On the Horizon

Three Science and Technology Trends That Could Affect Society

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Cover: Illustrated depiction of examples of orbital debris mitigation, general robotics, and neural implant technology.

Source: GAO. | GAO-26-108079

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Foreword

Science and technology (S&T) are constantly evolving, and there is a need for analysis of emerging trends to help prepare us for the benefits and disruptions that they may bring. To address this need, we developed a report series focused on technologies that may develop significantly over the next 10 years. Our goal is to provide foresight into developing technologies that could have significant impacts on Americans. We are in an ideal position to inform Congress about S&T to assist them in their role in oversight, but also in evaluating technology through our technology assessment reports.

For this second annual edition of our S&T trends report, we identified and monitored developments in science, technology, and engineering that may grow over time as the United States continues to innovate. As there are many possible future trends, we did not take an exhaustive approach but identified three significant technologies we think are demonstrating progression. Periodically, we plan to add to this body of work with new technologies that show signs of maturing and appear to be benefiting from improving market conditions.

Many methods exist to identify emerging technologies, but most do not work well for our ten-year time horizon. Common methods that appear in popular literature use frequency analysis to identify trending terms. These methods can be valuable for technologies that are nearing maturity but are less effective for technologies that are 10 years out from it.

Our specific method leverages the expertise of GAO scientists and engineers to identify developing technologies that may not yet have gained popular attention but show significant acceleration in maturity. To guide our approach to horizon scanning and evaluating the technologies for this work, we followed the STEER framework. For each of the three technologies we address key elements derived from the **s**ocial impacts, **t**echnology drivers, **e**nvironment impacts, **e**conomic drivers, and the **r**egulatory landscape.

Figure 1: STEER Framework

Source: GAO (icons). | GAO-26-108079

Each of these elements plays an important role in maturing a technology and creating market conditions that can bring an innovation to the American public. Innovations do not live in a vacuum, so societal, environmental, regulatory, and other factors may also be useful to consider and evaluate for opportunities to accelerate innovation.

One important form of technological innovation is the move from specialized use in specific applications to general use across a broader range of tasks. The three technologies we selected for this year's report—neural implants for human augmentation, general purpose robotics, and orbital debris mitigation systems—are examples of such innovation. For example, neural implants have been developed to treat specific conditions, and researchers are exploring how to move beyond that to develop implants that augment human capabilities. Similarly, the field of robotics has expanded from dedicated industrial machines performing repetitive tasks to versatile systems capable of adapting to a wide range of environments. Orbital debris mitigation systems likewise are progressing from technology developed to mitigate a small number of large objects to newer systems that could potentially mitigate much smaller objects, which are significantly more numerous. As these transitions from specialized to broader applications continue, considering regulatory approaches that balance the resulting applications with public safety will be important for policymakers.

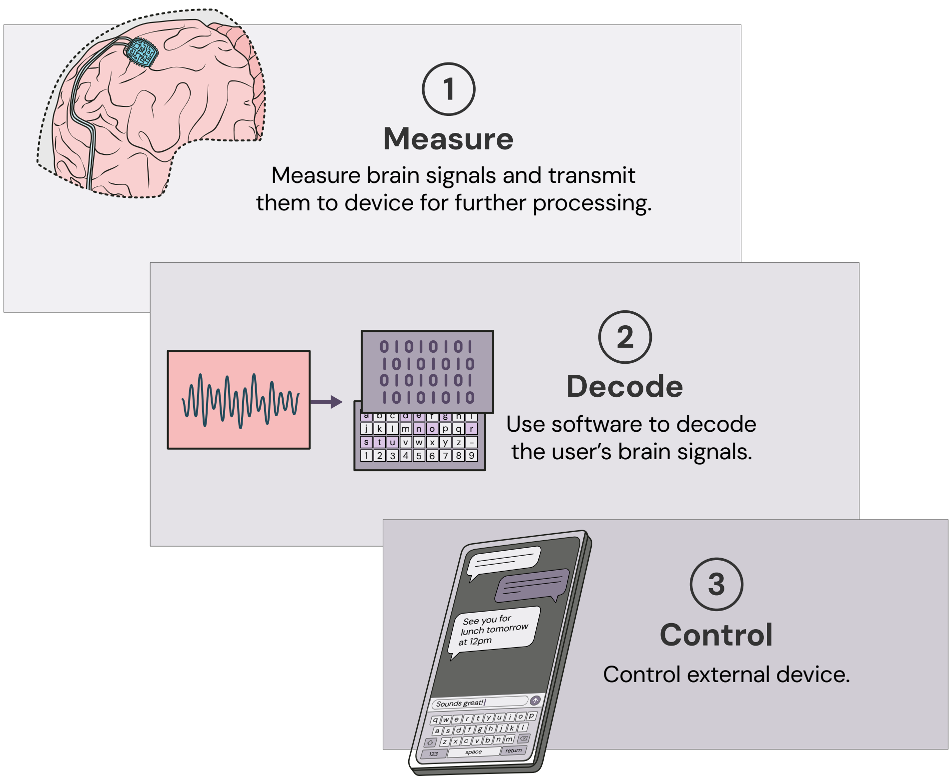
The three technologies also share commonalities in their underlying technical foundations and developmental trajectories, highlighting the fact that breakthroughs in one area can accelerate capabilities in another. For example, orbital debris mitigation systems, robotics, and neural implants all depend on advances in control algorithms, sensors, materials science, and energy storage. Additionally, progress in artificial intelligence (AI) informs development across all three fields, allowing systems to accomplish tasks in unpredictable environments, such as navigating a disaster area, interpreting brain activity in real time, or maneuvering through a congested orbit.

To conduct this work, we relied on a review of scientific literature from academic journals and position papers and held semi-structured interviews with 11 experts across the three identified technologies. The experts were selected based on the results of our literature review, previous GAO reports, and the expertise and judgment of GAO scientists and engineers. To help identify trends, we consulted internal specialists with a wide variety of scientific and technological backgrounds. We relied on our collective judgment and consideration of the collected information to describe key aspects of the technological trends, including identifying technological developments, market conditions, or economies of scale that could further accelerate the maturity of these new technologies, and considerations for policymakers, such as legislative bodies, government agencies, academia, industry, and other groups. We then developed specific scenarios for how each of our three technologies could evolve and how they might be used over the next 10 years, which may vary in scope and extent depending on the nature of the technology. Finally, we derived implications and policy considerations for policymakers based on those scenarios.

Neural Implants for Human Augmentation

Neural implants are devices surgically placed on or beneath the surface of the brain. Researchers are currently testing neural implants for medical applications in clinical trials. These implants may offer quality-of-life improvements for people living with disabilities due to neurological disorders, stroke, or injuries. For example, some implants can measure a user's brain signals and decode the intent of those signals to allow for hands-free control of devices. As of September 2024, fewer than 70 people worldwide have used this type of implant through participation in clinical trials. Other types of neural implants can send electrical signals to certain areas of the brain, altering brain activity to establish normal function (e.g., to reduce tremors in people with Parkinson's disease). While these types of neural implants are more mature relative to those that measure and decode a user's brain signals, their use is limited to conditions (e.g., Parkinson's disease or epilepsy) affecting individuals who are not responsive to other forms of treatment. More than 200,000 people worldwide have undergone a procedure to receive this type of implant.

Figure 2: Example of How a Neural Implant Could Work



Measure brain signals and transmit them to device for further processing.

Use software to decode the user's brain signals.

Control external device.

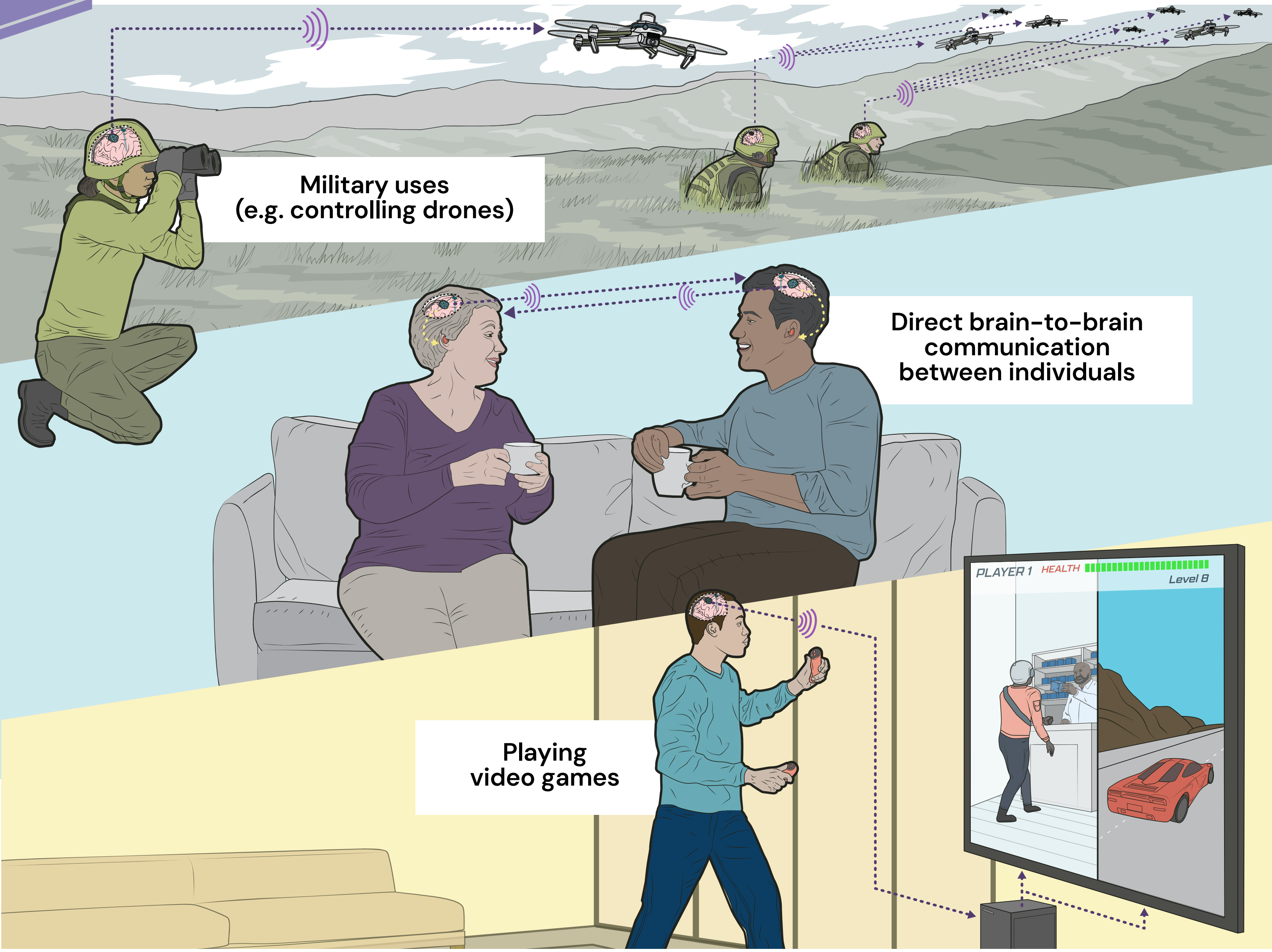
Source: GAO (illustration). | GAO-26-108079

Although the use of neural implants is currently limited to people with medical needs, their advancement through technological hurdles could enable development of neural implants that augment human capabilities (see fig. 3). For example, neural implants could eventually:

- Allow military service members to control drones, hands free
- Enable development of new types of video games that provide a competitive edge to neural implant users
- Enable real-time seamless translation between languages, eliminating language barriers to global cooperation and business
- Allow users to quickly develop new skills and abilities
- Enable direct brain-to-brain communication between individuals.

However, policies, regulations, and societal interest and concerns could affect the extent to which people use or accept others' use of neural implants that augment human capabilities.

Figure 3: Potential Future Applications of Neural Implants



Source: GAO (illustration). | GAO-26-108079

Developments on the Horizon

Technological advancements in the following three areas could shape the future of neural implants for human augmentation:

1

AI

Researchers are using AI to predict the intent of users via their brain signals in real-time, allowing faster and more flexible control of devices. This contrasts with prior efforts in which neural implant use required a more time-consuming process to calibrate the device to the user's specific brain signals.

2

Advanced materials

Advanced materials allow neural implants to measure brain signals with higher resolution while reducing risk to users. High-resolution measurement of brain signals allows researchers to more accurately decode the user's intended action. Some neural implants in development are becoming smaller and, unlike others, do not require open brain surgery. Soft, flexible, and organic materials mitigate the risks of more invasive implants. For example, in 2019, one company began in-human studies of a neural implant inserted through a vein in the neck. This implant is composed of flexible material and measures brain signals with high resolution.[1]

3

Communications

While neural implants have required wired attachment to large external pieces of equipment, researchers are developing neural implants that connect to other devices wirelessly.

These and other advances have already contributed to the development of neural implants for medical applications. For example, through participation in a clinical trial, in 2025 a person with amyotrophic lateral sclerosis (ALS) was able to use a wireless neural implant inserted through a vein in his neck to use a computer, send a text message on a smart phone, play music on a speaker, feed his dog, turn on lights, and start a robotic vacuum cleaner.

In addition to technological advances, other factors could affect development of this technology. One such factor is regulatory review. FDA currently reviews the safety and effectiveness of medical devices. As developers and FDA reviewers build consensus on methods to assess the clinical outcomes of emerging types of medical devices that include neural implants, other, similar neural implants could move through regulatory review more quickly. If certain types of neural implants for medical use become available in the market, individuals might want to use them for both medical reasons and augmentation. In the future, some individuals without medical needs might want to use neural implants solely for augmentation purposes only.

The cost of neural implants for medical use could also influence the feasibility of broader use for augmentative purposes. In 2024, we reported that public and private health care insurers may look to Centers for Medicare and Medicaid Services (CMS) coverage decisions when making their own coverage decisions.[2] Coverage of neural implants authorized for medical use could incentivize investors to further fund their development. This could lead to downstream technological advances that both push the state of the technology forward and reduce the cost of developing neural implants for human augmentation.


Source: Vadim/stock.adobe.com. | GAO-26-108079

Implications

We highlight potential implications of using neural implants for human augmentation below, assuming a scenario in which such implants are available for general consumer, occupational, and military use.

Neural implants for augmentation

SOCIAL
- Ethical issues
- Data privacy

TECHNOLOGICAL
- Device malfunctions
- Device security

ENVIRONMENTAL
- Radio signal interference in built environment

ECONOMIC
- Development linked to insurance coverage
- Increased productivity

REGULATORY
- Device safety
- Evaluation of capability claims
- Sufficient oversight tools and expertise

Source: GAO (icons). | GAO-26-108079

The following explores three of these implications in more detail.

