Nano/Pico/Femto-Satellites: Review of Challenges in Space Education and Science Integration towards Disruptive Technology

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Abstract—**This paper reviews the mini/nano /femto-satellites. The aim of this paper is to increase the awareness and interests of the students from the University of Montenegro in a space related research and technology development. This paper adds value to research where the main objectives of the study are: to identify the evolution path and origin of the dramatic changes of the architecture concept towards shrinking the size and mass of satellites; to explore the nature of improvements and benefits they allow to integration of sciences (such as biology and genetic research in space); to summarize the benefits associated with the accelerated maturity of CubeSat and to emphasize disruptive feature if CubeSats.**

Keywords-CubeSat, nanosatellites, disruptive technology, proof-of-concept, technology reediness assessment

I. INTRODUCTION

There is an on-going paradigm shift occurring in the satellite industry that may be compared to events dating back more than three decades to when personal computers disrupted mainframe computing. Small spacecraft, and their most popular sub-classification, CubeSats, hold tremendous utility and potential, not only in the commercial realm, but also by innovating established space programs through the use of CubeSats for research and technology development and demonstration. The questions are what disruptive technologies were born in university-class satellites and are student-built spacecrafts valuable because they provide technological innovation or because of the student training opportunities? Another intriguing question whether CubeSat reached its own technology maturity spontaneously or it was silently fostered by NASA's vision that was partially impacted by Near Earth Object mission's delay. Whatever we synthesize as the answer one thing is true: CubeSat's CV, bibliography and "family tree" is impressive. Decade ago, some authors claimed that despite of claims and expectations of many of new participants that contributed to CubeSat "explosion", university satellites have not "disrupted" industry practice in favor of small spacecraft [1-2]. For instance, the author in [1] which was written in 2004 stated that there are three ways in which universities typically participate in space missions: 1) as a principal investigation for the science experiments on board for spacecraft; 2) as technology developers for further spacecraft components and 3) as spacecraft designers, integrators and operators for a complete (usually school-sponsored) mission. It was also claimed that "mission in third mentioned category have not revolutionized the space industry with a few notable exceptions" such as the Orbiting Picosatellite Automated Launcher (OPAL), whose mission began in 1994 at Stanford University and was launched in January 2000 on a Minotaur rocket as part of the JAWSAT mission. The reason for University-built spacecraft not being the disruptive technology is explained mainly due to lack of professional support and the fact that they are forced to be of low-capability, high-margin systems, followed by established design practices. However, there was interesting statement which we will recall here: "because of these obstacles university-class spacecraft poses the ability to become disruptive research platform, introducing technologies and practices to change both the small and large satellite industries" since university has "freedom to fail" [1]. In other words, the University due to its primary mission which is educational has power to rich higher if inspired with higher aspiration for own students without being judged if fail. Their primary mission (education) gives them greater tolerance for failure. The crafting knowledge through the experimental failure is not only inevitable but needed. However, a "freedom to fail" does not mean or imply that a university should pursue unreasonable projects. The significance of student–built spacecraft design and its beneficial outcomes are explored in [3-7]. It was stated that the cost of space mission and boom of commercialized satellites limited university research to exercise this freedom to pursue high-risk projects but as we will see the challenges posed by NASA to students brought the impressive amount of diverse space missions and emerging technologies.

During last decade CubeSat was subjected to accelerated maturity. This paper explores the CubeSat's maturity path and its impact on the way the science research is conducted today. The paper is organized as follows. A tendency of shrinking in mass and size of satellites is examined in Chapter 2. A brief architecture overview is given in Chapter 3 including brief introduction to femtosatellites. In Chapter 4 we examine the blossoming CubeSat maturity (used in technology readiness level or for verification and validation a proof of concept or offering its payload platform for biology and chemistry research). Chapter 4 is closed with final remarks.

II. THE NEW TRENDS: SHRINKING IN SIZE AND MASS

A clear tendency of shrinking in mass and size of satellites was observed in the last couple of years (see Figure 1 [8]).

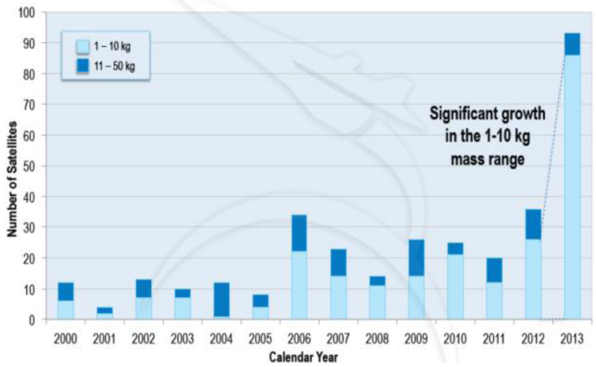

Figure 1. Distribution of satellite masses over periods: 2000-201 [8].

