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Project-based learning applied to spacecraft power systems: a long-term engineering and educational program at UPM University

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Abstract

The IDR/UPM Institute is the research center responsible for the Master in Space Systems (MUSE) of Universidad Politécnica de Madrid (UPM). This is a 2-year (120 ECTS) master's degree focused on space technology. The UPMSat-2 satellite program has become an excellent educational framework in which the academic contents of the master are trained through project-based learning and following a multidisciplinary approach. In the present work, the educational projects developed and carried out in relation to spacecraft power systems at the IDR/UPM Institute are described. These projects are currently being developed in the framework represented by the aforementioned MUSE master's program and UPMSat-2.

Keywords Spacecraft power systems · MUSE · UPMSat-2 · IDR/UPM · Project-based learning

1 Introduction

The aim of the present work is to describe the academic design of the education on space power systems at IDR/UPM Institute; this task is carried out through:

- the power systems subject of the Master in Space Systems (MUSE¹), and
- the projects offered to the students as case study II and case study III within this master's program; these projects are directly derived from space engineering contracts and missions in which IDR/UPM Institute is involved.

This paper is organized as follows. In this first section, the background in space engineering at IDR/UPM Institute is described, in order to explain the framework in which the education on space power systems has been developed. In Sect. 2, the design of the power systems subject of the MUSE is described, whereas in Sect. 3 different projects carried out by the master's students as case study II and case

study III are summarized. Finally, conclusions are included in Sect. 4.

1.1 Space engineering at Universidad Politécnica de Madrid (UPM)

Projects on space systems engineering have been carried out at Universidad Politécnica de Madrid (UPM) since the early works carried out by Prof. Da Riva and Prof. Meseguer, analyzing the effect of microgravity on liquid bridges in the late 70s [1–8]. This initial research on liquid bridges was maintained until the mid-1990s by the academic and research group under the supervision of the aforementioned Profs. Da Riva and Meseguer (see Fig. 1).

Other relevant examples of space engineering activities carried out by this engineering research group that became the IDR/UPM Institute² in the late 90s are:

- The Handbook on Spacecraft Thermal Control for the European Space Agency (ESA), which was developed in collaboration with Dornier System GmbH, in 1975 [9]. After several updates and amends, this work has become

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² The IDR/UPM Institute (Instituto Universitario de Microgravedad “Ignacio Da Riva”) was established as a research institution inside Universidad Politécnica de Madrid in 1998.

Fig. 1 Breaking of a cylindrical volume liquid bridge by stretching during the Spacelab-D2 mission (experiment STACO) in 1993

Fig. 2 Sketch of the UPMSat-1: 0: multilayer insulation, 1: antenna, 2: magnetic coils, 3: liquid bridge cell, 4: gyroscopes, 5: magnetometers, 6: electronics box, 7: batteries, 8: side panels, 9: solar panels. See [10–12]

the Spacecraft Thermal Control Design Data Handbook, STCDD ESA PSS 03-108.

2. The UPMSat-1³ (see Fig. 2), a 50-kg microsatellite designed, developed and constructed by professors, students and other staff of the Aeronautical Engineering school of UPM under the guidance of Prof. Meseguer and Prof. Sanz [10–12]. This spacecraft was the first 100% Spanish satellite and it was successfully launched in 1995. It should be also mentioned that according to the last work from Profs. Swartwout and Jayne, this mis-

sion is 12th in the ranking of the 272 university-class satellite missions developed since the Australis OSCAR 5 mission in 1970 and the UoSAT 1 mission in 1981⁴ [13].

3. The CPLM payload (the acronym stands for liquid bridge behavior under microgravity experiment, in

⁴ In fact, the UPMSat-1 mission is not mentioned in the list provided in the work by Swartwout & Jayne. Nevertheless, once informed by IDR/UPM staff in April 2017, Prof. Swartwout committed himself to include the UPMSat-1 mission in future works.

³ Also known as UPM-Sat 1.

