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IFAC PapersOnLine 52-12 (2019) 484–489

An Experience of Project Based Learning in Aerospace Engineering

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Abstract: Based on the authors teaching experiences this paper proposes the developing of a ProJect-Based Learning (PJBL) environment for Automatic Control Education in Aerospace Engineering (ACEAE), which have been developed in several projects that involved the same authors. The PJBL approach have been based on the following major aspects: a Hardware/Software platform (quadricopter and related ground station, etc) as an environment to design and implement automatic control laws, and a proper choice of such tools in order to facilitate the communication of the knowledge between student of different classes and academic years, thus also improving communication skills and teamwork experience. A new didactic formulation is thus proposed, summarized by a Professional Readiness Level (PRL) table, useful to organize the learning of automatic controls for the Aerospace Engineering faculties. The actual status of this concept is applied at the University of Bologna in the courses of Automatic flight Control and Applied Control. In this work the choice of educational tools which could make the academic laboratory activities sustainable over time is proposed and the effectiveness of the proposed approach is assessed by means of the direct experience of the authors which summarize the feedback of the students involved in courses.

Keywords: Project Based Learning, Laboratory Education, Learning Tools, Professional Readiness Level, Projects.

1. INTRODUCTION

Having a famous and successful research laboratory represents a boutonniere for any academy, especially for engineering schools. The fame of a research laboratory is directly linked to the quantity and the quality of their scientific results. Unfortunately, in small realities not always the necessary resources to sustain the same production rate and quality of large teams are available, so the students become a fundamental help to the application of the theoretical research. Keeping the focus on academic laboratories on Automatic Controls and in particular Automatic Flight Control, this paper presents the base ingredients which could make effective a small research group mostly populated by students.

The Educational methodologies characteristics of the majority of Bachelor or Master courses of AC in Aeropace Engineering faculties are based on the classical methodology "Theory Based Learning" (TBL). This so called Chalk and talk education methodology could be effective in teaching theoretical aspects but research on education have shown its ineffectiveness in providing students with problem solving skills [Mills and Treagust (2003)]. To remedy this situation, student-centered educational methods have been proposed, namely Problem based Learning and Project Based Learning. Both problem-based learning and project-based learning are referred to as PBL, and some find it confusing to separate the two pedagogies.

By means of Problem-based learning, originated in the 1960s, students learn about a topic through the solving of problems and generally work in groups . Project-based learning has its origins back in the work of John Dewey and William Kilpatrick and dates back to 1918 when the term was first used. Project-based learning is an instructional approach where students learn by investigating a complex question, explore real-world problems and find answers through the completion of a project. Students also have some control over the project they will be working on, how the project will finish, as well as the end product.

The difference between problem-based learning and project-based learning are that [Straub et al. (2017)]

- students who complete problem-based learning often share the outcomes and jointly set the learning goals and outcomes with the teacher.
- project-based learning is an approach where the goals are set. It is also quite structured in the way that the teaching occurs. Project-based learning is often multidisciplinary and longer, whereas problem-based learning is more likely to be a single subject and shorter. Generally, project-based learning follows general steps while problem-based learning provides specific steps.

In the case of Aerospace Engineering the problems are often multidisciplinary [National Academy of Engineering (2005); Grega W. (1999); Oliveira et al. (2011)] and the implementation of a control system, such as an Automatic Flight Control, often involves the need for knowledge in various fields and therefore the subdivision of the project into several tasks managed by different and communicat-

10.1016/j.ifacol.2019.11.290

ing students groups. For this reason, in this work we propose a Project Based Learning (from now PBL) divided in various phases of learning, rather than a transition from a Problem based to a project-based learning and we will define, a Professional Readiness Levels (PRL) Table, as a guideline for the different educational levels.

Throughout the paper we will also present our PBL experiences, that have consisted in real projects conducted as an educational exercise too. In the development of these experiences of PBL several lessons been learned, and in particular that in order to implement the various PRL effectively, it had to be defined a framework for the laboratory, both SW and HW, which ensured the transferability of the instruments and the results obtained both over time (students in successive years academics) and transversally between groups operating in different tasks of the project.

