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Design of a CubeSat test platform for the verification of small electric propulsion systems

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Abstract. Small satellites represent an emerging opportunity to realize a wide range of space missions at lower cost and faster delivery, compared to traditional spacecraft. However, small platforms, such as CubeSats, shall increase their actual capabilities. Miniaturized electric propulsion systems can provide the satellite with the key capability of moving in space. The level of readiness of miniaturized electric propulsion systems is low although many concepts have been developed. The present research intends to build a flexible test platform for the assessment of selected small propulsion systems in relevant environment at laboratory level. Main goal of the research is to analyze the mechanical, electrical, magnetic, and chemical interactions of propulsion systems with the modern CubeSat-technology and to assess the performance of the integrated platform. The test platform is a 6U CubeSat hosting electric propulsion systems, providing mechanical, electrical and data interfaces, able to handle a variety of electric propulsion systems, thanks to the ability to regulate and distribute electric power, to exchange data according to several protocols, and to provide different mechanical layouts. The test platform is ready to start the first verification campaign. The paper describes the detailed design of the platform and the main results of the AIV activities.

Keywords: CubeSat test platform; miniaturized electric propulsion system; verification of small satellites

1. Introduction

In recent years, CubeSats have gained much attention in the space field due to the lower cost, and the faster development process, if compared to traditional larger satellite missions.

Invented in the university field as a hands-on team work, as in Puig Suari *et al.* (2008), CubeSats are standardized small satellites that are obtaining the interest of space agencies and private companies for pursuing a large set of mission goals. This success derives from the opportunity to build new architectures–that would have been unfeasible or unaffordable with larger spacecraft–allowing to gather unprecedented information and measurements. Examples in this context are the constellations of CubeSats and small satellites for Earth Observation, e.g., Lemur constellations described by Hand (2017) or in support of aerial and terrestrial systems, as in Nguyen (2015). Space exploration is another field where CubeSats can provide valuable support.

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There are many conceptual designs of CubeSats for planetary investigation: examples are in Perez *et al.* (2018), Viscio *et al.* (2013), and they are reality in the last few months with the NASA/JPL MARCO mission, as in Klesh *et al.* (2015). Cubesats are often used as in-orbit technology demonstrators, such as for the rendez-vous and docking and proximity operations Bowen *et al.* (2015). Moreover, CubeSats can support the space missions based on bigger satellites, e.g., to provide communication services and in-orbit inspection.

However, this important contribution of CubeSats to future space missions requires that a new generation of miniaturized technologies reaches a high level of maturity. These technologies are: high data-rate communication systems (Babuscia *et al.* 2015 and Pittella *et al.* 2015), onboard computer able to increase mission autonomy in terms of decision making (Franchi *et al*, 2018), high performance thermal control systems, as in Nur Athira *et al.* (2014) and Conigliaro *et al.* (2018), precise orbit, attitude determination and control systems (Modenini *et al.* 2018) and propulsion systems. Miniaturized electric propulsion systems (PS) have the potential to deeply increasing the range of mission concepts achievable with multi-unit CubeSats (6U+) in terms of orbit change and raising, station keeping and orbit maintenance against the disturbances, formation flying, proximity operations and de-orbit.

A growing number of developers around the world are concentrating their efforts on miniaturized electric PSs, based on both traditional and innovative principles. Dedicated overviews of the miniaturized propulsion technology have been conducted by Muller *et al.* (2010), Staehle *et al.* (2012), Lemmer (2017), Walker and Liu (2013), and Levchenko *et al.* (2017). In the European context, several companies are developing products both with traditional and disruptive technologies. Enpulsion proposes an Ion Electro-spray propulsion system and *Krejci et al.* (2018) presents the results of the in-orbit demonstration. ThrustMe is developing an innovative neutralized-free gridded ion thruster ready for test campaign (Rafalskyi and Aanesland 2017). ExoTrail is working on hall effect thrusters (Lascombes and Henri, 2017), while T4I has developed and tested in relevant environment an innovative, miniaturized helicon plasma thruster (Manente. *et al.* 2017). The Institute of Space Systems (IRS) at University of Stuttgart developed PETRUS, a coaxial, breech fed and low energy PPT for CubeSat applications, delivered at ESA-EPL in January 2018 for test activities (Montag *et al.* 2017). Out of the European boundaries: Parker K.L. (2016**)** summarizes the features of the RF Ion thruster provided by Busek *et al.* (2017) deal with the Accion's electrospray propulsion system, and Siddiqui *et al.* (2017) describe the Phasefour ambipolar thruster.. The majority of these propulsion systems has a level of readiness that is growing up but still remains low. They are deeply tested at propulsion-system level but rarely they are integrated into a CubeSat platform, and few data are available about verification of CubeSats with one of the cited propulsion systems. The complexity of a propulsion system imposes specific attention in the integration with the Cubesat bus because it impacts on the volumes and the internal layout, the required electrical power and the operativity of solar arrays, the chemical contaminations and thermal environment, the electro-magnetic compatibility, the amount of data and the navigation accuracy. Propulsion systems also require special tests on ground to verify the new technology before the in-orbit activities. Weak design and ineffective verification campaigns caused major failures of CubeSats in the past, definitely compromising entire missions.

