AA Strategic Plan: Space Chapter

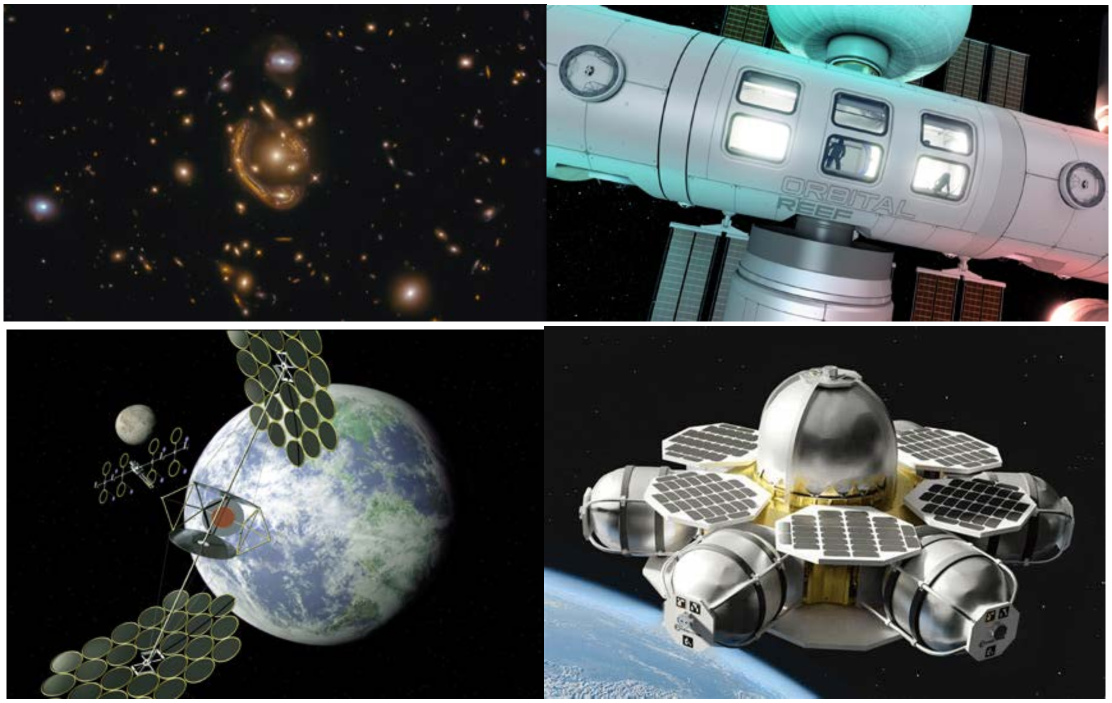
Final Version Delivered to Department: 04/25/2023

Introduction (Simone D'Amico)

The exploration of space embodies humanity's intrinsic desire for knowledge, to overcome limitations and the pursuit of long-term survival. This ultimate frontier holds the potential to profoundly impact our lives, from education and the economy to national security and morale. It is the mission of the Stanford AA department to answer the fundamental questions of technology and science that can unlock this potential in the years to come. Before addressing the 5-years objectives of the department, this section provides an outlook on the long-term vision, its societal impact and challenges.

Over the course of the next 30 years (see Box 1), it is expected that humans will be able to mass-survey and directly image Earth-like planets in the search for life through advanced techniques such as internal, external coronagraphs and gravitational lensing. Advanced infrastructures and human habitats will be commonplace in Earth's orbit and on the Moon in the quest to colonize other planets. Most probably the first humans will be able to follow the footsteps of our Mars' rovers and drones and walk on the Red Planet. Solar-power space stations will provide sustainable electric energy anywhere/anytime to the human population in space and on the ground. Boosted by ever more advanced algorithms of artificial intelligence and remote sensing technology, humans will start creating digital twins of the Earth and other planets to predict, prevent, monitor, mitigate natural disasters and even for Terraforming. Similar to today's infrastructures and technologies which allow the navigation and exploration of sea, ground, and air, near-Earth and cislunar space will be routinely serviced by propellant depots for refueling, by space tugs for on-orbit transfers, and by spaceships for inspection, repair, lifetime prolongation, decommissioning and debris-removal.