The description of this experiences and the development of our educational proposal is presented in three main sections: the first one reports the past laboratory activities, mostly relate to projects, and describes the goals and the obtained results. At the end of the first section the main drawbacks of the strategies adopted to work the project tasks are pointed out. The analysis of these problems leads to the definition, in the second section, of a sustainable laboratory organization based on the students. Finally, the third section describes the solutions adopted to manage the current projects which have been defined in agreement with the rules detailed in the second section.

2. PAST LABORATORY ACTIVITIES

Hereafter, the project and laboratory activities that led to the definition of the PJBL organisation presented in this article are proposed

2.1 Project LAURA

The project LAURA (Aerospace Research University LAboratory) [Bertoni, Castaldi and Penati (2012)] was a three-years Italian national project whose goal was to develop a supervised ultra-light aircraft (maximum take-off weight less than 430 Kg) equipped with sensors and actuators suitable for the investigation of fault detection and isolation algorithms and fault tolerant controls. In the project LAURA the University of Bologna was in charge of the design of the scientific payload (sensor suite, flight control unit and the actuators) and of the modification of the aircraft to install the scientific payload. The laboratory activities focused on the design of the software system for the creation for the control loop. The hardware solution was based on the products by National Instruments and, in particular, was composed by a PXI computer equipped with an FPGA module to which the sensor suite was connected (see fig. xx). Finally, the team, besides the academic researchers, was composed by only three people: an aerospace engineer, a software engineer and an electronic engineer. The number of students involved in this project was five. After the conclusion of the funding period, the aircraft has been used for more than 3 flight-hours despite the team who worked on the project was totally renovated and successively composed by master students only.

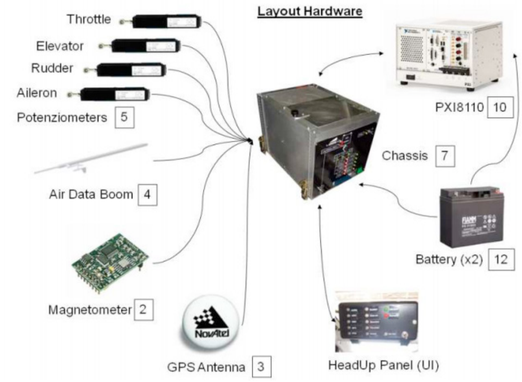

Fig. 1. LAURA architecture

2.2 SHERPA

The project SHERPA (Smart collaboration between Humans and ground-aErial Robots for imProving rescuing activities in Alpine environments) was an FP7 European funded project which goal was to develop a mixed ground and aerial robotic platform to support search and rescue activities in a real-world hostile environment like the alpine scenario. The project lasted for four years. In the context of SHERPA, the University of Bologna (UNIBO) was in charge of developing some quad-copters dedicated to search and rescue operations in avalanche. The team of UNIBO, besides the academic researchers, was composed by seven people: two aerospace engineers, two software engineers, one electronic engineer, two control engineers. The number of students involved in this project was about thirty. The laboratories of UNIBO designed the hardware system architecture in terms of sensor suite and electronic boards to fulfil the following needs: to be sufficiently compatible with possible extra sensors, to create a robust safety switch logic (to let the remote pilot taking over the commands), to have a dedicated reliable low level flight control unit implementing the stabilization control laws and to have an extra computational power to elaborate high level data such as images and videos. The result was a hardware composed as in Figure 1 which programming required four different languages, C/C++, Arduino and Phyton, organized in three different systems, Pixhawk Flight Stack, ROS and Arduino. The team composing the UNIBO research group were dismantled after the end of the project and no successive flight-hours were reported.

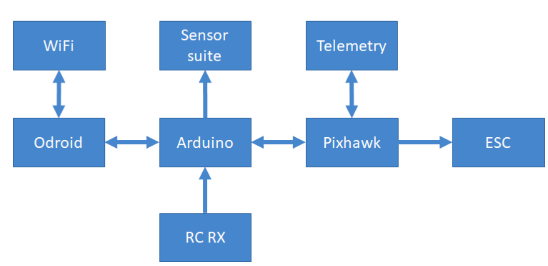

Fig. 2. SHERPA drones control architecture

2.3 Lesson Learned

The comparison of the project LAURA and Sherpa clearly highlights some important aspects:

- The projects were conducted by a different number of researchers/students: SHERPA was conducted by a team five times bigger than that working for LAURA;
- The number of software and hardware equipping the aircraft (LAURA) and the drones (SHERPA) were different: those equipping the SHERPA drones were three times those equipping the LAURA aircraft;
- The post-project maintenance was much better for LAURA than for SHERPA;

The participation to research projects is, for the research teams, one of the most important way to increase its knowledge which represents a sort of research energy. During the project period, indeed, the group produces scientific results thus increasing its research kinetic energy which should be converted into a research potential energy at the end of the project. Keeping the focus on the practical aspects, this stored energy is represented by prototypes (both hardware and software).

On the other hand, in small research groups, researchers and students hired just to cover the project period are the actual depositaries of this knowledge (kinetic energy). So, since they leave the research team at the end of the project, the academic laboratory experiments a pathologic post-project depression if the project results are not stored in an understandable and usable way, thus transforming the kinetic energy into a potential one (to be exploited in future projects).

In practice, the possibility to easily maintain the hardware and the implemented software constitute the main dissipating phenomena which make the energy transformation from kinetic to potential not ideal. As example, the project SHERPA taught that a system composed by three electronic boards (Arduino, Odroid and Pixhawk) with also three different programming languages was too complex to be maintained and developed by students. As consequence, the drones developed during the SHERPA project, even representing extremely performing machines, were discarded. Furthermore, the absence of robotic applications slowed down all the off-project laboratory activities due to a lack of attractive thesis topics.

In conclusion, the lack of software tools able to automatically deploy to different hardware the control algorithms coded with intuitive high level systems has been identified as one of most critical points for the sustainability of the laboratories activities.

3. PROFESSIONAL READINESS LEVELS

The involvement of students in practical activities can happen in different ways such as term papers, internship or master theses. The topics of these practical activities are usually selected on the base of the programmed laboratory needs. In particular, the laboratory life is dictated by the presence of funded projects for which results must be provided at given deadlines. Usually, these projects are well organized and a GANTT chart represents a good base to plan the laboratory activities.

In this framework, the practical activities are oriented to the solution of a specific problem and are always associated with quite hard constraints in terms of expected performance and deadlines. On the other hand, in absence of funded project, the practical activities are mostly related to:

- the assessment of the students capacity of translation of the theoretical knowledge into the solution of practical control problems;
- the improvement of the facilities of the laboratory (hopefully part of a long-term planning);
- the application of the last scientific research results;

Regardless the origin, the practical activities are assigned to the students by following a complexity-difficulty based approach. As example, simple problems, maybe already solved or not necessarily linked to something really useful, are usually assigned to bachelor students for their term papers whereas, master students are called, for their thesis, to implement, test and evaluate the performance of a control algorithm in a context of a funded project.

The topics are then classified in levels of difficulty-complexity in a scale compose by six different degrees. Students able to solve a problem rates at sixth level show a good propensity and aptitude to demanding works to demonstrating a good Level of Professional Readiness (PRL). At the opposite, students able to solve only problems rated at the first complexity level are good students but not yet ready for being engineers.

Table 1 reports these readiness levels and the associated topics describing the complexity of the problems the students can solve. The same table also reports a statistics relation between the professional readiness levels and the kind of academic activity: usually the students PRL increases with their academic age evaluated on the base of the activity they are involved in. But it is worth nothing that, often there are cases in which a bachelor thesis is worked much better of a master thesis thus confirming that the table reports only the mean values of this statistics.

A further interesting aspect of this classification is that the so called Problem-Based Education (PBE) and the Project-Based Education (PJBE) can be seen the extremes of the ranking in which the PRL 1 correspond to a pure PBE and the PRL 6 is representative of a PJBE. The classification proposed in this paper configures each students activity as a weighted mean of PBE and PJBE.

4. BUILDING A SUSTAINABLE HIGHLY DYNAMIC LABORATORY ACADEMIC TEAM

The execution of laboratory activities [Saunders- Smits (2011); Sanjay et al. (2010)], in agreement with the foreseen efforts, requires the composition of a stable team with dedicates skills and competencies. Unfortunately, the nature of the activities, with or without funds and the kind of funds, represents a constraint for the creation of a long-term team. So, small laboratories without considerable funds are sustained by teams mostly composed by few senior long-term positions and many junior short-term people.

