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Integration and Miniaturization Challenges in the Design of Micro-Propulsion Systems for Picosatellite Platforms

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ABSTRACT

As a further step in the research towards miniaturization of satellite components and sub-systems, the Department of Space Systems Engineering at the Delft University of Technology has recently embarked in the end-to-end engineering of the Delfi-PQ picosatellite platform, designed according to the PocketQube size standard. This new satellite platform, inspired by the success of previous Delfi satellite projects, is seen as a great opportunity for innovativeness and offers great research challenges. Since a consolidated standard for PocketQubes has not been established yet, a significant amount of design freedom can be harnessed despite the small volume available. The miniaturization process required to integrate the core bus forces the team to think differently about space technology: it is not sufficient to simply down-scaling existing concepts used in larger satellites, and it is often necessary to develop and qualify completely new components and integration methods. The paper is about systems engineering process, technology developments, and verification and validation for the design and development of the micro-propulsion payload for PocketQubes and its integration with the core bus platform.

KEYWORDS: Micro-propulsion, Micro-resistojet, MEMS, CubeSats, PocketQube

1. Introduction

CubeSats [1], [2] have become extensively popular especially for Earth observation missions [3–5], nevertheless, a few interplanetary missions [6], [7] have also been anticipated for multiple-units CubeSats.

Recently, the Delft University of Technology has embarked on a new satellite development program based on the PocketQube standard [8], [9] as a showcase of the next class of miniaturized satellites. In the past decade, CubeSats [10] have grown towards an extremely successful business with mature capabilities as opposed to PocketQubes that are still in their infancy.

TU Delft contemplates that the small size of the PocketQubes will force one to think differently about the space technology and enable new applications. An important feature of Delfi-PQ will be the possibility to accommodate one or more advanced payloads that either need to be qualified for space or can act as a scientific or educational experiment [2]. One of these payloads is expected to be a micro-propulsion demonstrator currently under development at TU Delft.

Miniaturization in space technology with a special focus on micro-propulsion systems enables future small satellites to perform more missions, like orbit change and raising, formation flying, precise

attitude control, station keeping and de-orbiting [9], [11], [12]. Much of the attractiveness and competitiveness lies in the design of highly efficient propulsion system components within the tightened requirements and stringent constraints such as mass, volume, and power budget [13].

The design of a micro-propulsion module able to provide thrust in the levels of micro-N up to a few milli-N with strict constraints for the pocket-sized format is indeed a big challenge. Even if the aforementioned requirements are feasible with current technology, the concept itself is subject to design constraints that require mindful decisions for the individual parts [9], [14]. Currently, TU Delft is working on a micro-propulsion system based on a second generation VLM (Vaporizing Liquid Micro-resistojet) thruster as well as an LPM (Low-Pressure Micro-resistojet) thruster for PocketQube applications. The developments on the first generation micro-resistojet [15–17] started already in 2010/2011.

This paper describes the mission concept followed by complete systems engineering process involved in the design of the micro-propulsion payload for Delfi-PQ and its integration in the core bus platform. Then, the initial generation of the requirements, the trade-off study, risk analysis, development schedule and verification & validation strategy are presented in the forthcoming sections. Particular emphasis is given to the top-down methodology used in the

design process for translating the mission objectives and requirements into propulsion subsystem requirements. Finally, a summary of technology developments of the design so far is presented along with conclusions inferred and the recommendation for future works.

2. Mission Concept

The new pico-satellite platform, inspired by the success of previous Delfi satellite projects, is seen as a great opportunity for innovativeness and offers great research challenges in the miniaturization field. Figure 1 shows the Delfi-PQ CAD model with antenna deployed. The mission of the first Delfi-PQ [8] is to test in flight the core BUS platform and outer structure for the 3P PocketQube (see Table 1 for clarification of 1-2-3P). This will be the first iteration of a series of PocketQubes to be developed by the Delft University of Technology. The core BUS shall eventually fit in one unit (1P), having an aim that after further miniaturization and optimization, the second unit will contain an advanced subsystem and the third one will consist of a scientific payload (**Figure 2**).

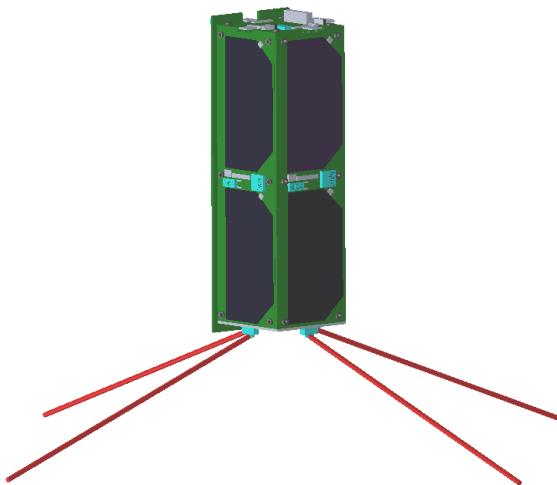


Figure 1. Delfi-PQ CAD model with Antenna Deployed

The team is focused on the miniaturization process for the first Delfi-PQ. Despite the existing down-scale concepts used in larger satellites, it is almost necessary to develop and qualify completely new components and integration methods.



