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Development Of A New Course: Control Design for Autonomous Vehicles Using A Quadcopter As The Learning Platform

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Introduction

Modeling, simulation, control system design, navigation and guidance of autonomous vehicles (AVs) have become highly sought research areas in the mechanical engineering community [1] due to the advancement in microelectronics, computational technologies and machine perception. Because of the increasing popularity of self-driving cars, autonomous vehicle refers to self-driving cars in public perception [2] although it covers a wider research area. AVs can be examined under, aerial, underwater, surface and terrestrial robotics. Unmanned Aerial Vehicles (UAVs), Autonomous Underwater Vehicles (AUVs), Autonomous Surface Vehicles (ASVs), and Unmanned Ground Vehicles (UGVs) are the respective examples of the AVs in robotics.

Recent developments and advanced research findings in robotics enabled the use of UAVs in commercial, military, and scientific areas for many different purposes such as inspection and maintenance of urban and transportation infrastructure, surveillance and security, traffic control systems, law enforcement, mapping and surveying large areas. A rapid advancement of AUVs and ASVs were achieved with the developments in oceanic control, guidance and navigation technologies [3]. UAVs, AUVs and ASVs are used in military, commercial and research areas such as unexploded ordnance (UXO) detection, oil and gas pipeline monitoring, sea-floor mapping, naval surveillance and coastal security, hydrographic-oceanographic surveys, marine biology, and environmental monitoring. Advancements in tracking control, specifically steering and longitudinal control [4], satellite communication and localization technology provided a fast development in UGV design and manufacturing. UGVs are also being used in military and commercial areas, interplanetary research and transportation of humans and commercial goods.

With the increasing interest from commercial, scientific and military investors and expanding application areas of AV research, development and manufacturing attract engineers from almost all disciplines. Considering its revolutionary effects on vast engineering areas such as automation and robotics [6],[7], logistics [8], [9], aviation [10], healthcare [11], [12], mapping and surveying [13], artificial intelligence (AI) also revolutionizes AVs [2] in terms of intelligent control, visual recognition and object detection, environmental perception, simultaneous localization and mapping (SLAM), guidance and navigation and mission planning. AI involvement with AV research will constantly provoke curious learners and attract future engineers. One of the most important responsibilities of the engineering education providers is preparing engineers of the future for the jobs of tomorrow [14], [15]. Therefore, a course about AV fundamentals such as mathematical modeling and control system design is crucial to include in engineering curricula.

In this study, the authors described the development of a new undergraduate elective course (Advanced Topics in Engineering-400 level) module in modeling and control system design of AVs, which is offered in the Mechanical Engineering Department of a national university. Considering the multi-disciplinary nature of the AV study, the course offered to undergraduate students studying Mechanical Engineering, Electrical Engineering, Computer Engineering and Computer Science majors. The structure of the course comprises 3 main components: theory, simulation and application.

The theory component aims to review the necessary mathematics related to the control system design and a brief review of the software packages to be used in simulations and applications.

Then, it covers the topics to obtain linear and nonlinear 6 degrees of freedom (DOF) mathematical models of a UAV. For navigation and guidance purposes, reference coordinate frames, principal rotations and the transformation between coordinate reference frames are extensively taught. Three different control strategies, angular velocity, attitude/altitude and translational position controller are also taught. Weekly research paper reviews are required to connect students with the current trends, sources and development in the area.

The simulation component is taught in parallel with the theory. After every theory component, a simulation study is performed by using numerical simulation software to reinforce the subjects taught and to see the effects of them on the AVs.

To apply the theory that is taught during the course and to compare simulation studies to the reallife control, navigation and guidance problems, a UAV, quadcopter in specific, is used as the learning and testing platform. The mathematical model parameters, control algorithms and all the simulation scenarios are to be applied to the quadcopter.

The reasons behind choosing a quadcopter as the testing and learning platform are that they have open hardware-open software, reachable in terms of finances, versatile, usability in various areas and vast amount of research material due to the high interest in scientific area.

The unique contributions of this course to the engineering education are as follows,

- Supporting undergraduate research with mathematical control theory in AV research area.
- Providing the necessary software knowledge for both simulation and application in the control system design for AVs.
- Using specific vehicle, control and perception instruments to apply the theory taught during the course and providing various opportunities to the students to realize unique projects in AV research.
- Discussing the current developments in AV research by reviewing the research papers providing scientific literacy on the topic.

