STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW

A Deeper Dive into Space

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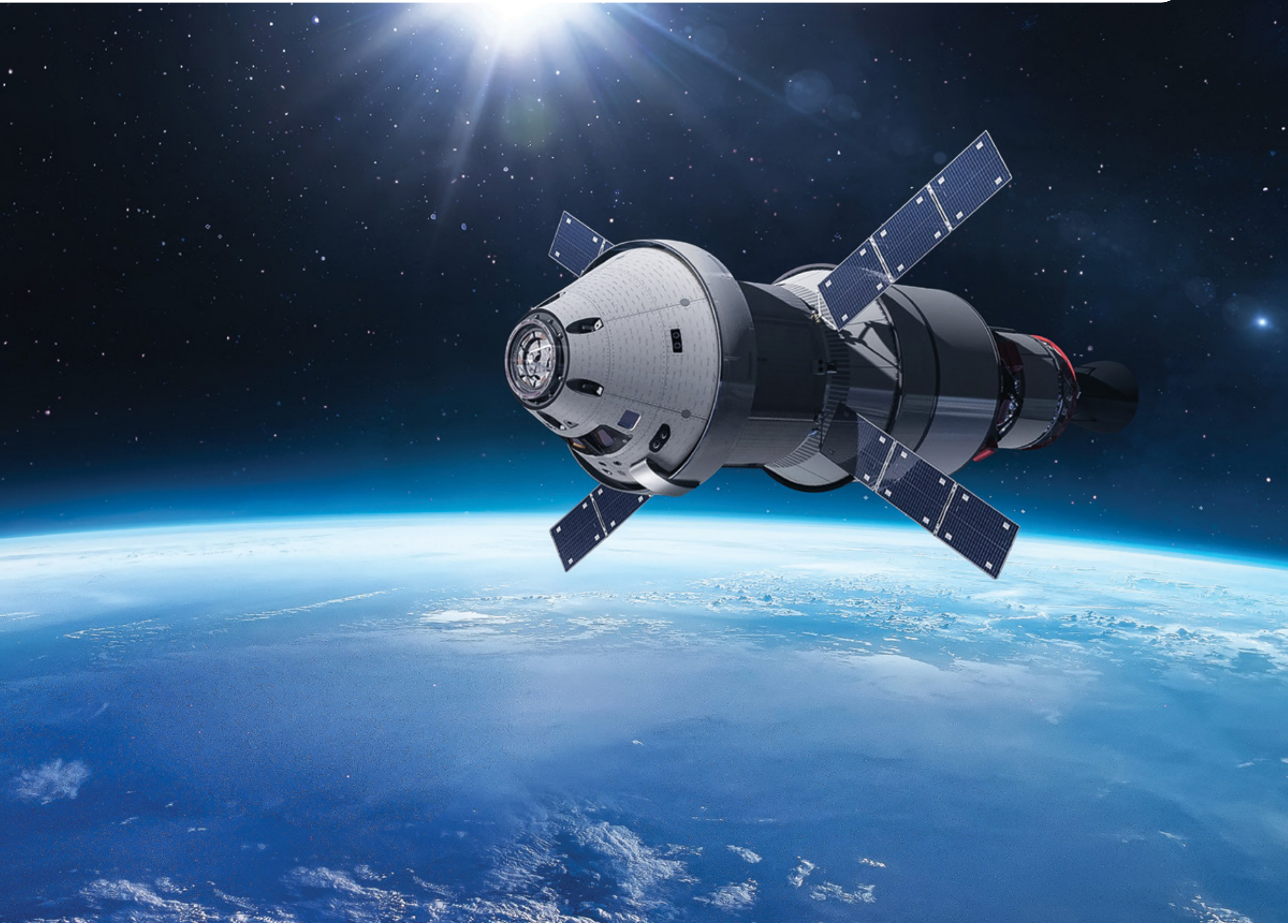

SPACE

Introduction

Thousands of satellites orbiting Earth provide earthbound nations and their citizens with communications, navigation, multispectral observation, and imagery of terrestrial phenomena that are useful in many walks of life. A substantial amount of scientific discovery is also made possible with spaceborne instrumentation. Finally, space operations support military forces on Earth, and space itself is a domain in which international conflict and competition play out.

