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Internet of Things in Space Exploration

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Abstract:

The Internet of things (IoT) broadly refers to the ecosystem where billions of interconnected physical objects/devices/end-nodes are equipped with communication, sensing, computing, and actuating capabilities. It is a key technology in space exploration that enables real-time communication, data collection, and safety monitoring. The integration of the IoT in space exploration and colonization represents a major leap forward in technological innovation, allowing for continuous data collection, automated operations, and enhanced scientific discovery. This paper examines the integration of IoT in space exploration.

Keywords: Internet of things, IoT, space exploration, space colonization.

INTRODUCTION

The exploration of space has always been a fascinating subject for humans. Space technologies have countless applications on earth and significantly contribute to economic growth, employment, innovation, and societal progress. The spacecrafts with their sensors and communication systems can relay the information to the orbiters, which can further transmit the data to the earth ground stations

Internet of things (IoT) refers to the idea of connecting virtually any electronic device to the Internet and connecting them through the Internet to each other. The rate of connected devices is overwhelmingly increasing and continuously growing with time. With every addition of an IoT object, there is an increase of information in the form of data in the Internet. In various IoT applications, end devices/sensors and controllers are dispersed across a wide geographical area. The advent of IoT has propelled various “smart” or “intelligent” systems across various fields, such as smart homes, smart cities, logistics, manufacturing, agriculture, intelligent transport systems, etc.

The IoT is playing a critical role in enabling this new era of space exploration. IoT in space exploration is a critical step in human evolution. It is a key technology for interplanetary exploration, enabling connected devices to communicate and work together. It will open up new possibilities for scientific discovery and unlock business opportunities in industries like telecommunications, agriculture, logistics, and environmental monitoring.

One of the primary ways IoT is used in space exploration is through the deployment of small satellites, which are equipped with IoT sensors that collect data on everything from weather patterns to radiation levels. With IoT, communication can also be established between spacecraft, rovers, and other connected devices, allowing for more efficient coordination and information sharing [1].

OVERVIEW ON INTERNET OF THINGS

The Internet began with some military computers in the Pentagon called Arpanet in 1969. It expanded throughout the 1980s as a set of four parallel military networks, each at a different security level. The core technology which gives the Internet its particular characteristics is called Transmission Control Protocol/Internet Protocol (TCP/IP), which is essentially a set of rules for communication [2].

Internet of Things (IoT) is a worldwide network that connects devices to the Internet and to each other using wireless technology. IoT is expanding rapidly and it has been estimated that 50 billion devices will be connected to the Internet by 2020. These include smart phones, tablets, desktop computers, autonomous vehicles, refrigerators, toasters, thermostats, cameras, alarm systems, home appliances, insulin pumps, industrial machines, intelligent wheelchairs, wireless sensors, mobile robots, etc.

There are four main technologies that enable IoT [3]: (1) Radio-frequency identification (RFID) and near-field communication, (2) Optical tags and quick response codes: This is used for low cost tagging, (3) Bluetooth low energy (BLE), (4) Wireless sensor network: They are usually connected as wireless sensor networks to monitor physical properties in specific environments. Figure 1 illustrates the Internet of things [4].

IoT technology enables people and objects to interact with each other. It is employed in many areas such as smart transportation, smart cities, smart energy, emergency services, healthcare, data security, industrial control, logistics, retails, structural health, traffic congestion, manufacturing, and waste management. The Internet of things is extensively developed world-wide with a focus on civilian applications such as electric power distribution, intelligent transportation, healthcare, industrial control, precision agriculture, environmental monitoring, etc. Military logistic is perhaps the most important application domain for IoT [5].

SPACE INTERNET OF THINGS

Space exploration has fascinated humans for centuries. It is no longer improbable and limited to large national government initiatives. It has become an active area of research in academia and industry. There are already many exciting initiatives developed by small startup companies to large private aerospace companies. Elon Musk’s SpaceX has also recently become the first private company to launch a spacecraft to the International Space Station (ISS). Popular media has often discussed the “Mars Race” or “Race to Mars.”