The main reason for miniaturizing satellites was to reduce the cost of deployment aiming for merging the terrestrial wireless network with satellite connections in low-orbit. Heavier satellites require larger rockets of greater cost to finance; smaller and lighter satellites require smaller and cheaper launch vehicles, and are often suitable for launch in multiples. But small satellites require technical challenges too: innovative propulsion, attitude control, and communication and computation systems. For instance, micro-/nano-satellites have to use electric propulsion, compressed gas, vaporizable liquids, such as butane or carbon dioxide, or other innovative propulsion systems that are simple, cheap and scalable. Micro-satellites can use radio-communication systems in the VHF, UHF, L-, S-, C- and X-band. On-board communication systems must be much smaller, and thus more up-to-date than what is used in conventional satellites, due to space constraints. Furthermore, miniature satellites usually lack the power supply and size required for conventional bulky radio transponders. Various compact innovative communication solutions have been proposed for small satellites, such as optical (laser) transceivers, antenna arrays and satellite-to-satellite data relay. Consequently, electronics need to be rigorously tested [9].

For better understanding of further reading, the meaning of terms such as femto/nano/micro-satellites are given in Table 1. The satellites are categorized/named according to their mass.

Table1: Satellite class according to their mass

Satellite Class	Mass Range
Femtosatellite	10 – 100 g
Picosatellite	< 1 kg
Nanosatellite	1 – 10 kg
Microsatellite	10 – 100 kg
Small Satellite	100 – 500 kg

A clear tendency of nanosatellite acceleration (its quantity, quality, diversity, multidisciplinarity) was reported too. Research [10] reflects a significant increase in the quantity of future nano/microsatellites needing a launch. The data source for that study was the SpaceWorks Satellite Launch Demand Database (LDDB). Nano/Microsatellite Trends by Purpose (1 – 50 kg) and predicted interpolation is shown in Figure 2. The civil sector remains strong, but the eruption of commercial companies and start-up activities was predicted to continue its influence on the nano/microsatellite market as shown in Figure 3. Applications for nano/microsatellites diversify significantly, with increase use in the future for Earth observation and remote sensing missions. Further, according to Survey in [10], 1U (1 kg) CubeSats, while still immensely popular, will comprise less of the market in the future (35% of future nanosatellites compared to 47% from 2009 to 2013), see Figures 4 and 5. Also, 25% of future nanosatellites (1-10 kg) are in the increasingly popular 6 kg mass class (compared to only 3% from 2009 to 2013). The type of CubeSat mission developer by launch year is displayed in Figure 6 [11], while Figure 7[11] shows mission status by launch year. Research on failure sources was summarized in Figure 8 that visualize the classified sources using pie chart. The authors of pie chart stated that 24 of the 30 failures in the no-contact or functional integration categories are university-led missions. Such failures were not assigned to obstacles such as system-level design, component-level design, and component-level assembly but to the system-level dysfunctional behavior, namely to the incompetently performed system-level functional tests.

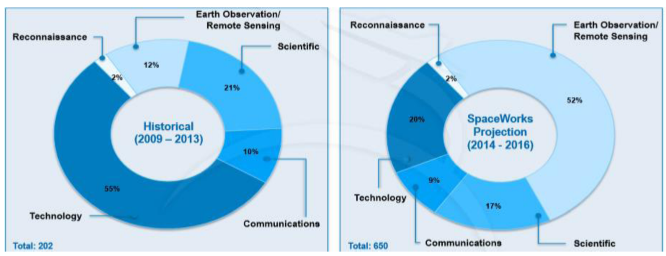

Figure 2. a) Nano/Microsatellite Trends by Purpose (1 – 50 kg) b) Predicted scenario) [10]

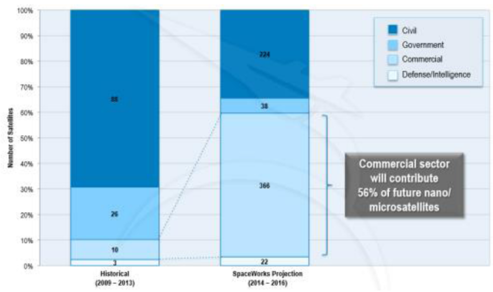

Figure 3. Nano/Microsatellite Trends by Sector (1 – 50 kg) [10]