Space technology can be defined as any technology developed for the purpose of conducting or supporting activities beyond the Kármán line (i.e., 100 kilometers, or 62 miles, above Earth's surface). A space mission is a system of systems that is designed to optimally accomplish objectives, and it includes several components:

- The mission objectives, which can be scientific, commercial, or military
- A space segment, which includes the spacecraft and orbits that have been selected and designed to accomplish these objectives
- A ground segment, which includes the rocket launcher, ground stations, and mission control centers
- A link segment, which includes communications protocols, radio and/or optical terminals, data encoding schemes, telemetry, and often encryption
- A user segment, which includes modems, remote terminals for user access, endpoint data consumption devices, and user interfaces

There are numerous applications of space technology, and they fall into roughly two categories. One category is direct applications of space-based

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technologies to support consumer, commercial, and government users. These include geospatial intelligence imagery; sea level rise predictions for coastal development; sea ice detection for naval, maritime, and submarine navigation; and global navigation satellite systems (GNSS), such as the United States' Global Positioning System (GPS) for position, navigation, and timing (PNT) services, which enables myriad applications across many sectors. Space-based manufacturing offers microgravity environments for the production of semiconductors for commercial and defense applications, such as quantum computing. Low-power, hard to detect, passive radar in space can survey military targets. Space-based PNT can be used for aviation (e.g., to support safer flight paths for landings, a.k.a. continuous descent approach) and agriculture (e.g., to enable precision farming, which increases efficiency in plowing and reduces chemical runoff from applying pesticides). Also in this category are astronomical telescopes and exoplanet imaging through adaptive optics, as well as digital image processing for space applications, with spin-offs for medical imaging such as magnetic resonance imaging (MRI) and computed tomography (CT) scans.

A second category of space technology helps to improve and evolve other space technologies in one or more dimensions (e.g., simplicity of the ground segment, reduction of person-hours needed to operate satellites, and improvements regarding in-space capabilities and technological product performance). This category includes novel multisatellite guidance, navigation, and control (GNC) algorithms and autonomous capabilities for various applications such as on-orbit servicing, space domain awareness (SDA), Earth monitoring, and space science; in-space servicing, assembly, and manufacturing to support satellites in orbit; space-based solar power; plasmas for high specific impulse, low-thrust propulsion for commercial and government spacecraft that could possibly be applied toward collision avoidance; GPS for space docking and on-orbit services; the Wide Area Augmentation System (WAAS) to improve the accuracy available from GPS alone; and high-density energy harvesting in space from meteoroid collisions.

Space systems are in the midst of a revolution in philosophy and approach. When the space age started in 1957, with the launch of Sputnik 1, national governments were the sole operators of space vehicles. These vehicles tended to be large, heavy, and expensive; they were intended to last in space for extended periods (decades in some cases) and were launched relatively rarely. Such vehicles are still important, yet a new approach is taking hold: smaller, less expensive, and easier-to-launch satellites working together are increasingly common. Small satellite ("smallsat") constellations support many applications, including synthetic aperture radar (SAR), multispectral imaging, PNT, and SDA. In addition, space launch capabilities are increasingly shifting to the private sector, at least in the United States.

Research

All of the items above are subjects of active research across the entire field of space technology. Traditional challenges for spacecraft include size, weight, and power (SWaP) limitations, extreme environmental conditions, and limited situational awareness. For sensors and instrumentation, the challenges are stability, precision, and sensitivity. For plasma, there remain many questions about the fundamental physics of how plasmas behave, especially in space. Scalability of space services (which can mean growing a large satellite constellation or creating in-space manufacturing facilities) is a significant problem. For microgravity in-space manufacturing, the challenges are getting the hardware into low Earth orbit (LEO), having a sustainability model, and having access to elements in space.

At Stanford, a substantial amount of research focuses on multisatellite autonomy; in-space logistics, servicing, assembly, and manufacturing; sustainability; and spacecraft systems and structures. Other research focuses on providing services for earthbound users.

Multisatellite Autonomy

The technical challenges of operating satellite constellations for a given application are complex. Multisatellite, or distributed space systems (DSS), autonomy aims to overcome the key limitations of current technology in three main areas: the resolution and high-contrast imaging of current instrumentation in space; mission lifetime and available fuel in space; and the trade-off between signal-to-noise ratio and coverage provided by current satellite systems (satellites closer to Earth offer stronger signals but have less coverage). Multisatellite systems promise breakthroughs and new capabilities to overcome these limitations in three major sectors: Earth and planetary science and remote sensing; astronomy and astrophysics; space logistics, infrastructure, in-orbit servicing, and SDA; and space-based solar power. The competitive advantages and benefits of multisatellite systems include sustainability on Earth and in space and also climate science and disaster risk reduction, mitigation, and prediction. Such systems enable intelligent data gathering and the development of new fundamental knowledge, which can then be applied in multiple sectors.

Regarding multisatellite autonomy, challenges and advances are present in all elements of the GNC autonomy pipeline. In general, tasks that in the past were accomplished on the ground by humans are being automated and transferred so that they are on board the space segment. These include autonomous guidance and decision making; constrained optimal control with diverse propulsion technologies; navigation around known or unknown and cooperative or noncooperative targets with various metrologies; dynamics modeling around Earth and in the three-body environment; the matching of requirements of miniaturized low-SWaP and commercial off-the-shelf technology (e.g., microprocessors, bandwidth, power, actuation, etc.); systems engineering to integrate requirements of multisatellite payload and GNC; and integration of artificial intelligence (AI) into all elements of the GNC pipeline.