Back in 2015, the National Aeronautics and Space Agency (NASA) created a lab dedicated to the study of IoT and space-related applications. NASA set up a lab at the Johnson Space Center and created four teams to research multiple aspects of IoT: security, protocols and monitoring, data analytics, and end user experience. NASA has an extensive network of antennas around the globe

— over all seven continents — to receive transmissions from spacecraft. In addition to direct-to-earth communications, many NASA missions rely on relay satellites in order to get their data to the ground. Currently, NASA relies primarily on radio waves for communications, but the agency is developing ways to communicate with infrared lasers. NASA's Laser Communications Relay Demonstration (LCRD) will showcase the benefits of optical communications. Figure 2 shows the Laser Communications Relay Demonstration [6].

APPLICATIONS

Traditional popular space applications include the use of satellites to support telecommunications and global positioning systems (GPS). Key areas of IoT in space include satellite communications, edge computing, Internet of space, aerial network, satellite-terrestrial integrated networks, and space-based 5G networks. Key areas where IoT-integrated space technologies have real-world applications include the following [7,8,9]:

- *Satellite Communications:* Space communications basically relies on two things: a transmitter and a receiver. Satellites have long been the backbone of global communications, but IoT has taken this to the next level – offering real-time data transfers in areas. Space network consists primarily of the satellite communication network, with the first satellite launched in 1957. Since then, satellite systems have grown exponentially more complex. Large networks of interconnected satellites can provide global coverage for IoT applications like environmental monitoring and asset tracking. For example, Iridium constellation comprises 66 active LEO satellites providing global voice and data coverage in some of the world's most remote regions. Iridium's services connect over a million devices globally, and IoT devices use this network for applications like aircraft tracking, maritime monitoring, and emergency communications. Both NASA and ESA have prepared plans to deploy satellite networks around earth, spanning Mars and the Sun. The networks consist of microwave antenna arrays with miniaturized satellites and lasers pointing through free space. LEO satellites are smaller, cheaper, and easier to produce than their GEO and MEO satellite cousins. It only takes 3 GEO satellites to provide 100% communications coverage at an altitude of 22,000 miles above the Earth's surface. GEO satellites remain visible at all times from a single fixed location on earth. But they are only suited for IoT applications where the content needs to be delivered to the users, without much latency constraints. Satellite-enabled Internet at the LEO level, also known as Satellite Terrestrial Network (STN), is intended to augment the existing terrestrial Internet. Besides the communication subsystem, global positioning system (GPS) is one of the essential but significantly energy-guzzling subsystems in a satellite. Figure 3 displays satellite communications [6].
- *Internet of Space:* Space is the next frontier for innovations in IoT, leading to the "Internet of Space." Leading companies around the globe have started seriously considering the concept of the Internet of Space (IoS) or Internet of Space Things (IoST), a cyber-physical system that integrates on-the-ground data and satellite information to enable a wide range of applications. Figure 4 shows a typical IoT in Space [10]. It may be regarded as an extension of the Internet of things (IoT) concept into space. The IoST concept was introduced by an innovative group from the Georgia Institute of Technology. It involves a satellite, or a network of them, to address the main challenges in terrestrial IoT deployments – global coverage, scalability, and connectivity. The system is controlled and managed using software-defined networking (SDN) and network function virtualization (NFV). The "things" in IoST specifically refer to a new class of small satellites called CubeSats, indicating that small satellites are the building blocks of Space-IoT. Their role primary revolves around data collection and transmission to and from the earth. They can communicate directly over hundreds of kilometres with various IoT devices on Earth. They enable the realization of a new global cyber-physical system that can be used for a multitude of applications on land, in the air, and in space. Space-IoT relies on a constellation of hundreds of

satellites to accomplish global coverage. Security is built into the IoST architecture through the use of different security profiles and delivered as-a-service to protect the availability, integrity, and privacy of all connected resources and information. The IoST can be used for a variety of applications, including monitoring and reconnaissance, in-space backhaul, and cyber-physical integration services. New scientific discoveries will be made possible by the IoST. The system architecture of IoST is shown in Figure 5 [11].