Current privacy law may not protect neural implant users

Without clear privacy policies, data associated with neural implants could provide organizations with access to intimate information and inferences about users' emotions, attention, and thoughts. Neural data may not be protected under existing laws. In 2024, we reported that the Health Insurance Portability and Accountability Act of 1996 (HIPAA) does not cover data collected for nonclinical reasons outside of the clinical context.[3] While a patchwork of state-level data privacy laws is in place in some jurisdictions, comprehensive federal privacy legislation does not exist.[4] If an organization were to acquire data from users' neural implants, it could use those data as a tool for manipulation and control of users. For example, depending on the circumstances and legal landscape, an employer could use neural data to penalize workers who are inefficient, or even detect emotions and use them as a basis to terminate employment or deny promotions.

Neural implants may be vulnerable to a variety of attacks

Use of neural implants could expose users to new vulnerabilities. A 2018 report on dual-use neurotechnology stated that recent advances in military-funded neurotechnology, including neural implants, provided novel opportunities for misusing these devices and highlighted the inherent problem of dual use technology within the field of neuroscience.[5] If an adversary intercepted and decoded a signal to or from a neural implant, it could compromise the security and privacy of users' neural data or cause harm. For example, if an adversary intercepts signals from a neural implant user controlling a military drone, that adversary might be able to reroute or take control of the drone.

The available encryption protocols may be difficult to implement for signals relayed from neural implants. For example, neural implants that provide the user with sensory feedback (e.g., a sense of touch) must operate at a certain speed to be felt as natural by the brain. Encrypting these signals could delay the speed at which users receive sensory feedback.

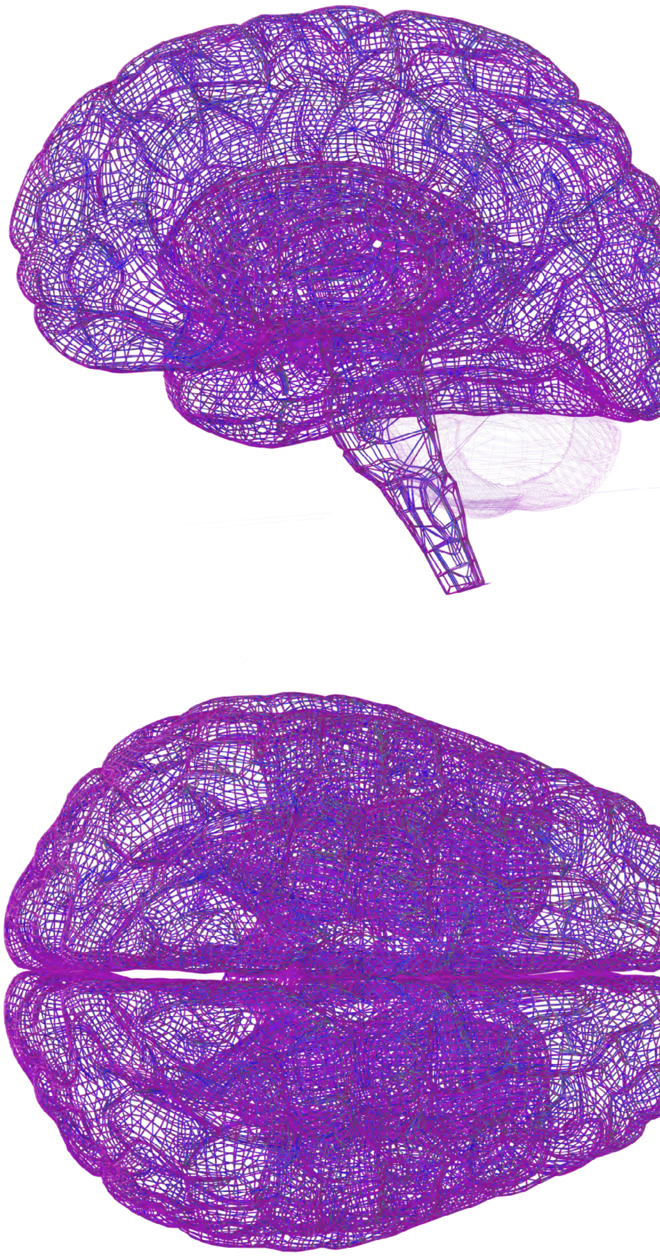
Existing medical device review process may not adequately capture nuances of non-medical neural implants

The FDA reviews products, including neural implants, that meet the definition of a medical device.[6] However, some ethicists have said that reviewing implants that augment human capabilities inherently requires risk and benefit assessments that are subjective value judgments and outside the scope of the existing FDA device approval evaluation.[7] As we previously reported, certain types of neural implants that assist a user with a disability could augment the capabilities of another user.[8] For example, a neural implant that uses AI language models to enable hands-free typing could help a user with paralysis. However, that implant could also enable a user without paralysis to work faster.

Potential Considerations for Policymakers

Policymakers may want to consider tradeoffs among a broad range of options as the technology advances. For example, policymakers could develop standards for the ethical use of neural implants. The development process could include standing up a temporary entity or commission to propose standards for ethical development and use of neural implants, along with potential mechanisms for regulatory oversight. Stakeholders could advise the commission on strategies to balance individual rights with societal interests. Once the temporary entity or commission completes its work, policymakers could consider requiring elements of the standards or oversight mechanisms included in the committee output be used by entities developing and implanting neural implants for augmentation.

Policymakers could consider steps to ensure neural implants are sufficiently secure. For example, they could consider whether neural implants should be subject to import and export controls, or whether additional controls might be necessary. The U.S. has taken initial steps in this direction, with the Department of Commerce's Bureau of Industry and Security hosting a conference with industry experts to consider the national security implications of certain types of neural implants and the extent to which export controls would be required to protect national security.[9] Export controls could prevent adversaries from acquiring and using neural implants to augment military capabilities—for example, by increasing attention spans. Export controls could also prevent adversaries from reverse-engineering the implants. For example, potential dual-use technologies, such as sensors and encryption software used with neural implants, may be subject to U.S Department of Commerce export controls to ensure national security. Import controls could prevent the U.S. government, developers, and consumers from acquiring potentially compromised components or fully assembled implants from adversaries.



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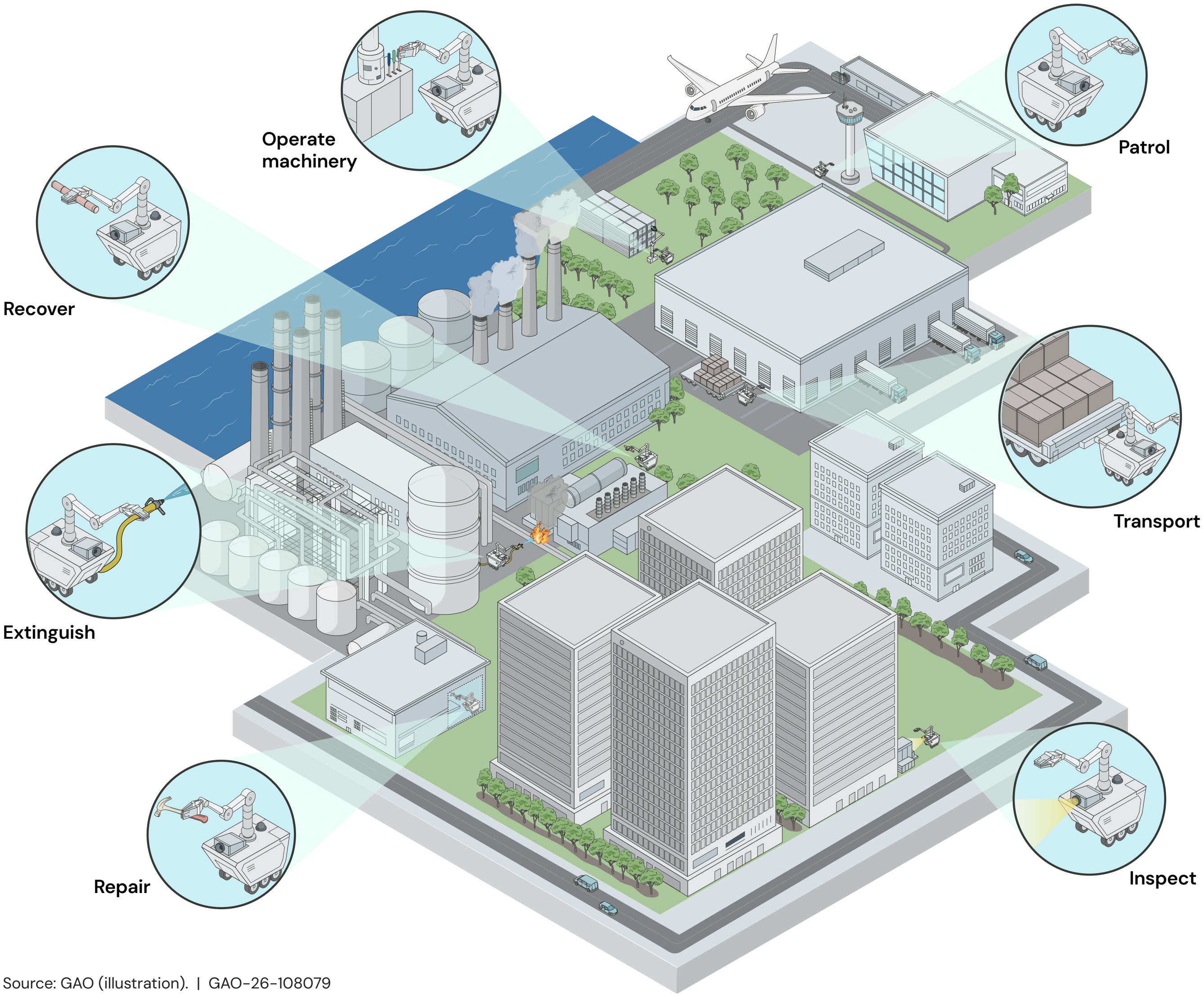
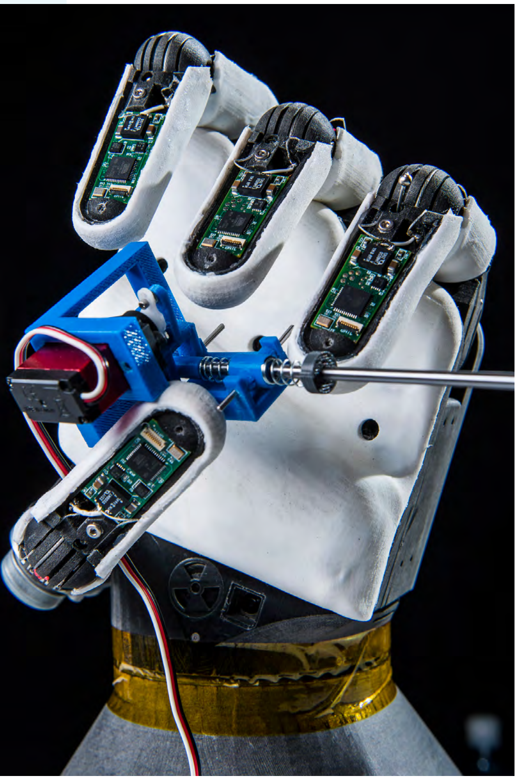
General Purpose Robotics

Robotics development has followed a similar trend to that of computers: moving from devices that perform a single task to devices that can perform many tasks. General purpose robotics represents a fundamental shift from task-specific automation to flexible, reasoning machines capable of performing a wide range of tasks in real-world environments. If the field continues on its current trajectory, general purpose robots will also be able to adapt to new tasks not previously programmed into the robot, and to do so in a range of settings rather than solely in an isolated environment like a factory or laboratory. Research and development towards more general purpose robots is focusing on robots that combine actuators and motors, sensing capability, and AI to navigate varied terrain, manipulate objects, and adapt to different tasks. These systems aim to match human agility, dexterity, and

Figure 4: Examples of General Purpose Robotics Use Cases



Source: GAO (illustration). | GAO-26-108079



The Sandia Hand addresses challenges that have prevented widespread adoption of other robotic hands, including cost, durability, dexterity and modularity.

Source: "Robotic Hand" by Sandia Labs, CC BY-NC-ND 2.0, Photo by Randy Montoya. | GAO-26-108079

versatility. Recent breakthroughs in AI have added momentum to these efforts, although significant challenges remain.

Successful development along these lines could produce robots with numerous applications. For example, general purpose robots with the right capabilities might be able to improve the safety, speed, and efficiency of infrastructure maintenance and disaster response. This is an important area of application because infrastructure needs continue to increase as populations grow and severe weather events intensify. By combining advanced sensors, AI, and mechanical capabilities with human expertise, such robots may be able to provide continuous monitoring and maintenance that could prevent small problems from becoming major failures. In addition, they may be able to autonomously respond to developing circumstances in hazardous environments, help with search and rescue operations, or assist with coordination during large-scale emergencies.

Developments on the Horizon

The following four areas of technological development could significantly advance general purpose robotics.

1 Sensor Integration

An adaptable, general purpose robot would need to gather far more information about its surroundings than a single-purpose robot. For example, a robot capable of manipulating many different objects would need visual sensors to locate objects, pressure sensors to detect contact, and force sensors to handle objects without damaging them. It would then need to combine information from these multiple sensors.

Recent advancements in semiconductors have brought this capability within reach by enabling the production of sensors with better performance, smaller size, and lower cost. However, today's robots can still struggle with accurate perception and interpretation of their environment. Additionally, some sensor types—such as force sensors at joints and pressure sensors on robotic hands—remain expensive or largely ineffective at allowing the robot to complete relevant tasks, such as those that require strong forces or gentle touches.

2 Human-Robot Collaboration

Because of their increased capabilities and adaptability, general purpose robots are also likely to interact more with people, and to do so in a greater variety of ways than current task-oriented robots. Human-robot collaboration also requires increased social communication capabilities to achieve a similar level of performance as human-human collaboration because interpreting human intentions, preferences, and contextual cues is a complex task.

In the International Space Station's Destiny laboratory, Robonaut 2 is pictured during a round of testing for the first humanoid robot in space.

Source: National Aeronautics and Space Administration (NASA). | GAO-26-108079

Furthermore, human-robot collaboration in shared spaces presents unique safety risks. For example, if robot hardware or software fails while the robot is holding a heavy object, it could injure or kill people nearby. The robot must therefore be designed to fail safely—for example, by understanding that it should never hold a large object in such a way that a loss of power would cause it to fall. Currently research focuses more on performance capability than on this need, according to robotics researchers we spoke with.