Some effort has been already made in order to define tools and standards for CubeSats verification. ECSS (2016) traces guidelines for the environmental test campaign and Mozzillo *et al.* (2015) present the application of a tailored procedure for the functional and environmental verification of an educational CubeSat. Stesina *et al.* (2017) present solutions based on "In the

Loop" simulations that get more effective the functional verification of CubeSats, reducing time and cost efforts. For the verification of electric propulsion systems of large spacecraft, in-flight set-up health monitoring systems exist, as for example at IOM (Bundersmann *et al.* 2017). IOM developed an Advanced Electric Propulsion Diagnostic (AEPD) platform, which allows for the in-situ measurement of a comprehensive set of thruster performance parameters. The platform utilizes a five-axis-movement system for precise positioning of the thruster with respect to the diagnostic heads and different set-ups are possible. In the small satellites context, complete ePSs are still rare and, consequently, the facilities able to perform *in situ* tests and diagnostics are very few and still under preparation or certification, e.g., the "Automated Integrated Robotic System for Diagnostics and Test of Electric and micro-Propulsion Thruster", at Singapore. In Europe, a valuable example is the "In the Loop" test bench that has been developed at University of Stuttgart (Montag *et al.* 2017) to characterize the thruster of the PETRUS 2.0 miniaturized electric propulsion system. In particular, this miniaturized Pulse Plasma Thruster (PPT) system is tested in a relevant laboratory environment and the thruster relevant parameters, measured in real time in the lab facility, are directly conveyed to an ASTOS-based model including both the near Earth space physics and the physical model of a spacecraft. The facility under development by POLITO and ESA-EPL adds a CubeSat Test Platform (CTP) in the verification loop aiming at verification of the integrated spacecraft.

The promising perspectives for the Cubesat space missions of the next future and the resulting necessity of new, more performant onboard technologies highlight the importance of tools and procedures that favor the integration and verification between electric propulsion systems and CubeSat bus.

ESA and Politecnico di Torino are carrying out a research program with the objectives of 1) building specific instruments for the verification and validation of miniaturized propulsion systems and 2) identifying an effective and standardized Assembly Integration and Verification (AIV) process for CubeSats equipped with propulsion systems, as in Obiols-Rabasa *et al.* (2015). The final goal is the construction of a facility focused on the qualification for launch of the integrated space system and the assessment of the impact of new technologies at system/subsystem level. The program has been divided in three phases and, at the moment, the first phase is completed with the design, the production and the functional verification of a prototype called CubeSat Test Platform (CTP). This prototype is based on CubeSat technology, compliant with CubeSat specification and ESA requirements, and able to host a wide range of miniaturized electric propulsion systems.

The present paper shows the first results of the program with a focus on the CTP. In particular, the paper deals with the identification of the relevant parameters for the qualification of an integrated CubeSat equipped with an electric PS, the software and hardware description of the CTP and the planned verification campaign. At the present status of the project, the major result is that the CTP can host a range of miniaturized electric propulsion systems with different electrical, mechanical and data interfaces, and fits with the facilities of the ESA Propulsion Laboratory (EPL). Unprecedented measurements can be obtained to assess the mutual impact of the electric PSs and the other onboard subsystems.

2. Cubesat test platform

A 6U CubeSat Test Platform has been designed with the objective of testing at system-level (i.e., CubeSat level) a variety of electric propulsion systems. Some key features drive the design of the platform: safety, reliability, autonomy, flexibility, cost, quantity and quality of measurements. Regarding *safety,* the leakage of fluids and contaminants, over-voltages and over-currents, off nominal temperatures and electromagnetic interferences are threats that have to be assessed, with their effects limited or cancelled. For these purposes, mechanical and electrical protection elements are inserted in the CTP. High *reliability* is pursued through fault tolerance techniques such as the redundancy on critical elements and the distribution of the main functions. In this way, any test is executed nominally, although failures occur in the system: in particular, one failure is tolerated without impact on the test; in presence of two failures the test is completed with degraded performances. For example, relevant data of the experiment are saved and stored in two independent items, and the propulsion system is commanded by two independent lines, where possible. In any case, no single-points failure exist for vital functions. High *autonomy* of the CTP has been designed in order to increase the value of the project in terms of fidelity with respect to the final case of CubeSat in orbit, and also to reduce the effort and workload of operators, and, in consequence, the cost of the test campaign. In any case, a skilled operator can constantly monitor and intervene during the test execution through the ground support equipment. CTP is *flexible* in order to be compliant with a variety of miniaturized electric propulsion systems and to run different functional and environmental tests. Flexibility is reached through a high number of electrical and data interfaces and versatile mechanical supports. However, some modifications could be required in the area of electrical power to adapt the platform to the specific propulsion system under test.