- *Aerial Network*: This has become increasingly popular in the last decade as an intermediate layer between the ground and space networks. Aerial networks are usually served by Unmanned Aerial Vehicles (UAV) and are classified as Low-, Mid- and High-Altitude Platforms, commonly referred to as LAPs, MAPs and HAPs, respectively. UAVs in the form of airships, tethered balloons, and drones, can provide gateway for remote sensor networks, deployed on the ground network. Due to the possibility of limited line-of-sight at higher altitudes and greater distances due to the curvature of the earth and the fact that HAPs might pass beyond the coverage range of ground cellular and IoT networks, connecting UAV networks directly to the satellites is a better alternative.
- *Ground Network*: This is terrestrial (including IoT) networks in the ecosystem. It consist of the satellite ground stations, i.e., the satellite gateways and user terminals, the IoT sensor networks, terrestrial telecommunications networks such as 5G networks, optical networks and wireless local area networks, and IoT gateways. The ground network such as a remote IoT sensor network can be connected to a user satellite terminal. IoT technologies are implemented in ground station operations for efficient monitoring and management of satellite communication. This includes network monitoring, data analytics, security, and automation of ground station functions. Network engineers carefully plan communications between ground stations and missions, ensuring that antennas are ready to receive data as spacecraft pass overhead. Ground station antennas range from the small very high frequency antennas that provide backup communications to the space station to a massive. Figure 6 shows two ground antennas located in Fairbanks, Alaska [6].
- *Sea Network:* This comprises of sea ships, submarines, underwater sensors, and other maritime communication equipment. One important maritime use case is the tracking of containers and transmitting the sensing data from remote marine locations to the core network. Due to the lack of 4G/5G coverage in the seas and oceans, except ports, space segment is the only feasible option for transmitting and receiving data. Satellite network covers a wide area and provides seamless connectivity to ocean and mountain areas.
- *Robots in Space*: Automation and robotics will be expected to be important for maintaining and aiding activities in space. Different types of large structures can be autonomously assembled in space, in particular, structures that are too large to be launched as one piece into space. Remote control of a large robotic arm for assembly is not feasible given the significant time required for the synchronization of operator commands and actions. Therefore, the autonomous performance of an (even complete) sequence of assembly tasks is required. Robots that assemble structures have been investigated in different projects, though not specifically for space structures. A swarm of robots can construct a structure collaboratively. Apart from large robot arms for assembly or self-assembling parts, there could be robots helping humans within space stations and entertaining human astronauts. Kirobo is Japan’s first robot astronaut, which was demonstrated in the International Space Station in 2013. For robots in planets and space, a challenge is how such robots can be empowered by cloud/fog/edge resources. Figure 7 shows some space robots [1].
- *Space Colonization:* This involves building a colony on another planet. Ideas have been suggested for new horizons of infrastructure development on other planets, including

infrastructure for sensor networks, navigation, and data communications that will be needed wherever humans live. Although there is no GPS on other planets, a planetary rover can navigate by computer vision techniques and image comparisons. Sophisticated transportation land and air infrastructure will be needed to accompany human habitats on planets. It has estimated by mathematical simulation that the minimum number of settlers for survival on another planet such as Mars is 110 individuals. Such a population of 110 people will need to be technologically supported. IoT can automate the management of critical systems, such as life support, resource utilization, and environmental control. This could help create self-sustaining colonies on other planets.

BENEFITS

Integrating IoT technology into space exploration signifies a significant step towards more advanced and comprehensive space missions, opening up new possibilities for scientific discovery and exploration beyond Earth. The integration is unlocking numerous benefits and opportunities for related industries to innovate further. Whether it is CubeSats or LEO satellites, the growing availability of commercially available space parts is allowing more companies to get into the space business. Existing satellites are generally equipped with onboard health monitoring units as a part of the subsystems. Other benefits include the following [8]:

- *Data Collection:* IoT devices on satellites collect vast amounts of data, from climate monitoring to crop health analysis, providing valuable insights that can lead to better resource management on earth. IoT sensors on spacecraft and rovers can continuously monitor various parameters like temperature, pressure, radiation levels, and geological conditions, sending data back to earth for immediate analysis. LEO satellites are often used to collect data in space for applications such as weather forecasting environment monitoring and target surveillance. Once collected, these data need to be downloaded to ground servers via earth Stations.
- *Mission Efficiency*: IoT networks facilitate communication between multiple spacecraft and ground stations, enabling better coordination and decision-making during space missions. Real-time monitoring and predictive maintenance systems enabled by IoT ensure that space missions are more efficient and less prone to failure. This reduces costs and increases the chances of mission success.
- *Global Connectivity:* Satellite communication can be used to provides backhaul connectivity for different types of wireless base stations. Miniaturized satellites, known as CubeSats, has emerged as a viable solution towards establishing global connectivity at low costs. IoT-driven satellite networks provide global connectivity, which is essential for industries like logistics, environmental monitoring, and emergency response. They ensure that no part of the world is out of reach. The Starlink satellites supported by SpaceX aim to provide rural areas with high-speed broadband connectivity previously only available in urban areas.
- *Scientific Discovery:* IoT technologies enable continuous data collection and monitoring in space, leading to new scientific discoveries about our universe and planetary geology, space weather, and even potential life forms. The vast amount of data collected through IoT sensors can lead to new insights into planetary geology, space weather, and potentially even the existence of extraterrestrial life.
- *Autonomous Operations:* By utilizing IoT connectivity, robots and automated vehicles can perform complex tasks in space with minimal human intervention, like repairs on the International Space Station or exploration on other planets. IoT will enable the development of robots and automated vehicles that can perform complex tasks in space.
- *Space Debris:* IoT is critical for tracking space debris and managing space traffic. With the increasing number of satellites and spacecraft, maintaining situational awareness is vital to

avoiding collisions and ensuring safe operations in space. The US Space Surveillance Network operates the Space Fence system, which tracks space debris and satellites in real-time.

- *Colonizing Planets:* As humanity looks to colonize other planets, IoT will ensure that life support systems, habitats, and infrastructure are functional, sustainable, and safe, making long-term human presence in space feasible.
- *Safety:* IoT is also being used to improve the safety and sustainability of space exploration. It can monitor astronaut health and safety, track spacecraft movement, and recycle waste. Connected devices can monitor the health and safety of astronauts, track the movement of spacecraft, and even recycle waste into usable resources. This technology can help extend the lifespan of exploration missions and make space exploration more sustainable in the long term.
- *Data Transmission*: IoT can transmit data between sensors and devices through space, even in areas with poor network coverage on earth. Satellites can act as a transmission bridge, enabling data transfer at any time.
- *Environment Sensing*: This involves sensing the environment using satellites. Project SatSense is focused on using satellite telemetry to develop new techniques for environmental monitoring. We believe this will lead to gaining accurate insights about today's ecosystem at large-scale including forestry, agriculture, oil & gas, etc. Figure 8 illustrates environmental sensing using satellites [12].

CHALLENGES

To truly jumpstart space markets, commercial off-the-shelf costs will have to come down for high-quality components. It is essential to address the key challenges, such as scalability, ubiquitous global coverage, and real-time connectivity that arise due to this immense growth of IoT devices in space exploration. One of the main challenges in inter-planetary communications is free space loss. While the potential of IoT in space is vast, several challenges must be addressed [8,13]:

- *Robust Communication:* Space is a challenging environment for IoT systems due to high radiation levels and potential signal interference from cosmic sources. Developing radiation-hardened components and robust communication protocols is essential to ensure the reliability of IoT systems in space. IoT devices must be designed to withstand extreme temperatures, radiation, and vacuum conditions.
- *Interference:* As communications transmissions travel over long distances or through the atmosphere, the quality of their data can deteriorate, garbling the message. Radiation from other missions, the Sun, or other celestial bodies can also interfere with the quality of transmissions. Radiation from the Sun is one potential source of interference for space communications transmissions.
- *Space Pollution:* The increasing number of satellites and IoT devices in space contributes to the growing problem of space debris. Companies like Astroscale are developing technologies to remove defunct satellites from orbit.
- *Power Constraints:* Spacecraft often have limited power sources, requiring energy-efficient IoT devices. Resources are severely constrained in terms of size, mass, and available power. Due to the sheer distance of other planets from the earth, the power required for sending data is large. While big satellites typically do not have any constraints on energy consumption for GPS subsystem, such is not the case in miniaturized satellites.
- *Communication Latency:* Most IoT applications are bounded by delay or latency requirements. Communications do not take place instantaneously. They are bound by a universal speed limit: the speed of light, about 186,000 miles per second. IoT applications can be mainly categorized into delay-tolerant applications and delay-sensitive applications. Signal delay in deep space can

