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Multiyear Vertically Integrated Engineering Design Project: A Story of Student Success

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Abstract

Since 2014, engineering students of all ranks at Colorado State University Pueblo (CSUP) were involved in a multiyear research/design project dealing with electrical vertical takeoff and landing (eVTOL) unmanned aerial vehicles (UAVs). Supported by three external educational grants and internal departmental funds, the project involved undergraduate and MS graduate student researchers spanning a period of about ten years. Students worked with their faculty mentors to investigate new UAV applications as well as to create new UAVs. Students' work resulted in a number of internal posters and PowerPoint presentations at university-wide STEM research symposia, four senior project reports with posters and presentations, and one MS thesis. Students' designs involving a novel octocopter with overlapping propellers were also used in writing an external grant application. Furthermore, all students engaged in this vertically integrated project (VIP) were retained or graduated. In addition, 20% of the students obtained MS degrees. It is hoped that this work will add to the VIP body of knowledge and will inspire readers to implement similar projects in their own institutions.

Introduction

The main goal of this work is to increase student retention, graduation rates, and students' resolve to continue their studies beyond bachelor's degrees by working closely with program faculty and graduate students on important projects. In this case, the multiyear VIP described in this work deals with eVTOL UAVs as a possible solution to the well-known problem of traffic congestion and pollution in large cities. One could frame the research question of this work as follows: Does the student engagement in undergraduate research of important societal problems with discipline faculty improve retention/graduation rates and affinity to graduate studies?

Due to rapid population growth in large cities, traffic congestion is becoming more severe and longer lasting. With new advances in battery and motor technologies as well as the arrival of more sophisticated controls, eVTOL unmanned aerial systems (UAS) capable of carrying people short distances became commercially feasible. Flying commuters may relieve some of the traffic congestion problems of large cities without increasing pollution in those cities.

The theme of this VIP project is building and using eVTOL UAVs. A 3D printed quadcopter UAV gave way to a commercially available larger frame UAV (over 1 m in diameter), which in turn inspired the design and construction of a cargo octocopter (about 2.64 m in diameter) capable of lifting heavy loads (200 kg max). Other UAV projects described here include a spray-painting UAV, a wildfire fighting UAV, and a rescue drone. The next research/design challenge is transforming the cargo drone to a personal air vehicle (PAV) with a pilot/passenger on board.

What follows is the section on previous work addressing experiential and project-based learning (PBL), senior projects, vertically integrated projects (VIPs), and eVTOLs state-of-the-art.

Previous Work

Over 85 years ago, Dewey [1], one of the founders of modern educational thought, recognized that practical laboratory experiences and projects are important parts of learning. Moreover, Kolb's Experiential Learning Cycle (KLC) [2] teaches that learners learn best when they follow a cyclical process consisting of four steps: experiencing, watching, thinking/modeling, and applying/doing. This makes all engineering projects consisting of conceptual designs, computer models, simulations, and physical implementations essential elements of learning. For undergraduate engineering education, capstone projects are exceptionally important. Howe and Goldberg [3] analyze current practices, trends, and strategies. Furthermore, since this work addresses a multiyear design project, the pedagogical value of project-based learning (PBL) as a part of experiential learning, is also well documented [4]-[6]. In addition, since students work in teams, some of the peer learning (PL) practices are implemented. PL is extensively addressed in education and psychology literature [7]-[11].

Teams undertaking multiyear projects can be either replacing some members each year (VIPs) [12]-[13] or replacing an entire team every year [14]. There is a VIP Consortium led by the Georgia Institute of Technology consisting of forty-eight mostly large research-intensive educational institutions [15].

Unmanned aerial systems (UAS) comprising UAVs, ground stations, communication systems, and launch/retrieve systems are slowly coming of age. The eVTOL developmental ecosystem is improving rapidly due to the commercialization efforts of companies like Joby Aviation [16]. Moreover, the Federal Aviation Administration (FAA), through their Urban Air Mobility concept, is developing new standards that include eVTOLs [17].