Although these are only some examples of what's to come, this long-term vision faces tremendous multi-disciplinary challenges at the intersection of materials and structures, fluids and propulsion, artificial intelligence and autonomy, remote sensing, astrodynamics and space system engineering. The need to conceive, design, build, implement, operate such complex, over-constrained systems in extreme environments calls for a reimagination of many of these disciplines. At the same time, aerospace engineering must be able to address the societal impact and policy implications of the developed technologies. Here, the notion of circular economy and two-way sustainability will play a major role. On the one hand, spaceflight technology will represent the most important tool to gain an holistic understanding of our planet as an interconnected dynamics system governed by feedback mechanisms. On the other hand, near-Earth and cislunar space represent a precious and finite resource to be carefully managed and regulated to avoid disruption through the Kessler Syndrome and to ensure its continued and efficient use.



Box 1. AA over the course of the next 30 years. Direct imaging through gravitational lensing - Einstein ring by NASA Hubble Space Telescope (top left). Advanced infrastructures and human habitats in orbit and on the Moon - Blue Origin's Orbital Reef (top right). Space-based solar power anywhere/anytime - NASA Integrated Symmetrical Concentrator concept (bottom left). In-orbit servicing and manufacturing - Orbit Fab's Fuel Tanker (bottom right).

In the following sections, details are provided on how the Stanford AA department plans to tackle some of these challenges in a 5-years time frame.

Distributed Space Systems (Simone D'Amico and Marco Pavone)

The long-term vision outlined in the previous section requires two or more spacecraft to interact to accomplish scientific, commercial or technological objectives that are otherwise very difficult if not impossible to achieve using a traditional monolithic spacecraft. The interaction can be remote or through physical contact, cooperative or uncooperative. The Stanford AA department has been pioneering these architectures for the past 10 years, also called Distributed Space Systems (DSS) for brevity. DSS arise to overcome three fundamental limitations of space technology: *1*. Imaging/remote sensing resolution limited by the size of the collecting aperture; *2*. Global coverage of planetary targets at high signal-to-noise ratio limited by the number of satellites; *3*. Mission lifetime limited by propellant mass fraction.

DSS can be classified in many ways depending on their key characteristics and a convenient classification is based on the requirements of inter-satellite separation and relative navigation/control accuracy between the agents of the DSS. Historically, the best known and arguably most researched DSS are constellations and satellites for rendezvous/docking. The formers are characterized by large separation for global coverage and loose relative orbit control requirements (they address primarily limitation number *2*). The latters are characterized by small separations and tight relative orbit control requirements (they address primarily limitation number

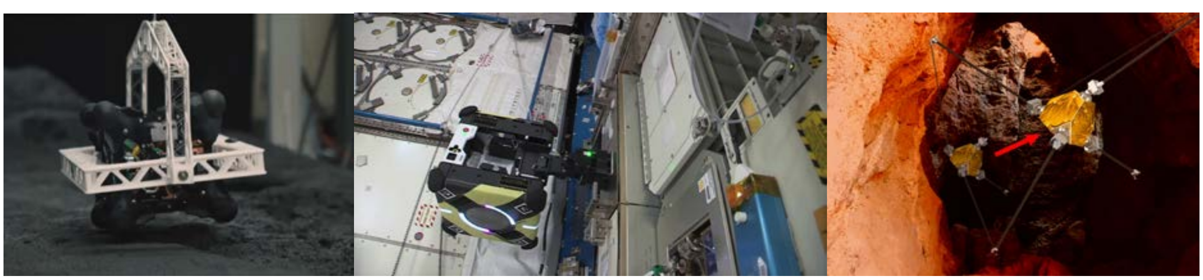
3). However, several intermediate typologies of DSS such as satellite swarms and formations exist that promise technological breakthroughs but are less explored due their complexity and challenging requirements (they address primarily limitation number *1*).

