CUBESATS: An Overview of Capabilities And Future Potential

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Abstract - *The space industry has always been dominated by large spacecraft, which are monitored by major space agencies and other developed countries. However, this trend was undermined by the introduction of CubeSats in the late 1990' s. CubeSats were first introduced as educational tools for university-level experiments and to give essential exposure for university-level students. However, as years passed, with various research and development, CubeSats have solely started its transition from an educational and technology testing platform to a low-cost, high value mission's platform that can change the space industry holistically. Today, CubeSats have become vital in most of the technological fields like telecommunication, weather forecast, space research, and many more. This paper will be looking into the major sections like power, propulsion, structure, and different payload capabilities of Nanosatellites like CubeSats. We will look into the rise of small satellites from an early period to the present paradigm of technology. Finally, we will investigate the limitations and future of this section of the space industry.*

***Key Words*: CubeSats, Small Satellites, Space Industry, Nanosatellites, Power, Propulsion, Payload**

1. INTRODUCTION

Space exploration and research on our solar system and universe have always been the main agenda of our spatial expeditions, but for the past 60 years, many constraints, mainly cost and lack of resources, have played a vital role in depleting our growth. From the launch of Sputnik 1 in 1957 by the Soviet Union [1], we have been marching towards our goal of dominating the space and using its merits like weather forecasting, telecommunications, navigation, and many more for our benefits. Large spacecraft and satellites have always been the pillars of our technology, but nowadays, the trend has shifted with time, and the replacement of such expensive technologies with cheap and efficient spacecraft like CubeSats and other small satellites are becoming more quotidian.

The recent development in the field of small satellites has led to the invention of CubeSats. CubeSats were first developed by California Polytechnic State University(Cal Poly) and Stanford University in late 1999 to help students and other researchers to get a chance to design, manufacture and test spacecraft deployed mainly in the low earth orbit(LEO). This created opportunities for the youngbloods to get real-life exposure, which would help them build their careers in their respective fields. CubeSats were categorized as multiples of 10cm×10cm×10cm cubic units or 1U, with a mass of not more than 1.33 kg per unit [2] and mostly used commercial off the shelf (COTS) components for electronics and structural systems. Thus, the long vindication of the heavy expense in the space industry was starting to see a veracious and effective movement. Researchers were able to make CubeSats for a very low cost when compared to other large satellites, and it took only a few years to complete the production of these amateur products. By 2013, CubeSats usage for educational purposes started to shift towards more commercial and technical projects. More companies seeing this golden opportunity started to come forward to make use of this chance, and more than 1200 CubeSats have been launched by 2020 [3]. This trend will escalate in the future and will help in the better understanding and utilizing of the abundant resources in space.

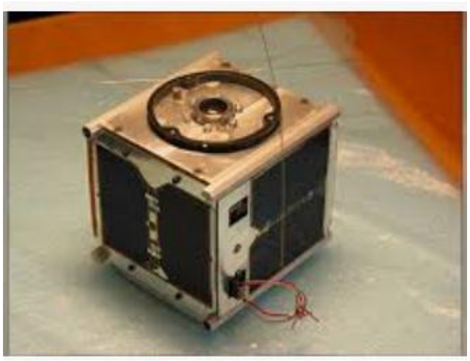

Fig 1- 1U CubeSat

This paper will reflect the CubeSats' basic knowledge like their structure, propulsion, power, and payload capabilities. The 'New Space' concept will also be discussed in this paper and its limitations. This paper will help us in getting a better picture of the new era of small satellites that have already started to take over our space industry. The paper provides a holistic review of CubeSats.

2. 'NEW SPACE'

With the combination of low cost and increased utility, CubeSats have become one of the most magnetic fields in the 21st century, which is attracting the major agencies and governments to invest heavily in this field. High value for the return of investment has also made the big private companies start new start-ups and projects which rely on the development of small satellites. The latest market applications can only be balanced by the development of these new fascinating technological sectors. The old established companies like Google, Amazon are also trying to get into the business by adopting this technical innovation so that they can stay updated and dominate the industry.