In engineering education, faculty of the Department of Mechanical and Aerospace Engineering at West Virginia University designed an undergraduate area of emphasis in UAS [18], as did faculty at Southern New Hampshire University [19]. Furthermore, an undergraduate engineering student team from Mercer University used a 3D printer to create a small quadcopter frame and built a drone that could fly [20].

Objective and Principles

The main objective of this work was to increase the retention and graduation rates of undergraduate engineering students through research activities with peers and discipline professors.
The work is based on the following principles:

1. *Selection of a meaningful research theme that is attractive to engineering students.* Here, a multiyear VIP theme (eVTOLs) that is of interest to students and faculty was selected.
2. *Sustained student engagement.* Through weekly meetings, weekly individualized written reports, weekly oral reports, poster presentations each semester, unlimited lab access, and teamwork, student engagement is assured.

3. *Multiyear student engagement and project continuity*. Each year new students are assigned to existing research teams. This vertical integration enables project continuity from year to year. Also, all research/design project files are shared between team members.

Curricular Context and Funding

Colorado State University Pueblo (CSUP) is a small, fully accredited, regional comprehensive, Hispanic-serving institution (HSI) enrolling nearly 4000 students. The university is a part of the Colorado State University System. The School of Engineering, a part of the College of Science, Technology, Engineering, and Mathematics (CSTEM), hosts five undergraduate BS programs: Industrial Engineering (IE), Mechatronics Engineering (ME), Civil Engineering (CE), Civil Engineering Technology (CET), and Construction Management (CM), as well as two MS programs, one in Mechatronics Engineering (MSME) and one in Industrial and Systems Engineering (MSISE). The series of projects described here (a multiyear theme on UAVs) includes mostly students from the ME and the MSME.

The four-year Bachelor of Science in Mechatronics Engineering (BSME) program includes 3 semester credit-hours of technical electives (this may include research and/or independent studies courses), the Senior Seminar course for 2 credits, and the capstone, Engineering Design Project for 3 credits, where the Senior Seminar and the Engineering Design Project are offered in the Fall and Spring semesters of the senior year, respectfully. These courses present an environment conducive to multiyear design/research projects. Specifically, the technical elective hours can be split in ½ hour increments per semester allowing students to be involved in research/design continuously for 3 years. In the fourth year, the Senior Seminar and the Senior Design Project allow continuous engagement of students in multiyear projects.

It is worth mentioning the 3+2 Program offered at CSUP where, after completion, students receive simultaneous BS and MS degrees in ME. Namely, for tuition and other funding purposes, students enrolled in the 3+2 Program are treated as undergraduate students, and thus they are eligible for funding as they work on multiyear projects with undergraduate students.

Note that the project described here does not entirely fit the VIP Program definition from the VIP Consortium [15]. Namely, students may take research credits which are graded S/U. If they take these credits as Independent Study, then they are graded A-F. Also, Senior Seminar is graded S/U while Senior Design Project is graded A-F. So, there is a mix of grading types that was agreed upon by the program faculty.

Moreover, stipends to fund participating students are secured through grants. About $2000 per student team for a senior design project is allocated from the School of Engineering. Through the years, funding for student participation and hardware was provided by various grants. Colorado-Wyoming Alliance for Minority Participation (CO-WY AMP), Communities to Build Active Stem Engagement (CBASE), and Mentoring Access and Platforms in STEM (MAPS) grants were the main sources of funding. The CO-WY AMP Grant (active) emphasizes undergraduate research as a retention and graduation tool in STEM disciplines. The CBASE Grant (inactive) offered five prominent undergraduate research programs to enhance the retention and program completion rates of Hispanic, low-income, and minority students. The building of Research Communities (RCs) through multiyear student research experiences is a particularly interesting segment of this grant. The MAPS Program, funded by the Department of Education, expands on RCs to include student internships and continuous summer research support for both students and faculty mentors. It provides paid research experiences for students both on-campus and in the community.

