Acta Astronautica 67 (2010) 854–862

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Survey of worldwide pico- and nanosatellite missions, distributions and subsystem technology ☆

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ARTICLE INFO

Article history:
Received 19 January 2010
Received in revised form
21 May 2010
Accepted 5 June 2010
Available online 23 June 2010

Keywords:
Picosatellites
Nanosatellite
CubeSat
Small satellite mission
Small satellite technology

ABSTRACT

This paper provides the results of a global survey of publicly known pico- and nanosatellite projects. The standard of CubeSats has boosted the development of nanosatellites by the end of the twentieth century and the total amount of projects has grown to about a hundred projects worldwide until August 2009. Pico- and nanosatellites can in general be distinguished from satellites with bigger mass ranges by their relatively short development time, low cost and usage of the latest technologies. To obtain a better understanding of the current technology level and applications of nanosatellites and to spot trends in the global development and growth of such projects, a survey is performed including almost all launched pico- and nanosatellites. A key finding is that most subsystem technologies used are rather advanced, except for the attitude control systems and performance characteristics of subsystems that depend on attitude control. Education and technology demonstration remain the most dominant mission objectives, although some scientific experiments have already been conducted.

1. Introduction

A survey of worldwide launched pico- and nanosatellites and the performance characteristics of their subsystems has been conducted. The satellites used in this survey have the following characteristics:

- The satellite mass is between 0.1 and 1.0 kg (picosatellites) or 1.0 and 10.0 kg (nanosatellites).
- The satellite is active, yielding at least an electrical power system and a radio.
- The satellite flies autonomously in orbit.
- The satellite has been launched or has been destroyed in a launch failure.

In this paper the terminology 'pico- and nanosatellites' is used for satellites with the above characteristics.

The data used for this survey has been put in a database and originates from a variety of sources, including papers [1–8], technical design reports [9,10], several (online) databases [11,12] and project websites. The SCALES, a small satellite database developed by Delft University of Technology, is used as a major data source in this survey [13]. Although not all details could be found or verified, a total of 94 satellites are used for statistical analysis and probably yields a complete overview of launched pico- and nanosatellites within the given constraints. For subsystem technology assessment, unknown data is discarded in the statistics.

In Section 2, the pico- and nanosatellite missions and their distributions are investigated. Section 3 provides statistics and analysis on key subsystem specifications. In Section 4, the general status of nanosatellite projects is summarized and an outlook is provided.

☆ This paper was presented during the 60th IAC in Daejeon.

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doi:10.1016/j.actaastro.2010.06.004

2. Pico- and nanosatellite missions and distributions

The first nanosatellite mission was the Vanguard TV3 [14], unsuccessfully launched on 6 December 1957, only a few months after the launch of the first artificial satellite Sputnik-1. The latest satellites used in this survey are AggieSat-2 [15] and BEVO-1 [12], launched on 30 July 2009.

In Fig. 1, the number of launched pico- and nanosatellites per year is presented. It shows that nanosatellites were launched in the early days of spaceflight (1957–1962) and pico- and nanosatellites where launched in the past decade since 1997 with total absence between 1963 and 1996. In the early days of spaceflight, nanosatellites were part of the Vanguard, Pilot and Pioneer programs and there were also two radio amateur satellites called OSCAR-1 and OSCAR-2 [11]. The reason for the small mass of these satellites was mainly due to the limited payload capabilities of the launch vehicles. All satellites were simple satellites and once the launch vehicles became capable of launching larger satellites, satellites became larger and more advanced as well. It is plausible to think that in the decades to follow there was no apparent need for simple satellites like in the first years of spaceflight. Advanced satellite technology was too big to integrate in a very small satellite. However, in the late nineties this changed due to the availability of low power micro-electronics, providing a potential for a high performance over mass ratio. In 1999, the CubeSat standard was introduced by California Polytechnic State University and Stanford University [16], which boosted the number of developed pico- and nanosatellites enormously, especially amongst universities. As of 1 September 2009, a total of 94 active pico- and nanosatellites have been launched.

More than half of the pico- and nanosatellites were built with an educational objective: university-class satellite projects (Fig. 2). Out of a total amount of 118 university-class satellites [17], 49 are pico- and nanosatellites. This means that there is a strong correlation between pico- and nanosatellites and universities, but this is not predominant. Technology demonstration is the most common objective (Fig. 2) for pico- and nanosatellites, although only 14% of the missions are technology demonstration only. Operational use, like scientific measurements or radio communications, is also an objective of more than half of the pico- and nanosatellite missions. However, it has to be noted that the scientific measurements are often very limited compared to large scientific satellites. Of the satellites with radio communication as operational objective, this is always for radio amateur hobbies or experiments and the performance is not comparable to commercial communication satellites.

The geographical distribution of pico- and nanosatellite developers (Fig. 3) clearly shows that the United States of America is one of the greatest actors in the field of pico- and nanosatellites. For the rest, the geographical distribution does not clearly correlate with the distribution of national space budgets.

The target mission duration of the satellites is unknown for more than half of the 94 pico- and nanosatellites, especially for the educational satellites, but for the known pico- and nanosatellites they vary from a few days up to five years. The average intentional mission duration is about eight months, showing that most pico- and nanosatellites are build for a relatively short lifetime.