Professor Simone D'Amico is focused on advancing multisatellite autonomy.[1] Research on autonomy in the Stanford Space Rendezvous Lab (SLAB) has four key pillars: the design of new mission concepts; the development of new multiagent algorithms for space applications; the training and validation of the new algorithms using robotics and virtual/augmented reality; and the embedding and integration of the new algorithms into real space missions as flight software. In the short term, the objectives of this research are to support the operations of challenging multisatellite missions, support the validation of the algorithms in orbit, and maximize the broad impact by making the codebase open-source. In the medium term, the research supports the commercialization efforts and fielding of the new algorithms in collaboration with industry. In the long term, SLAB seeks to realize its own visionary mission concepts (recognizing that this realization has both competitive and political aspects) and to make advanced autonomy algorithms and AI viable for space.

AI is appealing for many space applications because its predictions require low computational power compared to conventional techniques. This tends to make AI-enabled applications more suitable for real-time operation. Computational tasks that typically cannot be performed online using conventional

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techniques can be efficiently performed offline and executed aboard a space vehicle using AI. For example, AI can be used to generate high-quality trajectory candidates as starting inputs into conventional trajectory optimization algorithms, significantly reducing the computational effort needed to find optimal trajectories.[2] Such capabilities affect the complete GNC pipeline, as well as the decision-making chain. AI is an enabler for multisatellite autonomy in many areas: mission planning; controls; navigation; fault detection, identification, and recovery; and payload autonomy.

In-Space Logistics, Servicing, Assembly, and Manufacturing

To sustain operations in space, the United States needs an infrastructure similar to what it has on the ground for road and air traffic service and management. Such an infrastructure requires cheap, quick, reliable access to space and the capability to approach, inspect, assess damage, repair, prolong the lifetime of, retire, or remove space assets without jeopardizing the space environment. This includes eyes both on the ground and in space to monitor and avoid surprises. Approaching and responding to objects in space is particularly challenging, especially when those objects are noncooperative or are partially or fully unknown targets.

This logistical infrastructure—increasingly the province of new private-sector companies—is generally referred to as in-space servicing, assembly, and manufacturing.[3]

- Servicing includes repairing, upgrading, and resurrecting satellites. A good example is satellite refueling. Even if all other parts of the satellite are fully operative, a satellite without fuel will rapidly become useless, and in-space refueling allows the satellite to continue operation. In-space servicing refers to any work to refuel, repair, replace, or augment an existing asset in space and enable both life extension and upgradability as technology evolves on Earth.

- Assembly involves putting together multiple parts in space that have each been individually launched from Earth to form a single, functional aggregate structure. In-space assembly facilitates the construction of large structures, such as habitats beyond LEO. It is also necessary for building large telescopes and other platforms that would otherwise be impossible to launch due to size constraints.

- Manufacturing is the fabrication of components in space as the need arises. Often based on 3-D printing, in-space manufacturing potentially enables space vehicles to avoid the need to carry repair parts into space. It also allows the in-space production of large monolithic structures, such as jointless thirty-meter truss beams and the restoration of optically or thermally relevant surface coatings.

Through the lens of multisatellite autonomy, D'Amico studies the development of capabilities to service, repair, and refuel resident space objects (both cooperative and noncooperative).

Sustainability

Space research examines sustainability from two different perspectives. The first is that of in-space sustainability—what is needed to ensure that near-Earth and cislunar orbits, as finite resources, can continue to be usable for the long term. The second is that of on-Earth sustainability—how space technologies can be used to support sustainability efforts on Earth. Together, these two perspectives create what is known as the space sustainability paradox:[4] the situation in which "the increased use of space to support sustainable development [i.e., the second perspective] leads to heightened adverse impacts to both the space and Earth environment [i.e., the first perspective]."

In-space sustainability entails issues such as debris mitigation, prolongation of the lifetime of space assets, and space traffic management. Professor Sigrid Elschot studies the impact of the space environment on satellites, including the electrical effects of meteoroid and debris impacts.[5] In addition to SDA, D'Amico studies improved GNC and onboard autonomy to mitigate the risk of collisions in space.

On-Earth sustainability efforts are greatly enhanced by space technologies, specifically remote sensing. Remote sensing measures physical characteristics of an area on Earth by detecting, often from space, radiation reflected and/or emitted from that area at a distance. Many things can be detected this way, including the movement of vegetation cover, forest fires, deserts, weather, glaciers, city or farmland boundaries, temperatures, and elevation from sea level.

Satellites offer many advantages for remote sensing. They can gather images of a given area more rapidly than airplanes can, and they can do so without the permission of the government responsible for those areas. Especially when equipped with SAR, a satellite constellation can provide 24-7 global remote sensing capabilities irrespective of weather and illumination conditions. However, their distance to the target area from LEO is large enough to have a negative impact on resolution. D'Amico's research on multisatellite autonomy directly enables a number of smallsats working together to produce higher-resolution images than a single satellite might generate through various forms of interferometry. These techniques can also be used for high-contrast imaging for heliophysics applications and direct exoplanet imaging.