Course Description

The course aims to focus on the fundamentals of autonomous vehicle modeling, simulation, guidance and control at the undergraduate level. A small-scale UAV, a quadcopter, is modeled, simulated, and deployed during the semester. The course is planned as a 3-credit selective undergraduate 400-level module in Mechanical Engineering. It was delivered in Fall 2024 semester for the first time and was offered by the Department of Mechanical Engineering of a national university. Due to the multi-disciplinary nature of the course topics, enrollment was also open to Electrical Engineering, Computer Engineering and Computer Science students. Prerequisites are defined based on major. For the Mechanical Engineering students, prerequisites are Modeling and Analysis of Dynamic Systems I and II. Prerequisites for the other majors are Signals and Systems or Digital Systems Engineering or Systems I and II.

Course Overview

The first goal of this course is to introduce mathematical modeling to the target audience which are mechanical and electrical engineering, and computer science-programming students. The foundation of autonomous vehicles (e.g., Uncrewed Aerial Vehicles (UAV), Autonomous Underwater Vehicles (AUV), Remotely Operated Vehicles (ROV), Autonomous Surface Vehicles (ASV)) control is the mathematical modeling of the rigid bodies in 6 Degree of Freedom (DOF). In this regard, kinetics (dynamics), kinematics (geometry of the vehicle motion), vectorial mechanics, equations of motion of the vehicles in 4 and 6-DOF, environmental effects such as wind and wave models, and maneuvering of the vehicles will be covered.

The second goal of the course is to simulate the motions of the vehicles in the time domain by using the models previously obtained. These models will include simulation models, models for control, and models for observers. Simulations will be studied using various numerical simulation software and open-source visual and physics simulators.

The third goal of the course is to introduce the basics of guidance, navigation, and motion control systems. This includes introducing the geographical and vehicle body-fixed reference coordinate systems, and rotations between coordinate systems. Traditional guidance systems will be covered. Vehicle models will be simulated under different environmental conditions and failure modes. Motion control systems such as Linear Quadratic Gaussian (LQG) control and state feedback linearization will be studied in this regard. State estimation techniques such as Kalman Filtering will be covered.

The goal of the term group project of the course is to apply the theories covered during the semester to a small-scale uncrewed quadcopter. Necessary hardware will be provided to the students. Groups will work together to deploy the vehicle. Each group will perform a mission related to the topics taught.

The students who successfully complete the course requirements can

- Obtain 6-DOF mathematical model of a rigid body in space.
- Obtain a linearized mathematical model for unmanned aerial vehicles (UAVs).
- Simulate autonomous UAV dynamics using numerical simulation software.
- Design a motion control system for UAVs.
- Simulate controlled autonomous UAV using numerical simulation software. Additionally, model and simulate environmental effects such as wind and drag forces.
- Install and commission a small-scale UAV (a quadrotor type vehicle). Apply designed control algorithm to the vehicle.
- Additionally, students will develop the skill to read and understand the publications about the topic.
- Students will develop skills on project management, reporting and contributing the larger scale research and development projects.

Design of the Course

The design of the course can be examined under three main sections: theory, simulations and application.

Theory

As previously mentioned, one of the main goals of the course is to teach the mathematical control theory used in AV research. In Table 1, the theory topics to be covered during a semester are shown. Most of the topics were drawn from current research publications on aerial, underwater, surface and ground robotics. Necessary mathematical fundamentals were drawn from various textbooks that are available both online and in the library of the university. Additionally, examples of recent publications related to each individual topic are discussed during the lectures.

Simulation

Numerical simulations are an essential part of today's engineering education. They are used as learning support and understanding tools of complex systems [16] such as an UAV. Authors suggest that modeling and control design for AVs can be taught more effectively using the simulations. To do that, during the semester, students are assigned to create a numerical simulation of the overall system and examine various control scenarios such as effects of the environmental disturbances on UAV, effects of the initial conditions of the system on trajectory tracking control. Simulation study consists of four sections:

- 4-DOF mathematical model of the system. This simulation study includes rotational and translational dynamics, transformation between references frames and thrust calculation.
- Rotational velocity controller.
- Rotational position and altitude controller
- Translational position controller.

