and operators.

My research in low-gravity fluid dynamics addresses this and other relevant questions about the use of liquids in spaceflight.

I'm a leader in numerical modeling of important capillary fluid physics during spaceflight. These liquids show seemingly bizarre positioning and movements in propellant tanks in flight. Applying fundamental research in capillary fluid physics to practical spaceflight hardware is necessary to continue advancing spaceflight capabilities for both commerce and exploration.

Diverse studies of liquids in spaceflight have multibillion-dollar impact, such as propellant gauging in satellites. Others include managing liquid helium in the Gravity Probe-B spacecraft, experiments launched to the International Space Station and even research to facilitate emergency medical procedures in long-duration spaceflight. The numerical modeling performed for spaceflight fluids studies also has applications on Earth for design of microdevices that use liquids in their miniature channels where the effects of surface tension can overwhelm the effects of gravity.

My experiments with liquid and gas together in zero gravity cannot be done in a traditional laboratory. They require the same physical environment as being in orbit. Fortunately, this environment can be accessed frequently for quick experiments in a drop tower. In addition, weightlessness in parabolic aircraft flights and commercial reusable suborbital rocket flights are available about four times a year.

Because we lead the world in revolutionary new capabilities of the emerging reusable suborbital industry for both research and education, we already have flown more than 10 original experiments on new commercial rockets. Future experimental suborbital flights also are planned.

Purdue also is under contract with NASA to support an upcoming orbital technology demonstration of the Radio Frequency Mass Gauge (RFMG) instrument. RFMG is poised to become one of the primary low-g gauging methods for long-duration human space exploration missions that will depend on rapid, repeatable cryogenic propellant gauging. Accurate modeling of the low-gravity fluid configuration will correlate data from both the RFMG and the wet-dry sensor rake data, providing a more accurate comparison of fluid quantity from the combined technologies. Future customers for RFMG technology could include all cryogenic in-space vehicles and upper stages in NASA, industry, and military spaceflight as well as future cryogenic propellant depots and transfer systems.

This fluids experiment produced benchmark zero-gravity data to verify a Surface Evolver model of low-gravity fluid configurations inside a cryogenic tank experiment in orbit. This modeling by Purdue University under contract with NASA provides new fluid physics knowledge to support the Radio Frequency Mass Gauge (RFMG) instrument technology demonstration in the International Space Station.

T-MINUS 13

APOLLO 11

WILLIAM CROSSLEY
J. William Uhrig and Anastasia Vournas
Head of the School of Aeronautics and
Astronautics and Professor of
Aeronautics and Astronautics

DESIGNING FOR UNFORESEEN CHANGE

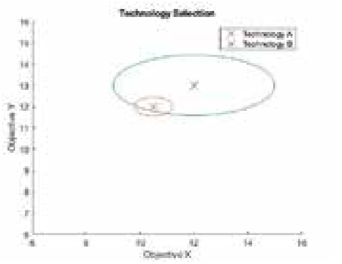
Spacecraft design involves multiple disciplines. Key disciplines include propulsion, structures, trajectory design, power, etc. Spacecraft face cost, schedule, safety and reliability constraints. Long development time often means that technologies considered for the spacecraft, stakeholder requirements and governmental policies can change from when the team begins generating spacecraft concepts to when the spacecraft starts its mission.

In the Aerospace Systems Design Analysis and Optimization lab, we investigate, develop and use methods to improve aerospace systems design. We are asking: “How can methods for multi-objective optimization and design under uncertainty provide spacecraft design teams with decision-making support that satisfies changeable requirements during the development process — while also keeping the spacecraft design technologically competitive?”

Typical spacecraft design begins with a set of specific mission requirements. Engineers then begin designing a concept to meet these requirements. Motivated by the desire to minimize impact to program cost, schedule or mission success, often the design team starts with an existing spacecraft design and performs trade studies by making incremental changes to that existing design. This approach, although effective at generating designs that meet original requirements, is slow to disrupt the frontier of spacecraft technology development. This approach also risks missing out on exploring more promising concepts because the number of options and decisions available exceeds what members of the team can easily consider. Using design optimization allows the computer to coordinate how to make changes in a large number of design variables while meeting a set of requirements and balancing a set of objectives.

If stakeholder needs were static, meeting the original requirements would suffice for mission success. However, more than ever, spacecraft today have much longer operational lifetimes — often operating beyond their mission life. Stakeholder demands have become more dynamic, and they demand more flexibility from their assets. In contrast with the desire to minimize program risk mentioned above, a company developing a new spacecraft may need to select technology for a spacecraft design before that technology is fully mature. This provides a potential competitive advantage for the proposed design.

Our research group is examining how multi-objective optimization applied to spacecraft design can provide a better picture of the design space, handle a mixture of continuous and discrete variables, and also account for uncertainty in technology performance and in stakeholder requirements. Envisioned outcomes of this work include ways to visualize the likelihood that one technology choice might provide better performance than another.



Technology A is more mature than Technology B, so B has a wider range of possible performance on the competing objectives. There is a small chance the design with B will be notably better on Objective X. With this kind of information, a design team can begin to weigh the issues associated with the cost of maturing B to realize this potential improvement in X.

T-MINUS 12

APOLLO 11

DANIEL DELAURENTIS
Professor of
Aeronautics and Astronautics

THE GREATEST OF ALL AEROSPACE CHALLENGES

My research team and I are working to answer the question: How do we comprehensively define and systematically solve the grandest, most complex mission challenges in aerospace and beyond?

There is no better example of such a challenge than the quest to explore the Moon, Mars and beyond with sustained human presence. These grand challenges require far more than just the amalgamation of many different technological innovations. They require a means to scientifically identify and integrate the right technological innovations, policies and incentives to realize our full potential. It is truly a complex design problem. Our success or failure has huge implications, both in space and here on Earth.

Our research group has adopted the aspirational concept of "system of systems," (SoS), to anchor our efforts. Contrasted to a mere amalgamation of components, an SoS is a collective whose ideal architecture reflects the operational and managerial independence of each component while enabling them all to interact naturally to produce desired mission outcomes unique to the integrated whole.

We have forged innovations in advanced computer modeling and simulation, adapted the mathematics of network theory, and created methods for novel aerospace system design to uncover such ideal architectures in the midst of massive complexity and uncertainty. In partnership with NASA, our SoS methodologies are informing real decisions necessary to establish robust portfolios of systems and technologies — and the system-of-system architecture that integrates them. That architecture achieves lunar exploration goals that can be evolved to support other grand destinations like Mars. Key aspects of the analytics we are advancing now were pioneered with our work with the Jet Propulsion Laboratory and Purdue Professor Barrett Caldwell. That work substantiated how we should design lunar command, control, and communication operations in the presence of human and robotic systems.

