Self-Designed Drone as a Platform for Engineering Education

Andrew Aquino, Bobby Tang, Utsav Shah, Daniel Khodos Mechatronics Engineering,
Vaughn College of Aeronautics and Technology, NY, USA, andrew.aquino@vaughn.edu, bobby.tang@vaughn.edu, utsav.shah@vaughn.edu, daniel.khodos@vaughn.edu

Mentor: Shouling He, Ph.D., Amir Elzawawy, Ph.D., Hossein Rahemi, Ph.D.
Vaughn College of Aeronautics and Technology, NY, USA, shouling.he@vaughn.edu, amir.elzawawy@vaughn.edu, hossein.rahemi@vaughn.edu

Abstract – This paper describes an educational approach that uses the development of a drone system as a teaching and learning platform to introduce engineering concepts, which includes the explanation of working principles of components to build a drone, computer aid design and 3D printing the drone frame, software and control algorithm development, as well as system integration design. The primary targeted learners are students of STEM in middle and high schools as well as drone hobbyists who are interested in systems and engineering designs. The designed approach has been used to teach students and drone hobbyists through several workshops on International Drone Day and Manufacturing Day; events held at Vaughn College of Aeronautics and Technology. The workshop assessment results demonstrate great promise not only in terms of improved learning in designing of a drone among middle and high school students and hobbyists, but also a valuable experience for the Vaughn College UAV (Unmanned Aerial Vehicle) club members to develop the educational hardware and software platform for experimentation and education in flying robots, graphics design and animation, as well as developing an algorithm for a UAV control system.

Keywords – drone, component & system designs, workshops, UAV.

I. INTRODUCTION

The dramatic progress in engineering and technology over the past decades has motivated researches and educators to explore more efficient and effective ways of education in various areas of engineering to prepare the future workforce. In recent years, applying drones (or UAVs) for engineering education is becoming popular. According to the reported documents, drones have been used for the improvement of the quantitative research [1] and undergraduate education [2][3]. In particular, drones have been recommended as an excellent platform for capstone degree projects [4][5] as well as active learning [6].

This paper presents the outcomes of such a project that aims for engineering education for middle/high school students and drone hobbyists through designing and building a drone. Unlike a small ground robot, a drone is a relatively sophisticated mechatronics system since it requires autopilot technology, coupled with sensors, actuators and control surfaces. In addition, it has much more constraints in the design of a frame, the selection of motors, electronic speed control (ESC), propellers, an on-board controller, and a battery. However, through the practice of the design process, i.e. understanding the working principles of components of a drone, designing a drone frame via a computer aid design (CAD) software, soldering the circuit board and assembling the parts together and learning the control algorithm programmed and downloaded onto the on-board microcontroller to stabilize a hovering drone, a person can substantially envision how an engineer applies the knowledge from mechanical, electrical, computer and control engineering to solve a problem in the real world. Due to its nature to cover a wide range of disciplines and concepts relevant to different engineering areas, a drone can be considered as an excellent platform for engineering education.

The workshops to design and build a drone have been held at Vaughn College of Aeronautics and Technology twice. The UAV club members are working as mentors to bring the knowledge to the workshops. The first workshop was separated into several sections with different well-planned section schedules up to 1-2 hours. Through organizing the workshop, the UAV club students increased professional knowledge and improved communication skills by teaching the relevant materials. At the same time, it created the increased motivation and understanding of engineering and engineering design process for middle/high school students and drone hobbyists.

In this paper, we present the essential aspects to design and build a drone as well as how the workshops were held for middle/high students and drone hobbyists. The paper will be organized as follows: in Section II, the drone system components and the system level design are discussed. Section III describes the frame design using a CAD software and the control algorithm development for the designed hardware system and implementation. Section IV depicts the workshops held at Vaughn College and discusses the survey obtained from a workshop.

II. Drone Components and Design Aspects

A. System Components and Working Principles

Many components are needed to be selected and designed to build a drone. The range is from brushless motors, electronic speed controllers (ESCs) to a flight controller. All components must work in coordination to create a functional flight system.

