

Return: Group Design Project for Pin-Point Landing Demonstrator using Drone Technologies

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Abstract:

In a rapidly changing world, engineers must identify societal needs, solve problems with ingenuity, and create new knowledge. While conventional taught-based courses provide a solid foundation of knowledge, they often fall short in stimulating creative thinking, translating theoretical knowledge into real-world solutions, and fostering leadership and teamwork. This paper proposes a project-based learning course designed to solidify and amplify the technical knowledge gained in preceding taught-based modules while developing essential soft skills. The course covers various stages of designing a reusable launcher-like demonstrator, aiming to simulate take-off and pinpoint landing operations using drone technology. This involves identifying system requirements and designing both software and hardware components. Throughout the course, students enhance their ability to critically formulate, solve, and evaluate engineering problems. They gain and apply technical knowledge in all aspects of drone technology, including flight dynamics, control, navigation, guidance, situational awareness, and communication. Additionally, students explore key aspects of systems engineering practices, risk management, and time management. This paper details the problem design, course timeline, outcomes and key lessons learned from the course.

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Keywords: Pin-point landing, multidisciplinary project, Project-Based Learning, system engineering, launch vehicles and landers.

1. INTRODUCTION

Currently, we can see a rapidly changing world of technologies, so the knowledge gained by students during even a one-year MSc program may not be up to date by the time they finish their studies. In this context, the most important thing is not the technological knowledge itself, but rather the students' autonomy and ability to explore new technologies capable of solving engineering problems efficiently, as well as critically designing and assessing engineering approaches. This imposes additional challenges on educators. One possible way to address these challenges is through Project-Based Learning (Shpeizer (2019); Hong et al. (2019); Ignatyev et al. (2021)).

Propulsive pin-point landing of launchers' first stages and boosters has been recently demonstrated as a key technology enabling the realization of reusable launch vehicles and, therefore, laying down the foundations for a sensible reduction of costs associated with access to space. This is the case, for example, of the commercial advantage of Space X against other launcher providers and the latter's necessity to cover this technology gap to remain competitive in the market (Motta et al. (2024)). On the other hand, the exciting images of such landings are inspirational for many young space enthusiasts who see the complexity and multidisciplinary aspects of such systems

as an exciting challenge to be investigated and studied in their professional development. Moved by the ambition of developing a testbed for examining the key Guidance, Navigation and Control (GNC) technologies associated with this challenge, our group decided to propose an exploratory design and practical project to a selected team of MSc students of the MSc in Autonomous Vehicle Dynamics and Control at Cranfield University.

This activity provided a practical application of theoretical knowledge and posed an engaging challenge for students to develop a technical solution for advanced GNC applications in space. Aiming to create a prototype mimicking Vertical Take Off and Landing (VTOL) systems, students had four months to conceptualize, design, realize, and test a complex engineering system, tackling multidisciplinary challenges.

This activity not only served as a practical application of the theoretical knowledge offered during the program, but students integrated knowledge from various domains, including aerodynamics, structural design, control systems, and sensor technologies, to address GNC architecture and algorithm issues. They experienced real-world engineering complexities, enhancing problem-solving skills and fostering teamwork crucial for their future careers Hmelo-Silver (2004). The project followed systems engineering

practices involving requirement definition, progress review meetings, and project management in terms of budgets, risks, and time (NASA (2012)). In addition, the students get involved with the practical aspects characterizing real projects, such as procurement, manufacturing, assembly, integration, and testing phases, employing time-management and risk mitigation strategies that proved essential to project success. This hands-on experience exposed them to real-world industrial development processes, cultivating resilience and adaptability and preparing them for the dynamic field of engineering innovation.

This paper outlines the educational aspects associated with this journey, but at the same time, it will focus on the analysis of the key skills developed by the students within this learning activity, highlighting the educational successes achieved during the project but also the challenges and areas of improvement that teaching team has collected during the journey. Indeed, the structure of the paper follows this logic and starts with Section 2 focusing on the definition of the Group Design Project's intended learning outcomes and, consequently, outlines the aim and objectives that have been delivered to the students. Section 3 describes the project management aspects of the activity, showing how we can adopt a milestone-based approach to drive the development of the activities. Section 4 describes the key developments obtained by the team, focusing on the key disciplines that were used within the project. Section 5 summarizes the key educational achievements and challenges experienced during the project. Finally, a concluding remarks section completes the paper by drawing the lesson learnt and outlining the possible areas of improvement for the continuation of the project in the next year.

