The Future of Space Technology and How It May Benefit Humanity

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Introduction

Space technology—defined here as the practical applications of scientific knowledge to space—has contributed immensely to our daily lives. Although some may be apprehensive as to where technological advancements may lead, including increased potential for self-destruction, space technologies have not only had tremendous tangible benefits in various areas of life but have also deepened the understanding of what the essence of humanity is. Advances in space technologies will undoubtedly transform physical reality over the next century and will potentially ensure human survival.

The initial question posed for this paper was "What is the future of space technology? What benefits will humanity derive from the growing accessibility of space and the space economy?" This paper refocuses the question from "benefits" to "effects" for while space technology will certainly benefit humanity, it will likely present challenges as well. Even so, this paper takes a more optimistic view of the impact of space technologies perceiving the latter in terms of creating opportunities rather than vulnerabilities.[1]

This paper proceeds as follow: it first briefly summarizes past applications of space technologies in daily life before reviewing current and proposed space technological developments. Then, it discusses how those may impact lives economically, socially, and politically over the next century.

Past Spinoffs of Space Technology

Space technologies that were developed to counter the harsh environment of space often found practical applications on the ground. The National Aeronautics and Space Administration (NASA) estimates that, since 1976, there have been more than 2,000 spinoffs of NASA technologies that have benefited life on Earth in the form of commercial products.[2] Some of those include camera phones; scratch-resistant, polarized lenses; CAT scans; LED technology; land mine removal techniques; athletic shoes; foil blankets; water purification systems; dust busters; ear thermometers; home insulation; memory foam; wireless headsets; freeze-dried food; adjustable smoke detectors; enriched baby formulas; artificial limbs; the computer mouse; portable computers; insulin pumps; noninvasive internal imaging; cochlear implants; GPS navigation systems; weather forecasting; and flame resistant fiber, just to name a few.[3]

A Recent Trend in Space Technology: Miniaturizing the Size of Satellites

Space technologies are evolving continuously. One recent development, that is likely to impact many other activities in space, is the miniaturization of satellites.

In the past, traditional satellite architecture produced heavy, bulky, specialized, and costly payloads that took years to manufacture and were often behind schedule (see Table 1). Traditional satellites weigh in the 1,000s of kilograms, cost more than $500 million each (often in the billions of dollars), and have 5-to-10+ years of production time. Due to their dedicated, highly specialized mission, they are high-risk desirable targets with low-tolerance and low-redundancy levels.

Table 1: Traditional vs. Small Satellites Architecture

	Traditional Satellite Architecture	**Current Satellite Architecture: Small Satellites**
Size	1,000s of kg	<100s of kg
Cost/Satellite	$500million - $3+billion	<100s - 10s of millions
Quantity	1 - 2 satellites per generation	Large constellations possible
Development Time	5 - 10+ years	< 2 - 3 years. Rapid iterations possible
Risk Posture	High impact capability loss per satellite Low risk tolerance	Inherent redundancy across constellation High risk tolerance
Security	Attractive targets for counter-space activities	Greater resilience to counter-space activities
Launch	Dedicated missions	Rideshare opportunities
Capabilities	Dedicated, specialized, high-performance instruments on limited vehicles	Opportunities for distributed command & control in contested environment, increased revisit rates for data collection, etc.

Credit: adapted with permission from Ariel Sandberg, MIT Lincoln Lab, 2022

In contrast, recent developments in satellite architecture have produced smaller, lighter satellites, such as CubeSats[4] and Nanosats, with shorter production times. Small satellites weigh less than 1,200 kg (2,600 lbs.),[5] and are further categorized into mini,[6] micro,[7] nano,[8] pico,[9] and femto[10] satellites based on their mass (see Table 2).[11] The five smallest mass class satellites (<600 kg) are referred to as "smallsat" or "very small satellites."

Small satellites have transformed in-space satellite architecture. They are cheaper (low tens of $ millions/each) and faster (2-to-3 years production time) to develop, produce, and launch. Small satellites lend themselves to rapid iterations and can form large constellations, which improve their resilience and lower their risk level as the command-and-control functions can be distributed, if needed.