A second example is Professor Dustin Schroeder's work with ice-penetrating radar.[6] Schroeder gathers data on and helps to predict the movement of the large ice sheets and glaciers in the Antarctic region and Greenland. These ice masses influence climate conditions globally, including the rate and extent of sea level rise. Through this research, he is developing measurement techniques for things that move and change very slowly; these techniques can also be used across a wide variety of civil, defense, and environmental applications, particularly those that involve specific observational targets or that are otherwise too expensive to pursue. Beyond Earth, he uses these techniques to investigate the question of habitability on icy moons like Europa and Ganymede or even on Mars.

Spacecraft Systems and Structures

Through advanced engineering and design, experts at Stanford are contributing to the development of more advanced spacecraft. Components of such spacecraft include satellite buses that can withstand more extreme environments, deployable structures, energy storage and generation systems, propulsion systems (e.g., plasma-based propulsion systems), GNSS and GPS technology, and atomic sensors.

Space labs at Stanford are making spacecraft tolerant to more extreme environments, more precise, more accurate, and more robust against failure.

- Professor D'Amico is working to improve navigation techniques based on differential GNSS, spaceborne vision, and their fusion. These allow sub-centimeter relative navigation accuracy in space at high dynamic range with respect to both cooperative and noncooperative targets. Such accuracy is a prerequisite for high-precision DSS applications such as telescopy, Earth monitoring, and on-orbit servicing. D'Amico is the Stanford principal investigator of several satellite swarms that use the technology developed in his lab, including the National Aeronautics and Space Administration's Starling (launched by NASA in July 2023), and the National Science Foundation's Virtual Super Optics Reconfigurable Swarm and SWARM-EX missions (both NSF missions due to launch in 2025).

- Professor Debbie Senesky researches materials and electronic devices to advance space missions.[7] She has studied the influence of extreme environments on materials and electronic devices such that they can withstand environments far beyond Earth.

- Professor Elschot's research focuses on the impacts of meteoroids and debris on spacecraft. She investigates many aspects of this phenomenon, from the initial formation of plasma upon impact to potentially harnessing the resulting energy for propulsion or power generation. A key area of study is the ionization and plasma dynamics (and the resulting electrical effects) that occur in the vicinity of the spacecraft during these collisions with meteoroids and debris. This work aims to enhance our understanding of these high-velocity impacts and their effects, with potential applications in spacecraft design and operations. For example, it may be possible to harvest the energy of a high-speed meteoroid impact on a space vehicle from the electromagnetic pulse generated by such an impact. If this is feasible, satellites could operate in applications where solar or nuclear power is unavailable.

  She does related research in observing the atmospheric entry of meteoroids and debris particles, examining how they might disrupt communications with spacecraft. These phenomena are related to objects traveling at hypersonic speeds—for example, when an object reenters the atmosphere from space, a dense plasma sheet forms around the object that creates a communications blackout with the object.

- Professor Manan Arya does research on space-deployable structures that can change shape.[8] For example, the accuracy and resolution possible from optical, radio, and radar instruments increases with aperture size. But launch vehicles are limited in the size of instruments that they can carry into orbit. One solution to this problem is to develop instruments (more specifically, reflectors for these instruments) that can be mass-produced and folded into smaller volumes for launch and then unfolded (expanded) once in orbit. Especially when these instruments operate at high frequency (as they must for high resolution and penetration through the lower part of Earth's atmosphere when necessary), there is a high premium on precision and stability to maintain optimal accuracy.

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The techniques developed for folding and unfolding reflectors are also useful in certain shape-changing applications for space robotics, such as stowing solar panels for improved maneuverability or reducing structure cross sections to reduce the likelihood of meteoroid impacts. A key goal is to create foldable reflectors with solid surfaces made from carbon fiber composites that can be oven-baked and folded without labor-intensive assembly using fragile mesh materials. This would enable a repeatable molding process for mass production and significantly reduce costs for communications and remote sensing satellites.

- Professor Mark Cappelli is developing new electrothermal plasma engines to perform station keeping and orbit transfer, as well as space propulsion.[9] Plasma engines have many advantages over chemical rocket engines, including, most importantly, a much more efficient use of fuel to generate forward thrust. Plasma engines could thus achieve a much higher velocity from a given mass of fuel than is possible with chemical rocket engines.

Services to Earthbound Users

IN-SPACE PRODUCT MANUFACTURING

Certain products are more easily grown or fabricated in the zero gravity environment of space. For example, manufacturing facilities in space are able to produce crystals that are larger, more well-ordered, more uniform, and freer of defects. Materials synthesized under these conditions have potential applications for pharmaceutical products and semiconductors. Senesky researches nanomaterials and semiconductor manufacturing in LEO. One example project is a graphene aerogel collaboration with Redwire Space. Graphene oxide flakes and water are sent in vials to the International Space Station (ISS) and heated to form the aerogel. The idea is to send the materials to space and then bring them back to study the influence of microgravity. Other things one could manufacture better in space than on Earth include large silicon ingots, small perfect films, and sensors (e.g., flexible strain sensors, magnetic field sensors, and Hall effect sensors).