2. DESIGN OF THE PROJECT ACTIVITY

The group design project is one of the key activities characterizing the program of the AVDC MSc at Cranfield University. This activity runs in parallel with the other taught modules for 5 months, from November to March.

2.1 Intended Learning Outcomes

The intended learning outcomes (ILOs) of the activity are meant to bring the student to be able to:

- **(ILO1)** Demonstrate originality in the application of knowledge and skills.
- **(ILO2)** Collaborate as a member of a team to solve a defined problem.
- **(ILO3)** Self-direction in practical problem-solving.
- **(ILO4)** Plan, manage and execute work effectively in a team environment.
- **(ILO5)** Communicate and present both orally and in writing in a team environment

The ILOs aim to the original application of the knowledge acquired as well as point towards the collaborative effort that the team should have in solving the given task originally. For this reason, we decided to keep our initial inputs to the students broad enough so that they could explore and trade different options and implementations during the project. Thus, our initial inputs were limited to providing a solid justification for the project, showing the

ambition of the team to develop a test platform that allows for testing GNC hardware and software architectures for powered descent and landing of launchers, allowing the students to find a feasible solution based on the time and budgetary constraints of the activity.

2.2 Aim and Objectives of Return

The initial aim of the activity was to develop a testbed for testing GNC sensors, actuators, and algorithms that would enable vertical take-off and pin-point landing of launchers. We have foreseen the associated objectives:

- (1) Identify the suitable propulsion technology that allows the testbed to take off and land in a safe and controlled manner.
- (2) Identify the suitable GNC architecture that allows for performing a pin-point landing to pre-selected target areas with and without the aid of external positioning systems (e.g., GNSS, optical tracking system, etc.).
- (3) Prototype with commercial-off-the-shelf (COTS) components a dynamically equivalent test platform to the most common vertical take-off and landing launch systems.
- (4) Perform a validation and verification test campaign showing that the platform successfully performs the landing in selected scenarios.

In particular, an incremental set of scenarios was provided to the students, allowing them to aim, in the first instance, to accomplish the landing in baseline target scenarios and then, upon successful demonstration of these, to point towards more ambitious and complex scenarios. Specifically, the baseline scenarios were identified as the following ones:

- (1) Pin-point landing with support of external positioning towards a target located in a known position and identified with an Aruco marker.
- (2) Pin-point landing without the support of an external position system but only using onboard sensors and the target identified with an Aruco marker.

The stretched scenarios read as follows:

- (1) Landing on a target in motion identified with an Aruco marker.
- (2) Autonomously select and land towards a favourable zone based on the analysis of the inputs from onboard sensors and cameras.

It was also worth mentioning that two major constraints were provided to the students:

- the overall project cost shall be less than £2,000
- the duration of the project shall not exceed 5 months

3. PROJECT MANAGEMENT, SUPERVISION AND SUPPORT

The group design activity follows a standard system design approach, with milestones scheduled throughout the overall period of the project. The students were supported by a team of supervisors and given access to key laboratories. In the following subsections, an overview of such key educational aids is presented.

3.1 Project Management and Timeline

An indicative timeline is shown in Table 1. The course spans 18 weeks, with the first 12 weeks running concurrently with other foundational courses. Lectures, delivered after presenting the project aim and scenario, enable students to actively acquire technical knowledge and skills while critically assessing the challenges of applying theoretical concepts to real-world practice.

Week	Tasks	Baseline Courses
1	Introduction & teaming	Unmanned aircraft
3	SRR	dynamics & control
8	PDR	Guidance & navigation
	& purchasing	for autonomous systems
12	CDR	Sensor fusion
14	TRR	
18	Final presentation & demonstration	

Table 1.
Course
time-
line

In week 1, the students were asked to form sub-teams by discussing their preferences and expertise with their team members. Each sub-team was recommended to consist of not more than 3 students because the small-group format enables students to achieve higher satisfaction in knowledge acquisition, learning performance, and skill development, particularly in an oral presentation, paper writing, and problem-solving (Chou and Chang, 2018). This ensures that each student has a significant contribution and responsibility, making it easier to assess the individual contributions of each student.