The most commonly built drones use direct current brushless electric motors instead of direct current brushed motors [7]. As shown in Figure I, a brushless motor does not use brushes or commutators. Instead, brushless motors use a small circuit that coordinates the energy delivery to the windings. As a result, the electronics communicate directly with the stationary windings, and the motor will adjust according to the task.

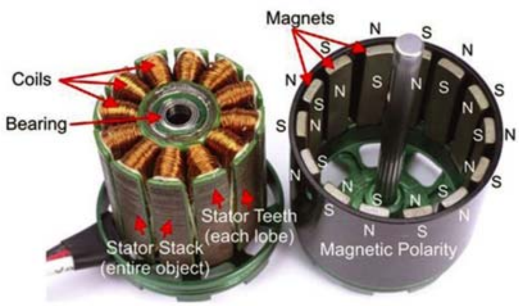

FIGURE I
MAIN COMPONENTS OF A BRUSHLESS MOTOR

In deciding on the specific type of motors for the quadcopter under design, several factors must be accounted for. Normally, the brushless motors come with a description, "2206 2300KV Brushless Motors." The first four digits refer to the motor diameter and height in millimeters. The four-digit code is essential in choosing motors to fit the designed drone frame. As the diameter and height increase, the size of the drone frame will increase as well. The three to four digits followed by "KV" refers to the revolutions per minute (RPM) per volt. This value describes the RPM of the motor for every volt applied. In the case of the drone a brushless motor with a higher KV rating provides less thrust, but more speed and agility. Thus, the drone will be more sensitive and responsive to inputs and commands. A lower KV rating brushless motor provides more stability and less battery consumption, but lacks in speed.

It is important that the data sheet be with the selected motors since it provides valuable information in deciding the maximum weight of the drone system and the thrust of different propellers to be used.

The electronic speed controllers (ESC) is an important component in controlling the speed of the motors. In general, an ESC has three sets of wiring, as shown in Figure II. On one side of the ESC, there are two wires (one black and one red) and a receiver cable. The purpose of the receiver cable is to connect with the flight controller. On the other side of the ESC, there are three wires [8]. The three wires perform the same function and make the motor work as an Alternating Current system. A feature seen inside speed controllers is the usage of Battery Elimination Circuit (BEC) which supplies power to the radio receiver and the flight controller. The BEC feature eliminates the need of a separate power source to power the components.

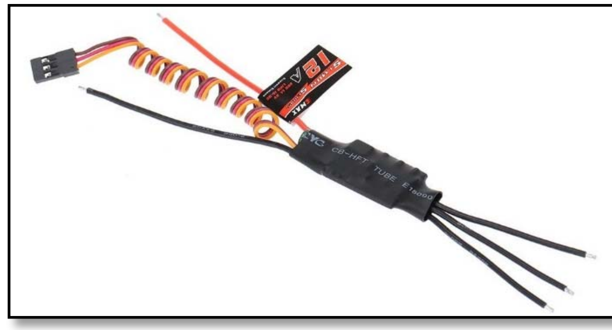

FIGURE II
ELECTRONIC SPEED CONTROLLER

To choose the correct ESCs for the brushless motors, the most important specifications are current rating, voltage rating, and the BEC feature. A vital rule to choose a speed controller is its current rating must be more than 1.5 times that of the brushless motors. If a motor is pulling more current than a speed controller can provide, the speed controller will be damaged and destroyed. Besides the current rating and battery rating of the ESCs must match those of the brushless motors. By selecting matching battery rated components, the drone can fly more efficiently and save more power.

The flight controller, which regulates the movement and actions of a drone, functions as the brain for the drone. The controller is a circuit board that generates the motor speed based on gathered sensory data and user commands. Depending on the command received, the flight controller in general consists of basic sensors such as gyroscopes and 3-axis accelerometers. A more advanced flight controller can also have barometers, magnetometers, and global positioning systems (GPS) [9].