GNSS AND GPS ROBUSTNESS

Earthbound users are highly dependent on space-based PNT services offered by the United States' GPS. Thus, increasing the robustness and protection of GPS navigation is a high national priority. Professor Todd Walter's expertise is in GPS: how it operates, its risks and weak points, and how to protect it.[10] For the use of GPS to guide aircraft, for example, he developed a method for assigning a box around a known position within which the aircraft is guaranteed to be located. This guarantee is based on the redundancy of GPS, or the likely availability of a number of satellites in excess of the minimum number needed for basic information about an object's position and velocity.

Another method to improve robustness of position-finding systems for aircraft is the ground-based augmentation system, wherein infrastructure at every airport provides position and error bounds. This approach provides sufficient precision for a fully automatic (unassisted by a pilot) landing. Finally, a satellite-based augmentation system (known in the

United States as WAAS) provides similar functionality that can be used in locations other than airports. Almost all WAAS integrity algorithms were developed at Stanford in cooperation with other organizations.

Walter was a principal player in the development of Xona, an alternative GNSS constellation with security enhancements that better protect its signals compared to traditional GPS signals. The fundamental approach is based on the fact that Xona satellites are in LEO, while GPS satellites are in considerably higher orbits; Xona signals are therefore stronger on Earth and thus better protected against jamming. He was also active in developing navigational applications based on Starlink, OneWeb, Iridium, and other communication satellites, even though these systems were not originally designed to support navigation.

Organization

Research in space involves a choreographed relationship between universities, industries, and government (especially national laboratories). Maintaining this three-way relationship is important to driving US leadership in the sector. Grant programs like the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, NASA's Innovative Advanced Concepts, and the National Science Foundation's Innovation Corps are a vital part of this ecosystem.

For example, government actors often move more slowly than universities and industries with respect to innovation, adopting an innovation only when tried-and-true techniques prove nonviable or cannot meet any requirements. However, SBIR and STTR grants require cooperation between academia and industry. Through these grants, the government offers money that is split between private industry and academia to solve technological problems; as a result, flight demonstration and commercialization follows more rapidly than it would if government alone were involved.

The Stanford space research community has historically focused on Pasteur's quadrant (i.e., the conduct of use-inspired basic research). As opposed to basic research that makes no purpose-driven discoveries, Stanford research is able to make and discover for a purpose. This means the university is generative, responding to the needs of industry or an application area and answering the fundamental questions in a scholarly way.

For example, the Stanford Center for Aerospace Autonomy Research (CAESAR) starts operations on May 22, 2024, with the aim to advance the standard for infusing autonomous reasoning capabilities into aerospace systems. The center will focus on spearheading foundational technologies to enable trusted deployment of AI tools; developing novel

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algorithms at the intersection of GNC and machine learning to enable future DSS and space robotics tasks; and training and validating the new technologies through first-of-their-kind hardware-in-the-loop demos and space missions. CAESAR links industry, academia, and government to enable trusted aerospace autonomy and multiagent capabilities. It also fosters new talent to achieve rapid innovation in a unique environment that implements the full project cycle, from vision to spaceflight, iteratively.

The Federal Aviation Administration Center of Excellence for Commercial Space Transportation was active from 2009 until 2022; it included Stanford research on risk assessment to spacecraft and on responsive airspace management for minimizing the impact of increased spaceport activity due to new space operations.

Stanford's partnerships with national labs and government agencies also include D'Amico's work with NASA and the NASA Jet Propulsion Lab (JPL), the European Space Agency (ESA), the National Science Foundation, the Air Force Research Laboratory and the Air Force Office of Scientific Research (AFOSR), and the US Space Force; Senesky's experiment on the ISS National Lab; Arya's work with the NASA JPL on astrophysics and earth science; Schroeder's radar work with NASA on the Lunar Reconnaissance Orbiter and with ESA on the Europa Clipper mission; Cappelli's work with both the National Ignition Facility on fusion energy research and also with AFOSR; and Walter's GPS collaborations with the US Departments of Defense, Transportation, and Commerce.

Finally, Stanford has many collaborations with space-focused private-sector firms. Industry benefits from robust academic research because a profit motive can impede necessary fundamental research and preclude technology development. Private companies need both a business case (economic viability) and a competitive advantage (through intellectual property) to develop new technology. Public entities, meanwhile, focus more and more on activities that are not in competition with the private sector. Public entities are also more risk averse because of the political blowback accompanying taxpayer-funded failures.

At Stanford, there are many examples of fundamental research that supports the private sector, as well as examples of partnerships with private companies. These span such research topics as smallsats and autonomy, propulsion systems, and GNSS and GPS.