The success rates of pico- and nanosatellites are somewhat disappointing (Fig. 4). More than one third is destroyed due to launch failure. However, this figure is highly influenced to the risky early satellite programs like Vanguard and Pioneer and the catastrophic launch of a Dnepr rocket on 26 July 2006 with 15 (!) pico- and nanosatellites onboard [12]. Only considering mission success rates for successfully launched nanosatellites, one could still notice a relatively high amount of failures.

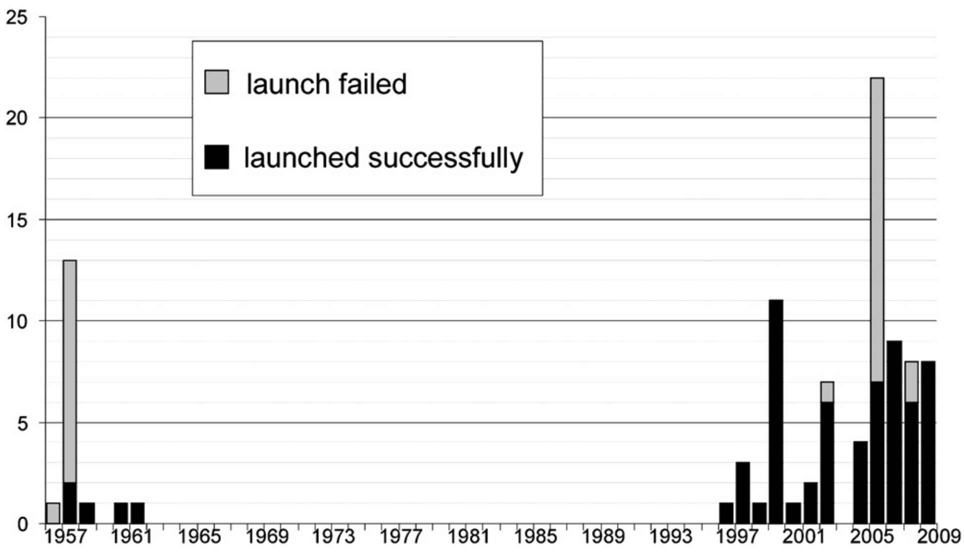

Fig. 1. Launched nanosatellites over time.

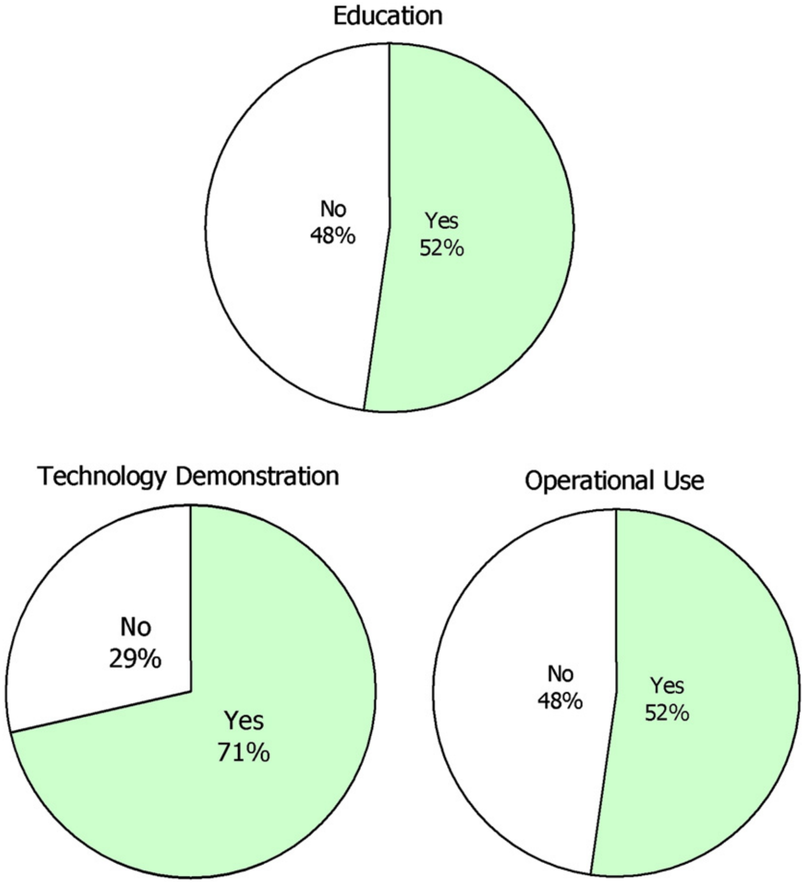

Fig. 2. Distribution of pico- and nanosatellite mission objectives.

Unknown pico- and nanosatellite success rates have a high chance that they should also count as failures, since the project websites are only maintained up to the launch and failures are not easily exposed to public.

Most of the pico- and nanosatellites are launched from the USA (41), followed closely by Russia/Kazakhstan (39). Furthermore, there have been launches from India (6), Japan (4), China (1) and Brazil (1). This shows a more close correlation with the national space budgets compared to the countries of pico- and nanosatellite developers as discussed in Section 2, which can be explained by the fact that there are no dedicated launch vehicles for very small payloads.