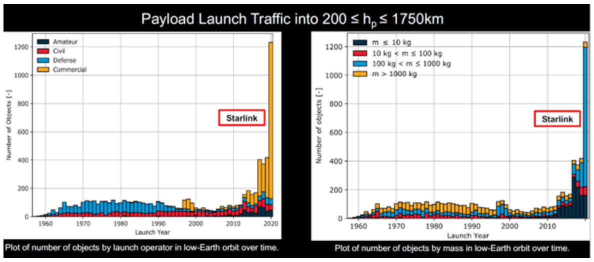
Thanks to those advantages, the popularity of small satellites soared over the last 10 years. While there were 53 smallsats launched in 2012, that number jumped to 1,743 in 2021, representing 94%[12] of all spacecraft launches in 2021 (see Figure 1).[13]

Table 2: Size of Satellites

Mass Class Name	**Kilograms (kg)**
Fento	0.01 - 0.09
Pico	0.1 - 1
Nano	1.1 - 10
Micro	11 - 200
Mini	201 -600
Small	601 - 1,200
Medium	1,201 - 2,500
Intermediate	2,501 -4,200
Large	4,201 - 5,400
Heavy	5,401 - 7,000
Extra Heavy	>7,001

From: FAA, *The Annual Compendium of Commercial Space Transportation*, 2018 [Smallsats: Fento to Mini]

Figure 1: Evolution of Mass Traffic in Space per Mass Category



perigee height hp and apogee height ha.
Source: “ESA’s Annual Space Environment Report,” ESA 2021, p. 26, 31, the units are km. Formatted by Ariel Sandberg, MIT Lincoln Lab, 2022.

Overall, the number of small satellites launched in space has increased exponentially over the last 10 years, most supplied by commercial providers, as in the case of Starlink or OneWeb.

Potential Repercussions of Small Satellite Architecture

Small satellites, in general, and the Starlink project, in particular, represent a key departure from traditional aerospace practices. The traditional, heritage satellite architecture was complex, costly, and specialized, resulting in long lead assets deployed as one-offs or limited constellations. In contrast, modern satellite architecture focuses on design simplicity, rapid design updates, fast-paced production, rideshare launch, on-orbit testing, and large constellation redundancy, all of which result in cheaper, faster, and more expandable satellite practices.

These recent developments in satellite architecture will result in access to space becoming à la carte where interested parties can enter space at different levels of engagement (see Table 3). One may expect, therefore, that space will become even more congested as the number of new entrants increases. It will, however, also become more diversified in terms of capabilities, interests, and stakes, which will transform the current environment.

Table 3: À La Carte Access to Space

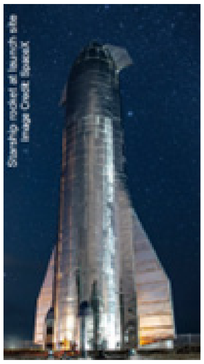
	Purchase as a Service	**Weightless Secondary Payloads**	**Hosted Payloads on Common Bus**	**Custom Spacecraft in Constellation**	**Custom Constellation w/ Industry Practices**
Advantages	Only pay marginal cost for data/service	Only pay marginal cost for data/service	Reduce dev/time cost by leveraging payload partner bus and standardized interfaces	Reduce dev time/cost for supporting infrastructure and protocols	Full flexibility with ops and priorities
	Immediate access to capability	Innovate in software, operations, electronics			Leverage practices for cost and schedule savings
Examples	Purchasing imagery from commercial partners	Nav signals over comm lines	Small payloads	Fully mission capable satellite fliying within another constellation	Dedicated LEO satellite architecture built using COTS components
		Custom waveforms	New technologies	Leverage cross-links, ground infrastructure	
		Custom camera modes	Components for space qualification		

Credit: Ariel Sandberg, MIT Lincoln Lab, 2022 (used in ppp with permission).

Space Technologies in Development

This section discusses select current developments in space technology, focusing mainly on (1) new spaceship design, (2) alternative propulsion methods, (3) artificial intelligence (AI), and (4) quantum communications.

