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Cloud Computing in Space Exploration

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ABSTRACT

Cloud computing is the on-demand delivery of computing resources, such as storage, processing power, and applications, via the Internet. It uses the Internet to quickly access, study, and read data over a shared server. Cloud technology is now transcending earth into space. In the space exploration, cloud computing plays a pivotal role in managing the vast amounts of data generated by satellites, telescopes, and other space-based assets. The adoption of cloud services by space industry players has increased significantly. These players have been making strategic moves to integrate space technology into their cloud services. Satellite-based cloud computing has the potential to revolutionize space exploration. This paper reviews the role cloud computing plays in the space exploration.

KEYWORDS: cloud computing, space exploration, space colonization, aerospace

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INTRODUCTION

Cloud computing is a means of pooling and sharing hardware and software resources on a massive scale. Users and businesses can access applications from anywhere in the world at any time. Companies offering these computing services are called cloud providers and typically charge for cloud computing services based on usage [1]. Some features of cloud computing are displayed in Figure 1 [2]. The goal of cloud engineering is to create a highly scalable, flexible, and secure computing environment that can support the needs of modern businesses. Here on planet Earth, cloud computing has revolutionized the way we access and analyze data.

Space activity and exploration have a huge impact on daily life on earth. The space economy has seen significant advancements in recent years, with more companies exploring and commercializing space-related technologies. Space exploration is going through a major transformation period [3]. Cloud computing has emerged as a crucial factor in achieving success and progress for space exploration. It is used in space exploration for a variety of reasons, including data storage and management, data processing, access to information, communication, monitoring. Cloud service providers should target government organizations, satellite operators, and space exploration players that are keen to use cloud computing in their low-Earth orbit and lunar activities. The transition from the ISS to commercial space stations will generate new opportunities for partnerships between space industry players and cloud service providers [4].

CLOUD COMPUTING BASICS

Cloud computing represents a newly emerging service-oriented computing technology. It is the provision of scalable computing resources as a service over the Internet. It allows manufacturers to use many forms of new production systems such as 3D printing, high-performance computing (HPC), industrial Internet of things (IIoT), and industrial robots. It is transforming virtually every facet of modern manufacturing. It is innovating, reducing cost, and bolstering the competitiveness of American manufacturing [5].

The key characteristic of cloud computing is the virtualization of computing resources and services.

Cloud computing is implemented in one of three major formats: software as a service (SAAS), platform as a service (PAAS), or infrastructure as a service (IAAS). These services are illustrated in Figure 2 [6] and explained as follows:

SaaS: This is a software delivery model in which software and associated data are hosted on the cloud. In this model, cloud service providers offer on-demand access to computing resources such as virtual machines and cloud storage. Nowadays oil & gas companies transition to cloud computing and implement SaaS solutions for operations.

PaaS allows the end-user to create a software solution using tools or libraries from the platform service provider. In this model, cloud service providers deliver computing platforms such as programming and execution.

In the IaaS model, cloud service providers can rent manufacturing equipment such as 3D printers.

Just like cloud computing, CM services can be categorized into three major deployment models (public, private, and hybrid clouds) [7]:

- Private cloud refers to a centralized management effort in which manufacturing services are shared within one company or its subsidiaries. A private cloud is often used exclusively by one organization, possibly with multiple business units.
- Public cloud realizes the key concept of sharing services with the general public. Public clouds are commonly implemented through data centers operated by providers such as Amazon, Google, IBM, and Microsoft.
- Hybrid cloud that spans multiple configurations. and is a composed of two or more clouds (private, community or public), offering the benefits of multiple deployment modes.

These models are shown in Figure 3 [8]. Cloud computing finds application in almost every field

CLOUD COMPUTING IN SPACE EXPLORATION

Space exploration is one of the most challenging and complex tasks humanity has ever undertaken. It requires advanced space technologies and techniques to overcome the obstacles it presents. One such technology that has the potential to revolutionize space exploration is satellite-based cloud computing. Satellite-based cloud computing can unlock the potential of space exploration by improving data processing and analysis, enabling autonomous operations, and enhancing collaboration and coordination. The management, security, and rapid exchange of an ever-increasing amount of data, much of it tactical, are crucial elements for the country's defense.