There have been 42 distinct launches equipped with pico- and nanosatellites. Since 1997 there have been only 25 launches for 77 satellites, yielding an average a little above three pico- and nanosatellites per launch. It must be noted that since 1997 pico- and nanosatellites were always secondary or tertiary payloads along one or more satellites of much larger classes, while in the years before 1962 the launches were almost always single satellite launches.

All pico- and nanosatellites were launched into a target low Earth orbit, except for the Pioneer satellites (heliocentric orbit) and the Pilot satellites (Medium Earth Orbit). A Sun synchronous orbit is the most popular orbit used by 42 satellites. For the rest, most orbits are near circular, near polar orbits, although some elliptical orbits and low inclined orbits have also been reported.

3. Pico- and nanosatellite subsystem technologies

3.1. Electrical power supply

About three-quarters of all pico- and nanosatellites are equipped with solar cells (Fig. 5). From 1997 this is even 85%, thus there are still some pico- and nanosatellites which run on batteries as electrical power supply only. Gallium Arsenide (GaAs) solar cells are used the most since they provide a very high conversion efficiency up to 30% and are widely available. Silicon solar cells are also used, even in recent pico- and nanosatellites. Although they have lower efficiencies, the cost of such cells is very low compared to the GaAs cells.

About 16% of the satellites have deployable solar panels, all others which do have solar panels have them body mounted. In this case the size of the structure is limiting the area of the solar array significantly.

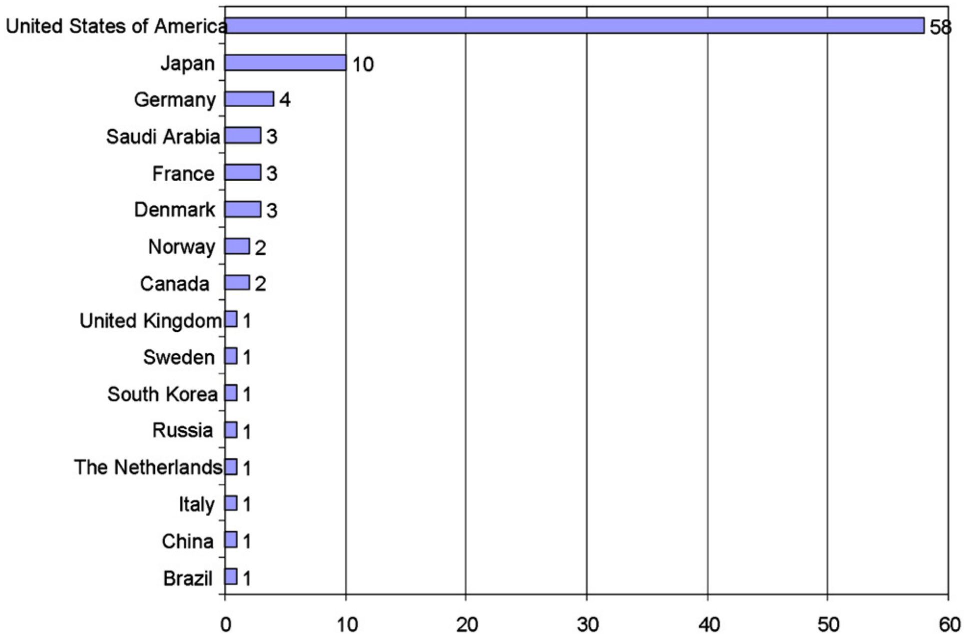

Fig. 3. Geographical distribution of pico- and nanosatellite developers.

The average power available ranges from ten milli-Watts to seven Watts. For 43 pico- and nanosatellites, the available bus power could be divided by the total mass of the satellite, which is presented in Fig. 6. What can be noticed is that the average specific power increases when the mass of the satellite becomes lower. This can be logically explained by the fact that the mass of the satellite is related to the volume (third power), while the effective area of body mounted solar cells is related to the area of the sides of the satellite (second power). One outlier can be noticed, which is StenSat [18]. This is one of the smallest satellites, but is very flat with a relatively large solar cell area combined with sun pointing.

The conversion method of raw available power from the solar cells to power on the spacecraft bus is Direct Energy Transfer (DET) or Peak Power Tracking (PPT) for most pico- and nanosatellites. The DET method takes the power at a predetermined voltage point on the current–voltage (IV) characteristic of the solar cells and shunts excessive power. This is a very simple and reliable method, but because the IV-curve shifts with temperature and degradation of the solar cells, the point should always be taken with a margin from the maximum power point. The PPT method just follows the IV-curve from the open-circuit voltage with DC-DC convertors, but can lead to problems if there is a too large instantaneous current surge. The maximum power point tracking (MPPT) is the most elegant method, since it will retrieve the maximum power from the solar cells. Excessive power can be easily measured and either shunted or used advantageously. Due to the increased complexity of the MPPT method, only 7% of the pico- and nanosatellites are using this.