Bigger, Reusable, Deep-Space Capable Spaceships

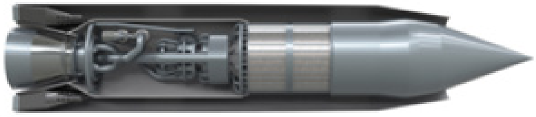

Starship rocket at launch site
Image Credit: SpaceX

When first announced in 2005,[14] Starship was intended primarily to go to Mars; since then, its mission expanded to include delivering more than 100 tons (220,000lb) of cargo to low Earth orbit—thus, designated as a super heavy-lift launch vehicle,[15] cleaning up space debris, landing on the Moon,[16] and traveling between locations on Earth.[17] Starship can be seen as a first step toward an Interplanetary Transportation System.[18]

Alternative Propulsion Methods

To make space both affordable and accessible, NASA's Advanced Space Transportation Program (ASTP) has set a specific goal to reduce the cost of getting to space from $10,000 per payload pound currently "to hundreds of dollars per pound within 25 years and tens of dollars per pound within 40 years."[19] To that end, NASA has been developing new propulsion technologies including:

1. air-breathing engines[20] that "breathe" oxygen from the air once the vehicle's velocity reaches twice the speed of sound and reverts to conventional rocket-powered systems when the vehicle's speed increases to 10 times the speed of sound. Others are pursuing similar research. The UK firm Reaction Engines for instance is developing a new class of propulsion system, the Synergetic Air Breathing Rocket Engine (SABRE) that should have similar, fully reusable, hybrid-air-breathing rocket engines.[21]



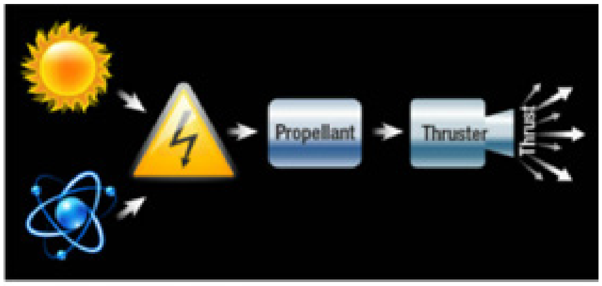
SABRE unleashed A concept image of Reaction Engine's Synergetic Air Breathing Rocket Engine (SABRE). (Courtesy: Reaction Engines)

Illustration of a SABRE engine

2. Magnetic-levitation launch assist (maglev) technologies that use magnets to accelerate a vehicle along a track up to 600 mph when rocket engines would kick in to launch the spacecraft into orbit[22] (i.e. StarTram[23]).
3. Beamed-energy propulsion that uses remote energy sources (e.g., the Sun, ground- or space-based lasers) to send power to a space vehicle via a "beam" of electromagnetic radiation.[24]
4. Electrodynamic tethers (EDTs) whose long, electrically conducting wires are used as thrusters to either raise or lower the orbits of satellites or spacecraft using electromagnetic principles.[25]
5. Pulse detonation rocket engines (PDE) use detonation waves to combust the fuel and oxidizer mixture to propel an aircraft. PDE-powered engines were successfully tested in 2008, abandoned, and recently resurrected in 2020 when a new propulsion system, "the rotating detonation rocket engine" was tested that used similar PDE supersonic detonation, instead of traditional subsonic combustion, techniques to power a spacecraft.[26]
6. Two types of nuclear propulsion systems: nuclear electric[27] and nuclear thermal[28] propulsion (NEP and NTP). Both have higher fuel efficiency relative to traditional chemical fuels.[29] While NTP has been on NASA's agenda for more than 60 years, NEP builds on the agency's more recent work on solar electric propulsion (SEP) thrusters and systems for the upcoming Artemis mission to support life on the lunar surface. NASA is exploring both NEP and NTP for crewed Mars missions.

In that regard, three important developments took place recently. First, in March 2021, NASA's Gateway's electric propulsion system completed its first test.[30] It uses Power and Propulsion Element

(PPE) that is a high-power, 50-kilowatt solar electric propulsion (SEP) developed by Maxar Technologies.[31] Second, in July 2021, NASA and the Department of Energy (DoE) awarded three reactor design proposals for a nuclear thermal proposal system to be potentially used for crew and cargo missions to Mars as well as for science missions to the outer solar system.[32] Third, in November 2021, the DoE sent out a request (still open) for proposals to design and build a 40+ kWe (kilowatt-electric) lunar surface fission reactor using low-enriched uranium with at least a 10-year lifetime warranty on the lunar surface "to support sustained lunar presence and exploration of Mars."[33]



A simple illustration of how electric propulsion systems work
Credits: NASA/ATS Lisa Lizzo

A simple illustration of how electric propulsion systems work

Developing alternative, viable propulsion systems will accomplish two main goals: lower the cost to access space and ensure the long-term sustainability of space missions.