- Satellite miniaturization and the development of smallsats in LEO is an important private space-sector trend supporting the new space economy; there are hundreds of companies in the sector. The CubeSat, a standard form factor smallsat that can be built and launched at low cost and at scale, originated at Stanford. Increasingly, constellations of these and other smallsats downlink multisensor measurements, GNSS, communications, and research. Stanford research is supporting satellite constellation design and operation by advancing spacecraft autonomy, GNC, and decision making for DSS.

- The private launch-industry efforts to reduce cost per kilogram to orbit are also making it easier for academia to get into space. Stanford labs are launching research missions on smallsats. Undergraduate students of the Stanford Student Space Initiative are launching and operating CubeSats, accessible at ultralow cost with open-source spacecraft designs. Thus, mutual advancements in the private sector and academia are together making space more and more accessible. D'Amico is partnering with and advises private entities—including start-ups like Ten One Aerospace and Infinite Orbits (whose business cases are on-orbit servicing), Capella Space (which builds and operates a remote sensing SAR constellation), Reflect Orbital (which works in space-based solar power generation), plus larger companies like Blue Origin and Redwire Space—to develop the next generation of GNC algorithms and multisatellite autonomy.

- Many private companies are active in propulsion research. These companies include established defense contractors and private launch providers, as well as engine start-ups looking to perfect liquid and solid rocket engines. We see private companies flying Hall thrusters (for example, SpaceX flying krypton Hall thrusters on Starlink satellites), but Hall thrusters were developed in both university and government settings, with notable contributions from Professor Kentaro Hara and Professor Cappelli. In industry, there has been a slow evolution of electrical propulsion technologies moving from arc jets to Hall thrusters.

- Walter's GPS Lab is working with private companies including Trimble and NovAtel; the latter is a Canadian company that provides services to farmers and is moving toward providing integrity bounds for automobiles (as is already done for airplanes). Lockheed Martin consulted the Stanford GPS Lab after Brexit, which caused the United Kingdom to lose access to the inner workings of Galileo, the European Union's GNSS, leading the country to want its own regional system.

Public Policy Issues

National Security

The areas of challenge for national security in space are mainly in global tracking and spacecraft identification, autonomous GNC capabilities, and resilience to potential attacks. Cybersecurity for spacecraft is underprioritized, and in the past academia has been excluded from the conversation. The topic of data encryption for telemetry and telecommand and for authentication codes, such as Chimera (Chips-Message Robust Authentication) for GPS, is currently getting a lot of attention. Passive devices that do not emit electromagnetic signals in optical and radio frequency spectra are also of interest at the moment due to their low power consumption and stealth potential.

Indicators of attack on the space segment are problematic today. It's currently difficult to distinguish an anomaly caused by the space environment from one caused by a direct attack—for example, a meteoroid hitting a satellite may look the same as a kinetic anti-satellite weapon hitting it. Satellites can be instrumented better to differentiate between such events (for example, a kinetic energy anti-satellite weapon would likely hit the satellite at significantly different speeds than a meteoroid would, and the difference in speed could be detected), but such instrumentation consumes size, weight, and power on spacecraft that satellite owners would prefer to use for other purposes. Elschot is developing instrumentation analogous to an airplane's flight recorder to help determine the cause of an anomaly or a failure in a satellite. This work entails the use of machine learning to predict what impactors are most likely to disrupt satellite operations.

A second national security issue revolves around the global navigation satellite systems, which can be subjected to spoofing (i.e., the broadcasting of fake signals that trick earthbound receivers into reporting positions that are incorrect). For example, areas around the Kremlin in Moscow are being spoofed, apparently to protect leaders, such as Vladimir Putin, from drones or other weapons that might be guided by GPS. Observed spoofing incidents in China are harder to explain—China's automatic identification system (AIS), which broadcasts the positions of boats, has been reporting that vessels are circling on land near Shanghai and other locations. It is unclear whether this is an attempt to hide activities, undermine confidence in the system, or something else entirely. The Chinese state likely wants ships to use AIS, so it is unknown if these incidents are perpetrated by local criminal elements or state-sponsored actors. Apart from foreign government actors, one of the driving forces behind the rise in popularity of spoofing has been the augmented reality mobile game *Pokémon Go*. The game incentivized users to spoof their locations to collect Pokémon that were not available in their

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actual geographic area, providing both a reason and tools for spoofing.

It turns out that the approach used in Schroeder's lab to obtain high radar sensitivity can also be used to improve the performance of sensors to such an extent that it may be possible to detect radar signals based on reflections from ambient radiation, such as those potentially available from the sun. In other words, such radar would be passive and hence undetectable in operation, in contrast to present-day radars that rely on the active emission of radar beams to generate reflections from possible targets.

Through NASA's Starling mission, D'Amico is demonstrating an alternative space-based PNT system through a distributed optical navigation payload based solely on passive cameras. In fact, objects resident in space can be regarded as beacons emitting in various bands of the electromagnetic spectrum. If an observer satellite can associate the resident space object to a catalogue of space objects, then bearing angle measurements can be used for self-localization.