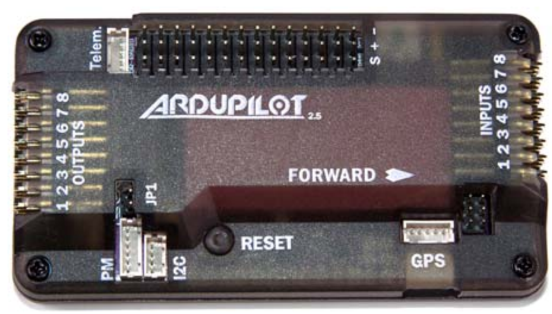

FIGURE III
ARDU-PILOT MEGA(APM) 2.8 FLIGHT CONTROLLER

A large range of different flight controllers is available in the market. However, the flight controller needs to be chosen based on the application of the drone. In general, a Naze32 or CC3D is selected for racing and free style drones. Simply because they are easy to calibrate and use; they are the perfect flight controllers for the beginners. To build a drone with high stability and autonomous capability, the most commonly used flight controller is Ardupilot Mega (APM) (See Figure III). The APM flight controller is more suitable for autonomous and stable flight since it can be programmed to follow waypoints or fly autonomously following an autonomous program.

A power distribution board (PDB), as shown in Figure IV, plays a crucial role in supplying steady power from a battery to speed controllers and motors. The PDB board can provide a safe and neat way of connecting the battery to the ESCs of a drone. It generally consists of positive and negative terminals used to connect the ESCs and the battery. Normally, it is important to find a PDB board that will be able to fit neatly into the drone [11].

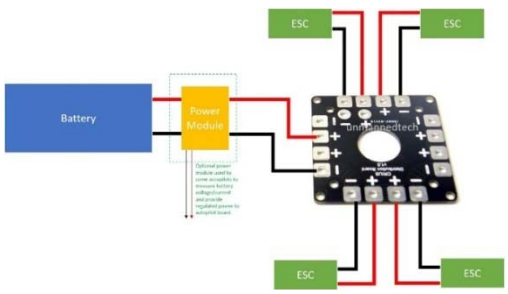

FIGURE IV
DIAGRAM OF POWER DISTRIBUTION CIRCUIT TO BATTERY

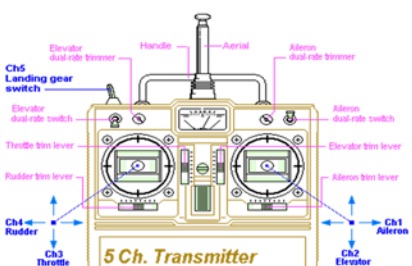

FIGURE V
DIAGRAM OF RADIO TRANSMITTER

The radio transmitter is a remote control that sends signals to the receiver on a drone depending on the inputs provided by the user. The receiver on the other hand is a module on the drone that receives signals from the transmitter and relays the information to the flight controller. A common transmitter has four to six channels with four of them moving proportionally to the movements of the control sticks. These four channels control the Throttle, Aileron, Pitch, and Yaw of the drone, respectively. The remaining channels function like a switch and are used to actuate certain components or perform certain pre-programmed actions such as landing [12].

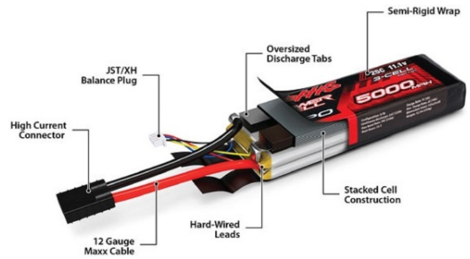

FIGURE VI
A 3 CELL (3S) LITHIUM POLYMER (LIPO) BATTERY

The most commonly used type of battery for a drone is Lithium Polymer (LiPo) battery [13]. LiPo batteries provide longer flight times and high power. Compared to other types of RC batteries, LiPo batteries weigh lighter, offer higher capacities with a higher discharge rate.

To select the correct battery for a drone, the battery rating of electrical components must be considered. It is imperative that a higher rated battery should never be plugged into an incompatible component. The capacity is usually stated similar to "1500 mAh" and influences the weight of the battery as well as the flight time of the drone. The higher the capacity of the battery is, the more flight time the drone has, but weighs more. For smaller drones, it is essential to select a battery that does not weigh too much, but provides a proper flight time.