I remain inspired by the magnificent accomplishment of Apollo 11, but also sober to the knowledge that the missions before us are even more complex. Future missions will require intellectual innovations and a renewed unity of effort. A growing cadre of system-of-systems thinkers and doers skilled in critical thinking and problem solving is key to rise to this challenge, and is the ultimate desired outcome of my efforts in AAE at Purdue University.

Cesare Guariniello and his team use system-of-systems tools to determine what happens in large and complex space networks like the one depicted here. The goal is to capture the big picture without losing any details.

T-MINUS 11

APOLLO 11

CAROLIN FRUEH
Assistant Professor of
Aeronautics and Astronautics

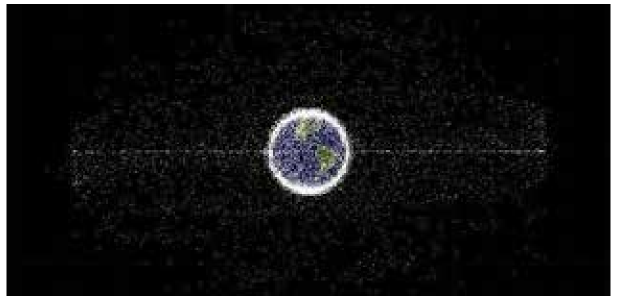
CONSTRUCTING SUSTAINABLE SPACE

The near-Earth region has undergone dramatic change since the launch of the first satellite, Sputnik. Many everyday services, such as weather forecasting, communications and GPS, rely on satellites. At the same time, human space activity has led to a significant amount of space debris. Currently about 23,000 space-debris objects are catalogued, and the actual number of all human-made, Earth-orbiting objects larger than 1 centimeter is over 100,000.

I work on space situational awareness (SSA), space traffic management (STM) and onboard optical satellite navigation. Optical navigation involves autonomous, onboard determination of position, velocity and attitude of a satellite in orbit. We use the stellar background, far-field or near-field images of stellar objects for onboard autonomous navigation solutions. One research study includes the development of efficient low-cost star-tracker solutions in the highly computationally constrained onboard environment. SSA and STM aim to fully know, understand and regulate all objects in the near-Earth realm and beyond, with the ultimate goal being the sustainable use of near-Earth space and beyond.

Our active research in SSA and STM uses the Purdue Optical Ground Station (POGS) to collect measurements. POGS, which is located in New Mexico, is controlled remotely. Our ongoing work involves the fully automated use of sensor networks. This first involves image processing, after which we find efficient methods for a first-orbit determination when no a priori knowledge on the object is available and only a short set of observations (one tracklet) is available. We develop new methods in multitarget tracking to track objects and determine which observations belong to which object in the presence of clutter in an astrodynamics-driven approach. The objects' orbits, and the predictions and descriptions of their associated uncertainties, form the basis for our methods of collision avoidance. Collision avoidance requires the timely and reliable prediction of objects that are in danger of colliding so collision avoidance maneuvers can be developed. All of this research involves concepts of astrodynamics, information theory, finite set statistics, neural networks and machine learning.

Objects' orbits and additional characterization information, such as shape, attitude and materials, are paramount in identifying them, their origins and capabilities. Characterization information also is key for active space-debris removal and close approaches. Our current work is focused on using light curves — a series of brightness measurements over time — with new methods to solve this severely under-determined inversion problem. We also are going further to combine characterization and orbital information, a research thrust to judge intent of the objects and find automatic, autonomous grouping of objects as space debris or different classes of active objects. Current research partners are the Department of Defense, NASA, international space agencies and private industry.



Current cataloged human-made space object population in the near-Earth space.
(Credit: Nathan Houtz and Carolin Frueh)

T-MINUS 10

APOLLO 11

JAMES GARRISON
Professor of
Aeronautics and Astronautics

PURSUING SIGNALS OF OPPORTUNITY

Space provides a unique viewpoint from which to monitor and manage essential natural processes and human activities on Earth. Concerns about food and resource production, hazardous weather, climate change, access to clean water, and military activities, including the development of weapons of mass distribution, are all critical today. Satellites allow us to uniformly observe any location on Earth, unconstrained by inaccessible geography or political boundaries.

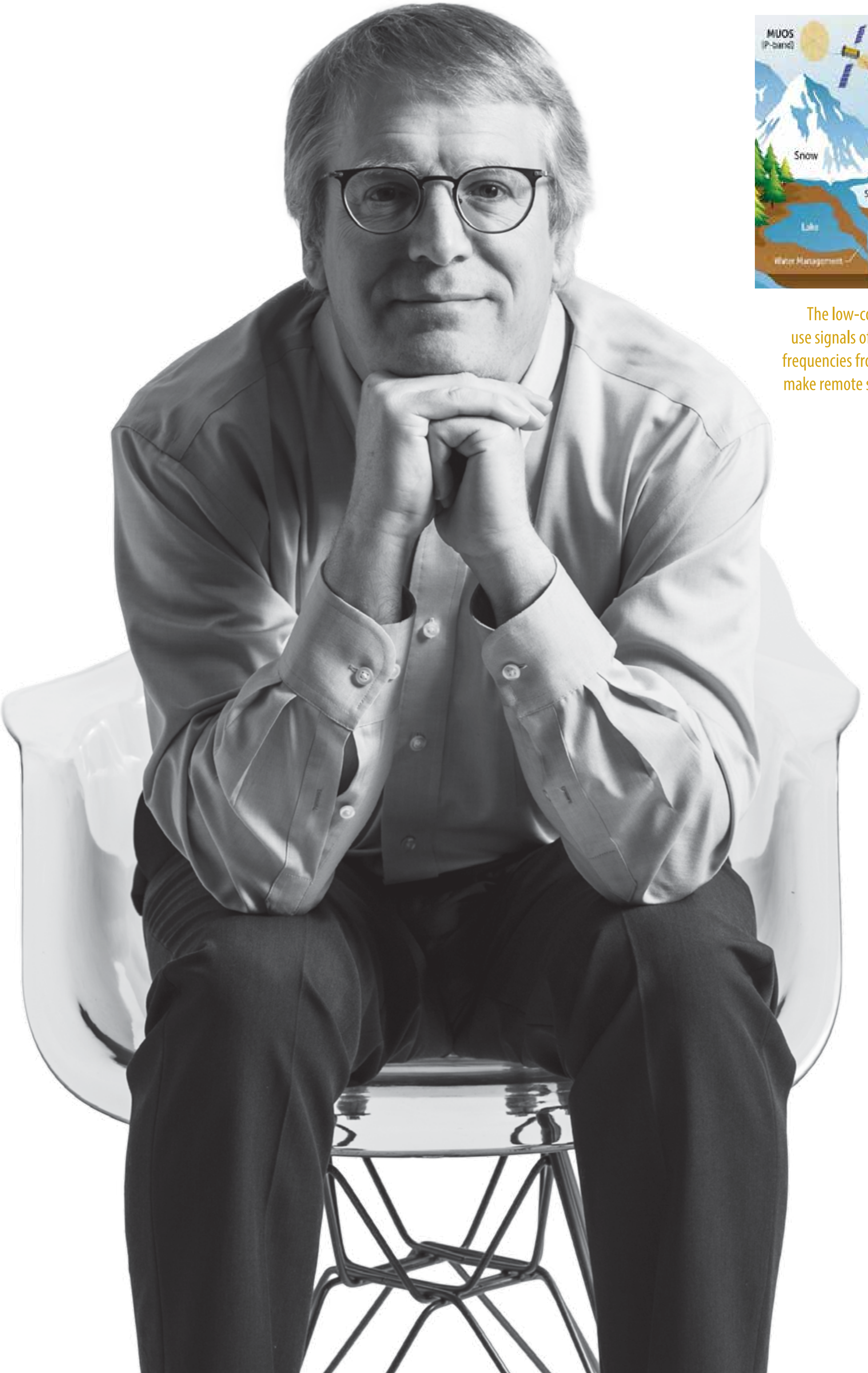
All of these observations use electromagnetic radiation within one of only two very narrow “windows” for which the atmosphere is mostly transparent. The optical window, containing visible light, is familiar to anyone who has seen the stars, planets or moon at night. That everyday experience also illustrates the key limitation of the optical window — clouds.

