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# An Introductory Aeronautics Course for Pre-Engineering Students to Understand How Drones Work

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***Abstract***

Robotics has emerged as one of the most popular subjects in STEM (Science, Technology, Engineering and Mathematics) education for students in elementary, middle, and high schools, providing them with an opportunity to gain knowledge of engineering and technology. In recent years, flying robots (or drones) have also gained popularity as a teaching tool to impart the fundamentals of computer programming to high school students. However, despite completing the programming course, students may still lack an understanding of the working principle of drones. This paper proposes an approach to teach students the basic principles of drone aeronautics through laboratory programming.

This course was designed by professors from Vaughn College of Aeronautics and Technology for high school students who work on after-school and weekend programs during the school year or summer. In early 2021, the college applied for and was approved to offer a certificate program in UAS (Unmanned Aerial Systems) Designs, Applications and Operations to college students by the Education Department of New York State. Later that year, the college also received a grant from the Federal Aviation Administration (FAA) to provide tuition-free early higher education for high school students, allowing them to complete the majority of the credits in the UAS certificate program while still enrolled in high school. The program aims to equip students with hands-on skills necessary for successful careers as versatile engineers and technicians. Most of the courses in the certificate program are introductory or application-oriented, such as Introduction to Drones, Drone Law and Part 107 License, or Fundamentals of Land Surveying and Photogrammetry. However, one of the courses, Introduction to Drone Aeronautics, is more focused on the theory of drone flight and control. Organizing the lectures and laboratory of the course for high school students who are interested in pursuing the certificate can be a challenge.

To create the Introduction to Drone Aeronautics course, a variety of school courses and online resources were examined. After careful consideration, the Robolink Co-drone [1] was chosen as the experimental platform for students to study drone flight, control and stabilize a drone. However, developing a set of comprehensible lectures proved to be a difficult task. Based on the requirements of the certificate program, the lectures were designed to cover the following topics: (a) an overview of fundamentals of drone flight principles, including the forces acting on a drone such as lift, weight, drag, and thrust, as well as the selection of on-board components and trade-offs for proper payload and force balance; (b) an introduction to the proportional-integral-directive (PID) controller and its role in stabilizing a drone and reducing steady-state errors; (c) an explanation of the forces acting on a drone in different coordinates, along with coordinate transformations; and (d) an opportunity for students to examinate the dynamic model of a 3D quadcopter with control parameters, but do not require them to derive the 3D drone dynamic equations.

The course was offered during the summer of 2022 to 35 high school students from 17 high schools in the economically disadvantaged communities in New York City. These students were from ethnic minority families. The prerequisite for recruitment was that students' GPA must be higher than 2.5 with a recommendation letter from their school advisor. After the completion of the course, the students were asked to complete survey, and their performance was evaluated using various assessment tools such as laboratory reports, quizzes and a final examination. The results shows that the students had significantly improve their knowledge of drones, but their level of enjoyment of the course is different based on their mathematical background. Students who had strong mathematical skills were excited to work on various mathematical operations, while others felt they needed more mathematical courses before taking the class.

In the future, the course can be improved to cater to the diverse learning needs of the students. More interactive and accessible tools can be developed to help different types of students understand drone aeronautics. For instance, some students may prefer to apply mathematical skills to derive results, while others may find it easier to comprehend the stable flight of a drone by visualizing the continuous changes in forces and balances resulting from the control of DC motor speeds. Despite the differences in students' mathematical abilities, the course has helped high school students appreciate that mathematics is a powerful tool for solving complex problems in the real world, rather than just a subject of abstract numbers.

## *Introduction*

### *I. UAS Education in the United States*

Over the past two decades, UAS systems have experienced a tremendous amount of growth, and this trend is expected to continue in the near future due to the vast potential uses of drones in the real world [2]. As UAS systems represent a rapidly expanding market and segment of technology, it is essential for academic institutions to be actively engaged in this area and play a vital role in continually updating the relevant technologies. Graduates of leading institutions must be prepared to drive change in this expanding area, while other academic institutions must also collaborate to improve traditional higher education approaches, as the complex UAS system designs have demonstrated their interdisciplinary nature and complexity.