The satellites with non-rechargeable batteries used Mercury batteries in the early pico- and nanosatellites and Lithium batteries for pico- and nanosatellites in the last decade (Fig. 5). Most satellites with solar cells have rechargeable batteries of Lithium-ion or Lithium-polymer type, although some use Nickel–Cadmium or Lithium–Chloride batteries. Delfi-C^3 [8] is the only nanosatellite known which does not have any battery at all.

3.2. Attitude and orbit determination and control

Almost 40% of the pico- and nanosatellites have active attitude control whereas a same amount has passive control, mostly by means of magnetic material (Fig. 7). A little more than 20% does not have any attitude control at all, leaving the satellites tumbling free in space.

The function of most attitude control systems in pico- and nanosatellites is simple rotational damping to limit the rotation rate of the satellite. This is important for a reliable power generation and communications (Fig. 8). About 15% of the pico- and nanosatellites use the attitude control to point in instrument. This is mainly nadir pointing of a camera or pointing of a radiation detector along the magnetic field lines. The used control for this is currently very simple compared to larger satellites and one should not expect more than just a rough pointing of the instrument.

Very few pico- and nanosatellites have attitude control for pointing a solar array or to perform ground station tracking. These types of control are always more difficult to obtain than the ones stated above, since they require at least two axis active control.

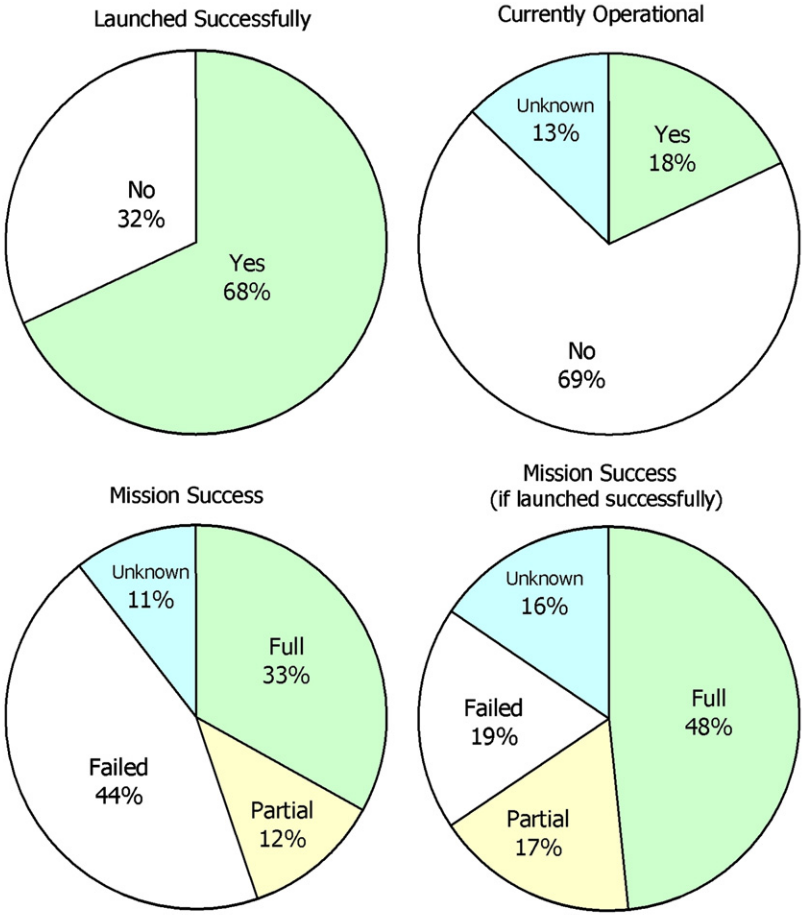

Fig. 4. Success rates of pico- and nanosatellites.

The most common used sensors are sun sensors and magnetometers (Fig. 9). Earth sensors and gyros are also used, but one should consider the few star trackers/sensors not to be real high accuracy sensors so far.

Magnetic control, either passive or active, is very popular in pico- and nanosatellites (Fig. 10). Since almost all pico- and nanosatellites operate in LEO (Section 2), magnetic control is a simple and effective means of attitude control. Spin-stabilization and a gravity gradient boom are also simple but effective means of attaining static attitude. Momentum wheels, reaction wheels and thrusters are actuators which are suitable for more precise and dynamic control, but still remain scarce among pico- and nanosatellites.

It is difficult to obtain and compare accuracies and reliability figures of attitude control systems, but in general it can be stated that attitude control in pico- and nanosatellites is still in an early development phase and does not yet allow for precise remote sensing or ground station tracking.

About 16% of the pico- and nanosatellites are equipped with a GPS receiver, thereby having a direct means of onboard navigation. Only eight pico- and nanosatellites (9%) are equipped with means of orbit control, five of them with cold gas propulsion, one with electric propulsion, one with chemical propulsion and one with a solar sail.

3.3. Communication

Most pico- and nanosatellites have a downlink frequency in the UHF band (Fig. 11) and transmit their data with a digital form of modulation. Typical data rates are between 1200 and 9600 bps, but higher rates up to 80 kbps are seen as well. The VHF band and S-band are also used (sometimes as secondary downlink frequency). VHF limits practical data rates (<9600 bps), while on the S-band high data rates up to 256 kpbs are used.

