The Fourth Industrial Revolution Launches into Space


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Scientific progress is driving the convergence of several emerging technologies with disruptive consequences — both positive and negative. To date, discussion of this convergence — dubbed the "Fourth Industrial Revolution" — has been in the context of terrestrial manufacturing and industry; however, the impact of the Fourth Industrial Revolution is equally apparent in space, where it is making space more accessible, innovative, and useful to society.

The 4th Industrial Revolution & the Space Domain

The term Fourth Industrial Revolution describes the fourth major shift in how humans produce goods and services. Klaus Schwab, the founder and executive chairman of the World Economic Forum (WEF), identifies the first three industrial revolutions as 1) society's use of "water and steam power to mechanize production", 2) society's use of "electric power to create mass production", and 3) society's use of "electronics and information technology to automate production". Efforts to characterize the Fourth Industrial Revolution occurring today have proven somewhat elusive, with experts offering varying definitions. Nevertheless, these definitions, despite their differences, tend to describe the convergence of several new and emerging technologies that is producing a rapid, disruptive impact across economic sectors.

Technologies associated with the Fourth Industrial Revolution include many of the "buzzwords" heard in industry, government, and the media, such as the Internet of Things (IoT), artificial intelligence (AI), 3D printing, cloud computing, and big data analytics. Other Fourth Industrial Revolution technologies include robotics/autonomy, nanotechnology, biotechnology, materials science, energy storage, quantum computing, and augmented/virtual reality. These technologies are alike in the rapid and widespread manner in which they are transforming or promise to transform economic sectors. Their impact is especially pronounced when they are combined, resulting in entirely new production processes, management systems, and government regulations, and facilitating unlikely business partnerships.

While the Fourth Industrial Revolution is mostly associated with technologies and changes on Earth — especially in factories and other manufacturing centers — it is also in full swing in the space domain. Indeed, companies associated with the burgeoning space industry (estimated by Morgan Stanley to be worth approximately $350 billion) — are leveraging technologies associated with the Fourth Industrial Revolution — from AI to energy storage — to offer innovative products and services. In addition, government-sponsored research projects are facilitating the development of the next wave of disruptive technologies to transform the space domain, such as nanotechnology and biotechnology.

The Internet of Things

One of the technologies most closely associated with the Fourth Industrial Revolution is IoT — a term used to describe networks of inexpensive, ubiquitous sensors capable of collecting enormous amounts of data. IoT applied to the industrial sector (known as the Industrial IoT) enables applications like predictive maintenance, production flow monitoring, inventory management, and logistics/supply chain management. US market research firm Gartner estimates that 8.4 billion IoT devices were in use in 2017 and that 20.4 billion IoT devices will be in use by 2020.

The space domain is experiencing a similar boom in sensor growth thanks to the increased accessibility of small satellites and the rise of mega-constellations. For many years, the trend in the space industry has been to deploy constellations that feature a small number of large, expensive satellites. The US Global Positioning System (GPS), for example, features a constellation of 31 satellites. However, decreased launch costs — driven in part by advances in 3D printing and materials science — and dramatic improvements in processing power, data storage, camera technology, miniaturization, solar array efficiency, and propulsion have made constellations with several small, less-expensive satellites a more attractive option, especially for new space companies trying to find their market niche.

This trend is readily apparent in the remote sensing segment, where new market entrant Planet has been able to capture some of established firm DigitalGlobe's market share. DigitalGlobe (recently acquired by Maxar Technologies) uses a constellation of just five satellites each worth hundreds of millions of dollars to provide high-resolution imagery. Instead of challenging DigitalGlobe head on, Planet has built a constellation of 193 low- and medium-resolution satellites (currently the largest privately-owned constellation) capable of imaging the entire world every day. While Planet's constellation cannot take images of the same quality as DigitalGlobe, its anytime-anywhere availability appeals to customers in the remote sensing market that require "good enough" imagery at a moment's notice. The Fourth Industrial Revolution's proliferation of cheap sensors has allowed Planet to offer a unique service that complements — rather than directly challenges — DigitalGlobe's higher-resolution satellites.

This trend towards larger constellations of smaller, less expensive satellites is also evident in the satellite communications segment, where a handful of companies are proposing mega-constellations that are many times larger than the one operated by Planet. In March 2018, the US government approved SpaceX's proposal for a 4,425-satellite broadband constellation. The US government has also approved applications from OneWeb (720 satellites) and Telesat Canada (117 satellites) to build large broadband constellations within the last year. Companies as diverse as Samsung (4,600 satellites), Boeing (2,956 satellites), Commsat (800 satellites), and Astrome Technologies (648 satellites) have also discussed mega-constellations.

