International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2019): 7.583

Small Satellites Applications, Classification and Technologies

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Abstract: ***Small satellites with less than 500 kg mass have come back with improved capabilities. The small satellites are the stepping stone for new comer coming to the space field. Mass and size reduction is possible due to miniaturisation of electronic hardware and converting many hardware logics into software logics. Further mass reduction is achieved in small satellites by introducing new lighter materials in mechanical systems and designing the sub systems without redundancy. Continuous development of new technologies reduces the mass of satellites. Some payloads like high resolution cameras and communication antennas cannot be accommodated in small satellites, but those applications are better served by multiple small satellites together. Though the small satellites have advantages of launched as piggyback with bigger operation satellite with reduced launch cost, in most of the launches they are launched to the orbit of the primary satellites. Dedicated small satellite launch vehicle will solve this problem. This paper discusses the advantages, applications and classifications of small satellites. Challenges and technologies used in the small satellite missions also presented.***

Keywords: Satellite, Autonomy, COTS, Miniaturisation

1. Introduction

Satellite era started with the launch of small satellites Sputnik (83 kg) and Explorer-1 (14 kg) by Russia and United States of America respectively. Following these satellites, numerous small satellites were launched in 60s. Bigger satellites had become attractive in 70s and 80s due to the user requirements to accommodate bigger, more payloads and larger solar panels to generate more power. The increase in launcher capacity to lift more mass also contributed for this change. Bigger satellites carry more fuel for orbit rising and correction which extends the life of the satellites. As the cost associated with the design, production, qualification, launch and operation of a satellite is very high, so far, the space industry was restricted to huge space organisations supported by governments and major industries of developed countries. New comers to the industry were forced to find a cost-effective solution to penetrate the market. The present trend in space systems is to get more benefit by providing less input. This has led to the "Smaller, Cheaper, Faster, Better" concept. Due to these reasons the small satellites have re-entered the market with increased capacities. The small satellite missions provide more opportunities for access to space with less time and cost. Many constellation missions are realised using small satellites.

The high-resolution remote sensing satellites with bigger payloads and communication satellites with more transponders to meet growing demand direct the industry to make bigger satellites. On the other hand, requirement of low cost and less turnaround time makes small satellites attractive. Due to these contradicting requirements, many organisations which are making bigger operational satellites have started research in miniaturisation and small satellite technologies. The National Aeronautics and Space Administration (NASA) has started a separate program for small satellites "Small Spacecraft Technology Program (SSTP)" to develop and demonstrate new technologies and methods for small satellites. The European Space Agency (ESA) has many programs for making small satellites including famous "fly your satellite" program for the students of ESA member countries. The Japan Aerospace Exploration Agency (JAXA) has carried out many research and development programs on small satellites and launched its first small satellite Micro-Labsat in 2002. ISRO started its activity with small satellites, namely Aryabhata, Bhaskara, APPLE and Rohini satellite series in 70s and 80s. After launching many bigger, operational satellites for remote sensing and communication applications, it revived the small satellite programme in 2004. This programme designed and fabricated small satellites namely IMS-1 and Youthsat for earth observation and space studies [Thyagarajan et al 2009]. It also fabricated nanosatellites for remote sensing purpose. This programme provides guidance to the educational institutes of India to fabricate small satellites for educational purposes.

Some applications need launch on requirement short duration missions. The concept of 'less mass low cost' forces the designers to remove the redundancy in subsystems of satellites. If there is any unrecoverable problem found in the satellite on orbit, it is replaced by a new satellite. Satellite designed for short duration applications uses the Commercial Off-The Self (COTS) components that meet the requirement for specified duration with low cost. The miniaturisation technology of electronic components with new methods accommodate many discrete components in single Integrated Circuit(IC). Some mechanical devices are also implemented along with electrical systems in Micro Electrical Mechanical Systems (MEMS). This reduces the size, mass and power requirement. Implementation of many logics in software, instead of hardware also reduces the size of the satellite

2. Applications of small satellites

The space industry is in the phase of transformation and slowly switching over to small satellites for suitable applications. Important applications of small satellites are provided in following sections.

