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# PIRAMIDE: An Innovative Educational Program based on Research - Some Results and Lessons Learned

## ABSTRACT

*By the end of 2019, Technical University of Madrid (Universidad Politécnica de Madrid - UPM) from Spain granted support to the 1-year*[1] *innovative educational project PIRAMIDE, within the call for projects Innovative Education Program of UPM*[2]*. PIRAMIDE aimed at boost academic results from Bachelor and Master students by doing research on space engineering. This project was coordinated by professors from the IDR/UPM Institute and STRAST group. The program was structured into five different case studies: 1) Design of a space mission (phase 0/A) in a Concurrent Design Facility (CDF); 2) Selection and study of an on-board computer for a CubeSat mission; 3) Intelligent design methodologies applied to graphic engineering; 4) Analysis of power systems for space applications; and 5) Design of a spacecraft Attitude Determination and Control Subsystem (ADCS). The program ended by the end of 2020. In the present work, some results from each one of the studies that compose PIRAMIDE are summarized. These results are classified into two different categories: results of the different case studies (work carried out), and perceived results, from both students and professors. Besides, some critical analysis is included with the lessons*

[1]PIRAMIDE was finally extended to two years.
[2]https://innovacioneducativa.upm.es/.

*learned that might help to design better innovative educational projects in the future.*

**Keywords:** *research-based learning, working methodologies, educational innovation, space engineering, concurrent design, space systems*

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## Introduction

In the last years a quite large effort has been done related to Project Based Learning (PBL), within the aerospace academic programs at *Universidad Politécnica de Madrid* (UPM). One of the most relevant programs in which teaching is mainly based on PBL is the Master's Degree in Space Systems (MUSE[3]) of the UPM, managed by *Instituto Universitario de Microgravedad "Ignacio Da Riva*[4] (IDR/UPM) (Álvarez-Romero, Roibás-Millán, Pindado, Pérez-Álvarez, and Sanz-Andrés 2020; Álvarez-Romero, Roibás-Millán, Pindado, Pérez-Álvarez, Cubas, et al. 2020; Pindado et al. 2016, 2017; Elena Roibás-Millán et al. 2018). This is a center within UPM mainly specialized in three different research areas: 1) space engineering projects, 2) civil aerodynamics, and 3) wind speed sensors calibration.

The academic environment at IDR/UPM Institute is a mix of three different activities: 1) Research, 2) Teaching, and 3) Engineering consulting. From the very first moment, these activities have been interconnected as a way to boost research and improve the quality of teaching continuously. On the other hand, graduates that worked at IDR/UPM during their Bachelor or Master degrees seem to be very welcome at their first job in engineering companies, as they have gained professional skills which reduce the initial transition period at the aforementioned companies.

### *PIRAMIDE: Research Projects Carried out by Master/Bachelor Students for Innovation and Space Development*

In this context, the educational innovation project PIRAMIDE (*Proyectos de Investigación Realizados por Alumnos de Máster/Grado para la Innovación y el Desarrollo Espacial*) was proposed in 2019 to the UPM as an initiative to improve the skills and academic results of Bachelor and Master students from the Aerospace Engineering Faculty (ETSIAE[5]) at UPM.

The main objective of this project is to use the knowledge transference of the research activities for the students training. The initial design of PIRAMIDE was based on three interrelated tasks:

- The acquisition of the research skills, encouraging the students' critical thinking to make them progressively autonomous within the research decision-making process.
- Collaboration between students from different degrees, professors and researchers, to increase motivation by showing the students the wider possible perspective of a research process.
- The evidence gathering, made possible by a systematic review of the project.

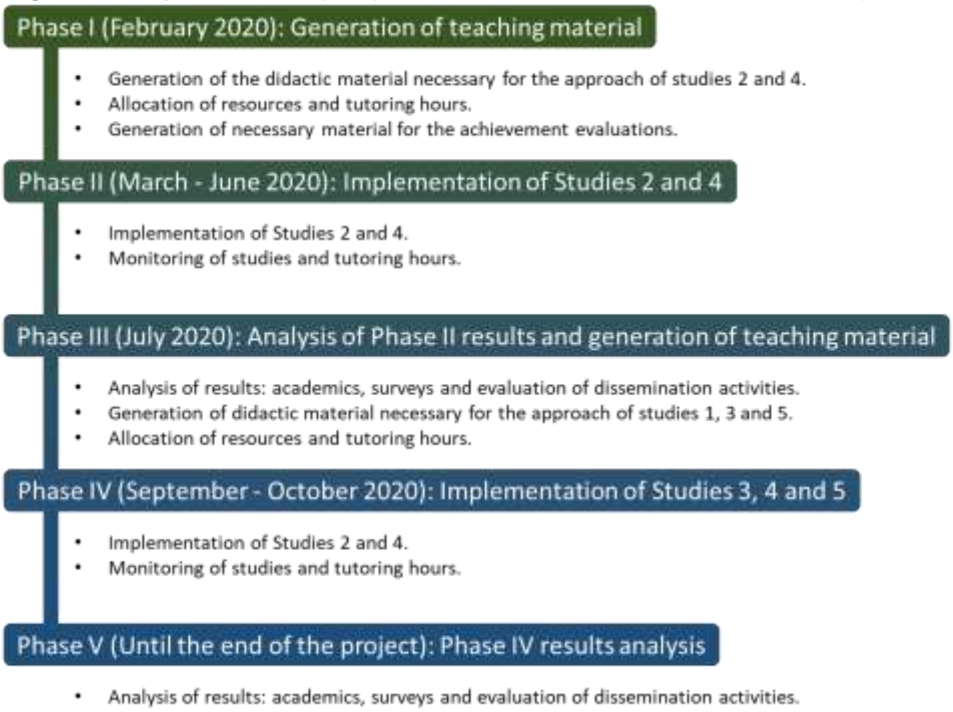
[3]Máster Universitario en Sistemas Espaciales, http://muse.idr.upm.es/.
[4]http://www.idr.upm.es/.
[5]Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio.