Fig. 3 UPMSat-2 CAD (Computer-Aided Design) sketch by MUSE students with CATIA™

- Spanish), designed and manufactured in the late 1990s for the Spanish satellite MINISAT [14].
4. The OSIRIS (optical, spectroscopic and infrared remote imaging system) thermal control analysis. This instrument was developed for the Rosetta mission of the European Space Agency (ESA), devoted to the exploration of the 67P/Churyumov-Gerasimenko comet. OSIRIS is a dual infrared camera system consisting of a high-resolution narrow-angle camera (NAC) for the study of the nucleus of the comet and a wide-angle camera (WAC) designed for recording dust and gas emissions on the surface of the comet [15].
 5. The SUNRISE thermal control. This telescope was flown on a balloon at stratospheric altitudes to analyze the structure and the dynamics of the solar magnetic field. SUNRISE can be considered as a precursor of the instrument PHI, which is one of the payloads of the Solar Orbiter mission of ESA [16, 17].
 6. The thermal control subsystem and the structure analysis of the NOMAD⁵ payload for the ExoMars mission [18, 19].
 7. The thermal control subsystem and the structure analysis of the SO/PHI⁶ and EPD⁷ payloads for the Solar Orbiter mission [20].

It should be underlined that today, the educational and research activities related to space power systems at IDR/

UPM Institute represent the logical evolution from the projects mentioned above. More precisely, these activities are mostly derived from the works carried out within the UPM-Sat-1 mission, which can be briefly summarized as:

- Solar panel testing.
- Battery development, testing, and qualification.
- Power distribution subsystem (harnessing).
- Power subsystem integration.

Unfortunately, the engineering work related to the UPM-Sat-1 power subsystem was interrupted for 15 years (the know-how being almost completely lost), as the resources of the research group were focused on space projects carried out in collaboration with the European Space Agency (ESA) and the IDR/UPM Institute foundation. Nevertheless, the spacecraft power subsystem engineering reborn within the IDR/UPM Institute activities thanks to both:

- the development of the UPMSat-2 satellite, and
- the development of the academic program related to the Master in Space Systems (MUSE) of Universidad Politécnica de Madrid (UPM).

1.2 The UPMSat-2 mission

As the aforementioned UPMSat-1, the UPMSat-2 is a 50-kg university-class satellite entirely developed at Universidad Politécnica de Madrid (see Fig. 3 and Table 1). This long-term project was started in 2009 thanks to the vision of

⁵ Nadir and Occultation for MArS Discovery.

⁶ Solar Orbiter Polarimetric and Helioseismic Imager.

⁷ Energetic Particle Detector.

Table 1 General characteristics of the UPMSat-2 mission

Mission life	2-year
Orbit	Sun-synchronous 10:30 (almost noon) (*) Altitude: 700 km (*)
Mass	50 kg
Dimensions	0.5 m × 0.5 m × 0.6 m
Attitude Control	Magnetic SSBV magnetometers ZARM Technik AG magnetorquers Control law designed by IDR/UPM [22]
Thermal Control	Passive
Power	Based on solar photovoltaic panels and batteries 5 body-mounted solar panels (Selex Galileo SPVS-5 modules with Azur Space 3G28C triple junction solar cells) Li-ion battery designed by SAFT batteries Direct Energy Transfer (DET)
On-board electronic box (E-BOX)	Based on FPGA (designed by Tecnobit S.L. and programmed by STRAST/UPM). Includes On-board computer Data handling Power supply control Power supply distribution
Communications	Link at 436 MHz frequency 4 monopole antennae system Emsys communication card installed in the E-BOX Ground station software programmed by STRAST, hardware configuration supervised by INTA
Payloads	Bartington magnetometer SSBV rotation wheel Iberespacio thermal microswitch Solar sensors Tecnobit on-board computer (E-BOX)

(*) This data has been recently updated

119 Prof. Meseguer and Prof. Sanz, who decided to restart the
120 satellite-class program initiated with the previous spacecraft.
121 An engineering and flight model was produced by 2013.
122 However, this mission has suffered two delays in the launch,
123 as it is planned to be launched as a secondary payload of a
124 much bigger satellite mission. This delay had an important
125 academic outcome: the engineering projects related to the
126 different UPMSat-2 subsystems development readjusted
127 their rhythm, allowing the involvement of students from the
128 MUSE since 2014. From this moment, this satellite became
129 the perfect platform to train the students of this master in
130 space technical requirements at professional level, taking
131 into account that the main objective of their work is a real
132 mission [21].