Collaboration would also require general purpose robots to adapt to human behavior and problem-solve. For example, when working with a human user to clear heavy debris, these robots would need to quickly recognize a user request to lift an object, then plan the movements needed to lift it and place it in the desired location. Given current limitations in robotic dexterity and problem-solving, one strategy would be to allocate simpler tasks to robots. For example, a person could select the debris to be moved and its destination, and the robot could do the heavy lifting. In addition, the level of autonomy of operation for such robots could be flexibly adjusted depending on the safety and risk factors involved in a task. There are a variety of ways of accomplishing this. One study described how an autonomous firefighting robot might adjust its level of autonomy depending on the situation—for example, by operating autonomously for low-risk tasks but waiting for a human operator to make decisions about high-risk tasks.[10]

3

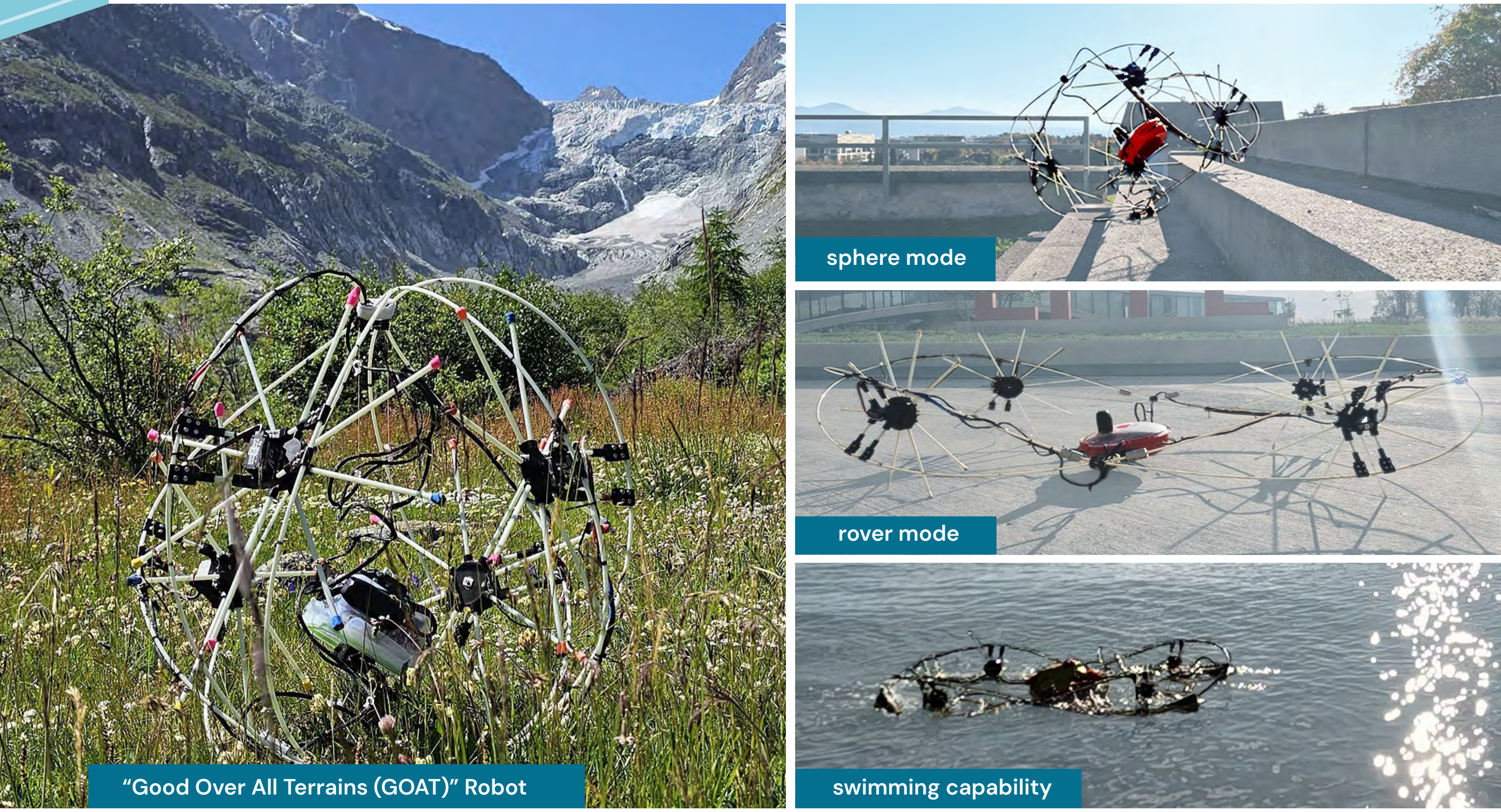
Hardware-Software Co-Development

The technological sophistication of robots can grow more effectively with a stronger connection between hardware and software. To accelerate the development of general purpose robots, developers will therefore likely need to develop hardware and software together, in an iterative cycle of design, development, and deployment. For example, developers of a new type of robot might want to create a digital environment to simulate and assess the abilities of a particular combination of hardware and software before building the hardware. The developers could then iteratively adjust the hardware and software specifications as they better understand the capabilities and limitations of the robot. This approach may also help to avoid the need for late-stage hardware redesigns, potentially reducing development costs.

Co-development can also expand robot capabilities; for example, developers could reduce the amount of computation needed to accomplish complex tasks by changing the physical structure of a robot.[11] In one such scenario, the computationally intensive task of traveling over complex terrain can be simplified by abandoning the design template of the human body. A robot body with two rigid legs can require very complex software to handle all possible terrain changes. Alternative designs and materials can solve such problems more efficiently. For example, researchers have built a "Good Over All Terrains" (GOAT) robot that can tackle difficult terrain by changing shape (see fig. 5). The shape change allows it to roll when going downhill, then switch back to active driving on flat ground or when climbing. This design improves speed and efficiency, while reducing the complexity of the software.

The field of autonomous, form-changing robots has arisen from elements of three emerging fields: modular robotics, soft robotics, and hardware/software co-design research. Research is making progress in demonstrating proof-of-concept systems such as GOAT, but widespread adoption faces substantial technical, computational, and materials science challenges. According to two researchers we interviewed, shared infrastructure that could resolve some of these challenges is lacking.

Figure 5: The Experimental Shape-Shifting “Good Over All Terrains (GOAT)” Robot



Source: © Computational Robot Design & Fabrication Lab (CREATE), Swiss Federal Institute of Technology Lausanne (EPFL); School of Engineering (STI); https://actu.epfl.ch/news/morphing-robot-turns-challenging-terrain-to-its-ad/; This content is distributed under a Creative Commons CC BY-SA 4.0 license; GAO (labels). | GAO-26-108079

4 AI for Robotic Software

Integration of AI foundation models such as large language models (LLM) and vision language models (VLM) into robot software is driving a rapid shift towards general purpose capabilities.[12] Previous generations of robot software were task-specific—divided into modules tailored to specific tasks (e.g., perception, planning, actuation modules). Robot software can leverage foundation models in two ways:

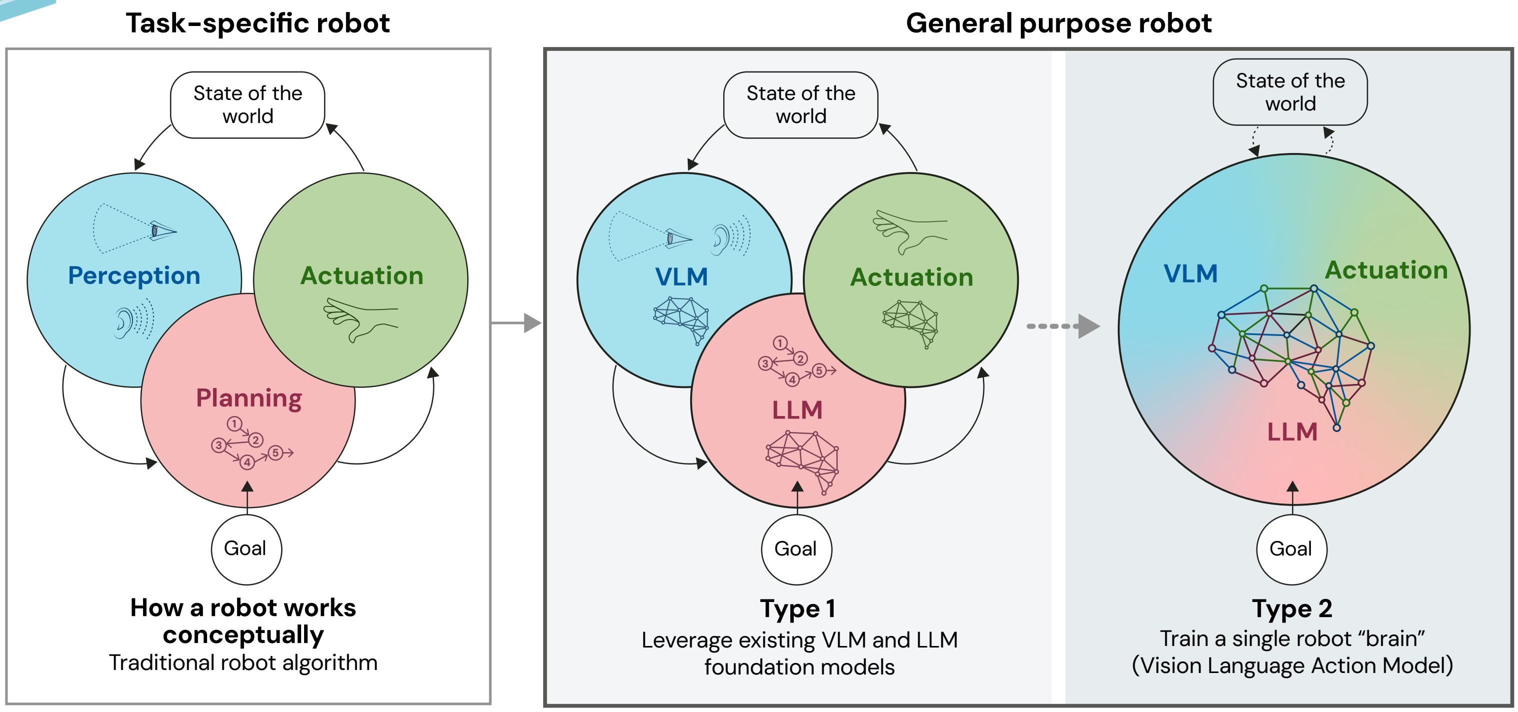
Independently use existing models

For example, a software module designed for perception can leverage a VLM to enable the robot to understand its surroundings using visual data (see fig. 6, "Type 1"). A module devoted to planning can then use an LLM to act like a brain, enabling the robot to communicate and plan a task based on a natural language prompt. For example, if a robot receives the command "bring me the coffee from the table", it would use its VLM-based perception module to understand what is on the table (e.g. a glass of soda and a cup of coffee). It would then use its LLM-based planning module to break down the task into small, actionable steps, such as picking up the cup of coffee, avoiding the glass of soda, bringing the coffee to the user, and putting it down within reach. However, effectively translating the high-level task plans to generate the low-level action commands on robot hardware remains a challenge. Existing LLMs and VLMs are not developed specifically for robots, which may cause them to give high-level commands (e.g., pick up the cup of coffee), without specifying more precise movements or considering the robot's current state (e.g. coffee cup slippage due to insufficient grip force). There are details the robot will need to incorporate into its model to be successful, such as whether a cup will be in arm's reach or whether the robot should wait to grasp the coffee cup until brewing is complete. In addition, sequential communication among VLM, LLM, and actuation submodules may cause delays. For example, the software might first engage the VLM to detect a cup, then the LLM to develop a plan, then the actuation module to use a robot arm to pick up the cup. Passing information among the models requires additional processing. By the time the plan is complete, the coffee cup might have been removed from the table by other people.

Create a unified robot foundation model

To solve the challenges described above, researchers have trained foundation models specifically for robots. One group of researchers merged VLM, LLM, and actuation modules into a vision language action (VLA) model.[13] Such models enable robots to jointly perceive, plan, and act, and to use real-time feedback to adjust their behaviors (see fig. 6, "Type 2"). The VLA model can directly output precise actions based on vision and language inputs, resolving the problem faced by robots that use a combination of independent models. For example, in the coffee pickup scenario, if the cup is moved, the VLA model can directly get the real-time update and adjust its grasp trajectory accordingly. This behavior mimics human adaptability and overcomes type 1 robot's pipeline-based delay issues.

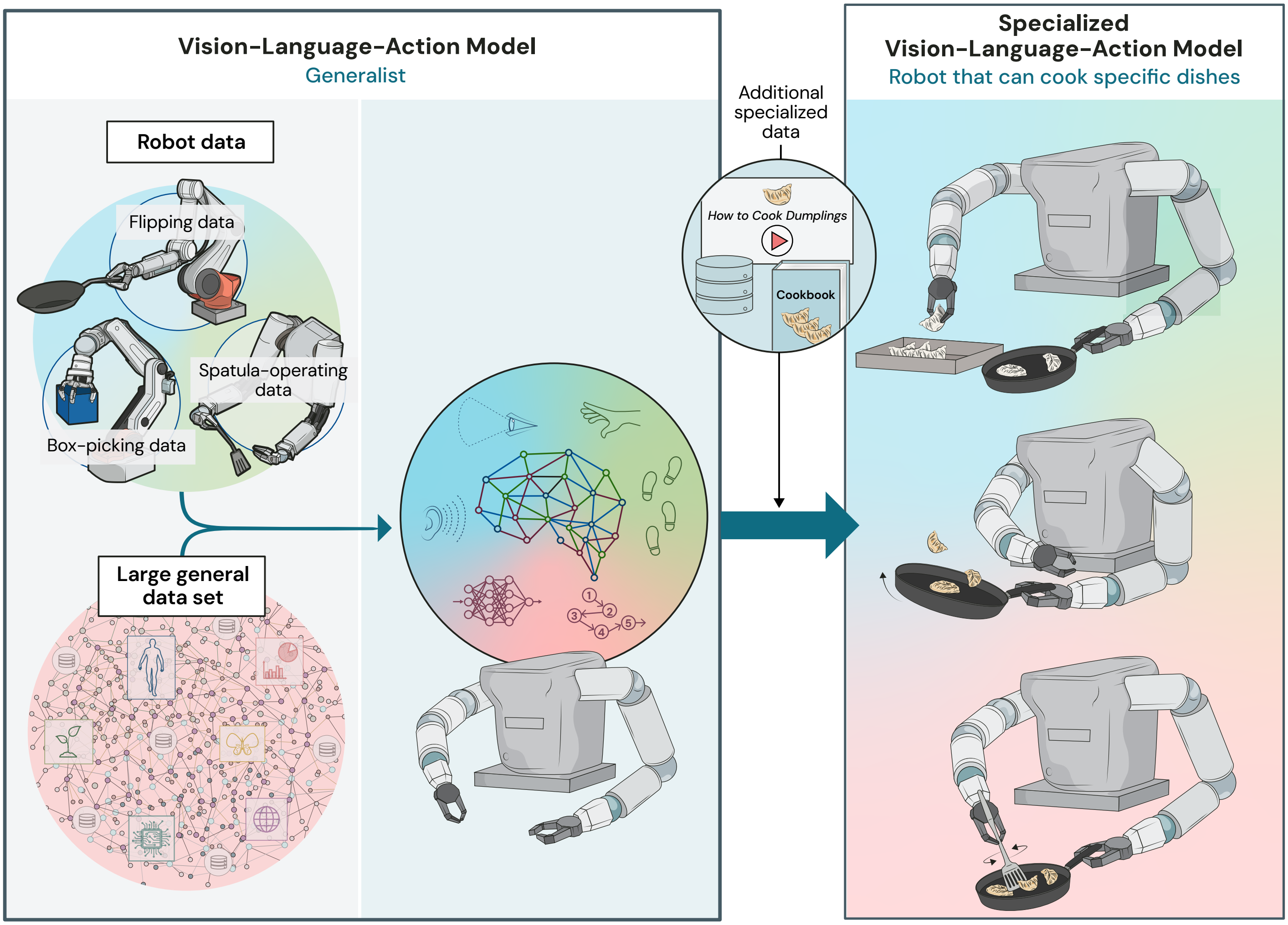
Figure 6: Robot Foundation Model Architecture Evolution Examples



Source: GAO adaptation of figures by Eleanor Tomlinson from *The State of Robot Learning* by Vincent Vanhoucke, Medium, March 6, 2024, https://vanhoucke.medium.com/the-state-of-robot-learning-639dafffbcf8. | GAO-26-108079

Robot foundation model development is progressing rapidly and shows promise for increasing the generality of tasks a robot can complete. Researchers train robot foundation models using the same successful techniques of LLMs and VLMs. First, they are trained on large-scale, diverse datasets to support a broad range of general tasks across different robot embodiments. For example, these models could be trained on robot embodiments such as mobile robots and non-mobile robots for lifting or manipulating a wide variety of objects in diverse environments. After that, they are fine-tuned for specific downstream applications (see fig. 7). Just as a person can learn a new skill quickly by drawing on a lifetime's worth of experience, such a robot foundation model could be fine-tuned to be specialized in new tasks with only modest amounts of high quality data. Recent robot foundation models have applied this approach and have successfully demonstrated task generalization to new environments such as cleaning a kitchen or bedroom whose layout they did not know in advance.