The entire system makes use of commercial *off-the-shelf* technology and low-*cost* processes.

2.1 Measured parameters

CTP gathers many measurements which are fused and analyzed with the information derived from instruments placed in the EPL facility. The information allows to assess the conditions and the phenomena related to the simultaneous operations of the electric PS and the other onboard subsystems.

Table 1 List of measurements

Parameter [unit]	Instrument	Range	Accuracy
	Thrust performance		
Thrust [mN]	Torsional thrust balance (GSE), accelerometer (CTP)	[0 ; 40]	0.05
Specific Impulse [s] and effective specific impulse [s]	Indirect measurement obtained from thrust measurement	[0 ; 5000]	1
Impulse bit [µNs]	Indirect measurement obtained from thrust measurement	[0 ; 5000]	1
	Mass flow and mass variation		
Mass flow rate [mg/s]	Mass flow sensors (GSE)	[1 ; 10]	0.1
Flux mapping (plume residual contamination)	Kapton tape (CTP), Microscope (GSE), Spectrometer (GSE)		
Propellant mass variation per area [g/cm^2]	Quartz Crystal Microbalance (GSE)	[0 ; 10]	0.1
Propellant mass consumption[g]	Balance (GSE)	[0 ; 1000]	10

Table 1 List of measurements

Parameter [unit]	Instrument	Range	Accuracy
	Electrical and environmental diagnostics		
Current [mA]	Amperemeter (GSE), current sensing (CTP)	[0 ; 5000]	10
Voltage [V]	Voltmeter (GSE), voltage sensing (CTP)	[0 ; 28]	0.01
Temperature [°C]	Thermocouples (GSE), NTC temperature sensors (CTP)	[-20 ; 150]	0.1
Magnetic field [T]	Magnetic Field Mapper (GSE), Magnetometer (CTP)	[10^{-5} ; 10^{-2}]	10^{-5}
	Other (parameters of specific ePSs)		
Radio-frequency emission [dB/Hz]	Spectrum analyser (GSE)	[0 ; 60]	0.1
Ion energy [eV]	ExB probe (GSE), Retarding Potential Analyser (GSE)	[0 ; 500]	0.1
Ion current [$\mu A/m^2$]	Faraday Cups (GSE), Langmuir Probe (GSE)	[0 ; 300]	0.1

Four sets of parameters can be identified for characterizing the propulsion system performance and its impact on other subsystems: 1) thrust performances, 2) mass flow and mass variation, 3) electrical and environmental diagnostics and 4) other parameters specific to the single type of electric PS. Table 1 reports the list of measured parameters, the adopted instruments, the range and accuracy of measurements. In details, CTP is equipped with a triaxial accelerometer, Kapton tape on the surfaces, ten NTC (Negative Temperature Coefficient) thermistors, current and voltage sensing circuits, and a triaxial magnetometer. To complete the measurement suite, external sensors and tools (which are part of the Ground Support Equipment - GSE) are included in the set-ups: torsional thrust balance, mass flow sensors, microscope, spectrometer, Quartz Crystal Microbalance, amperemeter and voltmeter, thermocouples, Magnetic Field Mapper, Faraday cups and Langmuir probes.

Depending on the electric PS under test, different sets of measurement and related sensors are used and/or activated. For example, testing PPTs will require to measure the impulse bit via a balance different from that used to measure continuous thrust. The accelerometer has been introduced to assess the forces acting on the platform during firing of the thruster in the specific point of interest of the CTP, when necessary.

Electro-Magnetic Interference is evaluated through measurements and analysis of the magnetic field and the electric field. The measurements are performed by a spectrum analyzer, and a Magnetic Field Mapper. Moreover, in some points of the spacecraft, magnetometers are available to complete the assessment. All these measurements allow to assess the mutual impact of ePS and CTP avionics and support the identification of the boundaries and, consequently, of the requirements about the EM environment generated and tolerated.