The goal of the Stanford's AA department for the next 5 years is to conceive, develop, embed and integrate novel algorithms for multi-satellite Autonomy and Guidance, Navigation, and Control (GNC) into first-of-its-kind satellite swarms and formations. The portfolio of DSS which are under development in collaboration with several partners in Industry and Academia is summarized in Box 2. NASA's Starling satellite swarm mission consists of 4x 6U CubeSats and is due to launch in Q3 2023 with the primary goal to demonstrate autonomous satellite swarming technology. For the first time, Starling will demonstrate the capability of a swarm of satellites to autonomously navigate using only optical inter-satellite navigation without external means. This is done through a new distributed navigation system developed by the Stanford's AA department called Angles-only Absolute and Relative Navigation System (ARTMS) which will be validated in the month-long Starling's Optical Formation-Flying Experiment (StarFOX). NSF's VISORS satellite formation-flying mission consists of 2x 6U CubeSats and is due to launch in Q3 2024 with the primary objective to obtain ultra-high resolution images of the Sun's Corona in the extreme ultraviolet spectrum (0.1 arcsec). This is done by a segmented telescope with a focal length of 40m which is provided by precise relative orbit control of the two satellites with sub-cm accuracy. The Stanford's AA department is responsible for the orbit design, GNC algorithms/software, and collision avoidance of the formation, including features of passive and reactive safety. NSF's SWARM-EX satellite swarm mission consists of 3x 3U CubeSats and is due to launch in Q4 2024 with the primary objective to characterize the upper layers of the ionosphere and space weather through distributed measurements of neutral and mass air density. The Stanford's AA department is responsible for the orbit design, GNC algorithms/software, and collision avoidance of the swarm with separations between the spacecraft between hundreds of kilometers to 2 kilometers. For the first time, a satellite swarm will be optimally controlled using a combination of propellant-based (cold-gas) and propellant-free (differential drag) actuation.

In addition to the aforementioned spaceflight missions, the Stanford's AA department is leading the conception and design of DSS with unprecedented capability. Key example is given by the mission concept called Autonomous Nanosatellite Swarming (ANS) using Radio-Frequency and Optical Navigation. ANS consists of a mothership spacecraft that deploys several nanosatellites to autonomously recover shape and gravity of small celestial objects with high resolution in full autonomy. ANS is powered by a set of GNC algorithms for Simultaneous Navigation and Characterization (SNAC) which relies on distributed radio-frequency and optical sensing, nonlinear astrodynamics and sequential estimation, reinforcement learning and optimal control. Primary objectives for the next 5 years include the full integration and validation of the algorithms with hardware-in-the-loop as well as the elevation of ANS from a preliminary concept to an actual flight mission.

Box 2. DSS over the course of the next 5 years. NASA's Starling satellite swarm mission equipped with Stanford's StarFOX visual navigation experiment (top left). NSF's VISORS satellite formation-flying mission enabled by Stanford's GNC algorithms and software (top right). NSF's SWARM-EX satellite swarm mission enabled by Stanford's GNC algorithms and software (bottom left). Stanford's Autonomous Nanosatellite Swarming (ANS) mission concept using distributed radio-frequency and optical navigation (bottom right).

Finally, the Stanford's AA Department is developing robotics technologies to provide DSS with in-situ exploration capabilities (e.g., for the exploration of small Solar system bodies or Martian caves) or assistive on-orbit capabilities (e.g., to assist astronauts with carrying out on-orbit tasks). Specifically, the Department has pioneered the development of minimalistic rovers for the exploration of microgravity bodies (Box 3 - left), and has been developing robotics concepts for robotic satellite servicing, which are undergoing a series of tests on the International Space Station (Box 3 - center). During the next five years, the Stanford's AA Department will focus on continuing the development of key technologies for robotic satellite servicing (with an emphasis on making operations increasingly autonomous through the use of cutting-edge AI techniques), investigating novel robot designs for the exploration of steep and overhanging surfaces on planetary bodies (e.g., Martian caves - Box 3 - right), and developing technologies for the multi-agent exploration of extreme extra-terrestrial terrains (e.g., to enable the exploration of lunar permanently shadowed regions).