Five different research studies were proposed, in accordance with five different disciplines in the space sector, each one of them linked to one subject from MUSE:

- Study 1: Design of phase 0/A of a space mission in a CDF. Linked to the subject "Systems Engineering and Project Management" from the Master in Space Systems (MUSE) (1st year, 1st semester).
- Study 2: Selection and study of an On-Board Computer for CubeSat missions. Linked to the subject "Data Handling" from MUSE (1st year, 2nd semester).
- Study 3: Intelligent design methodologies applied to graphic engineering. Linked to the subject "Graphic Design for Aerospace Engineering" from MUSE (1st year, 1st semester).
- Study 4: Analysis of power systems for space applications. Linked to the subject "Power Subsystems" from MUSE (1st year, 2nd semester).
- Study 5: Design of an attitude determination and control subsystem. Linked to the subject "Orbital Dynamics and Attitude Control" from MUSE (2nd year, 3rd semester).

These studies were scheduled in five stages of development, which are shown in Figure 1.

**Figure 1.** *Sequential Design of PIRAMIDE Education Innovation Project*



It should be also said that, as part of MUSE academic staff, members of the STRAST[6] research group from UPM, were also involved in PIRAMIDE, this strong collaboration framework between IDR/UPM and STRAST being initiated with the development of the UPMSat-2 satellite in 2011.

In the following sections the five studies within PIRAMIDE are reviewed. Additionally, a section devoted to the lessons learned is included before conclusions.

## Study 1: Design of Phase 0/A of a Space Mission in a CDF (Concurrent Design Facility)

In the last two years, within the Systems Engineering and Project Management subject, concepts related to the new trends in space mission pre-design and feasibility phases (E. Roibás-Millán, Sorribes-Palmer, and Chimeno-Manguán 2018) has been included. Between those concepts it is emphasized the Concurrent Engineering (CE) or Concurrent Design (CD), which can be defined according to European Space Agency (ESA) as: "*a systematic approach to integrate product development that emphasizes the response to customer expectations. It embodies team values of cooperation, trust and sharing in such a manner that decision-making is by consensus, involving all perspectives in parallel form the beginning of the product life-cycle*" (Braukhane and Quantius 2011).

Space projects are characterized by the complex interconnections between all the disciplines involved in the project, called subsystems. Each discipline is strongly related with the others, causing that the impact of any change must be carefully evaluated through all project life-cycle. Therefore, during the first phases of the design, system engineers must consider the multiple design options that should be synthesized, computed, and simulated to select the optimum design option. Concurrent Engineering facilitates this process through the tasks parallelization, improving the flux of information by working in a collaborative environment.

### *Study Definition*

IDR/UPM Institute has his own Concurrent Design Facility (CDF), which includes the technology and resources needed to perform parametric studies with the objective of finding a mission solution that fulfils the technical requirements. Through this Study, students are guided in a Concurrent Design process within the CDF (Bermejo-Ballesteros et al. 2018). A mission is proposed in base of a set of mission requirements, so a preliminary design is requested as result of the work. Students are distributed in two or three teams; each one of them performing the same mission design, so the results obtained by each team can be compared.

[6]Sistemas de Tiempo Real y Arquitectura de Servicios Telemáticos.

By the implementation of this Study, students are trained to understand the mission requirements, transform them into a set of technical requirements and to propose a set of innovative solutions to comply with them. Therefore, students gain the capacity of taking technical decisions, analysing options and reliability, and using advanced technological resources.

*Study Development*

At the first stage, four introduction classes were organized, where the concepts of CE and CDF were explained and developed. At the end of the introduction, a small exercise to introduce the students into the complexity of space mission was carried out. Several groups were created, associating each of them with a different satellite discipline, denominated subsystem. The groups were asked to define the inputs and outputs list and to request them to the corresponding subsystem that they consider. This exercise, based on the creation of design parameters, demonstrated the complexity and the interrelation between subsystems that exists in a space project.

The second stage was another two classes where a space mission was proposed, based on a detailed description and a set of mission requirements. The students had to carry out an understanding of the mission, as well as translate the requirements from scientific language, obtaining the necessary design parameters for each subsystem.

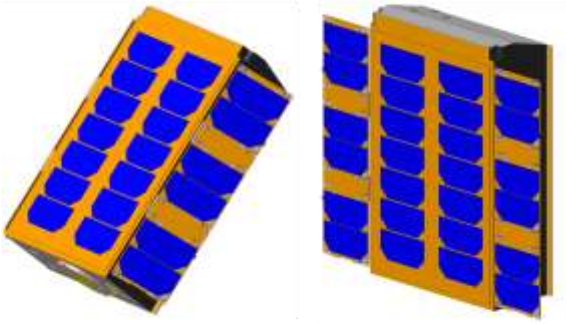
The students were randomly divided into two design teams, which were also organized according to the different design disciplines. Each team was asked for a preliminary design as a result of the work. As both teams had the same mission requirements, it was possible to compare the different design options obtained by each team.

The third stage consisted of each design team working on the mission requirements and design options for three months. The teams were supported by professors with class/videoconference sessions to answer questions and provide guidance on the different solutions selected.

*Study Results*

The students submitted a Preliminary Design Review (PDR), which included a detailed development of the solutions selected for each of the subsystems. Besides, they included a complete satellite configuration (Figure 2), as well as a design risk analysis.

**Figure 2.** *CubeSat Preliminary Design at the CDF*



By implementing this work, students were trained to understand the main phases of a space project pre-design; also including the mission requirements analysis and their transformation into a set of technical requirements. The teams proposed a set of innovative solutions to fulfil the mission objectives, obtaining a feasible mission with overall good results.

The research method and the investigation process are fundamental terms in a CDF preliminary design. As the iterative design process is a basic characteristic of CE, students had to consult, at the first time, in different satellites databases in search of missions with similar parameters.