The uplink frequencies show a similar distribution, but S-band is scarce. Also data rates are limited, possibly due to the fact that uplinks are mostly used for short commands rather than large data packets.

It can be stated that communication capabilities between pico- and nanosatellites and the ground are mostly limited due to the link budget rather than the radio technology, since micro-electronics for high data rates are widely available and are applied in the systems, but available power is scarce and the potential of ground

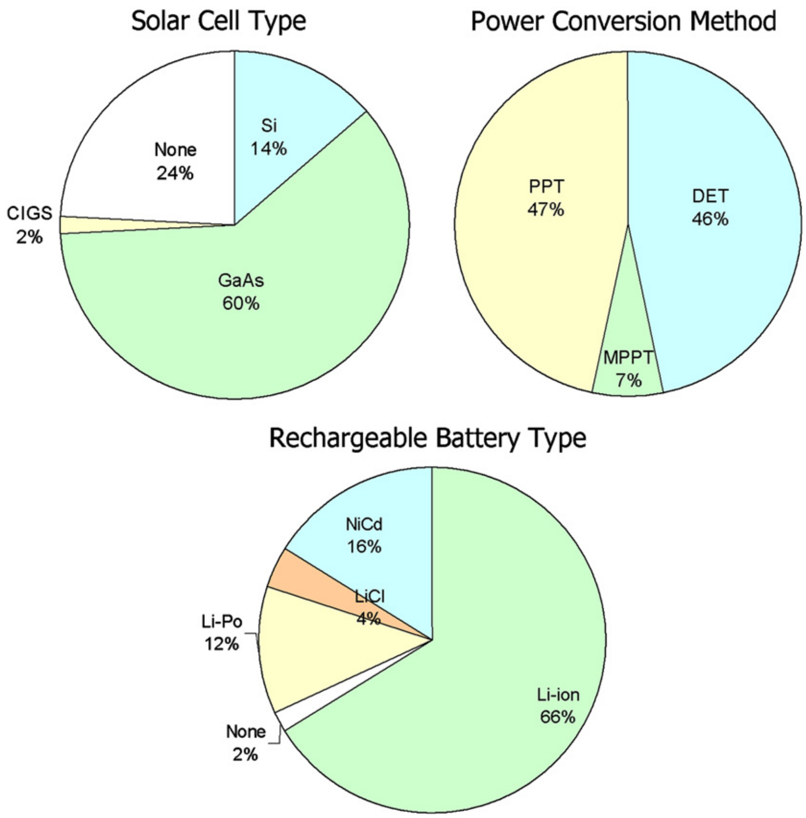

Fig. 5. Solar cell type, electrical power conversion method and battery type.

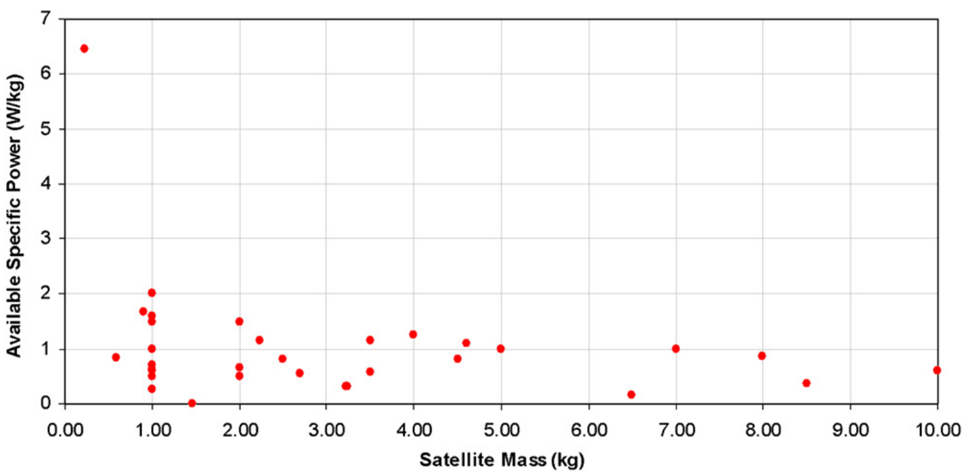

Fig. 6. Available bus power with respect to satellite mass.

station tracking with high gain antennas is limited by the performance of dynamic attitude control system (Section 3.2).

3.4. Command and data handling

Since the late nineties, low power microcontrollers have gradually become available. Their processing performance is similar or even better than most of the outdated but space qualified processors used in satellites and their power consumption is only in the order of milli-Watts. The downside of those processors is their high susceptibility to particle radiation in space. The risks are sometimes tackled by redundancy on different components and a distributed command and data handling architecture with multiple microprocessors spread across the satellite.

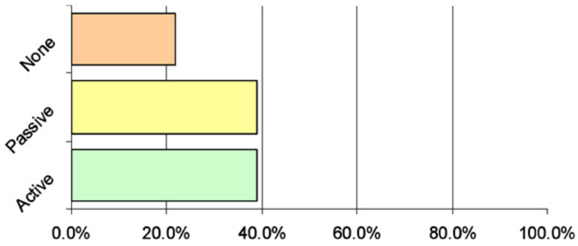

Fig. 7. Pico- and nanosatellite attitude control.

