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Cubesats to pocketqubes

Opportunities and challenges

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CUBESATS TO POCKETQUBES: OPPORTUNITIES AND CHALLENGES

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Abstract
    In the last two decades, CubeSats have changed the perception of satellite missions aided by standardization and usage of commercial-off-the-shelf components. CubeSats have also proven the feasibility of low cost and short development time space missions. The PocketQube with a form factor of 5x5x5 cm has been proposed as the next class of spacecraft to benefit from miniaturization. This paper presents a comparison between the two standards and analyzes the impact of miniaturization on spacecraft design and performance. At satellite level, the reduction of volume has a tremendous impact on the available power and makes energy management and efficiency critical. Thermal issues become important due to the reduced thermal capacitance, leading to higher thermal swings and larger temperature variations than CubeSats. The other important impact on the satellite bus is the reduced communication capacity due to several reasons: the reduced volume limits the available antenna size and also the available power available. At mission level, other factors have a substantial impact: de-orbit time becomes a major criterion in the launch selection process to comply with orbital debris policy. The volume reduction also affects the radar cross-section making the satellite more difficult to detected for space surveillance radars. Despite these challenges, PocketQubes are an attractive standard currently for academic and research groups as a way to reduce the cost and development time considerably. Payload capabilities also can force a paradigm shift from single to multiple satellites more than it was already happening with CubeSats: PocketQubes could better fit certain niches where high spatial or temporal resolutions are required instead of full resolution. Distributed space weather monitoring could be an interesting application where specific phenomena could benefit from multi-point sensing. All these strong points can also be coupled with a bigger satellite to complement and enhance its capabilities.
    Delfi-PQ is a PocketQube currently being developed at TU Delft using an agile approach, contrary to the typical V-model design. Shorter life cycle development benefits students, allowing them to get more involved in every iteration. The reduction in cost and development cycle increases the launch frequency. Incremental engineering becomes fundamental, also providing benefits on the reliability side because flight experience becomes more frequent than when following traditional development strategies. End-to-end development motivates students and provides them with a better insight into real-world engineering opportunities and training experiences. With this strategy, technical and educational objectives are more aligned, and the integration of such a project in the curriculum is facilitated.

Keywords: PocketQube CubeSat agile development Delfi-PQ

1. Introduction

CubeSats have been getting a steady growth in popularity in the past years after they were first proposed in 1999. The concept of a modular standard coupled with a simple and (relatively) inexpensive deployment system allowed an institution with limited budgets a direct access to space [1]. CubeSats are based on standard modules of 10x10x10 cm (also called units or just U) that can be coupled together in different fashions.

In the push to further democratize this, PocketQubes were proposed to evolve regarding reducing costs and system size: now the core building block has been shrunk to 5x5x5 cm (small enough to fit in someone pocket, as the name was originally conceived) [2].

Both standards became the most popular for two different class of satellites: CubeSats typically span from 1kg till 10kg in mass (but bigger and heavier examples have also been proposed) while PocketQubes target the range between 0.1 and 1kg.

This paper presents a comparison between the different satellite classes rather than on the specific standards or configurations to highlight challenges and opportunities for PocketQubes. In section 2 the dependence of the key features of size are discussed, and the ability of current systems to track these tiny spacecraft is addressed.

Delfi-PQ is the PocketQube currently being developed at the Delft University of Technology. The preliminary design of Delfi-PQ is presented in section 3 and the development strategy for the PocketQube line of spacecraft is provided in section 4.

2. Size comparison

Several parameters can be used to characterize the different satellite classes but, since both "standards" are focused towards a small building block that can be repeated multiple times, we will look at the basic building block. In CubeSats, as it was already pointed out, this is a 10x10x10 cm cube while in the PocketQubes this is a 5x5x5 cm cube.

To make an effective comparison, a set of common and constant factors have been considered. For example, satellite side (L) that was established to 10cm (as in CubeSats); satellite density (D) is assumed to be constant due to the common concept the satellite are built on; solar power conversion efficiency (η) considering that the same type of solar cells is used. A brief comparison is presented in Table 1 based on these constants. Side, area and volume are straightforward, while other quantities require a bit more investigation. Solar power depends on the available area for solar cells (making the hypothesis of a constant fill factor) and on the conversion efficiency (which is supposed to be

constant and it was shown in both cases). The inertia has been calculated as the inertia of a cube supposing a constant density D. The magnetic moment has been considered for his implications with attitude control and is expected to be generated by a coil (magnetorquer).