In Fig. 1, a schematic of the simulation study is shown.

Table 1: Theory to be covered during the semester

Lecture	Topics
1-2	Required mathematics review
3-4	Required software review
5	Introduction to autonomous vehicles
6	Reference frames used in design
7	Principal rotations and transformation between reference frames
8-9-10	Kinematics and dynamics of UAVs
11-12	Forces and moments acting on a UAVs
13	Mathematical model of UAVs
14	Linearized mathematical model of UAVs
15	Decoupled hovering model for UAVs
16-17	Control design review

18	Angular velocity controller design for UAV
19	Attitude/Altitude controller design for UAV
20	Translational position controller design for UAV
21	UAV sensors and their mathematical models
22-23-24	Vehicle installation and instructions

Application

According to The National Research Council's definition of learning in a laboratory [17], physical simulations or applications of the theory generates many opportunities for the students to gain field experience, using various tools and equipment, conducting experiments under different conditions, acquiring data, analyzing and presenting the results [17].

During the application phase of this course, a quadcopter based on X500 V2 platform will be installed by the students as the main application platform. The course also requires students to design their own control solutions. Thus, various sensors and technologies are provided such as light detection and ranging (LIDAR) rage finders, stereo cameras for image processing, real-time

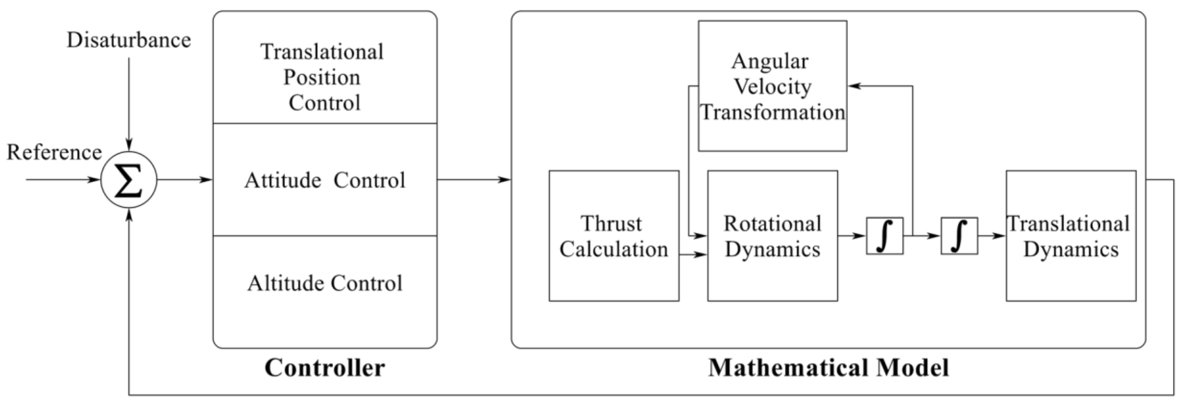
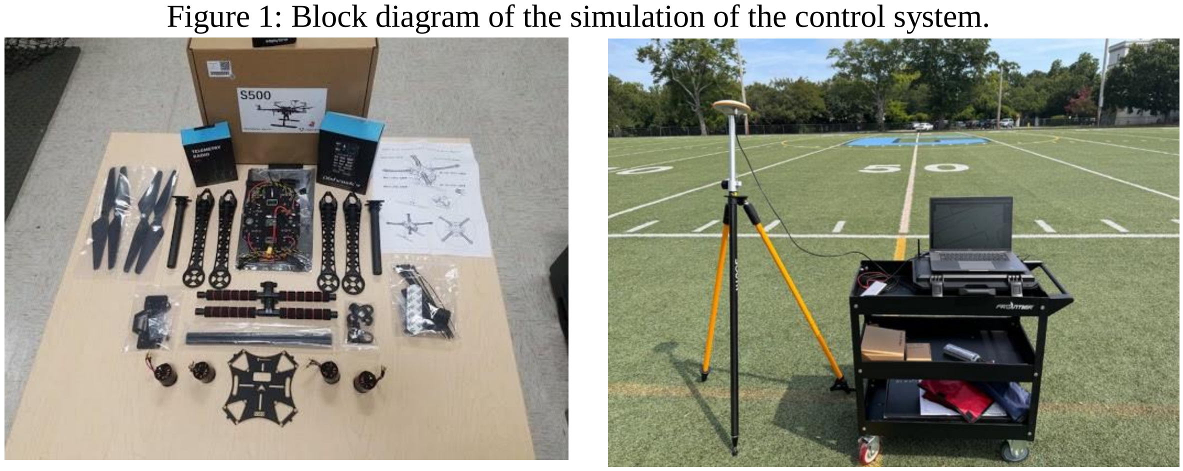


Figure 1: Block diagram of the simulation of the control system.