Currently, educational research in this area is very active, with many institutions offering UAS programs. Ward and Ward [3] have published a paper detailing the universities in the United States that offer UAS programs, with hundreds of small and medium-sized educational institutions offering minor degrees in the UAS system. Dr. Sadraey has shared his experience on teaching fixed-wing aircraft designs and provided the design steps for a UAS system [4]. However, due to the lack of a standard design process for developing a drone, the programs offered by different schools may vary considerably. Moreover, most graduates from a minor degree or a certificate program of UAS systems may focus more on the drone applications with essential concepts of UAS working principles rather than an intensive study of science of flight. Therefore, the development of drone education is significant for the rapid growth of drone applications.

*II. UAS Certificate Program at Vaughn College*

Vaughn College is an Aeronautics and Technology school that serves one of the most diverse communities in the nation. It has been designated as a Hispanic-Serving Institution (HSI) by the Department of Education, with 88% of its students coming from minority, low-income, first-generation, and new immigrant families. The college traditionally provides degrees in aviation-related aeronautical and avionic technology, operations, and management. However, in recent years, the institution has transformed its culture to adapt to the changing world in the emerging field of robotics, flying robots, and automation. In 2020, the college's Department of Engineering and Technology applied to offer a certificate program in UAS Design, Application and Operation which was approved by the New York State Department of Education in January 2021. This program is a strong complement to the Mechanical Engineering with Aeronautics Concentration and Aeronautical Engineering Technology program.

The UAS certificate program consists of five courses totaling fifteen credits. Students in this certificate program will learn about UAS design, application, and system integration. They will also gain hands-on experience in designing drone communication and control systems. Additionally, through courses in drone law and remote pilot training, students will learn about FAA's new Part 107 regulation, which will prepare them for the required aeronautical knowledge test. Graduates of this certificate program will be equipped with the knowledge and skills required for today's industry positions that involve UAS design, manufacturing, application, and operations.

In April 2021, Vaughn College applied for an FAA grant to educate the next generation of pilots and aviation professionals as part of the Aviation Workforce Development Grants Program. The grant aims to provide a tuition-free early higher education experience for high school students, allowing them to fulfill 80% of the UAS certificate program's credits during the summer, evenings, or weekends while they are still enrolled in high school. The FAA strongly supports this proposal because creating a robust pipeline of skilled and diverse professionals is essential to maintaining the safest and most efficient aerospace system, and education needs to start from young adults. The college plan to recruit students from economically disadvantaged communities and ethnic minority families. To meet the higher education standard, applicants need to have a cumulative GPA of 2.5 or higher, successfully complete at least two credits of math and three credits of English and provide a signed and dated letter of recommendation written by their instructor addressing the student's dedication and commitment to learning, especially in a STEM discipline. In summer 2022, the college welcomed the first group of high school students to join the program.

*III. Drone Aeronautics Course in UAS Certificate Program of the College*

As mentioned previously, the certificate program is designed to equip students with practical skills and knowledge in drone applications. However, creating a curriculum that covers drone aeronautics with essential subjects like mathematics and computer programming can be a challenging task. To address this, the program organizers scheduled the Introduction to Drone Aeronautics course in the summer II session, following the course in summer I for Drone Law and Part 107 License that covered the basics of drone operations and requirements. To ensure equitable access to the program, the organizers focused on recruiting students from economically disadvantaged communities. The participating students were divided into two sections, with 18 and 17 students in each section, respectively. All students were from Black, Asian, and Hispanic families, with 15 females and 20 males.

