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SMALL SATELLITES AND TECHNOLOGY DEVELOPMENT. A REVIEW

Cosmin GOGU[1,*], Cristina PUPĂZĂ[2], George CONSTANTIN[3]

[1)] Ph.D. Student, Eng, Robots and Manufacturing System Department, University Politehnica of Bucharest, Romania
[2, 3)] Prof., Ph.D., Eng, Robots and Manufacturing Systems Department, University Politehnica of Bucharest, Romania

Abstract: *The paper's main objective is to present the current stage of development in the aerospace field. A brief history of small satellites and the classification of satellite sizes is presented. Research directions in the aerospace field are presented as defined by the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA). An analysis of the research directions is proposed for development for materials, design, production and testing of spatial structures. Improvements in designing of structures focuses on Modeling, Optimizations and Validation stages, with recommendations for each stage. Small satellites development is accelerating for nano-satellites class, which offers best cost-performance ratio, recent developments are enabling bigger size Card Sat like 12U and 16U to be used in upcoming missions.*

Key words: *small satellites, design methodology, modeling, optimization, validation, development.*

1. INTRODUCTION

Evolution of technology in aerospace comes with increasing maturity of satellite communication and manufacturing technology; the development of small satellites, known as mini-, micro-, nano, and pico satellites, has grown exponentially, and the industry has experienced accelerated growth in recent years.

Most small satellites are used for short-term missions, which have a limited validity period of no more than three years, but some satellites have been in orbit since 2003, for example, CUBESAT XI-IV.

Development of satellites used to take a long time and be quite expensive. Only national entities or commercial companies with significant budgets and resources often attempt to develop and operate these satellites. However, in the small satellites domain, the technical and capital entry barriers are significantly lower and ordinary businesses or smaller administrations can quickly complete the development of satellites due to reduced costs, straightforward design, and flexible launch and payload transport configurations.

In general view, there are different ways of using small satellites, their inherent costs and specific task development advantages. What must be considered as well is the fact that this area attracts new participants who may not have the knowledge or experience in the related fields necessary to develop from scratch the project, so "platforms" are being developed that allow the integration of the desired experiment, into an already developed platform, with minimal costs and implementation time [1].

*Corresponding author: Splaiul Independenţei 313, district 6, 060042, Bucharest, Romania,
Tel.: 0040 21 402 9369
E-mail addresses: *cosmin.gogu@stud.fiir.upb.ro* (C. Gogu), *cristinapupaza@yahoo.co.uk* (C. Pupaza)

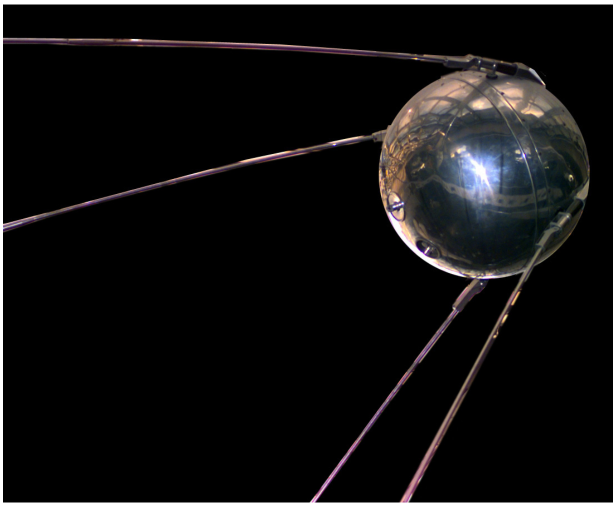


Fig. 1. Sputnik 1, the first small satellite.

Launch of Earth's first "small" satellite Fig. 1, has brought the start of the "space race" in 1957.

The next decades, increasingly large satellites were developed to provide reliable services from space over extended periods. The demand for the use of radio spectrum and satellite orbit has increased, and the sustained increase in technological advances and the innovation of space communications, together with the expanding capabilities of satellite production, has seen a dramatic increase in the number of satellites and small systems. Many of them launched in the last ten years. The industry of small satellites is facing an era of unprecedented changes [2].