Figure 2. Spacecraft Architecture supported by PocketQube

The core platform of the first Delfi-PQ will consist of the Electrical Power System (EPS) (including the main board, batteries, and solar panels), On Board Computer (OBC), COMMS and Attitude Determination & Control System (ADCS) (including magnetometers and magnetorquers).

Table 1. PocketQube Standards

No of Units (P)	Cube Dimensions (mm)	Sliding backplate dimension (mm)
1P	50 x 50 x 50	58 x 64
2P	50 x 50 x 100 (114)	64 x 128
3P	50 x 50 x 150 (178)	64 x 192

The foremost long-term goal of Delfi-PQ is to validate a reliable core platform that has at least one advanced subsystem which acts as demonstrator or payload. While designing the mission, several constraints were imposed with respect to orbit characteristics, out of which the most important one is the minimum inclination orbit that shall be 52° . This value corresponds to the lowest latitude for which visibility is ensured over Delft ground station. The currently most probable orbit of Delfi-PQ is at 350 km with an inclination of 96° .

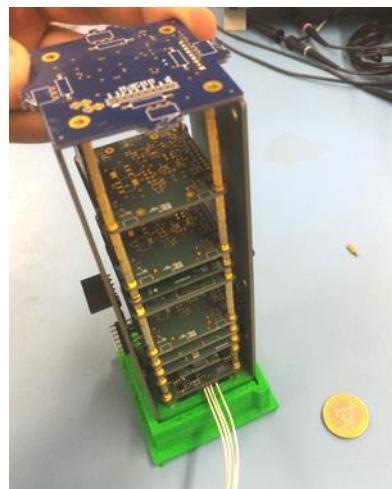


Figure 3. Stack approach for the inner structure of the final design

The inner structure of Delfi-PQ consists of 1 stack of PCBs. The assembling procedure starts from the middle of the satellite and the boards are placed on rods with their afferent spacers. This approach simplifies the assembling/de-assembling procedure (for example, you need to de-assemble at most half of the satellite to remove one board). This option was selected in order to try a simpler and fast approach that includes both the structure and solar panels (Figure 3).

Currently, the Delfi-PQ is having an engineering model of the core at FlatSat level testing to check all electrical connections, communication between subsystems and test the overall satellite before final integration. All primary subsystems are verified on the FlatSat along with other critical components (magnetometers, Torquer coils, etc).

One of the first demonstration payloads expected to fly on Delfi-PQ is a dual thruster micro-propulsion system, specifically designed for this format. In PocketQube satellites, volume becomes the most important and challenging constraint, differently to larger formats where mass and power often pose more significant limitations. The main mission objective of the propulsion system is to measure its performance in the space environment. The important performance parameters are the behaviour of the thruster, the functioning of the valve, functioning of the nozzle and the amount of leakage from the system.

3. Systems Engineering Process

Systems Engineering typically focuses on design, integration, and implementation of complex engineering systems over their life cycle. These project cycle phases are proposed and described as per the European Cooperation for Space Standardization (ECSS) [16], [18] and National Aeronautics and Space Administration (NASA) standardization.

The various available systems engineering tools [47] like top-level requirement generation, trade-off process, sequence diagram, N² chart, risk analysis, verification, and validation, help in developing and unfolding low cost, reliable, highly efficient systems which meet the stakeholder needs. Systems engineering of the platform, therefore, poses a number of challenges, from the identification of interface constraints and requirements to the integration of the demonstration payload(s) in the imposed volume limitation. Three levels of requirement generation are adapted for the design of the micro-propulsion system for Delfi-PQ, namely, system, subsystem, and component level using a top-down methodology.

The micro-propulsion system requirements are generated based on the specified mission objective. The requirements for the propulsion system as a whole are divided into six main categories: General Requirements & Constraints, Performance Requirements, Functional Requirements, Interface Requirements, Assembly, Integration, Verification And Testing (AIT) Requirements/ Reliability, Availability, Maintainability, and Safety

requirements (RAMS) and Environment & Launch Load Requirements.