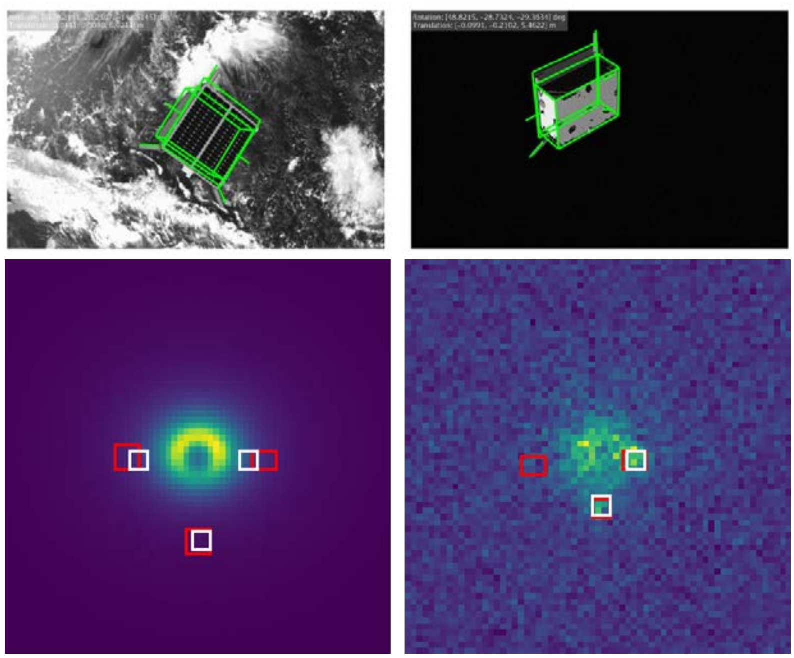


Box 3. The development of rovers for the exploration of small Solar system bodies required the development of a one-of-its-kind 6 DoF microgravity test bed built on a powered gantry crane; the gimbal frame allows the robot to rotate in all three axes (left). Robotic grippers and guidance algorithms for satellite servicing are currently being tested on the

International Space Station (middle). ReachBot uses its extendable boom arms to navigate the treacherous geometry of a Martian cavern (right).

AI for Space (Simone D’Amico and Marco Pavone)

Modern machine learning and Artificial Intelligence (AI) algorithms represent a huge potential for space applications. The potential boils down to key features such as unparalleled generalizability to new tasks and near-real-time capabilities with low compute time at inference. Tasks that conventional methods cannot solve online on spacecraft microprocessors due their complexity and computational effort can potentially be learned offline through training on carefully designed machine learning datasets and simulations, and perfected online through rapid adaptation. This feature affects the complete GNC and Decision Making chain and can be seen as an enabler for spacecraft autonomy, including mission planning, Fault Detection, Isolation and Recovery (FDIR), situational awareness, and payload efficiency. However, this potential comes with three key challenges. First of all, it is technically difficult to enforce strict constraints on AI algorithms. Second, it is technically difficult to provide guarantees of performance especially when the algorithm is exposed to input data from a statistical distribution that differs from the training data distribution. Finally, the training of AI algorithms is typically very data-hungry. These challenges are exacerbated in space applications which are very risk-averse (i.e., hard constraints must be enforced), where the operational environment is not available in a lab (i.e., out-of-distribution data are more likely), and face lack of data due to limited adoption of the technology.



Box 4. AI for space over the course of the next 5 years. Preliminary results from robust spacecraft 6D pose estimation, 3D model abstraction using machine learning (top). Preliminary results from robust exoplanet detection and characterization using machine learning (bottom).

The goal of the Stanford’s AA department for the next 5 years is to fully explore how to harness the full potential of AI for space applications while addressing the aforementioned challenges.