During the summer II section (July 4 – August 12), the two sections of students attended classes and laboratories at two different high schools with one section attending classes on Monday and Wednesday and the other section on Tuesday and Thursday. To meet the contact hour requirements for the 3-credit class, each section received 7.5 hours of intensive instruction per class day, which include a 3-hour lecture and 4.5-hour laboratory exercise. The designed schedule accommodated students' other commitments as one section of students were free from this class on Tuesday and Thursday and the other on Monday and Wednesday.

***Course Development***

*I. Course Lectures*

Summer is an ideal time for the program as students typically have a break from their regular high school study. To optimize the summer schedule, the organizers arranged for classes and laboratory exercises to take place in two days per week for each section of students. The instructor and teaching assistant provided 3 hours of lecture and 4.5 hours of laboratory exercise on each day, Monday through Thursday. The lecture portion of the course covered topics outlined in Table 1, which were discussed in class.

Table 1. Lecture Topics for Introduction to Drone Aeronautics

| Week | Meeting | Scheduled Topics |
|---|---|---|
| 1 | 1 | Introduction to the Unmanned Aerial Systems (UAS) and Quadcopters |
| | 2 | Introduction to Basic Mechanics and Control of Quadcopters |
| 2 | 3 | More Examples of PID Controller and Parameter Adjustments |
| | 4 | Design Considerations for Quadcopters |
| 3 | 5 | Vectors and Matrices and Basic Operations of Matrices |
| | 6 | Euler Angles and Rigid Body Transformations |
| 4 | 7 | Planar Quadrotor – Linear Dynamic Model |
| | 8 | 3D Quadcopter Model and Control Equations |
| 5 | 9 | Aerodynamics of Fixed-Wing UAS Systems |
| | 10 | Final Examination |

As seen the course schedule outlined in Table1, the course begins with an introduction to unmanned aerial systems (UAS) and quadcopters in the first week. To facilitate this, the instructor used Dr. Dougherty's Illustrated Guide to Drone [5] and Dr. Kumar's online course on Muti-rotor Aerial Vehicles [6] as reference materials. In the second week, the course delved into PID control and parameter adjustments. Dr. Sprague's PID control video and notes were used as a reference [7]. The instructor developed a PID control simulation to help students understand how the changes of the Kp, Ki, and Kd coefficients affect system responses. The week also covered the trade-off design, including the evaluation of payload by using one or two cameras and how the weight of a laser sensor affects the flight control.

The third week introduced students to mathematical concepts like Euler angles and rigid body transformations. The instructor taught matrix & vector operations to explain transformations, including translations and rotations, and demonstrated how an aerodynamic force is transformed from the body frame to the inertial frame through the rotations of three Euler angle [8]. The mathematical foundation prepared students to understand aircraft control algorithm theory for real drone systems. In the fourth week, the course presented 2D and 3D quadcopter models and corresponding control algorithms to stabilize the quadcopter and navigate it along a desired trajectory. Finally, the last week covered the basic aerodynamics of fixed-wing drones [9], giving students insight into different drone structures in the real world.

### *II. Laboratory Exercises*

The laboratory exercises for the course utilized the Co-drone Pro/Lite package which was provided by Robolink company [10]. This particular package was chosen due to its ability to showcase the fundamental functions of a quadcopter and the fact that it can be easily programmed using Arduino Integration Design Environment (IDE) [11], a popular programming environment used in high schools and lower-level college courses.