From week 2 to 14, four design reviews are scheduled (DoD (2012)), which allows students to develop their project management skills to deliver the project according to the system requirements within the time and budget limits. It also allows students to familiarize themselves with industry standards on the Lifecycle of Major Capability Acquisition. System Requirements Review (SRR) aims to define functional and performance requirements for the integrated system and subsystems. The overall development plan, risks, and mitigation plans are prepared at this stage. In the Preliminary Development Review (PDR), each subsystem is designed, providing the rationale for selected concepts, components and characteristics based on the technical knowledge acquired from the parallel taught modules. Validation & Verification (V&V) plans are prepared at this stage for the integrated system and subsystems, and the purchase orders for the equipment are raised. Critical Design Review (CDR) scrutinizes the maturity of the subsystems based on the subsystem validation results, and Test Readiness Review (TRR) evaluates the overall system's readiness to conduct final tests.

The last four weeks (15 - 18) are reserved for the system implementation, namely, integrating the components, and analysing the data from the hardware-based V&V.

3.2 Supervision

During the whole timeline, supervisory meetings are held weekly. Supervisory meetings are important not only for providing a formative assessment for students but also for

organising a forum where students can efficiently discuss problems and make decisions. This is especially important at the initial stages of the project when all sub-teams work on their sub-systems and a lack of communication could cause larger problems at the later stages of the project due to incompatible solutions.

Given the project's multidisciplinary nature, it was supervised by three mentors with different expertise: space systems and control engineering, propulsion, and flight dynamics and aerodynamics. This diverse supervision ensured comprehensive support for the students.

In the initial weeks, the supervisors organized the team, assigned roles, and facilitated discussions to select the project concept. Later, they focused on guiding the students through technical challenges, providing advice on key technologies and algorithmic solutions. In the final stages, the mentors concentrated on advising verification and validation plans and assisting with effective project documentation.

3.3 Facilities and Laboratories

To support these activities, the students could access two dedicated labs, namely the Cranfield University Flight Arena, shown in Fig. 1, and the Autonomous Ground Vehicle laboratory. In addition, the students could get access to UAS fast-prototyping laboratory and 3D printers.

3.4 Assessment

The assessment has been designed to ensure constructive alignment with the ILOs (Biggs, 1996). The course assessment consists of three elements: group presentations (40%), group report (60%), and individual contributions. Individual contributions are reflected in the group presentations and the report, weighted based on individual contributions.

Group presentations include the four design reviews (SRR, PDR, CDR, TRR) and the final presentation. During the SRR students have a formative assessment, however at the PDR, CDR, TRR and final presentation they have a summative assessment. Feedback, both formative and summative, is provided by industrial supervisors as well as the extended academic team.

For the design reviews, overall presentation and project management comprise 30%, assessing **ILO4** and **ILO5**. Each sub-teams are marked with respect to their literature review (20%), methodology (30%), and progress (20%). The emphasis is on methodology, to assess **ILO2** and **ILO3**. For the final presentation, the overall presentation comprises 30% for **ILO5**, and each sub-teams are marked with their methodology (20%), results (20%), and analysis and discussions (30%). The emphasis moves from literature review and progress to analysis and discussions.

At the end of the project, students submit a group technical report which includes problem formulation, proposition, rationale, developments, results, analysis, and discussions. The overall report comprises 15% for **ILO5**, each sub-teams are marked with its design (6%), results (15%), and analysis and discussions (30%), and the integrated system is marked with its design (4%), results (10%),



Fig. 1. Cranfield University flight arena

and analysis and discussions (20%). The emphasis is on analysis and discussions, to assess **ILO1** and **ILO3**.

Individual contributions are assessed through 1-page bullet point reports, with each student submitting their report. These reports should be agreed upon by the team, ensuring that no contribution point is duplicated among members. This approach is designed to minimize free-rider effects in project-based learning while avoiding peer assessments, which can potentially lead to conflicts between students (Lin et al., 2021).

4. STUDENTS' TEAM ACTIVITY AND RESULTS

This section outlines the key technical achievements obtained by the students' activity, highlighting the key educational aspects that we could notice throughout the project.

4.1 Project and Team Management

One of the key aspects characterizing this activity was the project and team management. First, the students needed to organize themselves by nominating a team leader, who was supposed to organize and lead the team activities. Then, the team members distributed themselves into different sub-teams addressing the key technical areas characterizing the project as follows ¹:

- Structure and aerodynamics: 2 students
- Guidance navigation and control: 3 students
- Communications: 2 students
- Propulsion and actuation: 2 students

Alongside the activity during the supervisory meetings, the students were supposed to carry on most of the activity during the week between the supervisory meetings. The team leader, supported by the supervisors, could assign tasks to the team members and monitor the overall progress of the project through a Gantt chart.