Table 1: Length scaling of key parameters

	CubeSat	PocketQube
Side	L	$\frac{1}{2}L$
Area	L^2	$\frac{1}{4}L^2$
Volume	L^3	$\frac{1}{8}L^3$
Mass	DL^3	$\frac{D}{8}L^3$
Solar power	ηL^2	$\frac{\eta}{4}L^2$
Inertia	$\frac{DL^5}{6}$	$\frac{DL^5}{64}$
Magnetic moment	$\frac{6k}{DL^3}$	$\frac{2}{3}\frac{k}{DL^3}$

2.1 Satellite Tracking

This section focuses on the tracking of PocketQubes and CubeSats, analyzing a real case: the launch of the Dnepr-19 on Nov 21st, 2013. This launch was the first (and only one at the time of writing) with PocketQubes and CubeSats. 31 satellites were launched, 23 of them directly from the deck and 8 of them from a micro-satellite (UNISAT-5) 49 minutes after deployment from the rocket [3][4]. The comparison is performed based on the data provided by NORAD by analyzing the TLE of each satellite [5]. Position accuracy cannot be estimated at this stage due to the lack of a second reference, like a GPS receiver onboard some of the satellites, but tracking update rate and TLE acquisition time can be compared.

The first parameter considered was the acquisition time, defined as the time in between satellite deployment from the rocket (07:11 UTC on Nov 21st, 2013) and the time the first TLE was available for each satellite. Figure 1 shows the acquisition time for all the satellites deployed as a function of the approximate satellite cross-section (estimated from public information about the satellite size). PocketQubes and CubeSats are highlighted in the figure showing no major difference in object acquisition performances. It can also be seen that statistically bigger objects are acquired

first, and smaller objects took on average more time (with exceptions, as is evident from the figure).

Most likely due to the limited Δv provided during this deployment, the satellites remained too close to be detected. After approximately nine days most of the satellites were acquired, showing that 3 PocketQubes (WREN, 50$-Sat and BeakerSat) were acquired approximately at the same time as HUMSAT-D and ICUBE-1 (both 1U CubeSat). The sixth object tracked was identified as Dove-4 (3U CubeSat) even if its deployment was not confirmed [3]. One further PocketQube (QUBESCOUT) and one CubeSat (PUCPSAT-1) were acquired four days later probably due to the small Δv provided during the deployment. Figure 2 shows instead only the satellites deployed from UNISAT-5.
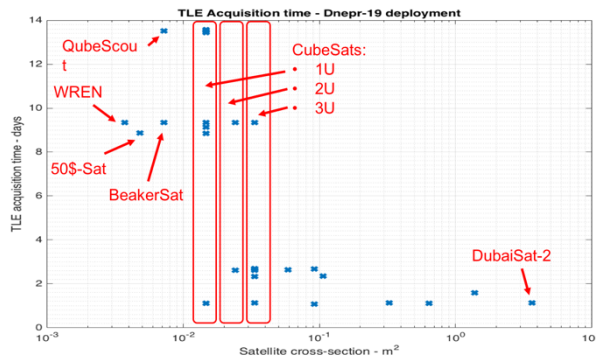

Figure 1: TLE acquisition time for the Dnepr-19 deployment
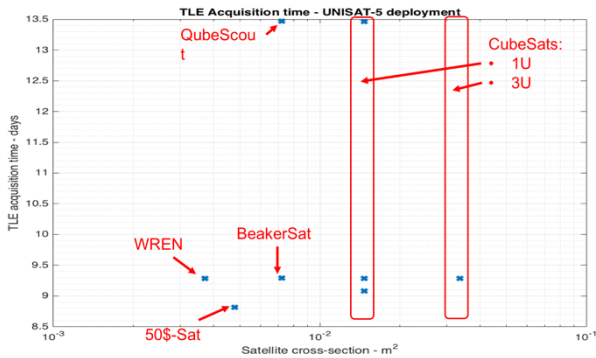

Figure 2: TLE acquisition time for the UNISAT-5 deployment

The Figure 1 and Figure 2 show that a correlation between acquisition time and size (or radar cross section) exists, but it shows no significant difference between CubeSats and PocketQubes.

