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Various student's projects related to aerospace control education

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Abstract: This paper presents the various types of projects that students have to deal within the area of automatic control and signal processing applications at CentraleSupelec, School of Engineering, Université Paris-Saclay. The courses offered during the academic teaching terms or through the elective courses and the laboratory practice sessions are devoted to enable the students to gain knowledge on the one hand and, on the other hand, to foster their skills in different topics. Besides, a focus is made through engineering projects in a framework of industry fulfillment, including professional projects.

The aforementioned students' projects have to be related to the subjects that may or may not be taught as well as to an industrial problematic, encouraging students to propose innovative solutions. Besides, they constitute the first step to get the opportunity to be hired right after graduation. The different subjects are thus adequately designed to train the students on the way forward work in a framework of industry collaboration and requirements. Similar projects are also offered to students enrolled in exchange programs with top European institutions (especially within the Erasmus program). In this paper, some examples of these projects are described, including indoor tests as well as the organization planning.

Keywords: Student projects, UAVs, control engineering, guidance law, control education.

1. INTRODUCTION

CentraleSupelec is a higher education and research institution in the engineering and systems sciences, it is well ranked in Automation Control (ranked 1st in France, 32nd in the world) and in Telecommunications, one may refer to (ARWU, 2019). CentraleSupelec was established in January 2015, and it is the result of the merger between Ecole Centrale Paris and Supelec, both reputed as being among the best engineering schools in France for almost two centuries for the former and more than one century for the latter. Both schools have trained great personalities; let us mention, for instance: G. Eiffel for whom the name alone is used to identify Paris and even France; L-C. Breguet, who was one of the early aviation pioneers, aircraft designer and builder, the mathematician P. Bezier who popularized the Bezier curves and surfaces that are now used in most computer-aided design and computer graphics systems, and so many others who are well known for their contributions in several fields. Therefore, as one can guess, the industrial component and technological innovation are quite strong and deeply-rooted in CentraleSupelec's education and research programs.

The CentraleSupelec curriculum is organized over a three-year study path; the admission process is made through competitive examinations. Last year, a new curriculum for engineering courses was launched. As a result, over the next two years, three study programs will run in parallel to allow all students to move on to the new courses on an ongoing basis.

CentraleSupelec is an international institution with about one-third of students' population coming from overseas, with over seventy nationalities being represented. Since half of the local students opt for a double-degree program, one of its four pathways is completely offered in English, from courses to tutorials, lab practice sessions, and exams. 20% of the students are girls.

Also, CentraleSupelec offers a Master program which globally reflects the significant areas of its research domains, and often in line with its industrial partners' needs. After the achievement of the engineering degree and the national Master's degree, the students should expect to get a high-level position within a company or a research organization.

Furthermore, CentraleSupelec offers a doctoral program for students coming from abroad or those who want to pursue a given fundamental research work or developing innovative application methods. The major skills that CentraleSupelec engineers can deploy may be found in the website URL [CS]. CentraleSupelec is a part of Université Paris-Saclay network and for which it will lead the Engineering and systems sciences Graduate School [UPSaclay] in the near future.

The present paper will focus on student projects, in particular on those that are related to aerospace in the field of automatic control, guidance, and navigation. Indeed, students enrolled in the third year of engineering studies have to deal with projects in collaboration with industrial partners and, under their co-guidance, together with a local supervisor, develop innovative solutions to the presented task. In general, students work in a team made up of two or three individuals, depending on the scope and complexity of the problems. The industrial partner entirely funds these projects.

The paper is organized as follows. Section 2 gives an idea of the educational method. Section 3 describes the first project, helpful to understand the fundamental steps that the students have to follow as well as what they can retain in terms of objectives fulfillment, theoretical development, control implementation, and test conduction. Section 4 presents a project in collaboration with the French Defense Agency. Section 5 offers a Master thesis work that an international student accomplished within an exchange program. Finally, Section 6 gives some discussions, and finally concluding remarks end the paper.