2.1 Single satellite applications

The short duration applications employ small satellites to reduce the cost and realisation time. Some satellite buyers are not looking for expensive larger satellite with ten to fifteen-year lifetime. Instead of having a bigger satellite to serve for long lifetime, multiple small satellites are launched with required time delay. The small satellites are used for many applications like Earth observation[1-8], Automatic Identification System (AIS)[Bjorn], training/ capacity building, data store and forward[Addaim et al. 2008], communication[Zong and Kohani 2019], disaster management[Mohammed 2014, Giancarlo 2018], space science[Fajardo 2019], microgravity research missions[Ui 2005], gravitational field strength measurement, Earth Quake forecast[Qiang 2000] etc., Main area to be addressed in small satellites are the Electromagnetic Interference (EMI) and Electro Magnetic Compliance (EMC). Special isolation and filters are being used to solve these problems. Such a small satellites are utilised for microwave related applications like Signals Intelligence (SIGINT), Internet-of-Things (IoT) etc.

2.2 Constellations

While many small satellites are operated independently, some satellites are launched to work together as a constellation. The constellation of satellites consists of two or more spacecraft in similar orbits with no active control to maintain a relative position. Constellations are utilised for special applications, such as Earth observations, Navigation[Mukesh et al. 2019], disaster forecasting and Damage estimation[Giancarlo 2018], Low earth orbit (LEO) based communication etc. The constellations improve the temporal resolution in remote sensing and visibility times in other applications The constellation concept is used to replace bigger satellites with multiple small satellites. For example, geostationary communication satellites are being replaced with constellation of small satellites launched to Low Earth Orbits (LEO). In remote sensing applications the temporal resolution is improved drastically with constellation of small satellites. The space company, Planet has launched a constellation system with 175+ small satellites for optical remote sensing. Thirteen skysat satellites provide one meter resolution data and Five Rapid eye satellites provide five meter resolution data. A huge constellation with 750 small commercial satellites is planned by OneWeb and Airbus for global internet service.

2.3 Formation flying

The concept of formation flight of satellites is different from that of a satellite constellation. The formation flying mission has two or more spatially distributed satellites with autonomous interaction with each other to maintain desired form. (Bandyopadhyay et al. 2015, Liu 2018) In formation flying, active control scheme is used to maintain the relative positions of the spacecraft. Maintaining the formation is the act of keeping a relative position between spacecraft in continues action of disturbances. Satellites used in formation flying are similar in nature and can be produced in bulk thus reducing the cost of the satellites.

The recent trend in space technology is using a number of small satellites to fly in a formation than to use a single large satellite. For example, the experimentation of magnetosphere or aurora needs bigger satellites and large aperture antenna to provide a wide coverage area. Instead of using such a high-performance satellite, many small satellites having small aperture antenna can be used to fly in circular form to produce the output similar to large aperture area.

3. Classification

The satellites are classified based on their applications, orbits, mass etc. The mass-based classification is useful to study the advantages and the technologies used in different class of satellites. The classification ranges of mass of the small satellites vary with organisations and users. The classification accepted by many organisations and study groups [Mauro 2017, Hameed 2018] is provided in Table-1

Table 1: Classification of satellites

Class	*Mass (kg)*
Large Satellite	> 1000
Medium Satellite	500 - 1000
Small satellite	<500
Mini Satellite	100-500
Micro Satellite	10-100
Nano Satellite	1-10
Pico Satellite	0.1-1
Femto Satellite	<0.1

The satellites with less than 500 kg mass are called as small satellites.

3.1 Large satellites

Large satellites are designed mainly for operational purposes with long life time (Five to Ten years). These satellites are mainly used for carrying bigger remote sensing payloads or a greater number of transponders and bigger antennae for communication purpose. These operation satellites have redundancy for all important subsystems to take care of random failure in subsystems and extend the life time. The larger satellites are generally fabricated with the radiation hardened space qualified electronic components. They generate more power with bigger deployable solar panels to support all subsystems and bigger payloads. As the large satellites have large body and solar panel area, they face more atmospheric drag. This leads to bigger, high capacity propulsion system. Normally large satellites carry chemical propulsion system for orbit raising and attitude correction.

3.2 Mini satellites

Mini satellites are with mass from 100 to 500 kg. Mini satellites are competing with large satellites in many applications. Many mini satellites are fabricated with miniaturised electronics but with redundancy. The electronic miniaturisation reduces the size and mass of satellites. Many functions are carried out with field-programmable gate array (FPGA) and Application Specific Integrated Circuits (ASIC) instead of hardware. Most of mini satellites carry propulsion system for orbit correction which extends the service of the satellite.