Figure 7: Robot Foundation Model Training Example



Source: GAO adaptation of slides from *Robotics Foundation Models* presentation by Sergey Levine, UC Berkley, March 24, 2025, https://www.youtube.com/watch?v=EYLdC3aONHw. | GAO-26-108079

Implications

General purpose robots could have far-reaching implications for society. We identified the implications below by considering a scenario of general-purpose robotics use in public infrastructure maintenance and disaster response. We provide examples from this scenario, but our analysis can be extended to other scenarios as well.

General purpose robots could autonomously inspect and repair infrastructure such as electrical grids or underground pipes. In addition, general purpose robots could support disaster response, including assessing damage, clearing debris, performing repairs, and establishing temporary communication networks. These robots could also sort recycling and monitor and address pollution. They could be able to operate in normal or unusual (including hazardous) environments. They could be deployed on various physical and software platforms and work collaboratively to achieve the tasks described above.

General purpose robotics

SOCIAL

- Privacy issues
- Public trust and moral decisions

TECHNOLOGICAL

- Adaptive design for task and environment
- Robot software steerability

ENVIRONMENTAL

- Power and water use impacts due to increased computation demands
- Contaminated component disposal

ECONOMIC

- Retraining and job displacement
- Supply chain vulnerabilities

REGULATORY

- Safe and responsible deployment; misuse liability
- Robot safety standardization and certifications

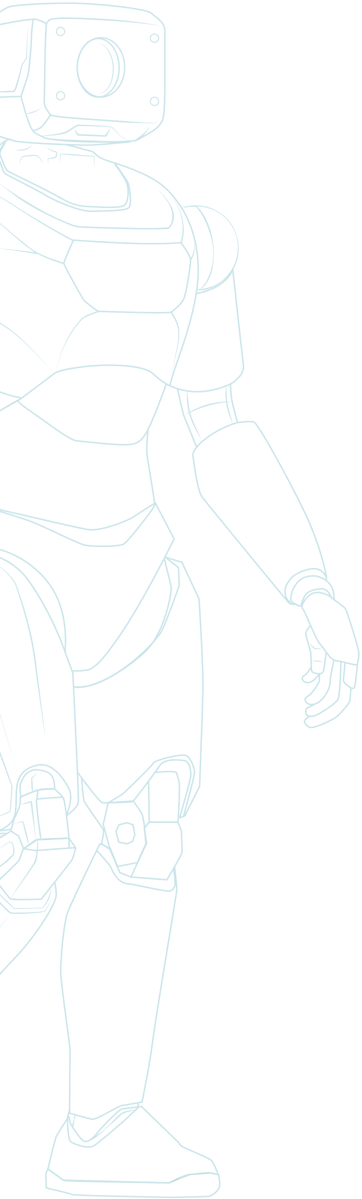
Source: GAO (icons). | GAO-26-108079

The following explores these implications in more detail.

General purpose robots could have significant social impact

First, risk or harm to property or human life caused by a lack of human awareness and oversight of faulty repairs performed by robots would likely erode trust in those providing the service and oversight (e.g., the government or contracted companies). Second, in an unfolding disaster situation, human oversight may be limited or unavailable. This combined with increased autonomy could eventually result in people's lives being affected by the decisions robots make.

To reduce such risks, awareness of the key risks that the increased use of robots present will be important. For example, robots leveraging foundation models such as LLMs and VLMs inherit the same risks that traditional foundation models do. As a result, robot learning and decision-making may inherit the same problems as existing AI systems, including: (1) difficulty in aligning robotic outputs with human values, (2) potential unintended bias, and (3) challenges in assessing safety due to lack of understanding in how the system generates outputs. As with existing foundation models, robots using these models or new models trained in a similar manner may not perform as well in situations not represented in their training data. In addition, they could deviate from desirable behavior due to hallucinations (e.g., in perception or planning). These challenges could become particularly dangerous if a robot becomes uncontrollable, for example due to loss of control of the underlying AI.



Robots used for disaster response across different environments could be directly beneficial to people

For example, if robots can successfully enter and work in hazardous environments, they could rescue stranded people after a hazardous waste spill that precludes human action. Additionally, if fleets of robots are mobilized to respond to a disaster, they could be outfitted with mesh networking capabilities that would enable emergency personnel to maintain peer-to-peer communication networks in the absence of traditional telecommunications infrastructure that might be offline.

Additionally, the development and use of general purpose robots for infrastructure use would likely require a variety of downstream changes to the design and building of structures. For example, if a fleet of robot maintenance workers will be the primary means of skyscraper maintenance, the architects may design the building environment to allow for more efficient access and use by robots. Building codes may need to be adjusted for these changes to be accommodated.

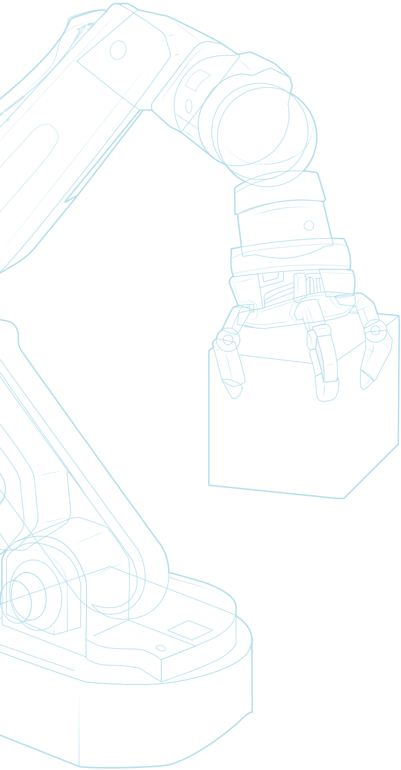
Increased use of robots could result in substantial environmental impacts

As we have previously reported, training and using generative AI can result in substantial energy consumption, carbon emissions, and water usage.[14] For example, one academic paper estimated the water consumption from training a particular generative AI model could directly evaporate 700,000 liters of fresh water for cooling a state-of-the-art data center.[15]

As we described above, the robot foundation models being developed for robots to use are trained in a similar fashion to the generative AI currently available. To incorporate new data and algorithms as they arise, these models will have to be regularly retrained, requiring a steady supply of energy and water, and emitting carbon. Additionally, as we previously reported, disposal of electronic waste can be challenging, and electronic devices require a more complex level of disassembly and separation.[16] Disposing of increased robot waste could further exacerbate this issue. For example, lithium-ion batteries may be used to power general purpose robots, and such batteries currently are only recycled 10 percent of the time. The remaining 90 percent of the time, the batteries are disposed of in traditional waste streams, which can cause fires.

Wide-scale deployment of general purpose robots could lead to uncertain economic outcomes

The distribution of robot deployment may present risks to economic resilience. For example, uneven deployment may widen resilience gaps with wealthy jurisdictions able to afford these advanced technologies while poorer communities could face greater damage, slower recovery, and economic stagnation over time. In addition, the extent these robots will create new tasks and roles; augment human workers by shifting tasks toward safer, higher skilled, and more productive roles; or substitute for workers altogether is unknown. The balance between new roles, augmentation, and substitution will likely depend in part on the pace of workforce transition. Also, rapid deployment may increase risks as general purpose robots currently depend on globally networked supply chains for semiconductors and critical minerals that are vulnerable to export controls, natural disasters, and logistic disruptions. These vulnerabilities can undermine the safety and effectiveness of relying on robots as public service and disaster response needs continue to rise.



Potential Considerations for Policymakers

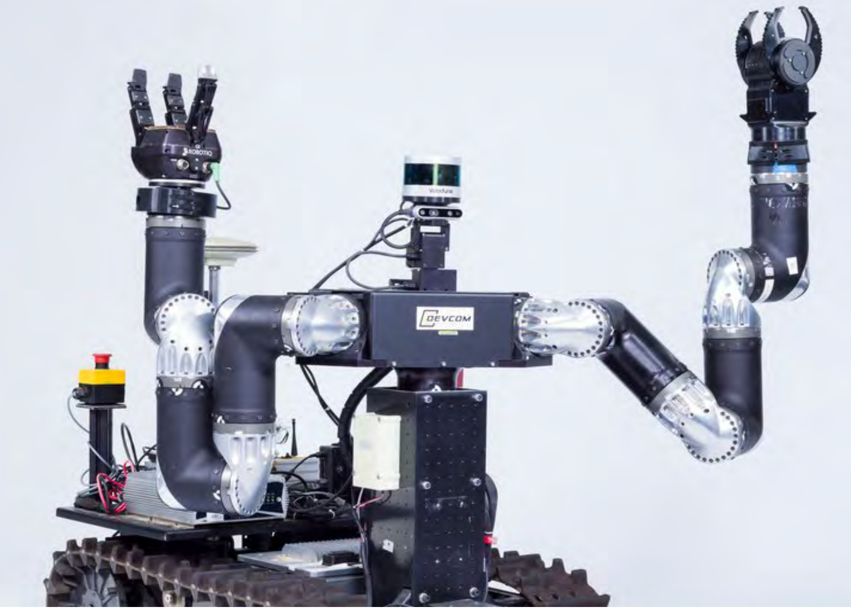
Policymakers will have to consider the tradeoffs among various actions related to managing societal implications, hardware and software co-development, and safety standardization and what actions, if any, will be necessary as this technology becomes more widely used throughout society.

Societal Implications

Policymakers will have to consider how and to what extent oversight will be exercised over the use of general purpose robots in various applications, such as robots making high-risk decisions while responding to a disaster. Oversight requirements could be part of a comprehensive risk management framework and sequence of risk assessment processes. They could include elements detailing the types of situations (e.g., damage or incidents exceeding a risk threshold) that require oversight or human involvement and the timeliness of such oversight (e.g., immediate response or takeover). The frequency of reporting and oversight check points may be adjusted based on the risk profile. Consideration could be given for situations where typical networks for communication or control are not available. Reporting for human oversight or review could take the form of security reports and alerts. For autonomous decision-making, a robot could communicate about what it did (transparency), how it made decisions (explainability), and how a user can make sense of those decisions (interpretability). Technology development at the cutting-edge may increase the variety and degree of uncertainty, resulting in potentially greater disparities in knowledge and perspectives. Thus, a consensus around these oversight requirements and the risk management framework they will be a part of could be challenging for policymakers to reach.

Hardware and Software Co-Development

Policymakers will need to consider the benefits and costs of assisting hardware and software co-development. For example, incentivizing the creation of shared infrastructure could be a way to address the need for developing robot test and training environments that may be too expensive for individual institutions to support. This would allow member academic and private-sector partners to share their existing infrastructure and build new infrastructure as needed but would require tradeoffs with other S&T developments and priorities. Members could also create and share training datasets for public use, publish technical guidelines, and papers to share their progress, which could help encourage closer collaboration of robot software and hardware communities. Regulators could also work with the members of the shared development environments to develop regulatory sandboxes that would allow regulators to explore real or perceived regulatory barriers, potential safeguards and certification mechanisms, and consideration of current or future regulatory positioning.



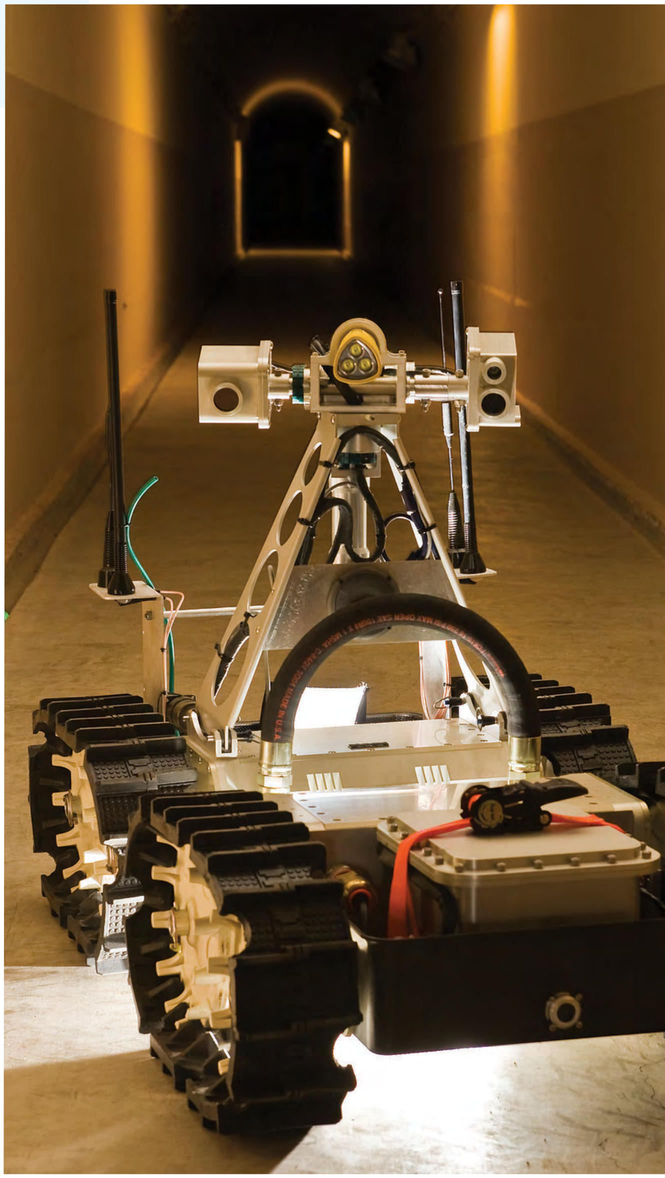
RoMan was built to advance the ability of autonomous robots to interact with the wide variety of objects that they might encounter in human-scale environments, be they small and hard to grasp or large, heavy, and difficult to move.