pose challenges for real-time data transmission. For GEO satellites, the minimum propagation delay adds up to half a second, which is not suitable for time-critical IoT applications, such as sensor networks for autonomous driving. The ability to provide broadband access depends on the low-latency, high-speed communications provided by low earth orbit (LEO) satellite constellations.

- *Cost*: One challenge with the space industry is the cost of developing and launching satellites, which makes access to space expensive. Costs are based on the data rate because IoT is still in the development stage. The considerable reduction in launch costs and the ability to reuse rockets will help drive down costs in space travel.
- *Space Debris:* These are problematic if space is to be further populated. The challenge of tracking people and things in space will be enormous, not only in detecting and tracking space debris, but also in tracking people and things. Cooperation among different parties is required to be able to adequately track objects in space to ensure the safety of space flights. Space situational awareness is required if collisions are to be avoided and the space within the earth's orbit is to be best utilized.
- *Security:* This has been a contentious topic of conversation. We are still not sure how companies will deal with the massive amounts of data IoT will generate. As more devices become connected, the risk of cyber-attacks, data breaches, and unauthorized access increases. Ensuring the security and privacy of user data is critical to maintaining user trust and avoiding potential financial and reputational damage.
- *Standardization:* With numerous manufacturers and vendors in the market, there is a lack of consistent standards and protocols for communication between devices. This can limit the functionality and efficiency of IoT systems, as devices may not work seamlessly with each other.
- *Regulation:* IoT devices and systems are subject to various legal and regulatory requirements, including data protection laws, consumer protection laws, and industry-specific regulations. Space-based IoT systems require international collaboration, agreements, and regulation. International regulations are needed to manage space traffic and ensure the sustainability of space exploration. Organizations like the International Telecommunication Union (ITU) play a critical role in managing the allocation of radio frequencies and ensuring that space-based IoT systems do not interfere with one another.
- *Data Management:* The IoT industry generates vast amounts of data, which can be challenging to manage, store, and analyze effectively. Companies must develop robust systems for handling this data to derive valuable insights and make informed decisions.
- *Scalability: As* the number of IoT devices grows, it becomes increasingly difficult to manage and maintain them. Ensuring that networks, systems, and infrastructures can scale to accommodate growth is a significant challenge.

CONCLUSION

The space industry is projected to experience skyrocketing growth. When it comes to applications in space, IoT currently has more conceptual uses than physical applications. IoT enables remote monitoring in space missions by using sensors and communication networks to collect and transmit data from spacecraft and equipment continuously. The IoT has the potential to change our space exploration immensely, presenting new opportunities as well as new challenges. The enthusiasm for space exploration is driving innovation across the IoT. As interplanetary exploration continues to expand, the importance of IoT in this field will only continue to grow and enable real-time communication, data collection, safety monitoring, and sustainability. More information about IoT in space can be found in the book in [14].

