Paper

Technologies for low cost small satellites

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Abstract— Paper presents short description of satellite structure and characterization of its subsystems. Review of technologies used in small satellite missions is presented, considering possible solutions in low cost projects. Three common solutions: the use of commercial off the shelf (COTS) components, miniaturization, remote testing and integration of subsystems can be used to significantly reduce cost of the satellite.

Keywords—small satellites, satellite systems, space technology.

1. Introduction

Satellite industry is one of the most dynamically developing discipline of world economy, beside of satellite communications other applications, like navigation and positioning systems, observation of the Earth and space, stay more important [1]. Last years it is observed increase of interest of small satellites (mini- and microsatellites) placed in low Earth orbits (LEO), used specially in no communications applications. Small satellites although their small dimensions and mass do not differ from large ones, including practically the same systems and blocks and realizing the same functions. Classical satellites are large and expensive, and process of their building lasts for many years and requires vast financial expenditures that can be bear only by large organizations. Technology development leading to miniaturization of electronic elements has allowed to build small satellites that could be used in different applications [2, 3]. Short time of building and smaller costs of launch makes use of these satellites very attractive.
Small satellites can be used in many applications:

- **Earth observations**. Standard methods of observations using large satellites are expensive. Small satellite using proper instruments (cameras, sensors) can realize observations with large resolution.
- **Tests and verification of new technologies in space environment**. Because of cost and time of realization of a small satellite is considerably smaller, it is ideal to realize different tests of a behavior of units and materials in space.
- **Education and training**. It is a cheap method to educate engineers in area of space technology. Education process includes project, realization and tests of the satellite, launch, monitoring and control of the satellite in an orbit.
- **Military applications**.
- **Exploration of space**.
- **Special communications**.

Electronic elements working on the satellite have to meet specific requirements relating to miniaturization, energy savings, resistance to gravity load and radiation, reliability. Scientific research considering possibilities of use in small satellites of commercial off the shelf (COTS) components instead special space ones are done [4]. Use of these components requires proper system solutions, securing large reliability, but can significantly reduce cost of the satellite building, that is essential matter in short time and education missions, i.e., SSETI ESEO satellite [5].

2. Satellite structure

All systems of the satellite can be divided on two parts:

1. Payload – containing instruments, equipment, transponders necessary to realize mission of the satellite.

2. Satellite bus (space platform) – ensuring conditions to proper work of payload. Following subsystems can be identified:

   - mechanical structure – carriage, alignment of systems, shielding, heat dissipation, interface with launcher;
   - communication system (Comm) – realization of communication with ground stations and eventually with other satellites;
   - on-board data handling system (OBDH) – control and steering of all satellite systems;
   - attitude control system (ACS) – control of satellite orientation in the orbit;
   - electrical power system (EPS) – generation of voltages to supply all subsystems;
   - thermal system – control of temperature inside the satellite;
   - propulsion system – realization of orbit maintenance.

Satellite in the orbit is exposed on environment conditions that have influence on its subsystems:

- Gravity overload and vibrations during launch – all satellite subsystems have to work properly after such stress.

- Vacuum – problems with heat dissipation, degassing of some materials.