In this context, the success and the progress of the laboratory activities can be hard unless suitable countermeasures are taken. Since small laboratory teams are mostly composed by students, the biggest problem to be solved is

Professional readiness level	Nominal Target Activity	Topics	Effort [man-hours]
1	Bachelor term papers	Solve an academic "ideal" problem without time of performance constraints.	20
2	Master term papers	Solve an academic "ideal" problem without time constraints but guaranteeing the prescribed level of performance.	40
3	Bachelor internship	Investigate a real system of low complexity and learn how to manage it. No deadlines are foreseen.	160
4	Master internship	Investigate a real system of high complexity and learn how to manage it. No deadlines are foreseen.	160
5	Bachelor thesis	Implement the theoretical knowledge to real but not complex systems making the control system working in the laboratory. Time deadlines are given.	320
6	Master thesis	Implement the theoretical knowledge to real, complex systems making the control system working in the laboratory and assessing the obtained performances. Time deadlines are given.	640

Fig. 3. Professional Readiness Levels

represented by the necessity of creating a sustainable and easily accessible information repository over time. Indeed, the short-term nature of the activities that the students do deeply impact on the dynamics of the team which is quasi-totally renovated each six months. The essential point is to take advantage by any single student activity and avoiding the repetition due to a missed knowledge transfer across the activities. To make the time varying team effective, students with different PRL must interface by means of a unique communication system which maximize the information exploitability in terms of easiness of access and understandings.

4.1 A framework for sustainable academic applications

Practical tools The range of application of automatic control is wide and covers most of the facilities humans use daily spanning from industrial to embedded systems. For several reasons, the applications on which aerospace engineering schools usually focus are limited to small unmanned aerial/space vehicles. Despite their small dimensions, objects such copters (both heli- and multi-), small fixed wing UAV and micro-satellites represent good twofold benchmarks: from one hand, they are suitable to assess the students ability to translate their theoretical knowledge into practical analysis or design activities and, from the other hand, they represent sufficiently accessible application for testing the last research outcomes.

The purpose, common to these scenarios (knowledge assessment and research in automatic controls and automatic flight control), is that of coming to quick results represented by a laboratory prototype. Unfortunately, this whish is in contrast with the typical complexity of aerospace applications which are, by nature, multi-disciplinary systems. Taking as example the development of a multi-copter the necessary subsystems are: airframe, power distribution (battery-ESC-motor-propeller), control unit and sensors. The choice of the combination of airframe and power distribution suitable for the purpose of the project (thesis or research) requires the involvement of several engineers such as an aerospace engineer to select the right couple motor-propeller, a mechanical engineer to design a sufficiently light and robust airframe and an electronic engineer to choose the right power-train (battery and ESC).

Despite this design process is exciting, it is hard to be implemented because it requires different competencies which are not always available. Furthermore, it is not profitable because it requires time and moves the focus of the project on the aircraft design and not on the control design. Fortunately, the availability of ready-to-fly UAVs, in which the airframe and the electrical wiring are ready, allows to focus only on the selection and the integration of additional payloads, required by the experiment. Going back to the multi-copter design example, the payload is constituted by the suite of sensors and the controller board. Even restricting the attention to the selection and the integration of the payload, the problem remains complex because there are several aspects to be taken into account such as the electrical and communication compatibility between the sensors and the control board, the number and the kind of available ports on the control board, the computational power and the programming language.

In most of the applications developed by universities, the selected hardware for the control is not fully compatible with the selected sensor suite thus requiring the installation of, sometimes several, intermediate layers. This design choice, or necessity, makes the project more complex due to the presence of extra wirings, weight, volumes and programming languages. In turn, this increasing in complexity leads to a slower development or to the need of an increasing number of man-hours probably involving a software developer (to handle different programming languages).