Artificial Intelligence (AI)

In February 2022, the Pentagon's Joint Artificial Intelligence Center (JAIC) announced that it had completed the first "integration layer" for Artificial Intelligence (AI) algorithms.[34] The Department of Defense (DoD), as part of the Artificial Intelligence and Data Initiative (AIDA), announced in 2021 its intent to integrate AI in joint military operations to assist combatant commands (COCOMs) by processing data and streamlining decision making.[35] AI could enhance national defense[36] and provide a solution to ever-increasing space traffic.[37] Currently, with more than 4,800 operational satellites in space[38] and more than 25,000 trackable debris larger than 10 cm,[39] integrated AIs, also known as Artificial Neural Networks (ANN), can process mass data faster and more accurately, reducing, thereby, the tasks of human operators by implementing automation, lowering the data processing and decision-making time, decreasing false alarms, improving orbit determination of operational and defunct satellites, and coordinating between various actors. However, the lack of appropriate real-life scenarios to train ANN models, the classified nature of certain space data, and internal institutional rigidity present real impediments to fully implement integrated AI in space.

Quantum Communications

On March 7, 2022, NASA announced that the International Space Station (ISS) would host a "self-healing" quantum communications demonstration[40] called the Space Entanglement and Annealing QUantum Experiment (or SEAQUE), part of a planned global quantum network. SEAQUE is a milk-carton-size tech demonstrator that will be attached on the ISS's Bishop airlock. A key component in this network is space "nodes": points that receive and transmit photons using lasers as transmitters.[41] SEAQUE will demonstrate three quantum phenomena, all linked to quantum entanglement,[42] namely that (1) orbiting nodes can securely connect quantum transmitters and receivers over great distances, (2) space-based nodes can "self-heal" from radiation damage using an "annealing" process that repairs radiation effects in the lattice with a laser, and (3) the generation of entangled photon pairs through a waveguide.[43] Quantum computers hold the promise of almost immediate speed: They operate millions of times faster than conventional computers in solving specific problems and can measure minute changes in physical processes, such as quantum gravity. Eventually, quantum cloud computing may enable us to exchange and process data, including communications, almost immediately and across great distances.

Proposed Space Technologies

In addition, a number of proposed technologies, if realized, may have tremendous impacts on humanity. This section discusses those futuristic projects based on their proximity to Earth, starting with the closest orbits.

Earth and Close Orbits

To counter the innate hostility of outer space to the human body, new proposals focus on enhancing humans with a variety of bionic and prosthetic technologies, brain-computer interfaces, cognitive and body enhancers, as well as controversial gene editing. In parallel, advanced robotic artificial intelligence bots continue to be developed in anticipation that one day we may need to send them on space missions where humans cannot go.[44] Enhanced humans and advanced human AI bots create bioethical and social concerns centering on questions as to how these technologies should be used, to what end, who should regulate their use, and whether they will exacerbate social and economic inequalities. In addition, if AI humanoid bots become self-aware and evolve beyond our control, the limits of humanity will be tested in redefining their rights and how to integrate them within the existing bioecology.

In close-Earth orbits, such as low-Earth orbit (LEO), medium-Earth orbit (MEO), and geostationary-Earth orbit (GEO), companies are developing space habitats, including a space hotel: Orbital Space Corporation[45] plans to open Voyager Station by 2027 and host some 280 guests plus 112 crew members. Other companies, in collaboration with NASA, are working on various versions of human habitats and commercial stations in space.[46] In addition, a handful of companies aim to construct a space elevator—also termed "spaceline" if closer to the Moon and balanced at the L1 LaGrange point—by 2050.[47] Thanks to federal deregulation that opened the doors to an increasing influx of commercial space actors, such projects are within reach, propelled by a wealth of innovative ideas and private financing.

Stakeholders have discussed developing and installing solar factories—in GEO or on the Moon—since the 1970s. Space-based solar power (SBSP) refers to the ability to collect solar power in outer space using solar power satellites and beaming the energy back to Earth or to any other point at radio frequencies. Despite various proposals, none has been shown economically viable with current space launch costs.[48] With the advent of new launch and propulsion technologies, as well as the development of mining in space, solar factories in space may yet become a reality.