The last component needed in building a drone is the propellers. Propellers are usually made in plastic or carbon fiber material. To choose the correct propeller for a drone, two dimensions should be considered. The first dimension is the size of the propeller and the second one is the pitch of the propeller. These dimensions are usually given by the description, "5030 Propellers." The 50 in this case, states the dimension of the propeller is 5 inches. The last two digits of the description indicate the pitch of the propeller [14]. For the drone to stay in the air, there should be an equal division of clockwise (CW) and counter-clockwise (CCW) propellers. Figure VII shows a pair of GEMFAN plastic properllers.

FIGURE VII
GEMFAN 5030 PLASTIC PROPELLER

The pitch of the propeller refers to the traveling distance for a single revolution of the propeller. A lower pitch propeller generates more torque for lift. On the other hand, a higher pitch propeller can displace a greater amount of air, but cause more turbulence and produce less torque. The size of the diameter also influences the effect of the drone. A larger propeller takes more effort to change the speed. Thus, the drone is less responsive, but more stable when hovering. A smaller propeller requires less effort to change the speed which creates a more responsive drone, but is less stable.

Motor	Sunnysky X2204S
KV number	2300
LiPo	3S 1300 mah 25C
Propeller	5030 Gemfan ABS
Peak thrust	423 gram

Thrust	Voltage	Ampère	Watt	RPM
100 gram	12,03	1,1	13,23	10.022
150 gram	11,94	1,9	22,69	12.591
200 gram	11,85	2,8	33,18	15.085
250 gram	11,77	3,8	44,73	16.851
300 gram	11,69	5	58,45	18.617
350 gram	11,66	6,1	71,13	20.125
400 gram	11,73	7,3	85,63	21.394
423 gram	11,92	8,1	96,55	22.162

FIGURE VIII
MOTOR RPM VERSUS THRUST GENERATED

B. System Weights and Force Analysis

In the system design, a critical factor to be considered is the overall weight of the aerial vehicle. The motor data sheets provide valuable information including the thrust that a motor can produce with a specific type of propeller. The thrust produced by one motor should be multiplied by the number of motors installed on the drone. The resulting value is the maximum thrust that the drone can weigh. In performing system and force analysis, it is crucial to ensure that the total thrust of the motors is at least double the total weight of the drone. In table I, a quadcopter was designed with all the necessary components including a frame and propeller guards. The total weight of the drone was calculated to be 529.92 grams.

TABLE I
SYSTEM DESIGN OF A DRONE

Item	Unit Weight (g)	Quantity	Total Weight (g)
Brushless Motors	21	4	84
Brushless ESC	22.6	4	90.72
Naze32 Flight Controller	4.5	1	4.5
Power Distribution Board	5.7	1	5.7
3S Lipo Battery 1400mah	115	1	115
5045 Propellers	2	4	8
3D Printed Drone Frame	130	1	130
Propeller Guards	23	4	92
Total Weight: 529.92 grams			

The motor datasheet provides the information about the efficiency of the motors and the amount of weight the motors can handle. From the data sheet shown in Figure VIII, it can be seen that each motor is able to produce 423 grams of thrust with a 5030 propeller. In total, the motors produce a thrust of 1,692 grams. From the analysis, it can be seen that the motors is able to produce a thrust that is triple the weight of the drone.

C. System Cost Analysis and Summary

TABLE II
COST ANALYSIS OF A DESIGNED DRONE SYSTEM

Item	Price	Quantity	Total
Drone Components			
SunnySky X2204 2300KV Brushless Motors	$9.99	4	$39.96
Emax SimonK 12A Brushless ESC	$5.49	4	$21.98
CycleMore AfroFlight Naze32 Flight Controller	$19.49	1	$19.49
KK MultiCopter Quadcopter ESC Power Battery	$7.99	1	$7.99
Total: $89.32			
External Equipment and Accessories			
Turnigy 2200mAh Lipo Battery	$15.98	1	$15.98
FS-I6 2.4GHz 6CH Radio System	$49.99	1	$49.99
5030 Propellers (1 Set)	$5.00	1	$5.00
Total: $70.97			
Overall Total: $160.29			

Some of the components required to build a drone need to be purchased. The components that were purchased from a vendor is shown in Table II.