133 It should also be mentioned that the UPMSat-2 mission
134 has produced a successful collaboration between many
135 partners: the IDR/UPM Institute (leader of the project);

the STRAST⁸ research group of Universidad Politécnica
de Madrid (Responsible of developing the UPMSat-2 (on-
board and ground control station software); TECNOBIT
(E-BOX,⁹ see Table 1); EADS CASA Espacio (electrical
and communication wire harness of the satellite); INTA¹⁰
(ground control station development and testing); SAFT bat-
teries (support in relation to ground and pre-launch battery
maintenance); CT Ingenieros (harness development); DHV
Technology (solar cells/panels development support).

1.3 The Master in Space Systems (MUSE) at Universidad Politécnica de Madrid (UPM)

The Master's degree in Space Systems (MUSE) at Univer-
sidad Politécnica de Madrid (UPM) is a 2-year degree Mas-
ter's program that comprises 120 ECTS.¹¹ This educational

⁹ Electronics Box.

¹⁰ National Institute of Aerospace Technology "Esteban Terradas" (INTA). Spanish National Aerospace Research Agency.

¹¹ European Credit Transfer and Accumulation System.

⁸ Sistemas de Tiempo Real y Arquitectura de Servicios Telemáticos (Real-time Systems and Telematic Services Architecture). <http://www.dit.upm.es/~str/>

Table 2 Subjects included in the Master in Space Systems (MUSE) of Universidad Politécnica de Madrid (UPM), classified by types of learning

Types of learning	ECTS (total)	Subject	ECTS	Semester
M	54	Advanced mathematics 1	6.0	1
		Advanced mathematics 2	6.0	2
		High speed aerodynamics and atmospheric reentry phenomena	4.5	2
		Vibrations and aeroacoustics	4.5	1
		Quality assurance	4.5	3
		Space industry and institutions seminars	1.5	1
		Production technologies	4.5	3
		Space integration and testing	4.5	3
		Spacecraft propulsion and launchers	4.5	1
		Orbital dynamics and attitude control	4.5	3
		Communications	4.5	4
		Data housekeeping	4.5	4
M + PBL	34.5	Graphic design for aerospace engineering	4.5	1
		Space environment and mission analysis	4.5	1
		Heat transfer and thermal control	6.0	2
		Power subsystems	4.5	2
		Space structures	4.5	2
		Space materials	4.5	3
		Systems engineering and project management	6.0	1
PBL	31.5	Case study I	3.0	2
		Case study II	7.5	3
		Case study III	6.0	4
		Final project (i.e., master thesis)	15.0	4

M mono-disciplinary learning, *M + PBL* mono-disciplinary learning with some academic load carried out by project based learning and multi-disciplinary approach; *PBL* project-based learning

program is based on all the research and academic work carried out by the staff of the IDR/UPM Institute in space technology within the last 40 years [23]. Besides, it should be mentioned that this is the first official master's degree that has been developed and organized by a research institute within the UPM instead of any of the engineering faculties/schools, which are normally responsible for managing all educational programs.

The academic load of the Master's degree in Space Systems (MUSE) was designed taking into account two major guidelines: (1) multidisciplinary approach and (2) Project-based learning (PBL). Both represent a key factor in engineering education, as students involved in these programs seem to be capable of better solutions when compared to other students from mono-disciplinary approach programs [24]. This is a fact in space engineering education [25], where PBL has proven to be the best way to combine both the academic requirements and the needs from the industry [26].

With regard to the general competencies and learning objectives, MUSE's academic program was design to allow the students master the following:

- Be able to develop original ideas to solve problems in professional and research contexts.
- Use the acquired knowledge in space systems to solve problems in multidisciplinary and less familiar contexts.
- Be able to integrate different knowledge to draw conclusions from limited amount of information, preserving social and ethical responsibilities.
- Communicate conclusions to specialized and non-specialized audiences, being clear and without ambiguity.
- Be able to fulfill further studies and research/academic degrees.
- Predict and control the evolution of complex situations within the multidisciplinary research, technological, and professional context related to space systems developing new methodologies.
- Be familiar with the quality control systems applied to spacecraft and space engineering, particularly with ECSS (European Cooperation for Space Standardization) standards.
- Be able to work in group, leading it when required.

In Table 2, the subjects of this 4-semester Master's degree program are shown. These subjects are classified into three categories:

- Mono-disciplinary (i.e., traditional) learning (Advanced Mathematics 1 and 2, Quality Assurance...).
- Mono-disciplinary learning with part of the academic load carried out by PBL and multidisciplinary approach (heat transfer and thermal control, power subsystems...).
- Project-based learning (PBL) subjects (case study I, II and III, and final degree project).