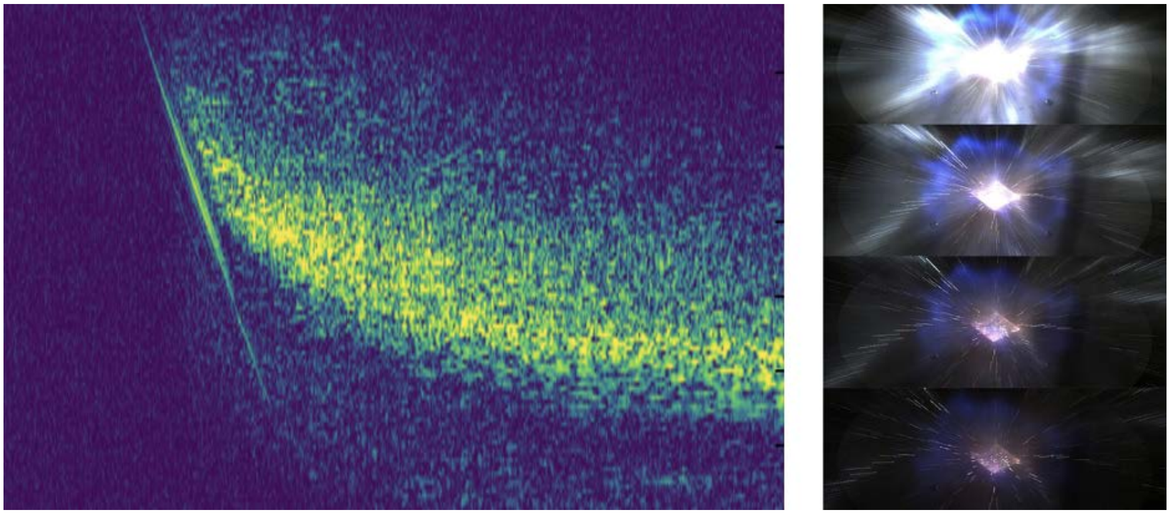
Preliminary results include methods for spacecraft 6D pose estimation (Box 4 - top), run-time monitoring and data life cycle management of AI models for pose estimation, and 3D model abstraction for applications in In-Orbit Servicing and Manufacturing (ISAM) as well as exoplanet detection and characterization for applications in future starshade and coronagraph missions (Box 4 - down). Stanford's AA has already extensively worked with the European Space Agency and NASA/JPL to create the most realistic physics-based datasets for these applications and hosted international machine learning competitions on these topics. In the next 5 years, robustness to out-of-distribution data will be achieved through experimental and theoretical means. On the experimental side, Stanford's AA will create new machine learning datasets specifically designed to bridge the domain gap through augmented reality, robotics, and data augmentation techniques. On the theoretical side, Stanford's AA will create and explore new techniques inspired by multi-tasking, on-line domain refinement, loose and tight data fusion with sequential filters, robust statistical propagation of uncertainties, run-time monitoring to endow AI with guarantees of performance.

This research will be largely conducted within the new Center for AEroSpace Autonomy Research (CAESAR) which is currently being created at Stanford's AA under the sponsorship of key industry stakeholders to pursue these objectives. The goal of CAESAR is to advance the state-of-the-art in infusing autonomous reasoning capabilities in aerospace systems, with a focus on: *1*. Spearheading foundational technologies to enable trusted deployment of AI tools; *2*. Developing novel algorithms at the intersection of guidance, navigation, control, and machine learning to enable future distributed space systems and space robotics tasks; *3*. Training and validating the new technologies through first-of-its-kind hardware-in-the-loop demos and space missions. CAESAR will link Industry, Academia, and Government to enable trusted aerospace autonomy and multi-agent capabilities. At the same time, it will foster new talent and achieve rapid innovation in a unique environment that implements the full project cycle iteratively from vision to spaceflight.

Space Environment and Space Sustainability (Sigrid Elschot)

In-space sustainability requires an understanding of spacecraft systems and their interaction with the space environment. This environment can vary drastically from Low Earth Orbit where debris is a major threat, to cis-lunar and interplanetary space where the plasma and radiation conditions can vary over many orders of magnitude in density and energy. The next 5–10 years of research and development into space sustainability at Stanford's AA will focus on *1*. developing new capabilities to provide space surveillance and tracking; *2*. characterizing unknown parameters in the space environment; and *3*. understanding spacecraft failure modes stemming from interactions with the space environment.

Space surveillance and tracking is a constantly evolving capability that depends on detection and measurement of objects in orbit, propagation of orbit trajectories, and effective communication of relevant information to satellite operators. Various methods for detection and measurement of space debris include ground-based radar and optical instruments, direct impact sensors, and in-space remote sensing techniques such as RF detection and optical/LIDAR payloads. We utilize a variety of plasma simulations employing Particle-in-Cell (PIC) techniques to model the propagation of solitary waves, known commonly as solitons, to investigate the potential of solitons as a means of detecting sub-centimeter orbital debris in space.



Box 5. Radar observation of a meteor from a campaign conducted by Stanford's AA at Jicamarca Radio Observatory in Peru (left); Impact of a 5 km/s projectile from an experiment conducted by Stanford's AA at the NASA Ames Vertical Gun Range (right).