Source: Courtesy NASA/JPL-Caltech. | GAO-26-108079

Safety Standardization

Policymakers would have to consider options to address safety concerns, especially surrounding the impracticality of testing robots in all the environments they may eventually be deployed in. For example, one option policymakers have is to incentivize the private sector, international standardization groups, and related government agencies to collaboratively develop a robot observability framework. A robot observability framework is a software system that goes beyond monitoring (what happened) to understanding (why it happened) by analyzing logs and real-time performance data collected from every robot component to provide insight into the robot's planning and behavior. This observability framework could act as a base layer to support high-level requirements embedded in a risk management framework. The observability framework could support accessing real-time information of a robot system (or fleet of robot systems) via metrics and logs. It would support real-time monitoring of robot task planning and actions, detection and prediction of robot safety issues, and proactive risk mitigation actions with human oversight and feedback. Policymakers could incentivize academia and private-sector groups to conduct robot safety and oversight research to inform this framework. This research could cover robot monitoring, safety control, risk mitigation, and autonomy level classification. The framework would allow those monitoring the robots to more quickly and effectively shut the robots down should the robots stray from acceptable behaviors or otherwise become unsafe. Once complete, policymakers could consider requiring elements of the framework be used by entities developing or using these types of robots.

In addition to an observability framework, another option policymakers have to address safety concerns could be to encourage robot system designers and end users to settle on a mode of human-robot interaction that balances a variety of factors such as end-user, safety, and regulation requirements. For example, even if a robot designed for infrastructure maintenance has the capability to autonomously plan, assess, and take its own actions during a pipeline repair, a system designer can add a software control layer requiring human confirmation for each step of its planned action. Policymakers could stipulate when such a control layer might be warranted.



Sandia's Gemini-Scout Mine Rescue Robot is equipped to handle any number of obstacles, including rubble piles and flooded rooms, to help rescuers reach trapped miners safely and efficiently.

Source: "Gemini-Scout Mine Rescue Robot" by Sandia Labs, CC BY-NC-ND 2.0, Photo by Randy Montoya. | GAO-26-108079

Remediation of Orbital Debris

Orbital debris remediation refers to emerging technologies and strategies to actively reduce space debris. The thousands of satellites currently in orbit—as well as those planned in the years to come—provide critical services like communication, navigation, timing, and observations used for weather forecasting. Yet these critical assets face a growing threat from orbital debris—pieces of "space junk" such as defunct satellites and fragments of rockets. More than 30,000 objects are now tracked in orbit, and more than half of them are debris.[17] An additional estimated 1 million or more pieces of space debris are too small to reliably track—ranging from 1 to 10 centimeters—but still capable of damaging spacecraft.[18] Even a paint fleck can be dangerous at orbital speeds, which can exceed 25,000 kilometers per hour (about 15,500 miles per hour). Unchecked debris growth could imperil the space infrastructure that underpins our economy, security, and daily life. One way to mitigate the risk posed by orbital debris is to actively remove, relocate, or repurpose the debris. Such activities are called debris remediation. Development of remediation technologies is underway, but effective use of these technologies faces a variety of economic and regulatory hurdles.

Figure 8: Visualization of Distribution of Debris across Various Orbits

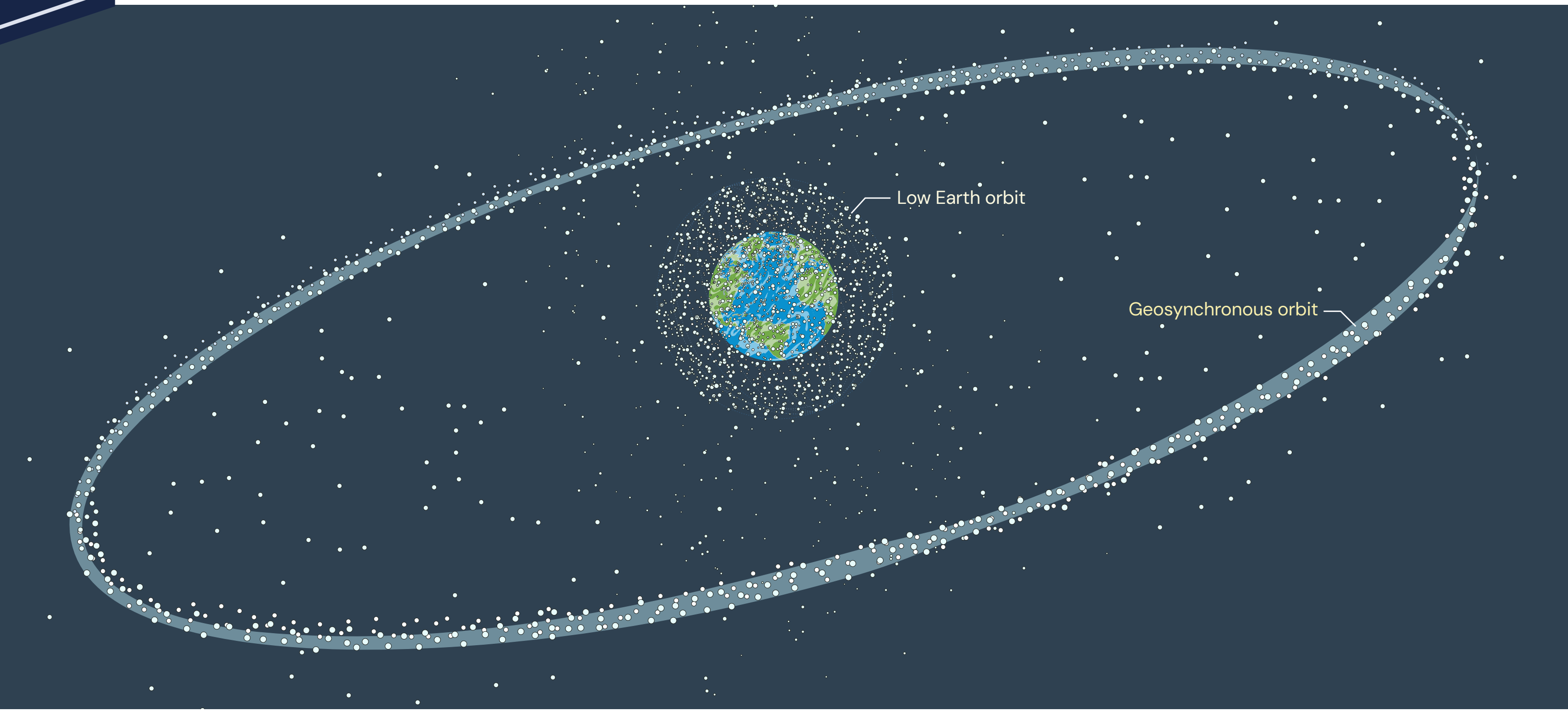


Image not to scale.

Source: GAO (illustration). | GAO-26-108079

Close calls and collisions involving debris are becoming more frequent, posing risks for both uncrewed satellites and crewed space stations. For example, three Chinese astronauts were forced to extend their stay aboard a space station after a piece of debris damaged their return vehicle. One analysis of a subset of orbits showed that the number of close calls roughly doubled between 2015 and 2023.[19] Each new collision in space can spawn a cloud of fragments. These fragments can gradually drift into other orbits where they cause further collisions (see fig. 9). For example, in 2009, a defunct Russian satellite struck an active commercial satellite, producing thousands of pieces of debris that remain in orbit today. Five orbital debris experts we spoke with expressed concern that, without intervention, debris collisions could intensify, making certain valuable orbits unusable,[20] a scenario commonly known as the Kessler syndrome.[21]

Figure 9: Estimated Spread of Debris After a 2009 Collision in Space

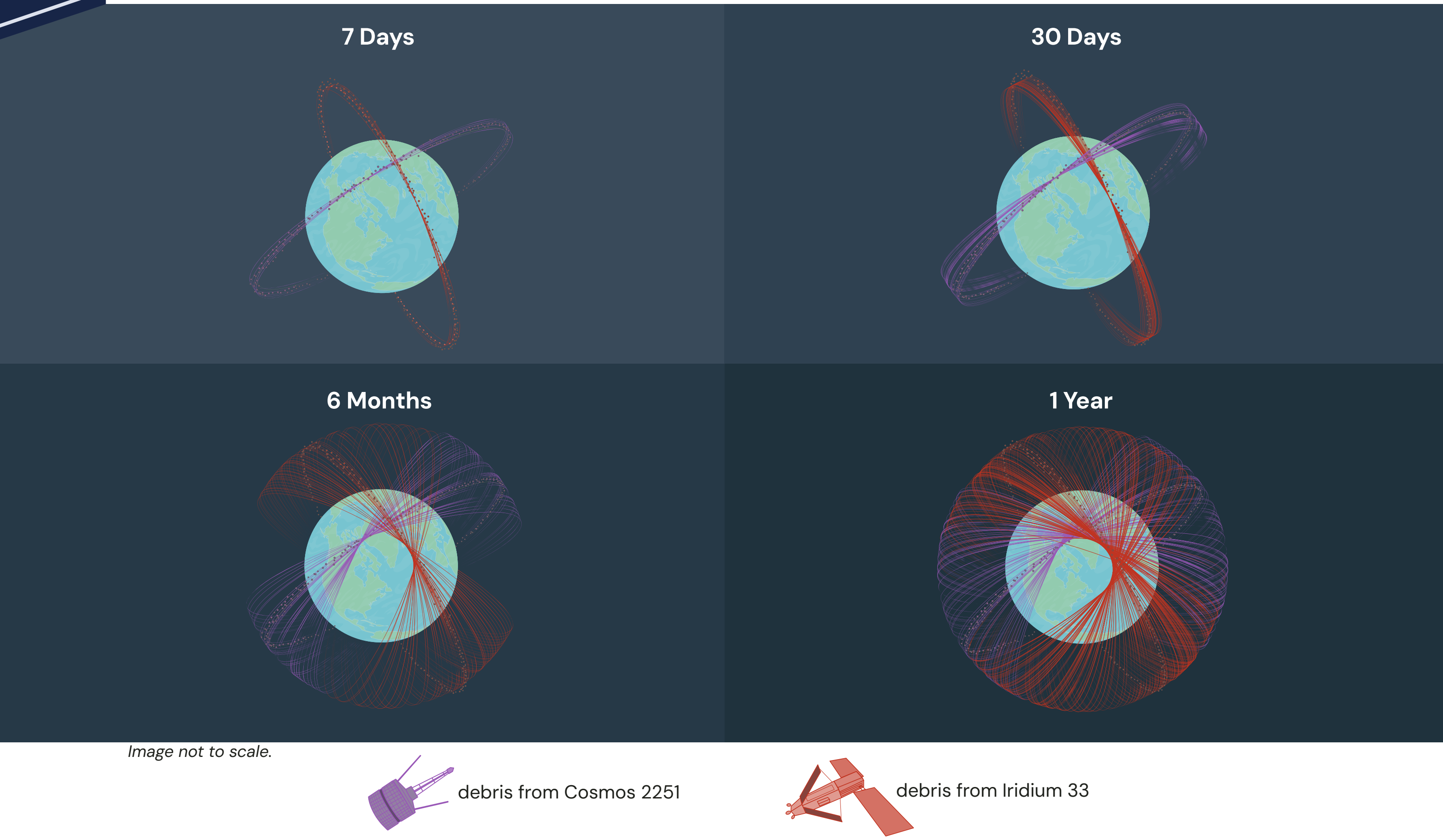
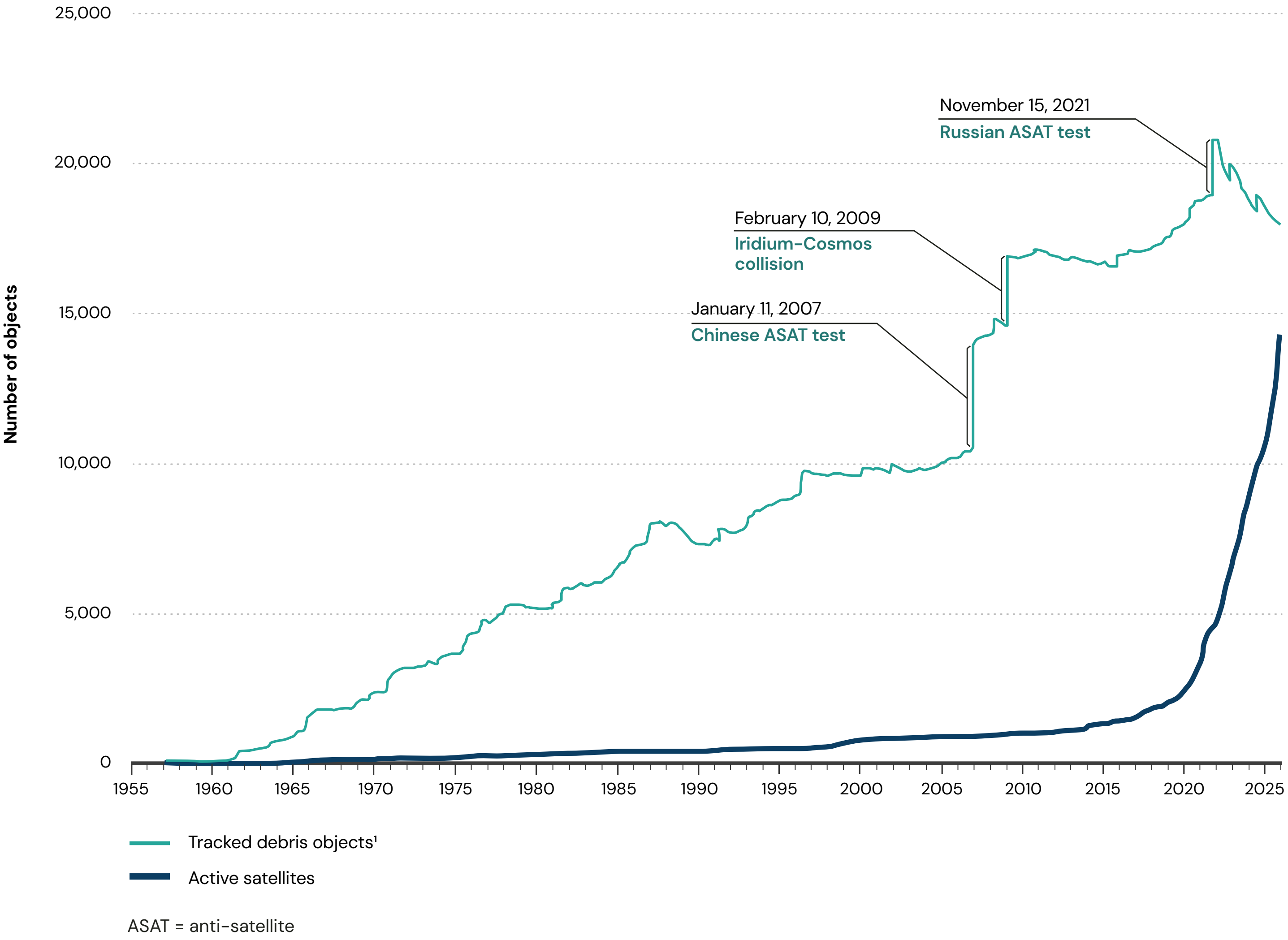


Image not to scale.