The academic load distribution, in terms of ECTS, is also indicated in Table 2. Taking into account these figures, it can be observed that PBL represents more than 50% of this master's degree academic load. More information on this Master's degree can be found in [23].

Finally, it should be underlined that the results of the 2017 survey on the Master's program show quite positive results among the 2016 and 2017 graduates and the companies that hired them. On the one hand, the PBL academic load and the multidisciplinary approach are both highly appreciated by the graduates. On the other hand, the companies involved in that enquiry seem to value the results of the graduates, giving good marks (average beyond 8 in a 0–10 scale) when asked about the competencies and learning objectives. Additionally, it should be also fair to say that these companies suggest to improve the competencies on systems testing, especially in relation to the use of lab instruments. This concern is now being taken into account in the design of the future Master's program (starting from 2018).

2 The power systems subject of the Master in Space Systems (MUSE)

Spacecraft power systems are taught at the IDR/UPM Institute as a subject of the MUSE. First of all, it should be mentioned the multidisciplinary design of the subject Power Systems within the master program, as students use the know-how from other subjects that are taught in the previous semester. Specifically, the know-how from Space Environment and Mission Analysis and Graphic Design for Aerospace Engineering is a key factor to analyze the performance of a spacecraft power subsystem along one mission, or to train the harnessing process (that is, the development of a spacecraft power and communications wiring harness from CAD design) properly.

Besides, the know-how gained in this subject turns to be extremely important in other subjects such as orbital dynamics and attitude control, where the expertise gained on Matlab–Simulink is relevant, or space integration and testing.

Fig. 4 Block diagram indicating the educational links between power systems and other subjects of the Master in Space Systems (MUSE) from the previous and the following semesters. See also Table 2

See in Fig. 4 a block-diagram indicating the links between power systems and other subjects of this master's program.

The power systems subject of the MUSE is divided into six classical chapters that can be well taught with the help of classical references from the literature related to space engineering [27–29]:

1. Elements of a spacecraft power system.
2. Primary energy sources.
3. Secondary energy sources.
4. Power regulation and control.
5. Power distribution.
6. Power subsystem integration and testing.

Together with this traditional mono-disciplinary approach to the academic contents, two different academic activities are included in the subject design:

- Performance analysis of a spacecraft power subsystem along a mission.
- Training in space harness design and manufacturing.

As it is obvious, the learning within the first activity is purely based on a PBL approach, whereas the second one is a training activity in which the students carried out a harnessing project, starting from the CAD design and the connections described in the power and data signal ICD (Interface Control Document¹²), and then constructing the

¹² This document describes the electrical pairing between the different electrical pins from the on-board hardware connectors of the satellite.

Fig. 5 General design of the satellite distribution system proposed to the students of the subject power systems. This is a simplified sketch of the UPMSat-2 power distribution subsystem

harness (wire preparation, crimping pin connectors, soldering...) that will be connected in a mockup of the satellite. This procedure of developing a harness follows the standards used in the space industry.

Finally, the professors of the master program involved in power systems offer each year projects related to this subject as case study I (2nd semester of the master, see Table 2), case study II (3rd semester), case study III (4th semester), and the final project/master's thesis (4th semester).

2.1 Performance analysis of a spacecraft power subsystem along its mission

Once both a satellite and its mission are proposed, the students have to analyze the power subsystem performance in normal condition and in case of different failure scenarios. The simulation is carried out using Matlab–Simulink and in four different steps:

1. Simulation of a solar panel given the irradiance, its direction in relation to the panel normal direction, the temperature, the solar panel cells manufacturer's data sheet, and the number of solar cells (in series and in parallel) that comprises the solar panel.
2. Simulation of a Li-ion battery for space applications. Some discharging and charging curves are given to the students to develop their own battery model that relates output voltage and output/input current of the battery.
3. Simulation of the power distribution subsystem, taking into account example loads and the efficiency of the DC/DC converters.
4. Final simulation of the whole mission. This final simulation:
 - Integrates the previous simulations. Therefore, the students are asked to program their simulations

Fig. 6 1-Diode/2-Resistor equivalent circuit to a solar panel (top). I - V curve of the UPMSat-1 CISE GaAs experimental solar panel tested at AM0 irradiance and 25 °C (bottom). The I - V curve from a 1-Diode/2-Resistor model (Eq. (1)) fitted to the experimental data is also plotted in the graph (see also Table 3)

bearing in mind a modular design towards this final simulation. The direct energy transfer (DET) is considered in the whole design of the power subsystem (see Fig. 5).