Lunar Space

In 2020, NASA selected 14 American companies to develop "Tipping Point" technologies for the Moon and Mars. The chosen space proposals offered to develop, among other projects: (1) long-term cryogenic fluid management to store, preserve, and transfer super-cold liquids, used as propellants, which is essential for long-term stay on the Moon; (2) small, deployable hopper landers capable of accessing lunar craters and transmit high-resolution images of the lunar surface over short distances; (3) a lunar mobile evaluation lab to conduct tests at different locations on the lunar surface; (4) precision landing and hazard avoidance capabilities across various lunar surfaces; and (5) closed-loop descent and landing on the Moon.[49] In 2021, NASA gave additional awards to six teams that developed winning proposals on best ways to deliver cargo to the lunar surface.[50] Those proposals, if realized, will allow us to establish long-term human settlements on the Moon and beyond.

Deep Space

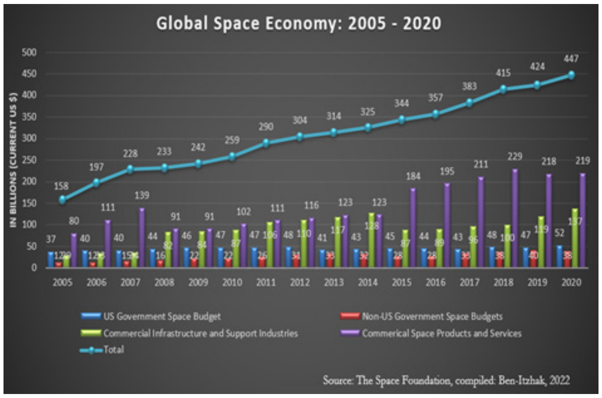
Improved technology, decreasing costs, and potentially enticing economic gains have excited space entrepreneurs to take first steps toward one of the most daring ventures in space: mining the Moon, Mars, and select asteroids.[51] In 2020, NASA awarded contracts to four companies[52] to extract small amounts (50-500 grams) of lunar regolith, marking, thereby, the de facto beginning of commercial space mining. As resource depletion on Earth becomes a reality, the idea of extracting valuable elements from celestial bodies and returning those to Earth for profit is becoming more appealing.

In fact, we have already demonstrated the ability to land on an astronomical body and extract material: (1) Japan's Hayabusa-1 mission was the first to collect dirt from the asteroid Itokawa in 2005 (returned in 2010) and Hayabusa-2 mission brought back a sample of carbon-rich dust and pebbles from another asteroid, Ryugu in 2018 (returned in 2020)[53]; (2) NASA's Osiris-Rex touched down on and extracted samples from asteroid Bennu in 2020[54] (due to return in 2023); and (3) the European Space Agency's (ESA) Rosetta's Philae lander successfully landed on comet 67P/Churyumov-Gerasimenko in 2014 (although it did not return due to depleted solar power).[55] Those incredible feats demonstrated that, thanks to advanced space technologies, spacecraft can conduct autonomous navigation, including low gravity precision and rendezvous proximity operations around an asteroid or a celestial body; land; collect materials; depart; and return safely. If further developed, such technologies will pave the way to mining any celestial body[56] and establish off-world colonies to that end.

Effects of Space Technology

Space technology will have various economic, social, and political impacts on humanity.

Economically, the space economy will continue its steady growth as space tourism becomes more accessible and as the number of commercial actors, facilities, and activities in space increases. One example is Virgin Galactic. Before Richard Branson's flight to the edges of space in July 2021, Virgin Galactic had sold more than 600 seats, each costing as much as $250,000, to people in 58 countries. After the flight, as demand grew, some industry observers expect new passengers to pay at least $450,000 per seat.[57] There is no shortage of buyers.[58] States also encourage such commercial initiatives. For instance, the first private astronaut mission, Axiom 1 (Ax-1), launched on April 8, 2022, taking four astronauts on an eight-day stay at the ISS.[59] Ax-1 is the first of several planned Axiom missions to the ISS, ushering in a new era of increased access to and commercialization of space.[60] It is a collaboration between private companies (in this case: Axiom Space and SpaceX Crew Dragon) and a state agency (NASA). Such trends are likely to increase.



Source: The Space Foundation, compiled: Ben-Itzhak, 2022

Graph showing the growth of the global space economy from 2005 to 2020

In 2020, commercial spending in space remained the most significant driver of the overall global space economy, representing almost 80% of total revenue.[61] In 2020, the global space economy reached nearly $447 billion: an increase of 4.4% from the previous year (2019: $424 billion). This growth has remained steady, and the global space economy will continue to grow as the number of commercial actors and activities in space increases. In the long term, space business parks and centers will be established that will facilitate economic activities, including mining in space.