The project development was not immune to risks: these were indeed included in a risk management plan that could define the impact, the probability, and the eventual strategies to be adopted to mitigate the risks.

Given the hard constraints in the budget, the overall expenditure needed to be monitored via a detailed budget sheet.

4.2 Concept selection and system requirements definition

In the initial stages of the project, the students were asked to define the specific requirements of the demonstrator and, consequently, select a concept to develop through the

¹ Some students participated in multiple sub-teams



Fig. 2. Final concept design for the Return project

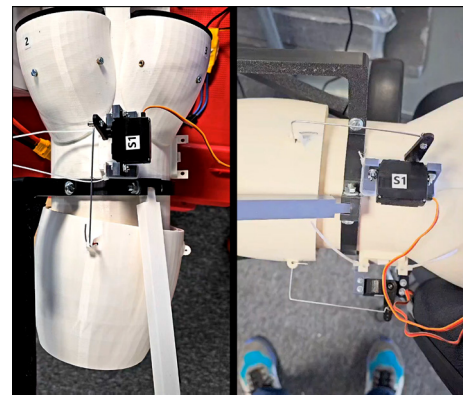


Fig. 3. Nozzle design, TVC and servo actuation system

project. The project's top-level requirements are summarized as follows:

- (1) Design similarity with existing rockets: the prototype shall exhibit similarities with existing rockets, including the same thrust-to-weight Ratio, equivalent centre of gravity to centre of thrust distance and comparable landing pad proportions.
- (2) Full controllability: the prototype shall demonstrate full controllability throughout its operational phases.
- (3) Structural and payload constraints: mass less than 4.5 kg and payload mass less than 0.8 kg.
- (4) Safety and reusability: the prototype shall be safe to use and reusable.
- (5) Budget limitation: the total budget allocated for the prototype development must not exceed £2,000.

Several solutions were explored by the students, but the configuration shown in Fig.2 was judged to be the most effective solution based on the requirement imposed.

4.3 Propulsive System

The adopted configuration uses EDFs, which mitigate safety concerns present in other propulsion systems (e.g., chemical, hybrid). This solution provides sufficient thrust for demonstrations and offers better performance in compactness, low acoustic signature, and instantaneous thrust for agile manoeuvres. EDFs also ensure higher reliability and safety due to the natural protection provided by the duct compared to propellers. Thrust Vectoring Control (TVC) (Fig. 3) with differential rates of EDFs was used to enable the rocket's angular control.



Fig. 4. Final realized prototype

4.4 Structural Design

The design shown in Fig. 4 was crafted to serve dual purposes: facilitating easy access and adaptability for mounting larger components while also ensuring robust support for enduring high loads, especially due to the dynamics requirements faced during the rocket's operation and eventual collisions in case of failure of the operations. By providing a user-friendly platform for accessing and installing key components such as batteries, the design enables swift maintenance and adjustments, which were crucial for efficient operations in both testing and final demonstration scenarios.

The overall structural integrity was also assessed via Finite Element analyses carried out by the students. Most of the parts were also 3D-printed by the students.

4.5 Estimation and Control

Part of the student activities were also focused on the selection and development of the GNC architecture necessary to accomplish vertical take-off and landing operations. Figure 5 shows the baseline sensor architecture and configuration adopted by the students. The system is supposed to detect and recognize eventual landing sites marked with Aruco markers.

The students needed to interface all the sensors with the onboard computer and develop ad-hoc code to elaborate the readings of the sensors. This involved key application of image processing techniques, noise reduction techniques, data fusion and navigation algorithms. Kalman filter was used for sensor fusion using both the camera inputs, the Time of Flight (ToF) sensors and the IMU. The sensor data acquisition and interpretation as well as the Kalman filter implementation were validated and verified via simulations and experiments.