Table 2. Top-level System requirements

ID	Name	Requirement
General Requirements		
PROP-SYST-100	Mass	The total wet mass of the propulsion system at launch shall be ≤ 75 g.
PROP-SYST-200	Volume	The total size of the propulsion system shall be within 42 mm x 42 mm x 30 mm
PROP-SYST-300	Peak Power Consumption	The peak power consumption of the propulsion system during ignition or heating shall be not higher than 4 W.
PROP-SYST-400	Idle Power Consumption	The idle power consumption of the propulsion system shall be not higher than 10 mW.
Performance Requirements		
PROP-PERF-100	ΔV	The first prototype shall be a technology demonstration, No ΔV requirement from mission side.
PROP-PERF-200	Maximum Thrust	The thrust provided by the propulsion system shall be 3 mN as a maximum.
PROP-PERF-210	Minimum Thrust	The thrust provided by the propulsion system shall be at least 0.12 mN.
Functional Requirements		
PROP-FUN-100	Modes of Operation	The micro-propulsion system shall have at least two modes: idle and full thrust mode.
PROP-FUN-200	Thruster Operation	The thruster shall be able to operate on gaseous N ₂ , as well as on water.
Reliability, Availability, Maintainability, and Safety requirements (RAMS)		
PROP-RAMS-300	Materials	No hazardous materials for operators or other subsystems shall be used
PROP-RAMS-310	Materials	Pyrotechnics shall not be permitted.
PROP-RAMS-320	Materials	No toxic materials shall be used.

All the operational aspects of the propulsion system will be covered in these aforementioned requirements. The Table 2 shows a non-exhaustive

list of top-level system requirements. The requirement generation starts off by analyzing stakeholder needs, which would address the TU Delft's final goal, and followed by a requirements discovery tree (RDT), trade-off process, N² chart and a sequence diagram. The N²chart (Figure 4) is used to check if any interface requirements are still missing.

ADCS	Required control Power		Available pointing accuracy	Store data& telemetry	Control forces	TLE data
Available control power	Power	Deliver power	Deliver transmit power	Deliver processing power	Deliver power	Power given to control thrust
	Power required Battery temperature	Thermal & Radiation		Store temperature telemetry		
Required pointing accuracy			Communication	Bus interface		
	Power required		Data rate	OBC	Command to deploy	Switch ON & OFF
	Power required			Store deployment info	Structure & Configuration	Spacecraft weight Max acceleration
Thrust stability & accuracy	Required propulsion power	Generate heat, radiation & temperature limits		Store data & telemetry	Thrust acceleration Propellant storage space	Micro-Propulsion

Figure 4. N² chart of the Delfi-PQ design interface

A trade-off is performed for selecting the most appropriate propulsion concept [2], [10], [19] for this mission. A numerical trade-off approach is used to find the best viable option taking into account advantages and disadvantages of each concept. The design concepts are given in the first column and the trade-off criteria with the assigned weights are given in the first row. The judging of concepts and criteria are based on total points. Each category has been given a weight depending on the importance of the mission (ranging from 1-10). Each concept will, then, be awarded points (ranging from 1-10) in each category depending on their performance (Table 3).

Seven main criteria can be used to compare and judge the different propulsion concepts [20]: mass, TRL, cost, safety, manufacturability, power, storability. In Table 3, each concept is scored based on these criteria and their assigned weights, in order to identify a winner and thereby the most feasible option.

Many propulsion technologies with different capabilities have been selected for the trade-off [8], [11], [12], [14]. It is, however, important to note that all these systems are under development (especially for what concerns their applicability to the PocketQube standard) and are therefore subjected to undergo continuous improvement in their capabilities.

Table 3. Numerical trade-off Approach

Criterion \ Weight Concepts	Mass (7)	TRL (6)	Power (8)	Manufacturability (7)	Safety (8)	Cost (8)	Storability (7)	Total	Rank
Cold Gas	1	6	8	5	7	6	7	295	1
Solid Chemical	1	5	8	2	4	5	8	243	5
Mono Propellant Chemical	3	4	9	4	5	6	4	271	3
Bi Propellant Chemical	1	4	9	2	4	5	5	224	7
Resistojet	2	5	5	6	7	7	7	287	2
Arjet	4	5	3	4	7	7	7	261	4
Solar thermal	2	4	8	1	7	3	7	238	6

From the plethora of existing propulsion systems for nanosatellite missions, the trade-off shows that cold gas thrusters [9] are the most thoroughly tested and flight qualified technology of propulsion for small satellites. Nevertheless more recent satellites seem to prefer resistojet (electrothermal) [21] and electric [22] methods of propulsion which are more efficient in terms of volume and ΔV though their TRL is low. While reviewing the trade-off, cold gas and resistojet still seem to be potentially the best promising candidates for the kind of mission concept considered in this paper [8], [14]. The final choice would, of course, depend on the mission needs and the capabilities of the system in terms of performance, thrust, and Delta-V, which have not been directly considered in the trade-off.