Socially, space technologies will improve life in numerous and unpredictable ways, including access to faster and more reliable communications; clean, cheaper, renewable sources of energy, such as solar electric power beamed from space; faster transportation options for people and cargo (expected worldwide two-hour express package delivery); and improved medical facilities and treatments, including space hospitals for treatment of chronic pain and disabilities.[62] For those who choose to have human enhancements, the quality and—very likely—the length of life will improve drastically.

Politically, relations among and within states may be challenged at all three levels: individual, state, and system. At the individual level, notions of human rights may need to account for the presence of advanced, empathic, self-aware humanoid bots and how they fit within the fabric of humanity. At the state level, political institutions may need to consider how to spread domestically the wealth amassed from space and how to diminish the severity of internal social, economic, and political disparities that will undoubtedly ensue from participating in a growing space economy.

At the systemic level, states will have to grapple with four main issues. First, leading space-faring states will have to decide a fair way to share the riches of space with non- or less-active space-faring states, in accordance with the 1967 Outer Space Treaty (OST) that stipulates in its preamble that “the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development.”[63] Second, the proliferation of actors, objects, and activities in space will require agreed-upon, coordinated, and enforceable international regulations to ensure long-term space sustainability.

Third, as people venture beyond close-Earth orbits, off-world human settlements will be established on the Moon, Mars, and beyond. What type of government will those off-world colonies have? In this respect, the current space law statute giving states jurisdiction and control over objects and personnel launched under their registry (OST, Art. 8) may prove insufficient as it does not consider potentially impactful technological developments, the settlements' mission, or their physical distance from Earth.

Fourth, the current international system of Westphalian states may, itself, be challenged as the core of what constitutes a state—namely, sovereignty and territoriality—will be tested in space. This systemic conflict will become even more acute as states venture farther out, in deep space, where territorial boundaries will become blurred, and the survival of a state may depend on the survival of an individual. As a result, the current system of nation states may have two options: revert the focus back to the individual, much à la classical, Morgenthau[64] realist fashion, or consolidate states into blocs of strategic space alliances.[65]

Conclusion

Space technology has transformed our lives and will continue to do so.

In the short term, from the present day to 30 years, we will be able to journey to the edges of Earth's atmosphere; peer into the beautiful, silent darkness of space; experience the overview effect from a comfortable, artificial gravity room in a space hotel; take an elevator to the stars (or at least to some point in cislunar space); perform an extravehicular activity (EVA) walk like an astronaut; and even leave our own footprint on the Moon.

In the longer term, 30 to 100 years, we will be able to take a spaceship to Mars (along with 99 other people) while communicating effortlessly across vast distances with family and friends back on Earth or the Moon; eat Martian potatoes; climb Mars' Olympus Mons (the largest volcano in our solar system), and mine gold on an asteroid. Advances in space technologies will translate into new medicines and improve human lives both qualitatively and quantitatively. The current cost of investing in space technology was less than 1% of total U.S. government spending for 2020.[66] Is it worth it? Absolutely. The current and potential future benefits of space technologies are likely to far outweigh incurred costs and anticipated risks.

While challenges in space exploration remain, opportunities abound. Seizing those opportunities has been the privilege of a few, but this is slowly changing. Traditionally, national agencies that had sufficient manpower and finances pioneered space efforts. Over the last 10 years, non-state actors have taken a lead role in undertaking daring space ventures, dreaming the impossible, and achieving the incredible. Space trailblazers have opened the way for others to follow and to partake in the immense treasures that space holds: not only in terms of material riches, but also in terms of expanding our knowledge and understanding of who we are and what our humanity means.

Endnotes

1. Due to length constraints, I do not discuss how space technologies may benefit first movers in this area or how internal institutional dynamics may impede or enhance the integration of such technologies; rather, in this paper, I focus only on general tendencies as the question—as posed—directs the discussion toward "humanity" in general.

2. An entire website dedicated to spinoffs of NASA technology can be found at https://spinoff.nasa.gov/.

3. More on space technologies integrated in medicine: https://www.nasa.gov/audience/foreducators/postsecondary/features/F_At_the_Hostipal_with_NASA.html; water purification systems: https://www.nasa.gov/missions/science/f_water.html; and other various: https://www.nasa.gov/offices/oct/feature/did-you-know-thats-a-nasa-technology.