On-Earth Sustainability

Multisatellite systems can generate data to create a digital twin, or representation, of Earth for disaster prediction, prevention, monitoring, mitigation, and recovery. From space, we can seek a holistic understanding of Earth as a dynamic system governed by feedback mechanisms. The usage of multiple spacecraft for remote sensing allows for measurement of Earth's shape and gravity, high-resolution imaging, tracking changes, and much more. Multisatellite systems such as constellations and formations already play a vital role in gathering sustainability data, and they will play a bigger role in future efforts toward Earth's digital twin.

With Earth rendered as a "digital computer," we can simulate and predict behavior, forecast disasters, and so forth. We can understand Earth science and global processes as either natural or human. Multiple relevant remote sensing technologies are enabled by multisatellite autonomy. These include synthetic interferometers (e.g., SAR) and gravimeters. These technologies can also aid in space weather and physics research (e.g., characterizing the upper layers of the atmosphere or obtaining high-resolution images of the sun to understand energy release mechanisms).

Glaciology and ice remote sensing contribute to the management of water resources and the understanding of sea level rise. In regard to the former, the water supply in many locations on Earth, such as mountainous areas like the Andes or the Alps, depends on glacial melt, so the rate at which glaciers melt is obviously a public policy concern. Concerning the latter, sea level rise has a significant impact on infrastructure and security.

In-Space Sustainability, Debris Management, and Space Traffic Management

Outer space is obviously quite capacious, so it is difficult to conceive that space is not an unlimited resource. But any given orbit around Earth (and any other celestial objects) has a finite capacity for the number of satellites it can hold while guaranteeing safety; exceeding that capacity is likely to lead to a cascade of collisions that generate debris in quantities large enough to cause severe damage to other satellites (a phenomenon known as the Kessler syndrome). This would lead to a chain reaction and render space potentially unusable for generations to come.

LEO presently contains the vast majority of satellites and is the most likely destination for space operations in the foreseeable future. Debris management—the task of minimizing the amount of human-generated debris in LEO—is thus a particularly important public policy issue that is fundamentally international in scope. As with the climate crisis, it will take diplomacy for the major spacefaring nations to work together on curbing space debris and managing space traffic.

Similar considerations apply to space traffic management, for which a system does not exist today. Current behavior in space is based on guidelines and a code of conduct, but neither is binding on spacefaring nations. Possible responsibilities of a space traffic management system include enforcing rules of conduct, introducing space-traffic-footprint sustainability metrics similar to a carbon footprint, removing nonconsensual debris, enforcing transparency, and facilitating the exchange of data. In-space sustainability can also be supported through technology development for tracking, servicing, and debris removal capabilities, as well as by making all spacecraft serviceable and capable of autonomous collision avoidance.

International Competition

GLOBAL NAVIGATION SATELLITE SYSTEMS

The European Union and China have developed their own GNSS, called Galileo and BeiDou, respectively, which offer more innovative and accurate signals than the United States' aging GPS. Unlike GPS, which must maintain backward compatibility with 1970s technology, Galileo and BeiDou can implement modern advancements without such constraints. China aims to reduce reliance on the United States' GPS, especially for military applications, and can offer enhanced services to companies through BeiDou.

The European Union has taken an innovative approach in its commitment to Galileo. For example, it is integrating Galileo into its rail infrastructure, whereas in the United States, the responsibility for similar actions lies entirely on the railroads themselves. The European Union also boasts a larger talented workforce

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Integrating the EU and Chinese GNSS alongside GPS requires significant effort, and seamless integration of multinational GNSS poses an immense technical challenge. The European Union has made early strides in GNSS signal authentication for safety. Last year the European Union and China made commitments to the International Civil Aviation Organization regarding the trustworthiness of their systems, though these were not as stringent as longstanding US military assurances for GPS.

As the capabilities of other GNSS mature, the United States risks falling behind if its funding and talent development don't keep pace with the accelerated innovation of the European Union's and China's programs.

PRESENCE IN SPACE

Regarding a permanent crewed presence in space, China and some Middle Eastern nations have announced ambitious plans to establish their own space stations. Geopolitical considerations can be expected to become increasingly important as the United States forges ahead with initiatives related to in-space manufacturing. Russia's recent decision to withdraw from the ISS has threatened the collaborative efforts of international groups that have been working together on the ISS for the explicit purpose of promoting cooperation across borders. There are numerous areas within the broader realm of in-space manufacturing—such as biology research, plant cultivation, space tourism, and asteroid mining—that could potentially yield significant benefits for stakeholders from all corners of the world if they are pursued through multinational partnerships. However, these dynamics are expected to change with the retirement of the ISS and the advent of new commercial space stations being pursued by several companies in the United States.