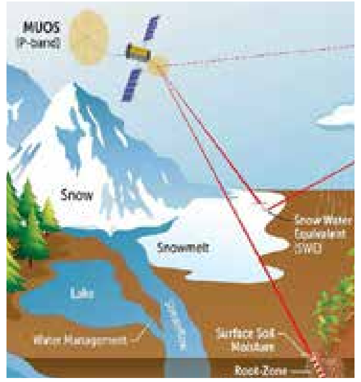
The other atmospheric window is that of radio waves, or more precisely microwaves with wavelengths between a centimeter and a few meters. Microwaves can penetrate clouds and are much less susceptible to atmospheric variation. The challenge in using microwaves, however, is the competing use of radio frequencies for other services, notably communications. Using conventional methods, just a few microwave bands are protected for scientific or Earth-observation use and interference within them from other transmissions is a severe problem, degrading the quality and utility of the data at certain times and over certain geographical areas. This interference makes the optimal microwave frequency completely unusable for some measurements,.

My research seeks to get around this problem by essentially reusing existing powerful communication transmissions, extracting information from these signals as they pass through the atmosphere and scatter from the Earth’s surface. This approach, now known as “Signals of Opportunity” (SoOp), now allows measurements to be made in many frequencies that had previously been unavailable for scientific use. I began basic research in this area over 20 years ago, starting with Global Positioning System signals.

That research eventually led to the NASA-funded Cyclone Global Navigation Satellite System (CYGNSS) constellation to observe tropical cyclone development with a revisit time of a few hours. CYGNSS was proposed to improve hurricane forecasts through increased sampling of the wind field during the storm’s rapid intensification. More recently, I have demonstrated SoOp measurements of subsurface, root-zone soil moisture, ocean wind fields, and sea-surface height in various experiments on aircraft and towers. As a result of these demonstrations, I was selected to be principal investigator for the NASA CubeSat mission called SNoOPI, SigNals of Opportunity P-band Investigation. This mission will demonstrate the feasibility of root-zone soil moisture measurement from space using SoOp.

These are exciting times in Earth observation, with many new missions being planned. Some will be managed by private companies, some will involve constellations of small satellites, and many will employ new technologies, including SoOp.





The low-cost SNoOPI CubeSat will use signals of opportunity in P-band frequencies from orbiting satellites to make remote sensing measurements.

T-MINUS 09

APOLLO 11

REVVING UP ENGINE ADVANCEMENT

There have been precious few advances in the performance of rocket engines since the development of the mighty F-1 engine that powered Neil Armstrong and other astronauts to the Moon five decades ago. During the 1980s, the Soviet Union advanced hydrocarbon engine technology with the RD-180 engines that now power the Atlas V launch vehicles and take astronauts to the International Space Station. Regrettably, there has been little advancement in engine technology since this time. My research group is working to advance space launch propulsion with a whole new class of combustors based on rotating detonations.

Rather than using a cylindrical combustion chamber, we use an annular chamber. Under the right injection conditions, hydrodynamic instabilities developed in this topology lead to the formation of powerful detonation waves that consume propellants roughly 10 times faster than in a conventional engine. This rapid combustion not only reduces chamber volumes — and, hence, weight — but also provides thermodynamic advantages via combustion at the very high pressures and temperatures behind the detonation wave that traverses the chamber annulus at speeds in excess of 1,000 meters per second. This thermodynamic advantage can also translate to enhanced thrust, and my group is working feverishly to prove that this theoretical improvement can actually be attained at high pressure rocket combustion conditions. We are working with gaseous and liquid propellants that are directly applicable to use in today's or future launch vehicles. Current testing employs gaseous oxygen, produced in a preburner such as that employed in the RD-180 engine. This fluid is combusted with liquid kerosene injected through a number of radial channels feeding into the detonation annulus. An amazing blue plume is formed from the detonative combustion, drastically different than orange/yellow plumes typically formed by kerosene combustion in today's engines.

Our group also is working on concepts in which both fuel and oxidizer are injected into the annular combustor as liquids. Combining liquid propellants, such as liquid oxygen, with fuels like cryogenic liquid methane or kerosene, creates the potential for detonations to occur in the liquid or "condensed" phase. These physics create powerful explosions that the rocket propulsion community has not yet studied. The Air Force is supporting our group in its development of technology for future launch and space propulsion systems. Soon, we hope to have more efficient engines for space travel.

STEPHEN HEISTER
Raisbeck Engineering
Distinguished Professor for
Engineering and Technology Integration

This gaseous oxygen/kerosene high pressure rotating detonation combustor is currently under study at the Maurice J. Zucrow Laboratories.

T-MINUS 08

KATHLEEN HOWELL
Hsu Lo Distinguished Professor of
Aeronautics and Astronautics

BUILDING CISLUNAR AVENUES

I have long maintained a technical research focus on astrodynamics in complex gravitational environments. My methodologies have been used successfully in numerous NASA missions in various space regimes. From proposals for planet finders around other suns to the Genesis sample-return of solar wind particles, innovative spacecraft trajectories have enabled new concepts for science returns.