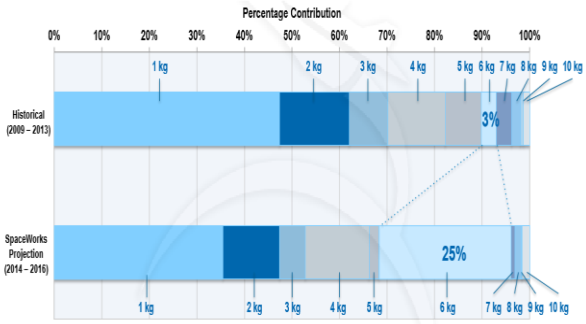

Figure 4. Percentage contribution of CubSats [10]

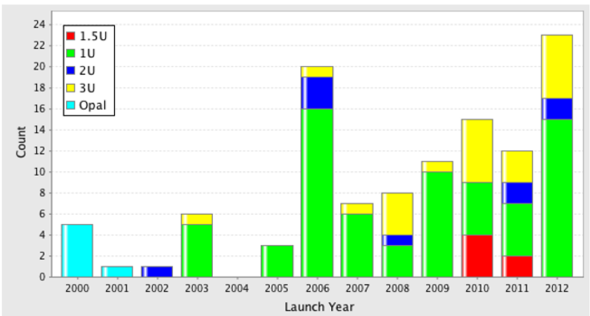

Figure 5. Number of CubeSas Launched of Each Form Factor per Year [11]

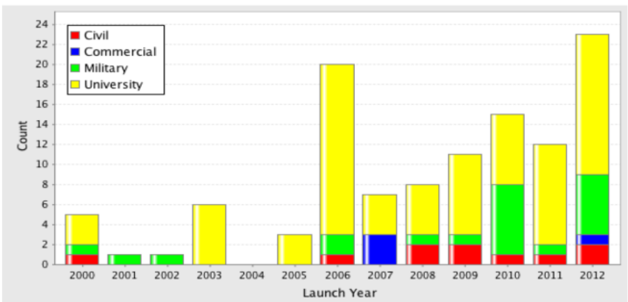

Figure 6. Type of CubeSat Mission Developer by Launch Year [11].

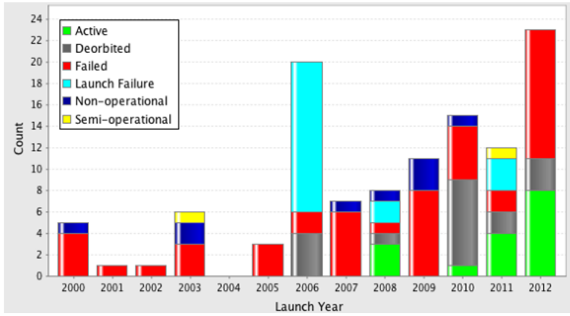

Figure 7. Mission Status by Launch Year [11].

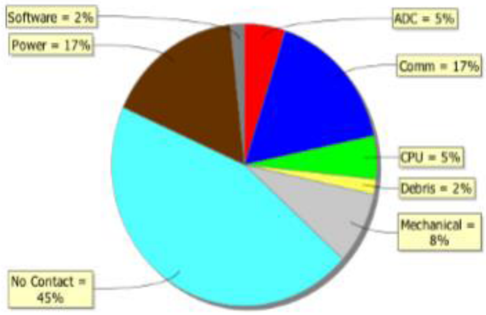

Figure 8. Causes for CubeSat Mission Failure, 2000-2012 [11].

III. CUBESAT: ARCHITECTURE DESIGN

The nanosatellites were mainly possible because of the state-of-the-art VLSI digital microelectronics which enable very sophisticated functions to be achieved without having the constraints of small mass, volume and power.

A CubeSat is a miniaturized satellite used primarily by universities for space exploration and research, typically in low Earth orbits (e.g. sun-synchronous) [12]. More precisely, the CubeSats belong to the genre of pico-satellites; their maximum weight lies on the borderline between pico- and nanosatellites. The design protocol specifies maximum outer dimensions equal to 10×10×10 cm3, i.e., a CubeSat occupies a volume up to 1 litre. CubeSats weigh no more than 1.0 kg, whereas their electronic equipment is made of Commercial Off-The-Shelf (COTS) components. The CubeSat as initially proposed did not set out to become a standard; rather, it became a standard over time by a process of emergence, and culminated in a very popular and standardized satellite concept. The break-through was the development of a standardized deployed system which consists of a container for a CubeSat (P-POD (see Figure 9).