Figure 1. Package of a Co-drone Pro/Lite

Table 2. Laboratory Exercises in Course Syllabus

| Lab No | Topic |
|---|---|
| 1 | Introduction to Co-drone, Hardware Building and Calibration. |
| 2 | Arduino Integrated Development Environment (IDE) & Sample Programs |
| 3 | Block and Unblock a Remote Co-drone Pair with Flight Events |
| 4 | 3D Movement with Light Emitted Diode (LED) and Buzzer Indicators |
| 5 | Conditions, If-Statements and Digital IR (Infrared) Sensors |
| 6 | Flags and Timers |
| 7 | Void Functions and Return Values |
| 8 | Arrays, While-Loops and For-Loops |
| 9 | Analog Read and Controller Flight |
| 10 | Laboratory Project Development and Demonstration |

The Co-drone Pro/Lite package depicted in Figure 1 comes equipped with Light Emitted Diodes (LEDs) that indicate the drone's readiness and hovering status, as well as a 6-minute battery flight time. Students can program the Co-drone in both autonomous and remote-control modes. The library functions provide advanced commands to be used in both modes. Table2 provides a detailed breakdown of the laboratory exercises that were developed for the course.

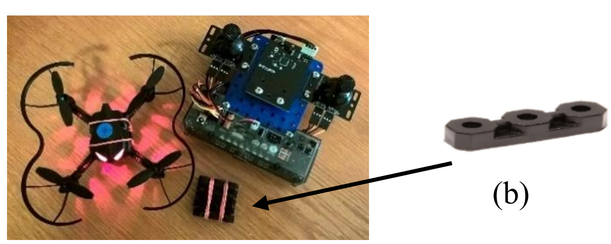
The laboratory exercises for the course began with an introduction to drone hardware and the software programming environments. These sessions took place during the first two laboratory exercises, where students were able to test a simple program (depicted in Figure 2) to verify remote control functionality and other related functions.

```
#include <CoDrone.h>
void setup() {
            CoDrone.begin(115200);
            CoDrone.pair();}
void loop() {
      byte bt8 = digitalRead(18);
      byte bt4 = digitalRead(14);
      byte bt1 = digitalRead(11);
     if (PAIRING == true){ //PAIRING is defined in the library
            CoDrone.setYaw(-1*CoDrone.AnalogScaleChange(analogRead(22)));
            CoDrone.setThrottle(CoDrone.AnalogScaleChange(analogRead(23)));
            CoDrone.setRoll(-1*CoDrone.AnalogScaleChange(analogRead(24)));
            CoDrone.setPitch(CoDrone.AnalogScaleChange(analogRead(25)));
            CoDrone.move(ROLL, PITCH, YAW, THROTTLE);}
      if (bt1 && !bt4 && !bt8){
            CoDrone.emergencyStop();}
}
```

Figure 2. Remote Control Verification of Co-Drone System

The third laboratory exercise focused on pairing, unpairing and repairing the co-drone with the remote controller, while also testing the payload that a Co-drone can carry. The exercise was crucial as it allowed students to apply the trade-off concept that they learned in the lecture to determine if the Co-drone could sustain with added weight. To test the payload, the laboratory exercise used VEX robot parts called bearing flats which weighed 1.63 gram each. Students attached multiple bearing flats to the Co-drone using rubber bands and added them one-by-one until the Co-drone could no longer fly. By doing this, students were able to determine the Co-drone's payload limitation. Figure 3 illustrates the bearing flats used in this laboratory exercise.

(a)



(b)

Figure 3. Package of VEX Bearing Flats (b) as Payload

The laboratory exercises #4 and #5 focused on 3D drone flight with sensor inputs. Students were introduced to the working principles of a drone and Euler anglers in the lectures and were guided through the examination of Yaw, Pitch and Roll angles. By controlling these angles, students learned how to change the drone's trajectory, as illustrated in Figure 4. Hovering in space is achieved when the throttle is equal to the gravity, while increasing the pitch angle enables drone's forward movement due to the increased thrust. The roll angle, together with the forward speed, allows the drone to turn, and Yaw angle control (by controlling opposite DC motors in the same rotation direction) allows the drone to rotate in a desired direction.  Additionally, the Euler anglers were compared with those of the fixed-wing aircraft, as shown in Figure 5.