TLE update rate has also been compared to verify if smaller satellites would receive less frequent updates than bigger ones. Results shown in the following tables confirm this even if the refresh rate difference is not

significant. It is interesting to notice that the TLE update rate for nano- and pico- satellites increased after August 2015 (an improvement in update rate can be noticed from Figure 3 for small satellites probably due to a system upgrade).

Table 2: TLE acquisition time (Before August 2015)

Satellite class	Average [days]	σ [days]
1P PocketQube	4.475	15.745
1.5P PocketQube	0.987	0.393
2.5P PocketQube	0.942	0.355
1U CubeSat	1.180	0.364
Mini-Satellite (DubaiSat-2)	0.332	0.095

Table 3: TLE acquisition time (after August 2015)

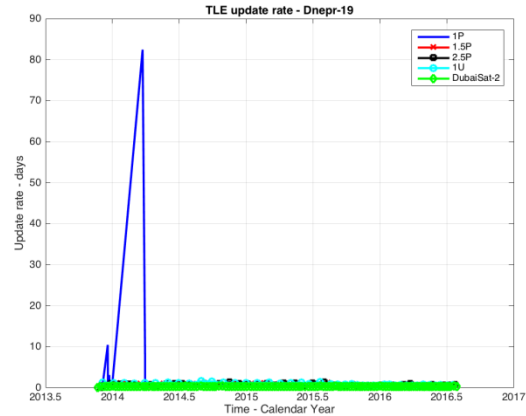| Satellite class	Average [days]	σ [days]
1P PocketQube	N/A	N/A
1.5P PocketQube	0.649	0.350
2.5P PocketQube	0.633	0.290
1U CubeSat	0.630	0.288
Mini-Satellite (DubaiSat-2)	0.308	0.083

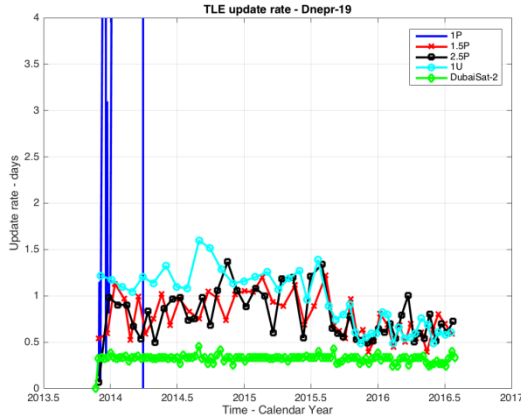*Figure 3: TLE update rate as a function of satellite cross-section*

Figure 4: TLE update rate as a function of satellite cross-section: detailed view for update rates shorter than four days.

From Table 1 and Table 2, it can be seen that satellites with bigger cross-section have a faster TLE update rate: this can be due to several reasons (special agreements between JSPOC and satellite operators, higher signal-to-noise ratio, among others) but again no particular difference can be noticed between CubeSats and PocketQubes. There is only one exception to this general trend, and it is WREN (1P PocketQube) which is the smallest object deployed. Its TLE has always had a quite long update rate (more than two days, and from Figure 4 it can be defined as "sporadic") and its TLE was not updated anymore after April 2014. This being the smallest object, it is likely that 1P PocketQubes are on the edge of the detection capabilities of NORAD (even if no official confirmation was acknowledged) while bigger PocketQubes (1.5P and 2.5P) show no difference in update rate compared to CubeSats and bigger satellites.

3. Delfi-PQ Preliminary Design

3.1 Lean bus interface

A lean 9-pin bus interface has been designed and developed for the Delfi-PQ PocketQube. The PQ-9 connector configuration is shown in figure 5. Table 4 maps the connector pins with the signal functionality. The PQ-9 standard makes provision for four switched power lines. Line voltage is unregulated and should be regulated at subsystem board if necessary. Maximum current rating is 1.5 A. It is a recommendation (and followed in Delfi-PQ) to connect V_BUS1 (Pin 5) to power the OBC and COMMS subsystems jointly. V_BUS2 to V_BUS4 (Pins 6 to 8) are provisioned for advanced subsystems (e.g. Micro-propulsion, ADCS) and payloads. For options such as kill-switch, battery charging and debugging, breakouts will be employed. Figure 6 shows the spacecraft architecture supported by

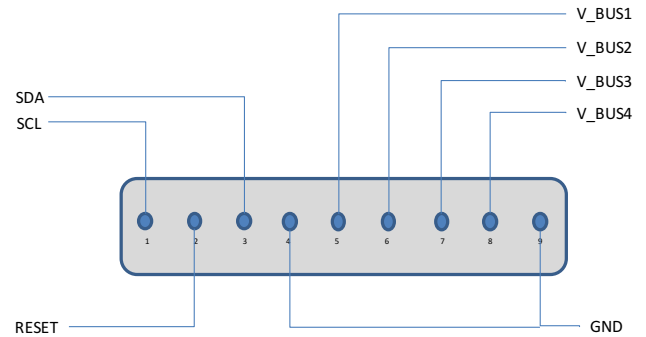PQ-9. Figure 7 shows the PQ-9 connector on PCB layout.