4. CubeSats have a standard form factor of 1 kg, 10-centimeter cube that makes 1 unit (1U) that can be combined with other 10-cm units to form larger CubeSats (e.g., 3U, 6U, etc.).

5. This is the total, wet mass (including fuel).

6. Examples of small, mini satellites (100-500 kg) include Demeter, Essaim, Parasol, Picard, MICROSCOPE, TARANIS, ELISA, SSOT, SMART-1, Spirale-A and -B, and Starlink satellites. The Starlink satellites, for instance, weigh about 260 km (570 lbs) and are roughly the size of a normal table. (See, NASA's Small Satellite Missions, https://www.nasa.gov/mission_pages/smallsats).

7. Examples of microsatellites or microsats (10-100 kg) include Astrid-1, Astrid-2, a set of satellites to be launched on Virgin Galactic's LauncherOne, and the two MarCO (Mars Cube One) microsats (just 13.5 kg or 30 lbs. each) that became the first to leave Earth's orbit and venture into interplanetary space.

8. Examples of nanosatellites or nanosats (1-10 kg) include CubeSat, a 10cmx10cmx10cm cube, with a mass of 1.33 kg per cube, as well as ExoCube (CP-10), ArduSate, and SPROUT. (See, Loisel, Julie 2022. "CubeSat Technology and Periglacial Landscape Analysis," Treatise on Geomorphology, Vol 1, pp. 18-29; and EU's Nanosats Database at https://www.nanosats.eu/cubesat).

9. Examples of picosatellites or picosats (0.1-1 kg) include PICASSO CubeSat (https://www.aeronomie.be/en/news/2020/picasso-picosatellite-ready-launch) and TUPOD (see, Cappelletti, Chantal. 2021. "Structure, new materials, and new manufacturing technologies," Cubesat Handbook, pp. 165-183). Picosats are used together to form "swarms," based off of a larger "mother" satellite to communicate with the ground. Due to their low mass, they are cheaper to launch, at about $12,000-18,000 per picosat, that is about the size of a soda can. (see, Defense Industry Daily. 2011. "Small is Beautiful: US Military Explores Use of Microsatellites" https://www.defenseindustrydaily.com/Small-Is-Beautiful-US-Military-Explores-Use-of-Microsatellites-06720/)

10. Femtosatellites or femtosats (< 100 grams) also known as "chip satellites." Examples of femtosats include ThumSat, Sprites, and, more recently, ChipSats.

11. Bryce Space and Technology. 2022. "Smallsats by the Numbers" online at https://brycetech.com/reports.

12. Despite this overwhelming percentage of total launches, small satellites represent only 43% of the total upmass. See, Bryce Space and Technology. 2022. "Smallsats by the Numbers" online at https://brycetech.com/reports.

13. Bryce Space and Technology. 2022. "Smallsats by the Numbers" online at https://brycetech.com/reports.

14. Foust, Jeff. 14 November 2005. "Big plans for SpaceX." Space Review.

15. O'Callaghan, Jonathan. 7 December 2021. "How SpaceX's massive Starship rocket might unlock the solar system—and beyond." MIT Technology Review.

16. Baidawi, Adam, and Kenneth Chang. 28 September 2017. "Elon Musk's Mars Vision: A One-Size-Fits-All Rocket. A Very Big One." New York Times.

17. Starship is expected to provide point-to-point transport as early as 2025. However, several issues need to be addressed first, in particular logistics in defining flexible launch sites, landing protocols, safe trajectories, etc. (credit: Sandberg, Ariel, MIT Lincoln Lab, class lecture, March 2, 2022.)

18. Foust, Jeff. 26 September 2016. "SpaceX performs first test of Raptor engine." SpaceNews.

19. Marshall Space Flight Center, NASA, Advanced Space Transportation Program: https://www.nasa.gov/centers/marshall/news/background/facts/astp.html.

20. Nailard, Oliver. 2020. "Eliminating the boundary between sky and space," Physics World, vol. 33, no. 10: p. 31

21. Physics World. 15 Oct 2020. "Air-breathing rocket engines: the future of space flight," at https://physicsworld.com/a/air-breathing-rocket-engines-the-future-of-space-flight/

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23. StarTram is a proposed space launch system propelled by maglev. It has three planned generations. (1) Generation 1 facility would launch cargo only, at high acceleration (30g).