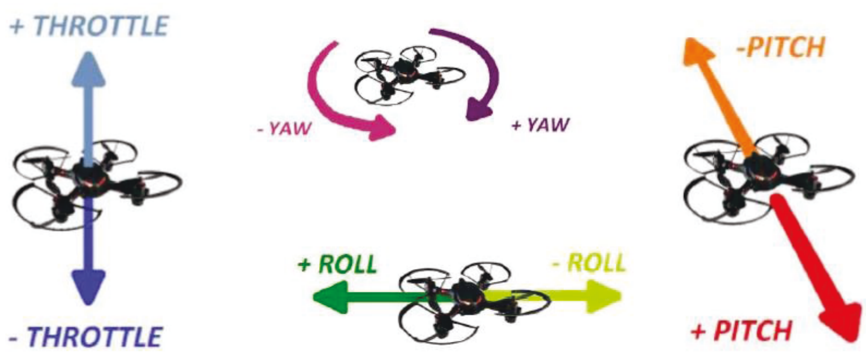



Figure 4. Flight Directions with Throttle, Yaw, Roll and Pitch Angle Adjustments

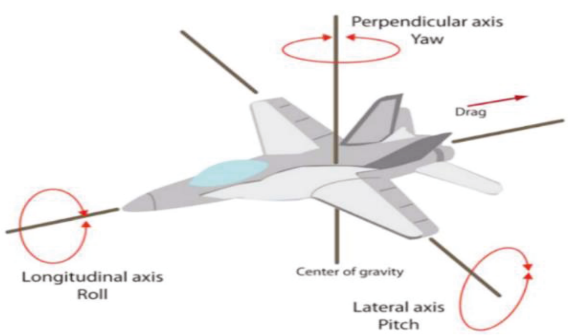



Figure 5. Euler Angles of an Aircraft

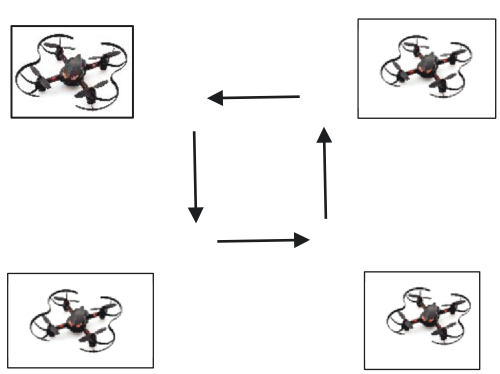


Figure 6. Co-drone Flight Trajectory

The sixth laboratory exercise involved in-depth programming using timers, function calls and control strategies. Students were required to program the Co-drone in autonomous mode using timers and checking flags, as outlined in laboratory handout. One of the exercises involved the flight trajectory shown in Figure 6. Since the flight trajectory navigation is in open-loop control, students could easily observe any errors, such as errors in turning 90 degrees or distance errors, etc.

Moving to the laboratory exercises #7 and #8, students were introduced to programming techniques using function calls and more efficient approaches in arrays, for-loops, and while-loops. Students were encouraged to use functions developed by Robolink with parameter corrections, such as

```
CoDrone.go(FORWARD, 0.5, 30);          //To move forward at 50% power for 30 seconds
CoDrone.turnDegree(LEFT, ANGLE_90);   // To turn left 90 degrees
```

By incorporating sensor measurements to correct the angles and distances, the required trajectory in Figure 6 was completed with relatively higher accuracy. The laboratory exercises emphasized the importance of control system designs with sensor measurement as feedback signals.

Starting from the first laboratory exercise, students were required to submit a laboratory report for each section. A sample laboratory report was posted on the course website at the beginning of the semester to help students write their reports in the appropriate style. As a result, out of 35 students, 18 received an A grade, 4 received a B grade, and 8 received a C grade. Five students did not complete the course due to COVID-19 or family issues.