Table 4. Design criteria and performance capabilities of propulsion concepts

Criteria \ Concept	Thrust (mN)	Specific impulse (s)	Application	Power (W)
Cold Gas and Warm Gas	0.0001-100	30-100	Station Keeping & attitude control (Suitable for small ΔV : 4-5 m/s)	2-6
Micro-Resistojet	0.1-10	80-200	Station Keeping & attitude control (ΔV >10 m/s)	4-10
TU MEMS VLM	1.7-4.2	110-130		0-2
TU MEMS LPM	0.5-3.0	80-120		
Pulse Plasma Thrusters	0.0001-0.001	300-3000	Station Keeping, attitude control & slow orbit transfer	2-10
Electrospray	0.005-0.05	1000-5000	Accurate Orbit Control Slow orbital transfer	1-15
Chemical	100-1000	150-350	Orbit Transfer	10-20
Water Electrolysis	50-500	110-300	Accurate Orbit Control (but difficult in controllability)	-
Ion/Hall Effect	0.1-5	1000-4000	Precise pointing, slow orbit transfer/manoeuvres	10-30

Table 4 shows some reasonable design criteria and performance capabilities for different competitive propulsion system options suitable for small satellites with the maximum available power of 10 W. Clearly this is a preliminary list, not necessarily inclusive of all the propulsion concepts and the performance criterions.

As shown here, electric [22] propulsion is power-limited, has a very high specific impulse but a low thrust level as a direct consequence of the small satellite power limitations. These thrusters can be used efficiently for station keeping, attitude control, long burns and drag correction with high ΔV requirements. On the other hand, chemical propulsion [22] is temperature-limited but has very high thrust level and can be used effectively for orbit transfer. Cold gas thrusters, resistojets, and

monopropellant systems generate relatively high thrust levels but have a specific impulse of 50-250 seconds. These thrusters can be very useful when fast maneuvers & precise attitude control is required in terms of stability, agility and pointing accuracy. Cold gas systems usually have lowest specific impulses, causing them to be disadvantageous in both volume and mass terms, also considering potential safety issues with the launch service provider in case very high propellant pressurization levels are required. The micro resistojet seems to be a good candidate compared to cold gas in terms of power, high thrust-to-power ratio, temperature, simplicity, scalability and high specific impulse.

The main goal of the payload is to test two novel micro-propulsion resistojet technologies namely, Vaporizing Liquid Micro-resistojet (VLM) [21], [23], [24] and the Low-Pressure Micro-resistojet (LPM) [21], [25], [26], in space. Note that any amount of ΔV would be sufficient as long as the thruster can operate in space. As this mission is a technology demonstration, our attention is on obtaining practical information on thrust and specific impulse over the full thrust range including the capability of providing thrust control by on/off modulation of the propellant control valve [27].

4. Technology developments

The target for the micro-propulsion payload which will be integrated on Delfi-PQ is to simultaneously test two different resistojet technologies: one based on vaporization of slightly pressurized liquid water (VLM) and one based on the free molecular acceleration of propellant molecules stored at very low pressure (LPM). Both the concepts of VLM and LPM work with water as the propellant [28] and gaseous nitrogen as pressurant gas could be set as the baseline for this design. The payload has propellant storage for these two concepts, based on the use of the capillarity properties of water in small diameter tubes and two separate MEMS chips with their own dedicated valves (for heating and accelerating the propellant).

The main requirements that were set for this demonstration payload are for a thrust level between 0.1 and 3 mN and a specific impulse from 50 to 100 s. The selection of micro-resistojet has very particular characteristics which make it compatible with the required miniaturization process. Some of these characteristics are high thrust-to-power ratio, low system specific mass and the possibility to use almost any type of fluid as a propellant [25].

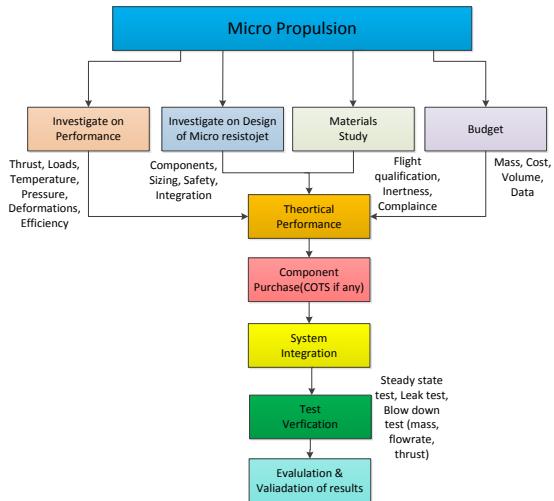


Figure 5. Process Flow Diagram of the propulsion system

The process flow diagram of micro-propulsion subsystem development is shown in Figure 5. As depicted here, the main phases involved in the design and development are to come up with a good and viable design concept, investigate on the various performance characteristics, an estimate on different budgets (mass, volume, data, cost) and material study. The next immediate phase is to have an estimate of theoretical performance which is then followed by COTS component purchase if any and or manufacturing of components. The most vital step is the system integration, testing and validation phase. This is an iterative process and will recur until the design meets the requirements.

The dual thruster micro-propulsion system is divided into thruster including VLM & LPM, common propellant tank, feed system, sensing electronics and other supporting control electronics. A block diagram of the complete micro-propulsion system is shown in Figure 6. An initial estimate of the mass for Delfi-PQ micro-propulsion system, based on real hardware for micro-valve, micro-thruster, tank, feeding connections and electronic board is shown in Table 5. Also, the mass can be further optimized by introducing MEMS valve and by optimizing the mechanical interface including channels and connections.