Now, 50 years after the historic Apollo landing on the Moon, the international community is poised to begin a new chapter in cislunar space development and solar system exploration. NASA is moving forward with Gateway, an orbiting platform near the Moon. Gateway is intended to be a proving ground for deep space technologies and a staging location for missions throughout and beyond cislunar space.

To support these initiatives, my team has been constructing pathways through the cislunar region for many years, including early analysis for the Themis/Artemis mission in 2010 — the first spacecraft to leverage nontraditional, multibody transfers in the Earth-Moon region. In fact, the baseline trajectory for Gateway is also a multibody orbit denoted by a near-rectilinear halo orbit (NRHO). NRHOs provide a stable location for the Gateway spacecraft, reasonable station-keeping costs in the primary orbit and an opportunity to move the spacecraft to other destinations in cislunar space for flexibility in support of other goals, such as eventual missions to Mars.

NRHOs near the Moon serve as potential long-term orbits for a crewed vehicle in the cislunar region because they offer advantages such as relatively inexpensive transfer options from the Earth, feasible transfer options to the lunar surface and other orbits in cislunar space and beyond, as well as advantageous eclipsing properties. Current research activities include further concepts for rendezvous in support of the vehicles that transfer between Gateway and low lunar orbits well as the lunar surface.

The mission architecture for Gateway includes multiple hardware components, not all of which are crewed. Thus, an important research direction in this regime are pathways and transfers for components with low-thrust engines. The techniques to produce these very new types of trajectories are critical to the success of the concept, and graduate students are actively engaged in these efforts. In the long term, of course, moving throughout cislunar space, essentially a transportation network, is a required capability in this space regime, and is in development. As part of this network, our team also is seeking links such that Gateway also can serve as a hub for translunar destinations, such as Mars. As a resource, the Rune and Barbara Eliasen Visualization Laboratory is an important component in constructing and assessing the trajectories for all the various research directions. The team's efforts are pivotal in delivering functions to render Gateway as an adaptable infrastructure with resilient systems, a base for transportation to and from the surface of the Moon, an interface for commercial vehicles engaged in various activities near the Moon, and as a proving ground for deep space missions.

A Purdue graduate student from Kathleen Howell's research group views the paths of two Themis/Artemis spacecraft moving in cislunar space from Earth orbit to lunar orbit using minimal propellant.

T-MINUS 07

APOLLO 11

INSEOK HWANG
Professor of
Aeronautics and Astronautics

INTELLIGENT SYSTEMS GET SMARTER

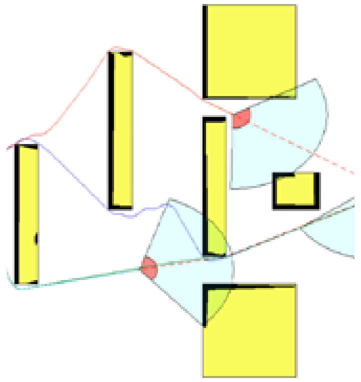
My Flight Dynamics and Control/Hybrid Systems Lab is working on developing intelligent and high-assurance autonomy for cyber-physical systems. These systems involve complex interactions between cyber (or logical) elements and physical components in the presence of uncertainty. Aerospace systems are a good example.

Imagine a Mars exploration mission using an autonomous unmanned rover that has onboard computers (cyber elements) that can perceive unknown environments (uncertainty) using various sensors. Its computers make decisions on where to go and what to do (logical components), and drive the rover (physical component) to a desired location to accomplish the mission. Due to recent rapid advances in computing, sensing and communication technologies, modern aerospace systems are becoming increasingly complex, and their requirements more stringent than those of conventional and successful system models and control tools — such as those illustrated in the above Mars mission.

My research develops modeling, analysis, and control methodologies and theory, for aerospace systems composed of multiple vehicles (e.g., formation flying of spacecraft and multiple space robots cooperation). These methodologies can collectively understand dynamically changing environments using information from a suite of heterogeneous sensors. In addition, they can autonomously operate together to achieve given goals with guaranteed safety and security.

My research also focuses on space situational awareness (SSA). As space has become highly congested by objects, SSA has become crucial for the safe operation of space assets. One of the challenging tasks in SSA is the surveillance and tracking of spacecraft that can maneuver to perform space missions. SSA tracking is essential to accurately predict the trajectories of maneuvering spacecraft, and keep adjacent spacecraft safe.

The accurate tracking of impulsively maneuvering spacecraft is a challenging problem because the magnitude and timing of impulsive maneuvers are usually unknown. To deal with this problem, I have developed tracking algorithms to account for the motion of spacecraft with and without impulsive maneuvers. By explicitly accounting for the fact that impulsive maneuvers usually occur during certain specific conditions of the spacecraft, the tracking algorithms can predict the impulsive maneuvers more accurately and track the spacecraft more precisely. In addition, due to the advent of new propulsion systems, such as low-thrust engines (e.g., ion engines) for spacecraft, the trajectory characteristics of such spacecraft are much different from those of conventional spacecraft using chemical propulsion systems. For example, the trajectory of a spacecraft with a low-thrust engine may not be a Keplerian orbit that conventional spacecraft follow. This knowledge opens new areas of research in space applications. I have developed theory and algorithms to address challenging problems, such as non-Keplerian satellite tracking and spacecraft maneuver detection and characterization. I am also working with a simulation testbed in which various types of spacecraft can perform a wide range of missions in a realistic space environment.



Autonomous unmanned vehicles (in red) perceive unknown environments using sensors (the sensors' ranges are shown in blue). The vehicles safely navigate around the yellow obstacles to accomplish their mission at a desired location.

T-MINUS 06

APOLLO

11

TIMOTHÉE POURPOINT
Professor of
Aeronautics and Astronautics

EFFICIENT, SAFER IGNITION IN SPACE AND ON MARS

Since starting my PhD work in 2001, my propulsion research has focused on the ignition and combustion of chemical rocket propellants with an emphasis on hypergolic propellants. Hypergolic propellants ignite very quickly after contact without the need for external ignition. The reactions between liquid hypergolic propellants are so rapid that ignition typically happens in less than 3 milliseconds after contact. That is about 100 times faster than the blink of an eye. Such reaction speeds mean that liquid hypergolic propellants can be ignited and shut down hundreds of times per second. This provides very precise control of spacecraft, whether on orbit as countless spacecraft currently do, or to land on or take off from the Moon, as the Apollo program demonstrated. It also has been used to approach and dock to the Space Station by the Space Shuttle for several decades, and will be used on upcoming missions involving U.S. and international space agencies and a number of commercial partners.