Cloud computing is making its way into space as cloud suppliers continue to push the frontiers of the technology. Satellite-based cloud computing refers to the use of satellites to provide cloud computing services, such as storage, processing, and software applications, to users on the ground. This can be useful in remote or underserved areas where traditional Internet infrastructure is lacking. The satellite-based cloud computing is still in the development phase, but it can potentially bring cloud computing capabilities to places where it was previously unavailable. One of the key benefits of satellite-based cloud computing is its ability to offload data to ground-based data centers for processing and analysis. Satellite-based cloud computing can also support autonomous operations on spacecraft [9].

APPLICATION OF CLOUD COMPUTING IN SPACE

The space economy has experienced significant growth in recent years, driven by advancements in technology, increased investment, and a growing interest in space exploration and commercialization. The possible applications of cloud tech to space travel are many. The following are typical applications:

- *Space Cloud:* This refers to utilizing satellites in low-earth orbit to provide cloud computing services. It is widely considered to be the next frontier in cloud computing, offering potential for significantly reduced latency, global reach, and enhanced data processing capabilities, particularly for applications requiring real-time data analysis and remote locations with limited terrestrial connectivity. Space cloud offers a unique solution to data management, along with unparalleled processing speed, flexibility, storage capacity and security on a global scale. The space cloud initiative integrates cloud infrastructure, AI, and supercomputing within a secure network of satellites orbiting the earth. Space cloud is expected to have a transformative influence on how governments and defense forces utilize and share data. Space cloud pushes the boundaries further to overcome limitations of speed, capacity, latency and security [10].
- *In-space Data Center:* This may be the next step for space cloud computing. Right now, everything is sent back to earth for storage and processing. In the future, data centers may be deployed in space to improve data transmission speed and processing power capacity. The

commercialization of the low-Earth orbit (LEO) market and long-term lunar and space exploration missions will increase the use of data centers in space. The transition from the International Space Station (ISS) to commercial space stations are the main factors that will boost the use of in-space data centers. Figure 4 displays the Destiny Module inside the ISS, where astronauts perform many of their experiments [3]. Applications related to earth observation, communications, science, and human spaceflight will drive the use of data centers in space. Government players drive most of the demand for in-space data centers in the science sector because they conduct most of the major scientific missions. R&D is required to overcome the major challenges regarding the implementation of in-space data centers.

- *Space Economy:* Cloud computing has become an integral part of the growing space economy. Numerous space economy businesses are currently using cloud computing for a diverse range of applications. By leveraging cloud-based platforms, space economy businesses can scale their operations, reduce costs, and drive innovation in space-related applications and services. In order to see the space cloud succeed, technologists must get innovative on how to efficiently transmit and store data collected from space probes and spacecraft. A space cloud would provide more efficient storage and transmission methods, so that power consumption would be reduced [11].

BENEFITS

Cloud computing enables real-time communication between the rover and mission control on earth, facilitating remote operation and data transmission. Less reliance on ground networks minimizes external influence, ensuring uninterrupted operations crucial for national security. Cloud-based services are finding their way into space to analyze satellite imagery and monitor space debris. Other benefits include [9,10]:

- *Decision Making:* Space cloud facilitates in-orbit decision-making, which includes reactive planning, scheduling decisions, and complex resource management within space networks. The Spaceborne Computer-2 on the International Space Station (ISS) is already using artificial intelligence, machine learning and cloud processing to make predictions and draw conclusions. Figure 5 shows the Spaceborne Computer-2 on the ISS [3].
- *Reduced Latency:* Processing data in orbit minimizes latency, facilitating real-time decision-making by reducing space-to-ground data transmissions.
- *Storage:* Storing data in space offers a secure backup solution that is less vulnerable to natural disasters, enhancing communication and data network resilience. Increased activity and the growing number of satellite constellations are driving the demand for data storage in space.
- *Accessibility:* Space-based cloud extends the reach of data processing capabilities to remote areas lacking the accessibility to traditional ground-based cloud infrastructure.
- *Security:* The space environment mitigates risks of cyberattack and physical tampering risks, ensuring secure data transmission and storage.
- *Situational Awareness:* Integrating data gathered and processed from satellites and unmanned aerial vehicles enables more comprehensive asset tracking and threat monitoring, enhancing situational awareness.
- *Autonomy:* Autonomous operations, such as taking images or adjusting the spacecraft's trajectory, require significant computing power and storage. These operations can be performed on a cloud-based infrastructure which allows for real-time adjustments and decision making. This can greatly enhance the capabilities of spacecraft, allowing them to perform complex tasks with minimal human intervention.
- *Collaboration:* Cloud-based platforms foster collaboration between teams and organizations, streamlining the development of new space technologies. Satellite-based cloud computing plays a critical role in collaboration and coordination among space agencies and organizations. A centralized platform for collaboration can be provided through cloud computing, allowing team members to access and share data and resources easily. Engineers, scientists, and other professionals can work together seamlessly, accessing and sharing data from any location.
- *Cost-Effectiveness:* Satellite-based cloud computing can help to reduce the costs of space missions. By offloading data processing and analysis to ground-based data centers, spacecraft can more efficiently use their limited resources while also gaining access to more powerful computing resources.
- *Scalability*: Cloud computing enables organizations to scale their infrastructure according to their needs, providing a flexible

environment for data storage and processing. As companies grow and their data requirements change, they can easily adjust their cloud resources, ensuring they can efficiently manage their operations.

- *Cost Optimization:* Cloud computing allows businesses to optimize costs by paying only for the resources they use. The pay-as-you-go model offered by cloud providers helps organizations better manage their budgets and avoid investing in expensive physical infrastructure.
- *Data Analysis:* Space economy companies generate vast amounts of data from various sources, such as satellites, telescopes, and space probes. Cloud computing facilitates the rapid analysis of this data by providing access to powerful data processing and analytics tools.
- *Space Debris:* Another area where cloud technology could be applied in space is the identification and management of space debris, which astronauts at the International Space Station have had to navigate around to prevent catastrophic collisions. Figure 6 shows an artist's conception of just some of the trillions of pieces of debris orbiting the Earth [12].

CHALLENGES

There are data security challenges and huge power requirements, along with costs associated with data egress and other cloud services, which may be significant setbacks for the growth of cloud computing market. One thing that all satellites share is a long development and production cycle. These are complex machines that cannot easily be replaced. They take years to design, build, test and finally launch. Other challenges include:

- *Data Collection:* There is the issue of data collection. Satellites produce huge quantities of data. At present, it takes days for their findings to be analyzed
- *Lack of Expertise:* Space industry players' lack of expertise regarding cloud computing/big data requirements along with the disconnect between the cloud computing and space industries limit the adoption of this technology.
- *Delay*: The constrained connectivity can delay communicating critical decisions to the astronauts, who often have to wait for information to reach ground control and be analyzed there and then returned with the necessary insight. That's hard enough with the space station, which orbits as high as 250 miles above the earth. Further mission into outer space will need stronger computing power at the astronauts' fingertips and a better pipeline for sharing information.
- *Astronauts' Healthcare*: A major challenge addresses the needs of healthcare for astronauts on longer space missions. The effects on a human body of lengthy sojourns in space are not fully known, making technology that allows frequent monitoring of changes over time especially important.

CONCLUSION

We are living in a new era in which data and software can be accessed anywhere with an Internet connection. Cloud computing is crucial for space exploration because all the new missions emerging in space in the next 10 or 20 years are going to require cloud-based technology. Governments and cloud service providers should work with space industry players to increase the use of in-space cloud computing. Engineers and researchers across companies should work together to improve communication and enabling experiments that will propel astronauts further into space while improving the lives of the earthbound as well. More information on the integration of cloud technology into space exploration is available from the books in [13-15].