In addition, students acquire the ability to make technical decisions, analyse options and reliability, and utilize advanced technological resources. Since one of the main requirements was the use of Commercial Off-The-Shelf (COTS), students had to research from the main spacecraft and CubeSats manufacturers, analysing the datasheets and properties in order to find the optimal design option.

## Study 2: Selection and Study of an On-Board Computer for CubeSat Missions

The On-Board Data Handling (OBDH) subsystem encompass a vast range of functional blocks in a space mission, including Telemetry, Tracking and Command (TT&C) Modules, On-Board Computers (OBC), Data Storage and Mass memories, Remote Terminal Units and Communication protocols and Busses (Addaim, Kherras, and Zantou 2007; Arseno et al. 2019; Karlsson 1999). These elements are common to all projects and are subject to a demanding set of evolving requirements from Science, Exploration, Earth Observation and Telecom missions (Wenping et al. 2017).

Nevertheless, most MUSE students come from a bachelor's degree in Aerospace Engineering, so they have a limited knowledge of computer structure, operating systems and programming. Currently, the academic program of the MUSE has the Data Handling subject, conducted in collaboration with the UPM IT faculty, in which an approach to the main concepts of this subsystem is taught.

*Study Definition*

Computer structure is the first topic of the course. It is intended to provide the basis of computer components, including I/O devices that are present in on-board computers. At the end of this topic, students were asked to put into practice the acquired knowledge by refining the selection of the On-Board Computer (OBC) that they chose during the design of phase 0/A of the space mission for Systems Engineering and Project Management. The study consists of analysing the initial decision that was made in the preliminary design and, as they acquire more knowledge regarding the OBDH, analysing the decision made, looking for better alternatives, etc.

For example, at this point, selections were mainly based on the number and type of I/O devices needed for the mission. However, when other topics were explained, and the course was progressed, other requirements were used, such as the availability of programming environments and real-time operating systems.

*Study Development*

The Data Handling course had 14 students. They were divided into 3 working groups, the same ones as in the Systems Engineering and Project Management course.

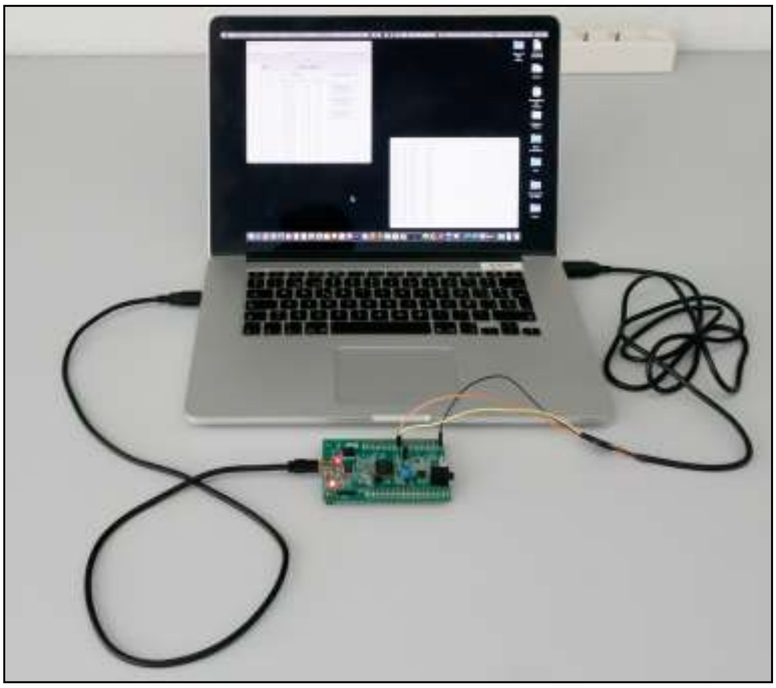
The students analysed again the requirements of the OBC for the proposed mission and set a list of minimum components that are needed to fulfil them. The next step was to search the Internet for a COTS (Commercial Off-The-Shelf) OBC that suits the project requirements. It must be noticed that the mission is based on CubeSat, and there are a pretty large amount of OBC providers for that segment. The mission requirements refer to the number of devices to manage in the different subsystems, the amount of information to store or the different operational modes of the satellite.

In addition, students were convened into the embedded software laboratory as a part of this course. Students were required to use the knowledge acquired in other topics and to put it into practice. In this laboratory, they used a reduced version of an on-board software system and a real-time operating system by means of an integrated development environment.

They installed the tools in their personal computers and were provided with a cheap computer board which can be used as a mock-up of a real OBC hardware system, similar to that used in CubeSat missions.

The installation of tools as well as setting up the cross-development environment were assisted by the teacher without major problems. A specific set of documentation was developed for this laboratory in order to further help the students carry out the required assignments. Figure 3 shows the setup for this laboratory.

**Figure 3.** *Laboratory Kit*



A reduced version of an on-board software system was provided to the students, who were required to compile the source files to produce executable files, which were loaded into the OBC mock-up. They also were asked to perform minor changes in the code. In this way, students experimented with the embedded software development process in order to understand its complexity.

*Study Results*

This task has been evaluated with two main evaluation methods: first, a written report in which the students developed the analysis of the requirements regarding the OBDH subsystem. In addition, they had to include the selection and correct justification of the appropriate CBO for the mission. As a second evaluation method, an interview to the groups was included with a set of oral questions about the process carried out and the results obtained.

The results were very good, and the selections were very successful. Thus, the teachers are very satisfied with the degree of assimilation of the course content.

## Study 3: Intelligent Design Methodologies Applied to Graphic Engineering

In the framework of the PIRAMIDE Educational Innovation Project, a working group formed with the 1$^{st}$-year students of MUSE (academic year 2020-21) was created to carry out a research project. Based on PBL methodology (Pérez-Benedito, Pérez-Álvarez, and Casati-Calzada 2015; Pindado et al. 2018; Straub and Whalen 2014), the outcomes of this academic initiative were integrated as part of the evaluation of the subject Graphic Engineering for Aerospace Mechanical Design.