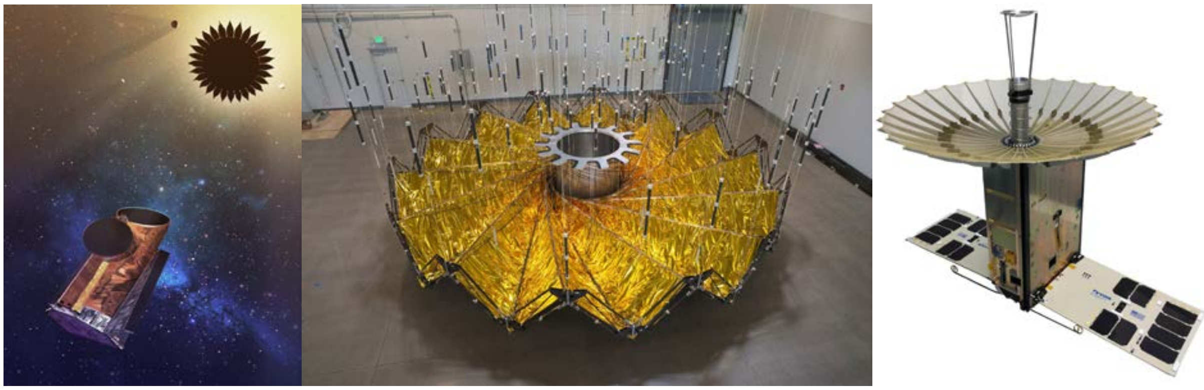
Asteroidal and cometary particles travel at tens of kilometers per second and are micrometers to millimeters in size, making them difficult to observe, and existing measurements of bulk density and mass contain significant uncertainty. This motivates more precise quantification of these properties using radar observations of meteoroids entering Earth's atmosphere. We calculate meteoroid properties, including mass and density, from observations of radar signatures in data collected from a range of specialized radar facilities located at diverse geographic locations (Box 5). This effort will refine existing uncertainty bounds on the properties of the near-Earth dust and meteoroid population.

One component of the space environment that has yet to be fully understood is the plasma that forms when a hypervelocity particle, such as a meteoroid or piece of space debris, impacts a spacecraft. Plasma is generated both from thermal ionization and from pressure ionization and can range from weakly to fully ionized, depending on the particle's velocity. We probe the complex behavior of impact plasma to understand the interaction of radiation with matter and the effect of the space environment on systems and sensors.

Each of these areas of focus leverages a combination of experimental and computational tools, collaborations with external specialized scientific facilities, and new advances in data analysis to support our continued presence in space and quantitatively assess the risks associated with when and where failures occur, why they occur, and how often they occur.

Space Structures (Manan Arya and Maria Sakovsky)

The spacecraft structures research program at Stanford's AA is driven by the task of developing the lightweight, ultra-stable, ultra-precise structures technologies needed to support future space missions (Box 1 and 6). Such structures will need to fold, deploy, potentially be assembled in space, and incorporate active shape correction. Developing the fundamental technologies to achieve these capabilities remains an engineering challenge and is actively pursued at Stanford's AA.