The latest developments and results at TU Delft on MEMS-based Vaporizing Liquid Micro-resistojet (VLM) and Low-Pressure Micro-resistojet (LPM) design concepts for CubeSats have been presented in [24–26], [29]. Also, the complete design of the corresponding micro-propulsion system including preliminary design, fabrication and test results for the CubeSats are presented in [17].

Table 5. Estimated Mass Budget for the Delfi-PQ micro-propulsion payload

Items	Mass [g]	Minimum Number of Components
Thruster and housing (VLM and LPM)	20	2
Feed system (Valves + connectors and tubing)	20	2
Storage tank plus sensors	10	1
Electronic board with microcontroller	13	1
Pressurant / Propellant	12	
Total	75	

5. System Integration Challenges

Direct downscaling [14], [30] of an existing propulsion system in terms of volume and power is not limited to physically miniaturizing already available parts, but by the integration of COTS components with completely redesigned microfluidic components without comprising in maintaining or increasing the system efficiency [11].

The most challenging part is the densification and fast integration of all the components of the

propulsion system consisting of the thruster, valve, sensors, electronics, and propellant storage are required to fit into one satellite unit of 4.2 x 4.2 x 4.0 cm volume. Therefore, the design of the system mainly focuses on volume-saving options. The COTS valve and the propellant tank are the most challenging components in terms of mass and volume in the propulsion module. Aside from the aforementioned challenges/metrics the availability of flight-ready components seems to be a critical factor.

The review of the other small satellite missions with micro-propulsion can be a baseline [14] for overcoming the potential challenges and lessons learned can be the impetus for an efficient design. The first instance of micro-propulsion occurred on the CanX-2 [31], [32] satellite carrying a cold gas propulsion on-board.

The advantage was the design of valves, which falls in closed positions for safety concerns if there is a full system power failure. Other significant design highlights include the propellant tank in the shape of a titanium pipe which was coiled around the rest of the satellite in SNAP-1 [33], [34] and the STRaND-1 [35] mission showing the need of a physical interface between the inlet of the MEMS thruster and the feed system. With Canx-4&5 [36] and the BRICSat-P [37] satellites, thrusters were aligned in X-wing configuration which will provide momentum changes in different directions.

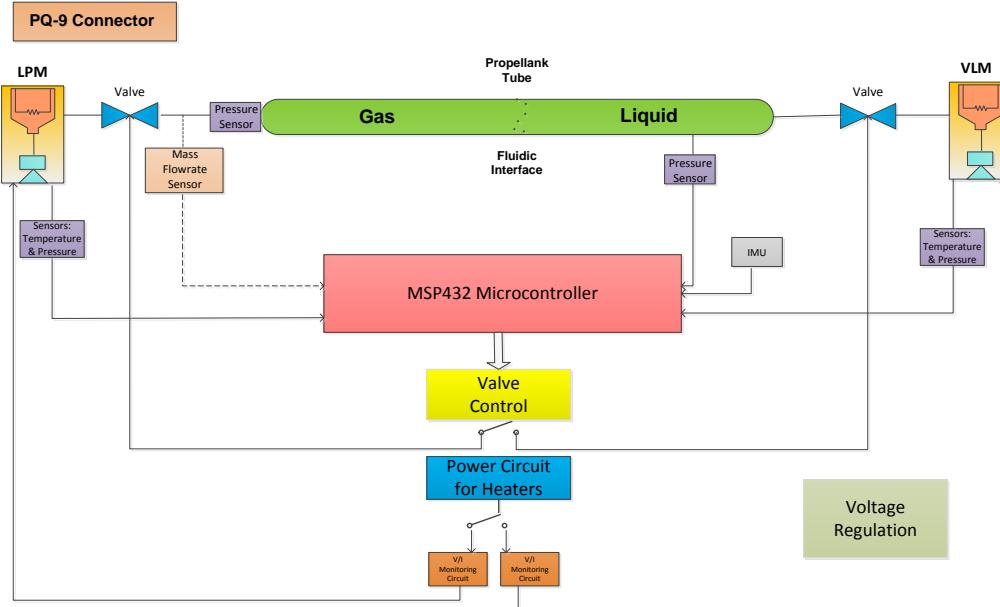


Figure 6. Schematic of the micro-propulsion system

The performance of a propulsion system is strongly dependent on temperature. The effectiveness of propellants storage can also be affected by too extreme temperatures and also to avoid risks of propellant freezing. Operational temperatures need to be controlled such that they do not exceed component specifications, especially maximum and minimum valve temperatures [31], [32]. The thermal stability plays a significant role in reducing the deformation of the thruster while in operation and for this reason, typically, micro-resistojets are operated under a range of temperature below 200 °C. The propulsion system has been designed keeping the thermal interface between the system and the satellite to stay in a temperature range between 5°C and +85 °C during all the mission phases.