Source: GAO adaptation of NASA, *The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come*, October 16, 2009. | GAO-26-108079

Space organizations report that the number of pieces of debris in orbit is rising quickly (see fig. 10) and that there are currently insufficient incentives for risk control practices to solve the problem. More satellites

Figure 10: Tracked Orbital Debris and Active Satellites over Time

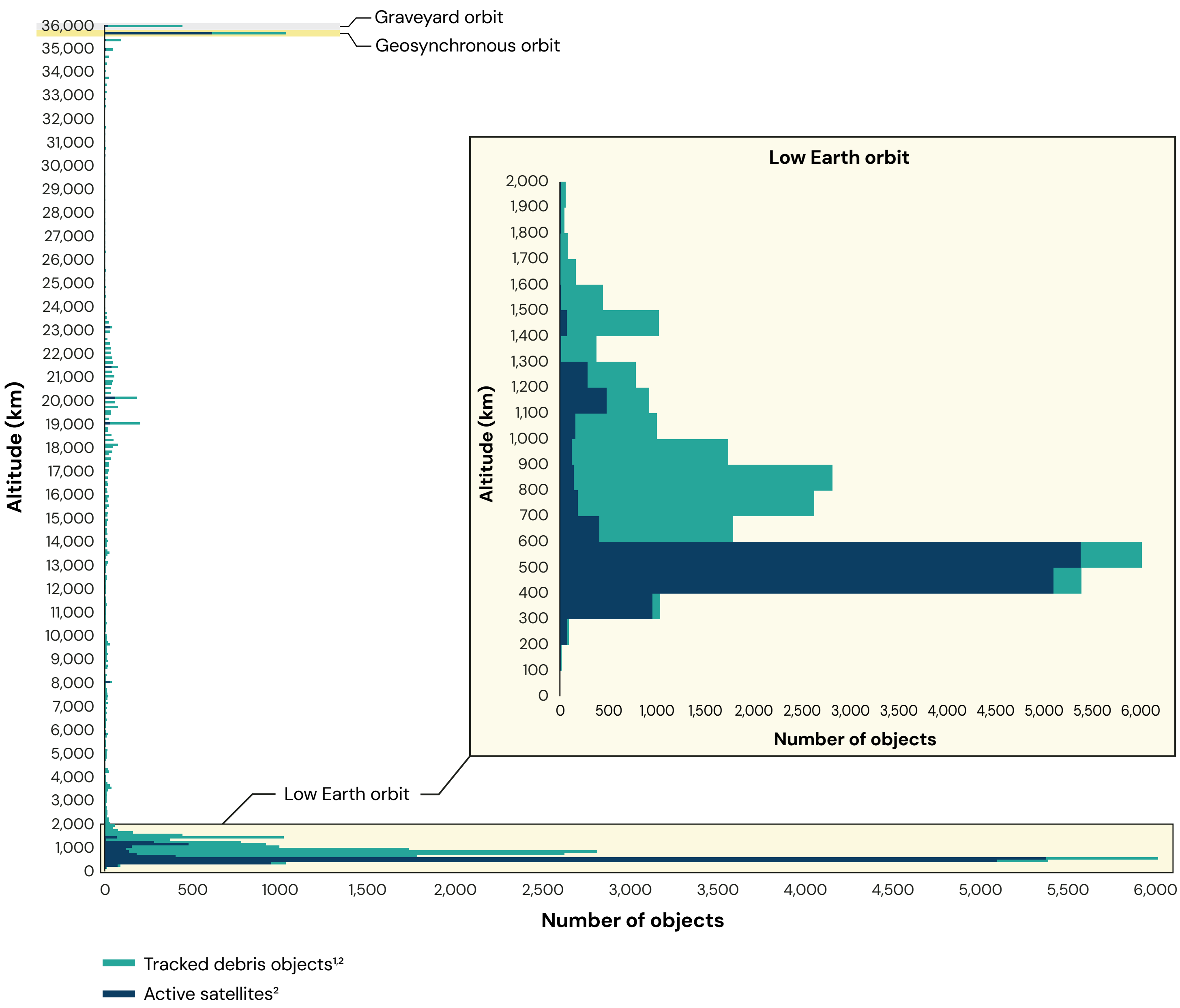


Source: GAO analysis of data from Jonathan McDowell's General Catalog of Artificial Space Objects, https://planet4589.org/space/stats/active.html (Tracked Objects vs Time). | GAO-26-108079

Notes:
[1] Tracked debris objects represent a small portion of the total dangerous debris objects in orbit.
The labeled events are examples of events that significantly increased the amount of debris.

are being launched than ever before, especially to popular orbits 400 to 800 km above Earth (see fig. 11). While current satellite operators are largely deorbiting newer satellites in a timely fashion, disposal of old satellites, rocket bodies, and other debris is not occurring at a rate to match the pace of new satellites launching and entering operations.

Figure 11: Tracked Orbital Debris and Active Satellites at Various Altitudes as of January 7, 2026

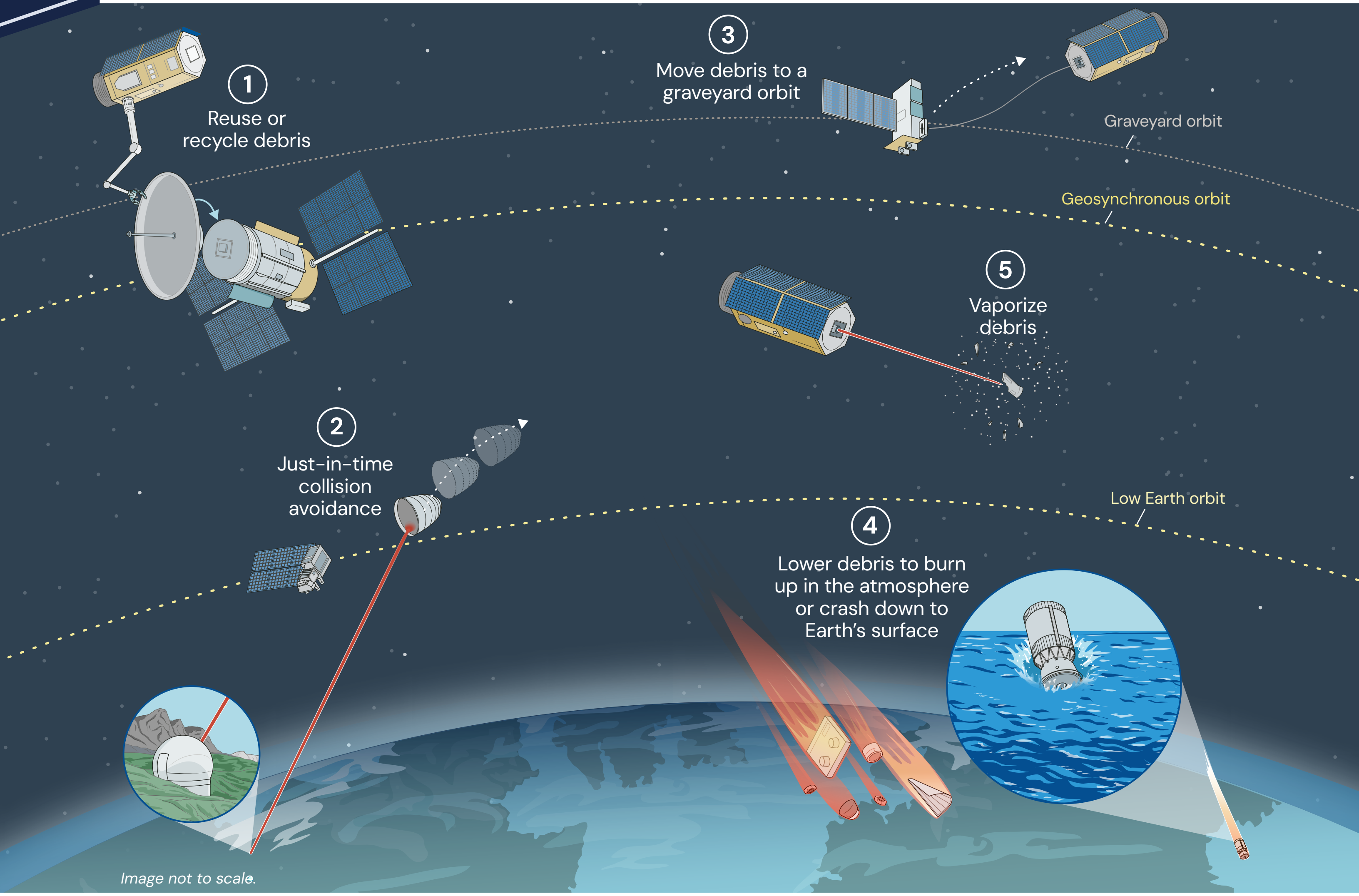


Source: GAO analysis of data from Jonathan McDowell's General Catalog of Artificial Space Objects, https://planet4589.org/space/stats/satht.html (Objects vs Height). | GAO-26-108079

Notes:
[1] Tracked debris objects represent a small portion of the total dangerous debris objects in orbit.
[2] Object counts current as of as of January 7, 2026.

Orbital debris remediation goes beyond preventive measures, such as requiring satellites to deorbit within 25 years, and involves actively removing existing junk from orbit or otherwise lessening the hazard it poses. On Earth, waste can follow several distinct paths depending on the object being disposed of and the technology available (e.g., transport to landfill, recycled, repaired and reused, composted). Similarly, there could be multiple ways of remediating debris in orbit depending on where the piece of debris is, what kind of debris it is, and which proposed technologies mature in the coming years. For instance, the European Space Agency (ESA) is funding its first-ever debris removal mission, called ClearSpace-1. This mission is intended to rendezvous with a large piece of debris, capture it, and drag it into Earth's atmosphere for disposal. Figure 12 shows examples of the primary paths that government agencies and private industry are pursuing or considering among space-faring countries.

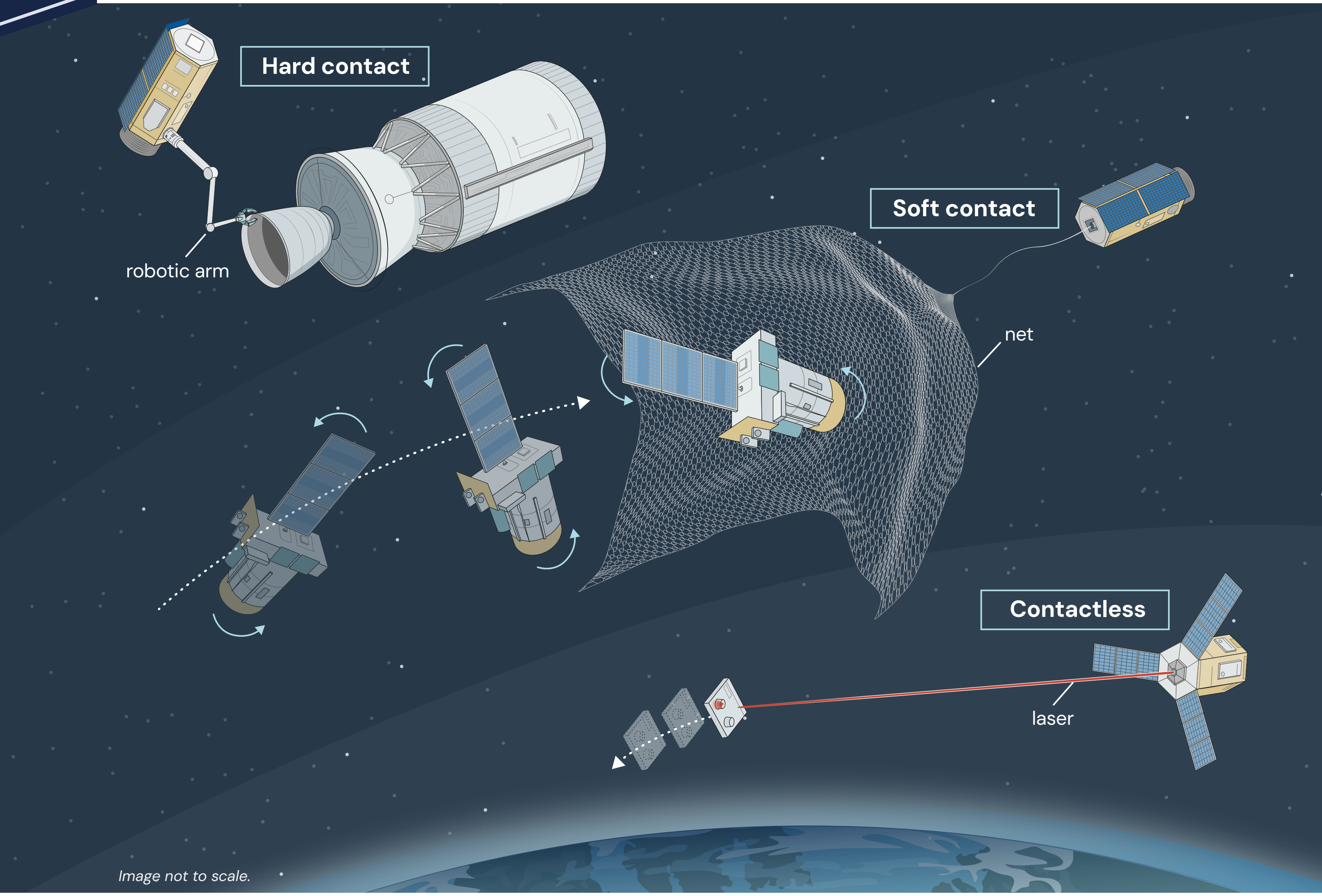
Figure 12: Examples of Various Methods of Remediating Debris



Source: GAO (analysis and illustration). | GAO-26-108079

Each of these disposal methods requires different technologies. For example, relocating geostationary debris to an unused, out-of-the-way orbit (commonly called a graveyard orbit) requires some way of transporting the debris, such as grabbing and towing it. Relocating a low-altitude satellite down into the atmosphere could be done by towing but could also be performed by increasing the atmospheric drag of the debris. Figure 13 shows some such technologies.