In a particularly exciting NASA-sponsored research project, my students and I have been working with the Jet Propulsion Laboratory in Pasadena, California, and the Marshall Space Flight Center in Huntsville, Alabama, on the design of a hypergolic propulsion system for a potential mission to Mars — the Mars Ascent Vehicle. If selected by NASA, the Mars Ascent Vehicle will be part of a large Mars Sample Return effort with the ultimate goal of bringing samples from Mars back to Earth. Our work could result in a Purdue-developed propellant technology on the surface of Mars. With Mars samples reliably back on Earth thanks in part to that Purdue technology, a new chapter in our understanding of the solar system could be written.

The conditions on Mars pose a number of engineering challenges for the Mars Ascent Vehicle. The chilly temperatures (often below minus 40°F) and low pressures, equivalent to the pressure at about 100,000 feet above Earth's surface, are particularly challenging and call for new ideas to ensure mission success. Among these new ideas, my team and I are evaluating solid hypergolic fuels as opposed to conventional liquid hypergolic fuels. This change from liquid to solid fuel prevents fuel-freezing issues in the extreme cold on Mars, and improves safety significantly by removing fuel-spilling concerns and dramatically reducing toxicity risks.

In the past year, our team showed that when it reacts with a low-temperature compatible oxidizer, a mixture of sodium amide and potassium bis(trimethylsilyl)amide added to a common fuel binder can provide the impetus necessary to ignite and combust a much larger propulsion system. During the coming months, we intend to demonstrate the same ignition and stable combustion in my altitude chamber at the ambient pressure expected at the surface of Mars.

Timothée Pourpoint and his team use hypergolic fuels to ignite and combust this hybrid rocket motor.

T-MINUS 05

MICHAEL SANGID
Elmer F. Bruhn Associate Professor of
Aeronautics and Astronautics,

TWINNING IN SPACE

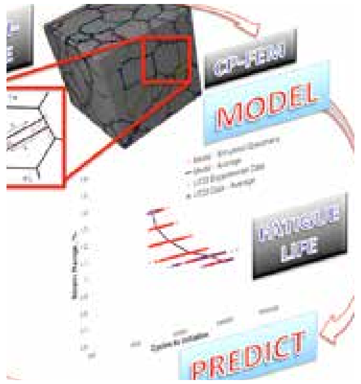
Lengthy space missions, such as the human journey to Mars, or permanent space outposts like the International Space Station, require new materials, manufacturing processes and continuous reliability assessment methods. My group is working on two such efforts, qualification of the safety and durability of materials produced by additive manufacturing, and advanced state awareness and prognosis efforts enabled by the concept of the digital twin.

Additive manufacturing (AM), or 3D printing, is the layer-by-layer creation of a material. We particularly focus on engineering structural metal alloys. AM technology has been touted as a game-changer because it can build complex shapes. For space applications, AM can solve challenging transportation issues because only an AM system and feedstock needs to be sent to space when structures are needed on demand, instead of sending structures into space after they're built on Earth. However, despite all the accolades, the structural soundness, reliability and durability of AM structures remain in question. Typically, answers would require expensive and time-intensive testing.

My research group is working on simulation-based strategies to rapidly qualify AM materials. The premise identifies unique defects and features at the micron and submicron scales — the microstructure — that are inherent to AM materials. Many sets of simulations are then created based on different microstructure combinations that faithfully represent distributions observed in AM materials. These simulations view how the material deforms and evolves when subjected to mechanical and thermal loading and predict their probability of failure.

To complement this work, my group performs small-scale experiments representing mirror replicates of the simulations to measure the point-by-point evolution of material damage over time and compare directly to the simulation results. These efforts assess the accuracy and precision of the simulations to establish confidence in the overall framework. My group has demonstrated this predictive framework to qualify AM parts resulting in a 50% time reduction and a two-thirds cost savings to generate initial data.

New approaches are needed to foster the real-time state awareness of space structures and spacecrafts. Often in movies, there are visions of onboard displays coupled to displays on Earth, showing a percentage of a spacecraft's health, with a zoom-in of the subsystem that needs repair. This is effectively similar to the concept of a digital twin. A digital twin of a specific space structure or spacecraft can be used to predict the future performance of a real-world physical system or subsystem, based on the current knowledge of its environment, health and subjected loads. The result is a quantitative assessment of the likelihood to survive and perform its mission, including the uncertainty of the prediction. These digital-twin simulations are periodically or constantly updated with new data and information, as it's available. My team has developed new approaches to predict material damage and failure to more accurately assess the remaining life of materials and structures. A major roadblock for the shared vision of the digital twin is that the disparate engineering disciplines often work in silos. To overcome this, we have worked toward unifying the flow of data and information over the complete engineering life cycle, developing linkages and pathways to directly combine intended design geometry, material specifications, analysis results, manufacturing process planning, inspection of the as-built geometry, and modifications through maintenance and repair. This new framework develops the integrated approach needed to enable the digital twin.



Simulation-based strategies are being used to rapidly qualify the use of additive manufacturing materials.

T-MINUS 04

APOLLO 11

ALEXEY SHASHURIN
Assistant Professor of
Aeronautics and Astronautics

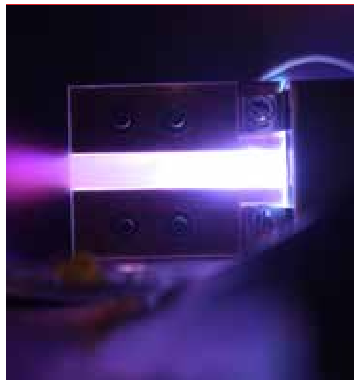
ANSWERING THE CALL TO IMPROVE CUBESAT PROPULSION

There has been a significant increase recently in the use of miniature satellites, known as CubeSats. These are made up of multiples of 10-centimeters-by-10 centimeters-by-10-centimers with a mass of less than 1.3 kilograms. The number of CubeSat launches has experienced exponential growth since the early 2000s, reaching over 1,000 CubeSats launched as of January 2019. These miniature spacecrafts use platforms that are much smaller than conventional satellites and, therefore, require compact propulsion systems. Micropropulsion systems for CubeSats are still in their infancy and require significant further development to overcome their inability to operate reliably for long periods, their contamination issues, and compact propellant storage problems.

My Applied Plasma Science Laboratory is working to advance electric micropropulsion systems for CubeSats. Electric propulsion offers efficiency advantages over chemical propulsion with its superior fuel economy. One of the central components of such micropropulsion systems are their ignitor subsystems, which are required to trigger the overall micropropulsion system. My group has modified classical surface flashover between two metal electrodes over a dielectric surface by minimizing spark energy used for ignition. To this end, the ignitor uses very short nanosecond-long sparks to limit the spark energy and minimize damage to the igniter assembly. This system demonstrates stable operation over several million pulses without any igniter damage. Current igniter systems can do only thousands of pulses. Increased capacity for pulses would allow the ignition and propulsion systems to function reliably for a long time. With rapid increases in CubeSat mission complexity, such a thruster is in high demand.