Another important concern is the placement of the propulsion module. In the current design, the propulsion system is installed in the middle unit of the PocketQube (Figure 7) which is the most advantageous in providing very accurate and slow attitude control and drag compensation. It can be concluded that the integration should be done by paying particular attention to the identification of flight-qualified COTS components, miniaturization of the custom-made thrusters, mechanical positioning, and alignment of selected/designed components[14].

5.1 Risk Management and Failure mode analysis

As part of the propulsion technology development, various risks [38] have been identified including the associated failure mode and their impact on mission success (Table 6). Risk management [39], [40] is a method to identify, access and mitigate the technical risks of a project. Risk management is of utmost importance for attaining a goal, objective or requirements where the level of innovation is very high. This is an iterative process which includes risk identification, risk assessment, risk analysis and risk handling.

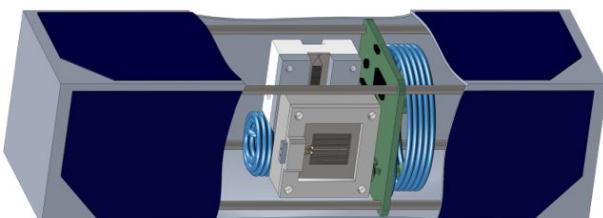


Figure 7. Schematic drawing of the micro-propulsion system components position in the satellite

Risk identification [41] is achieved by first analyzing the work breakdown structure in order to determine the risk areas. The Table 6 shows some of the identified critical risk and failure modes. During the second step, the probability of occurrence and severity of consequence are determined for every risk.

The probability of occurrence is a function of the state of technology and/or its maturity. To access the probability of risk for a certain element, it is preferable to determine the existing and proven design of similar missions. If so, it implies that the probability of technical failure for this risk is low and on contrary, if there is no such proven design and the mission is only feasible in theory then the probability of technical failure for this risk is high. The various stages are, in increasing level of risk: Proven flight design (Low), Extrapolated from existing flight design (Low - Moderate), based on existing non-flight engineering (Moderate), Working Laboratory model (Moderate - High), Feasible in theory (High). Similarly, the severity of the potential impact of a risk is defined as follows negligible, marginal, critical and catastrophic.

- Catastrophic: Mission failure or significant non-achievement of performance.
- Critical: Mission success is questionable or some reduction in technical performance.
- Marginal: Degradation of secondary mission or a small reduction in technical performance.
- Negligible: Inconvenience or non-operational impact.

Finally, the risk is mapped on a risk diagram (Figure 8) with the impact of failure on the horizontal axis and the probability of occurrence on the vertical axis. Mitigation strategies should then be formulated to move all the risks to the lower left corner of the map i.e. the ultimate goal is to lower the probability of occurrence and/or lower the impact of failure (Figure 9). The green, yellow and red regions are representative of low, medium, and high-risk levels respectively. Technical risks identified can be eliminated by two methods.

- Type I: Pre-development of prototypes of the propulsion system.
- Type II: Changing the design of the propulsion system by adapting more frequently used or flight qualified technology which would reduce the probability of failure. The design may also

include safety margins and redundancy, or foresee verification and testing campaigns.

At this stage of the project, it is still difficult to go into detail on exact measures to mitigate the risk.

5.2 Approach to Validation & Verification

Requirement verification & validation [42], [43] is an essential process that is conducted throughout the entire design process to check the product compliance with the user requirements. They are the primary requisites for the mission to alleviate risks which are intended to make sure the design of the propulsion system is on right track and to assure the nominal operation of all components after launch.

Verification checks [44] whether the requirements comply with the defined specifications and the descriptive documents, while validation checks the compliance with the intended purpose [45].

Table 6. Identified Risks and Failure Modes

#	Risk	Probability	Severity of Consequence	Mitigation
General				
1	Not meeting the requirements	Low-Moderate	Critical	Type II
2	Overdesign (budget)	Moderate	Critical	Type II
3	Manufacturing	Moderate	Catastrophic	Type I & Type II
4	Loss of Resources	Moderate	Marginal	-
5	Human Failure	Moderate	Critical	Type I
6	Power distribution system failure	Low – Moderate	Catastrophic	Type I & Type II
7	Software Failure	Low-Moderate	Catastrophic	Type I & Type II
Propulsion System				
8	Failure of electrical circuits/control electronics	Moderate – High	Catastrophic	Type I & Type II
9	Mechanical failure due to overpressure	Moderate	Critical	Type II
10	Propellant filling/draining options	Low-Moderate	Critical	Type I & Type II
11	Leakage of the fuel in thruster	Moderate – High	Marginal	Type II
12	Failure of one of the heaters in thruster	Moderate	Critical	Type I & Type II
13	Mixing of Propellant & Pressurant	Moderate	Critical	Type I & Type II
14	Microcontroller System failure	Low-Moderate	Critical	Type II
15	Valve stuck in closed/open position	Low	Critical	Type I & Type II
16	Malfunction/flow blockage of Thruster	Moderate	Critical	Type I & Type II
17	Overcurrent	Low-Moderate	Critical	Type I & Type II
18	Leakage of the fuel in Valves & Feed system	Low-Moderate	Marginal	Type I & Type II
19	Leakage of the fuel in Tank	Moderate-High	Marginal	Type I & Type II

Verification is done by one or more of the following methods according to European Cooperation on Space Standardization (ECSS) [46]: testing (including demonstration), analysis (including similarity), review-of-design [ROD], inspection. Each and every requirement must be verified by a different method and this is highly dependable on the requirement itself.

