

Project-Based Learning Course Design for Multi-Agent Autonomy Using Quadrotors

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Hae-In Lee* Dmitry Ignatyev* Hyo-Sang Shin**,
Antonios Tsourdos*

* Cranfield University, Cranfield, MK43 0AL, UK (e-mail: {haein.lee ;
d.ignatyev ; h.shin ; a.tsourdos} @ cranfield.ac.uk)

** Korea Advanced Institute of Science and Technology (KAIST),
Daejeon, 34051, Republic of Korea (e-mail: hyosangshin@kaist.ac.kr)

Abstract: This paper proposes a project-based learning course utilising multiple quadrotors, aiming to solidify and amplify technical knowledge and develop critical thinking capabilities. An engineering problem is provided as a surveillance mission with multiple quadrotors autonomously searching, detecting, and tracking ground vehicles. The course covers all stages of multi-agent autonomy development, from identifying system requirements, designing software and hardware, to conducting demonstrations in a drone flying arena. During the course, students improve their ability to critically formulate, solve and evaluate engineering problems as well as gain and apply technical knowledge in all aspects of autonomy such as flight dynamics, control, navigation, guidance, task allocation, situational awareness and communication. The paper details the problem design, course timeline, outcomes, and key lessons learnt from the course.

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Keywords: Project-Based Learning, Autonomous Multi-Agent System, Unmanned Aerial Vehicles, Quadrotor, Surveillance

1. INTRODUCTION

Higher education in engineering is seeing a dramatic change in the paradigm, from a theoretical and top-down approach from the teachers, to a practical and bottom-up approach from the students. There are two main reasons behind this shift: motivation of the students, and technological advances in information and artificial intelligence. Current generations of higher education students have been exposed to wider fast-changing information, the students can access various algorithms from the internet, and artificial intelligence even enables to develop their own with little knowledge. The focus of the teaching should be shifted to enhance students' autonomy, and teach them how to critically design and evaluate an engineering approach from the redundant knowledge and technologies. One of the methods most suited for this task is Project-Based Learning (PBL), which utilises in-depth inquiry processes around a carefully designed engineering problem to enable active and collaborative learning (Shpeizer, 2019).

There have been some previous works that applied PBL on aerospace control engineering. García et al. (2016) and Giurato et al. (2019) utilised a quadrotor to teach platform, graphic user interface, and flight controller design. Wilkerson et al. (2018) utilised a fixed-wing aircraft for the autopilot design activities, and a quadrotor for visual inspection. Nejjari et al. (2020) used a quadrotor for Guidance, Navigation, and Control (GNC) design from dynamics modelling to sensor fusion. Similarly, although

not an aerospace domain, Beuchat et al. (2022) suggested systematic activities for GNC design for a differential drive robot. Although these works have been successful in teaching control approaches for a single vehicle, control of Multi-Agent System (MAS) has not been covered.

Control of MAS poses different challenges from a single vehicle control. Developing an autonomous MAS solution includes not only perception and GNC of individual vehicles, but also a higher-level decision making to allocate appropriate tasks to multiple agents. The situational awareness can be synthesised from multiple agents, providing wider coverage and precision, and GNC should consider collision avoidance and coordination. McLurkin et al. (2012) proposed a multi-robot system to implement MAS solutions, but to the best of the authors' knowledge, there has been no previous PBL designed to use multiple quadrotors and demonstrate autonomous cooperative operations.

This paper suggests a PBL course designed for the students to learn how to design, build, and fly autonomous multiple quadrotors to collaboratively perform a surveillance mission. The course incorporates standard engineering design review processes (DoD, 2012), which covers a full system development cycle from system requirement identification to test readiness review through multi-phase validations. This enables the students to critically formulate, solve, and evaluate a given engineering problem. The student activities are designed to cover all key elements of multi-agent autonomy – situational awareness, task allocation, GNC, and communication. The authors' previous works have been on using commercial-off-the-shelf drones

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(Hong et al., 2019) and a software-based project (Ignatyev et al., 2021), but the proposed course differs by building own quadrotors and validating in real flight tests.

The rest of this paper details the problem design and course timeline in Section 2, student activities in Section 3, outcomes in Section 4, and key lessons learnt from the course in Section 5.

2. COURSE DESIGN

2.1 Intended Learning Outcomes (ILOs)

The proposed project-based learning course is a part of MSc in Autonomous Vehicle Dynamics and Control (AVDC), which is composed of eight taught compulsory modules. The MSc begins with the fundamentals of autonomous vehicle dynamics and control and progresses to the core subjects of guidance and navigation, sensor fusion, advanced control, decision making and artificial intelligence for autonomous systems. Within the discussed course the students are asked to design, build and fly autonomous multiple quadrotors, integrating and applying the knowledge acquired in the taught modules. The course also aims to provide students with experience of working on a collaborative engineering project.