Students are selected based on the quality of their applications, and then assigned to work on one of the available projects based, in part, on their preferences. For this, the participating faculty provide a list of projects. When assigning students to a project, faculty try to place new students with the students that are already working on a project, sometimes even involving graduate students.

Undergraduate research activities commence in October of each year and continue throughout summer. After an initial meeting of all students involved with MAPS, the students are divided into programs where they meet with their project mentors (program faculty). At that meeting, students are assigned to projects and mentors. In the ME program, faculty decided to implement a group mentoring model. Specifically, each project team meets once with their lead mentor at the beginning of each week, and then, at the end of each week, all program participants meet with all mentors in a larger meeting. This meeting is modeled to resemble company business meetings in industry. Here, each student prepares a one-page report that includes the work done, time spent on the project that week, total time spent on the project so far, and the plan for the next week. Reports are sent to all faculty mentors at least 1 hour before the meeting. At the meeting, one representative of each project gives a short verbal report addressing problems, breakthroughs, and the state of the project. The faculty found this format to be successful because students get to know all the program faculty since they are all engaged with all program projects. In addition, the same format is adhered to in the Senior Design Project course. Furthermore, all student participants are required to present posters and PowerPoint presentations at university-wide STEM research symposia that are organized every semester.

Project History

The eVTOL UAV project theme started in 2014 when a student decided to create his own 3D-printed UAV. Since the engineering department already had an established 3D printing lab with six Fused Filament Fabrication (FFF) 3D printers and a substantial amount of ABS filament, the student was encouraged to proceed. With the positive experience from this project, in 2016, a larger octocopter kit (over 1 m in diameter) was purchased and equipped with a mechanism for handling small packages weighing under 4.5kg. Then, additional novel applications (spray painting and wildfire fighting) with similar UAVs were proposed and designed. Finally, a larger octocopter (about 2.64 m in diameter) for carrying cargo was created from scratch. This UAV was designed to carry a payload of up to 200 kg for about 20 minutes. After carrying cargo, the UAV was modified to be a rescue UAV able to carry a person. The future goal of this project is to design a personal air vehicle (PAV) capable of providing personal transportation over short distances either piloting manually or following a prescribed route autonomously. Finally, improvements to the UAV’s landing gear were designed and implemented in MS thesis research.

In 2014, a small (about 60 cm diameter) quadcopter frame was designed, 3D printed, and tested as a part of a graduate intelligent robotics course. The created UAV was able to fly and hover as commanded by a remote controller. Fig. 1 shows the UAV frame.

Fig. 1. An early 3D printed quadcopter frame design using ABS plastic

Later in 2016, based on the previous experiences with a 3D printed quadcopter, a commercially available larger octocopter UAV kit was purchased, assembled, and then equipped with a device capable of holding and dropping small packages. The justification for using an octocopter was the increased system safety in flight. In general, octocopters can safely land after a failure of one of the eight motors, and in some special cases they can safely land even after losing power to two motors. With a large increase in e-commerce, the last mile transportation of goods using UAVs may soon become a commercially feasible solution, especially in high-density human environments. The octocopter addressed in this senior project promised to solve that problem. It used the A2 Flight Controller and S1000 Chassis by DJI. It could lift packages up to ten pounds and deliver them autonomously to locations within a two-mile radius. To achieve this, an electrically controlled payload handling mechanism was designed and built using an FFF 3D printer. The mechanism was controlled by an Arduino microcontroller with a GPS shield. Apart from the manual controls via a Remote Control (RC) transmitter and an RC receiver, an autopilot software called Ground Station connected wirelessly to the octocopter via a Bluetooth Datalink, also made by DJI, enabled autonomous flight. However, the autopilot software could only run on Apple tablets and phones. Fig. 2 shows the octocopter used in a package delivery application in a Ready to Fly (RTF) configuration. Fig. 3 shows the octocopter flying above the campus.