2. EDUCATIONAL METHOD

The purpose of this section is to briefly develop the content of courses related to aerospace only and methods used in teaching engineering. The core courses have a similar format; they are specifically designed to not only build a foundation of knowledge but to encourage students to be intellectually active in developing solutions for any complex practical problem. The teachers use face–to-face approaches, only a few specific courses are online and must match with nine major defined skills (CS-2, 2018).
A Master course on flight mechanics is included in the curriculum; it deals with the flight dynamics in 3D- space, the static and dynamic stability, and the different used aircrafts characteristics. Besides, during the second year of studies, an elective module is delivered on guidance and navigation of unmanned aerial vehicles (UAVs) in collaboration with the French Aerospace Lab ONERA. Typical tasks for students concern system modeling, behavior analysis, design, and implementation of control architectures to satisfy required system specifications, test conduction, and critical results interpretation.
The content of this elective course consists of six modules: (1) Different types of UAVs; (2) Analysis and Control methods; (3) UAV system modeling for control purposes (flight mechanics notions, sensors definition, guidance, and control); (4) Control of UAVs (fixed wings, rotating wings, engine control); (5) Guidance and Control (trajectory tracking, obstacles avoidance); (6) Examples with numerical simulations and experimentation. Each Module is delivered over a three-hour slot. A two-hour examination is held after completion of the last course.
Students have to deal with the complexity of the systems to understand the specific model dynamics of each type of UAV. Control theory allows for learning the different possible simplifications of the model to elaborate controllers that may lead to expected results with a certain level of robustness and to interpret obtained results. Practical exercises, as well as mandatory projects that may last between two and five months, are aimed to help the students to acquire relevant skills.
Indeed, students have to validate their theoretical and experimental work by using numerical simulations environments. At the end of the period devoted to the projects, they have to make a presentation and to provide a report on the work done. Students are then graded on a scale of one to 20 by a local committee composed of the supervisors plus several colleagues working in the same research field. In case their score is lower than 10/20, the students have to provide significant improvements within the two following weeks.
From the Professor's side, the best projects may be selected and employed as examples in the upcoming training modules. Their goal is to improve the understanding of the automatic control application methods and procedures or simply to work as relevant experimental test-bench for teaching and research purposes.

In order to emphasize the historical evolution of the proposed subjects over the last decade, it is worth describing the main results of the following project which has been undertaken by a student during the Master training. The teacher-supervisor work consists of advising the student during the different phases of the project. In the case of students who have not yet studied some of the required techniques, then the opportunity to learn them from the supervisor is offered.

3. PROJECT 1: DESIGN AND CONTROL OF A SPECIFIC DRONE

This project (Aubert-Moulin, 2006) aimed to control a particular autonomous vehicle (Fig. 3.1) that a student had previously designed and built during his first two years of studies using the available features. The learning outcome covered every step to complete the physical assembly as well as its computer unit and to design a linear controller according to the block diagram of Figure 3.2.

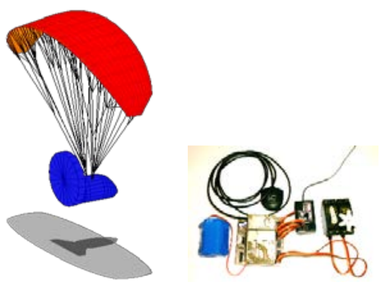

Fig. 3.1. Autonomous vehicle with its embedded computer unit

2.1 Characteristics of the drone

The main characteristics of the vehicle are:
- Sailing: 1,9 m^2, Spi canvas
- Hangers: 50 m
- Powertrain unit: 5.5 cm^3 engine, 12 N of thrust
- Brakes: operated by servomotors
- Nacelle: payload capacity, on-board electronics

- Sensor management: radio-controlled receiver, inertial unit, GPS
- Computer unit: pic18f6327, 20 MIPS
- Actuators: servomotor