On successful completion of the course a student should be able to:

- **(ILO1)** Critically evaluate challenges in autonomous MAS development;
- **(ILO2)** Demonstrate originality in the application of knowledge and skills;
- **(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.

2.2 Mission Scenario & Key Performance Indicators (KPIs)

The scenario is given as a surveillance mission, where a team of quadrotors should cooperatively detect and track multiple ground vehicles. The task is to develop a fully autonomous MAS solution, where human intervention is limited to only starting the mission. The quadrotors should autonomously make decisions, plan and follow the paths to cooperatively search the area, and nullify the detected targets by tracking them for 10 seconds. Note that the geometry of the search area is assumed to be known *a priori*.

KPIs of the scenario are:

- **(KPI1)** Time to detect, identify, and classify all the targets in the test area;
- **(KPI2)** Position error between the estimated and true tracks of the targets;
- **(KPI3)** Position error between the quadrotors and the targets being tracked.

2.3 Timeline

An indicative timeline is shown in Table 1. The course is designed to run for 18 weeks, where the first 12 weeks run

in parallel with other baseline courses. Delivering lectures after providing the project aim and scenario offers the students to actively acquire technical knowledge and skills, critically evaluating difficulties in applying theories into practice.

Week	Tasks	Baseline Courses
1	Introduction & teaming	Unmanned aircraft
3	System Requirements Review (SRR)	dynamics & control
8	Preliminary Design Review (PDR) & purchasing	Guidance & navigation for autonomous systems
12	Critical Design Review (CDR)	Sensor fusion
14	Test Readiness Review (TRR)	
18	Final presentation & demonstration	

Table 1. Course timeline

In week 1, with introducing the course aim and objectives, teams and sub-teams are formed. Teams of around 6-11 students are allocated by staff, considering uniform distribution of academic backgrounds, e.g., aerospace, mechanical, electrical engineering, computer science, and other Science, Technology, Engineering and Mathematics (STEM) backgrounds. Then, the students are responsible to form 4 sub-teams – task allocation, situational awareness, GNC, and communication – by discussing their preference and expertise with the team members. The number of students per sub-team is recommended as 2-3, to ensure each student has their own contribution and responsibility.

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. 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 PDR, each subsystem is designed, providing the rationale on selected concepts, components and characteristics, based of the technical knowledge acquired from the parallel baseline courses. Validation plans are prepared at this stage for the integrated system and subsystems, and the purchase orders for the equipment are raised. CDR reviews maturity of the subsystems based on the subsystem validation results, and TRR evaluates the overall system's readiness to conduct a flight test, based on the simulation-based validation and hardware test preparation.

The final month from week 15 to 18 is dedicated to flight demonstration. This includes implementing the developed solution to onboard computers, integrating the components, and analysing the data for hardware-based validation.

During the whole timeline, progress review 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 own sub-systems and a lack of communication could cause larger problems at the later stages of the project due to incompatible solutions.

2.4 Facilities and Equipment

An indoor flying arena as shown in Fig. 1 is used to get accurate information on position and attitude of the quadrotors and the ground targets, using a VICON motion capture system with 30 cameras. The quadrotor information is used for the GNC of the developed solution, whereas the target information is used only for assessing the KPIs. For the autonomous operation of the quadrotors, the target information should only be detected and tracked by onboard sensors of the quadrotors.

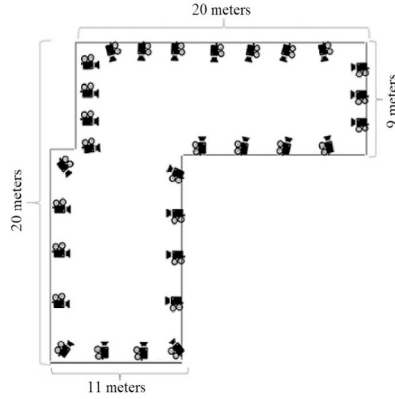


Fig. 1. Indoor flying arena

Basic equipment and a work station to build the quadrotors is provided, including drivers, soldering tools, multimeters, glue guns, and cutters. By PDR, the students are responsible to downselect all the other components to build the quadrotors, including frames, propellers, motors, Electronic Speed Controllers (ESC), batteries, communication modules, flight/companion computer boards, and any other onboard sensors to detect and track the ground targets. The downselection should be evidenced by their characteristics and system requirements defined in SRR.