*Study Definition*

The proposed study was the complete development of a micro-satellite modular structure, with designed alternatives according to different mission requirements, as well as different equipment and experiments.

The aim is to define a parametric 3D model (Lihachev et al. 2020; Zhu et al. 2019) of the complete structure of a micro-satellite composed of independent modules, including a system of deployable solar cell panels, in such a way that the dimensions, materials, mechanical interfaces of union, electrical wiring interfaces and equipment are compatible with the other modules to complete the final assembly, as shown in Figure 4. Besides, each module (regardless of its size and shape had the following common elements: support structure, trays, spacers, shear panels, closing panels, and mechanical and electrical interface with the other modules (see Figure 5).

**Figure 4.** *Sketch of the Micro-Satellite Module Structure*

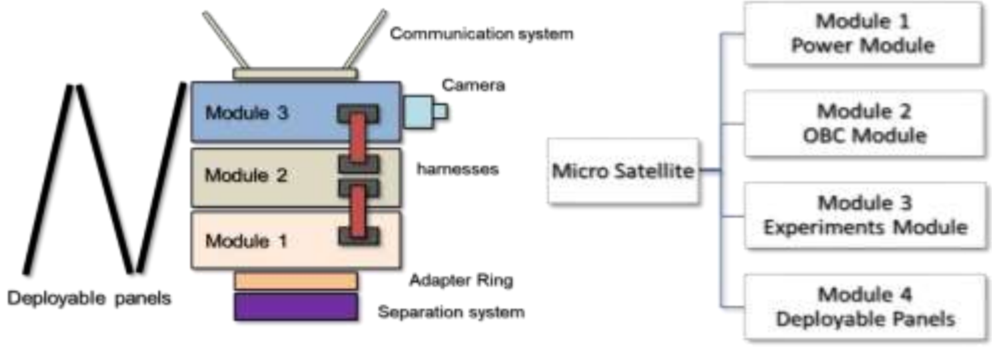
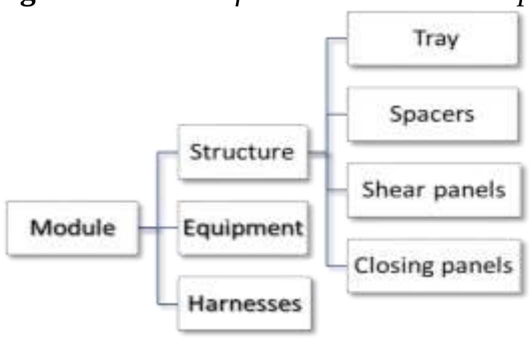



**Figure 5.** *Scheme of Elements that Make up Each Module*




For the design of each component, an adequate selection of materials also needed to be taken into account in accordance with the ECSS standards. That selection included: light alloys, different stainless steels, composite materials, and aerospace plastic materials. In addition, for the product design, each module had to satisfy the geometric and functional requirements included in Table 1.

In order to organize the selection within the different design possibilities (derived from the possibilities related to materials and requirements), the design of each module had to be controlled by a Graphical User Interface (GUI) that allowed the users to choose the composition of the elements of the more suitable module easily. This implied control over: parameters, relationship between parameters, design laws, control of values (Checks), design tables, and published parameters.

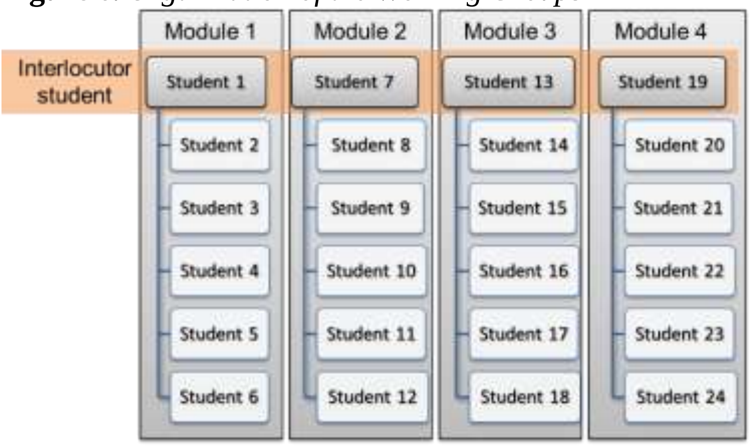
**Table 1.** *List of Requirements for Module Design*

| | |
|---|---|
| Geometric Requirements | |
| GR1 | Dimensions must not exceed a volume of 400 mm x 400 mm x 450 mm |
| GR2 | Square plan shape |
| GR3 | Hexagonal plan shape |
| Functional Requirements | |
| FR1 | Minimize the mass of the complete equipment (maximum 40 kg). |
| FR2 | Allow different payload spaces. |
| FR3 | Control of the plan shape of the structure |
| FR4 | Define zones for power system and computer |
| FR5 | Allow the joining of deployable solar panels |
| FR6 | Allow mounting in one direction only |
| FR7 | Definition of geometry based on type of material |
| FR8 | Interface with separation system |
| FR9 | Wiring of each module |
| FR10 | Include a camera on one side |

*Study Development*

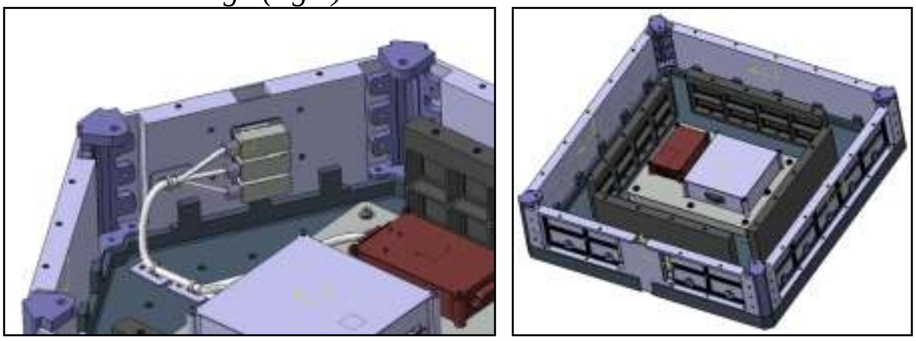
For the development of the study, the students were divided into four 6-student groups, each one responsible for a different module. One interlocutor/ reference student was elected per group to organize meetings and manage the instructions from the teaching staff (see Figure 6). The students acting as interlocutors for each group were not fixed along the project, but depended on the specific state of the project.