- A 2-year power budget is given to the students. This power budget is based on the power requirements from a real mission (data from UPMSat-2 and Lian-He missions has been selected in the past courses).
- The students are required to consider three different mission status: normal, low-battery (all payloads are disconnected, only the essential systems are functional), critical battery (the satellite is disconnected for 5 h, all power supply from the solar panels being used for the battery charging). All these levels need to be programmed based on battery voltage levels, taking into account the limits of the Li-ion technology.
- The students have to run the simulations considering:
 - No failure in any part.
 - Failure in one solar panel.
 - Failure in the battery (50% capacity reduction).
 - Failure in one solar panel and the battery.

Table 3 Characteristic points and parameters (Eq. (1)) of one of the UPMSat-1 panels, based on double junction GaAs solar cells [34]

I_{sc} [A]	1.423
I_{mp} [A]	1.309
V_{mp} [V]	25.844
V_{oc} [V]	31.351
n	32
a	1.1
I_{pv} [A]	1.4204
I_0 [A]	4.16×10^{-8}
R_s [Ω]	0.4576
R_{sh} [Ω]	1.49×10^3

$$I = I_{pv} - I_{D1} - \frac{V + IR_s}{R_{sh}} = I_{pv} - I_0 \left[\exp \left(\frac{V + IR_s}{naV_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}, \quad (1)$$

where R_s and R_{sh} are the series and shunt resistors, I_{D1} is the current through the diode, I_{pv} is the photocurrent delivered by the current source, I_0 is the saturation current of that diode, V_T is the thermal voltage (defined as a function of the temperature, the charge of the electron, and the Boltzmann constant), a is the ideality factor of the diode, and n is the number of series-connected cells in the device. In this first simulation, the students have to identify the five parameters of the equivalent circuit, taking into account the angle of

Fig. 7 Discharging (left) and charging (right) processes of the qualification battery model (equivalent to the flight model, manufactured by Saft Batteries) of the UPMSat-2

- The students are required to propose solutions and strategies to fulfill the mission requirements. These solutions need to be tested by simulation.

Going back to the first simulation ordered to the students, the simulation of a solar panel behavior consists on the calculation of the current–voltage curve, that is, the I – V curve, receiving the solar irradiance (AM0) at certain angle in relation to the panel surface normal, θ , and being the solar cells at a certain temperature, T . In Fig. 6, the measured I – V curve of one solar panel from the UPMSat-1 is plotted. Taking into account the equivalent circuit model formed by 1 diode and 2 resistors (see also Fig. 5), the mathematical equation that needs to be fit to the data is:

the aforementioned angle of the sun irradiance in relation to the solar panel and its temperature (see in Table 3 the characteristics of the UPMSat-1 whose I – V curve is plotted in Fig. 6). For this process, the master students benefit from the experience gained by the IDR/UPM staff in this kind of parameter extraction processes [30–33].

The second simulation represents the challenge of modeling a battery from the experimental data obtained by the students. This experimental work consists in several charging and discharging processes of a commercial battery similar to the one designed by Saft batteries for the UPMSat-2 satellite (see Fig. 7). The students can choose the model, from a very simple one (formed by an ideal battery with

Fig. 8 Efficiency, η , of the DC/DC converter ($v_{\text{out}}=3.3$ V) in relation to the output current, i_{out} . An exponential equation has been fitted to the experimental data

a resistor connected in series) to a more complex model (that includes pairs of sub-circuits formed by a resistor and a capacitor). The final task is to use the model to calculate a charging/discharging process and compare the results with experimental data.

With regard to the third simulation, the correct approach to the problem implies to take into account the efficiency of the DC/DC converters. In this particular case, the students can use the experimental data from the UPMSat-2 DC/DC converters. From these data, it is possible to fit an exponential mathematical expression (see Fig. 8).