Figure 4: PQ-9 connector configuration and pin allocation

Table 4: Pin functionality of PQ-9

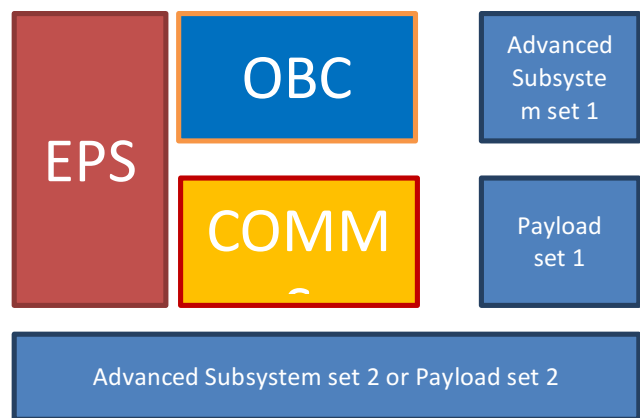| Pin Number	Signal	Function
1	SCL	I2C clock
2	RESET	System reset
3	SDA	I2C data
4	GND	Ground
5	V_BUS1	Power line (OBC and COMMS)
6	V_BUS2	Power line (Advanced subsystem set 1)
7	V_BUS3	Power line (Payload set 1)
8	V_BUS4	Power line (Advanced subsystem set 2/Payload set 2)
9	GND	Ground

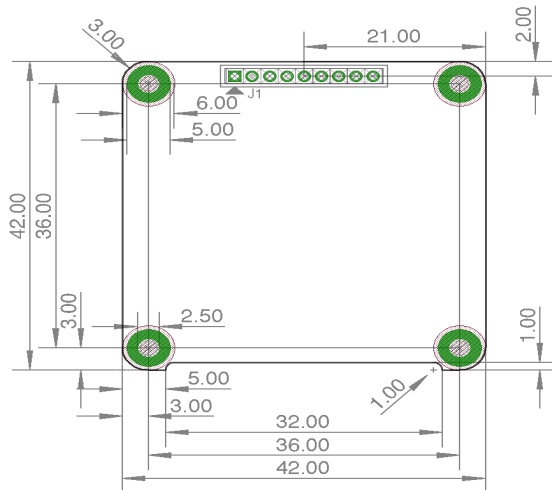*Figure 5: Spacecraft architecture supported by PQ-9*

Figure 6: PQ-9 connector form factor on Delfi-PQ PCB

3.2 Structure

The preliminary structural design of Delfi-PQ is presented here. By doing a mock-up test of the integration of the frames, it was found out that a simple framed and reinforced structure would suffice for the needs of the satellite. The design results are shown in Figures 8 and 9.
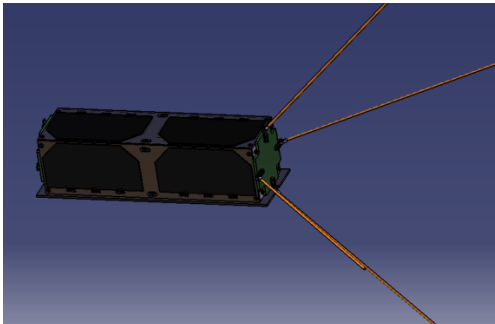

Figure 7 - CAD Model of the final design of the structure of Delfi-PQ. Antennae deployed.
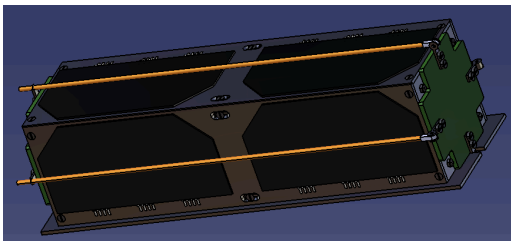

Figure 8 - CAD Model of the final design of the structure of Delfi-PQ. Antennae stowed.