***Course Outcomes and Assessment***

*I. Course Outcome Assessments*

The objective of this course was to introduce students to the filed of drone aeronautics and enable instructors to assess their performance on drone exercises. This assessment would be later utilized to refine and enhance the program in future semesters. During class, students were assigned the reading materials, videos, or handouts to review each lecture. In addition, three quizzes and a final examination was conducted to evaluate students' comprehension of the lecture contents. The three quizzes were designed to test students' understanding of (a) basic drone concepts and design considerations; (b) drone control and the essential PID parameters; and (c) fundamental matrix operations, Euler angles and transformations. The average grade for Quiz#1 was +88/100, Quiz#2 was +84/100, and Quiz#3 was +87.5/100, respectively.

The final examination was a comprehensive test that covered all lectures and laboratory exercises taught during five-week period. Prior to the exam, students were provided with a thorough review to help them systematically review and comprehend all the materials they had learned. The test consisted of 22 multiple-choice problems and two problem-solving questions to evaluate students' understanding of drone aeronautics. The first problem-solving question is to prove rotation matrix property while the second one asked the students to explain a complete Co-drone program, including the entire functionality of the program and meaning of each statement. The result showed that out of a total of 35 students, 10 received an A grade, 16 received a B grade, 4 received a C grade, and 5 were unable to complete the class due to COVID-19 or family issues.

*II. Course Outcome Assessment*

The goal of the course is not only to enhance students' knowledge of UAS systems but also to evaluate whether the course contents and laboratory exercises are suitable for teaching high school students in the future. At the beginning of the course when students were first introduced to the theory and programming of drones, it was apparent that students struggled to complete the laboratory exercises and apply what they learned from the lecture to the practical tasks. However, as they continued to review the theory covered in the lectures and conducted the troubleshooting in the laboratory activities, their performance gradually improved. One essential aspect of the course was that students had to write a laboratory report after each laboratory exercise and received immediate feedback on their performance and technical writing, which substantially enhanced their ability to explain the laboratory exercises and what they had learned. By the end of the course, it was evident from the quizzes, final examination, and laboratory reports that students could write and present their understanding in a professional manner. To evaluate the effectiveness of the course, students were given an anonymous survey about their experience, which was developed based on the FAA and certificate program requirements. The survey results from 25 students are provided in Table 3.

In accordance with the college's course assessment requirements, a rubric score above out of 5 indicates that students have a basic understanding of the course material concepts, and the overall goal is to ensure that at least 70% of students (success rate) achieve a score above 4 for each outcome. In this investigation, the percentage of students who achieved a score above 4 was 71.43%. In addition to the questions listed in Table3, students were asked if they would recommend the course to other students and if they had any suggestions for changes. Their responses are also included below.

**Table 3: Survey Result and Analysis**

| **Questions** | **Response in percent of participants (Number of participants: 25)** | | | | | |
|---|---|---|---|---|---|---|
| | Strong Disagree 1 | Disagree 2 | Neutral 3 | Agree 4 | Strong Agree 5 | **Success Rate (SR) % of student with score ≥ 3** |
| 1. This course provided me the fundamentals of flight principles on multirotor, such as quadcopters, as well as fixed wing UAVs. | | | 2 | 11 | 12 | Score=4.40 100% |
| 2. This course makes me understand the basic concepts of Euler angles, translations, and rotations of coordinate systems for aerial robot designs. | | | 4 | 13 | 8 | Score=4.16 100% |
| 3. The course gave me fundamental knowledge of kinematics and dynamics of multirotor as well as fixed wing UAVs. | | | 4 | 16 | 5 | Score=4.04 100% |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4. The course gave me essential knowledge of flight control elements and basic working principle of PID controllers. | | | 3 | 14 | 8 | Score=4.20 100% |
| 5. The course laboratory exercises provided me an excellent opportunity to gain the knowledge necessary to program UAVs in both autonomous mode and remote-control mode. | | | 1 | 15 | 9 | Score=4.32 100% |
| 6. My professor did an excellent job responding to student questions and concerns. | | | 0 | 14 | 11 | Score=4.44 100% |
| 7. My professors provided various learning materials, including videos, reading documents and other materials for me to understand the concepts. | | | 1 | 7 | 17 | Score=4.64 100% |
| **Overall average Learning Outcome Attainment** | 0% | 0% | 8.57% | 51.43% | 40% | |