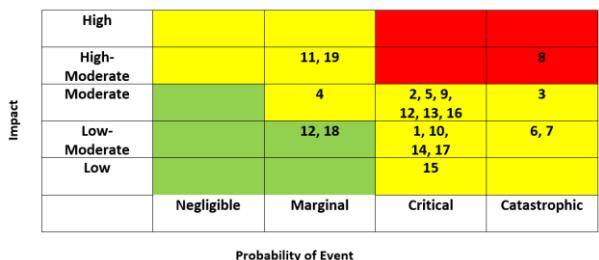


Figure 8. Risk Diagram before Risk Mitigation

Verification is done on the propulsion system by characterizing the performance of individual subsystems and comparing with the theoretical results and models. Each unit is verified by checking if its output matches the results obtained from analytical calculations. Also, the components is verified by unit testing each of them in a vacuum as well as at ambient conditions. The data derived from bigger satellites can still be applied to micro-satellites. Verification methods are selected based on minimum cost, schedule, and applicability. Inspection involves the measuring of a certain characteristic of the system to see if it matches the requirement and it deals with monitoring, keeping track and controlling the mission budgets (mass, volume, etc.) and constraints. The various interfaces like a static envelope, mass, surface finishing, thermal expansion characteristics can be evaluated by Inspection method.



Figure 9. Risk Diagram after Risk Mitigation

Analysis method consists of using models for verification where parameters and performance are assessed. Two different models, CAD model and Finite Element model (FEM) have been developed for the analysis of the system. The former aids in visualizing the design and the latter is used to perform a structural analysis of the assembly. The validation of this tool along with the results obtained is of extreme importance, as the calculations and assumptions made may not be appropriate. Some of the interfaces which can be verified by this tool are payload mass variability, the centre of mass and moments of inertia etc.

Finally, testing is the most visual and spontaneous verification method. In this work, verification by testing is given more preference because of the in-house availability of hardware and test facilities at TU Delft. The various interfaces like dynamic envelope, torque profile, angular momentum temperature range, expelled heat and payload EM field can be verified by testing. A prior analysis needs to be performed so as to evaluate the order of magnitude of different parameters, and to plan the testing campaign accordingly. As components have to survive the vibrations during launch, a vibration test has to be performed. Besides the

launch tests, the components need to be tested for space environment as well. The advantage of using COTS components is that most of these tests have already been performed on the hardware.

Table 7 shows verification matrix for the selected requirements. The software testing is a significant facet of the Delfi-PQ micro-propulsion payload test plan. The micro-propulsion system will use its pressure and temperature sensors to monitor the state of the thruster and propellant tank, and the onboard microcontroller will control the on/off valve capabilities. The EPS will supply unregulated battery voltage to the propulsion system, and commands will be sent using the RS-485 protocol.

Table 7. Verification matrix for the selected requirement

Requirement ID	Requirements Type	R	T	A	I
PROP-SYST-100	Payload Mass	X		X	
PROP-SYST-200	Payload Volume	X	X		
PROP-SYST-400	Delfi- PQ bus/ software interface compliance		X		
PROP-SYST-210	Static Envelope				X
PROP-SYST-220	Dynamic Envelope	X			
PROP-PERF-200	Torque Profile		X		
PROP-SYST-300	Power Consumption		X		
PROP- INT-300	Electrical Characteristics (Frequency, Current, Voltage)	X			
PROP- INT- 400	Data Volume (Bit rate, package size, Sampling rate)	X			
PROP-SYST-110	Payload mass Variability		X		
PROP-INT-100	Centre of Mass		X		
PROP-RAMS-300	Surface Finishing			X	
PROP-INT-110	Moment of Inertia		X		
PROP- INT-210	Thermal Conductivity			X	
PROP- INT-200	Temperature range	X			

The Delfi-PQ bus/ software interface compliance shall be verified by interfacing with other subsystems to assure the communication of micro-propulsion over RS485 is functional. The propulsion board dynamic envelope scaling is carried out for determining the geometrical dimensions of the board shall fit within a volume of 42 x 42 x 30 mm including margins. The electrical test is performed in order to validate if the board delivers the expected frequency, voltage, and current required for the nominal operation. An end to end communication test is also performed by integrating the bus platform to assure the payload communicates with the OBC and the COMMS. A comprehensive verification plan needs to be defined as the testing campaign is planned for summer 2018. The following test campaigns are planned for the Engineering Model of the payload.