2.2 CTP description

The physical layout (Fig. 1) of the CTP consists of two main parts, contained in a 6-unit (6U) structure. The *PS box* is a up to 4U-size box for hosting the propulsion system: thrusters, fluidic lines, tank(s), and Power Control Unit. A movable bulkhead fixes the electric PS to the structure

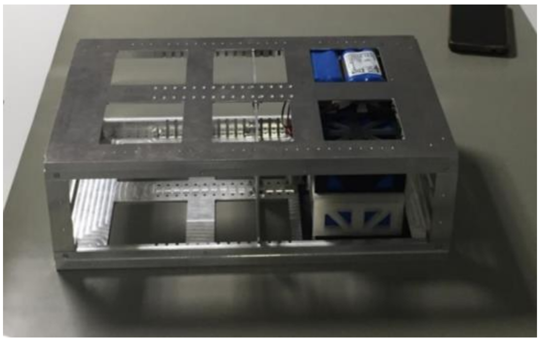

Fig. 1 CTP layout

and separates it from the *Service Module*. The *Service module* contains the avionics and the equipment supporting the test execution. The avionics subsystems are made of the Command and Data Handling (C&DH) System, the Communication System (COMSYS), and the Electric Power System (EPS). All the boards stay in the *avionics box*, and are connected through a 104-pin bus for electrical power supplying and data exchange. Mechanically, they are mounted on a stack of four bars that fix the *avionics box* to the structure. The dipole antenna of the COMSYS is mounted on the +Z face.

The entire *avionics box* occupies a 1U on the +X/+Y side of platform. The side +X/-Y is allocated to host the PS battery packs. The present version of the CTP has been thought as a laboratory test object but few interventions would be necessary to get this platform ready for a qualification campaign targeting in-orbit demonstration. Dimensions and masses are compliant with the CubeSat Design Specification, but no coating and surfaces treatments have been made, and some items should be replaced with space qualified elements. The avionics has parts that have already flown in other missions while other elements need to be qualified because some circuits have been redesigned and/or adapted.

2.3 CTP Interfaces

The variety of CTP interfaces confers the expected flexibility to host electric PS with different mechanical, electrical and data interfaces and to connect the platform with the test facility (i.e., to GSE).

Towards the propulsion system, the CTP provides a regulated operating voltage in the range [5; 28] V with a maximum current of 2 A, and it supplies autonomously the PS without the necessity to use external power suppliers. From a structural and mechanical point of view, the CTP hosts the PS with a maximum size equal to 4U and a mass up to 6 Kg, and guarantees the fastening of the PS within the 6U volume. CTP can also exchange information (commands and data) with the PS via I2C, SPI, RS232/RS485, USB and CAN bus protocols every five seconds, and it stores data from electric PS in onboard memories up to once per second

For the execution of the tests, the CTP is integrated in the vacuum chamber of the EPL. EPL standard Ground Support Equipment (EPL-GSE) are used to support the execution of test. They are power supply units to provide electrical power to the CTP, sensors and acquisition units to gather measurements, cables and connectors. A dedicated Ground Support System (GSS) is also developed to complement the CTP for the preparation and the execution of tests and the analysis of

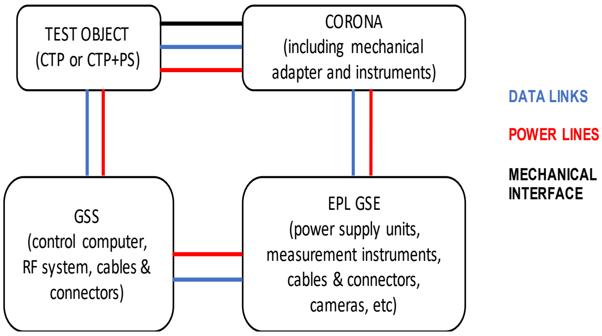

Fig. 2 System architecture

the results. A control computer with customized software and radio-frequency equipment constitutes the backbone of the GSS. The CTP interfaces towards the GSS and the GSE are available on the +Y face: battery charging ports, hard-line data connectors, and switches. The CTP receives from the power supplier up to 1. 8A @ 26 V to recharge PS battery, and up to 1A @ 16 V to recharge the avionics battery.

The CTP exchanges data with the EPL facilities via feedthroughs and GSE: the CTP sends data every 10 seconds via RF link and every second via hard-line. The radiofrequency link has been included for two main reasons: 1) to provide a redundant line, and 2) to emulate the only communication link which will be available during real mission operations, thus reproducing a more realistic conditions. In this way, it is possible to reach a higher level of confidence with respect to the mutual impact of avionics and electric PS in terms of power consumption and electromagnetic interaction.