Another critical part of the micropropulsion system is the plasma accelerator, which exhausts ionized propellant at high velocities of 10 kilometers per second. My group utilizes a Lorentz force pulsed plasma accelerator that operates on a principle similar to that used in railguns. The plasma accelerator operates with the liquid propellant, which can be compactly stored in the tanks and “green” for the spacecraft. It uses high-pulsed currents in the kAmpere range, and the plasma jet exhausts from the accelerator at velocities above 30 kilometers per second.

CubeSats are uniquely suited to offer significant advances to solar and space physics, Earth science, planetary science, astronomy and astrophysics, and biological and physical sciences in space. Future science investigations likely will require data from constellations or swarms of 10 to 100 spacecraft. CubeSats enable a cost-effective option for larger constellations that would have spatial and temporal coverage to map out and characterize the physical processes that shape the near-Earth space environment.



A liquid-fed pulsed plasma accelerator is currently studied at the Applied Plasma Science Laboratory.

T-MINUS 03

APOLLO 11

TAKING OUT THE SPACE TRASH

One of the biggest problems facing spaceflight is the accumulation of orbital debris. About 23,000 objects floating in space are currently being tracked by the U.S. Air Force. That number is expected to double within five years, due in large part to increased global demand for satellite internet services and private companies' launching of more space objects to meet that demand.

So, what happens to those floating satellites and other space objects when they have outlived their usefulness? They need to deorbit and reenter Earth's atmosphere. While most pieces of hardware in orbit fall back into the Earth's atmosphere within a few years and burn up harmlessly, items in higher orbits can continue circling the planet for more than a century. Our team at the Space Flight Projects Laboratory is developing a passive, aerodynamically stable drag sail to provide an efficient method for accelerating deorbit following the completion of a satellite's operational mission.

The Aerodynamic Deorbit Experiment (ADE) will provide flight qualification and characterize the performance of a deployable drag device to accelerate the deorbit of small satellites. Purdue's ADE CubeSat is a small-scale prototype of a device that could be used to deorbit 150 kg-class satellites from orbit altitudes of up to 1,100 km. The drag sail will be deployed using an autonomous preprogrammed timer or by a command sent from the ground. Four one-meter booms will extend from the device with a thin-membrane material stretched between them. Once fully deployed, the sail will present a drag area of approximately 1.8 square meters. The ADE will be deployed from the Centaur upper stage on a future United Launch Alliance launch.

The baselined orbit for the ADE mission is geosynchronous transfer orbit (GTO), with perigee/apogee orbit altitudes of 185 km/35,756 km and an inclination of 27.0 degrees. The expected orbital lifetime of ADE is 80 days following deployment of the drag sail. With no drag device, a standard 1U CubeSat would remain in orbit for approximately 2,500 days (6.85 years). ADE will collect acceleration and angular rate data during each pass through the upper reaches of the atmosphere. The data will be used to assess the aerodynamic stability of the system. While both active and passive methods for deorbiting satellites are likely to be necessary to maintain the utility of high value orbits, drag sails represent a low-impact deorbit approach for orbit altitudes of up to 1,110 km.

DAVID SPENCER
Associate Professor of
Aeronautics and Astronautics

The Aerodynamic Deorbit Experiment will provide flight qualification and characterize the performance of a deployable drag device to accelerate the deorbit of small satellites.

T-MINUS 02

VIKAS TOMAR
Professor of
Aeronautics and Astronautics

ADDRESSING SPACE-DWELLER DANGERS

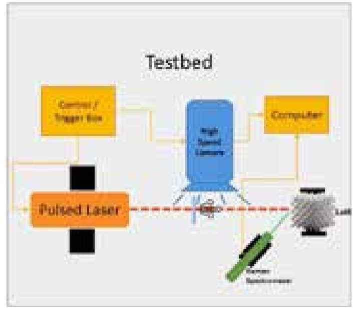
My Interfacial Multiphysics Lab is working toward new solutions for an age-old space venture problem: What if space travelers encounter high-speed space debris or hypervelocity micrometeorites? Would astronauts and devices be safe? The problem is being addressed through two separate avenues. One is design exploration of damage-resistant and damage-tolerant electronic circuits that can continue to operate even if the device has been through a barrage of hypervelocity impacts (> 1 km/sec). The other is the development of damage-tolerance protocols by embedding and exploring new material designs for fabrics and CubeSat structure.

The goal of one project is to study the resiliency of low-weight periodic structural components of spacecraft against the impact of micrometeoroids. These periodic structures, also called lattice structures, efficiently reduce the weight of spacecraft while maintaining the same structural reliability as solid structures, but their resistance against hypervelocity impact is still unknown. Micrometeoroids, with a size of about 1 mm and an average velocity of 10 kilometers per second, can pose significant threats to spacecraft, damaging components and affecting its functionality, this project aims to determine the amount of micrometeoroid damage a lattice structure can handle before becoming structurally compromised.

To study these micrometeoroid impacts, an impact test using laser-induced, micron-scale particles onto a lattice structure will be used. The pulsing laser induces motion into micron-sized particles of a given material up to speeds of about 4 km/s. Then, the experiment will be scaled to a real scenario with 1 millimeter meteorites. This will be accomplished by 3D printing the structure to be tested on a smaller scale than the actual lattice, making sure the experimental results match. Comparing the results is done by scaling through dimensional analysis and proving that the real structure and the sample obtain similar stresses by FEA simulation with different impactor sizes.

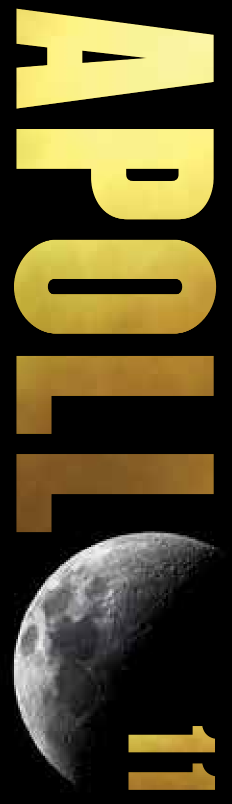
There is very little research published in the field of aerospace and structural engineering on the impacts of micrometeoroids on lattice structures or even the blast responses of lattice structures. Micrometeoroids remain a major threat to spacecraft, especially in areas of heavy space traffic. It can cost millions of dollars to send a payload or spacecraft into the atmosphere and beyond, so it is imperative to keep them operating.

Our team hopes to develop a new understanding of how lattice structures could potentially be used to protect spacecraft from the devastating force of micrometeoroid impacts. We will develop a knowledge base on how different lattice structures deform from impact with micrometeoroids, and hopefully, be able to translate this knowledge into new methods for reinforcing spacecraft against potential impacts.