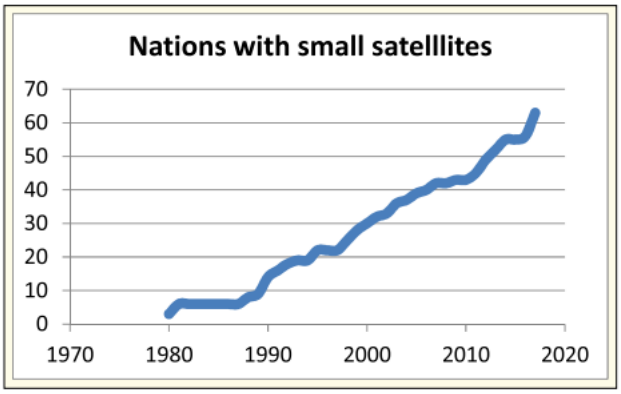

Fig 2- Growth of Small Satellites

Small satellites like CubeSats form the 'New Space' sector, which is growing and gaining attention nowadays. More number of nations are investing in small satellites to make use of the facilities which can be offered from space, thereby getting its benefits, (fig 2) shows the growth of nations with small satellites within the years, and this trend is going high. Projects like the Starlink of Spacex will be using small satellites like CubeSats to create mega-constellations that will change the phase of the internet in the world. Other counterparts like OneWeb and Boeing are also playing their part in this industrial revolution. These are only a few examples that indicate the era of CubeSats that is approaching mankind.

3. STRUCTURE

The structure is the primary substance of a spacecraft that mechanically supports all the essential components and acts as a protecting shield against harmful radiations, which are very common in space. One of the main criteria for selecting material as the structure is that they should have the coefficient of thermal expansion as the deployer to prevent jamming. The two main options of chassis for CubeSats are custom built and off the shelf-structures. Off the shelf-structures are simple and easily usable, whereas custom-built structure is mission-specific and requires intense testing and high expenditure. Most of the CubeSats structures are made of aluminum [4], but nowadays, 3-D printed structures are becoming more common, and few agencies have launched missions like 1U Printsat [5] that have 3-D printed structures. CubeSats generally do not have the strength problems as that of general satellites because deployers support them structurally during the launch. Even though CubeSats undergo some vibrational and structural analysis [6], which are significantly inferior compared to large satellites, CubeSats' failure rate due to mechanical issues is very minimal.

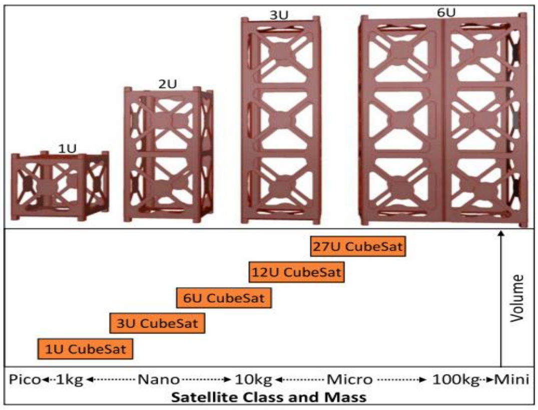

Fig -3 Structure of CubeSats

4. PROPULSION

Very few CubeSats have flown into space with their own propulsion systems [7]. This was acceptable when CubeSats were only used for university experiments, but because of the exponential growth of this class of spacecraft, the propulsion systems need to evolve at a rapid rate. Propulsion is the usage of propellant to create the required thrust for the movement of spacecraft. They have always been one of the most challenging sectors in the field of aerospace. The main hurdle in the field of propulsion is the rigorous testing and precautions needed for the proper implementation of a precise system in space. However, as the space industry using CubeSats as its capstone is marching towards new heights, the propulsion capabilities are becoming very important. In the last five years, many miniatured propulsion systems have been installed and used effectively because of the intensive research and development in this field. The main functions of propulsion in CubeSats are orbit change and rising, drag makeup, attitude control, and deorbiting abilities after the completion of their missions [8]. There are mainly three types of propulsion systems used in CubeSats; they are chemical, electric, and propellant fewer propulsion systems [9].

4.1 CHEMICAL PROPULSION

In chemical propulsion, different chemical reactions are used to produce high-pressure, high-temperature gas that provides the required thrust for the spacecraft when passed through a nozzle. Chemical propellants can be liquid, solid, or both. These propulsion systems can achieve higher trust levels than electric and propellant fewer propulsion systems although they have limited specific impulse. The major types of chemical propulsion systems are; monopropellant (liquid propellant) thrusters like hydrazine and hydrogen peroxide, which have low complexity, high thrust, and low power requirements [10], Water electrolysis thruster [11], which burns hydrogen and oxygen, which is generated by the electrolysis of water, and cold gas thrusters which store inert gases like nitrogen in a highly pressurized tank and releases the gas through a nozzle to produce the thrust.