4.6 Telemetry and Command

Figure 6 shows the system's high-level communication architecture. An onboard computer processes inputs from

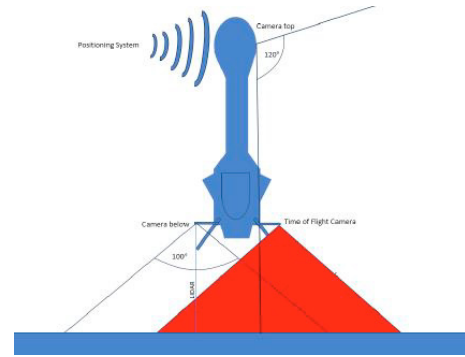


Fig. 5. Sensor configuration

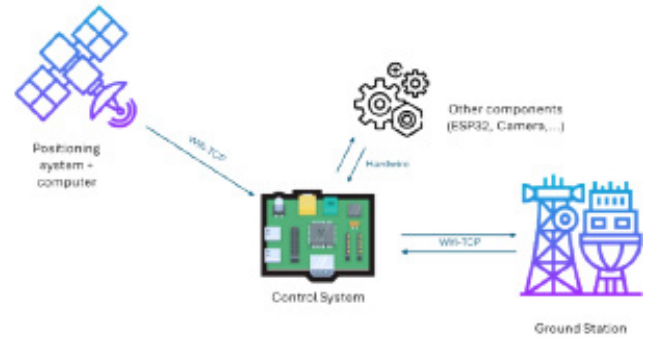


Fig. 6. Communication configuration

sensors, cameras, and peripherals, running the GNC algorithms autonomously. A Wi-Fi link to the ground station monitors telemetry and can abort the mission if needed. Positioning system data is transferred to the central unit in real time for operational use. The students interfaced these elements using a custom thread framework, establishing TCP links and evaluating communication performance.

4.7 Validation and Verification

Even if a final demonstration was not possible due to the lack of time, the students were able to carry on ad-hoc developed validation and verification strategies for each of the above-mentioned subsystems.

5. EDUCATIONAL ACHIEVEMENTS AND CHALLENGES

Looking back, we can conclude that all **ILOs** were achieved. Namely, students applied their knowledge and skills to develop an original concept of reusable rockets using drone technologies (**ILO1**). To achieve that they collaborated within the sub-teams and between different sub-teams (**ILO2**). The students owned the project concept and were responsible for the project management, including time and budget (**ILO3** and **ILO4**). Finally, the project outcomes were efficiently presented in the presentations and reports (**ILO5**).

The developed project manifests student's technical knowledge of the key elements of reusable rockets as well as drone technologies. It should be noted that students appreciated not only the theoretical aspects but also the practical and hardware matters that were met during the project implementation.

Supervision sessions and design reviews have revealed enhancements in students' cognitive strategies. We identified four levels of cognitive engagement from the revised Bloom's taxonomy (Stozhko et al., 2015): lower level (identification), basic level (knowledge and comprehension), middle level (application and analysis), and upper level (synthesis and evaluation). Unlike traditionally taught baseline courses, our PBL course enriched students' cognition to the middle and upper tiers.

Through this activity, students sharpened their technical skills in software and hardware development, as well as their soft skills, such as problem-solving, critical thinking, and teamwork. More importantly, they developed project management and systems engineering skills. Faced with an engineering problem within a defined scenario and specific goals, students defined system and subsystem requirements, researched potential solutions, validated their developments against the requirements, and identified necessary improvements. This comprehensive engineering cycle, enriched by design reviews, significantly enhanced their problem-solving and critical-thinking abilities. Additionally, strong collaboration and teamwork were evident, aligning perfectly with **ILO4** and **ILO5**.

The activity was also characterized by some challenges experienced by the students. Time management was noted as a recurring issue throughout the project: even if progress was monitored by well-detailed Gantt charts, the student faced some delays in the first part of the project where effort was required to conceptualize the design rather than going on the technical implementation. This led to delays in the preliminary design phase and, therefore, delays in placing orders for critical components. In any case, this created the opportunity to experience the importance of having risk mitigation strategies in place and definitively save the project from failure.

6. LESSONS LEARNED AND FINAL REMARKS

The constructivist learning philosophy posits that knowledge is generated through social interaction and engagement with the environment, constantly evolving through negotiation (Vygotsky (1962)). We found that integrating students from diverse backgrounds into PBL promotes effective peer-to-peer learning and knowledge generation.

However, this integration presents additional educational challenges, particularly in developing an efficient "collaboration forum" for students. Research indicates that regular face-to-face or hybrid meetings enhance communication within student groups and sub-teams Ignatyev et al. (2021). In this project, we intensified supervision meetings to provide feedback and to foster, reinforce, and solidify collaboration among students.

To develop critical thinking, we posed challenging questions during supervision meetings, especially at the concept development stage. We clarified this approach to students, showing it as a technique for enhancing critical thinking rather than an obstacle. Additionally, we shared examples of how critical thinking benefited past projects. This strategy not only improved their critical thinking skills but also prepared them for real-world engineering challenges.

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