Finally, last but not least, the laboratory teams, composed by students and researchers, are subjects to an inherent renovation process which makes the team periodically changing its composition. So, it is fundamental that the knowledge acquired and the results obtained during the laboratory activities are transferred to the new members which not always have the same competencies of the gone participants. Then, the choice of electronic hardware and software architectures assumes a fundamental role to guarantee not only a quick finalization of the practical activities but also their sustainability over time. Moreover, in both the research and knowledge assessment scenarios, the students represent a central element of the process chain from the theory to the practice. The hardness of building and keep a team of students having selected heterogeneous competencies besides the need to keep the focus only on control aspects and together with the necessity of shorting the time to results lead to the definition of technical requirements the developing platform should fulfil. In detail it should:

- Have only one programming language, better if of high level, which hide all the low-level problems such as the driver configuration and the memory allocation. Visual programming languages based on blocks and links are preferable because the code is extremely readable. The easiness of the reading of the code is directly linked to the settling time of new members of the team in understanding/modifying/developing the code. On the other hand, the visual program-

ming represents an intuitive programming tool which needs learning transients acceptable even for short term projects like bachelor thesis. Finally, a visual programming let the supervisor understanding better the meaning of the code by making evident the flux of the information from the sensors to the actuators;
- Be sufficiently reach in terms of computational power, number and kind of ports to be composed by only one electronic board. This reduces the number of electrical and communication problems thus leading to a higher reliability of the developing platform. Most of the times students spend considerable amount of time to understand strange results, which seems to be meaningless, and caused by unexpected problems linked to the boards interconnection.

Theoretical tools Since the topic automatic controls is one of the most theoretical among those taught at aerospace engineering schools, it is fundamental, to have good future control engineers in aerospace, to make the students completely aware of the performances and limitations associated to the control techniques. With this aim, a good automatic controls for aerospace or automatic flight control course should be built on the following elementary bricks: specifications, model, analysis and design. Indeed, the solution of any control problem is reached by following a logical process which starts by the identification of a model, an investigation of its properties (e.g. stability) and finally the design of suitable control systems to match given specifications.

To teach the basis elements, several approaches can be followed among which the authors prefers the Theory Based Education (TBE). In agreement with this teaching philosophy, formal and sufficiently detailed theoretical notions are taught as priority subjects. The aim of this phase is to provide the students the tools to understand and deal with fundamental systems properties such as the stability of a plant or the robustness of a control system. The theoretical knowledge of the maximum achievable performance and the limitations of control algorithms is then seen as necessary and sufficient element to make the students able to comment, and eventually criticize, the results obtained during the applications.

The TBE has its own positive and negative aspects. One positive aspect regards the potential level of insight which can be provided. Providing the students the suitable mathematical tools to model, analyse and design make them able to understand in depth the explanations for the applications outcomes. Thanks to the TBE, the students have the knowledge to answer to typical engineering questions like: what if I do this instead of ... ? what if I combine these two ... ? which control method should I modify/improve to solve my problem? Which part of my problem represents a substantial question which cannot be solved? A second positive aspect linked to the TBE is that, to understand the theory the students are called to open their mind and get used to deal with complex problems.

The authors think that this aspect is twofold: from one hand, the students become good control engineers (not only in aerospace) able to solve any problem on the base of the learned general solution theoretical tools; on the other hand, the ability of dealing with generic complex problems not necessarily linked with specific applications let the students discovering their inclination for successive higher level studies such as Ph.D. courses. Furthermore, a theory-based approach usually saves time because, starting by general abstract concepts, let the students taking on responsibility of specify the possible infinite cases. The exercises made during the classes are then seen as a method to consolidate the notions learned. These exercises can be made sufficiently simple and in a few number just to give the students a preview of what they might aspects during the solution of real-life control problems.

One possible drawback of a TBE is that the students feel the course more theoretical and far from the applications. Sometimes they fell discouraged because their engineering expectations of having fast and simple solutions to complex problems are disappointed. A second possible negative point of the adoption of a TBE in control is that it needs a not negligible amount of mathematics and physics background. The students which approach to a control course without this knowledge base are usually penalized because miss the tools needed to understand and appreciate some fundamental steps in the controls design for aerospace systems, i.e. procedure such as transformations, coordinate changes, model simplifications to highlight the most important phenomena, etc.

To avoid this problem there are two solutions: the first is represented by a suitable program of studies in which the Automatic Control course, taught in agreement with the TBE, is planned for the late years with mathematics and physics as propaedeutic matters; the second consists in an extended course in which selected mathematic and physic notions are preliminary taught before starting the pure control part.