The key features of the final design of the inner structure of Delfi-PQ are:
- The inner structure is composed of two open frames, four rods that support the PCB stack,

and middle reinforcements for the stack. The open top and bottom frames in combination with mounting blocks in the middle provide sufficient stiffness in a mass-efficient manner.

- To provide some extra stiffness to the rods, and to avoid rattling and torsion, four (one for each rod) small middle reinforcement pieces have been added. Their objective is to join two panels and one of the rods together to increase the strength of the structure. These reinforcements are introduced into the rods and are part of the stack. Due to their simplicity, they are easily integrated, and can act as a separator between two PCBs.

- A model of the stack of PCBs has been added to see how they would fit inside of the structure.

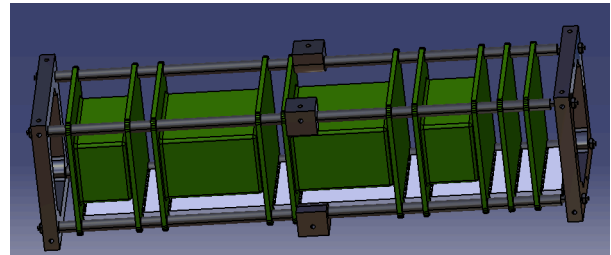The final results for the inner structure are shown in Figures 10 and 11, and Figure 12 shows the 3D printed model.

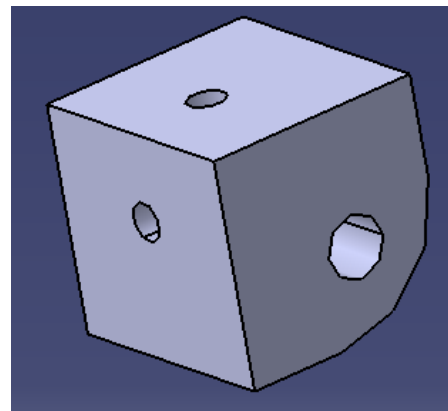*Figure 9 - CAD model of the inner structure of the final design.*

Figure 10: Detailed view of the reinforcement used for the final design

Figure 11: 3D-printed model of the Delfi-PQ structure

microcontroller, watchdog, I^2C pull-ups and monitoring circuits with a total power consumption under 40mW. The EPS monitors via I^2C the temperature of each solar panel and the current/voltage of the solar panels, unregulated battery voltage bus, 3.3V regulated bus and each of the four power buses.
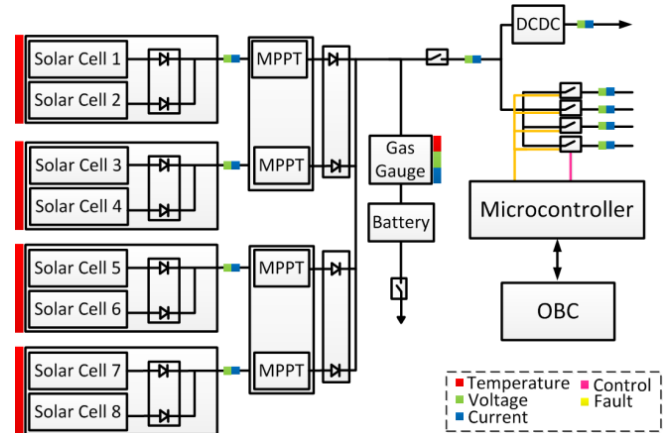

Figure 12: EPS architecture

3.3 Power

The EPS main function is to provide electrical power to the subsystems and payloads. The general architecture is presented in Figure 13. Delfi-PQ uses triple junction GaAs solar cells with approximately 30% efficiency as a source of energy. The satellite has four body mounted solar panels, each of them composed of two solar cells in parallel. The energy from each solar panel is regulated using a Maximum Power Point Tracker (MPPT) with an embedded Perturb and Observe algorithm; it offers maximum efficiency under varying irradiation, temperature or solar cell degradation. In the case of space constraints on the EPS board, it is possible to use a single MPPT for two panels as long as there is not a significant temperature difference between the solar panels.