Popular microprocessors are peripheral interface controllers (PICs) from Microchip and mixed signal processors (MSPs) from Texas Instruments. Advanced RISC machines (ARMs) from various suppliers are also becoming popular due to their higher processing power capabilities over the other microprocessors.

The satellites which use a distributed command and data handling system mostly use the I^2C data protocol for communication between the microcontrollers. USB and CAN are also used a few times, but are less popular. A reason could be the fact that these protocols require significant power with

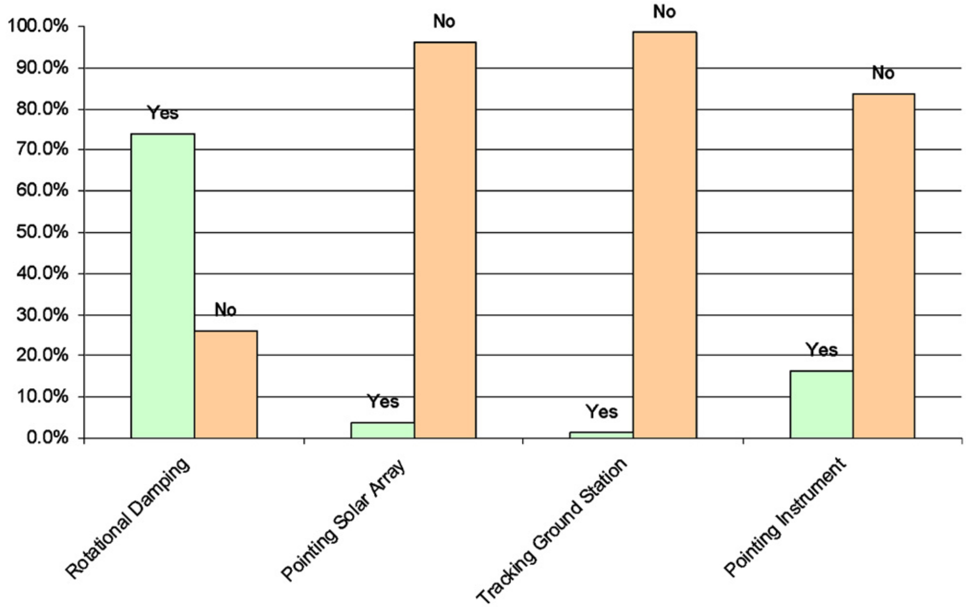

Fig. 8. Attitude control objectives.

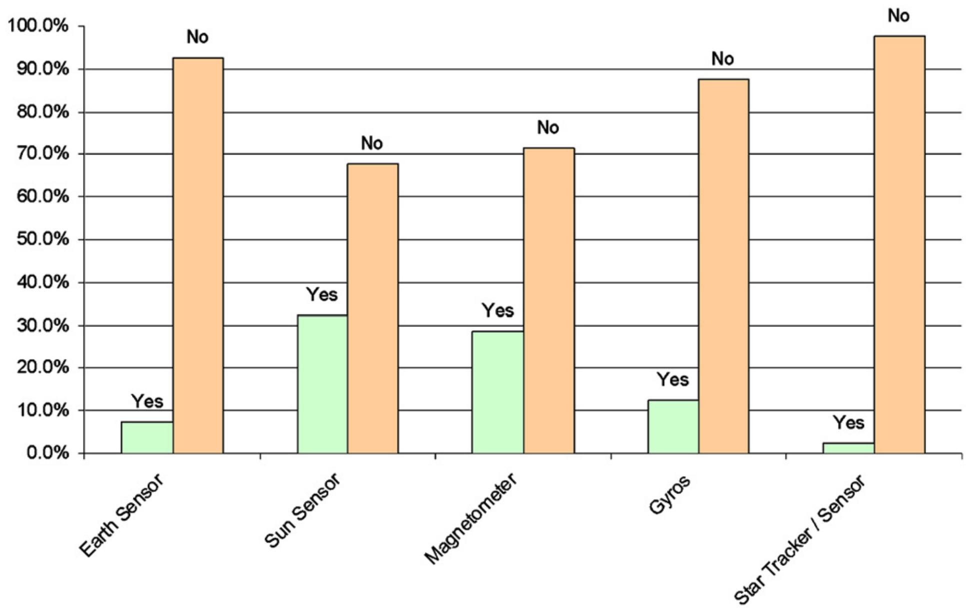

Fig. 9. Onboard attitude sensors.