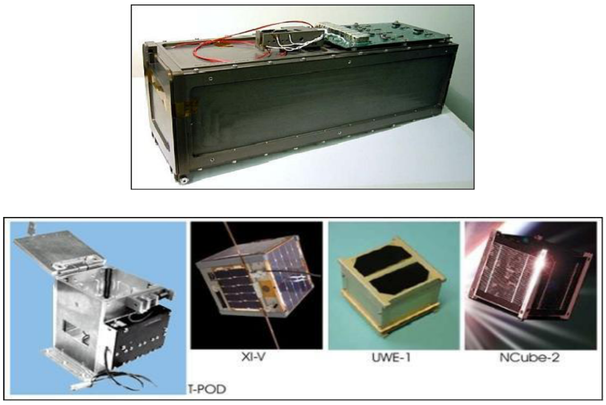

Figure 9. Top image: P-POD design of CalPoly'; Bottom image: T-POD (Tokyo Picosatellite Orbital Deployer):

The first CubeSats were launched in June 2003 on a Rockot launch vehicle. These days the CubeSat Initiative is a global congregation of universities and private companies from all over the world, trying to advance small satellite technology as tools for education and research. Fig. 10 [13] shows an example of CubeSat in 3D perspective.

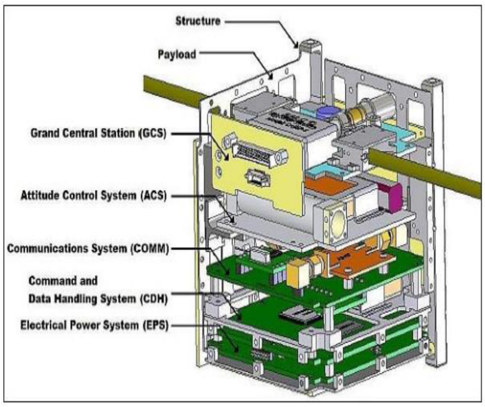

Figure 10. Schematic view of the E1P CubeSat architecture (image credit: MSU/SSEL). E1P-2 is a CubeSat mission of MSU/SSEL (Montana State University / Space Science and Engineering Laboratory), [13].

The requirements of Cubesat-class spacecrafts are significantly different from their ancestor's conventional satellites. The satellite's evolution is seen in integration of intelligence of satellite's subsystems [14]: "The goal of the integration of all the intelligences of the various satellite subsystems in only one intelligent subsystem is to minimize component expenditures while still providing the reliability necessary for mission success. Associating low cost ground terminals with a low cost Telecommunication CubeSat-class satellite will allow universities to access space communications with a very economical system". Thus, to design the Telecommunication CubeSat satellite, the adopted approach consisted in the integration of all the intelligences of the various satellite subsystems in only one intelligent subsystem is applied. This intelligent subsystem, Data Handling Subsystem, integrates the Telemetry/Telecommand functions, the Telecommunication payload as well as the active part of the thermal control subsystem. Importantly, the attitude control subsystem is designed completely with passive methods [14]; it does not have any programmed microcontroller to carry out an algorithm of attitude control and, on the other hand, it does not consume any electrical power provided by the power subsystem.

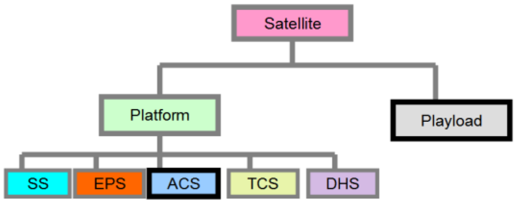

Figure 11. CubeSat architecture design (adapted from [14]

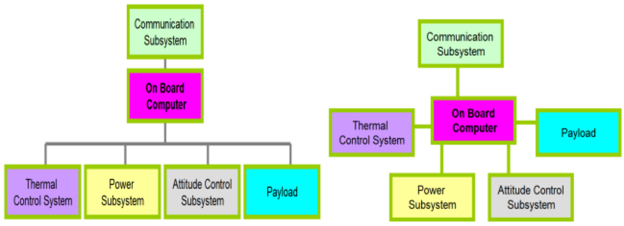

Figure 12. An example of a) bus architecture and b) star architecture (adapted from [14]).