2. AEROSPACE DOMAIN

2.1. Definition of small satellite

The definition of "small satellite," including the following terms: mini satellite, microsatellite, nanosatellite (nanosat), picosatellite (picosat), Femto-satellite (femto-sat), and other types, is becoming increasingly widespread in the scientific field. The definition of the term "small satellite" is not regulated. The term "small" generally refers to its size and mass. Still, these aspects are irrelevant to frequency and orbital regulations and therefore have no impact on the international regulatory framework which it is applied to it [3].

Small satellites offer technical, and capital barriers that are often low, and the development of small satellites can be more accessible and faster for entities (research institutions, universities, small companies, etc.) due to lower cost, simpler design, and flexible launch requirements.

The development of small satellites is an essential step in the satellite industry that provides opportunities for more entities and access to space services to more users [4].

2.2. Development of small satellite

Private enterprises, research institutions and recently private company's are developing small satellite projects to promote applications not only in satellite applications [5, 6] and development of multi-satellite fleets (constellations) [7] for satellite internet access, still allowing integration with 5G, but also in applications concerning:

Earth exploration,
Data communications [8],
Space research [9],
Environmental monitoring, including Climate change, Agriculture,
Testing of innovative technologies [10, 11].
Scientific experiments [12, 13],
National defense [14],
Live monitoring.

The performance of various tasks in space can be further analyzed and improved. There is a wide range of different possible applications that comes from small satellite features that can be summarized as follows:

- Fast cycle of development.
- Abundance of launch opportunities.
- Projects have lower initial investments and operating costs.
- Good coverage in all world areas.
- Integration of more small satellites to create a "constellation", fleet of satellites.
- Easy to update, expand, renew and enlarge fleets of satellites.

2.3. Recent years

In recent years, we can see a constant development and launching of new satellites [15], which gradually proved the feasibility of small constellations of satellites. The industry has seen an increase in the number of newly launched satellites. In the future, satellites developed with the newest technologies may also bring these technologies to various new fields (Fig. 2).

3. SATELLITES CLASSIFICATION

A legal or regulated definition of a "small satellite" does not exist. However, satellites can be grouped according to their mass, mission duration, functional density, and other criteria.

Currently, the best way to classify satellites is by mass [16].

Satellites weighing less than ~ 500 kg are often called small satellites, which can be further classified as shown in Table 1.

4. DEVELOPMENT OF SMALL SATELLITES AND LAUNCH INTO ORBIT

Depending on the specific objectives of a mission, nano-satellite and pico-satellite missions may be restricted to have a particular orbital path [17–21]. Depending on the task, nano-satellite and pico-satellite operators may have several launch possibilities. They may not know orbital characteristics until a launch