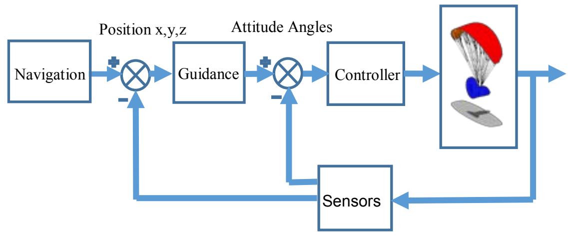

Fig. 3.2. Architecture of control block diagram

Concerning the estimation of the unmeasured variables involved in the control law (position, attitude angles), they were obtained by using Luenberger observer (Fig. 3.3a) and Kalman Filter for the estimation error with noisy measurements. The student had to analyze and compare both performances and to select the estimation approach that he had to implement in order to elaborate the vehicle trajectory according to the flight plan (Fig. 3.3b).

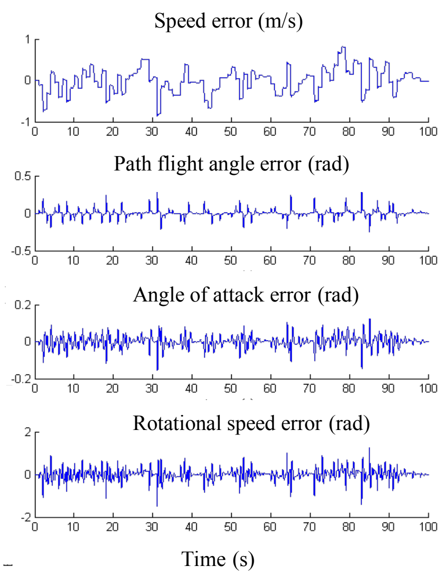

Fig. 3.3a. Estimation error with noisy measurements using Luenberger observer

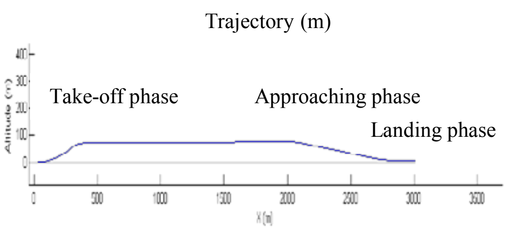

Fig. 3.3b. Real trajectory of the vehicle

4. PROJECT 2: GUIDANCE VIA FRENET METHOD OF AN UAV

To strengthen the relationships between our students and industrial companies, some subjects are co-supervised by an industrial partner who defined the project. The following project has been undertaken by a team of three students during their last year of studies, from November to March.

As a matter of fact, for four years, each year, the students have to work on the part of the subject to complete the essential flight simulator step-by-step while aiming at getting a new version, which can take into consideration more aggressive maneuvers. The section described herein concerns searching for some improvements in 3D trajectory tracking and guidance design law of a mini unmanned aerial vehicle called DRAC. This last one is a specific drone of our defense agency that provided the essential flight simulator, including the parameters of the vehicle.

The reference trajectory is generated based on a prescribed sequence of waypoints through the flight plan. For this purpose, it is shown that using Frenet based method and appropriate movements in turns arriving at the waypoints or manoeuvres in transitions from one type of trajectory to another type lead to better global performance, in comparison with some other approaches based for instance on asymptotic output tracking (as previously studied). The obtained improvements are shown based on the tests performed with the flight simulator, and which includes the implementation of the new guidance system according to the block diagram below (Fig. 4.1).

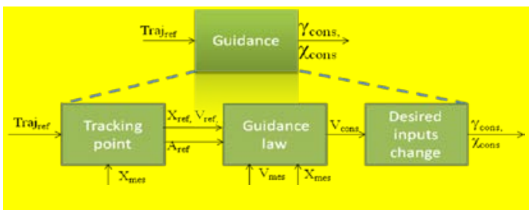

Fig. 4.1. Detailed Guidance bloc

This newly designed guidance system consists of three sub-blocks. The first one has, as inputs, the prescribed reference trajectory that provides the reference variables by means of the position reference X_{ref} as well as the references of the speed and the acceleration V_{ref}, A_{ref}, respectively. These variables are then fed as inputs of the second sub-block, which produces as output the input speed of the third sub-block. This sub-block via the guidance law calculation and the measurements of the position X_{meas} and the speed V_{meas}, provides the desired flight path and heading angles references. The angle references then produces as output the desired speed.
This guidance system is implemented in the flight simulator. Tests have been performed for the characteristics of the mini UAV type fixed-wing named DRAC/Tracker (Drone de Reconnaissance au Contact, as shown in Fig. 4.2). It holds the ability to perform a variety of missions. Indeed, it is