Figure 13: Example Categories of Orbital Debris Remediation Technologies



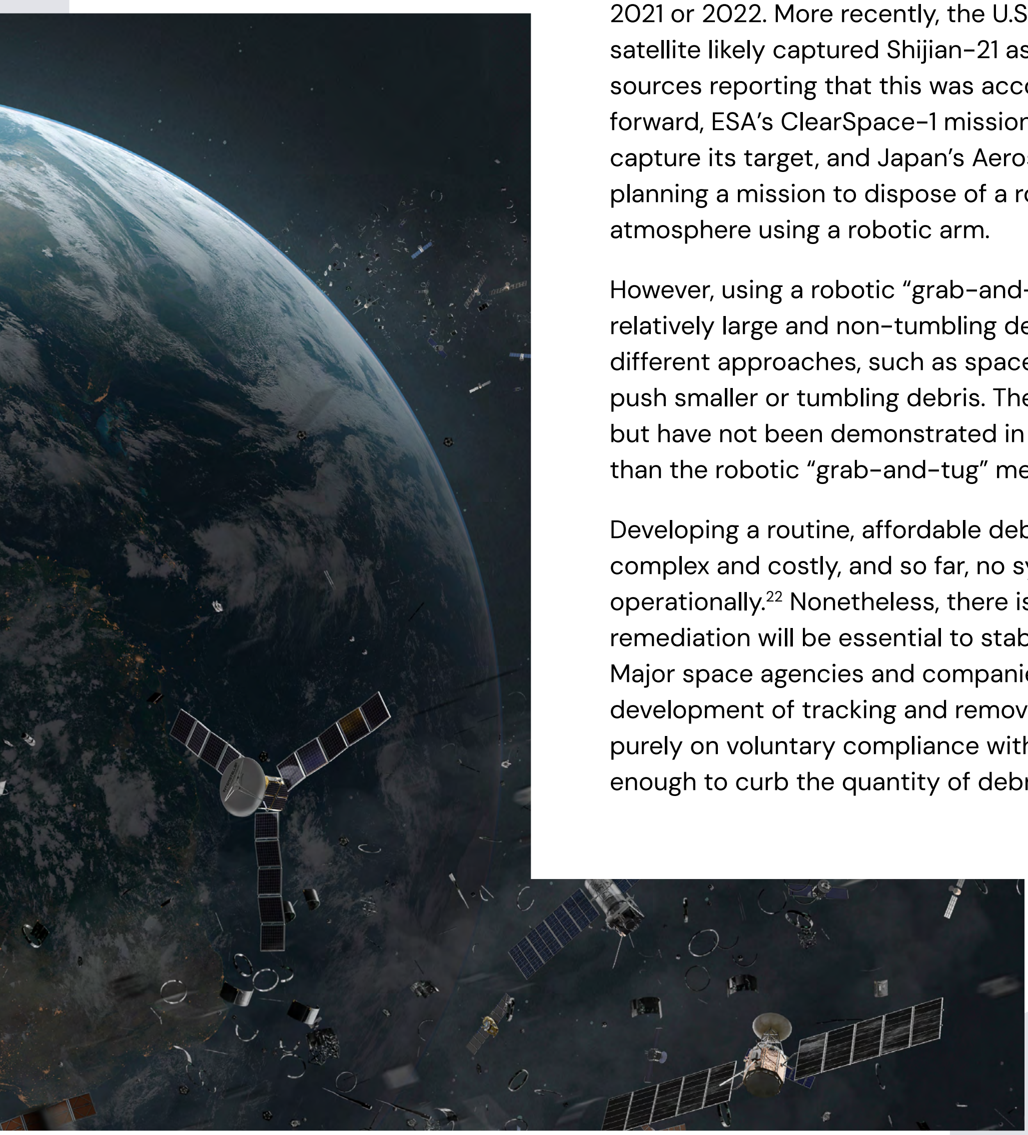
Source: GAO (analysis and illustration). | GAO-26-108079

Developments on the Horizon

Engineers at various space organizations around the world have demonstrated prototypes of some of these technologies. A European test mission captured one dummy satellite with a net in 2018 and another with a harpoon in 2019. In 2025 a U.S. company robotically latched onto a satellite and towed it into a graveyard orbit. The same year, another U.S. company tested an inflatable debris capture device inside the International Space Station. According to experts we spoke with, the most mature technologies involve directly capturing a piece of debris (typically using some kind of robotic mechanism) and then towing the debris to a desired destination. For example, the U.S. commercial satellite Mission Extension Vehicle 1 moved a geostationary communications satellite into a graveyard orbit in early 2025 using a robotic grapple. Similarly, the Chinese satellite Shijian-21 reportedly robotically grappled a geostationary navigation satellite and towed it into a graveyard orbit in 2021 or 2022. More recently, the U.S. Space Force stated another Chinese satellite likely captured Shijian-21 as part of a refueling mission, with news sources reporting that this was accomplished using robotic arms. Looking forward, ESA's ClearSpace-1 mission is planning to use robotic arms to capture its target, and Japan's Aerospace Exploration Agency is currently planning a mission to dispose of a rocket body by moving it down into the atmosphere using a robotic arm.

However, using a robotic "grab-and-tug" approach only works well for relatively large and non-tumbling debris. Other types of debris will require different approaches, such as space- or ground-based lasers that slowly push smaller or tumbling debris. These other approaches show promise but have not been demonstrated in space and in general are less mature than the robotic "grab-and-tug" method.

Developing a routine, affordable debris cleanup capability is technically complex and costly, and so far, no system has been deployed operationally.[22] Nonetheless, there is growing consensus that active remediation will be essential to stabilizing the orbital environment. Major space agencies and companies are increasingly investing in the development of tracking and removal technologies, recognizing that relying purely on voluntary compliance with debris guidelines likely will not be enough to curb the quantity of debris.



Source: Vadimsadovski/stock.adobe.com. | GAO-26-108079

Implications

Our STEER foresight scenario assumes that debris grows, technologies to remediate the debris advance but see limited use, and space operations continue without any catastrophic events. Robotic arms or similar methods could be used to remediate certain large debris, resulting in the regular removal of five to ten large derelicts annually by space-faring nations and thus holding debris mass in the 400–800 km altitude shell (the busiest part of Earth orbit) flat relative to 2025.[23] Alternative technologies to address tumbling or small debris may not mature in the next 10 years and may require expanded space situational awareness (SSA) capabilities to track small but dangerous debris.[24]

Conjunction (potential collision) alerts may increase, as could the rate of satellites that suddenly fail, likely due to collisions with small, untracked debris. Insurance rates may rise correspondingly though may still be manageable for satellite operators.[25] The orbital environment in this scenario would be stable enough for commerce but could be only one accident away from tipping toward a cascade of collisions, underscoring that incremental measures, though valuable, have not yet secured true long-term sustainability. This scenario poses a variety of implications.

Limited removal and remediation of orbital debris

SOCIAL

- Service outages
- Heightened public concern after cascade
- Perception of “solved problem”
- Dual use applications

TECHNOLOGICAL

- Currently pursued tech only useful for large, non-tumbling debris
- Remediation of smaller debris may be limited by tracking capabilities

ENVIRONMENTAL

- Reduced, but not eliminated, risk of crossing tipping point
- Atmospheric effects from deorbiting
- Safety hazard on ground from deorbiting

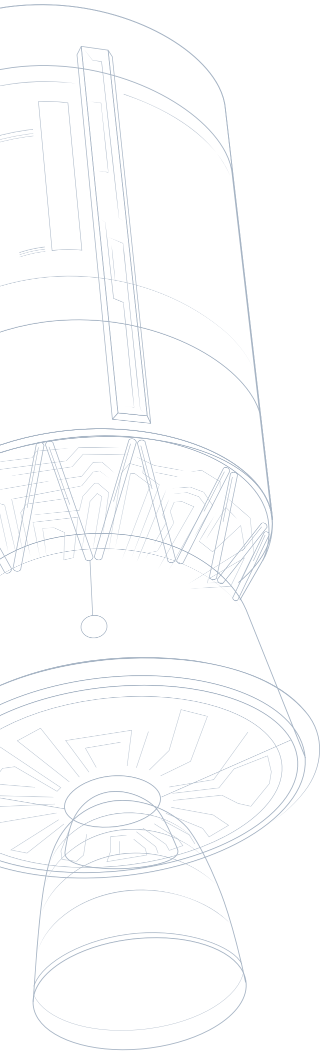
ECONOMIC

- Rising premiums increase satellite costs
- Deployment of tech hampered by lack of individual actor incentives to remediate debris

REGULATORY

- Property rights challenges
- Increasingly but not fully aligned disposal timelines across U.S. and international regulators

Source: GAO (icons). | GAO-26-108079



The following explores the implications of the above scenario in more detail.

Upcoming technology addresses some large debris but has limited capability to remediate small or tumbling debris

Today's hard-contact solutions, such as robotic grappling, only address large, non-tumbling debris, which constitutes a fraction of dangerous debris. Extending remediation capability to tumbling debris or the millions of sub 10-centimeter fragments will likely hinge on soft-contact or contactless techniques such as laser nudging, which are in the early stages of development. Remediating small debris, which can move at a wider range of speeds and directions than larger debris, may also require improvements in SSA capabilities, which currently cannot reliably track objects smaller than 10 centimeters in size. As a result of a limited capacity to remediate small or tumbling debris, collisions could increase, which could result in service outages for users of satellite services and abrupt cost shocks for satellite operators. Additionally, insurers could raise their rates—or withdraw from the market altogether—if risks continue to increase.

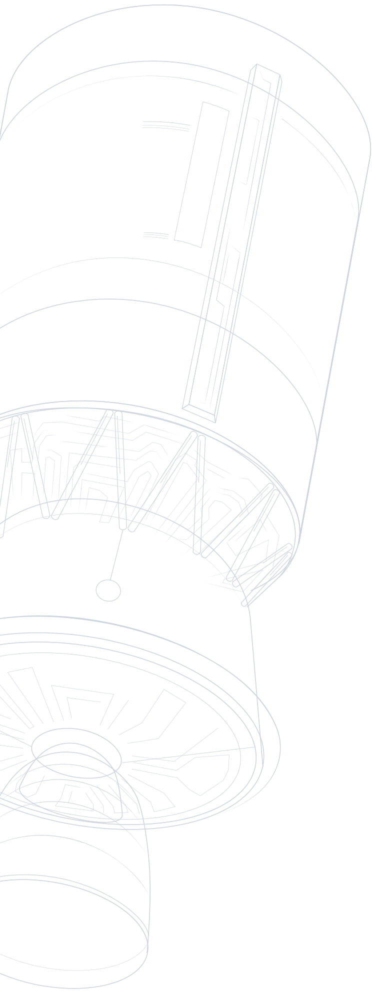
Technology deployment could be largely government-funded with limited private deployment

Financing the development and use of debris remediation technology is hampered by what has been described as a commons problem: no single operator has sufficient incentive to pay for remediation of debris they did not create, and the risks and expenses of which fall upon the entire industry.[26] As a result, there is a lack of a clear private market for debris remediation currently.

Novel technologies may be available but inhibited by legal challenges

Under the Outer Space Treaty, countries bear the responsibility for their activities in space whether carried out by government or non-government entities.[27] Many stakeholders believe that this responsibility extends to defunct satellites and debris from satellites. This requirement may impede salvage (where a piece of debris is reused or recycled); remediation of small debris (whose originating country may be difficult or impossible to identify); and remediation of debris of known, but foreign, origin (which may require diplomatic negotiations). Certain U.S. laws and regulations may inhibit the deployment of more novel forms of debris remediation, such as laser nudging, by U.S. companies.[28] Industry stakeholders also told us existing Federal Aviation Administration regulations may inhibit laser nudging.[29]

One potential negative implication of increased debris remediation technology use would be the risk of safety or environmental impacts. Larger debris may not burn up entirely in the atmosphere, introducing the risk of injury, death, or damage on the ground.[30] Additionally, debris reentry can inject particulate matter into the upper atmosphere. These particulates could change the temperature of the stratosphere, contribute to severe weather events, or deplete the ozone layer, which could increase the amount of harmful ultraviolet solar radiation reaching Earth. However, there is still large uncertainty regarding the scale and nature of these effects.



Potential Considerations for Policymakers

Policymakers will have to consider the tradeoffs among various actions as debris concerns continue to evolve. These actions for consideration can be grouped into four areas: (1) prevention, (2) monitoring, (3) advancement in debris-tracking technology, and (4) advancement in remediation technology.

Policymakers have several options for addressing the lack of technology to remediate small or tumbling debris. For example, they could support targeted research and development of technologies such as scalable laser nudging and autonomous rendezvous capabilities, enabling a deorbiting satellite to follow debris and gradually push it out of the way. This support could come in the form of a series of government-funded, on-the-ground tests and in-space demonstrations that would mature these technologies sufficiently for the private industry to adopt and develop further. Such an effort may cost hundreds of millions of dollars and would likely involve coordination across several federal agencies.

Policymakers could also consider supporting new monitoring infrastructure and capabilities. One way in which this could be accomplished is by deploying or funding the creation of improved debris detection systems. Data from these systems could be fed into monitoring programs such as the Traffic Coordination System for Space civil SSA program, which is currently under development and will track debris larger than 10 centimeters, to better track small but dangerous debris of 1 to 10 centimeters in size. These data could also be used to enable AI-powered conjunction prediction to predict when these smaller debris objects may collide with an operational satellite.[31] Such systems and capabilities would enable a deorbiting mission to identify where to go and which pieces of debris to prioritize.

Policymakers could consider whether to address the lack of a clear private market for debris remediation, by choosing from a variety of tools that better align private incentives and the long-run sustainability of low Earth orbit. One option for policymakers to consider is to fund a program to pay private companies to remediate debris. This funding could come from instituting a modest orbital-use fee, where satellite operators pay either a one-time fee upon launch or a recurring fee for as long as their satellites are operational. These fees could be structured similarly to fees currently paid by anyone launching a spacecraft or whose spacecraft reenters the atmosphere.[32] Alternatively, policymakers could include a bond requirement for satellite operators prior to launch. If the operator successfully deorbits the satellite within 5 years of designated lifespan as currently required,[33] the bond would be refunded. If not, the bond would be used to fund the remediation of that satellite or a higher-risk piece of debris. However, some experts we spoke with pointed out that current satellite operators are largely complying with this 5-year time frame already. As a result, a bond mechanism may not raise sufficient money to address existing debris that was generated by historical activities and still poses a growing risk in an increasingly congested space environment.

Currently, if a piece of space debris is of unknown origin, the Outer Space Treaty could pose challenges for remediation efforts, because the treaty assigns responsibility for human-made objects in space, both operational and debris, to the nation that originated the objects. As a result, debris remediation providers could be impeded because the originating country would need to be identified and provide subsequent authorization and supervision for the remediation activities.