4.2 ELECTRICAL PROPULSION

In electrical propulsion systems, electricity is used to create the required thrust by accelerating the propellant. It is believed that advanced electric propulsion systems will take us beyond Mars in the near future. This category of propulsion has a lot of added advantages over other traditional propulsion systems. They generally have less thrust and high specific impulse. Mainly there are three types of electric propulsion systems, electrothermal, electrostatic, and electromagnetic [12]. In electrothermal systems, the gas is heated using electricity and then passed through a supersonic nozzle, thereby converting the propellant enthalpy to kinetic energy. Few examples are arc jets, resistojets, and microwave heating.

Fig-4 Busek's BIT-3 ion thruster proposed for NASA's Lunar IceCube mission

Electromagnetic systems use both electric and magnetic fields to accelerate the propellant; few examples are vacuum arc thrusters, pulsed plasma thrusters, etc. Whereas in electrostatic propulsion, the required thrust is produced by the electrostatic acceleration of plasma. The most used electrostatic devices are Hall thrusters, ion engines, electrospray thrusters. Due to the inability of these systems to merge with the small satellite requirements, many new substitutes have been developed recently.

4.3 PROPELLANTLESS PROPULSION

Propellantless propulsion systems do not require any propellant to produce the required trust. This has a major impact in reducing the mass and systems complexity by a large margin, which will improve the flight capabilities for future interstellar missions.

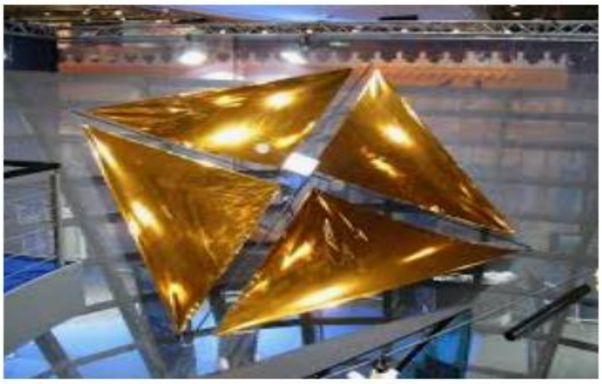

Fig 5 – Solar Sails

The solar sail is the epitome of propellantless propulsion, in which propulsion is attained by using the radiation pressure from different celestial bodies to move large ultra-thin mirrors to high speeds. They utilize the momentum of photons, thereby giving the thrust for the spacecraft. Projects like sun jammer [13], NEA Scout [14], OKEANOS [15] have used Solar sail as their propulsion system.

5. POWER

The main parts of the Electrical power subsystem are power source, energy storage, power distribution, regulation, and control units [16]. The primary power source for CubeSats is Photovoltaic solar cells with triple-junction solar cells, which give the optimum efficiency [17]. But due to the area constraints, solar cells can either be body-mounted or deployable depending upon the requirements of the specific missions. The current power can be generated up to 20-30 W using the existing solar panels [18]. Due to the continuous need for power, additional on-board energy sources are also installed to provide power during an eclipse and other natural events. Lithium-ion batteries are best suited for this purpose as they have a high energy density, voltage capacity, and lower discharge rates than other rechargeable batteries. However, long-term research and testing are required in the future to build advanced energy systems that will help mankind to reach the outskirts of space.

6. PAYLOAD CAPABILITIES

CubeSats payload has multiple specific applications that are helping us in taking the next step in the field of space exploration.

6.1 DEEP SPACE EXPLORATION

Till now, very few CubeSats have been launched beyond the low earth orbit, but the trend is changing, and many agencies have already started the usage of CubeSat for exploring the unknowns in our universe. NASA's Space Launch System (SLS) named Exploration Mission-1 in

2018 were the first few who used CubeSats for deep space exploration [19]. The main purpose of EM-1 was to evaluate the scientific and technological capabilities beyond the lower earth orbit [20]. Another noticeable example is the MarCo (Mars Cube One) mission, which was developed in the NASA jet propulsion laboratory. MarCo has 6U CubeSats that helped in the entry, descent, and landing of NASA's InSight [21]. This helped in transmitting the data from Mars and was one of the most vital missions of 2018. It is believed that the complex deep space exploration problems will be solved by using the small spacecraft capabilities, thereby answering many unsolved questions regarding our space life.