3.3 Micro satellites

Microsatellites are designed and fabricated for medium duration (maximum two year) application. Mass of micro satellites varies from 10 kg to 100 kg with various sizes. Microsatellites have redundancy for important subsystems like bus management unit etc. Some microsatellites carry the propulsions systems also. Microsatellites mainly used in constellations and formation flying.

3.4 Nanosatellites

Nanosatellites are used for relatively short duration missions (six months to one year). Nanosatellite are realised without redundancy. They are designed without propulsion system to reduce the overall mass of satellite [Raviprasad 2015].

3.5 Cubesat

Cubesat is subset of nanosatellite category. The cubesat standard and configuration were developed by California Polytechnic State University and Stanford University as university education program satellite. The size and configuration was decided to make it compatible with the launcher interface, Poly-Pico satellite Orbital Deployer (P-POD)[Puig-suari 2001, Swartwout 2013,]. The main objective was the spacecraft is to be fit inside the launcher interface to meet flight safety guidelines. As the P-POD is 13 cm x 16 cm x 40 cm, the 1U satellite size was finalised as 10cm x 10cm x 11cm without extrusion. Standard P-POD can carry 1U, 2U or 3U satellite. Cubesat satellites are with standard size of 10 x 10 x 11 cm and mass may be between 1 kg to 1.3 kg. As capacity requirement increases the standard extended to 1.5U, 2U, 3U and 3U+, and 6U form factors. This standardisation helps launcher to have standard **Satellite-Launcher interface and ejection system. The** advantage of standard bus is availability of fabricated subsystems from many venders.

3.6 Pico satellite

At present Picosatellites are launched for short duration experimental purposes. As their size is small, they may not generate more power to operate in continuous mode. Normally they operate with primary battery cells.

3.7 Femto satellites

Femto satellites are with very limited number of systems to carry out specific operation for a small duration from low earth orbits. Generally, these picosatellites don't have solar panels to generate power and attitude and orbit control system. Any Satellite can be divided into two main parts namely Payload and Bus. The payload is the sensor or instruments used for specific applications like remote sensing, space science or communication. Satellite bus is the carrier of the payload, includes electrical, mechanical, electro-optical and chemical propulsion subsystems.

The electrical systems consist of Power, Data handling, Attitude and control system, Telecommand, Telemetry and communication RF-systems. The mechanical systems are Structures, Mechanism and Thermal systems. Electro-optical systems are used for attitude measurements. These satellites are supported by ground stations to control the satellites and date reception from satellite.

4. Technologies specific to small satellites

The small satellites are expected to have almost same capacity like bigger satellites in terms of applications but with less mass and size to be cheaper [Rajendra 2012]. The research in science and engineering fields have developed new materials and advanced technologies. Many new technologies are utilised for miniaturisation of satellites without compromising the objectives. Some of important technologies incorporated in small satellites are explained in following sections.

4.1 Miniaturisation

The miniaturisation is an important activity which helps small satellites. Miniaturisation reduces the mass, size and moment of inertia (MI) of satellites. Electronics miniaturisation is happening due to modern fabrication techniques and accommodation of more gates in single chip. As moore's law says Number of gates in integrated circuits doubles in every two years. Miniaturisation of electronic components reduces the size of the satellite considerably. The reduction in the electronic components helps indirectly to reduce the mechanical housing also. Various concepts are employed in miniaturisation of satellites. Some concepts are,

1) System on Chip,
2) MEMs/NEMS,
3) Usage of ASICs & FPGAs,
4) SMD Based Systems.
5) Advanced technology Memory Devices,
6) 3D Packaging,
7) Nano electrons Devices and
8) Solid state switches.

4.2 Removal of redundancy

Bigger satellites designed for 10 to 15 years of operation are with redundancy in all important systems like onboard computer, attitude and orbit control system, communication system and power systems. In small satellites redundancies in these systems are reduced or eliminated to reduce the mass and power requirement. In case of major failure in any important systems which affect the mission objective, the satellite will be replaced with new one.