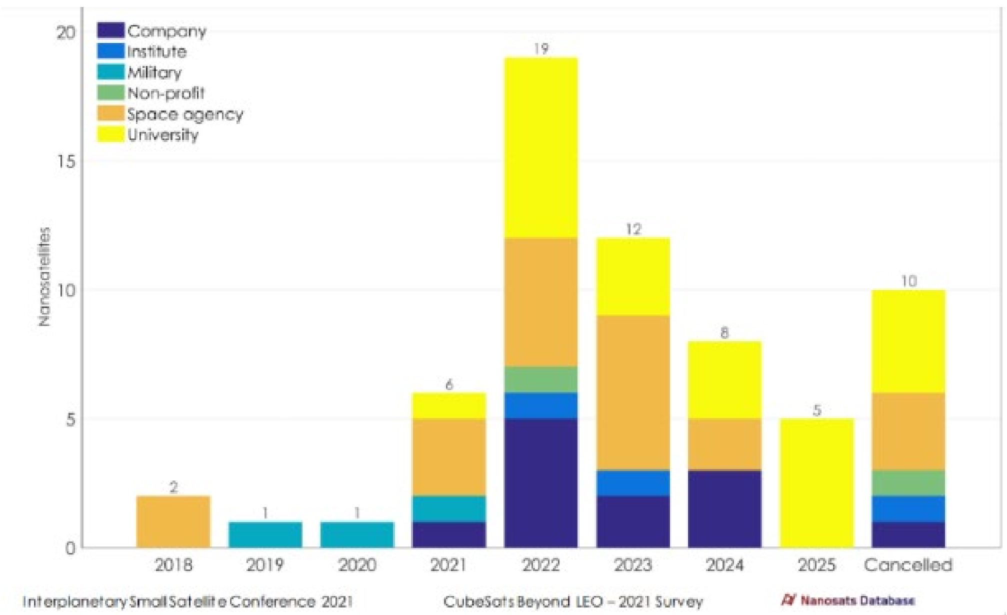


Fig. 2. Launches and types of nanosatellites missions.

Table 1

Classification of satellites

Category name	Mass [kg]	Maximum power [W]	Average cost [USD]	Maximum dimensions [m]	Development time [years]	Duration of the mission [years]
Mini-satellites	100–500	1000	30–200 M	3–10	3–10	5–10
Micro-satellites	10–100	150	10–150 M	1–5	2–5	2–6
Nano-satellites	1–10	20	100k–10 M	0.1–1	1–3	1–3
Pico-satellites	0.1–1	5	50k–2 M	0.05–0.1	1–3	1–3
Femto-satellites	< 0.1	1	< 50 k	0.01–0.1	1	< 1

vehicle is selected. This can take place just a few months before the actual launch and even after satellites has development, so only a few minor modifications can be made to fit the new characteristics.

Nano-satellites and pico-satellites have been launched as secondary payloads, which means that the primary mission of the launch vehicle involves launching larger satellites or another type of missions. Because the rocket often has excess lift capacity to add other small payloads to their load, satellites can "squeeze" on a primary payload as long as the mission requirements are similar to the rocket profile.

With the recent, high interest in nano-satellites and pico-satellites, mission developers are now considering whether dedicated launches and special delivery vehicles would help put even more satellites in orbit.

Currently, most small satellites are launched using deployers that require minimal interfaces with the launch vehicle. Such example of deployers are offered by big companies: such as Exo-launch whit the Exo-Pod deployer, that can launch 2 × 3U CubeSat and 1 × 6U CubeSat Fig. 3,*a* or IsiPod by ISISpace Fig. 3,*b* for deploying 1 × 3U CubeSat.

There are many separation systems with flight legacy on various launch vehicles. Inclusively several different manufacturers worldwide supply systems compatible with the Cube Sat standard, so that the developers focus to design their structure to a familiar form factor and encouraging the use of standard subsystems from various vendors [22, 23].

These features allow for quick launch and adaptation arrangements on the launch vehicle, often shared with a few other satellites from different organizations.

5. RESEARCH DIRECTIONS IN THE AEROSPACE FIELD

NASA explores a wide variety of technological development activities to enable the expansion of knowledge and capabilities in space, science and engineering. NASA uses a technological taxonomy to

a b

Fig. 3. Deployers for nanosatellites: *a* – Exo-Pod Deployer, multiple; *b* – IsiPod Deployer, single.

Fig. 4. Plans for the development of new technologies.

manage and communicate this extensive and diverse technology portfolio. The taxonomy, Fig. 4, identifies, organizes, and shares the relevant technical areas intended to be developed in the future [24].

Similarly, the European Space Agency (ESA) presents the Plan for Harmonization of European Space Technology, Fig. 4, in which ESA consults companies and the academic environment to propose new research directions. It also provides funding for projects targeting the areas indicated in this plan [25].

In the mechanical field, the points of interest are presented further on.

5.1. Materials

Materials that reduce mass and increase the efficiency of structures and structural components such as advanced metal materials, polymers, nano-materials matrix composites materials, multifunctional materials, damage tolerant materials and self-repair/self-healing materials [26].