Once the first three simulations have been carried out by the students, they have to integrate the three Matlab–Simulink programs in order to simulate the whole mission, taking into account the power consumptions by the payloads and the satellite on-board subsystems (attitude control, communications, on-board computer...). The first task of the students is to analyze the power supply along an average orbit. The students of the master are quite capable of carried out this task as they have studied Space environment and mission analysis in the first semester of the master's program, see Table 2 and Ref. [35]. This analysis can be performed using GMAT (General Mission Tool Analysis) and STK (Satellite Tool Kit), which are tools in which the students have been trained within that subject.

GMAT is an open source system for space trajectory optimization and mission analysis developed by NASA and private industry. The main goal is to work with universities, businesses and other government organizations to develop optimized spacecraft trajectories and mission technology [36]. GMAT has been verified and validated, its optimization capabilities being used to develop optimal solutions in several missions (MAVEN, OSIRIS-Rex, ACE, LCROSS, LRO, TESS, MMS, ARTEMIS). STK is a commercial package widely used throughout the aerospace industry (NASA, ESA, CNES, DLR, Boeing, JAXA, ISRO, Lockheed Martin,

Orbit side view

Sun direction

Orbit top view

Sun direction

Fig. 9 Position of a satellite in a circular orbit as a function of angles α (angular position in the orbit) and β (angular position of the orbit's plane in relation to the sun direction)

Northrop–Grumman, EADS, DOD, and Civil Air Patrol) to examine dynamic events through the use of a geometrical engine. The core component of STK includes various standard orbit propagators. STK is also used by universities in their lectures and also in design and optimization of satellites due to the difficulties in testing and verifying system parameters on the ground [37]. Both tools can be connected to Matlab–Simulink and make use of its functions to automatize simulations, optimize trajectories and post-process the results.

In Fig. 9, a satellite orbiting around the Earth is sketched. The relative position of the satellite in relation to the sun direction can be described with two angles, α and β . The angular position of the orbit's plane in relation to the sun direction, β , can be simulated with the aforementioned tools, GMAT or STK. In Fig. 10, angle β along the mission of the UPMSat-2 mission has been calculated with STK. It could be said that in this case and for the power system simulations this angle has a constant value, around $\beta=22^\circ$ (a more accurate approximation could be obtained with Fourier series expansion techniques, given the 1-year time period of this angular position of the orbit with respect to the sun direction).

Fig. 10 Angular position of the UPMSat-2 orbit's plane, β , along the 2-year mission. Simulation was carried out with STK

2.2 Training in space harness design and manufacturing

On-board satellites, the electrical harness is among the most complex electrical equipment only made of passive components. It is also a key element driving the performance of the electrical system as well as a significant contributor to the satellite's mass budget. The harness design must cover a huge range of environment conditions and loads according to the mission, as well as the various configurations for in-flight and on-ground operations.

In addition, the harness is submitted to a long list of requirements related to electrical performance, mass, EMC (electromagnetic compatibility) and ESD (electrostatic discharge) protection, thermal and radiation environments, mechanical mounting and usually some other requirements that are specific to each mission. The harness accommodation is also heavily constrained by the structure of the satellite and the location of the different units that are themselves driven by the mission's requirements.

As a significant contributor to the total mass budget, the optimization in the harness design is a usual practice in the space industry that is constantly looking for new saving opportunities.

Therefore, a good knowledge of the usual tools for harness design, simulation and manufacture is required within the MUSE, in order to train the students for working with space engineering standards, to introduce them into this particular

manufacturing methodology, and gain expertise in order to facilitate future interaction of the master's students with companies of the space sector.

The Electrical Harness Installation module, included in the multi-platform software suite CATIA for computer-aided design (CAD), is a product dedicated to the design of physical harnesses within the context of the 3D design. Their main advantage is that the electrical designs are totally integrated into the mechanical assembly.

Within the Graphic Design for Aerospace Engineering (GDAE) subject (taught in the previous semester, see Table 2 and Fig. 4), students learn how to use the aforementioned Electrical Harness Installation module of CATIA. Focused on a PBL scheme, they are trained into the key aspects of the electrical harness design discipline. Working with real satellite examples they learn to create the bundle segments, define their properties, and create the electrical links between bundle segments and devices. In Fig. 11, a full satellite harness design, similar to the ones designed by the students of the master, is shown. After this 3D design, a blueprint needs to be plotted in order to produce the harness. In Fig. 12, a picture of the harness design and manufacturing training process carried out by the MUSE students is shown. The purpose of this training exercise is focused on the minimization of the wires and cables length and the optimization in the use of supports to constraint the bundle segments. This is a practice considered as "normal work" during the accommodation of the satellite and the routing of the harness.