Fig. 2 summarizes the interfaces among the main systems. The Test Object refers to the CTP including the PS, or the CTP alone. For the first phase of the program, test object is the CTP without a propulsion system. CORONA is the EPL chamber selected for the verification campaign with the propulsion system. EPL GSE including sensors, power suppliers, and cameras, support the test execution. The GSS is the control center where the operators can monitor and assess the trend of the ongoing verification.

The current version of the CTP is compliant with EPL's interfaces but could be adapted to other laboratories with different instrumentation and test equipment.

2.4 Service module

Command and Data Handling. The C&DH core is the microcontroller, based on ARM9 architecture. It is located on the C&DH board together with acquisition units (multiplexers and Analog to Digital Converter – ADC) that acquire measurements of the NTC thermistors, and strain gauges, located both on the service module and in the PS box. A triaxial magnetometer and three accelerometers are surface-mounted on the board, and a slot is available to host the SD-card.

Linux Embedded 6.32 version is the selected Real Time Operating System (RTOS) that guarantees a soft real-time (+/- 100 μs) sufficient to accomplish all the software tasks without loss of synchronization. A customized kernel allows the interfaces via different protocols. Moreover, drivers, real time clock and General Purpose Input Output (GPIO) pins settings are available, and a software watchdog is enabled.

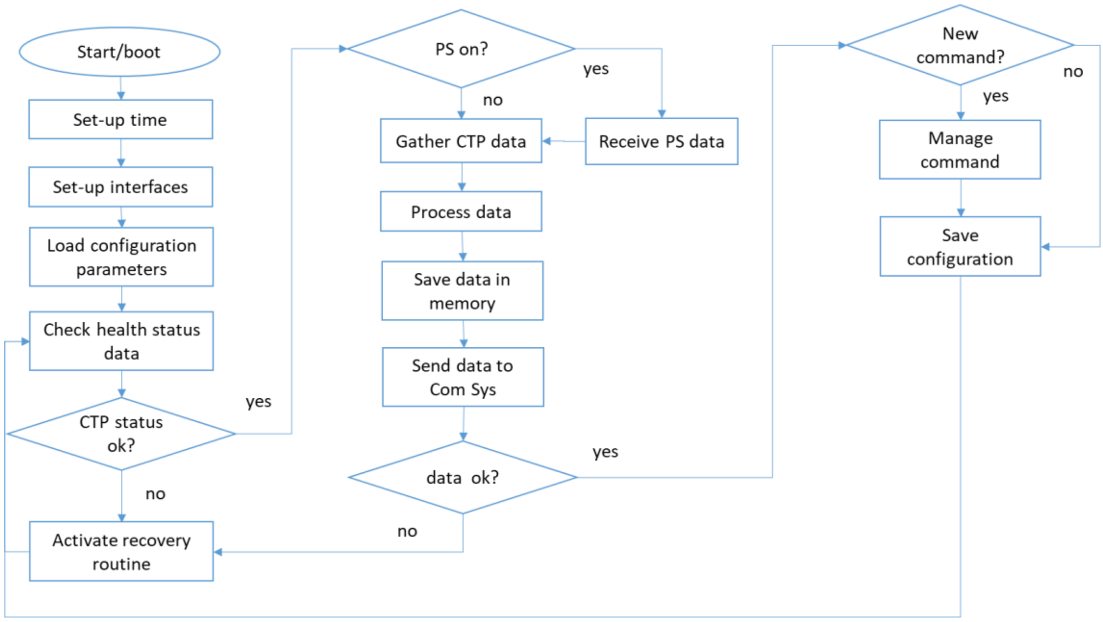

Fig. 3 CTP software flowchart

Application software of the C&DH system is written in C++ language, cross-complied and the executable file is uploaded onboard through USB or Ethernet port. The flow chart of the software is reported in Fig. 3.

The process initializes a set of parameters: time word, interface parameters, and configurations values. The main loop starts with checks of compliance of the critical parameters: batteries charge status, bus voltage and consumption, acquisition chains and command chain integrity. In case of non-nominal conditions, recovery routines are activated, else the command and data handling functions are performed. The data handling consists of receiving data from the propulsion system (if active) and collecting data from all the onboard sensors that give the status of the subsystems and the measurements of the interactions between the propulsion system and platform elements. Data are processed, formatted, saved in SD card and non-volatile memory, and get available to the COMSYS for the transmission. All the data are checked: if one of them is out of range, recovery actions are applied; instead, if everything is correct, a new command is validated, decoded and executed. The loop ends with the updating and saving of all the configuration parameters and the time word.