intended to provide reconnaissance capabilities at closer ranges for both military and civil customers. Furthermore, it may perform over-the-hill reconnaissance and surveillance, reconnaissance and battle damage assessment at closer ranges, and location, reconnaissance, identification, classification.

Fig. 4.2. DRAC picture

The guidance algorithm, based on an optimization criterion, selects the shortest trajectory, taking into consideration the maximum physical constraints of the vehicle, which is the straightforward way transitions in between two-way points; otherwise, it makes a turn with respect to the minimum curvature radius as shown in (Badatchef *et al.,* 2012) or in the resulting publication (Siguerdidjane *et al*., 2012).
One of the results of multiple form trajectory tracking is given in Figure 4.3 according to a reference one and in comparison with the first and second-order law of asymptotic output tracking-based approach previously studied.

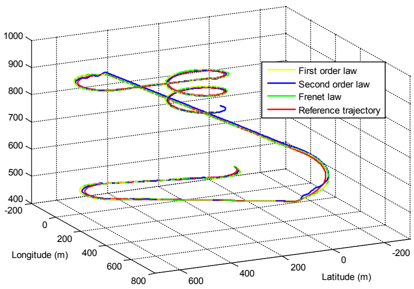

Fig. 4.3. 3D- trajectory tracking *using the flight simulator*

5. PROJECT 3: CONTROL IMPLEMENTATION STUDY

Based on the work performed by the previous Master student (Bouzid, 2015) using an octocopter for the experimental tests, the student (Sordi, 2019) has designed and implemented the control architecture on a micro UAV, more specifically a Parrot Mambo (Fig. 5.2). Once the modeling phase was established, the control architecture was drawn as the one represented in Figure 5.1. The decomposition into two subsystems, a rotational and a translational one, is adopted as usual in this kind of system. In the position control, the horizontal displacements x and y are controlled by the virtual inputs, u_x and u_y that ensures the tracking of the reference trajectories x_r and y_r while allowing the generation of the reference roll and pitch angles. The rotational subsystem is controlled through the inputs u_2 u_3 u_4, and the vertical displacement through u_1.

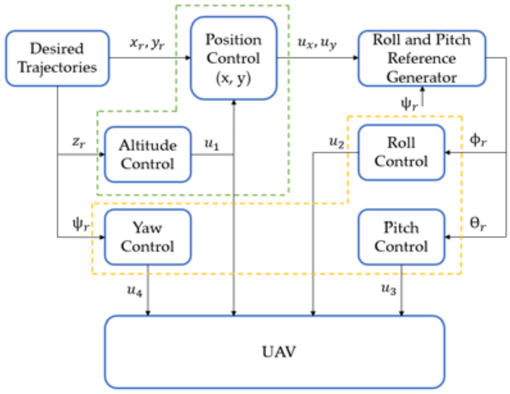

Fig. 5.1. Control architecture

5.1 Numerical simulation results

To perform the numerical simulations, the full non-linear model was implemented in Matlab and Simulink environments. The controllers studied rely on PID, LQG, and Feedback Linearization approaches; they are tested in different scenarios that will be introduced later to evaluate the effectiveness and robustness of these various control strategies. First, the simulation in the basic scenario is carried out in the absence of disturbances, where the reference trajectories are the ones shown in Figs. 5.3-5.4. Then, wind gusts, sensors noise, and model uncertainties are introduced. To emulate as far as possible the real system behavior, suitable saturation blocks are considered to constrain the maximum achievable voltage across the motors as well as maximum feasible inputs into the system. Kalman Filter and Complementary Filter were simultaneously employed for attitude estimation.