Generally, the satellite consists of two principal parts, namely: the payload and the platform. The payload is defined by the satellite mission. This payload can not function correctly in the space environment without platform. The platform is made up of several subsystems; each one has its own role. Recently limited orbit control using micro-propulsion, S-band instead of VHF/UHF and wireless data transfer inside the CubeSat started to be in use [14]. The S band is part of the microwave band of the electromagnetic spectrum. It is defined by an IEEE standard for radio waves with frequencies that range from 2 to 4 GHz, crossing the conventional boundary between UHF and SHF at 3.0 GHz. The general block diagram of CubeSat architecture design is illustrated in Figure 11 [14]: payload on platform in the first level, and subsystems of platform: the structural subsystem (SS), the power subsystem (PS);the thermal control subsystem (TCS); the attitude control subsystem (ACS); the data handling subsystem (DHS). The telemetry is essential for communication with the spacecraft on a ground. The on-board computer is the heart of the system. It monitors sensors, interpret commands, send data to ground, switch on or off subsystems based on remote commands or programmed options, adjust heating etc, The attitude control system allows maintain defined orientation of spacecraft. As already said, the Data Handling Subsystem modules include communication subsystem and on board computer which controls the satellite subsystems. But how these subsystems are attached to the onboard computer, two principal architectures are distinguished: bus architecture illustrated in Figure 12.a [14] and star architecture illustrated in Figure 12.b [14].

The minimization of nanosatellites was soon seen in PocketQub [15]. It is a new satellite standard that was proposed in 2009 by Professor Robert Twiggs for a satellite even smaller than the CubeSat. PocketQubs are 5 cm cubes and can literally fit in a pocket. The PocketQub™ leverages the CubeSat standard and also leverages the revolution in the miniaturization of electronics. PocketQub™s will ultimately have a wide range of applications including: Network Nodes, Sensor Systems, Satellite Constellations, Inexpensive, Redundant and Spatially. Further shrinking in size brought the satellite-on-a-chip (SpaceChip) and satellite-on-a-printed circuit board (PCBSat). [16, 17]. Figure 13 presents the satellite Space-on-a-chip design [17]. SpaceChip was designed using Space Mission Analysis and Design (SMAD) Principles [18]. A Small sensor such as the Miniature Electrostatic Analyzer (MESA) was used.

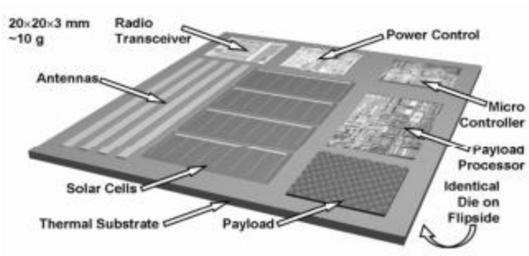

Figure 13. Example of SpaceChip [17].