Shown is a model experimental testbed for high throughput meteor impact simulations.

T-MINUS 01



HAIFENG WANG
Assistant Professor of
Aeronautics and Astronautics

A REAL AND VIRTUAL MISSION TOWARD A BETTER ENGINE

As the main propulsion power for its future space exploration, the U.S. aerospace program needs combustion engines that are designed for optimal stability and efficiency. Building these engines is enormously expensive and time consuming, so substantially reducing the cost of designing and testing combustion engines can significantly impact the future space exploration program.

We can reduce costs by building computer models to aid the design and testing in a virtual laboratory. This will lower the number of real tests and prototypes in a physical laboratory and their associated costs. Today's computer models have not achieved enough predictive capability to reliably replace lab testing. The goal of our research group, the Purdue Computational Energy and Propulsion Lab, is to enhance the predictive capability of combustion computer models so that eventually they can be confidently used for combustion engine design and testing.

Our work spans a wide spectrum, ranging from theoretical analysis of fundamental physical characteristics to establish the theoretical foundation for computer model design, to developing physically informed computer models, and validating the models in real problem analysis.

The smooth and stable operation of a rocket engine is undoubtedly critical to the success of space exploration. The undesired physical phenomenon called combustion instability (or thermoacoustic instability) can develop in a rocket engine and cause large fluctuations of pressure that pose a serious hazard to the engine and its mission in space.

Our current research is aimed at gaining understanding of the coupling mechanism between transient flame dynamics and the combustion instability developed in a self-excited resonance rocket combustor. Transient flame dynamics such as ignition-delay and localized flame extinction are caused by a strong coupling of turbulent mixing and finite-rate chemical kinetics. Our studies reveal that the occurrence of transient flame dynamics strongly influences the onset of combustion instability. Simultaneously, the occurrence of combustion instability reversely influences the development of transient flame dynamics to cause a two-way coupling between them. The observed two-way coupling provides a plausible mechanism of the self-excited and sustained combustion instability observed in the model rocket combustor. This finding is useful for guiding new designs of combustion configurations in future engine development.

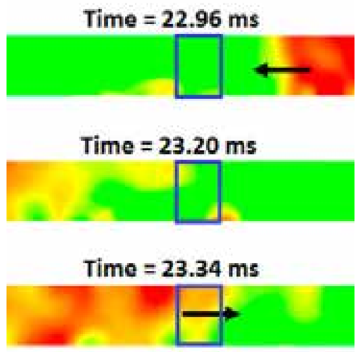


Image shows contour plots of instantaneous pressure inside the model rocket combustor at different instances of time for the unstable operating condition obtained by using the FPV model. The thermoacoustic instability in the rocket combustor gives rise to two pressure waves, one wave propagates inside the main combustion chamber and the other wave propagates inside the oxidiser post.

THE NEXT
GIANTLEAPS™

STUDENTS ENVISION THE FUTURE OF SPACE EXPLORATION

WHAT WILL SPACEFLIGHT LOOK LIKE ON THE 100TH ANNIVERSARY OF THE APOLLO 11 MOON LANDING? TEAMS OF STUDENTS ANSWERED THAT QUESTION AS PART OF THE SCHOOL OF AERONAUTICS AND ASTRONAUTICS' "FUTURE OF AEROSPACE" SYMPOSIUM ON MAY 10, 2019.

FIG. 01
A world made more connected, more self-aware, and more efficient by the development of improved satellite services, hypersonic flight, space tourism and Earth applications for advanced life-support systems and intelligent habitat technology.

FIG. 02
A dynamic and multifaceted domain of private and public space stations, running operations ranging from orbital pharmaceutical manufacturing to space tourism, serviced by single-stage spacecraft providing regular crew and cargo transport.

FIG. 03
A permanent human research facility analogous to the remote Earth-based facilities we currently operate on Antarctica, where scientists regularly visit to carry out important research. An improved orbital gateway will simplify access to the lunar surface and commercial ventures may be starting to make inroads to Moon operations.

FIG. 04
A more recent human triumph, where the architecture required for long-term human presence is still taking shape in the form of 3D printed habitats on the surface; crews of astronauts presently inhabit a rotating orbital station and make short excursions to the surface and the two moons of the Mars system.

FIG. 05
The next steps for space exploration after 2069, whether they take our crews to moons in the outer reaches of the solar system (Titan, Enceladus, Europa) or to the upper atmosphere of Venus (where airships could comfortably cruise), and whether they take swarms of robotic probes throughout the solar system, or take an uncrewed payload on our first true interstellar mission.
(Illustrations by Geoffrey Andrews)

FIG. 01

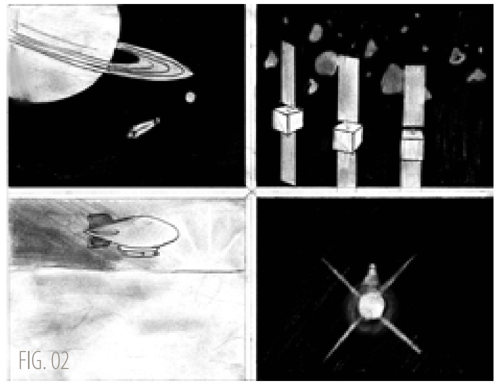


FIG. 02

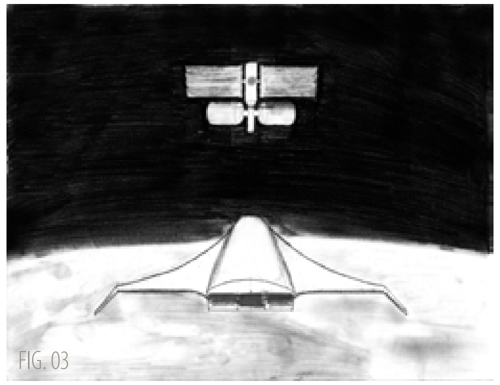


FIG. 03

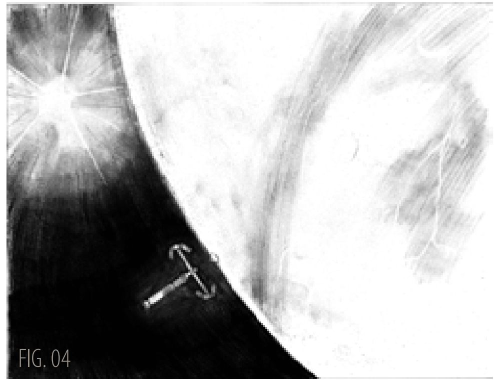


FIG. 04

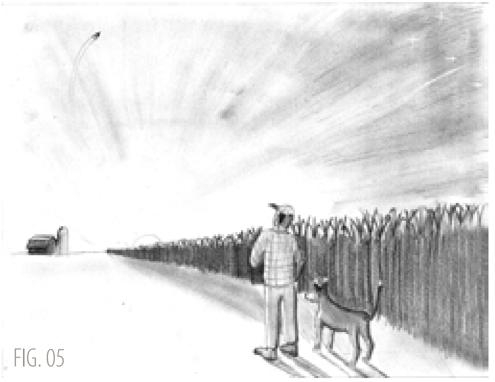


FIG. 05

Geoffrey Andrews and Justin Mansell, doctoral students in AAE, presented five key technologies they expect will be developed over the next 50 years.