The uncrewed craft will be accelerated through a 130-kimlober (81 mile) long tunnel whose exit will be on the surface of a mountain peak at an altitude of 3 to 7 kilometers (9,800 to 23,000 ft). The launch velocity will be ~ 9 kilometers per second (5.5 mi/s) at a 10-degree angle. The predicted launch cost is $20-$43 per kilogram of payload (versus current $10,000-$25,000 per kilogram to low Earth orbit). (2) Generation 1.5 would launch passenger spacecraft at lower velocities of 4 kilometers per second (2.5 mi/s) from a mountaintop at around 6 km (20,000 ft) above sea level through a 270 kilometers (170 mi) tunnel, accelerating at around 3g. In contrast to Gen 1, Gen 1.5 will use other means of propulsion, such as rocket propulsion or non-rocket ones, like a Momentum Exchange Tether. (3) Generation 2 system will use reusable crewed capsules that will transport passengers in low g-force (2 to 3g). At such low acceleration, the Gen-2 system requires a tunnel that is 1,000-1,500 kilometer (620 to 930 mi) long, with an estimated cost in several tens of millions of dollars per kilometer. Its track will gradually curve up. The elevated part of the tunnel will be supported by magnetic levitation, consisting of magnetized cables and angled tethers. The proposed completion of Star Tram is by 2030. Source: Powell, J., G. Maise J. Paniangua. 2001. "StarTram – The Key to Low-Cost Lunar Bases and Human Exploration of Space," 2001 IEEE Aerospace Conference Proceedings (part can be found here: http://www.spaceagepub.com/pdfs/Powell_2.pdf).

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rocket engines operate on the deflagration of fuel, that is, the rapid but subsonic combustion of fuel. The pulse detonation engine operates on the supersonic detonation of fuel. An important facet, not yet demonstrated practically, is the cycle time. A traditional pulsejet tops out at about 250 pulses per second due to the cycle time of the mechanical shutters; the aim of the PDE is thousands of pulses per second.

27. Nuclear electric propulsion systems use a nuclear reactor to generate electricity that positively charges gas propellants, like xenon or krypton, pushing the ions out through the thruster, which drives the spacecraft forward. See, NASA, "Nuclear Propulsion Could Help Get Humans to Mars Faster," https://www.nasa.gov/directorates/spacetech/nuclear-propulsion-could-help-get-humans-to-mars-faster.

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29. The standard means of propulsion for spacecraft use chemical reactions to produce a very hot, highly pressurized gas inside a combustion chamber. The engine nozzle provides the only outlet for this gas, which consequently expands out of it, providing thrust. The chemical reaction requires a fuel, such as liquid hydrogen or powdered aluminum, and an oxidizer (an agent that produces chemical reactions), such as oxygen. The efficiency of a rocket engines depends on many variables but carrying physical chemicals on a rocket takes physical space, which, in turn, increases costs and decreases functionality. See, Dorrian, Gareth and Ian Whittaker, 2021. "A new era of spaceflight? Promising advances in rocket propulsion," The Conversation. https://phys.org/news/2021-05-era-spaceflight-advances-rocket-propulsion.html.

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31. An electric propulsion system uses energy collected by either solar arrays (solar electric propulsion) or a nuclear reactor (nuclear electric propulsion) to generate thrust, eliminating many of the needs and limitations of storing propellants onboard. According to NASA, "Energized by the electric power from on-board solar arrays, the electrically propelled system will use 10 times less propellant than a comparable, conventional chemical propulsion system, such as those used to propel the space shuttles to orbit. Yet that reduced fuel mass will deliver robust propulsion capable of boosting robotic and crewed missions well beyond low-Earth orbit" (see, NASA, 2022. "Solar Electric Propulsion (SEP)" at https://www.nasa.gov/mission_pages/tdm/sep; NASA, Oct 22, 2020. "The Propulsion We're Supplying, It's

Electrifying," at https://www.nasa.gov/feature/glenn/2020/the-propulsion-we-re-supplying-it-s-electrifying; and NASA, May 23, 2019. "NASA Awards Artemis Contract for Lunar Gateway Power, Propulsion," at https://www.nasa.gov/press-release/nasa-awards-artemis-contract-for-lunar-gateway-power-propulsion).

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