The total cost of all the components required for the quadcopter was $89.32. It is worth to note here that the battery is considered as an accessory as it does not remain permanently on the drone and more than one can be bought. Similarly, the transmitter and receiver are used by the pilot to operate the drone. In general, a single transmitter is able to bind with multiple different drones. This eliminates the need to buy one transmitter for one drone. In Table II, it was listed that one set of propeller was required for a drone. Due to the weakness of propellers and the force of impacts or falls during testing, it is advised that spare sets should be purchased. The external accessories and equipment will cost a total of $70.97. Thus, a drone being built from start to finish will cost a total of $160.29 with each drone afterwards costing $89.32.

III. DRONE COMPONENT DESIGN AND CONTROL ALGORITHM DEVELOPMENT

A. Frame Design using CATIA Design Tool

When designing a drone, symmetry plays a critical role in stability. The arms of the drone should be equidistant in all directions essentially creating a square with the corners being the center points of the motors. Each component should be measured and a layout be mapped out to ensure housing of all components and promote uniform weight distribution. All designs should revolve around the chosen components.

A CAD software is needed to design a 3D printable frame that will fit in the allowable print plate area of the available 3D printer. For the design presented in this paper, Dassault Systems CATIA was used as the CAD software and Makerbot 5th Gen was used as the 3D printer [15]. Other CAD software's include Solid Works, Autodesk Inventor, and Autodesk Fusion 360. Figure IX shows the CATIA Assembly of the designed drone frame. For use in a class environment, Autodesk Fusion 360 is suggested because of its availability and ease of use for the beginning designer.

The base structure should begin with a cross with equal length arms. All other features should be designed around that structure. Assuming the use of the advised 5030 propellers, an allowance of 5.5in between the motor mounts is required generating a diagonal length of at least 7.75in. This is to assure that not only will the propellers not come in contact with one another but also that the air currents generated from the thrust of the propellers will not interfere with each other.

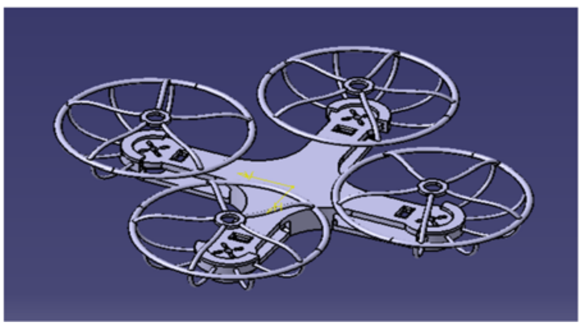

FIGURE IX
CATIA RENDERING OF DESIGNED DRONE FRAME

For the motor mounts, it is important that the holes are designed properly. The center hole should be approximately 6mm in diameter to allow the bottom end of the motor shaft rotate without obstruction. It is beneficial that the motor holes be elongated to allow for varying motors with different locations of the motor mount holes.

The motor mounts connected to the arms with the most minimal area covered by the propeller area. The airflow created by the propellers should hit the smallest area of the frame to reduce the thrust hitting the frame and reduce back flow of air which may cause instability.

Depending on the material and quality of the 3D printer, structural strength and stability is key to stable flight as vibrations may interfere with gyroscope readings. The strength of the material is important to the integrity and durability of the frame through multiple impacts during test flights. Figure X shows the fully printed drone frame.

FIGURE X
FINAL DRONE SYSTEM AFTER ASSEMBLY

Fundamental stress analysis may be conducted through hand calculations or through the CAD software itself. This step although not necessary may reduce the number of alterations to the frame design that need to be made through trial and error.

One such stress may occur due to pilot error. To withstand such impacts the material used plays an important role. Using an IZOD impact test, the impact strength of PLA and ABS plastic can be determined.