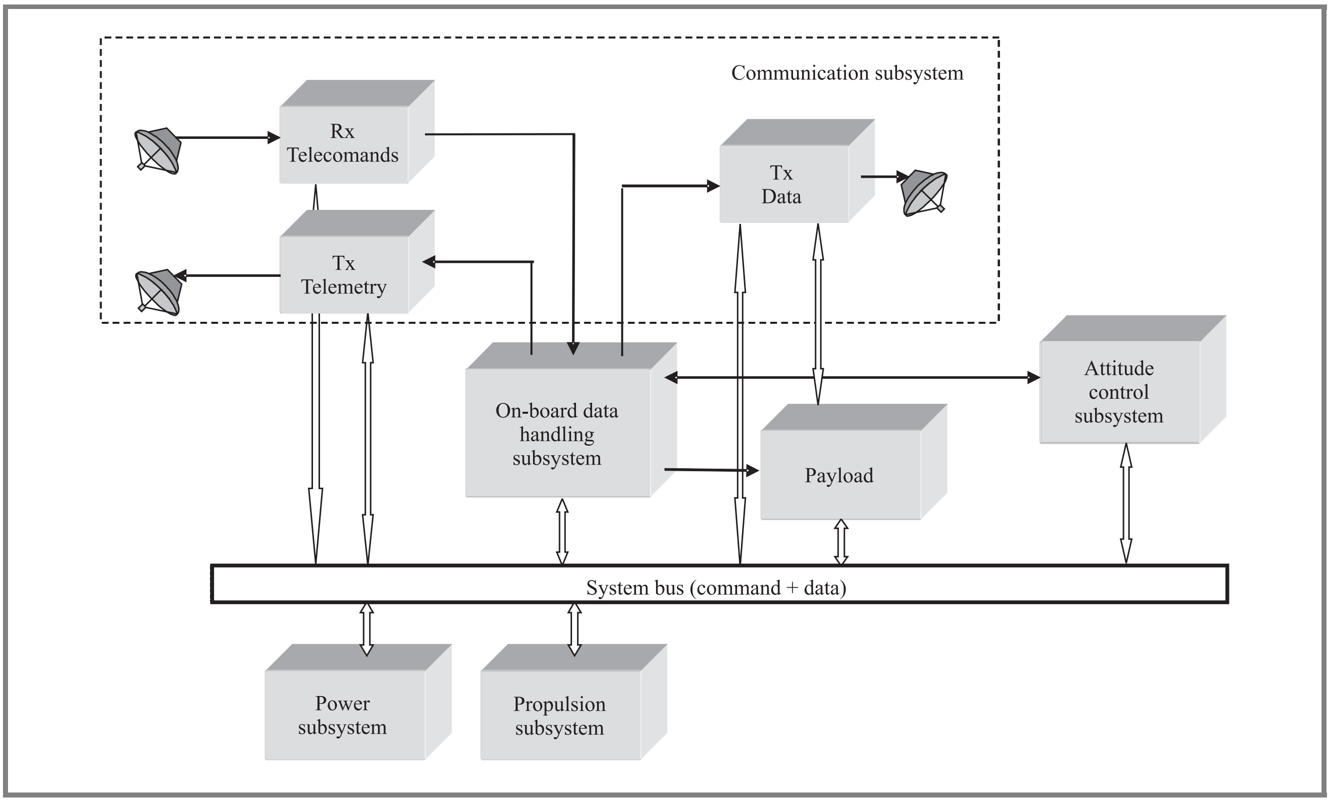

Fig. 1. Structure of the satellite.

- Radiation (large energy particles: electrons, protons, heave ions; electromagnetic wave) – causes errors in electronic circuits, specially in semiconductors (single event effects: SEL, SEU). Crucial parameter for semiconductors is total doze of accepted radiation, determining possibility of circuit failure. Level of radiation depends on orbit height, the higher orbit the larger radiation, but additionally around the Earth there are van Allen belts, where radiation is very high.

- High range of temperatures.

Connections between satellite subsystems are presented in Fig. 1. Communications between them is realized by system bus that allows OBDH to send commands to and receive telemetry data from all subsystems. Considering space environment conditions and impossibility of repair all satellite systems should be reliable and resistant to environmental stresses. Fulfilment of such requirements requires the use of elements able to work in space and proper system configurations. Systems important for satellite proper work are redundant (hot or cold redundancy).

On-board computer (OBC) of OBDH system controls and monitors proper operation of other subsystems, it realizes, by communications subsystem, communication with the ground control station receiving telecommands and sending telemetry data. Also ACS and payload can include computers supporting realization of main functions of these systems: respectively attitude control and correction and payload data processing. In low cost noncommercial missions, i.e., education, nanosatellites, there is often only one computer system on satellite, realizing functions of OBDH, ACS and recording of data from payload.

System bus allows to realize communications between satellite subsystems and have to guarantee high resistance to data distortions caused by space environment (radiation), therefore standards of serial transmission like CAN, RS-422, or I^2C in nano- and picosatellites, are commonly used.

In general payload can realize transmission and reception of data depending on mission principles (i.e., telecommunications satellites), but in earth observation and scientific missions data collected by payload are sent to the ground stations.

Depending on mission assumptions and aims configuration of satellite subsystems may be less or more complicated.

2.1. Mechanical structure

Satellite body must be light, simple and practical construction that can be adapted to requirements of different missions and launch rockets in easy way. It is build using aluminium or composite materials often as honeycomb structure. It should be modular construction easy to modification, with minimum number and variety of parts. All satellite systems are mounted to the structure and for different task realized by satellite different solutions are optimal (i.e., stacked panels, modules mounted to external frame).

2.2. Electrical power system

Solar arrays are main source of electrical power for satellite systems. In small satellites they are placed on its body, but in order to increase available power they can be also realized as deployable panels that are deployed after placing the satellite in the orbit. In such a case sun tracking system is not used, because of its necessary mechanical elements increase overall weight of the satellite. In order to maximize power obtained from the arrays for different illumination conditions and temperatures peak power track (PPT) systems are used.
Space qualified solar arrays are very expensive and terrestrial technology arrays are used in many low cost missions. Some modifications to improve arrays reliability and resistance to space environment must be considered. The solar cells are encapsulated between two layers of special polymer resistant to UV light and with good mechanical properties. Solar cells are built using two main single crystal materials:

- Si – wide use in space missions, efficiency: $\sim 10\%$;
- GaAs – higher efficiency: $\sim 20\%$, but larger weight and cost.