(a) (b)

Figure 2: Test Vehicle and ground station (a) S500 V2 platform (Source: adopted from [5]) (b) RTK-GPS and ground station.

kinetic global positioning systems (RTK-GPS) for accurate localization of the vehicle for accurate localization of the vehicle. In Fig. 2, the X500 V2 drone kit that is to be built by the students as an UAV, the ground station and RTK-GPS to be used are shown. In Fig. 3, stereo camera and the LIDAR to be used in student projects are shown. In Fig. 4 extended reality lens and a micro-UAV for the SLAM project are shown.

Some of the control applications to be investigated are:

- Use of artificial reality (AR)/extended reality (XR) in control applications of UAVs
- Machine learning based control applications.
- Image processing-based object detection.
- Image processing-based visual recognition.
- SLAM based navigation

Course Assessment

Assessment of the student performance is based on the homework assignments, exams and delivery of the semester project. In Table 2, the grading system of the course is shown.

Table 2: Percentage weight of the assignments

Weight	Assignment
20%	Homework
25%	Midterm exams
30%	Project delivery and demonstration
25%	Final exam

(a) (b)

Figure 3: Machine perception for student projects (a) Stereo camera. (b) LIDAR.

Homework assignments for theory and the simulations of theory are designed in a continuity of course progress such that each homework deliverable is used as input or a tool (e.g. a piece of computer program script) for the next homework. Homework assignments aim to obtain a fully functional system simulation at the end of the semester.

The Midterm exams and a comprehensive final exam aim to assess the student's knowledge of the control theory taught during the lectures. Reference coordinate system transformations, translational and rotational dynamics of the UAV and the position control problem are the main topics for the exams.

Students are asked to propose their course project ideas at the beginning of the semester since the semester project is a course-long assignment. They are also encouraged to propose their unique research ideas. Students are responsible to meet with the instructors about the progress of their project twice a month during the semester and are expected to demonstrate their project and prepare a short report and presentation analyzing and evaluating their project, comparing the application results with the simulation results. The planned homework assignments are shown in Table 3.

(a) (b)

Figure 4: XR lens and micro UAV (a) Microsoft Holo Lens. (b) DJI Tello.

Table 3: Homework assignments

Number	Homework topic
HW00A	Matrix algebra
HW00B	Software review
HW01	Coordinate frames and rotations

HW02	Kinematics and dynamics
HW03	Rotational dynamics
HW04	Angular velocity transformation and rotational kinematics
HW05	Thrust calculation
HW06	Translational dynamics
HW07	Translational position control
HW08	Attitude and altitude control
HW09	Rotational velocity control
HW10	Vehicle simulation under disturbance
HW11	Comprehensive paper review
HW12	Test flight-live demonstration

Conclusion

In this study, authors proposed a new course module for the modeling and control design for AVs. In their work, they designed the new course based on the three principles of theory, simulation and application. In the theory section, the necessary knowledge to obtain the dynamic model of a rigid body is aimed to teach the students. The numerical simulation assignments are used to support the learning process of the theory and as a tool to simulate the behavior of the vehicle under different scenarios such as environmental disturbances and changing initial conditions of the states of the vehicle. The term project assignment is used to provide an opportunity for the students to realize their controller design, to apply the theory that they studied and to compare real life control, navigation and guidance scenarios to the simulated ones. Additionally, every theory topic is supported by reviewing and discussing recent related research about AVs in this course module.

Student engagement and participation are aimed by providing a wide variety of equipment to be used in application and term projects. Main test platform is an X500 V2 quadcopter platform due to its open-source software and open-source hardware properties. For SLAM-related designs and in-course experience a micro-UAV and to increase the learning experience, AR-XR tools are also provided for student use. Furthermore, to support suggested project topics, all the necessary machine perception elements such as stereo cameras, LIDARs, localization sensors and GPS devices are supplied.

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