Some effort is also made on the optimization of existing components during this training, that is, the students have to use the right component for the right need and avoiding over-design. This task requires not only a good characterization of the component's loads and environment, but also clear rules and guidelines to perform the sizing of those components.

To achieve good results in this harness design training, the students are required to acquire a deep knowledge about wires, cables and connector specifications. Besides, students need to become familiar with the catalogs of space qualified components and standards related with requirements and acceptance for cable and wire harness assemblies (IPC/WHMA-A-620; ECSS).

Finally, it should be underlined that, as mentioned before, this full manufacture of a simplified satellite harness performed by MUSE students in the Power Systems subject represents the logical continuation to Graphic Design for Aerospace Engineering (GDAE) subject (see Fig. 4).

Fig. 11 CAD harness design produced within the training in space harness design and manufacturing of the subject power systems

Fig. 12 Students of the subject power systems of the Master in Space Systems (MUSE) during the training in space harness design and manufacturing (April, 2017)

3 Academic projects in relation to spacecraft power systems

As mentioned, four subjects of the MUSE: case study I, II and III, and final project, are fully based on PBL approach. These subjects represent, respectively, 90-, 225-, 180-, and 450-h engineering working loads for the students of MUSE. Obviously, the projects offered to the students lie within the scope of the subjects of the master, i.e., vibrations and aeroacoustics, heat transfer and thermal control, space structures, communications... More precisely, the proposed works are normally related to:

- Projects being carried out by the IDR/UPM Institute staff, mainly in relation to structural analysis and thermal control analysis.
- The satellites being currently developed at the IDR/UPM Institute:
 - UPMSat-2, and
 - UNION/Lian-Hé.

Fig. 13 Different units of the UPMSat-2 on-board E-BOX (top): PSU (Power Supply Unit); PDU (Power Distribution Unit); DAS (Data Acquisition System); and OBC (On-Board Computer). Pin-to-pin diagram related to the Bartington magnetometer of the UPMSat-2 (bottom)

Fig. 14 Testing setup of the BPX 61 photodiodes (solar sensors) to be qualified in the UPMSat-2 mission (top). I - V curves resulting from these measurements (bottom)

3.1 Electrical interface control document of the UPMSat-2

This project was offered as case study I. The goal was to identify and describe all electrical hardware on-board the UPMSat-2, and their connection interfaces (pin-to-pin diagrams). The most complex connections are located in the E-BOX (Electronic Box), which contains the Power Supply Unit (PSU), the Power Distribution Unit (PDU), the Data Acquisition System (DAS), and the On-Board Computer (OBC) (see in Fig. 13 the connectors of each unit of the E-BOX). The pin-to-pin diagrams of every connection between different hardware parts were sketched (see an example also in Fig. 13); this work was extremely useful during the UPMSat-2 integration stages.

Fig. 15 Experimental setup developed for the UPMSat-2 solar panels testing (left). Results of this testing: I - V and P - V curves (right)

3.2 UPMSat-2 solar sensors performance characterization

One of the payloads of the UPMSat-2 mission comprises 6 BPX 61 photodiodes. The purpose of these small solar sensors, which behave as solar cells, is to help the satellite's attitude control to calculate the relative position with regard to the sun direction.

The characterization was, in fact, a calibration in which the behavior of the photodiodes (i.e., the relation between the output voltage and the output current), was analyzed, taking into account:

- The direction of the irradiance with respect to the sensor.
- The irradiance level.

To perform this analysis, a testing campaign was designed, building a red light with LEDs. In Fig. 14, a picture of the experimental setup is shown, together with the results of two series of measurements. The result of this project, offered as case study II, was relevant, as it allowed the calibration of this sensors subsystem.

3.3 UPMSat-2 solar panels testing

This project was also proposed as case study II. However, two students instead of one were selected due to the large size of the working load. In recent years, a greater interest has arisen in the development of small-size satellites to be used as technological demonstration or as part of constellations for Earth observation purposes. The main advantage, in addition to the lower launch costs, is that the development

of each individual satellite is relatively cheap. This upward trend has led into a situation in which even small improvements of the development, production or qualification processes may result in significant saving for small satellite programs. As the power system is a key point to ensure that the satellite is able to work and survive in space for long periods, special interest is focused on the development of procedures for manufacturing and testing solar panels and batteries as easy as possible.