CISLUNAR SPACE

While definitions vary, cislunar space is generally regarded as the volume of space from geosynchronous orbit around Earth to somewhat beyond the Moon's distance from Earth. Objects traveling in this space are subject to the gravitational influence of Earth and the Moon, whereas for objects inside geosynchronous orbit, the Moon's gravitational effect can be mostly neglected for determining their orbital dynamics. (Different gravitational effects in cislunar space make the trajectories there quite different from those of objects inside geosynchronous orbit.)

The Moon offers tantalizing possibilities for mining resources in short supply on Earth (e.g., helium-3 and rare-earth metals) and harvesting solar energy unimpeded by an atmosphere or clouds. To the extent that civilian and commercial interests have a lunar presence, it may be necessary for military forces to protect that presence. Moreover, there may be advantages for a cislunar presence that directly supports military activities on Earth and in near-Earth space.

Earth-Moon Lagrange points are important because they are locations in space where the gravitational forces of Earth and the Moon cancel each other out. Objects at an Earth-Moon Lagrange point are in a fixed position relative to Earth and the Moon and can remain there with minimal fuel consumption. Satellites present at Lagrange points can be used for many purposes, such as providing early warning for solar disturbances or serving as space telescopes.

To support an international regime of cooperation in the civil exploration and peaceful use of the moon, NASA and the US State Department developed the voluntary and nonbinding Artemis Accords.[11] The signatories agree to operate in a transparent manner to prevent confusion and conflicts. They commit to supporting interoperable space systems for safety and sustainability reasons. They pledge to assist personnel in distress and provide the United Nations with details about the orbits of their launched objects. The signatories also agree to publicly release scientific information, preserve outer space heritage, extract and use space resources responsibly per the Outer Space Treaty, conduct operations that do not harmfully interfere with other nations, and plan for the safe disposal of space debris.

EXPORT CONTROLS

The US government uses export controls to promote its national security interests and foreign policy objectives.[12] However, export controls such as the International Traffic in Arms Regulations (ITAR) impose significant limitations on research, particularly in the space domain, and create substantial administrative burdens on researchers. In the academic realm, there is a lack of administrative support for large satellite projects and a dearth of engineering support for labs, particularly at Stanford, where competition with Bay Area industry presents a challenge.

A second issue is that export controls and ITAR limit international students' access to spacecraft data, experimental facilities, and funding sources. Stanford's policy on research—even for research on advanced technologies—does not differentiate students on the basis of their nationality or immigration status, in large part because Stanford believes that any student qualified to join its research programs can make important contributions to the university's research agendas. At the same time, this open research policy sometimes conflicts with program managers' and funding agencies' preferences to restrict foreign engagement.

D'Amico and Elschot have both recounted experiencing freer access to facilities and technologies while working in Germany compared to in the United States. In Germany D'Amico kept a GPS receiver without restrictions of altitude and speed on his desk to aid his research, while he says it has been hard for him to get a GPS receiver in the United States, even though GPS is a US technology. Elschot noted that in Germany there were more experimental facilities one could access for free, as opposed to comparable facilities in the United States that charge thousands of dollars a day to use.

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NOTES

1. See Professor D'Amico's publications web page at https://slab.stanford.edu/publications.
2. Tommaso Guffanti, Daniele Gammelli, Simone D'Amico, and Marco Pavone, "Transformers for Trajectory Optimization with Application to Spacecraft Rendezvous," arXiv, last revised January 5, 2024, https://arxiv.org/abs/2310.13831.
3. Jennifer M. Brill, ed., "In-Space Servicing, Assembly, and Manufacturing (ISAM)," NASA, last updated March 26, 2024, https://www.nasa.gov/nexis/isam.
4. Andrew Ross Wilson and Massimiliano Vasile, "The Space Sustainability Paradox," *Journal of Cleaner Production* 423 (October 15, 2023): 138869, https://www.sciencedirect.com/science/article/pii/S0959652623030275.
5. See Professor Elschot's publications web page at https://sess.stanford.edu/publications.
6. See Professor Schroeder's publications web page at https://www.radioglaciology.com/publications.
7. See Professor Senesky's publications web page at https://xlab.stanford.edu/publication.
8. See Professor Arya's publications web page at https://morphingspace.stanford.edu/publications.
9. See Professor Cappelli's publications web page at https://sppl.stanford.edu/publications.
10. See Professor Walter's publications web page at https://gps.stanford.edu/all-gps-lab-published-documents.
11. Gay Daines, ed., "The Artemis Accords," NASA, last updated April 19, 2024, https://www.nasa.gov/artemis-accords.
12. US Department of State Export Control and Related Border Security, "Overview of US Export Control System," 2011, https://2009-2017.state.gov/strategictrade/overview/index.htm.

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The topics covered reflect the interests of the specific Stanford faculty engaged for this effort. Had other faculty from the same departments been involved, the coverage would likely be somewhat different, emphasizing different topics and offering a different perspective on the technology landscape.

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Design: Howie Severson | Typesetting: Maureen Forys
Cover image credit: iStock.com/dima_zel

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