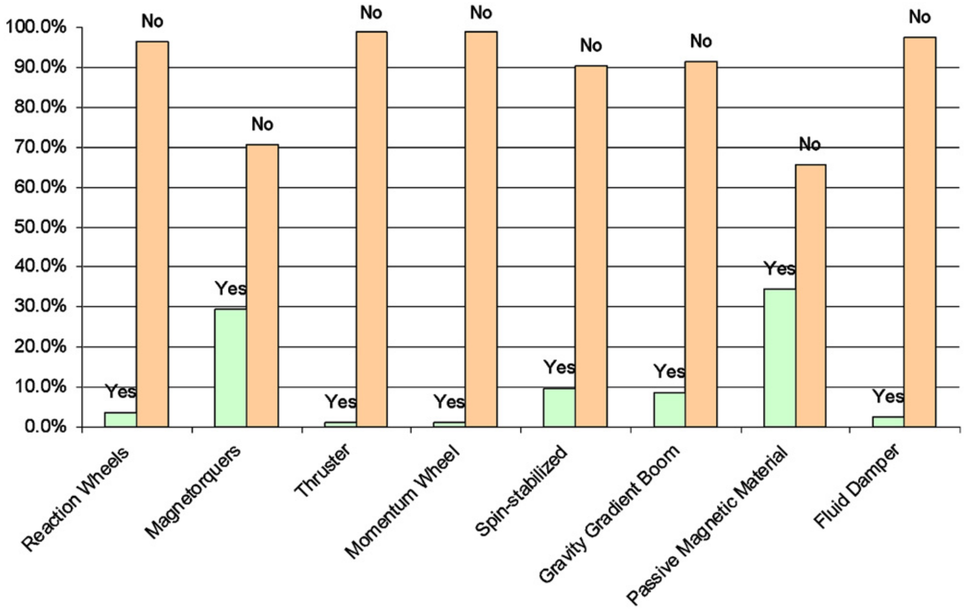

Fig. 10. Onboard attitude actuators or stabilizers.

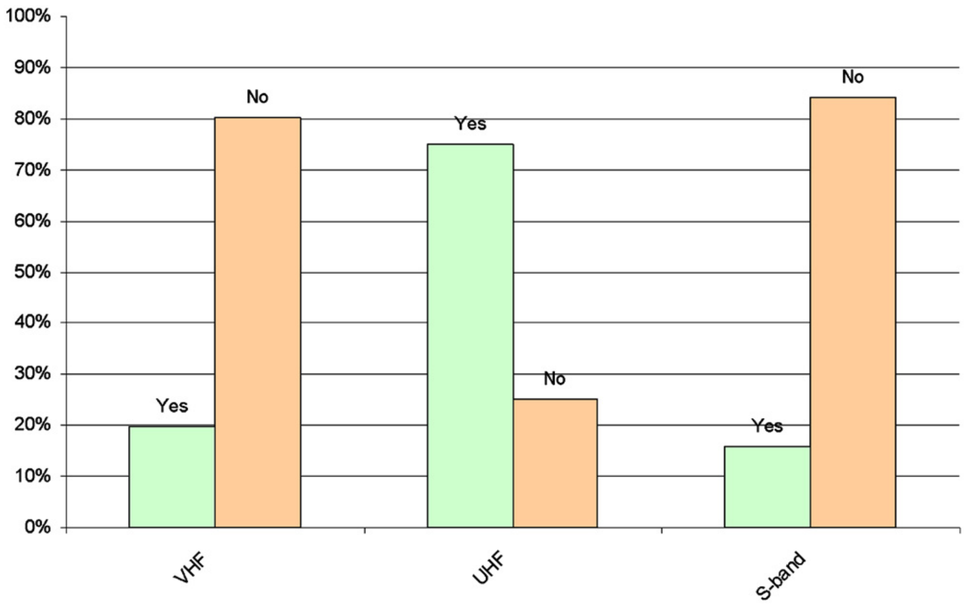

Fig. 11. Used downlink frequency bands.

respect to the total available power and require extra electronics for most microcontrollers, while I^{2}C support is already integrated in most microprocessors and consumes an insignificant amount of power [19].

3.5. Structure

Almost half of all pico- and nanosatellites launched have been in the CubeSat form factor (Fig. 12) with the single unit (1U) CubeSat being the most popular one. Only considering pico- and nanosatellites since the introduction of CubeSats, even 76% of all pico- and nanosatellites have been CubeSats. The popularity of this form factor comes due to the fact that CubeSat structures, subsystems and launch adaptors are commercially available and relatively inexpensive, yielding a low threshold for starting a CubeSat project.

All other pico- and nanosatellites have different non-standardized structural forms (Fig. 12).

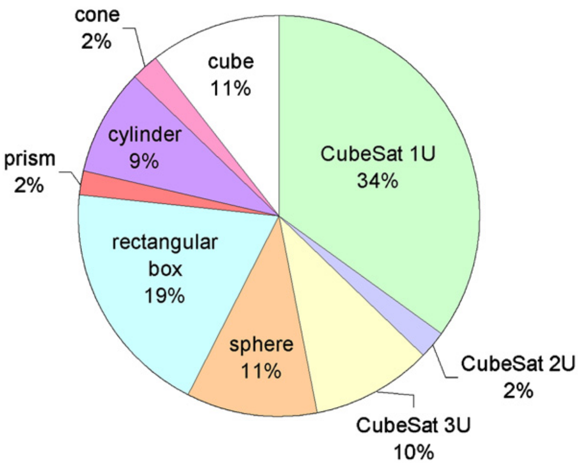

Fig. 12. Form (factor) of pico- and nanosatellites.