Framed within the context of the Master in Space Systems, a low cost method for solar panel testing was developed within this project and applied to the UPMSat-2 mission (this successful procedure will be used, if needed, in the following satellite projects).

Using a goal-oriented design, a steerable support unit was built to characterize the I - V curves using outdoor clean sky measurements, as shown in Fig. 15. As the testing was based on solar radiation in Earth surface (without using solar simulators), the solar panels parameters dependence on environmental conditions (temperature) was studied and precisely determined.

In the space industry, solar cells manufacturers' datasheet is expressed in terms of extraterrestrial radiation and nominal operating cell temperature. Because of that, the irradiance levels and solar cells temperature during testing campaign were monitored and a post-processing numerical code was developed to extrapolate data to the manufacturers' reference. A comparison between one of the measured I - V and P - V curves and the simulated with a usual 1 diode/2 resistor circuit model (Eq. (1)) using manufacturers' datasheet is also included in Fig. 15. The studied solar panel is formed by four parallel-connected groups of two series-connected

Fig. 16 Measuring setup in the IDR/UPM Institute clean room to monitor the UPMSat-2 battery

SPVS-5S modules of five triple junction solar cells (Azur Space 3G28C) mounted on an Al substrate, black anodized in order to guarantee a complete insulation towards the electrical network.

The values of the root mean square error (RMSE) were used as a criterion to quantify the difference between the model results and the experimental data [38]. As the RMSE values show ($RMSE = 0.73 \times 10^{-3} - 2.9 \times 10^{-3}$), a quite good agreement was found between the experimental data and the model results, taking into account the previous works on solar panel characterization carried out by IDR/UPM Institute staff [30, 33, 39–43]. As a result of this project, it can be said that the on-ground testing conditions used (AM1.5 solar irradiance, glass irradiance filtering...) can be applied to efficiently determine the main parameters of solar panels without the need for special and expensive test equipment. Finally, it should be also underlined that this work was recently published in a prestigious journal [44].

3.4 Multi-channel voltmeter for spacecraft batteries' maintenance

The UPMSat-2 battery, designed by Saft Batteries, is a 18 A h capacity battery based on Li-ion technology. It comprises 24 cells to achieve an output voltage from 18 to 24 V. This battery is designed for a 12-year mission (maximum life). Due to the launching delay of the UPMSat-2 mission, maintenance of the battery has been carried out for a quite long period (larger than expected). This maintenance has two main tasks:

- Battery monitoring, measurement of the output voltage of the battery, together with the output voltage of each one of the 24 cells that comprise the battery (see Fig. 16).
- Battery balancing, when the difference between the output voltages from two of the cells in one of the battery strings reach 50 mV. This balancing requires two charging and one discharging processes in which all the cells voltage needs to be continuously measured.

The maintenance of the battery is regularly proposed to students for their case study II. The students learn how to work in a clean room, to take measurements following an extremely detailed procedure, and to perform some balancing processes. Together with this task, a new project was offered as case study II, the development of a multi-channel voltmeter to continuously measure the cells voltage. This system was based on Arduino and, as the project described in the previous subsection, was carried out by two students on the MUSE. In Fig. 17, the electric sketch of this multi-channel voltmeter is included. Apart from the construction of the voltmeter, this instrument needed a calibration process. Finally, it was successfully tested measuring the UPMSat-2 battery.

4 Conclusions

In the present paper, the academic work on spacecraft power systems carried out within the last years at IDR/UPM Institute is described. It started in the late 1980s with the UPMSat-1 mission, although it inherited a longer tradition in working on space systems at that institution of Universidad Politécnica de Madrid (UPM).

The education on spacecraft power systems at IDR/UPM is carried out by a successful combination of both:

- the spacecraft missions in which the IDR/UPM Institute is involved (UPMSat-2, UNION/Lian-Hé...), and
- the Master in Space Systems (MUSE) at Universidad Politécnica de Madrid (UPM).

Thanks to this design, the students reach the required competencies and learning objectives through the programmed PBL tasks (simulation of different power subsystems behavior and training on spacecraft electrical harnessing), which require a multidisciplinary approach to the proposed problems.

Fig. 17 Electric diagram of the multi-channel voltmeter (top). UPMSat-2 battery monitoring process being carried out with this instrument (bottom)

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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