The proposed mega-constellations do not match the terrestrial IoT in terms of volume — which, perhaps, is a good thing, as the deployment of billions of satellites would almost certainly set off a chain reaction of collisions that would render much of low-Earth orbit useless. However, these mega-constellations do promise to dramatically increase the number of active satellites in orbit (approximately 1,700 at present) to the point that their disruptive impact will match or exceed the terrestrial IoT, especially when paired with cloud computing and AI to leverage the massive amounts of data collected by these satellites.

Big Data, Cloud Computing & AI

The growing number of satellites in orbit — particularly remote sensing satellites — are collecting and relaying back to Earth enormous amounts of data, forcing companies to develop or acquire complex cloud environments to process and store the data. Planet's constellation alone collects over one million images (7-10 terabytes of data) every day and uses the Google Cloud Platform to process and store the imagery collected. The ability to store petabytes of satellite data in the cloud is a technical accomplishment in and of itself, but the size of these databases makes them relatively useless if they must be manually exploited by end users. Consequently, several companies are using AI to turn the data sold by Planet, DigitalGlobe, and others into intelligence that can be sold to a wide range of companies, government agencies, and non-profit organizations.

According to Jeffrey Tarr, the former CEO of DigitalGlobe, there are more than 100 different companies that seek to "make sense" of the remote sensing data collected by satellites — to include optical data, synthetic aperture radar (SAR), and radio frequency data. Some of these companies, such as Planet and DigitalGlobe, are trying to exploit their own data, while others, such as Ursa Space Systems, purchase data streams from other companies instead of operating their own constellations. Regardless of where these companies get their data, they all rely on recent advances in the field of AI — particularly machine learning and deep learning — to process and analyze it.

Space companies are using large quantities of remote sensing data to train machine learning algorithms to perform tasks like classification, prediction, anomaly detection, and root-cause identification, enabling several new commercial applications for remote sensing data. Among others, Massachusetts-based Tellus Labs uses remote sensing data to monitor and model the world's food supply, Montreal-based GHG Satellite uses hyperspectral imagery to track greenhouse gas and methane emissions from industrial facilities, and New York-based Ursa Space Systems aggregates SAR data from various sources to evaluate the global oil and gas supply chain. Other

Photo 1: Rocket Lab

Rocket Lab's Electron rocket utilizes carbon fiber for the rocket's outer shell and 3D printing for the rocket's engines.

companies, such as New Mexico-based Descartes Labs, collect multiple forms of remote sensing data from diverse sources to offer their clients customizable business intelligence, helping them to predict "what will happen when" in response to specific questions.

Materials Science, Augmented/Virtual Reality & 3D Printing

Other Fourth Industrial Revolution technologies disrupting the space industry include materials science, augmented/virtual reality, and 3D printing, which are being used both individually and in tandem to increase manufacturing efficiency and enable more capable rocket engines.

In the area of materials science, space launch companies are utilizing advanced materials — particularly carbon fiber and advanced composites — to increase the durability and reduce the weight of their rockets. The Electron rocket of US-based startup Rocket Lab features an outer shell made almost entirely from carbon fiber. As a result, the Electron Rocket weighs only one third as much as other rockets with comparable size and payload, which can save millions of dollars in rocket fuel per launch. Several other space launch companies are also designing rockets that make significant use of advanced materials. Examples include Florida-based startup Rocket Crafters Inc.'s Intrepid-1 hybrid rocket (made almost entirely of carbon fiber composites), SpaceX's Big Falcon Rocket (which will feature a large composite tank that stores pressurized liquid oxygen, as well as a carbon fiber upper stage), Blue Origin's New Glenn rocket (which will feature carbon fiber parts like nose cones and fairings), and United Launch Alliance's Vulcan rocket (which will include carbon fiber structures like payload fairings and interstage adapters).

Augmented/virtual reality is also being utilized by space companies like Thales Alenia Space and Lockheed Martin to increase efficiency when manufacturing and assembling spacecraft. For example, Thales Alenia Space utilizes augmented reality in the form of tablets and goggles that provide their engineers with a virtual image of a planned satellite assembly, as well as all the information they need for assembling the satellite. Thales also utilizes virtual reality to simulate the optimal clean room configuration for satellite assembly, Photo 2: NASA/Bill Squicciarini

NASA tests carbon nanotube coating (slot "D" on sample tray) to make spacecraft instruments more sensitive without enlarging size.

integration, and testing. Lockheed Martin also makes robust use of augmented reality and virtual reality in the production of its space assets (e.g., the Orion Multi-Purpose Crew Vehicle and the GPS-3 satellite system), saving the company an estimated $10 million per year. Two or three times per year, Lockheed Martin engineers perform so-called "deep dive reviews" in which teams rehearse the entire assembly of a spacecraft in a virtual environment. In addition to these "deep dive reviews", Lockheed Martin engineers perform monthly simulations of component assembly that allow them to identify the most efficient installation processes.