2.5 Assessment

Elements	Subelements	Marks	ILO
PDR, CDR, TRR (8% each)	Overall	30	5
	Literature	20	1
	Methodology	30	2,3
	Progress	20	4
Final presentation (16%)	Overall	30	5
	Methodology	20	2,3
	Results	30	2,3
	Analysis	20	1,3
Group report Subteam/integrated (40%)	Overall	15	5
	Design	6/4	2,3
	Results	15/10	2,3
	Analysis	30/20	1,3

Table 2. Course assessment

The assessment has been designed as Table 2 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 weighted on the other elements.

Group presentations include the design reviews and the final presentation. During the presentations students have

a feedback from industrial and academic supervisors. Each sub-teams are marked with literature review, methodology, and progress. For the final presentation, the focus moves 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. Overall report comprises 15%, sub-teams 51%, and the integrated system 34%, where the emphasis is on analysis and discussions.

Individual contributions are assessed via 1-page bullet point reports, one per student. The individual reports should be agreed among the team, and the same contribution point cannot be shared with the others. This is introduced to minimise free-rider effects in PBL while avoiding peer assessments, which may cause conflicts between the students (Lin et al., 2021).

3. SUB-TEAM ACTIVITIES

The overall system architecture of the autonomous MAS solution is shown in Fig. 2. The students are asked to form sub-teams to develop each of the key technical elements, based on the baseline courses delivered.

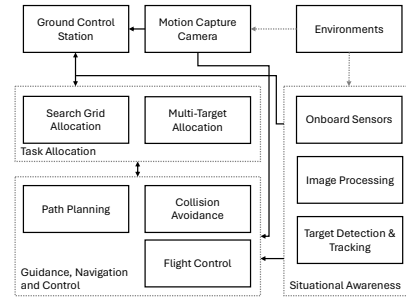


Fig. 2. System Architecture

3.1 Task Allocation

The role of task allocation sub-team is to develop high-level decision making to allocate search grids or targets to track. Here, search grids are geometric division of the search area as shown in Fig. 3. Note that this differs from Fig. 1, as the VICON available area is smaller than the whole facility. The algorithm should enable autonomous switching between the search mode and the target tracking mode based on the situational awareness. In the search mode, each quadrotors are allocated with a sequence of search grids to visit, minimising **KPI1**. Other factors to be considered may include battery levels, last time a certain search grid has been visited, status of the other quadrotors, and communication signal strength. In the tracking mode, the quadrotors are allocated to which targets to track, if multiple targets are detected. To minimise **KPI1**, the distance between the quadrotors and the targets is a key factor, but other considerations may include battery levels and heterogeneous sensor/platform specifications. The students are responsible for the problem formulation by defining the cost functions and constraints with the factors suggested.

Common algorithms to solve the formulated task allocation problems are suggested as:

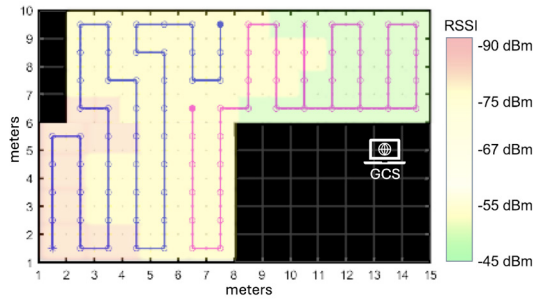


Fig. 3. Search Grid Allocation

- Exact algorithms – polynomial algorithm, branch-and-bound;
- Heuristic algorithms – genetic algorithm, particle swarm optimisation;
- Approximate algorithms – greedy algorithm, Hungarian algorithm.

The students should be able to critically evaluate, select, and design the algorithms providing the rationale with respect to the system/subsystem requirements. Hardware selection of ground control station should be evidenced by the required computational complexity and communication burden of task allocation algorithms. Task allocation algorithms are recommended to be validated in a simplified synthetic environment, setting performance indices to measure:

- Optimality;
- Computational complexity;
- Scalability;
- Robustness to failure/uncertainties.

3.2 Situational Awareness

The role of situational awareness sub-team is to develop algorithms to detect and track ground targets using on-board sensors, such as camera and LiDAR. This includes image processing, target detection and tracking, and if applicable, sensor fusion. Here, target tracking refers to estimating the position history of the targets in the reference frame, to provide their tracks to the task allocation and GNC subsystems. The students are responsible for downselecting the sensors, based on their availability, range, frequency, accuracy, and their fit to the system requirements. Although not compulsory, cameras are recommended as a main sensor involving image processing algorithms. Target detection and tracking algorithms should be developed to minimise **KPI2**, considering the frame rate, illumination, blur, and multiple targets in the frame. To further reduce **KPI2**, sensor fusion is recommended, either between different sensors or other quadrotors.