Energy storage is based on a single Lithium-ion battery; it charges when the incoming solar power is larger than the load demand, and it provides power when the system requires more energy than the incoming from the solar cells (until the Depth of Discharge (DoD) is reached). A gas gauge is used to ensure that voltage, current and temperature are within the safety limits. The unregulated voltage bus is determined by the battery voltage and distributed to the loads using power switches with precision current limiting. Each subsystem/payload has an internal power conversion instead of the standard 3.3V regulated bus, through better selection of the converter for a specific load higher efficiencies can be achieved. A 3.3V buck-boost converter is used internally to supply power to the

3.4 Communication

The communication system design is driven mainly by two parameters: the available power on the satellite side and the required throughput. The ground segment is used to fix the limitations on the satellite side: for example, ground station antenna size can be increased when limited power is available on the satellite side [6]. Size is also an important constraint for small satellites, actually ruling out several solutions.

In this case, the orbit average power available for the satellite is approximately 1W, actually limiting the available power for the communication system to about 20% (considering the other onboard systems). The available power just calculated is extremely challenging to achieve while including both a receiver (with an 80% to 100% duty cycle) and a transmitter (with 5% to 10% duty cycle).

The required throughput is also low for this type of satellite and is typically limited to few hundreds to few thousands of bits per second. Power levels and data rates fall very well in the range used for wireless sensor networks and Internet-of-Things devices [7][8].

Several devices are commercially available, like the one shown in Figure 14, similar to a credit card in size that would satisfy the requirements mentioned above.
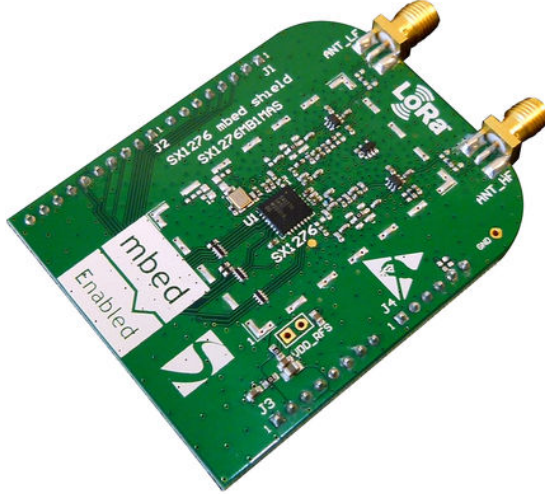
Figure 13: Semtech SX1276 development board

Figure 15: 3D representation of the interior

Table 5 - Orbit of Delfi-PQ – Reference case

Orbit	h	e	i	Ω	ω
Orbital Parameters	635 km	0	97.8º	9h 30min	0º

3.5 Thermal Analysis

The results of the preliminary thermal analyses are presented in this section. All the heat inputs are calculated as a function of the position in the orbit to compute the transient thermal behavior of the spacecraft in its orbit. Three external sources have been considered: The Sun, the thermal infrared emission of the Earth, and the albedo. Figures 15 and 16 show the 3D representation of the front side and internal structure of Delfi-PQ. The initial temperatures of each node are colored on its surface.
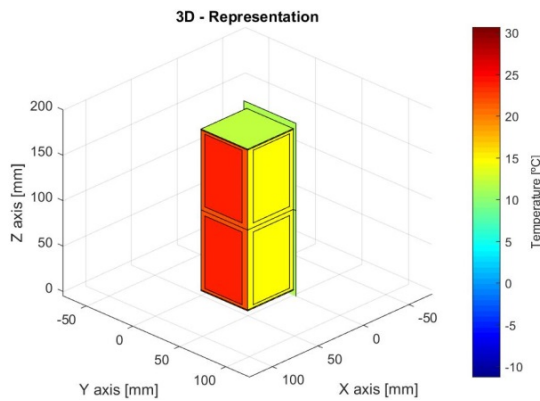

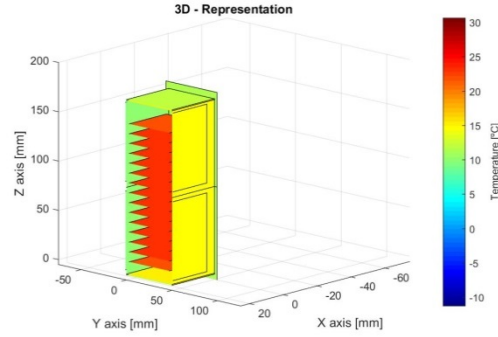Figure 14: 3D representation of Delfi-PQ seen from the front (Illuminated side)

Table 5 presents the orbital parameters for the reference case. Regarding the attitude, the spacecraft has been set to be tumbling at a rate of 5 times per orbit about the most general axis (no privileged directions). This represents the reference case. Additionally, the right ascension of the ascending node was set to a midday-midnight orbit (Cold case, maximum eclipse) and a noon-dusk orbit (Hot case, no eclipse). A fast tumbling mode was also considered and a nadir-orientation case. In all cases, the electronics have been examined to be working during the entire orbit. Table 6 presents the results of the thermal analyses.