In addition to materials science and augmented/virtual reality, space companies are also using 3D printing — the process of making a physical object from a 3D digital model by laying down many thin layers of material in succession — to lower spacecraft manufacturing costs and to enable new capabilities. This trend is especially prevalent amongst space launch companies developing rocket engines. For example, Rocket Lab's Electron rocket features 10 3D-printed oxygen/kerosene engines, each of which can be printed within 24 hours to enable rapid manufacturing cycles. Rocket Crafters Inc. also uses 3D printing to manufacture its D-Dart hybrid rocket engine, enabling the design of combustion chambers with unique internal geometries that avoid most of the excessive vibration and performance inconsistencies typically associated with hybrid rocket engines. Finally, Aerojet Rocketdyne uses 3D printing to produce the thrust chamber assembly of its RL10 rocket, leading to a 70% reduction in the thrust chamber's part content and a 50% reduction in production time.

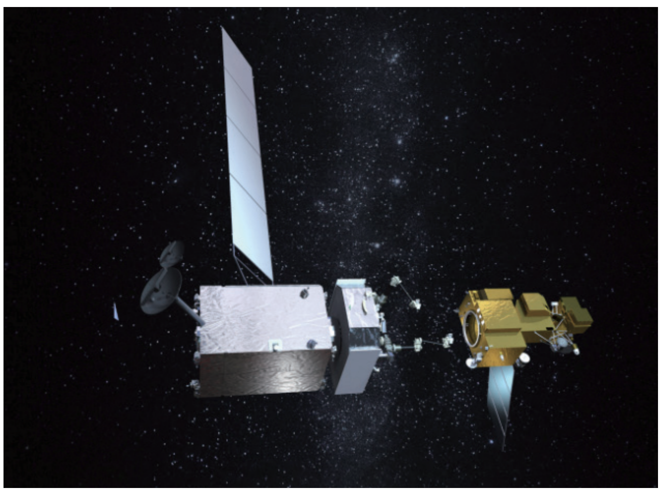
3D printing's disruptive impact is not confined to terrestrial manufacturing processes: the space industry is also exploring the benefits of 3D printing in orbit. These efforts are being led by Made In Space Inc., a California-based company that is best known for providing the first 3D printer to the International Space Station (ISS) in 2014. Made In Space's initial demonstrations aboard the ISS showed that astronauts could use 3D printers to produce small parts, such as buckles and wrenches, without the need to wait for a resupply mission. The company is now working towards more ambitious feats with the support of both US government and private funding. These projects include sending a bottomless 3D printer into orbit that is capable of printing constructions materials (e.g. trusses) and tools (e.g. telescopes), as well using space's microgravity environment to 3D print fiber optic cables with fewer impurities that are up to 100 times better than terrestrially fabricated fiber optic cables.

Robotics, Autonomy & Energy Storage

Space Systems Loral, a subsidiary of Maxar Technologies, and SpaceLogistics, a subsidiary of Orbital ATK, are applying robotics, autonomy, and energy storage technology to the space domain to develop satellite servicing platforms capable of extending the lifetime and upgrading the capabilities of satellites currently in orbit. Space Systems Loral's satellite servicing platforms are backed by US government funding from the National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency (DARPA), while SpaceLogistics' platform is privately funded.

Space Systems Loral has secured contracts with NASA's Restore-L program and DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program to develop robotic, solar-powered satellite servicing platforms. For the Restore-L contract, Space Systems Loral will collaborate with NASA to build a robotic spacecraft that will refuel the US government-owned Landsat-7 satellite in low-Earth orbit sometime in 2020. The Restore-L servicing platform will feature an autonomous relative navigation system, robotic arms, and a propellant transfer system, all of which will be fueled by a system of deployable solar array panels and battery storage. For the RSGS program, Space Systems Loral will work with DARPA to develop a robotic servicing vehicle ready for launch by 2021 that can perform cooperative inspection and servicing of satellites located in geosynchronous orbit — some 20,000 miles above Earth. Because communications between Earth and geosynchronous orbit experience significant latency, the RSGS spacecraft will need to exhibit even more sophisticated autonomy than the spacecraft assigned to the Restore-L mission. The RSGS mission will also make use of solar arrays and battery storage systems to power the robotic servicing vehicle. Space Systems Loral — in collaboration with Space Infrastructure Services — will be able

Photo 3: NASA

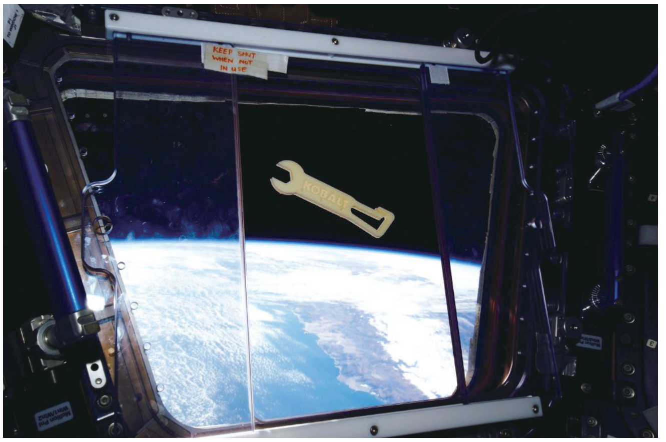


Artist's rendering of the RESTORE-L platform servicing a satellite in orbit.

to use the technology developed from RSGS for both commercial and government missions for several years following the initial demonstration in 2021.