Communication System. The CTP communicates with the GSS through a wired link and a radiofrequency link. The wired link is the serial connection made with RS232 protocol. For the radiofrequency link, a qualified system is selected and described in Busso (2017), and it is characterized by a 90x96 mm board equipped with a radio-module operating at 437 MHz frequency; a Terminal Node Controller (TNC) manages KISS AX.25 protocol frames; a clock counter oversees the synchronization; and a dipole antenna sends/receives the signal.

Electrical Power System (EPS). EPS has two main elements: 1) the main electronic board with avionics battery packs, and 2) the auxiliary electronic board with PS battery packs. The boards and the avionics batteries stay in the avionics box while PS battery packs stay in the second unit of the Service Module. The EPS main board contains the avionics battery recharging circuits, the

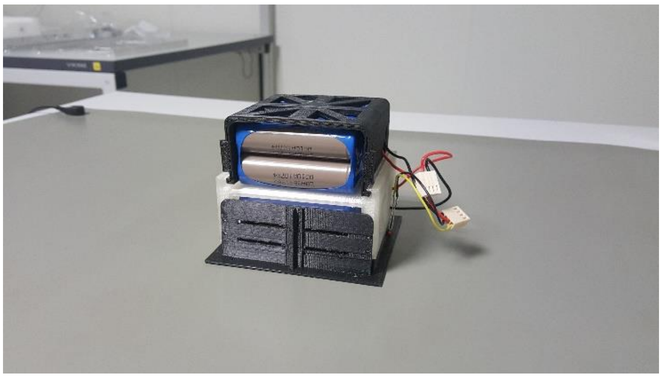

Fig. 4 PS battery mounted on their support

regulation units, the protection circuits, and the housekeeping sensors. Battery Charge Regulators (BCR) receive up to 16 W and provide energy for the two batteries (4 cylindrical AA-size Li-Ion cells with capacity of 2 Ah @ 7.4V). The regulation unit takes the voltage from the battery packs and provides the power bus voltages at 3.3 V and 5 V. Protection circuits are diodes that separate the batteries from power bus and recharging lines. Loads Switch (LS) controls the activation and the deactivation of the CTP and two Remove Before Test (RBT) switches allow to isolate each battery pack from the respective BCR when the CTP is not used and no recharging activity is foreseen.

The avionics batteries have to provide the peak power consumption of avionics (3.3 W, when RF signals are transmitted and PS is active) and to maximize the discharge cycle duration. Avionics battery recharging accepts in input up to 9 W, guaranteeing a complete recharging of both packs in less than 5 hours.

The Auxiliary board is dedicated to the electrical interface with propulsion system. BCRs accept in input up to 30 W and provide the energy to recharge the two PS battery packs (8 cylindrical AA-size Li-Ion cells with capacity of 5 A), as pictured in Fig. 4. Step-up circuit raises the 14.8 V of the PS battery up to 28 V, the maximum voltage that is provided to the PS. A Pulse Width Modulation (PWM) driver regulates the step-up circuit output in the range [5; 28] V, in order to give the desired voltage (and power) to the PS under test. Protection circuits prevent overcurrent, overvoltage or short circuits on the power bus. Two RBT switches isolate each battery pack from the respective BCR when the CTP is not used and no recharging activity is foreseen. PS battery recharging is performed through an external power supplier. The recharging unit is sized in order to accept in input 32 W, allowing a complete recharge of the battery in less than 6 hours.

Structure. The primary structure is constituted by two 29.6 cm x 20.2 cm Aluminum 6061 alloy elements joined by four brackets to form a rectangular box. Six panels protect the onboard subsystems from the external environment. The PS and the avionics elements are screwed to the primary structure. External mechanisms and removable structural parts can be mounted on the external panels to change the configuration for specific test needs, and to host antennas and sensors.

2.5 CTP modes of operation

The CTP has five operative modes. In *Dormant mode*, all the subsystems are switched off. In