Table 6: Thermal Analyses Results

Cases	Tmax S.P. [ºC]	Tmin S.P. [ºC]	Tmax PCBs [ºC]	Tmin PCBs [ºC]
Reference	30.7	-11.3	27.3	20.8
Hot	33.0	9.0	33.9	33.4
Cold	30.2	-13.2	26.2	19.2
Tumbling	19.8	-10.8	27.3	20.8
Nadir	26.0	-13.3	23.8	17.6

3.6 On-board computer

Within the Delfi-PQ spacecraft core, the onboard computer is in charge of executing the mission logic and coordinating with other systems for telemetry collection, energy management, telecommand processing among several other functions. Since the pocket cube form factor restricts the availability of power, while the number of duties remains constant, one

of the main challenges is the efficiency of its microcontroller unit (MCU).

For the MCU trade-off process, the following top-level requirements were taken into account:

- Highest power efficiency: choose a technology that optimizes the energy consumption
- Software development support from the open source community, to speed up the software development cycle.
- Commercially available development boards for fast prototyping.
- Support for distributed communication protocols, for example, I2C, SPI, UART for integration with other subsystems.

Three microcontrollers were evaluated: TI-MSP432, ATSAMD21G18, and the ATMEGA328. The TI MSP432P401R resulted as the most suited MCU for designing the pocket cube onboard computer. Figure 17 shows a block diagram of the pocket cube OBC design.
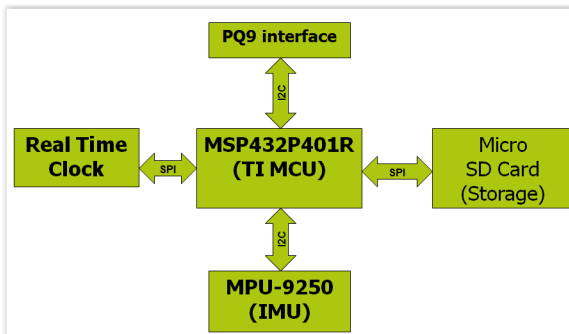

Figure 16: Delfi-PQ OBC block diagram

In figure 17, additional components for Delfi-PQ OBC are specified. The real-time clock provides support for time generation on the spacecraft bus; the micro-SD provides mass storage for the mission; the PQ-9 interface provides a communication channel for interacting with other subsystems in the satellite. The motion processor unit (MPU-9250) is an inertial measurement unit with 3-axis gyroscope, accelerometer, and magnetometer intended for attitude estimation algorithm testing, while the ADCS advanced subsystem is developed and implemented later on.

4. Development Strategy: An iterative bottom-up design approach)

Space projects typically follow a waterfall or V-model approach [9]. Both methodologies are linear and start with mission analysis, followed by several hierarchal levels of design, production, assembly, integration and testing and finally conclude with operations. This approach is divided into distinct phases, with dedicated extensive reviews to finish each phase and move to the next one. This methodology has also been the attempted approach for the Delfi-C3, Delfi-n3Xt and DelFFi mission. There are however many problems with this method, especially within a university environment. One major problem encountered is the discontinuity and limited experience of the human resources, which results in improper requirements and preliminary designs and lack of ownership by a subsequent generation of students and new staff. For students only seeing one of the design phases, a V-model project would not provide them the full experience of end-to-end engineering either, limiting their learning experience. Another obstacle within a university is that the V-model fixes the design in an early stage of the mission, whereas at a university there is a high motivation and push for continuous innovation and experimentation.

Even if the specifics of the academic environment are ignored, there are good reasons to look for different development approaches for small and lean satellites. In many sectors, industry has already stepped away from linear development approaches and replaced them with iterative approaches. In software development, many concrete methods are worked out under the umbrella 'Agile development' [10]. For example, in the SCRUM method [11], software parts are integrated and compiled each 2-4 weeks after which the client can review this software. In such a method, the requirements are not defined completely at the start in detail but evolve over time in cooperation with the client. This requires a flexible attitude from both the developer and the customer and a more intuitive feeling for the overall process, time and cost involved than completely pre-analyzed contract. According to the agile manifesto, it is more valuable to have this ability to adapt than following previously established plans that are based on many assumptions.