Common algorithms for each part of the situational awareness are introduced as:

- Detection – YOLOv3-v8, RetinaNet;
- Tracking – DeepSORT, FairMOT, ByteTrack;
- Sensor fusion – track-to-track, measurement fusion.

The students are asked to proactively evaluate their applicability to the system and downselect the algorithms. An example screenshot from the target detection algorithm is shown in Fig. 4. The downselection of compan-

ion computers is also the responsibility of the students, considering the sensor compatibility and computational complexity requirements for the situational awareness algorithms. The developed situational awareness algorithms should be validated in hardware-in-the-loop test before the demonstration, with the performance indices including:

- Precision, recall, Mean Average Precision (mAP), f1 score;
- Multi-Object Tracking Accuracy (MOTA), Identity-f1 score (IDF1), Identity Switch (IDSW).

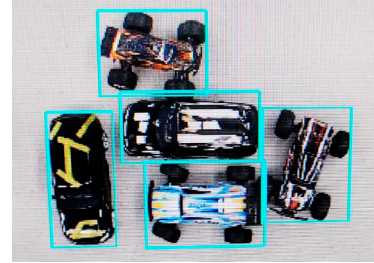


Fig. 4. Target Detection

3.3 GNC

The role of GNC sub-team is to develop path planning and flight control algorithms in both the search and tracking modes, ensuring safe distance with other quadrotors and geofence. In the search mode, path planning algorithm should be developed to safely and efficiently reach the allocated search grid, and the flight control algorithm to follow the path with minimal deviation. In the tracking mode, the flight control algorithm should be developed to keep the ground target within the field-of-view of the onboard sensors, minimising **KPI3**.

For path planning with collision avoidance and flight control, the following algorithms are covered:

- Path planning/collision avoidance – artificial potential field, geometric algorithms, A* algorithm, Dijkstra algorithm;
- Flight control – PID, adaptive/robust control, sliding mode control, backstepping control, visual servoing.

The students are responsible for critically evaluating the algorithms based on the system/subsystem requirements, and downselecting the flight computers considering their compatibility and computational complexities of GNC algorithms. The developed GNC algorithms should be validated in a high-fidelity simulation environment such as Gazebo and AirSim, as shown in Fig. 5, setting performance indices to measure:

- Efficiency – time and battery, deviation from the path;
- Safety – keeping distance between the quadrotors and to the geofence;
- Loss of target within the field-of-view;
- Robustness to failure/uncertainties.

3.4 Communication

The role of communication sub-team is to ensure inputs and outputs of the individual subsystems are connected,

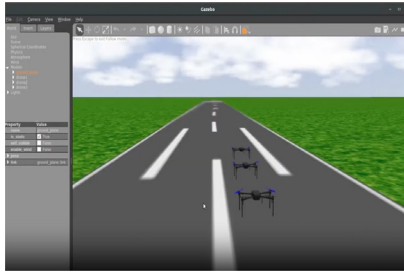


Fig. 5. Simulation-Based Validation

standardising their formats across the functionalities and components. This involves defining the type of data and communication methods of the black arrows in Fig. 2. The students are responsible of downselecting the communication devices and protocols considering their range, frequency, and bandwidth.

The communication between the subsystems is recommended to be validated with hardware-in-the-loop tests, validating the performance indices:

- signal strength; frequency; dropouts; latency; range.

4. OUTCOMES

The proposed course has been applied to the AVDC MSc students' Group Design Project in academic year 2023/24. The developed quadrotor platforms are shown in Fig. 6, which includes the components in total budget of 1,700 GBP:

- Frame/landing gear: F450
- Propeller/motor/ESC: T-Motor 1045 Self-Locking / AIR 2216 920 KV / AIR 20A ESC
- Battery: 4S 5000mAh LiPo
- Communication module: Intel 8265NGW, FlySky iA10B/FS-i6, ESP8266 WiFi telemetry module
- Flight computer: Pixhawk 6C with PM07
- Companion computer: Nvidia Jetson Nano 4GB
- Camera: HBVCAM-1716 2710 S1.0
- LiDAR: TF-Mini LiDAR



Fig. 6. Quadrotor Platforms

A demonstration screenshot of autonomous target tracking is shown in Fig. 7. The team has succeeded in measuring **KPI2** as 20.7 cm for a fixed target, but **KPI1** and **KPI3** were not measured due to failure in implementing the target tracking mode. The main causes were spending time on resolving unexpected issues such as Robotic Operating System (ROS) initialisation errors, communication of multiple quadrotors, and data rate synchronisation.