- AIR-BREATHING ROCKETS
  Air-breathing rocket propulsion seems to offer huge potential but has remained tantalizingly out of reach for decades. Among the best technology options are a rocket-based, combined cycle design, such as that proposed for the National Aerospace Plane, and NASA's GTX single-stage-to-orbit spacecraft. Another good option is the more exotic Reaction Engine's SABRE liquid air cycle engine. Regardless of the option chosen, the ability to use atmospheric oxygen as a primary or secondary oxidizer promises to revolutionize the way we access space. It also may prove to be a viable propulsion system for hypersonic point-to-point transport.
- DISAGGREGATED SATELLITE SYSTEMS
  The ability to launch and control vast arrays of low-cost satellites (as opposed to the singular, monolithic architectures that have thus far dominated satellite design) will allow redistribution and democratization of on-orbit capabilities. Satellite owners will be able to rent excess capacity on their constellations, and users on the ground will enjoy seamless, unfettered access to worldwide data services such as the internet and GPS.
- INTELLIGENT HABITATS AND EXPLORATION SYSTEMS
  Increased autonomy of habitation modules and rovers will allow greater capabilities for exploration in areas of deep space that may not always sustain human life. The planned Lunar Orbital Platform-Gateway, for example, likely will be uncrewed for relatively long periods (certainly during its early stages). The same almost certainly will be true for infrastructure needed for Mars exploration. Therefore, it will be crucial that future space systems can self-monitor and ideally self-maintain to ensure safety for astronauts and security for the expensive hardware.
- IN-SITU RESOURCE UTILIZATION
  Establishing a human presence off-Earth will require some degree of self-sufficiency. The Moon may be relatively accessible, but the same certainly can't be said of Mars, meaning that astronauts will have to learn to use the resources they find on-planet to spend any significant length of time on the surface . This likely will require extracting breathable oxygen and combustible fuel from the atmosphere, harvesting water ice for human consumption, or even mining frozen helium isotopes to power nuclear reactors. More than just consumables, astronauts likely will have to use local materials to construct habitats (though we imagine the actual construction will be left to robots to complete).
- NUCLEAR ROCKETS
  While traditional chemical rockets are capable of accomplishing our immediate exploration goals on the Moon and Mars, they leave much to be desired. Many months are needed for transit to Mars, for example, all but requiring a higher performance method of propulsion. Nuclear thermal rocket engines would enable astronauts to make the journey in a fraction of the time, minimizing exposure to cosmic and solar radiation as well as the risks of crew and equipment failure.

The undergraduate team of Ryan Alcorn, Wellington Froelich, Tomoki Koike, David Kosakowski and Jordan Soberg presented a timeline of advancements and shared visions of the space economy in 2069.

- IN THE 2020s, there is a dawn of true commercial space industries and greater leaps in exploration. NASA's Gateway will be the big bang of human expansion and development of extraterrestrial planets. New laser communication systems, such as NASA's Laser Communications Relay Demonstration mission, will boost the amount of data we can transmit to and from these new human outposts. Bigelow Aerospace will lead the adventurous space hotel sector and multiple firms will prove new transportation methods. Several startup companies will clean up the clutter of objects in low-Earth orbit.
- Pursuing opportunities to explore the solar system, there will be boots on the ground of Mars IN THE LATE 2030s. Before landing on Mars, we will prove our tenacity on the Moon by building a lunar base. The Moon also will serve as the cornerstone for mining and missions into deep space. On Earth, a new model of satellites will fly with the sole mission to replenish existing flights.
- THE 2040s will lead to turmoil. Claims to the Moon will boil over once the true value of the territory in space has been demonstrated through successful missions. The first colonizing astronauts will develop lunar communities and the first child will be born on the Moon. Detailed exploration to distant planets and to intergalactic space will be conducted with artificial intelligence onboard the spacecraft in order to support independent decision making as they travel those great distances. Most notably, the prospecting and mining industry will spread from the Moon to Near Earth Asteroids.
- BY THE 2050s, there will be over 75,000 residents on the Moon. These societies will be supported by robotic inhabitants to collect ice on the surface. Additional space stations will be orbiting Mars, which will be supported by a network of water suppliers harvesting water from icy moons and water-carrying asteroids.
- THE 2060s promise a great flowering of Earth's space economy. The term "Made on the Moon" will become prominent. Manufacturing goods on the Moon for Earth and the space outposts will begin. This will mitigate emissions on the home planet and eliminate flaws in manufacturing processes due to higher gravity. One class of products in particular will be human organs and tissues. Construction will start on some form of a space elevator, based upon technology that will be developed over the next 50 years. And, finally, we will explore the new horizons of Alpha Centauri with unmanned space missions.

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50 2019 2069

Chris Brand, Blair Francis, Melanie Grande, Fouad Khoury, Rob Kitching and Islam Nazmy, graduate students in AAE, envisioned the next 50 years of space exploration through the lens of Purdue students and young professionals.

- In the next 10 years and beyond, the aerospace industry in Earth orbit likely will see widespread access to space and increasingly commercial ventures and nations, as well as advanced launch and in-space propulsion systems that are reusable, efficient and environmentally conscious.
- As human exploration advances once again beyond our home planet, the future of lunar exploration may include the growth of the cislunar economy for science, resource utilization and mining, and tourism. Across the industry, sustainable human exploration likely will be enabled by the development of more efficient and reliable system architectures.
- Humanity's long-held sights on Mars may require evolution of autonomy for human/robotic exploration elements and emergence of machine learning and AI for systems planning. These advancements hopefully will lead to the establishment an outpost on Mars as a stepping stone for a continued and expanding presence. The design of sustainable, long-term settlements represents a multidisciplinary engineering and of science grand challenge for humanity.
- A greater vision of space exploration calls for cooperation between international governments, industries and academic institutions. The formulation of responsible and ethical space policy, increased diversity in the workforce, and strengthening STEM education for all ages will play pivotal roles here on Earth in advancing the future generations of mankind to step away from our planet and assume a new place in space.

APOLL

11

PURDUE
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50th ANNIVERSARY