For hardware development, there are less precise methods for iterative design and those who tried indicate that a larger iteration time is required (as hardware also involves procurement and production time) and in some cases require a bit more requirements analysis, especially if another cost than personnel becomes substantial. Also, the work is more multi-disciplinary than for software, so a bit more documentation is required. Still, there are many advantages of an agile development approach, especially if the majority of the cost is not on procured

hardware or facilities but in human resources. At this moment it can be seen that many developers of commercial products at least already implement an iterative approach for their product lines. For example, smartphone manufacturers release a new model each year for a particular series, such that they can stepwise modify their designs to accommodate for the latest available technology and adapt to the needs and evaluations of their customers.

The current worldwide biggest player in CubeSats, PlanetLabs, also follows an iterative design approach in which they have about 14 successive hardware 'builds' of their remote sensing CubeSats in just of few years of time [12]. Some of these builds have been launched and tested in orbit, while others have just been laboratory hardware baselines.

Considering all these aspects, it was decided to move to an iterative design approach for the next Delfi satellites. Secondly, because Delfi satellites are aimed at technology demonstration and not on pre-defined missions, requirements are very flexible, and the success per demonstrated subsystem or component can be varying from first in-orbit testing of partial functions to acquiring flight experience for ready-to-market product. The satellite project is no longer a top-down mission, but more a bottom-up integration project of projects. Each component and/or subsystem development are regarded as a small project on its own, with its organizational structure, funding, and resources.

For the Delfi PocketQubes, an agile approach is implemented, in which the spacecraft is divided into a core bus subsystem providing a core set of functionalities, and several specialized subsystems, including attitude determination and control, propulsion, cameras, among others. Each of the subsystems is led by a technical team, which provides specifications to the core team to work on core subsystem iterations and assembly, integration and testing of the entire spacecraft. Figure 18 illustrates the development process.
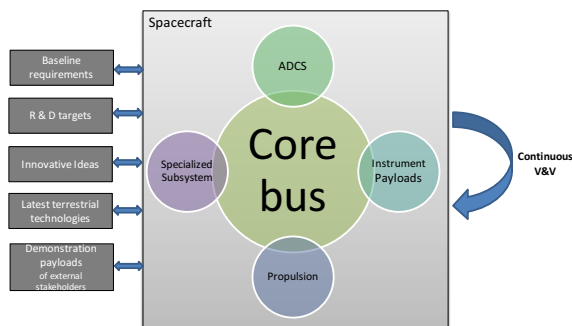

Figure 17: Proposed development life cycle for Delfi PocketQubes

In this figure, three key elements are identified. Initially, a set of needs and high-level requirements is defined which secure a minimum functionality and a proper integration of (evolving) subsystems. These are for instance process and interface requirements. Based on those requirements the first design of the core bus is established. Second, each of the payload and functional subsystems starts their first design to address these needs and the achieve a first complete but still limited functionality. In the next iterations, functionality and performance can be increased (internal incentive) while the capabilities of the core bus may be enhanced to support improved technical budgets or capacities (external opportunity). The third key element is the semi-continuous verification and validation process. For each iteration, all the subsystem and payloads are verified and validated in a complete satellite, ensuring reliability and a timely feedback when issues are encountered. The aim for Delfi PocketQubes is to have an iteration of the core bus every half year. Iterations of advanced subsystems and payloads can be integrated within the same cycle, or can be incorporated and tested whenever available: experience is required to discover the most efficient method.

5. Recommendations and Conclusions

PocketQubes are the next class of small spacecraft that push the limits of miniaturization. This paper has attempted to discuss key issues with going smaller in spacecraft size and additionally present a PocketQube design and development philosophy. The influence of length scaling on the main quantities has been discussed. One of the challenges and often a criticism for launching PocketQubes has been the potential (in)capability of tracking these tiny objects in space. The conclusion forms the results discussed on satellite tracking clearly show that for PocketQubes greater than 1.5P TLE acquisition and update rate is at par with what is available for CubeSats.

The preliminary design of Delfi-PQ, the PocketQube currently being developed at the Delft University of technology was presented. In the final section the development philosophy that advocates an iterative bottom-up design approach and a setup that favors an 'AGILE' methodology was proposed.

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