5.2 Indoor experimental tests

As mentioned above, the quadrotor used in this project work is a Parrot Mambo for which Table 5.1 gives its parameters. The simulations have been performed in the nominal case as well as in the case of model uncertainties, sensor noises, and wind disturbances. Such simulations allowed the student to tune control parameters to meet specific performance requirements progressively. Furthermore, a fan (with different level of the rotational speed) has been employed for emulating a wind gust. The student learned how to cope with the complexity of representing a real system into a simulation environment and how to refine initial assumptions progressively.

Fig. 5.2. Parrot Mambo vehicle

Table 5.1: Parrot Mambo technical specifications.

Parameters	Value
Size- Weight : 18x18x6 cm- 63 g	
Autonomy: 8 min	
Max horizontal speed: 8 m/s	
Max vertical speed: 2 m/s	
Max tilt: 25 deg	

Amongst the mini-drones, this vehicle is considered as one of the most robust and easy to fly. It is supplied with an Inertial Measurement Unit (3-axis accelerometers and gyroscopes) to evaluate translational accelerations and angular rates as well as obstacle contact. A pressure and an ultrasound sensor are employed for altitude measurement and a downward facing camera is used for optical flow estimation. This last one, used for horizontal speed measurement, runs at 60 FPS. The battery is a 660 mAh LiPo type that ensure a flight duration of approximately 8 minutes. The four DC coreless motors are instantly locked by a safety module in case of propellers contact with foreign bodies.

5.3 Software and communication

Parrot provides a Simulink Support Package for mini-drones that can be used to design and build flight control algorithms. The algorithms are deployed wirelessly over a Bluetooth Low Energy 4.0 connection allowing the access to onboard sensors as well as downward facing camera. The Simulink Coder is used to record flight data on the mini-drone and to access the C-code generated from the Simulink models. For the three dimensional animations, Simulink 3D Animation is employed. For further and more detailed information, relate to the Mathworks contents on Parrot Mini-drones.

5.4 Control design development

Hereafter, selected results are displayed only to show the relevant efforts made by the student (LQG in Figs. 5.3 and 5.4) and Feedback linearization in Figs. 5.5 and 5.6 and the performed experimental tests (Fig. 5.7). The student got the possibility to learn the Feedback Linearization approach during this project and to read many publications as for instance (Bouzid et al., 2017, Cowling et al., 2007, Gage, 2003).