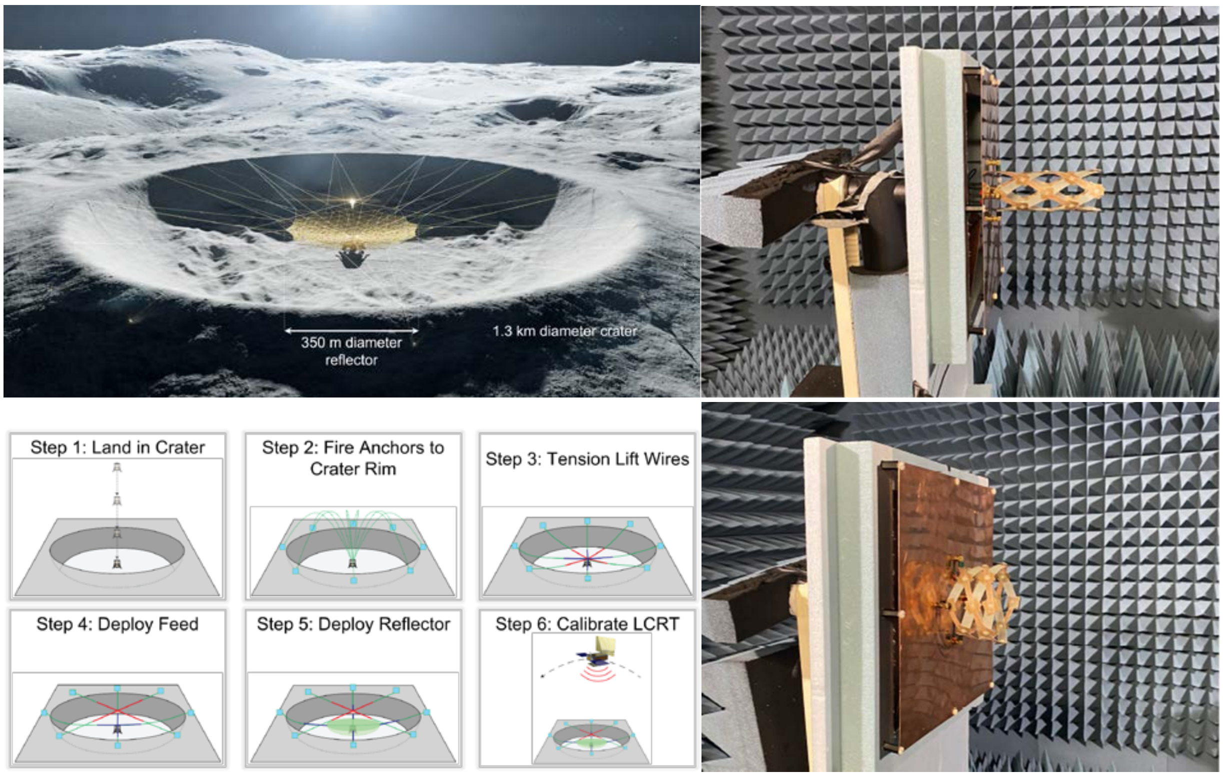


Box 6. Overview of priorities driving space structures research at Stanford's AA. Space-based telescopes for exoplanet detection with the Habitable Exoplanet Observatory mission concept as an example [Credit: https://arxiv.org/abs/2001.06683] (left). Precision occulters for direct imaging of exoplanets with an example of a deployable starshade [Credit: NASA/JPL] (middle). High frequency radar for Earth observation with RainCube as an example [Credit: NASA/JPL] (right).

A relevant future space mission concept is the Habitable Worlds Observatory (HWO), established by the Astro2020 Decadal Survey as the top priority for US space astronomy for the coming decade and beyond. The HWO concept comprises a space telescope to be launched in the 2040s with a 6.5 m-diameter aperture operating in UV/visible/IR wavelengths capable of directly imaging and characterizing Earth-like exoplanets around nearby sun-like stars. The metering structures for the HWO will require stability and accuracy better than those implemented for the James Webb Space Telescope (JWST). Additionally, the HWO may include free-flying starshades – precision occulters that fly in formation with a space telescope and suppress starlight to enable the direct imaging of exoplanets. Developing the constituent deployable structures technologies to enable starshades across a range of sizes is an area of expertise and focus.

The 2017 Earth Science Decadal Survey set several key priorities for future NASA Earth science missions. Two of these priorities – studying the planetary boundary layers, and monitoring precipitation, particles, and clouds in the lower atmosphere – could be enabled by high-frequency (i.e., 90 GHz and above) radar instruments on small spacecraft. Developing radio reflectors for such instruments is a challenge: these reflectors must have solid surfaces for operation at high frequencies, attain high surface accuracy, and be capable of stowage onboard small spacecraft. Stanford's AA is poised to address this challenge through the development of folding and deployment schemes for accurate thin-shell solid-surface parabolic reflectors made of high-strain thin-ply composite structures. More broadly, the application of high-strain composites to origami-folded structures to create accurate and stable deployable structures has applications including planar radio-frequency reflectarrays for remote-sensing and communication, deployable solar arrays, and deployable heat shields.

Future large space structures will involve robotic in-situ manufacturing, construction, or assembly. Stanford's AA research goals are aligned with this thrust: to build methods for designing, analyzing, and constructing high-accuracy lightweight structures amenable to in-space construction and assembly. For example, the Morphing Space Structures Lab played a key role in advancing the Lunar Crater Radio Telescope (LCRT) concept, funded by the NASA Innovative Advanced Concepts (NIAC) program. The LCRT concept envisions a kilometer-scale radio telescope deployed in a crater on the far side of the Moon using robotic means. LCRT is one example of the kind of large space structures that can be enabled by a combination of deployment and robotic assembly methods; this remains an active area of study at Stanford's AA (see Box 7).