4.3 Materials

When the mass and sizes of the electronic packages comes down, the structure mass also decreases correspondingly. The structural material selection for small satellite plays an important role in mass reduction. The small satellite structures are designed implemented with low density high stiffness materials. The structure of small satellites is designed with aluminium alloys, magnesium and carbon fibre reinforced plastics (CFRP). The stiffness is increased by the shape of the structures. The 3D printing technology is also used to fabricate the structure of small satellites.

4.4 3D printing

In the small satellite structure fabrication and small components fabrication, the 3D printing or Additive Layer Manufacturing (ALM) technology reduces development time and cost. Advantages of additive manufacturing technology are, fabricating lots of pieces in short time, no wastage of material, achieving the weight reduction in structure is easy, less environmental impact. The 3D printing technology supports many materials such as metals, composites, polymers or ceramics.

4.5 COTS Components

The main challenge in front of satellite developers and users is reducing cost while maintaining quality and reliability. Important contributor to the high cost of satellite is space qualified radiation hardened components. Recently many small satellite developers are selecting Commercial-off-the-shelf (COTS) components to reduce the cost. Since the COTS products are new, they provide much better processing power than the radiation hardened, space-qualified products [Ramesh et al 2017]. Commercial-off-the-shelf (COTS) means a component, assembly or part is designed for commercial applications. In this case the vendor is solely responsible for establishing the specifications for performance, configuration, and reliability. The usage of COTS components is increasing in satellites in general and small satellites in particular. It is due to their low cost, easy availability, Qualification methods and less regulation. The cost of COTS components is very less when compared with radiation hardened space qualified components as they are fabricated in bulk to meet large requirement of industrial applications. As the COTS components requirement is from many fields, they are produced in bulk, continuously and available at any time. As quality of COTS components is measured based on manufacturing process, which depends on the state of technology it is cheaper than testing. Usage of COTS components brings down the cost of satellites. Mainly the short and medium duration small satellite missions use the COTS components effectively. In relatively long duration satellites, important COTS components like Processors and FPGAs are protected from space radiation by suitable radiation absorption materials like lead sheets.

4.6 Body mounted Solar cells

Bigger satellites need more power to be generated and they employ foldable, multiple, larger, solar panels. Small satellites designed with miniature electronics need less power for its operations. Though some small satellites heavier than 100 kgs have smaller deployable solar panels, small satellites in less than 100 kg categories use solar cells mounted all around the satellites for power generation. In the body mounted solar cell method, the requirement of deployment mechanisms and solar panels are eliminated. Four-junction cells are being developed to increase the efficiency. Thin film based solar cells for space applications are also under development.

4.7 Autonomy

The inclusion of sophisticated systems with more features in satellite systems needs more telecommands to be uplinked and more parameters are to be monitored. This demands for more resources like ground stations, manpower etc. to support. These resources are vulnerable to faults and threats. As the small satellite operators used to have limited number of ground stations, monitoring and commanding the satellites continuously in all orbits is not possible. Due to these reasons, implementation of autonomy in satellite is increasing every year. In small satellite autonomy is implemented in almost all subsystems. Thermal heaters and coolers are operated with the feedback from the temperature sensors. Attitude control is done by actuators that are controlled by control electronics with the input from attitude sensors automatically. Payload operations like imaging interested terrain at a particular latitude and longitude are done by pre-programmed payload controller. The satellite manoeuvres required for pointing the camera towards a specified target are calculated and implemented by the on-board computer. In order to save power, many systems like telemetry, telecommand, receiver, transmitters are kept 'ON' during the satellite visibility to the ground stations only. As many decisions are taken onboard, number of telemetry parameters transmitted to ground has decreased. In small satellites high level of autonomy is implemented to operate these essential systems. The satellite autonomy reduces number of ground station requirement and operating cost.

4.8 Implementation of logics in software

Many logics implemented through hardware in bigger satellites are now implemented in embedded software. This reduces the mass, size and the cost of the hardware. Some logics implemented in software are,

1) Attitude calculation from sensors signal
2) Attitude correction estimation
3) Actuator control
4) Orbit estimation
5) Battery charge control
6) Payload data compression
7) Onboard data processing to reduce the data transmission rate by eliminating the data with cloud etc.

4.9 Plug and Play hardware

The small satellites are designed with plug and play technology to reduce the size and mass. The plug and play concept reduces the assembly and testing time also. Many small satellites systems are designed with motherboard – daughterboard concepts. Different systems are implemented in daughter boards. They can be inserted in motherboard to assemble the satellite. This concept reduces Integration and assembly time. If any card is misbehaving during testing, it can be replaced with other card immediately. This reduces connectors, harnesses and mass of the satellites.