Fig. 2. RTF octocopter designed for package delivery

Fig. 3. Octocopter flying autonomously under Ground Station mission control commands

In 2019, a tall building firefighting UAV was considered. The requirement was that the UAV takes a fire hose to the window where the fire was. However, this presented a huge challenge to the UAV's carrying capacity and control. Thus, the project was changed to a spray-painting UAV. A smaller quadcopter UAV was designed and built. The UAS included the frame, motors, an Arduino board, sensors (magnetometers, accelerometers, and a gyroscope), an R8EF 8-channel receiver, and a servo motor to operate the spray bottle. Free Arduino software package MultiWii was used for ease of programming. Fig. 4 depicts the spray-painting UAV quadcopter with a spray-paint bottle attached.

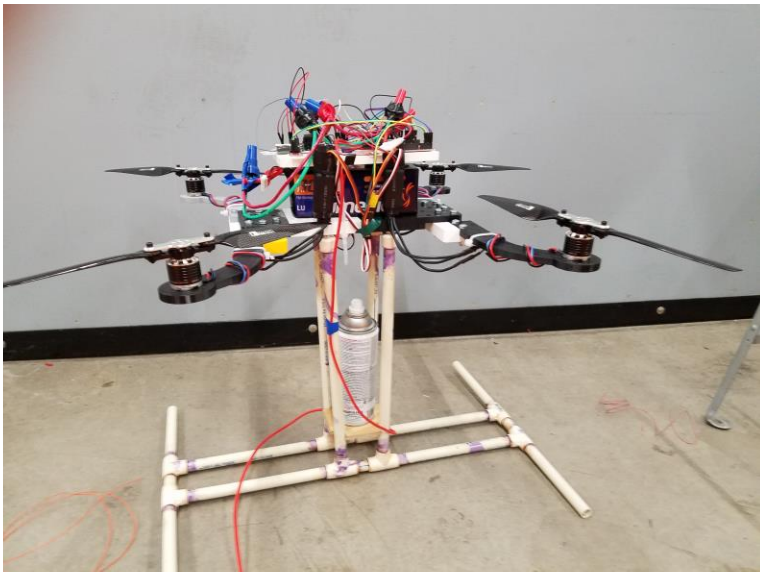

Fig. 4. 2019 Spray-painting UAV

In 2019, a design of a large octocopter UAV started as a multiyear undergraduate research project. The first goal was to design a UAV capable of carrying a payload of about 200 kg. The UAV was developed from basic principles. It was designed and simulated in SolidWorks, and then built using Aluminum T6061. The eight arms of the octocopter were vertically displaced to reduce its size. The propellers overlap 13%. Fig. 5 shows one version of the octocopter with extra weights ready for testing on an indoor sports field, while Fig. 6 shows tilting of the UAV during takeoff.

Fig. 5. Octocopter with overlapping propellers

Fig. 6. Octocopter tilting during takeoff indoors

Refinements to the basic design of the octocopter continued through MAPS undergraduate research, a senior design project in 2022, and MS thesis research. Currently, the graduate student that was the lead on the project through his MS thesis is training other undergraduate students in running the tests and performing tuning procedures.

Simultaneously with the large octocopter project, in 2021, and along the same lines as the package delivery UAV, a wildfire fighting UAV was developed. Here, a Vulcan hexacopter UAV was selected for the frame, motors, and Electronic Speed Controllers (ESCs). The UAS consists of a Vulcan UAV hexacopter frame with six motors and six ESCs controlled by a Pixhawk 4 autopilot flight controller with QGroundControl software. A Raspberry Pi 4 Single Board Computer (SBC) and a camera were added to control the fire suppressant system. The fire suppressant that was used in the prototype was an Auto Fire Off (AFO) ball. This is an approximately three-pound, 5.5-inch diameter ball that ruptures when exposed to fire thus releasing fire suppressant rated for all classes of fires. The prototype of the drone was successfully tested and was able to fly autonomously, with the fire suppressant system able to release the payload upon recognition of a fire. Fig. 7 shows the wildfire fighting UAV while Fig. 8 shows the fire suppressant system design.