**Figure 6.** *Organization of the Working Groups*




Once the groups were organized and the modules assigned, a schedule of meetings and presentations of the work in progress of each group (and between groups) was established. Additionally, a schedule of meetings with the teaching staff was also established, two per group, to avoid possible deviations in the project and to solve possible doubts in the design of each module. Finally, each group established its own calendar of partial delivery dates and assignment of working hours per student by means of Gantt charts.

**Figure 7.** *Hexagonal Proposal for the Module 2, which Integrates the OBC (left), and its Final Design (right)*



*Study Results*

During the work start-up phase, each group publicly presents both its design proposal and the work schedule; in this way, at the end of the work, design changes and deviations from the proposed work hours can be evaluated.

As a final result, each group presented the following information (see Figures 7-10): Parametric 3D model, Assembly drawing of the TAD model per module and complet, Work report, Presentation of the work and Poster, and Programming a Graphical User Interface to control the design.

**Figure 8.** *Final Design of the Satellite Panels, Deployed (left), and not deployed (right)*

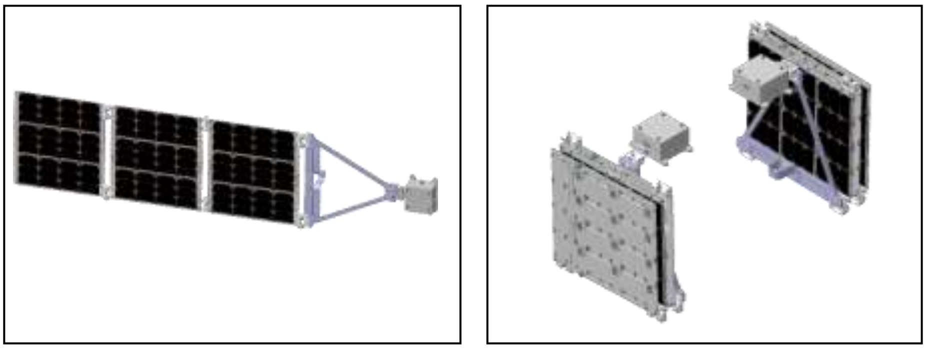


**Figure 9.** *Complete Set of Modules 1, 2, and 3 (Solar Panels Module not Included in the Drawing)*

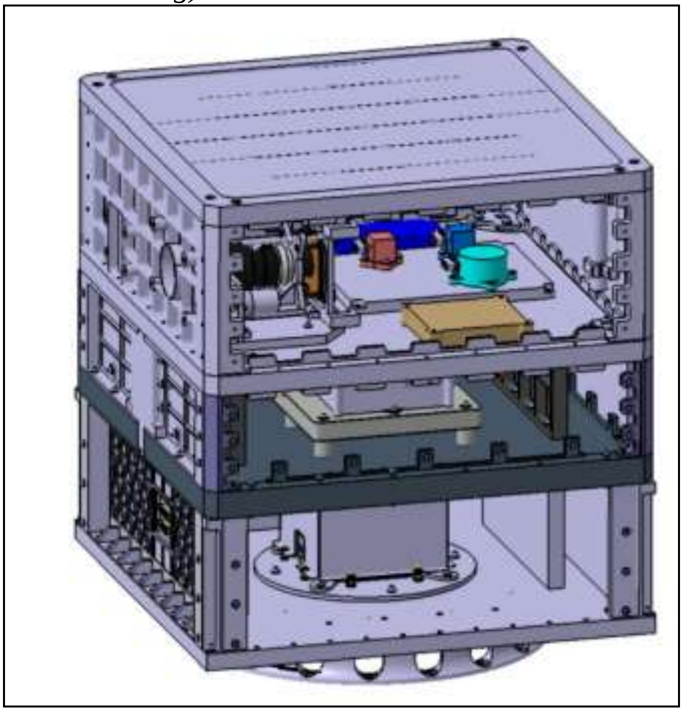
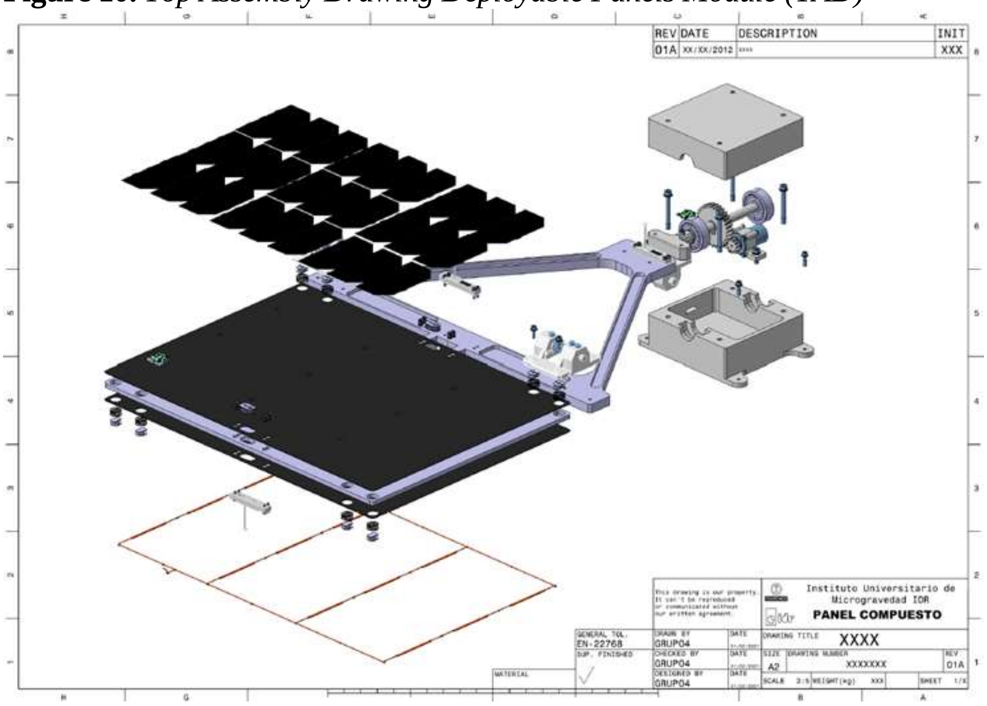