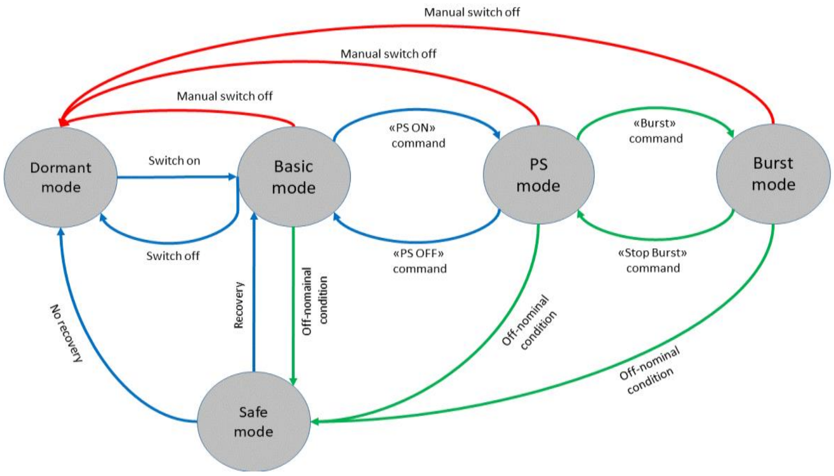

Fig. 5 CTP operative modes

Basic mode, the CTP avionics is operative while the PS is off. In *PS mode*, CTP avionics is active, PS is on but the thruster is not active. In *Burst mode*, avionics and PS are active and the thruster is boosting. In *Safe mode*, CTP avionics is active, recovery actions are performed, while PS is completely switched off. Fig. 5 shows the transition between operative modes: the red lines indicate a transition made with the intervention of the operator, green lines show autonomous transitions, and blue lines represent transitions that could be made autonomously and/or with the operator intervention. Manual transitions are foreseen for safety-critical functions. CTP avionics, PS and thruster burst can be activated/deactivated either with a command from the GSS or directly by the platform when well-identified conditions are checked. Transitions due to off-nominal conditions are managed autonomously by the CTP, while transitions after completion of recovery routines can be performed both by the operator and directly by the CTP.

2.6 CTP budgets

Mass budget in Table 2 reports the values of the mass for any part of CTP.

PS mass value refers to the heaviest candidate propulsion system, the *Regulus* Helicon Plasma Thruster from the University of Padua/T4I (Pavarin *et al.*, 2017). The dry mass of *Regulus* is 1.4 Kg, plus 1 Kg tank and propellant. Avionics box has a total mass of 1.3 Kg, including avionics battery, sensors mounted outside the avionics (e.g., temperature sensors) and the antenna. PS batteries have a mass of about 480 grams. Structure and Mechanisms have a mass of 2.1 Kg, including the mechanical interface with EPL chamber.

The power budget is driven by the consumption of the specific PS under test. Table 3 highlights power consumption for each CTP mode. *Regulus* has the highest power consumption (50 W) among the candidate propulsion systems. Power budget has been calculated estimating the peak and the average power consumption at subsystem level.

Data budget derives from the frequency and the format of the packets, and changes according the CTP operative modes. Each packet has 303 bytes that include the header, the time information, the configuration parameters, the housekeeping data, the PS data and the packet closer with the reliability code. From the storage point of view, during the basic mode and PS mode, the packet is

Table 2 Mass budget

Subsystem/Element	Mass [g]
PS*	2400*
C&DH –board and sensors	154
EPS- main + AV board	244
EPS – auxiliary	126
EPS - PS battery	220
COMSYS – board	152
COMSYS antenna	25
S&M	2120
Total	5431

*include 20% margin

Table 3 Power budget

			Basic Mode		PS Mode		Burst Mode		Safe Mode	
S/S	S/S mode	Power C. [W]	DC	Power C. [W]	DC	Power C. [W]	DC	Power C. [W]	DC	Power C. [W]
PS	ON/thrust	60	0	0	0	0	1	60	0	0
	ON/ No thrust	2.4	0	0	1	2.4	1	2.4	0	0
	OFF	0	1	0	0	0	1	0	1	0
EPS	ON/Burst	3.84	0	0	0	0	1	3.84	0	0
	ON/ Step up ON	0.12	0	0	1	0.12	1	0.12	0	0
	ON/ Step up OFF	0.18	1	0.18	1	0.18	1	0.18	1	0.18
CDH	ON	0.72	1	0.72	1	0.72	1	0.72	1	0.72
	OFF	0	0	0	0	0	0	0	0	0
COMSYS	ON–TX	2.04	0.1	0.204	0.2	0.408	0.2	0.408	0	0
	ON-RX	0.24	0.9	0.216	0.8	0.192	0.8	0.192	1	0.24
				1.32		4.02		67.85		1.14

generated every 5 seconds while during the burst mode and the safe mode, packets are generated every second. From the transmission point of view, differences on the data budget occur depending on the transmission line. During the basic mode and the PS mode, the packet is sent every 5 seconds while during the burst mode and the safe mode, packets are sent every second through the wired hard-line. Considering the RF link, packets are sent every 30 seconds in basic, PS and Burst modes, while no transmission is performed when the platform enters the safe mode.