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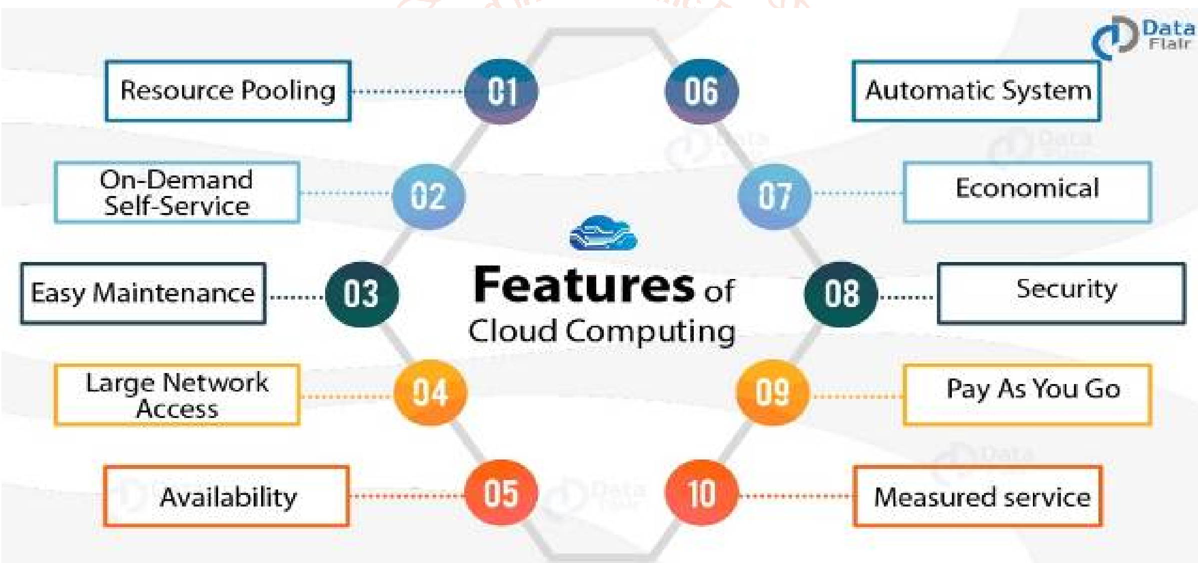

Figure 1 Some features of cloud computing [2].

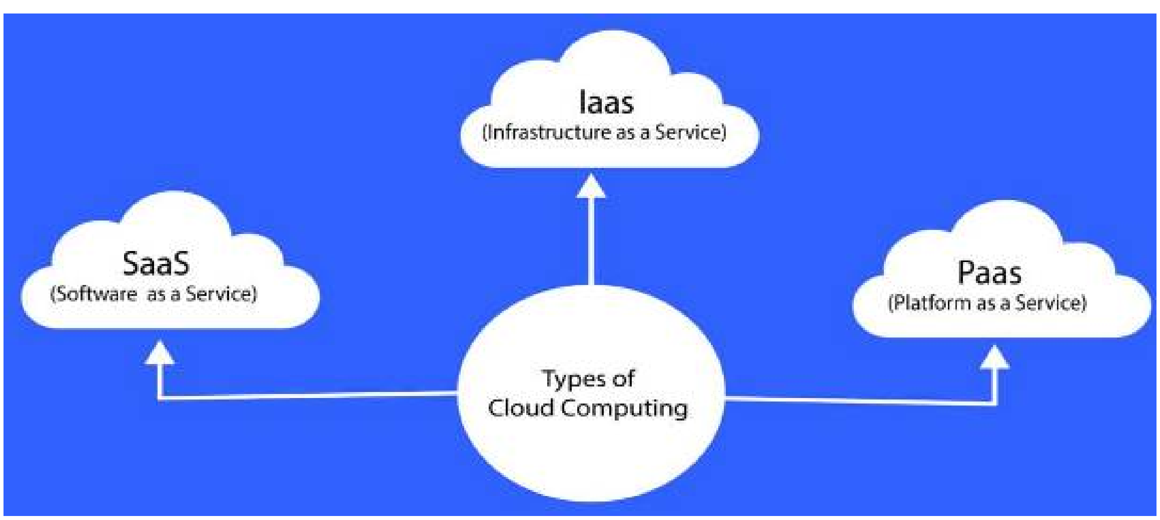

Figure 2 Three types of cloud computing services [6].