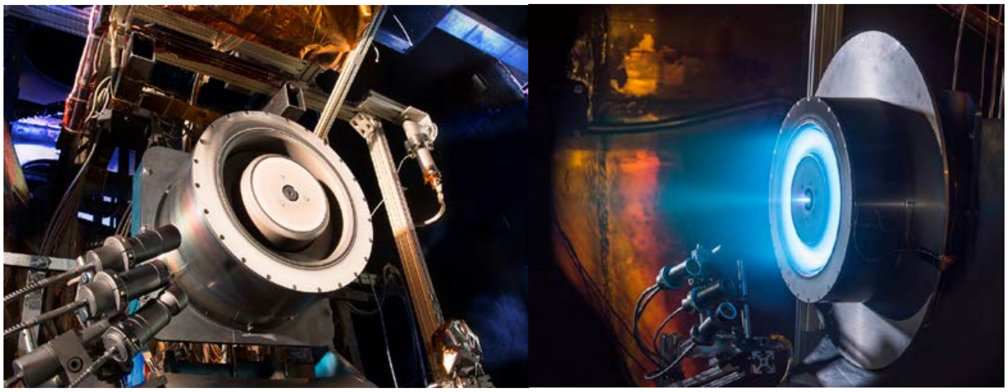
Box 7. Active space structures research at Stanford Aero/Astro. An overview of the Lunar Crater Radio Telescope (LCRT) mission concept and concept of operations (left). Radiation pattern reconfigurable helical antenna with multiple stable shapes providing a low energy reconfiguration solution to enable multi-functional communications antennas (right).

The increasing size of space structures to support future scientific missions and infrastructure for lunar and deep space missions, necessitates further reduction of mass and power use. Integration of a growing number of functionalities directly into structures is envisioned to support this. These functionalities include self-sensing, actuation, and reversible shape change thereby creating intelligent structures that can respond to the space environment or changing mission requirements. Research at Stanford's AA addresses several aspects of future space structures. Thin ply composites are an active area of research enabling large shape adaptation in stiff structures for deployment and adaptation. Smart materials are under investigation for their potential to actively change or correct the shape of structures. For example, research at Stanford's

AA explores low-energy shape change of antenna apertures to enable on-the-fly adaptation of antenna electromagnetic characteristics (Box 6). Intelligent structures promise to expand the functionality of spacecraft instruments and provide structural health monitoring of space assets.

Space Propulsion (Ken Hara)

Space propulsion is a critical part of the aerospace engineering community. In recent years, government agencies (e.g., NASA and Air Force) and industry have developed space propulsion systems mainly for station keeping and collision avoidance. The key metrics that are important for space propulsion include: *1*. thrust, *2*. specific impulse (Isp), and *3*. lifetime. In particular, electric propulsion (EP) or solar electric propulsion (SEP) can achieve high Isp (i.e., good fuel efficiency) due to the use of ionized gases, i.e., plasma, while the thrust is limited to a few hundred milliNewton.



Box 8. In-space propulsion research and development. Hall effect thrusters are one of the most used and promising space propulsion devices. Plasma is not turned on (left); plasma is turned on (right). [Courtesy: NASA]

The next 5-10 years of space propulsion research and development at Stanford's AA will focus on enhancing the thrust (> 1 N) and characterizing the lifetime between the laboratory experiments and space operations (cf. facility effect - Box 8). Stanford's AA focuses on developing predictive modeling tools of EP devices using physics-based and data-driven models.

Physics-based models including fluid, kinetic, and hybrid models are important to understand the plasma dynamics in multiple spatio-temporal scales (GHz - kHz; micron - meter; collisional - collisionless). The high-frequency, small-scale plasma turbulence can affect the low-frequency, device-scale self-organizing oscillations, and vice versa. The need for data-driven models has also increased over the recent years, as more experimental data for ground testing and in-space operations are obtained. Both offline and online validation techniques can help characterize the operation modes of EP devices. These computational tools are developed in collaboration with various experimentalists. While recent interests from an academic perspective are more towards high-power propulsion systems, there are other techniques that might be more suited for small satellites, e.g., electrospray and miniaturized plasma devices. The predictive modeling capabilities that will be developed at Stanford AA will be readily available for a wide range of space propulsion applications.

The impact of the EP research at Stanford AA goes beyond the astronautical engineering community. The plasma models developed can help other communities, such as semiconductor manufacturing, laser systems and diagnostics, computational fluid dynamics, high-power microwaves, pulsed power systems, space weather, and fusion energy (e.g., Z-pinch, laser inertially confined fusion).