3. Experiment phases

Each verification campaign shall pass through six main steps: 1) Integration, 2) Set-up, 3)

Table 4 Experiments phases

Phase	Sub-Phase	Start event	End event
Integration	Integration	CTP and PS tested	CTP and PS integrated
Set up	CTP installation	CTP and GSE checked	CTP installed in chamber
	Pre-experiment checks	Reduced functional tests	CTP, EPL chamber and GSE tested
	EPL chamber activation	EPL chamber switched on	EPL chamber operative
Execution	CTP activation	CTP switched on	CTP checks completed
	PS activation	PS switched on	PS checks completed
	Sequence execution	Test started (Thruster on)	Test stop (Thruster off)
	CTP deactivation	CTP checks started	CTP switched off
Conclusion	EPL chamber deactivation	EPL chamber switched off	EPL chamber checks completed
	CTP deinstallation	EPL chamber door open	CTP out of EPL chamber
Analysis	Data collection	Data gathered from CTP	Data downloaded
	Data analysis	Data available to users	Test results available
CTP stowage	CTP checks	CTP ready for test	CTP checked
	CTP stowage	End of data processing	Next test session

Execution, 4) Conclusion, 5) Analysis, and 6) CTP Stowage (Table 4). During the *Integration* step, the CTP and the PS (already tested as stand-alone systems) are integrated, all the mechanical, electrical and data interfaces are connected, and reduced functional tests are performed. In particular: data exchange, power supplying, voltage regulations, and communications are checked. *Set-Up* starts with the installation of integrated CTP in EPL chamber, followed by reduced functional tests to confirm the operativity of CTP, EPL chamber and GSS. The success of these tests leads to the activation of the chamber and the operative test conditions are reached. During the *Execution* phase, the CTP and the PS are activated and the planned test sequence is applied. At the end of the sequence, the PS and the CTP are progressively deactivated. The *Conclusion* step certifies the end of the test; the chamber is switched-off and the CTP is pulled out. The *Analysis* consists in data collection, analysis and delivery to users, as well as checking the CTP before moving to the *CTP Stowage*, that makes the CTP available for the next sessions.

4. Conclusions

With the strong market demand for affordable space assets, there is little doubt that the number of small satellites will continue to grow. Small satellites are projected into a brilliant future, but the technology still needs improvements and the process of manufacturing, assembly, integration and verification shall be made more efficient.

Miniaturized electric propulsion systems deeply increase the range of mission concept achievable with multi-unit CubeSats (6U+). However, a low TRL, poor integrability with existing small satellites technology and difficulty to effectively complete a test campaign, generate a significant gap for electric propulsion solutions with respect to traditional technologies, reducing the set of applicability of EP systems in the space domain.

To fill this gap, the work presented in this paper aims at certifying that the new electric propulsion systems are not a thread for the other onboard subsystems, and will assess the mutual effects between the platform bus and the propulsion system.

The outcome of the CTP project will guide the thruster and the hosting platform to the qualification for in-orbit demonstration, through the development and validation of a comprehensive test environment, including test platform and test procedures, able to qualify the electric propulsion system design at spacecraft level in relevant environment. The platform allows performing a complete qualification campaign of the entire system evaluating its efficiency through the merging of measurements obtained by sensors mounted inside and outside the CTP. In particular, information about electromagnetic compatibility, thermal environment induced by the operations of the subsystems (specifically, of the propulsion system), and electrical consumption are combined in order to provide an unprecedented framework to developers of electric PS and CubeSats, thus facilitating the transition of products from lab to market quickly and efficiently.

The CTP is a valuable instrument to increase the level of readiness of new technology and consolidate the capability and robustness of already available CubeSat equipment and subsystems. In the context of the proposed research, future efforts will be addressed to raise the quality and quantity of provided data, adding new sensors and acquisition instruments, to improve the flexibility of the interfaces, to support the functional tests on torsional balance, and to extend the test objects range to a wider type of CubeSat technologies.

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EC

Acronyms

ADC	Analog to Digital Converter
AIV	Assembly, Integration and Verification
BCR	Battery Charge Regulator
C&DH	Command and Data Handling
COMSYS	Communication System
COTS	Component Off The Shelf
CTP	CubeSat Test Platform
DC	Duty Cycle
ECSS	European Cooperation for Space Standards
EPL	ESA Propulsion Laboratory
EPS	Electric Power System
GPIO	General Purpose Input Output
GSE	Ground Support Equipment
GSS	Ground Support System

LEO	Low Earth Orbit
LS	Loads Switch
PCB	Printed Circuit Board
PPT	Pulse Plasma Thruster
PPU	Power Processing Unit
PS	Propulsion System
PWM	Pulse Width Modulation
PS	Propulsion System
QCM	Quartz Crystal Microbalance
RBT	Remove Before Test
RF	Radio Frequency
RTOS	Real Time Operating System
S&M	Structure & Mechanisms
SPI	Serial Parallel Interface
TCS	Thermal Control System
TNC	Terminal Node Controller