The learning outcomes are summarised with respect to the common elements of PBL (Guo et al., 2020).

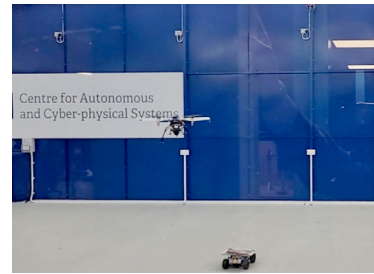


Fig. 7. Demonstration of Autonomous Target Tracking

4.1 Cognitive outcomes

The students have demonstrated their technical knowledge on each of the key elements of MAS. The task allocation sub-team applied a gradient descent-based algorithm, the situational awareness sub-team applied YOLOv3 and v5 with ByteTrack, and the GNC sub-team designed a waypoint-following guidance, an artificial potential field-based collision avoidance, and a PID controller. The communication sub-team enabled integration of the sub-teams via MAVLink and MAVROS. Not only the theoretic knowledge, but also practical hardware issues have been well-recognised by the students. The depth of the technical knowledge and its application to the system has shown the contents of **ILO2**.

Improved cognitive strategies have been also observed from the supervision sessions and design reviews. We observed four levels of cognitive strategies, namely lower level (identification), basic level (knowledge and comprehension), middle level (application and analysis), and upper level (synthesis and evaluation) from revised Bloom's taxonomy (Stozhko et al., 2015). In comparison with the students' learning from other baseline courses, the proposed PBL course especially improved the middle and upper levels of the cognition. The students have implemented the algorithms they have learned to the actual flight tests, synthesised the conclusions from applying the theories into practice, and critically evaluated current challenges in autonomous MAS development, showing **ILO1**.

4.2 Affective outcomes

Affective outcomes have been mainly assessed by students' perception and feedbacks at the final presentation. When the students were asked for the key lessons learnt, the comments from the students showed **ILO3** as:

We had resources helping us in a way to understand and implement whatever we have learned from the AVDC course. We have studied some of the task allocation, guidance and navigation, and some algorithms for computer vision. It was really nice to see that something like this could be implemented in such a small package and how it is being used in the industry. It also helps us further understand what steps that we could take to research and maybe progress with something of a higher scale.

4.3 Behavioural outcomes

From the proposed course, the students have improved not only the hard skills on software and hardware developments, but also soft skills such as problem-solving, critical thinking and team working skills. When an engineering problem is given with an overall scenario and KPIs, the students have defined specific system and subsystem requirements, researched for potential solutions, validated whether the developed solution meets the requirements, and reflected on the improvements. A whole engineering cycle of design reviews improved the problem-solving and critical thinking skills. Collaboration and team working skills have been also observed and reported from the students, aligning with **ILO4** and **ILO5**. Some of the students feedback include:

Everyone worked together, especially towards the end. It was quite a challenge because integrating all the software was really tough, but then everyone did manage to pull through. There were some late nights, we had to stay in the labs for quite a bit, but that helped us understand what it is like working together.

5. CONCLUSION

This paper proposed a PBL course to design, build, and fly multiple quadrotors, autonomously and cooperatively performing a surveillance mission. A surveillance mission has been provided with specific KPIs and the course ILOs were made clear with the assessment schemes. The course has been designed with conventional engineering design review processes to enhance critical thinking capability of the students. Also, technical knowledge on key elements of MAS autonomy has been covered, including task allocation, situational awareness, GNC, and communication. As a result of applying the proposed course to the AVDC MSc students, the ILOs of the course were met showing enhancements in cognitive, affective, and behavioural outcomes.

Limitations of the proposed course have been identified as failure of measuring some of the KPIs due to the delay of schedules resolving unexpected issues. Most of the problematic and time-consuming issues oriented from final integration, which is commonly expected but not well-recognised by the students at the sub-team levels. Two mitigation approaches are suggested for the next cohort: time management and workshops. Although the students manage their own project and it is a part of the learning, the supervisors may set concrete deadlines for the sub-team level developments and encourage integration, helping time management to measure the KPIs. Workshops in addition to the current baseline courses are considered useful, especially around practical use of ROS, VICON integration, and communication modules.

Another element that is to be improved is the assessment of individual contributions. Although the students are advised to be responsible for specific non-overlapping tasks, it is difficult to systematically quantify their individual efforts. For the next cohort, we would like to further investigate other evaluation methods of individual contributions as suggested by Tanabata et al. (2021).

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