Impact (Un-notched IZOD)

ASTM D256

PLA		ABS	
STD	1.8	5.7	STD
MAX	4.1	6.2	MAX

Impact Strength in ft-lb/in

FIGURE XI
IMPACT STRENGTH IN PLA AND ABS PLASTIC

Under standard resolution and infill the necessary thickness of the frame can be determined using the following equation,

$$Thinkness = \frac{Impact\ Energy}{Impact\ Strength} \quad (1)$$

The impact energy is determined by

$$E = \frac{1}{2}mv^2 \quad (2)$$

where m is mass and v is velocity. Unit conversions are necessary depending on if SI or English units are used. Assume an average impact speed of 10 mph. Mass may be determined through the 3D printing software (The amount of material to be used).

B. Control Algorithm Development

A quad-copter is stabilized by the flight controller which is considered as the brain of the quad-copter. There are several sensors on the flight controller to measure the position, angle and velocity of the drone in the air. The sensors can include a gyroscope, an accelerometer, a magnetometer and a barometer. However, most of the basic flight controllers only have a gyroscope and an accelerometer. Three Euler angles, roll, pitch, and yaw, are used as follows: roll controls turning left and right about a horizontal axis, pitch controls the forward and backward movements and yaw controls the rotation of the quadcopter. A gyroscope sends the angular position information to the flight controller. Accelerometer sends the acceleration data to the flight controller about the speed of a drone along each axis.

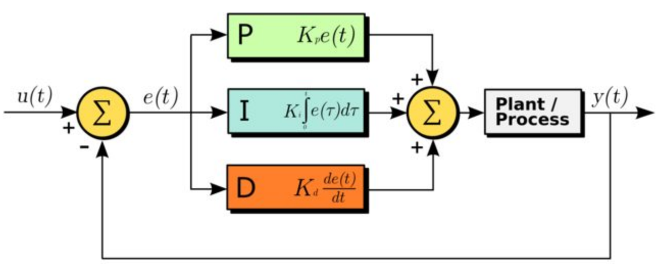

FIGURE XII
DIAGRAM FOR PID CONTROL ALGORITHM

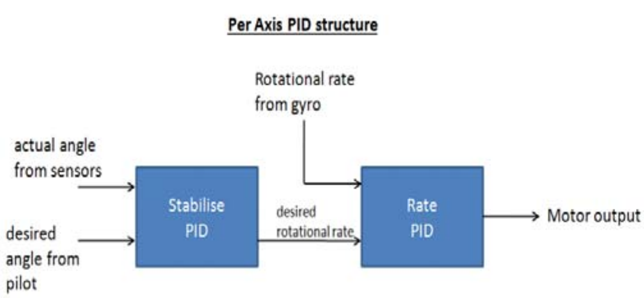

FIGURE XIII
PID CONTROL DATASHEET FOR SUNNYSKY 2204 2300KV BRUSHLESS MOTORS

Flight controller processes all raw data from the sensors and generates command signals to control the motors using a control algorithm. The algorithm includes calculating the error between the desired value and measured value and then computing the proportional, integral and derivative values of the error, which is normally called as a PID regulation, and altering the speed of the motors to compensate for any differences and maintain balances. For the PID regulation, P (proportional) value is the error at the present state, I (integral) is the value accumulated based off the past errors and D (derivative) is the prediction of the future errors. Therefore, when a signal (the desired value) is sent from the transmitter via the receiver to the flight controller, the flight controller calculates the error between the measurements from current sensors and the given values and then develop a command signal to control the motors to eliminate the error momentarily.

There are several programs that allow users to change the sensitivity of the flight controller like Clean Flight, Base Flight, Libre Pilot, and a few more.

IV. DRONE WORKSHOPS FOR COMMUNITIES

A. Organization of Workshops

FIGURE XIV
INTERNATIONAL DRONE DAY ANNOUNCEMENT FLYER

The Vaughn College UAV Club partnered with the college to host workshops for the community. The purpose of these workshops is to provide an insight on how drones are designed and how they are implemented and operated. On May 7, 2016, the college hosted International Drone Day, which was opened to the public. Vaughn College was the only college in New York City to host International Drone Day. International Drone Day is celebrated worldwide and it is a day where drone enthusiasts come together to promote the usage of drones across the world. Therefore, it is not only a day where people can come and fly their drones, but also a day that the drone community can show various potential applications of drones, such as in educational, recreational, and medical areas.