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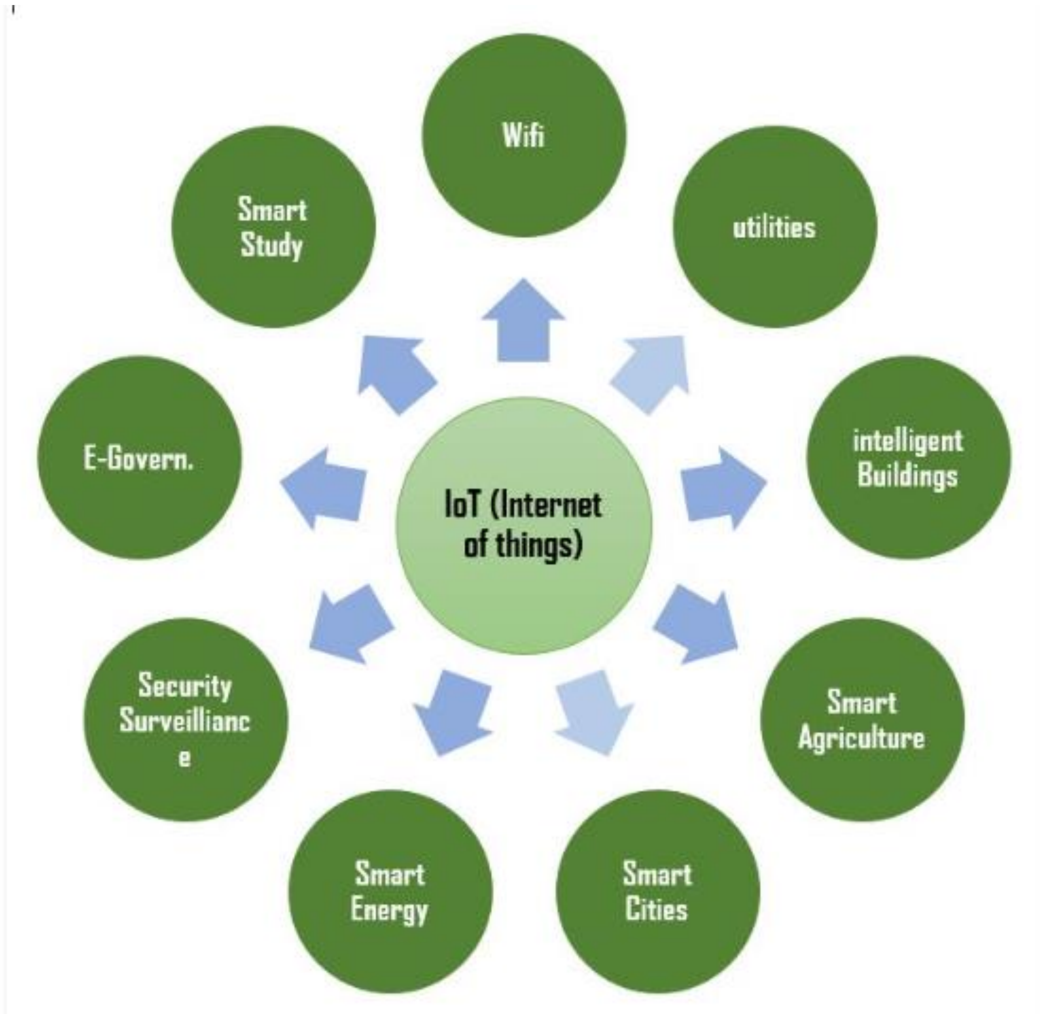

Figure 1. The Internet of things [4].