6.2 EARTH SCIENCE

Earth science is the study of the complex systems present around the Earth-like atmosphere, hydrosphere, and biosphere [22]. Our knowledge of such elements helps us in better understanding the natural phenomenon and human-induced effects on Earth. It also plays a very important role in other major fields like weather forecasting, climate change, and energy management, which help in the economic growth of many multinational companies.

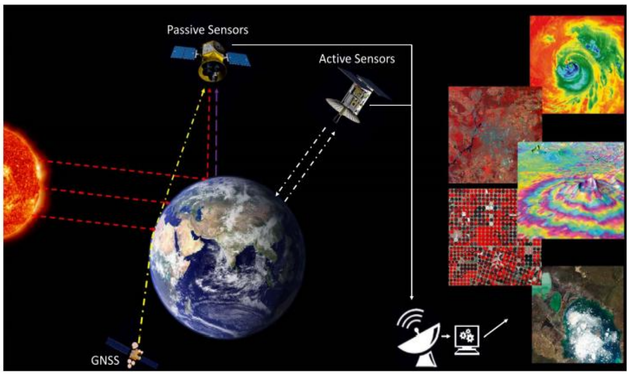

Fig-6 Space observation from Space (NASA pic)

Mainly there two kinds of sensing instruments installed in CubeSats for Earth Observation. Active sensors like radars, lidars, and lasers that generate their own radiation to provide a better image of the resulted object, and passive sensors like radiometers, spectrometers, and optical imagers that cannot produce their own radiation and make use of the radiation from the sun for getting the desired result [23]. CubeSats capabilities can also be used for specific missions that require multipoint detection of the target. Their low cost and fast production time will increase the number of research and eventually will benefit from the exponential growth of the space industry.

6.3 HELIOPHYSICS

Heliophysics is the study of the sun and its physical connection with the solar system. It can also be referred to as the study of space weather, which is of high importance because the variations in space weather can cause massive effects on ground and space instruments [24]. Thus, our knowledge of space would help us advance towards the better usage of modern technologies like telecommunications, navigations, and aviation. The first CubeSat mission based on this purpose was the Radio Aurora Explorer (RAX), consisting of two 3U CubeSats, which was developed at the University of Michigan [25]. CubeSats have clearly demonstrated that they are the future of space weather predictions. With the accelerated growth in the development of this field, we would expand our knowledge of the hidden secrets of space in the near future.

6.4 SPACEBORNE IN SITU LABORATORY

Spaceborne In Situ Laboratory means using CubeSats as a platform for conducting the cutting-edge experiments in space itself. Missions like 3U GeneSat-1 [26], PharmaSat 1 [27], O/OREOS [28], and SporeSat-1 [29] are successfully conducting many relevant scientific experiments like the effects of space radiation in microorganisms, metabolism, etc. Several new missions like 6U CubeSats EcAMSat [30] and BioSentinel [31] of NASA are also under development for conducting biological experiments in space that will revolutionize the face of CubeSat capabilities in the future. By using this platform, we could get access to many unique celestial situations like microgravity, space radiation, and other sophisticated environments; their analysis would be very helpful to our better understanding of the universe. Even though the International Space Station can conduct many scientific experiments, it has many limitations like limited capacity and strict regulations, so it indicates the need for CubeSats as the perfect alternative.

7. LIMITATIONS

There are many factors that hinder the growth of small satellite business in the present scenario. The most important of this is the launch to orbit. Other factors like space debris and frequency coordination are also vital while studying the limitations of CubeSats.

The lack of availability of efficient launchers to launch CubeSats to orbit is a major constraint in the development of this field. Also, the high cost required for such launchers makes the matter even worse. The rise in the need for better launch systems came when the number of applications of small satellites increased in the past few decades. The latest launchers emphasize more on the 'green propellant' so that they can create an impact against the booming pollution situation we are facing. Another major factor is the Frequency Allocations and Coordination problem. From early times most of the universities used the VHF and UHF, which were intended for satellite service and commercial allocations. This has caused congestion because the available bandwidth is limited. However, the new 'mega-constellations' that are aiming to provide effective connections through the world are using much higher allocations like the V-band.