Fig. 7. 2021 Wildfire fighting UAV

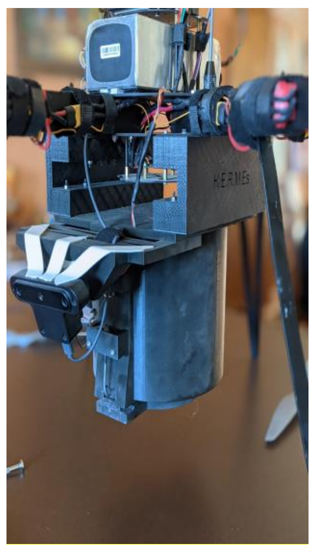

Fig. 8. Fire Suppressant System Design

Metrics and Results

While it is hard to judge the scientific/engineering success of the multiyear design projects, it is relatively easy to provide metrics and results justifying the support for such projects. The assessment metrics are retention rates, graduation rates, and success in completing graduate programs. The University's first-to-second year retention rate is 68%, second-to-third year retention rate is 90%, while the 6-year graduation rate is 38%.

Table 1 shows the number of students involved, the degrees attained, and student contributions/reporting. It should be noted that the table does not show the total number of students involved since some of the students continued with the project for more than one year.

Table 1. eVTOL themed VIP history

Year	No. of Students	Student Status			Contribution/Reporting
		Continuing	BS	MS	
2014	1			1	Report and Video
2016	2		2		Senior Project Report, Presentation, Poster
2017	0				
2018	2	2			Poster
2019	4	1	3		Senior Project Report, Presentation, Poster
2020	5	5			Virtual Presentation
2021	6	1	5		Senior Project Report, Presentation
2022	6	1	2	3	Poster
2023	4	1		3	MS Thesis, Presentation, Poster, Grant Application

Through the years, the students involved in these VIPs became leaders and mentors to new students. Student retention results due to student involvement in these projects show great success. Specifically, all 20 students involved in the described VIP were successful. They are either still enrolled, or they have graduated. Four students (20%) finished their MS degrees through the 3+2 Program. Based on the octocopter project, one of the students wrote an MS thesis titled "Tuning of Rate Controller Parameters and Landing Gear Design for an Octocopter with Overlapping Propellers." One student transferred to another university and is finishing his MS degree in quantum engineering. However, one first-year student changed his major from ME to game design. He is still enrolled. In conclusion, multiyear engineering project themes work well as retention tools, as graduation tools, and as inspirations for education beyond bachelor's degrees. Explicitly, the students involved with this VIP showed 100% retention and graduation rates with a high percentage of the students (20%) continuing to graduate studies.

While highly successful, this eVTOL VIP theme also presented several challenges. Some common challenges like project space availability, access, teamwork, scheduling of weekly meetings, etc. were dealt with as with any other project. However, there were some unique challenges for eVTOLs. Since the CSUP campus is within a five miles radius from the Pueblo Airport, a special permission to fly was required each time an eVTOL was launched on campus. In addition, the large octocopter was not even allowed to fly due to FAA regulations. For this reason, test flights of this eVTOL were performed on an indoor sports field. This required installation of a GPS repeater to enable the eVTOL to obtain accurate GPS data. Also, the octocopter was too large to fit through the double door of the lab, so it had to be disassembled/assembled for each test flight. Finally, as the FAA regulations changed, the eVTOL team had to have at least one commercial drone pilot during test flights. One faculty member and one student passed the test for the commercial drone pilot license. However, this requirement creates another challenge for project continuity.

Summary and Future Work

In this work, a set of related VIPs (building and using eVTOL UAVs) are described. Students were involved in projects like UAV package delivery, spray painting, wildfire fighting, and rescue operations. Students engaged in undergraduate multiyear vertically integrated research/design projects with their peers and mentors. Student engagement increased students' retention and graduation rates, as well as attraction to graduate studies. While this VIP worked exceptionally well with a small number of students and the mentoring approach described, it would be interesting to investigate the limits of scalability of this educational technique.

Acknowledgment

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