Short range, high speed real time miniature radio communication links are used in some satellites for disseminating the commands to the subsystems from telecommand system and collect telemetry information from various system. This technique reduces the harness mass and helps in faster assembly and integration of satellite.

4.10Expand in Space

Due to limited space inside the launch vehicle thermal shield (fairing), the satellite size should be smaller to be accommodated. At the same time some subsystems like solar panels, antenna sensor booms are to be larger to support the mission requirement. 'Expand in space' is an attractive concept which makes satellite small in size during the launch phase and after launch the size increases. Many appendages are kept in folded/squeezed condition during the launch time and deployed/enlarged on orbit. Deployment of antennas, Solar Panels, payload booms and the sensor mounts are some example. While bigger satellites employ the electronically triggered explosive devices (EED) for deployment systems, The Small satellites employ simple smart material or melting property of the nylon wire.

4.11 Micro Electro Mechanical Systems (MEMS)

The small satellites mainly in general and nano and pico satellites in particular use MEMS components to reduce the mass and size [Shea 2009, Bendong 2019] MEMS is a process technology to create micro integrated mechanical devices and electrical components together. MEMS are combination of mechanical microstructures, microsensors, microactuators and microelectronics integrated onto single silicon chip. The size of these devices will be from micrometers to few millimeters. MEMS are fabricated using integrated circuit (IC) batch processing techniques. Using this technology various components like sensor, actuator and control electronics are fabricated.

4.12 Optical Communication

The improved payloads and increased capacity of satellites demand for high data rate transmission. Usage of optical links like laser beams for high data rate communication is under experiment. These optical links are capable to carry high data rate for long distance compare to micro wave.

4.13 Propulsion systems

Though propulsion system has considerable mass, some small satellites carry it to increase the lifetime. While large satellites use complex chemical combustion systems with monopropellant or bipropellant for orbit raising and attitude correction, micro and nanosatellites use modern, lighter propulsion systems like electric propulsion. Cold gas and heated gas propulsion systems are used in nano-satellites, micro-satellites, due to their simplicity, high reliability, and low [Lev et al. 2017]. Electric propulsion is a generic name covering all the methods of accelerating a propellant using electrical power. Fuel mass requirement in these propulsion systems is very less. The advantage of electric propulsion is safe and efficient than chemical propulsion, i,e. they require much less propellant to produce the same overall increase in spacecraft velocity. The propellant is ejected much faster when compared to chemical thrusters and therefore the same propelling force is obtained with less propellant.

Propelling the satellite using solar sail is an innovative method of propulsion under development. Solar sail with large reflective area pushs the satellites by momentum of light from the Sun.

4.14 Piggyback Launch

The launch cost of the satellite to orbit is considerable when compare with total cost of a space mission. The cost for dedicated small satellite launch is too high. The launch cost of small satellites may be reduced by launching them as piggyback with bigger satellites. In some cases, many small satellites are launched together to reduce the launch cost [Nicholus et.al. 2014, Petro et al, 2019]. Though some launchers are capable to launch primary satellite and secondary satellite to different orbits (different altitude and inclination), many launchers place both satellites in the orbit required for the bigger primary satellite. At present dedicated small satellite launchers are limited in number. Many small satellite launchers are under development and testing. Once these launchers are operational, dedicated small satellite launch cost may come down.

5. Conclusion

The utilisation of small satellite is increasing in many fields. Small satellites provide technical and economic advantages compared to bigger satellites. Miniaturisation of electronics and development of new materials and alloys reduces the complexity of making small satellites considerably. Various techniques employed in the small satellite realisation are discussed.

6. Acknowledgements

The authors thank Mr. PJVKS Prakasha Rao, Programme Director, IRS & SSS programme for his support and Mr. P. Kunhikrishnan, Director, UR.Rao Satellite Centre, Bangalore for his continuous encouragement during this study. The authors also wish to thank Dr.A.Senthil Kumar, Ex-Director, Center for Space Science and Technology Education in Asia and the Pacific (CSSTEAP), Dehradun and Dr. Prakash Chauhan, Director, Indian Institute of Remote Sensing (IIRS), Dehradun for their motivation and suggestions.

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