5.4.1 Linear Quadratic Regulator

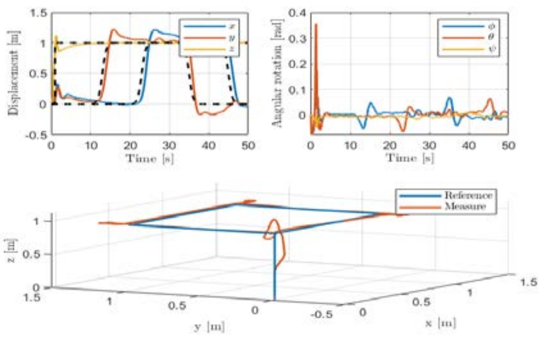

Fig. 5.3. LQR outputs for square reference trajectory

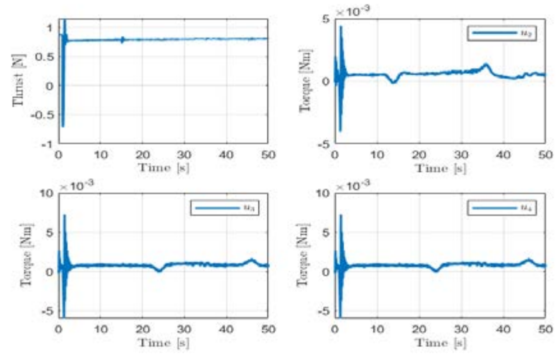

Fig. 5.4. LQR inputs for square reference trajectory

5.4.2 Feedback Linearization

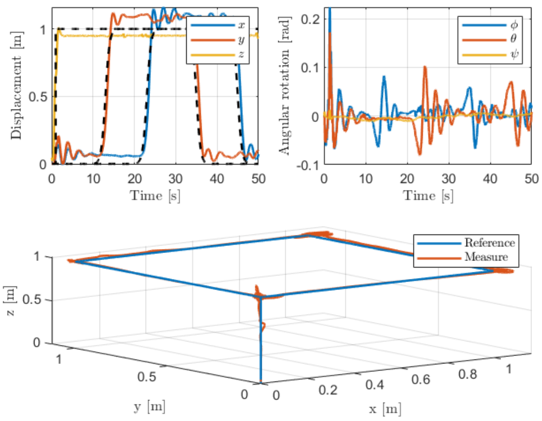

Fig. 5.5. Feedback Linearization outputs for square reference trajectory

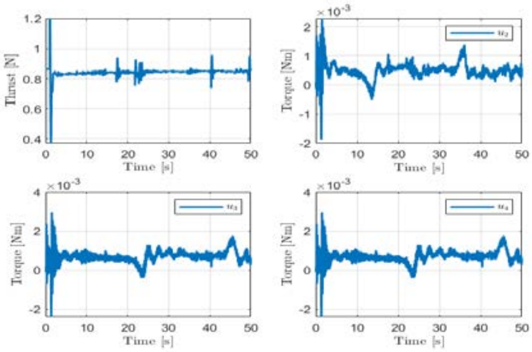

Fig. 5.6. Feedback Linearization inputs for square reference trajectory

Fig. 5.7. Experimental indoor tests

6. DISCUSSIONS

The examples of the student's projects presented above show the complete development cycle of handling a full project by a student. The successive steps in chain: the modeling, simulation without control development in a first stage; validating the model, controller design; implementation and testing in a second stage, demonstration to the students how the encountered difficulties may be overpassed. Also, the students learned and acquired sensitivity on which parameters one has to act on in the early stage to thoroughly carry out the experimentation phase, even in the presence of sophisticated software to transfer commands to the vehicle. Moreover, for some types of projects, working in teams of two or three students will be profitable since each of them improved relevant skills and knowledge towards complex task completion.

Concerning the third project, the student studied and compared the PID controller, with the LQG and the Feedback Linearization control using several scenarios in the nominal case and disturbed one. Nevertheless, only the main results are hereafter reported for the sake of conciseness. The students are always very motivated with this kind of project, allowing them to acquire skills in different domains, both from a theoretical and a practical point of view.

Indeed, the UAV of the third project will probably serve as a platform for upcoming student projects where advanced control concepts can be readily implemented, tested, and validated. They can also be used in the framework of teaching in the CentraleSupelec Executive Education, which offers a broad range of courses or customized programs.

7. CONCLUSION

The paper reported the main points of the projects only to outline the progress made by the students in terms of workflow, according to the available materials and equipment in their scientific environment (laptops, software, set-ups). These last ones are especially related to the budget of the laboratories and their financial supports by industries like in any other institution over the world. According to their feedback, they developed excellent performance from a practical and theoretical point of view, despite the applied theory that was often totally a new topic at their stage, they can carefully handle the problems and succeed in the implementation phase, leading to publications, as for instance (Hristea and Siguerdidjane, 2011). This also constitutes a good starting point for a PhD thesis research work (Bouzid et al., 2017-2018). Even though this paper reports three examples of projects beyond the guidance, navigation, and control topic, there are many other activities related to aerospace that the undergraduate students are dealing with.

As a result, the majority of students are delighted with the work performed, the teaching, and supervising approaches. Nevertheless, to improve the education system, the students are commonly required to address things that are not working well or running according to their expectations about the content of courses, tutorials, projects, as well as the pedagogy and the teaching style. That allows raising any mismatch between the engineering teaching approaches and students' expectations.

Up to now, the students remain quite motivated, and they should express a great interest in aerospace activities in the near future, pushed by the creation of a new structure ESA_Lab@Centralesupelec that the European Space Agency and CentraleSupelec have recently launched aiming to develop an interest in space exploration activities and in particular Earth observation, navigation, artificial intelligence.

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