**Figure 10.** *Top Assembly Drawing Deployable Panels Module (TAD)*



**Study 4: Analysis of Power Systems for Space Applications**

This study is related to the subject "Power Subsystems" from MUSE (Pindado et al. 2018). Although initially this study was organized by proposing the analysis of two main parts of the power subsystem of a satellite: the solar panels and the battery, only the former was faced by the students. A working group composed of six students was formed during the first months of 2020, supervised by a Professor: 4 Bachelor degree students of the Aerospace Engineering Faculty, 1 Master degree (MUSTA[7]) student, and 1 Ph.D. student working in space systems engineering and concurrent design. The students from MUSE program were offered to integrate the group but no one accepted the proposal.

The aims of this Study were different depending on the type of student. Bachelor students were focused on learning how to carry out research analysis by: analysing a problem proposed, making questions on that problem, finding, selecting, and organizing information linked to the proposed problem, deciding the appropriate tools (software) for working towards a solution, and reaching a reasonable solution to the proposed problem. On the other hand, Ph.D. students were responsible for giving support to the Bachelor students, especially concerning the analysis and the formulation of proper questions on an engineering problem.

This study started in March 2020 and ended by the end of June 2020 (although some of the results were published much later, due to the normal reviewing process of the journals).

*Study Definition*

The two main objectives of this study were:

- Analysing the behaviour of solar panels from some new perspective.
- Producing research results in terms of visibility of the work carried out.

Along the first stages of this study, the students were progressively provided with many research works related to solar panels, produced at the IDR/UPM Institute in the last decade. Additionally, the students were encouraged to search for more worthy published information (articles, conference proceedings), and recognize the different quality indexing of the publication (Web of Science Impact Factor –IF–, or SCImago Journal Rank –SJR–).

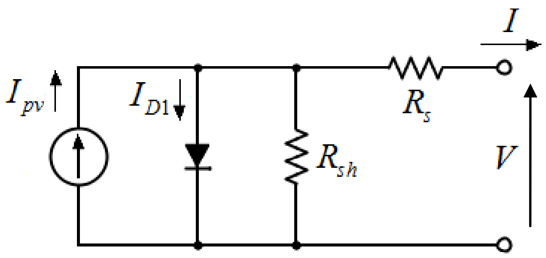
As part of this project, the students registered themselves in research/ professional networks such as Researchgate, ORCID or LinkedIn, to increase the impact of their work. Also, a Project in Researchgate web page was created, to inform each 1-2 weeks the research community on the work carried out.

[7]Máster Universitario en Sistemas del Transporte Aéreo.

*Study Results*

Two main problems related to spacecraft solar panel modelling were analysed: analysis of the best value for the ideality factor of the 1-Diode/2-Resistor equivalent circuit for photovoltaic systems modelling (Figure 11), and simplified expressions of the Lambert W-function applied to analytical calculations related to photovoltaic performance. It should be emphasized that the latter is a quite relevant question, as not only the analytical solution of the 1-Diode/2-Resistor equivalent circuit model requires the use of the Lambert W-function, but also some of the most accurate explicit equations for photovoltaic modelling do.

**Figure 11.** *1-D/2-R Equivalent Circuit Model for Analysing the Behaviour of a Solar Cell/Panel*



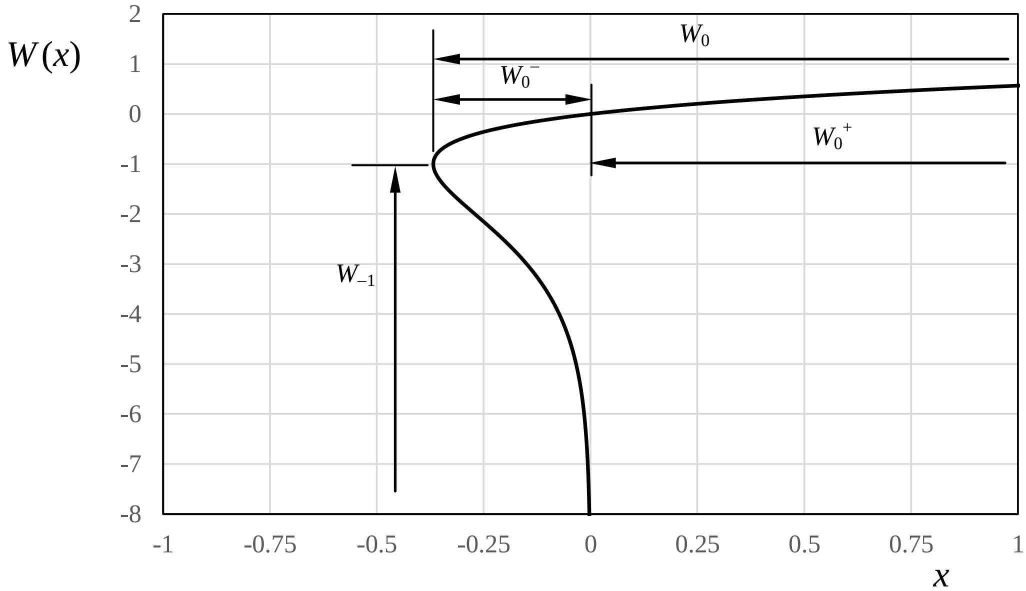

The students analysed the accuracy of the 1-Diode/2-Resistor equivalent circuit model:

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

in relation to the value of the ideality factor, *a*, for several solar cells and panels. It was concluded that $a = 1$ is a quite reasonable value for all the different photovoltaic technologies studied (silicon, Ga-As, triple-junction…).