Examples:

- Fibers, nano-fibers, resins, and adhesives that can allow the manufacturing of large structures.
- Materials that perform multiple functions, materials that include mechanisms for rapid, in situ repairs.
- Optimized structures with topology.
- New low-density metals (using additive powder manufacturing technology).
- Composite alloys.

5.2. Structures

In the development of space structures, there are pursued structures that are lightweight, robust, multifunctional, and intelligent that prove reliable and predictable.

Examples:

- Components for surface construction on other planets and space vehicles, space deposits, even solar or antenna networks, complex precision deployment devices, propulsion systems and cells, terrestrial engines operating either as primary support or as secondary structures.
- Technologies may include rigid constructions (e.g., casing or firm structures) or expandable configurations (e.g., inflatable structures) with efficient structural geometries (e.g., hardened housings) constructed from advanced material, using advanced manufacturing methods (e.g., additive manufacturing) [27].

5.3. Production

Tracking innovative physical manufacturing processes and integrating with analysis and design through digitalization.

Examples:

- Additive manufacture of new alloys.
- Manufacture, assembly, and repair in space.
- Advanced casting and injection molding of metal materials like amorphous metals, metal matrix composites, and high-strength alloys.
- Advanced manufacture of laminate or sheet metal.
- Additively manufactured materials for cryogenic applications [28].

5.4. Testing

Testing and validation of components and structures to deal with the interaction of aerodynamic, static, and control forces acting on vehicles and other finished products [29, 30].

Examples:

- Development of techniques for the analysis of coupled loads.
- Shock analysis methods and tools.
- Integrated thermal modeling.
- Cryogenic systems.
- Multi-physical simulations coupled with temperature-induced phenomena that affect system performance.
- Structural-thermo-optical analysis.
- Dynamics of computational fluids (gravitational and micro gravitational environments).

6. DESIGN OF STRUCTURES

Modeling is essential for all three of the integration objectives mentioned. Simulation and prediction are fundamental to an improved understanding, reducing uncertainty, and providing benefits. The big challenge is to have an observation system that manages all the critical variables of the system and assimilates this information into an integrated, interactive modeling system that includes all the essential elements necessary for developing a new product.

Further, the elements to be developed/improved are presented.

6.1. Modeling and methodologies

Simulations should also be fully connected with material structure models, allowing designers to make predictions based on high-fidelity calculations at the part and assembly level [31].

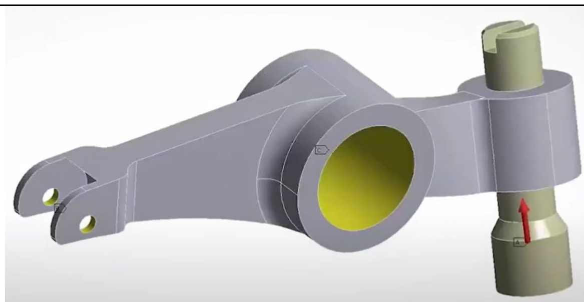
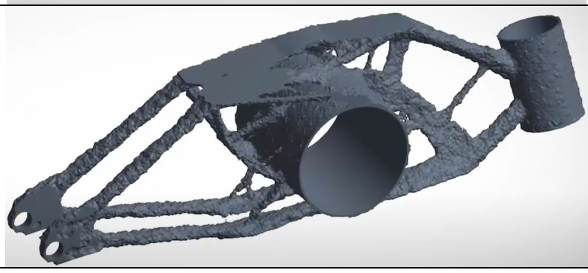
Additive manufacturing seems to have reached this level, where you can achieve virtual, 3D modeling, shape simulation, and optimization, but also a simulation of the process of obtaining the part. For example, the effects of the manufacturing process on the accepted function can be analyzed at the end of the process, resulting in a digital twin, as presented in Table 2.