5. CURRENT PROJECTS

5.1 SWAMP

The European project H2020 SWAMP is aimed to develop strategies to optimize fields irrigation in different pilots both in Europe and in Brazil. To this end the use of drones equipped with a multispectral camera is of fundamental importance, since the multispectral images allows to evaluate the health status of the crop and the related water need. The drone surveys on the crops include flights that have to be carried out with stable attitude and at constant speed even in the presence of significant wind.

The development of the drone from the choice of the configuration and the microcontroller programming was made by a student within his master thesis following the PJBE educational lines outlined above, thus resulting in the choice of an Intel drone equipped with the Intel Aero Board providing on the same board a Pixhawk 4 and an ATOM microprocessor. For the programming of the guidance and flight control law to carry out surveys on fields (mainly of vineyards, apple orchards), we used, in line with the above mentioned guidelines, a Simulink package that allows the Simulink programs to be transferred in the language of Pixhawk firmware. This way, the student does not get lost in low-level programming.

The student of the Master in Aerospace Engineering also participated in practical tests and meeting of the project, thus acquiring, in line with PJBE, non-acquirable capacities in the classroom, related to the ability to interact in team work and to disseminate the information about the research. Finally, he acquired new skillness related to the multidisciplinary environment provided by the PJBE. In particular the student has learned to adapt the characteristics of the flight in such a way as to meet specific relevant optimization of the image acquisition, taking into consideration the kind of crop too.

5.2 AIRBORNE

This project represents a follow-up of the SHERPA project. As for its predecessor, also AIRBORNE is a European Project but funded under the H2020 program. The focus of this project is on the development of the SHEPRA drones, developed by UNIBO, at high TRL values. In this project, the drones can load different payloads to form an heterogenous fleet to reduce the time for searching avalanche victims.

5.3 Organization of the current projects

The lesson learned guided the planning of the activities of the current European projects in which the laboratories of the University of Bologna are involved. Even if it is impossible to exactly satisfy the wishes detailed at the end of the section Practical tools, the senior researchers have tried to reduce at minimum the system complexity adopting off-the-shelf solution which are fully programmable. In particular, the recent availability of tools like the Pixhakw PX4 support for embedded coder, offered by MathWorks, make the board Pixhawk even more attractive thanks to the possibility of adopting Simulink for the design of control algorithms.

Up to now, this seems to have been a right choice because the students involved in the current projects (mostly aerospace engineers in SWAMP and control engineers in AIRBORNE) are producing clear and robust results after a short settling time (few weeks). The drones of the two projects SWAMP and AIRBORNE, despite in their early development stages, have flown for more than 48 hours respectively demonstrating their reliability.

It is worth nothing that all the issues occurred have been fixed quite easily by the team involved in the test sessions (who not necessarily corresponds with the development team). Thanks to this organization, the design of the control laws and their implementation is in charge of only two aerospace engineers, one for AIRBORNE (Ph.D.) and one for SWAMP (master student).

6. CONCLUSION

Based on the experiences both in teaching and in laboratory activity and in projects at various levels, the authors propose an organization of the educational activities for the Automatic Control and Automatic Flight Control courses in the Faculty of Aerospace Engineering. This organization takes its cue from the experiences, proposed also in the literature specialized in education, on Problem Based education (PBE) and ProJect Based Education (PJBE).

In agreement with literature, the authors acknowledge that the PBE is not suitable for an engineering faculty and in particular for the faculty of Aerospace, because of the multidisciplinary aspects that characterize the learning of automatic controls in the field of Aerospace. A new didactic formulation is thus proposed, summarized by a Professional Readiness Level (PRL) table, useful to organize the learning of automatic controls for the Aerospace Engineering faculties. This table covers the different levels of education from the Bachelor to the Master (and then to Ph. D).

The innovative aspect of the proposed approach, consists in a remodulation of the PJBL starting from the lower levels of learning, bachelor, and no longer reserved only to the students of the master or Ph.D. In order to implement the educational methodology, it is proposed an organization of the HW and SW tools of the laboratories in order to allow the acquisition of the knowledge and of the application capacities useful at professional level and the transmission of the same among the various levels and among students of successive academic years.

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