- Component level testing (thruster, valves and control electronics)

- Assembly, Integration, and Inspection (Feed System, Sensors, Microcontroller, tank, and thruster)
- Propulsion System Performance test
 - Leak test (Feed system, tank, thruster)
 - Mixing of propellant and pressurant
 - Pressure and temperature measurement of the pressurant gas in the tank
 - Mass flow rate
 - Heating test
 - Calibration of thrust bench
 - Thrust Measurement
 - Pressure drop test

The testing of the micro-propulsion system is done on the component as well as on system level. The testing of individual components allows better characterizing them and checks if there are any differences between the specified and actual performance. When all the individual components are tested for electrical, mechanical and performance characteristics, the system needs to be assembled and integrated. The good assembly requires numerous tests to verify nominal operational performance, the electrical system must be tested to ensure proper integration and interaction with the spacecraft bus. Thrust outputs will be measured by the AE-TB-5m thrust stand [20] available at the Delft University of Technology. The thrust is measured by displacement of the pendulum arm induced by the thrust of the engine. Pressure and temperature measurement of the pressurant gas in the tank will allow determining the propellant mass remaining versus time and hence also change in propellant mass and mass flow rate. It shall also allow to determine the leakage rates and together with the measured thrust it will allow for determining the specific impulse. For both thrusters, heater current and voltage is measured which will allow establishing the temperature of the heater and indirectly of the hot water vapor. It also allows determining the heater power. A thermocouple can also be used for sensing the chamber temperature just prior to the nozzle.

The validation of requirements for the propulsion system is based on the VALID criteria which are illustrated in Figure 10. The requirement validation is performed during the discovery of requirements. If the requirements according to initial design concepts are not properly validated this might result in problems and mistakes in later design phases. It is not easy to validate the design by comparing with other missions because of the nonexistence of data and limited missions on CubeSats with a propulsion system (an even worse

situation is currently faced for pico-satellites and PocketQubes).

The different performance capabilities of the thruster is qualitatively validated by downlinking the thruster data for comparison with ground test data. The thruster performance can be validated by measuring the orbit change, the thrust measurement using IMU/accelerometer, and verifying these values with the propulsion engineering data. Pressure data can be validated by measuring the pressure inside the tank & feed system using pressure sensors and comparing them with the expected value. The same applies to temperature which can be measured by using a temperature sensor on the propellant storage system/ thruster.

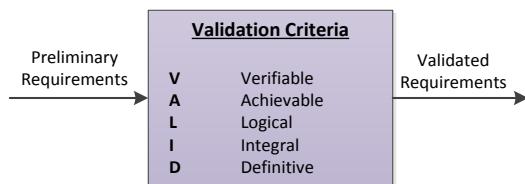


Figure 10. Requirement Validation Criteria [37]

The electrical characterization of thrusters can also be corroborated via resistance test (at a variable temperature) in order to characterize the temperature resistance coefficient and to figure out whether resistance measurements can be used as an indirect measurement of the temperature of thrusters[24].

6. Concluding Remarks

This paper provides an overview of the integration and miniaturization challenges in the design of micro-propulsion systems for picosatellite platforms. In spite of the rapid growth of small satellites, the implementation of propulsion has lagged behind because of system integration challenges. As far as the system development is concerned, currently the breadboard level prototype is being tested with all the components connected in a closed loop manner. This is used to get a better understanding and assessment of the expected micro thruster performance characteristics in orbit like specific impulse, thrust, power consumption, pressure drop, efficiency, mass flow, modes of firing etc. Two thrusters are analyzed and tested separately before final integration with the satellite. Furthermore, subcomponents are chosen based on technology maturity and flight-proven ones. In the meantime, some efforts are also done on the optimization of the mechanical interface of the thruster which is to be attached to the spacecraft. The results will be

verified and validated on the completion of testing as per the scheduled test and launch campaigns planned in early 2019. Based on the experience obtained from the testing of engineering model, a flight qualification model will be designed for the in-orbit demonstrator. When demonstrated on board of Delfi-PQ, this will be the first complete micro-propulsion system ever flown on a picosatellite platform.

7. ABBREVIATIONS AND ACRONYMS

The following abbreviations are used in this paper:

PQ	PocketQube
EPS	Electrical Power Subsystem
ADCS	Attitude and Orbit Control System
COMMS	Communication subsystem
FEA	Finite Element Analysis
LPM	Low-Pressure Micro-resistojet
MEMS	Micro Electro Mechanical System
OBC	On-board computer
VLM	Vaporizing Liquid Micro-resistojet
PCB	Printed Circuit Board
ECSS	European Cooperation for Space Standardization
NASA	National Aeronautics and Space Administration
AITV	Assembly, Integration, Verification & Testing
SYS	System requirements
PERF	Performance requirements
FUN	Function requirements
TRL	Technology Readiness Level
COTS	Commercial Off The Shelf
SSE	Space Systems Engineering

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