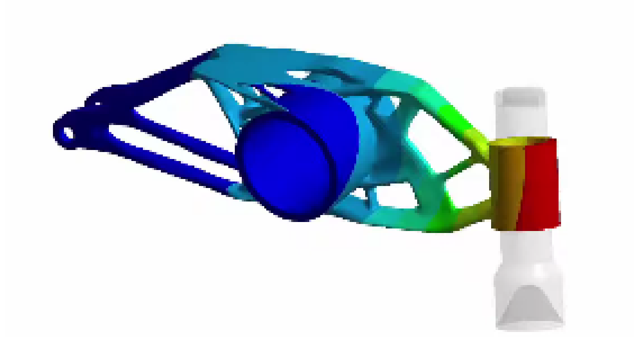
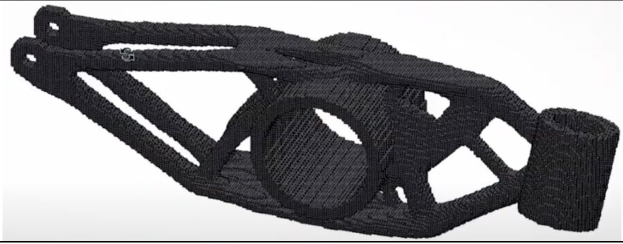
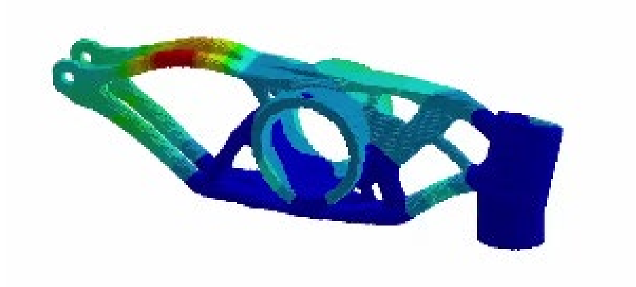
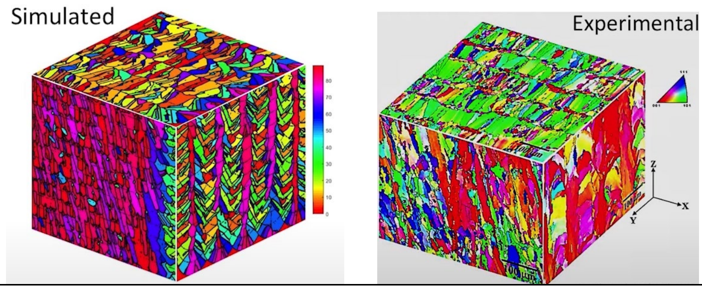
6.2. Optimizations and optimization techniques

The three main components in engineering design that can be considered are structural design, material design/selection, and production/processing, Fig. 5.

Table 2

Improvements for parts design using additive manufacturing [32]

CAD Design - Realized using standard techniques	
CAE process simulation	

- Topological optimization can be made using advanced algorithms.	
CAE process optimization	
Simulation and verification of the model	
CAM Simulation For additive manufacturing, process simulation is also available.	
A microstructure analysis can be made on the digital twin model generated by CAM simulation, preliminary results show that simulations match whit experimental data	

Optimization should ideally link the science of materials, design, and production. The optimization methodology for designing the material structures and systems, as well as multi-physical simulations to optimize the suitable materials for the specified purpose and their associated components/structures/machines. The extended values of the simulations should include durability, environmental requirements, end-of-life component recycling, and full use of materials and structures, as well as economic function [33 and 34].

6.3. Checks and validations

Verifications and validations should cover the entire design infrastructure of a product, including experimental

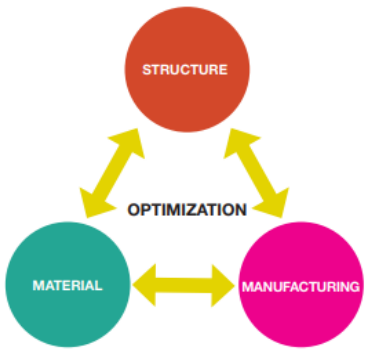


Fig. 5. Optimizations goals.