*Please share your comments regarding the course in the FAA program in the space below* (*do you recommend offering it to other high school students? what changes, if any, do you recommend?*)

1. Loved it.
2. I'd definitely recommend continuing this program, substituting a different class for the part 107 course and just having kids self-study for the test may be worthwhile.
3. Possibly teaching linear algebra and basic call before the Aeronautics course might smooth things out and help make the course more digestible.
4. I do recommend if you are into drones and programming. It provides a great opportunity for students. Changes: more breaks!
5. If possible, please provide the quality of drones provided. They often don't perform the program as intended due to the lack of error correction on the drone. Along with that, I would enjoy seeing more hands-on activities, especially more soldering.
6. I think this class was good for understanding the fundamentals on how drones work and the physics behind it. I would recommend it to people who want to create their own drones, but I wished the lectures were shorter and more hands-on experiences and building.
7. I would recommend this class to other high school students, but the level of math is a bit hard. It sometimes makes class seem frustrating.
8. A little bit more clear in the instructions.
9. I'd recommend this to anyone interested in drone or flying. It's very helpful.
10. Yes. I will recommend this to other high school students.
11. I strongly recommend for interested students.
12. If the students want to learn anything about aircrafts, then yes, I recommend it.
13. I would recommend it to other students I would suggest that students be given the opportunity to put what learned into practice.
14. I recommend this program to others.
15. Professors are very helpful.

*Result Analysis and Students' comments*

The results of survey and students' comments indicate that the course has been satisfactory and has provided students with a deep understanding of engineering education. Of the survey participants, 40 percent rated the course as excellent, and 51.43 percent rated their instruction as good. In the end results, more than 91.43% of students checked that they strongly agreed or agreed with each of the survey questions. However, several students expressed neutral opinion, stating that they found certain topics in the course can be difficult for them to follow along. However, they believed that if given less intensive (more breaks) or more time, they would be able to understand the materials better, particularly, if they could have a better math background.

After reviewing students' comments, the suggestions to add more hands-on contents related to the class and organize the classes in a better way to convey the essential drone knowledge to students have been discussed.

***Conclusion***

This paper outlines an innovative approach to teaching introductory drone aeronautics and programming to high school students. The five-week summer engineering course included lectures and laboratory exercises designed to provide students with experience in programming small, unmanned aircraft systems and exposure to the fundamentals of drone aeronautics. In addition, the course covered essential skills such as trade-off design, control system parameter tuning, and problem-solving strategies.

Upon the completion of the course, all students showed a better understanding of the working principles of drones (flying robots). However, students' sense of achievement varied depending on their mathematical background. Students with strong mathematical skill were enthusiastic about various mathematical modeling, computer programming and control system designs, while others felt that more mathematical courses were needed before the class and preferred more hands-on exercises. In the future, the course could be improved by providing more visible dynamic models for students to observe drone control results based on continuous changes of force balances in space.

Notice that the methodology discussed in this paper is not limited to teaching drone aeronautics but can also be applied to other areas of robotics due to the excellent development of programming modules and software package. For example, educators can use this approach to teach introduction to hydro acoustics with the applications for the autonomous unmanned underwater robots or introduction to artificial intelligence and machine learning with the applications to autonomous mobile robots. By providing students with opportunities to learn about fundamentals of flying and underwater robots, as well as intelligent vehicles combined with computer programming skills, educators are helping to prepare the next generation of engineers and scientists to improve themselves and work with rapidly evolving technologies in a wide range of industries. Moreover, this educational experience helps the college faculties develop courses and curriculums for various types of robot designs, controls, and applications comprehensively.

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