Besides, several simple equations for the different branches and sub-branches of the Lambert W-function (see Figure 12) were proposed. Finally, all the approximations proposed were tested with the experimental data from two different solar panels of the UPMSat-1 (developed by UPM and launched in 1995). The results of the methodologies proposed showed a quite good accuracy level when compared to the testing results.

**Figure 12.** *The Lambert W-Function, with its Two Different Branches,* $W_{-1}$ *and* $W_0$ *(the Later Divided into Two Sub-Branches)*




As part of this study, a bibliographic search and analysis of journals devoted to photovoltaic systems was carried out. The relevant categories in the Web of Science (WoS) and SJR were identified, the journals in them being classified by defining their evolution (position in the category) along the past 10 years.

Additionally, the students involved in this study showed great interest in research social media, registering themselves in Researchgate, ORCID or LinkedIn, and posting periodical updates of their work in a project created in Researchgate (Figure 13).

The results of this study were made public by being sent and accepted in two international conferences:

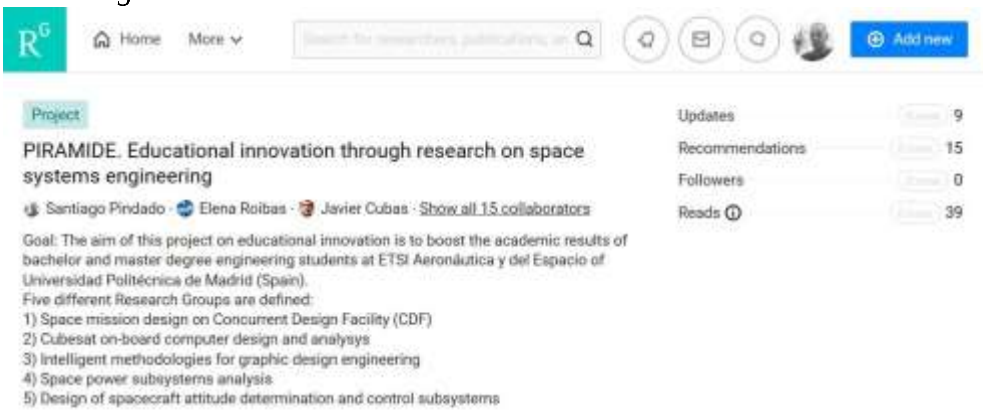
- 20TH IEEE International Conference on Environment and Electrical Engineering - IEEE EEEIC 2020. 9-12 June 2020. Madrid, Spain. (Elena Roibás-Millán et al. 2020).
- *III Congreso de Ingeniería Espacial*. 27-29 October 2020. Madrid, Spain. (Pindado et al. 2020).

Two papers were also published in prestigious journals such as:

- IEEE Transactions on Industry Applications (Pindado et al. 2021).
- Applied Sciences (Álvarez-Romero et al. 2021).

And a report on journals devoted to photovoltaic systems engineering was published in Researchgate.

**Figure 13.** *Project PIRAMIDE Page Created and Managed by Study 4 Students in Researchgate*




## Study 5: Design of an Attitude Determination and Control Subsystem

In this study, which is linked to the subjects Orbital Dynamics and Attitude Control (Pindado et al. 2016), students acquired practical experience in the design of attitude control subsystems. A special emphasis in PBL methodology (Pindado et al. 2018), (Sobota et al. 2013) will be used, taking advantage of tools with great educational potential such as development boards (Arduino).

The attitude control subsystem of a satellite consists of multiple elements (sensors, actuators, computers, data acquisition cards ...) that interact with each other through control laws, filters, etc. The complete operation of the control requires the integration, modelling and development of the algorithms, which is carried out in various stages and requires prior planning. The challenges of each step are easier to understand when students face a real project. To emulate this process, the Arduino development boards are an ideal element (Hertzog and Swart 2016), since they allow measurement, processing results, implementing algorithms and commanding actuators. Nowadays, their wide diffusion allows them to be employed even in industrial projects. Furthermore, they are compatible with design control tools such as Matlab-Simulink (Pires and Silva 2002).

### *Study Definition*

The problem proposed to the students was an adaptation of a Challenge developed by the Universidad Carlos III de Madrid (UC3M) for the students of universities participating in the project NANOSTAR (Lubián-Arenillas et al. 2019), among which is the UPM. The project was originally planned to be performed in groups. However, due to the COVID-19 recommendations it was replanned as an individual job. The activity was also modified so that it was less competitive (like a challenge) and more educational and linked to the Master's content (like a project).

Within this project, each student had to develop and implement a simple control subsystem to orient a CubeSat-like platform towards an incident light.

Hardware provided to students (see Figure 14) comprised (only the components of the kit used in the project are included here): Arduino Starters Kit UNO Spanish Version v.3, Arduino Projects Book (170 pages), Arduino UNO, beadboard, jumper wires, photoresistor [VT90N2 LDR], 3 10 kΩ potentiometers, small DC motor (6/9V), small servo motor, resistors, Osram Opto 20° infrared photodiode, battery, and a plywood platform for mounting. At first, the assembly platform was going to be 3D printed, but when the work became individual, the amount needed was multiplied. For this reason, in the end, for this first test the platform was constructed in plywood.