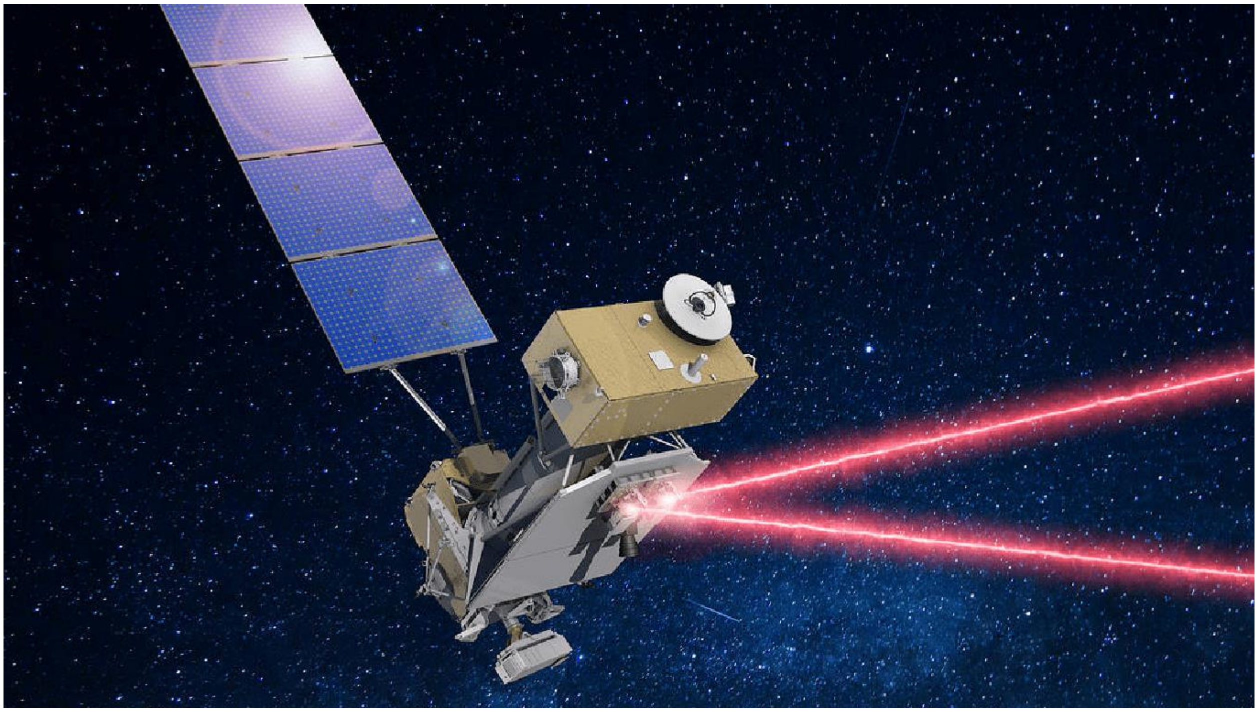

Figure 2. NASA's Laser Communications Relay Demonstration [6].

Figure 3. Satellite communications [6].

Figure 4. A typical IoT in Space [10].

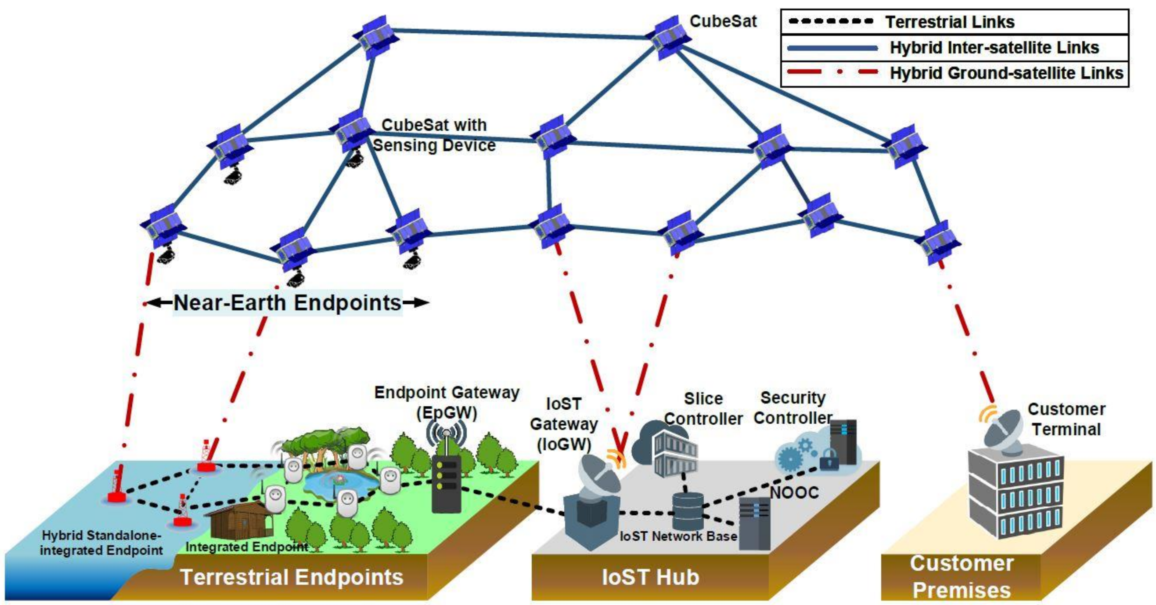

Figure 5. The system architecture of IoST [11].

Figure 6. Two ground antennas located in Fairbanks, Alaska [6].

Figure 7. Some space robots [1].

Figure 8. Environmental sensing using satellites [12].