IV. CUBESATS AS TECHNOLOGY DEMONSTRATION PLATFORMS, SWARM CONSTELLATION AND LAB ON CHIPS IN SPACE: FINAL REMARKS

What we see now is an emerging and rapidly growing launch market of Nanosatellites. Small can also mean affordable and rapidly transformative. A 330% increase in nanosatellite (1- 10 kg) delivers in 2013 compared to 2012 clearly confirm it. Furthermore, in 2014 it was predicted that half of future nanosatellites will be used for Earth observation and remote sensing. Studying the achievements of this radically disruptive technology and its growing path from being born for educational purpose but becoming a serious player in NASA technology readiness assessment we see that fate of nanosatellites went the most diverse path that one technology have had in the past. Nanosatellites radically evolved to be serious players *in sity* and *in sity* measurements and in *in sity* discovery and characterization of near Earth objects (NEO) that are objects that orbit the Sun and approaches or crosses the Earth orbit. NEO studies are motivated by several reasons and concerns, including scientific research, planetary protection, environmental studies and exploration. NEOs are believed to be remnants from early evolution of the solar system and hence studies of their pervading dynamics and chemical composition (mostly over ubiquity architecture of femtosatellites that are distributed through the space and attached to mothership CubeSat) may offer important information about conditions at that early epoch. Thus nanosatellites becoming crucial players in Planetary and Interplanetary research projects providing crucial technology tools and laboratory on the chip for developing clues about property of matter under high pressure. Moreover planetary interiors and magnetospheres demonstrate the curious behavior of magnetic fluids and plasmas. Thus *in sity* studies (only enabled through distributed and disseminated minimized technologies such as femtosatellite) of comets and other small outer solar systems objects will permit analyses of the best presented samples of premature matter. For this, challenge is to deliver more advanced thruster and propulsion technologies and scale it in order to be incorporated on system on chip. Another vision of CubeSats such as 'see further, rich higher' is visible in moving CubeSats from being deployed in Low Earth Orbit (LOE) to beyond LEO. What we emphasized up to here is mostly related to capabilities of CubeSats for Earth and space observations. But that is just one part of CubeSat's transformable fate and diverse applicability enabled by adaptable personality of CubeSats. What we see now is that 'Contemporary' CubeSat becoming serious players in validation and verification of proof of emerging concepts and emerging technologies (aiming for Mars, Moon and Venus research) in NASA's technology readiness assessments at technology readiness level (TRL). Beside Technology Development projects and NASA's NEO project it was demonstrated through student driven space programs and University-class satellite projects that even more minimized version of nanosatellites may play crucial role in measurements of ubiquity of biological evolution. Presumably, living organisms arose out of an organic, prebiotic preceded by an interval of chemical evolution which lead more or less continuously into biological evolution. Thus, it is strongly believed that, for instance, Mars have had prebiotic chemical species, leaving evidences of life we can still collect now. Hundreds of femtosaellites (with sensors for a certain chemical elements or some more advanced hybrid version that communicate to mothership CubeSat) can efficiently collect information about widespread biological evolution which still is in cosmos. In particular, such ubiquity architecture of swarm femtosatellites might become the biggest player in study to which extension special terrestrial conditions was involved in prebiotic chemical evolution which further was subjected to more radical biological evolution. What is missing at present is the grasping the wholeness of science (biology, chemistry, physics), namely the understanding of science wholeness through ubiquity of biological evolution that might enable link between biological life we see on Earth with biological life in space in the form of chemical prebiotic medium. Exobiology, astrobiology and solar ecology can be well emulated into a new transcendental discipline blowing away subject discipline boarders and bringing a new insight into origin of life.

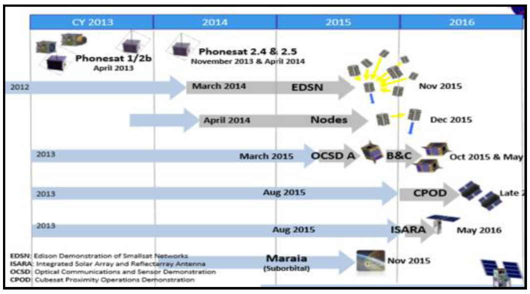

Figure 14. Summary of the small spacecraft technology – flight demonstrations [8]

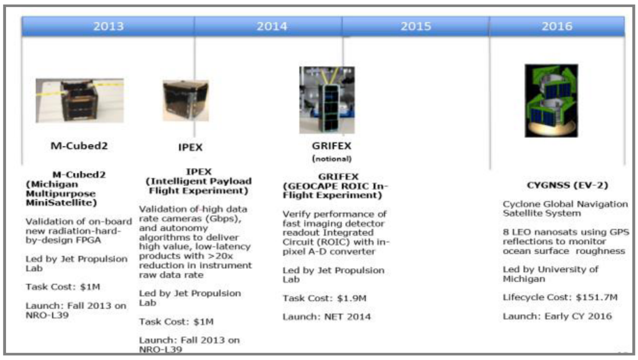

Figure 15. Chosen CubeSat missions for research science [8]

To summarize, there is no technology that had such diverse maturity growing path as was seen in the case of CubeSat. This is well seen through objectives of Small Spacecraft Technology Programs: to develop and demonstrate new small spacecraft technology and capabilities for NASA's mission in science, exploration and space operation; to promote the small spacecraft approaches as a paradigm shift for NASA and larger space community (technology development projects in communication, instrumentation, manufacturing; flight demonstrating projects in radio and laser communications, low cost satellite buses, smallest swarms for space science missions). In order to support what said we refer to Figure 14 and Figure 15. Figure 14 visually summarizes the small spacecraft technology –flight demonstrations, while Figure 15 gives impression about CubeSat involvement into validation and verification of proof-of-concepts.

This research confirms that CubeSat becomes disruptive technology that create agile and disruptive business economy models. CubeSats went similar path as digital technology did (form education and connective purpose to disruptive and agile economy). To some extension CubeSats share similar fate with Arduino and Raspberry pi ('openly sourced'): amusement and fascination of students and artists, knowledge sharing and open access to space, harvesting the collective intelligence through the collective awareness and responsibility and becoming the place where art meet science, technology meets science, human awareness meets the responsibility and biology life we know on Earth meets the organic-prebiotic medium but in chemical form in space.

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