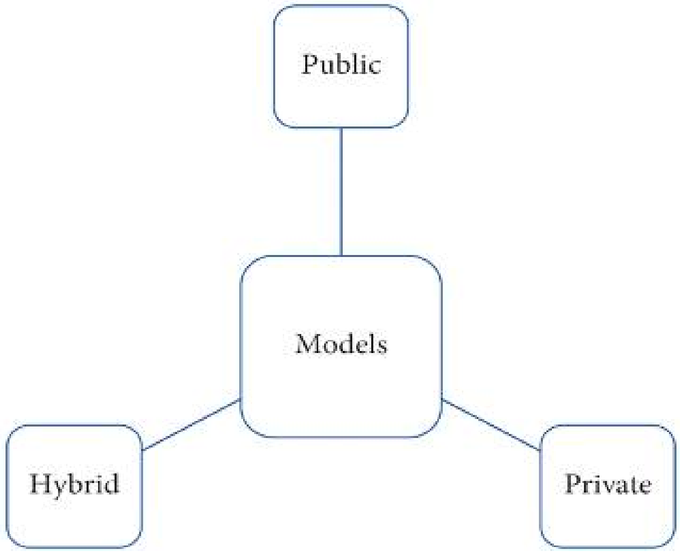

Figure 3 Cloud computing models [8].

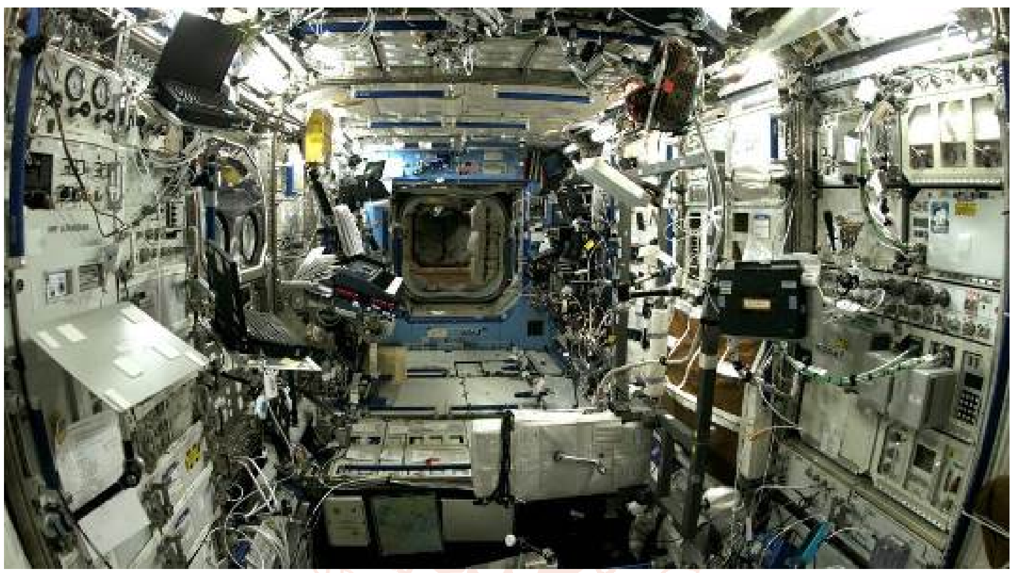

Figure 4 The Destiny Module inside the ISS [3].

Figure 5 The Spaceborne Computer-2 on the ISS [3].

Figure 6 An artist's conception of pieces of debris orbiting the Earth [12].