To increase of light conversion efficiency double and triple junctions cells can be used. Thin film photovoltaic (TFP) materials are other interesting solution [6]. Such materials have smaller efficiency, but they are chipper, flexible, more radiation resistant and have significantly smaller weight. Less mass of TFP solar arrays can significantly reduce weight and cost of satellite for certain missions. Additionally flexibility of these materials allows to build deployable panels in easy way – arrays can be rolled up during a launch and then deployed in an orbit.
When satellite is in the Earth shadow chemical battery must be used to allow proper continues work of satellite systems. Battery is charged during sunlight and special charge controller is used to protect the battery against overcharging and from other side against discharging. Regulation of power taken from the battery is realized by proper choose of modes of satellite systems (scheduling of tasks) in such a way that maximum power is taken when the battery is charged. When there is shortage of power, systems no critical for proper functioning of the satellite are switched off. Three main types of chemical batteries are mainly used in space applications:

- NiCd – high robustness and cycle life, but small energy density;
- NiH2 – larger energy density, high cycle life, pressure vessels;
- Li-ion – high energy density, more expensive, shorter cycle life.

In many missions in order to cost decrease terrestrial batteries, after tests of their proper operation in space environment, are used.

Voltage from the battery is used to generate all voltages necessary to supply all satellite systems, using switching mode DC/DC converters, and then distribute them to systems using separate lines protected by current tripping switches or by fuses.
Power system must be reliable and autonomous. Solar arrays are divided on independent modules and redundancy of electrical circuits is used to increase reliability. Simple logic unit, independent on OBDH, is used to control and monitor work of the system. Considering small weight and dimensions of small satellites (specially nanosatelites) the use of effective solar cells is critical factor. In addition other systems (antennas, payload) must be placed on the surface of satellite, that also limit size of solar array and results in significant power limitation for small satellites.

2.3. Communication system

Communication system realizes three communication channels with the Earth :

- telecommand channel (TC) – reception of commands steering work modes of satellite systems;
- telemetry channel (TM) – transmission of data about status of all satellite systems;
- payload/data channel – used to transmission of data obtained by payload.

Structure of transmitter/ receiver blocks responds standard solutions used in radiocommunication systems, but elements in satellite system must fulfil additional requirements coming from space environment conditions. For the sake of importance of communication with the ground control station for proper operation of satellite redundancy is used. Two receivers in TC channel operate simultaneously, and from two transmitters in TM channel only one operates (cold redundancy – in order to minimize power consumption by high power amplifiers). When the ground station does not receive telemetry data, it sends command to switch on second transmitter.
Transmission in TC and TM channels is realized using packet transmission with bitrate up to a few tens kilobits. In many cases (specially in nanosatellites) standard radioamateur UHF bands are used. This allows to receive signals from the satellite by radioamateurs in different locations, and increase amount of data received from the satellite. Antennas used in TC and TM channels must have wide radiation patterns assuring communication with the satellite independently on its orientation. It is possible using one omnidirectional antenna or a few sector ones properly placed on the satellite body. Transmission in data channel is realized when the satellite is in operation mode and it has proper orientation, so high gain narrow beam antenna can be used to improve properties of the link. If the same antenna is used to transmission and reception of signals the use of diplexer to separate frequency bands of the transmitter and receiver branches in antenna output is necessary.

2.4. On-board data handling system

The OBDH system consists of on-board computer, system bus to communicate with all satellite system, and direct connection to communications system to realize telecommand receiving and telemetry transmitting. Considering OBC special configurations and solutions are used assuring required high reliability and robustness, because of errors in program and data can cause wrong operation of the satellite systems. For digital circuits in space radiation is the most danger, it can cause damages or distortions in processed, stored and transmitted digital data. Separate RAM memories are used for data and program, and start up program is stored in EPROM, that is more resistant to radiation. Memories are protected against radiation errors. Performed research has shown that radiation level and caused by it errors depend on orbit height. For LEO errors occur rarely as single bit distortion in single words. When large amount of data (long block) is stored in memory two bit errors in single word can be observed, but probability of such situation is much smaller.

Three solutions are commonly used to protect memory data: triple voting memory, error detection and correction (EDAC) memory, and block code protection of blocs of data.