Space debris is one of the most concerning factors in the space industry. As the number of small satellites is increasing due to the rapid increase in the number of CubeSats, the debris rate is also going high, which is a very alarming situation. Many agencies, like the European Union (EU) have reacted to this issue and have come up with solutions like the low-cost microsatellite 'RemoveDebris' to eliminate the possible debris from space. Many legal and political concerns have started to rise against this complication, and we hope to find a perfect solution in the coming years.

8. FUTURE

The space industry has seen the rise of many new technologies in every sector of its wide systems in the past few decades, but the growth of CubeSats is one of the fascinating inventions in recent times. As we are marching towards a more advanced world, the developments in the field of artificial intelligence, machine learning, and other new areas are uplifting the standards of the way we use technology. The need for more efficient systems is becoming adamant; thus, the growth of projects like mega-constellations using the CubeSats has made the small satellite business one of the best upcoming business sectors in this decade. With the heavy rise in the amount of data transfer in recent times, the traditional Rf methodologies are not capable of delivering the required results. Thus, the use of small satellites will be an aid to the present situation. Thousands of new projects and innovations are being introduced every day, and this field is growing at an exponential rate.

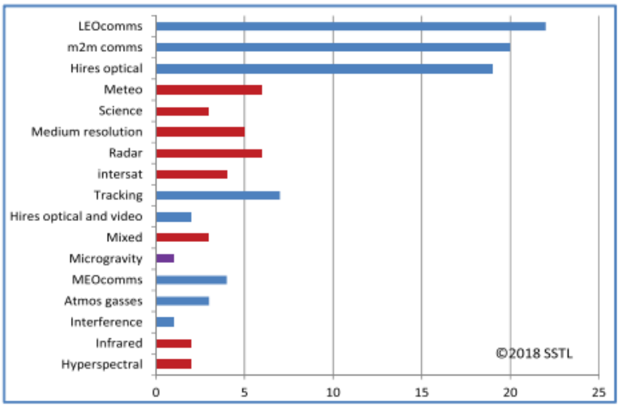

Fig-7 Applications of CubeSats

Projects like space wide web would be the turning point for humankind in dominating the unknown space. As most of the constraints of small satellites like the launcher hindrance are being studied and hopefully will be rectified in the coming years, the CubeSats role in molding the future of space technology would come to reality. CubeSats properties such as power, propulsion, structure, material, and many specific constraints have been the main factors that have undermined the growth of CubeSats in recent years [32], but as many agencies and companies have taken this field very seriously, most of the problems are being rectified at a very fast pace and the future of CubeSats seen very hopeful.

9. CONCLUSIONS

The growth of CubeSats has been so effective that it is now challenging or surpassing the traditional large spacecraft by a large margin., mainly by the effects of cost, size, and maintenance, which are the most vital factors concerning the space industry. However, small satellites can never completely replace the large satellites in all aspects but can only assist and fill specific niches, thereby helping them for better functioning, for example, providing better imaging, communication, and broadcasting. CubeSats can provide platforms for real life experiments and for commercial purposes as they can be built and launched within 2-3 years. CubeSats would change the telecommunication business forever; presently, the projects of companies like SpaceX called the Starlink are aiming to provide better connectivity throughout the world by creating huge constellations around the Earth. CubeSats would also be used for monitoring other celestial bodies and would be the perfect laboratory for space experiments which include biological experiments, material science, space radiation, and other highly complicated scientific fields. They would also help us in the study of deep space, which would increase our knowledge about the universe.

Despite the impressive growth in the number of applications where CubeSats play a vital role, there are many key areas that need to be rectified for the better future of this technology. The propulsion field should be developed with at most care because it will decide whether we will reach the unknowns of our space. The present propulsion systems are inefficient and would never go past the nearby stars. Understanding this situation, many agencies are developing the required propulsion technology that will hopefully take us beyond Mars in a limited time. Other areas like power and data downlinking also need to be studied and modified, which will increase the overall rate of applications of CubeSats in the future.

After 12 years and thousands of launches and trials, it is astonishing that CubeSats have completely transformed from their usage as an educational research tool to the platform that uses the latest technologies and the element that would lead us to our ultimate goal of dominating the space in future. The 'New Space' is sparkling and full of opportunities; with the increased investments and research, we will achieve our goal in the coming year.

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