Policymakers could consider a variety of approaches if they decide to attempt to mitigate potential legal challenges. For example, policymakers could consider whether proposing amendments to the treaty would resolve this issue, while weighing any potential second order effects. Alternatively, policymakers could initiate or support legal analyses that explore other options for alleviating these challenges in compliance with the Outer Space Treaty. For example, policymakers could support investigations into whether a “notice-and-wait” procedure is compliant with the treaty. Under such a procedure, a remediation provider would publicly identify a target piece of debris that poses high collision risk, wait for a specified period, and then, if no objections are raised, assume they had authorization of the (unknown) originating nation to remove the target debris.

In the case of debris of known but foreign origin, policymakers could consider whether it is permissible under the treaty to pursue a series of bilateral or multilateral agreements with other nations that have placed objects into orbit, granting blanket permission to remediate debris “belonging” to a particular nation and assess potential risks associated with doing so. Space policy experts we spoke with were confident that once the U.S. or another nation began pursuing debris remediation in earnest, solutions to such legal challenges could be found.

Source: Pincio/stock.adobe.com. | GAO-26-108079

Endnotes

[1] For more information, see: : “SWITCH: Stentrode First-in-Human Study of Implantable BCI for Control of a Digital Device,” accessed Sept. 16, 2025, https://clinicaltrials.gov/study/NCT03834857.

[2] GAO, *Brain-Computer Interfaces: Applications, Challenges, and Policy Options*, GAO-25-106952 (Washington, D.C.: Dec. 17, 2024).

[3] GAO-25-106952.

[4] According to the International Association of Privacy Professionals, several other states have enacted or proposed bills intended to have comprehensive approaches to governing the use of personal information. See “US State Privacy Legislation Tracker,” accessed Sept. 18, 2025, https://iapp.org/resources/article/us-state-privacy-legislation-tracker/. For example, some state laws, such as the California Consumer Privacy Act and Colorado Privacy Act, may extend protections to certain data captured by neural implants in those jurisdictions.

[5] Marcello Ienca, Fabrice Jotterand, and Bernice Elger. “From Healthcare to Warfare and Reverse: How Should We Regulate Dual-Use Neurotechnology?” Neuron. 2018 January 17; 97(2): 269-274 https://doi.org/10.1016/j.neuron.2017.12.017.

[6] The FDA currently considers a product to be a device, and subject to FDA regulation, if it meets the definition of a medical device per Section 201(h) of the Food, Drug, and Cosmetic Act. This definition includes, among other things, such devices that are intended to affect the structure or any function of the body

[7] Who, If Not the FDA, Should Regulate Implantable Brain-Computer Interface Devices?, https://journalofethics.ama-assn.org/article/who-if-not-fda-should-regulate-implantable-brain-computer-interface-devices/2021-09, accessed Mar. 23, 2026

[8] GAO-25-106952

[9] Announcement of the Brain-Computer Interface (BCI) Two-Day Hybrid Conference, 88 Fed. Reg. 7655 (Feb. 6, 2023).

[10] Ruben S. Verhagen, Mark A. Neerincx, and Myrthe L. Tielman, “Meaningful human control and variable autonomy in human-robot teams for firefighting,” *Frontiers in Robotics and AI*, vol. 11 (2024): 1-4 https://doi.org/10.3389/frobt.2024.1323980.

[11] Robot software consists of three major modules: perception, planning, and actuation. The perception module uses sensors to perceive the world like human eyes, ears, and skin. The planner module acts like the human brain, integrating information from the perception module with a stated goal of generating action plans. The actuation module functions like human muscles and limbs, executing action plans by moving the robot hardware.

[12] Foundation models are large-scale AI models trained on vast, diverse datasets that can fulfill a broad range of general tasks. Instead of one model built for one task, one foundation model can be adapted to many downstream tasks through fine-tuning. This training process for foundation models is similar to the way a student progresses though high school (broad learning) and then a university majoring in a specialized area. Both large LLMs and VLMs are examples of foundation models.

[13] Anthony Brohan, et. al., “RT-2: Vision-Language-Action Models Transfer Web Knowledge to Robotic Control,” Google DeepMind (July 28, 2023), https://robotics-transformer2.github.io.

[14] GAO, *Artificial Intelligence: Generative AI’s Environmental and Human Effects*, GAO-25-107172 (Washington, D.C.: Apr. 22, 2025).

[15] Pengfei Li, Jianyi Yang, Mohammad A. Islam, and Shaolei Ren. “Making AI Less ‘Thirsty’: Uncovering and addressing the secret water footprint of AI models.” *Communications of the ACM*, vol. 68, no. 7 (2025): 56 https://doi.org/10.1145/3724499.

[16] GAO, *Science & Tech Spotlight: Consumer Electronics Recycling*, GAO-20-712SP (Washington, D.C.: Aug. 31, 2020).

[17] Jonathan McDowell, “Tracked Objects vs Time,” General Catalog of Artificial Space Objects Release 1.8.0, accessed January 14, 2026, https://planet4589.org/space/stats/active.html.

[18] The prevalence of smaller debris is estimated by a combination of extrapolations from small objects briefly detected by radar systems and evidence of debris strikes on objects retrieved from orbit, as well as physics-based models of the orbital environment and break-up events. For more information on types of orbital debris and their behavior, see NASA Orbital Debris Program Office, “Frequently Asked Questions,” Astromaterials Research and Exploration Science, accessed August 27, 2025, https://orbitaldebris.jsc.nasa.gov/faq/#; The Aerospace Corporation, “Space Debris 101,” Center for Orbital and Reentry Debris Studies, accessed August 27, 2025, https://aerospace.org/article/space-debris-101. For a recent detailed assessment of the space environment, including estimates of the amount of various sizes of debris in orbit, see European Space Agency Space Debris Office, “ESA Space Environment Report 2025,” accessed August 27, 2025, https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025.

Endnotes (continued)

[19] This analysis was specifically for conjunctions ("a geometric close approach between two objects") in Sun-synchronous orbits between 400 and 1000 kilometers in altitude. For more information, see European Space Agency Space Debris Office, "ESA Space Environment Report 2025," accessed August 27, 2025, https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025.

[20] Not all orbits are equally used (see fig. 11). Experts consider the busiest portions of low Earth orbit to be at greatest risk of the debris snowball problem, though one expert we spoke with believes that the risks of collisions in geostationary orbit are generally underestimated. For more information on the risk of cascading collisions at various parts of low Earth orbit, see American Institute of Aeronautics and Astronautics, "Understanding the misunderstood Kessler Syndrome", Aerospace America, accessed August 27, 2025, https://aerospaceamerica.aiaa.org/features/understanding-the-misunderstood-kessler-syndrome/. For more information on the risks of collisions in geostationary orbit, see Oltrogge, D. L., et al. "A comprehensive assessment of collision likelihood in Geosynchronous Earth Orbit." *Acta Astronautica* 147 (2018): 316-345, doi.org/10.1016/j.actaastro.2018.03.017

[21] Kessler, Donald J., and Burton G. Cour-Palais. "Collision frequency of artificial satellites: The creation of a debris belt." *Journal of Geophysical Research: Space Physics* 83.A6 (1978): 2637-2646, doi.org/10.1029/JA083iA06p02637.

[22] For more information on the costs and benefits of various forms of orbital debris remediation, see National Aeronautics and Space Administration, Office of Technology, Policy, and Strategy, *Cost and Benefit Analysis of Orbital Debris Remediation* (Washington, D.C.: March 2023); National Aeronautics and Space Administration, Office of Technology, Policy, and Strategy, *Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris* (Washington, D.C.: May 2024).

[23] While small, untracked debris poses the greatest risk of directly colliding with and disabling a satellite, large debris in particularly busy orbits can suffer a collision or a spontaneous break-up event that generates hundreds or thousands of smaller pieces of debris. For this reason, experts we spoke to identified large debris objects as a major, long-term risk and researchers have identified particular "most-concerning" pieces of debris. See, for example, McKnight, Darren, et al. "Identifying the 50 statistically-most-concerning derelict objects in LEO." *Acta Astronautica* 181 (2021): 282-291, doi.org/10.1016/j.actaastro.2021.01.021. The five-to-ten estimate is based on studies that show that the growth of debris in LEO can be slowed by removing at least five defunct spacecraft every year. For more information, see NASA Office of the Inspector General, *NASA's Efforts to Mitigate the Risks Posed by Orbital Debris*, IG-21-011 (Washington, D.C.: January 27, 2021).

[24] The Department of Defense (DOD) defines SSA as "the requisite foundational, current, and predictive knowledge and characterization of space objects and the operational environment upon which space operations depend—including physical, virtual, information, and human dimensions—as well as all factors, activities, and events of all entities conducting, or preparing to conduct, space operations." SSA is enabled, in part, by radar systems that track the location of objections in space. For more information on the state of U.S. SSA, see GAO. *Space Situational Awareness: DOD Should Evaluate How It Can Use Commercial Data*. GAO-23-105565 (Washington, D.C.: April 24, 2023).

[25] Actors in the space industry may opt in to or, in certain cases, be required to obtain insurance for various activities and assets. For example, spaceport operators and launch providers may insure against damages to property or bystanders in the event of a mishap. Satellite operators may insure against pre-launch mishaps, failures during launch and initialization, or during operations. According to industry stakeholders and an expert we spoke with, satellite operators insure about half of satellites during launch but only rarely do so during operations. Orbital debris poses a risk to satellites during both the launch and operational phases.

[26] Orbital debris has been described as a tragedy of the commons: there exists a shared resource, widespread harms, and underinvestment in mitigation and remediation. More precisely, orbital debris behaves like a pollution externality in a global commons. Each satellite launch incrementally adds risk for all future users, but individual operators do not face the full social cost of that debris. The resulting overuse of low Earth orbit and underinvestment in remediation follow the tragedy-of-the-commons logic; the mechanism, however, is the buildup of debris over time rather than simple overuse of the orbits themselves.

[27] See Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 2410, (known as the Outer Space Treaty). The Outer Space Treaty assigns responsibility for human-made objects in space, both operational and debris, to the nation that originated the objects. This means that if a U.S. company launches a satellite, the U.S. federal government is responsible for that satellite. More specifically, the treaty states that, "States Parties to the Treaty shall bear international responsibility for national activities in outer space… whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space… shall require authorization and continuing supervision by the appropriate State Party to the Treaty."

Endnotes (continued)

[28] See e.g. 49 U.S.C. § 40103, Sovereignty and Use of Airspace, and the Public Right of Transit and 21 C.F.R. part 1040 Performance Standards for Light-Emitting Products. Existing Federal Communications Commission (FCC) satellite licensing processes may inhibit a debris removal provider from approaching and deorbiting multiple pieces of debris. For more information on FCC regulatory challenges, see GAO. *In-Space Servicing, Assembly, and Manufacturing: Benefits, Challenges, and Policy Options*. GAO-25-107555. Washington, D.C.: July 10, 2025.

[29] For more information on industry concerns about laws and regulations on the use of ground-based laser nudging systems, see Center for Space Policy and Strategy, *Policy Compliance Roadmap for Small Satellites* (Arlington, VA.: The Aerospace Corporation, 2022). https://aerospace.org/paper/policy-compliance-roadmap-small-satellites.

[30] For more information on the environmental and safety hazards posed by objects reentering Earth's atmosphere, see GAO. *Large Constellations of Satellites: Mitigating Environmental and Other Effects*. GAO-22-105166 (Washington, D.C.: September 29, 2022).

[31] For more information on the use of AI in tracking debris and predicting potential collisions, see NASA Orbital Debris Program Office, *Project Review - Machine Learning Applications Supporting the ODPO*, Orbital Debris Quarterly News, accessed August 25, 2025, https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNv29i1.pdf; and Massimi, Federica, Pasquale Ferrara, and Francesco Benedetto. "Deep learning methods for space situational awareness in mega-constellations satellite-based internet of things networks." *Sensors* vol. 23, no. 124 (2022).

[32] 51 U.S.C. § 50924.

[33] 47 CFR § 25.114, 25.283.

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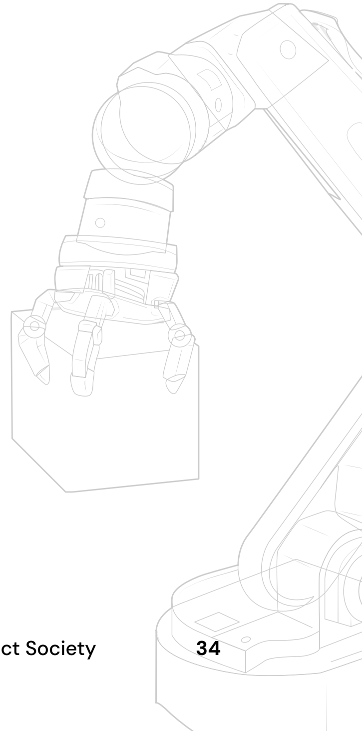

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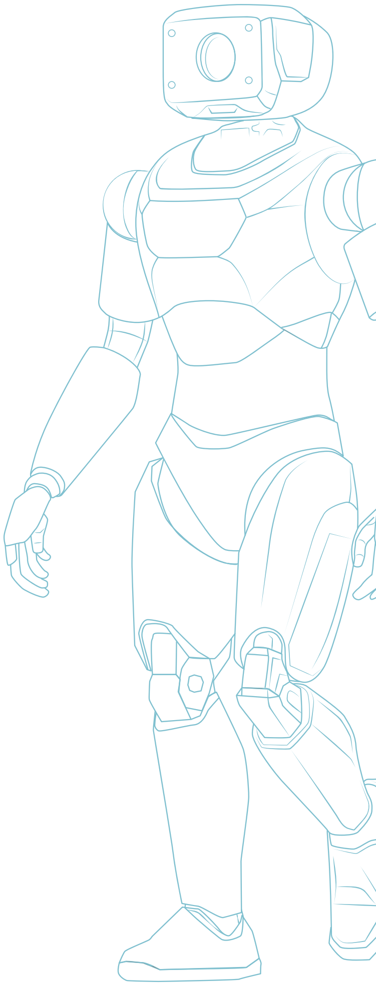

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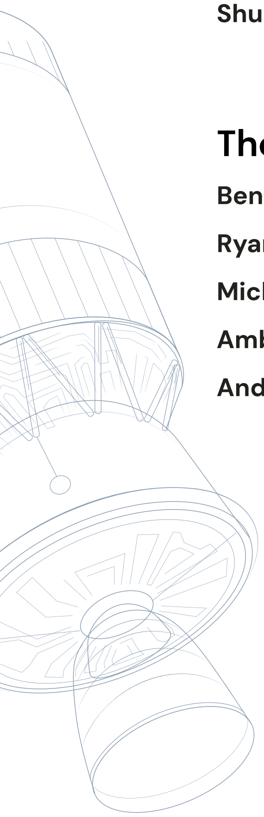

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