For the satellite placed into low orbit total doze of radiation is small, bellow 20 krad, and COTS elements can be used instead of special space radhard versions. Many different microprocessors are used in space applications depending on specific and requirements of the mission: Intel PC family, power PC, single chip microprocessors. Using of software processors implemented in programmable structure (field programmable gate array – FPGA) is other interesting solution. It allows to integrate all OBC systems (microprocessor, data and program RAM, I/O interfaces, system bus controller) in single structure – system on chip [7].

Some technology aspects are important when the choice of microprocessor is considered: small power consumption, resistance against radiation (proper technology and supply voltage), good software support.

2.5. Attitude control system

The aim of ACS is assure proper orientation and stabilization of the satellite position with required accuracy that depends on mission requirements. Stabilization can be realized using passive or active methods. In passive system spin of the satellite or gravity gradient are used to attitude control. These are simple solutions, but their accuracy is small (range of a few degrees). To increase accuracy active methods are used. Such a system consists of sensors, actuators that allow to change the satellite orientation, and control system (often realized as a Kalman filter) that generates steering signals for actuators using data from sensors.

Sun sensors, magnetometers, gyroscopes, earth surface sensors are used as sensors, and momentum wheels, magnetic torques, jet and compressed gas propulsions as actuators.

Actuators, specially momentum wheels are large and massive devices considering small satellite point of view. Conventional wheel can have 10–15 cm diameter and 5–10 cm height, mass above 1 kg and power consumption of 10 W. It can be used in satellites that have weight larger than 20–30 kg. For smaller satellites gravity booms and magnetic torques can be used, but achieved precision of attitude control is smaller. When life of a mission is very short microjets can be used. For longer missions micro-wheels, using MEMS (micro-electro-mechanical system) technology [8] or/and high temperature superconductors (HTS) [9], can be practical solution. Such micro-wheels can be used to attitude control and also to energy storage instead chemical batteries. Using pairs of counter-rotating wheels integrated in one package energy can be added and extracted from them without changes of the satellite orientation.

Nowadays also multiple antenna GPS (global positioning system) receiver can be used to determine of the satellite orientation. Using three or more antennas differently paced on the satellite body calculation of the satellite attitude can be realized with accuracy better than one degree. GPS is also a source of reference time for satellite systems.

3. Technology trends

Technical research in area of realization of low cost small satellites should consider following aspects:

1. Miniaturization and integration of satellite systems allowing to decrease dimensions, weight and cost of the satellite:
   - new types of batteries and solar cells (i.e., thin film technology);
   - the use of MEMS systems (micro-propulsion, micro-momentum wheels, micro-cooling);
   - electronic modules:
     - new types of microwave components to the transmitter and receiver modules (small light filters, high efficiency power amplifiers, patch antennas);
     - the use of programmable circuits (i.e., FPGA) to digital signal processing (DSP) realizing baseband and IF signal processing in communications subsystem (modulators, demodulators, filters, distortion precorrectors); this will allow to realize all signal operations in one unit in digital form, excluding only RF module and A/D, D/A converters; changes of parameters of the received or the transmitted signal can be realized by software changes;
     - integration of on-board computer OBC in single chip (system on the chip solution) in FPGA structures.

2. The use of COTS elements and methods of increasing of reliability of modules used such elements. In order to minimize cost of the satellite system in low orbit COTS solutions are preferable in both areas: hardware and software. Specially it is essential in education missions when minimization of cost is critical issue. For assumption of short mission life it is an optimal solution. But using proper elements and system configurations (redundancy, environment ground tests) it can also be adapted to commercial longer life missions, allowing required system reliability.

3. Remote testing and virtual integration of systems using Internet. Integration systems and complex tests of the satellite are ones of more essential stages of its design. Correction of any errors found in this stage is expensively and tools to earlier detection of such errors and problems should be considered. The use of Internet to virtual communications between satellite systems will be good solution, specially when the satellite is realized in international cooperation. After implementation of interfaces between systems and Internet virtual testing can be performed and if results will be positive real integration will be realized.

4. Conclusions

Short overview of satellite structure and technologies used in small satellites has been presented. The use of such satellites is attractive in many different applications, i.e., Earth observation, in-space technology validation and education missions. Limitations of weight, dimensions and available electrical power require the use of proper technical solutions of satellite subsystems. In case of LEO satellites COTS elements are commonly used, allowing to significantly reduce cost of satellite. But this requires proper system configuration and realization of ground tests to verify proper operation of such elements in space environment. Tendency to minimize size and weight of satellite subsystems, keeping their performances, is other important factor in small satellite missions. In this case MEMS systems that can realize different functions, are very promising solution. Also the use of thin film photovoltaic materials in solar panels and high temperature superconductors in momentum wheels can create new possibilities.

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