**Figure 14.** *Most Relevant Hardware Provided to the Students (left to right): Photoresistor, Breakboard, Arduino UNO, Battery, and Servo Motor*

*Study Results*

The work was relatively open, to allow students to experiment with different concepts and make design decisions. Two kind of sensors (photodiodes and photoresistors), and two kind of actuators (DC motor and servo motor) were provided. The number, location, and combination of them were not specified. Also, the control law was open, and it could be designed directly in Arduino software or in Simulink. Altogether, the project included the stages of hardware design and assembly; design of the control algorithm; and implementation of the subsystem. At the end of the project, the students had to submit a project report. However, the PBL approach of the activity also allowed evaluation by results. Half of the grade of the project was obtained in an operational demonstration of the CubeSat's control in front of the professor (see Figure 15). 11 of the 14 projects operated correctly, while 3 did so with some deficiency.

**Figure 15.** *Some Examples of the Works Developed by the Students*

Among the objectives of this pilot project were to learn how to improve it for following years and to know the opinion of the students. 11 of 14 students answered the following survey:

- Did you have previous experience with Arduino?
    - Yes: 36%
    - No: 64%
- Do you think that the project helped you to fix attitude control concepts?
    - A lot: 18%
    - Quite: 73%
    - Little bit: 9%
    - Nothing: 0%
- How difficult was the project for you?
    - Very difficult: 0%
    - Difficult: 36%
    - Average: 55%
    - Easy: 9%
    - Very Easy: 0%
- Would you like to add complexity to the practice and in what way? (more than one answer allowed)
    - Adding more sensors: 18%
    - Adding more actuators: 18%
    - With a more complex control law: 64%
    - It is already complex enough: 27%

- In which program have you designed the control:
    - Arduino: 9%
    - Matlab-Simulink: 82%
    - Both: 9%
- Do you think that it is necessary to include additional information about any of these topics? (more than one answer allowed)
    - About the hardware: 27%
    - About Arduino's software: 27%
    - About the use of Simulink with Arduino: 73%
    - It is enough: 18%

The students were also asked to rate the practice out of 10, with the average score being 8.2. In the suggestions section, the students mainly requested to start the project earlier within the academic semester, more in-depth explanations and asked for more ambitious control laws.

The main lessons learned and conclusions about the project are:

- The work was well received by the students, and they consider that it favoured their learning. Several students even requested paying for the Arduino kit to be able to keep it.
- It was the first contact with Arduino for most of the students. Despite this, it does not appear that this was a problem. This is because the "Arduino Projects Book" included in the kit is very comprehensive and allows self-learning.
- The difficulty of the project was in line with other works of the master's degree.
- One of the goals for the next few years was to include other sensors (magnetometers, IMU) and actuators (reaction wheels, magnetorquers). This was because it was thought that there were few options and work could be boring for students. However, the surveys seem to indicate that students prefer to study the laws of control and software in depth, considering that the hardware is enough. Therefore, the priorities regarding modifications in the project for the next few years will be changed.
- Next year the project will start earlier (this year it started late in large part due to the limitations of COVID-19), and more emphasis will be placed on control laws and Simulink.

## Some Lessons Learned

At the present stage of the project (evaluation of the results) and bearing in mind that the results of a survey among students and teachers needs to be programmed before June 2021, it can be said that PIRAMIDE has shown a great potential to motivate students towards research.

Also, the results showed that students had developed skills to produce high level space engineering results facing a proposed task.

The weakness of PIRAMIDE lies in gathering together five different studies which are in fact five different projects, with different groups of students (see Table 2):

- Group 1: 14 students of MUSE degree to be graduated in June 2021. This group was involved in study 2 and study 5.
- Group 2: 24 students of MUSE degree to be graduated in June 2022. This group was involved in study 1 and study 3.
- Group 3: 4 students of Aerospace Engineering Bachelor Degree, 1 student for MUSTA degree, and 1 Ph.D. student. This group was involved in study 4.

**Table 2.** *Groups of Students within Each One of the 5 Studies that Compose PIRAMIDE*

| Study | Group | Character |
|---|---|---|
| Study 1 | Group 2 | Compulsory. Integrated within a subject. |
| Study 2 | Group 1 | Compulsory. Integrated within a subject. |
| Study 3 | Group 2 | Compulsory. Integrated within a subject. |
| Study 4 | Group 3 | Volunteer. Not integrated within a subject. |
| Study 5 | Group 1 | Compulsory. Integrated within a subject. |

Group 1 and Group 2 students carried out the tasks assigned in Studies 1, 2, 3 and 5 as part of the contents of the corresponding subject. Therefore, their participation was compulsory. Nevertheless, based on the comments from the teaching staff, the students' reaction to this initiative was positive.

On the other hand, the participation of students from Group 3 in the Study 4 was voluntary. Students from Group 1 were offered to be enrolled in this group but all of them rejected the proposal, apparently due to their workload. This was a surprising reaction bearing in mind that: 1) these students were at that moment studying the subject related to Studio 4 as part of the MUSE program, and 2) the contents of the Study 4 involved learning about research visibility and that some of the students from Group 1 planned to continue their studies after MUSE with a Ph.D. Without the results from the programmed survey it is not possible to explain the aforementioned rejection, the only fact that can be highlighted is the lack of academic reward in terms of subject's marks in Study 4.

Additionally, PIRAMIDE is a 5-independent-study project. That implies a lack of synergy that could be reflected in redundant contents and waste of educational resources. This is one of the questions that will be addressed in the programmed survey.

## Conclusions

In the present work the results from PIRAMIDE Educational Innovation Project are summarized. PIRAMIDE is composed of 5 Studies (case studies) related to space engineering. Leaving aside that the results of a survey within the students and teaching staff that were involved in PIRAMIDE needs to be post-processed, it is possible to draw the following conclusions:

- Research is a powerful tool to motivate students in aerospace engineering academic programs.
- Motivation should include some sort of academic reward (credits, part of final marks in a degree subject…).
- A project that involves different case studies should involve at least a common objective/result to increase synergy.

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