SpaceLogistics offers services to satellites in geosynchronous orbit through two main platforms — the Mission Extension Vehicle (MEV) and the Mission Robotic Vehicle (MRV). MEVs dock with customers' satellites to provide the additional propulsion and/or attitude adjustment (the direction the spacecraft is positioned in 3-dimensional space) needed to extend its lifetime. MRVs are capable of deploying multiple mission extension pods (MEPs) that can perform attitude adjustments at a lower cost than the MEVs. In addition to deploying the MEPs, the MRVs also feature a sophisticated robotics module that enables basic repairs, detailed inspections, and the installation of new capabilities. Both the MEVs and MRVs are capable of semi-autonomous rendezvous and proximity operations and utilize solar arrays and battery storage in tandem to power the spacecraft.

Photo 4: NASA



Made In Space's 3D printer was used to make tools aboard the International Space Station, such as this space-optimized Kobalt wrench.

Nanotechnology

Nanotechnology is a Fourth Industrial Revolution technology still awaiting widespread commercial utilization in the space domain. Within the broader field of nanotechnology, carbon nanotubes (CNTs) are receiving significant attention because of their unique qualities and their potential widespread applications. CNTs are tube-shaped materials made up of a single layer of carbon atoms linked in hexagonal shapes that measure approximately 1 nanometer in width and up to several centimeters in length. CNTs exhibit several unique properties. For example, they have one of the highest strength-to-weight ratios amongst known materials, are extremely flexible and elastic, and have high absorption rates (approximately 99%) of ultraviolet, visible, infrared, and far-infrared light.

Most ongoing research, development, and demonstration associated with CNTs is funded by government organizations and universities. Experts at NASA believe CNT coatings in space-based scientific instruments (e.g. telescopes) could lead to more accurate observations by reducing the amount of stray light bouncing off of surfaces. South Korean researchers from the Gwangju Institute of Science and Technology and Sogang University are exploring the potential of CNT-electronic devices as a radiation-tolerant alternative to silicon-based electronics. Finally, the Aerospace Corporation, a federally-funded research and development center associated with the US Air Force, is exploring the use of CNTs as a conductive coating for solar array panels to make them thinner, lighter, stronger, and more flexible.

Biotechnology

Similar to nanotechnology, biotechnology represents another Fourth Industrial Revolution technology still awaiting widespread commercial application in the space domain. Most biotechnology research, development, and demonstration has been performed with the support of US government funding aboard the ISS, where the microgravity environment enables shorter development loops and new capabilities. For example, California-based Amgen was able to develop its osteoporosis drugs Prolia and Xgeva faster on the ISS than it would have if the research was performed on Earth. Also, Indiana-based TechShot will send a biofabrication lab to the ISS later this year to test the 3D printing of organs like hearts that can only be made in a microgravity environment. Biotechnology companies' use of the ISS is expected to continue to expand into the future and will become an import venue stream for the ISS if it is commercialized after 2025, as intended by the administration of President Donald Trump.

Challenges for the Future: Regulations & Standards for New Space Technologies

As on Earth, the adoption and diffusion of Fourth Industrial Revolution technologies in space are creating increasing pressure for the development of updated government regulations and new industrial standards. For example, in the United States, the trend toward mega-constellations of smaller, less expensive satellites is already challenging the antiquated licensing regimes used by the Federal Communications Commission (for communication satellites) and the Department of Commerce (for remote sensing satellites). The creation of robotic satellite servicing platforms has also necessitated the development of industry-wide technical and safety standards for on-orbit servicing operations.

To realize the full potential of Fourth Industrial Revolution technologies in the space domain, policymakers should look inward to identify and amend antiquated regulations that are stifling innovation and outward to identify areas where they need to convene industry stakeholders to develop novel, consensus-based technical standards. DARPA's decision to establish the Consortium for Execution of Rendezvous and Servicing Operations as a forum for industry and government to discuss standards governing on-orbit servicing operations represents a step in the right direction; however, more must be done — and quickly — to ensure Fourth Industrial Revolution technologies continue to make the space domain more accessible, innovative, and beneficial to society.

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