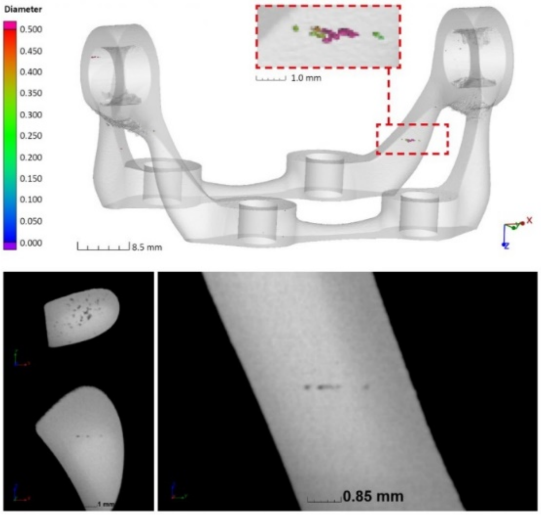


Fig. 6. Internal defects of additive parts.

methods and measuring instruments. A widely accepted framework of verifications and validations must be fully established with standards, procedures, and protocols. The framework thus defined requires verification and validation tools and is not only as guidance but also as a requirement for all simulations, thus encoded in the modeling and simulation processes so that only validated models/methods will be used to make predictions [30].

The result will be that state-of-the-art aerospace structures will be designed, validated, manufactured, and certified in less time (Fig. 6).

7. CONCLUSIONS

From the analysis of the current research in the field and the development plans proposed by the space agencies, important conclusions are drawn as follows.

Since 2003, when the Cube Sat concept was introduced, many small satellites have been developed that have had research missions or various services and experiments in orbit. In recent years, there has been a significant increase in the number of commercial tasks, and developers have turned to satellite constellations to offer services on a global scale.

Developers focus on nano-class technologies, which provide the best cost-performance ratio. They are launched into low orbits, effectively covering the whole Earth.

Currently, the development of a small satellite takes about one year. Even if they are not equipped with the "classic" systems found on large satellites, they are very flexible.

NASA and ESA present areas of interest that are intended to be studied for the development of innovative technologies and cost reductions of current technologies. For these, funding is also provided for the various projects proposed by the agencies.

In the mechanical field, the aim is to develop and integrate a PLM (Product Life Management) system. The development of methodologies and standards valid throughout the aerospace industry can lead to the achievement of this goal.

Even if an integrated software system does not exist on the market now, the development of the products can be integrated using various methods approved in the aerospace field.

In order to develop new concepts/products, users must consider the standards and methodologies applicable for each stage of development. The CAD models must be connected or synchronized with the CAE and/or CAM models. The capabilities of advanced software allow optimization of the highest levels. In the quality domain, the system must ensure that the piece obtained is the desired one, with the characteristics and properties designed. Even if software solutions are not always available, many regulations, standards, and concepts must be applied to obtain a part qualified for use in space.

Nano-sized satellites present the most developed category of small satellites. They provide an ideal ratio between the practical volume, size of the components, and cost of launching, service life, and other factors influencing a mission. Using advanced conception techniques, satellites and details can be developed to meet all the requirements, thus leading to a successful mission.

As technology advances and becomes more compact, the capabilities of small spacecraft are significantly enhanced. This evolution has diversified the standard framework, now encompassing larger CubeSats dimensions and can include configurations as large as 16U. The increased volume of these advanced CubeSat platforms allows for a greater installation of solar panels and more options for subsystem layouts. Small size satellites sector is innovating beyond conventional boundaries to fully utilize spacecraft volume and engineer increasingly sophisticated future missions.

Although the classic CubeSat design still prevails, there is a growing trend towards new enhanced models. The proliferation of new launch options, whit services like rideshares, hosted payloads and dedicated launchers, is revolutionizing the industry. Currently launching a bigger then 12U Card-Sat is a challenge, further development is needed towards 12U, 16U and even 27U sizes, using advanced methodologies and techniques, as presented in earlier chapters.

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