4. Conclusion and discussion

Pico- and nanosatellites, especially CubeSats, have become popular in the past decade and the amount of developers and projects is increasing. They are not only built by universities but also larger space organizations like NASA, Boeing and The Aerospace Corporation.

Technologies in the field of command and data handling and electrical power systems are quite advanced. The bottleneck for pico- and nanosatellites remains the attitude control performance, especially in terms of dynamic control and control accuracies. Communication is mostly limited by available power and antenna gain rather than the technical developments on that system itself, thus attitude control is indirectly limiting satellite-ground communication data rates.

Besides educational objectives, which can easily be met if students are working on the projects, technology demonstration objectives are very attractive and successful. In terms of operational missions, there is still a large gap between pico- and nanosatellites and larger and more expensive satellite projects [20]. Some (niche) scientific measurements and other operational objectives have been performed, but it is questionable if these are of enough quality to be comparable with larger satellite missions.

It has been identified that formation flying is a great opportunity for pico- and nanosatellites [20,21], opening new opportunities for operational missions. Several pico- and nanosatellite formation missions have been planned to demonstrate the technology [22], but have not yet been launched.

Since the spacecraft bus systems of pico- and nanosatellites can likely be improved significantly and there is still a large gap between current technology and the theoretical limits [21], more research should be conducted on possibilities and limitations for scaling down subsystems and payloads to pico- and nanosatellite level.

Acknowledgement

The authors would like to thank Christina Aas and Barry Zandbergen for providing their SCALES tool, used for conceptual design of small satellites [13] which has been used as initial small satellite data source.

References

[1] J. Farkas, CPX: Design of a Standard Cubesat Software Bus, California State University, California, USA, 2005.
[2] L. Dusseau et al., CUBE SAT SACRED: a student project to investigate radiation effects, In: RADECS 2005 Proceedings, Cap d'Agde, France, 2005.
[3] B. Larsen, The Montana nanosatellite for science, engineering, and technology for the AFRL/NASA university nanosat program.
[4] H. Ashida, Design of Tokyo Tech Nano-Satellite Cute-1.7 + ADP II and its Operation, International Astronautical Congress, Glasgow, Scotland, 2008.
[5] M.Y. Ovchinnikov, Attitude dynamics of the first Russian nanosatellite TNS-0, Acta Astronautica 2007/06, Russia, 2007.
[6] W.H. Steyn, Y. Hashida, In-Orbit attitude performance of the 3-Axis stabilised SNAP-1 nanosatellite, in: Proceedings of the 15th AIAA/USU Conference on Small Satellites, Logan, USA, 2001.
[7] S. Ose, Attitude Determination for the Norwegian Student Satellite nCube, Norwegian University of Science and Technology, Trondheim, Norway, 2004.
[8] J. Bouwmeester et al., Mission Results and Project Evaluation of Delfi-C3, in: Proceedings of the 4S Symposium, Rhodes, Greece, 2008.
[9] Preisker, R. et al., Compass-1 Phase B Report, Fachhochschule Aachen, Aachen, Germany, 2004.
[10] N. Paruchuri, The KUhabs, KUbesat & KUTESat-1 Technical Report, Design of a modular platform for picosatellites, University of Kansas, Kansas, USA, 2006.
[11] AMSAT Satellite Status, 〈http://www.amsat.org/amsat-new/satellites/status.php〉, last data retrieved July 2009.
[12] Michael's List of CubeSat Satellite Missions, 〈http://mtech.dk/thomsen/space/cubesat.php〉, last data retrieved July 2009.
[13] C. Aas et al., SCALES—A system level tool for conceptual design of small satellites, in: Proceedings of the Seventh Annual Conference on Systems Engineering Research, Loughborough, UK, 2009.
[14] NASA, Vanguard TV3, 〈http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=VAGT3〉, retrieved July 2009.
[15] Texas A&M University, AggieSat 2, 〈http://aggiesat.org/AggieSat2〉, retrieved July 2009.
[16] H. Heidt, et al., CubeSat: A New generation of picosatellite for education and industry low-cost space experimentation, in: Proceedings of the 14th Annual/USU Conference on Small Satellites, Logan, USA, 2000.
[17] M. Swartwout, The promise of innovation from university space systems: are we meeting it?, in: Proceedings of the 23rd AIAA/USA Small Satellites Conference, Logan, USA, 2009.
[18] Stanford University, StenSat Satellite, 〈http://www.stensat.org/stensat/Stensat.htm〉, retrieved July 2009.
[19] S. de Jong et al., Improved Command and Data Handling System For the Delfi-n3Xt nanosatellite, in: Proceedings of the 59th International Astronautical Congress, Glasgow, Scotland 2008.
[20] I. Nann, S. Abbondanza, Nanosatellites: what can they really do?, in: Proceedings of the 4S Symposium, Rhodes, Greece, 2008.
[21] J. Bouwmeester et al., Advancing nanosatellite platforms: the Delfi program, in: Proceedings of the 59th International Astronautical Congress, Glasgow, Scotland 2008.
[22] N. G. Orr et al., Precision formation flight: the CanX-4 and CanX-5 dual nanosatellite mission, in: Proceedings of the 4S Symposium, Rhodes, Greece, 2008.