The UAV club at Vaughn hosted three sections in the workshop during International Drone Day. The first section focused on teaching participants how to build a quad-copter drone as well as how to solder parts together. This section had a systematic tutorial on the parts needed to build a drone and assembling them. After the presentation, the participants soldered a light-emitting diode (LED) on a blank circuit board to achieve some knowledge of soldering. The second section of the workshop emphasized on programming an Arduino microcontroller in C++. Participants used the circuits from the previous section to connect to an Arduino Uno microcontroller, and then programmed the LED to light it up. Since an Arduino can be configured as a flight controller, this section introduced the main features of it. The third section showed participants how to make a drone frame using the CAD software, CATIA. This section addressed on teaching people to design a quad-copter frame and making it using a 3D printer. The section helped participants gain fundamental knowledge of CAD design and its applications.

The second workshop was held at Vaughn College during the Manufacturing Day on October 29, 2016, in which the school celebrates modern manufacturing to inspire the new generation of creators. The students from several high schools were invited to join the event. This workshop focused more on showing the students on how a drone operates, for example, introducing the working principles of main components of a drone, and then demonstrating them how to design and build a drone. Two critical components, the electronic speed controller (ESC) and the brushless motor, were discussed in detail.

In the workshop, the high school students created a simple configuration of ESC, a brushless motor and propeller. A potentiometer was used to act as an ESC, a basic brush DC motor was used to act as a brushless one, and AA batteries were used as a power source. High school students had to solder the DC motor wires to the potentiometer and then solder the AA battery holder to the power and ground wires on the motor. When the AA batteries were placed in the battery holder, the motor started to spin and the speed of the motor was controlled by the potentiometer. This workshop not only taught high school students how to solder but taught them the important relationship between the electronic speed controller and the brushless motor on a drone.

FIGURE XV
MANUFACTURING DAY WORKSHOP

The workshops made the UAV club members at Vaughn realize that engineering and engineering concepts can be taught through designing and building a drone. Not only do the workshop attendees learned engineering designs behind drones but they also obtained hands on experience. Exposing these drone workshops to young students is a successful approach for high school students to learn about engineering.

B. Survey and Analysis

At the end of the Manufacturing Day workshop, high school students were asked to complete a survey which included questions about their experiences in the workshop. The survey questions are listed as follows:

1. The workshop gives me the information about drones and their applications.
2. I know what the components of a quadcopter are and their functions.
3. I understand the relationship between the flight controller, ESCs, and motors.
4. The workshop helped me understand the compatibility of different components of a drone such as motors, ESCs, flight controllers, and batteries.
5. I can select the parts to build my own drone.
6. I feel confident in assembling my own drone from scratch.
7. I understand the basics of soldering.
8. I understand the safety requirements of operating and building drones.
9. I understand the applications and uses of drones in the world.
10. The workshop provided me a lot of hands-om learning experiences.

TABLE III
SURVEY RESULT

Questions	Strong Disagree/ Disagree	Neutral	Agree/ Strong Agree
1	0%	0%	100%
2	0%	17%	83%
3	0%	0%	100%
4	0%	11%	89%
5	0%	39%	61%
6	11%	44%	45%
7	0%	5%	95%
8	0%	5%	95%
9	0%	0%	95%
10	0%	0%	100%

The survey results are very satisfactory. All attendees were so excited about the information of drones and hands-on experiences they have gained from the workshop. Particularly, 100% of people showed their understanding of the relationship between the flight controller, ESCs, and motors by the demonstration and practical exercises, which is essential in designing a quad-copter. However, some issues can be improved in the future. Firstly, since the workshop was spent on teaching the students the relationship between drone components, the attendees didn't have enough time to be exposed to the process of assembling a drone. Therefore, the experiences of assembling a drone had a lower evaluation result as seen in the responses to question six. Future improvements are planned to add additional time to the exercises of assembling a drone. Secondly, selecting the correct drone parts for designing drones needs extensive research and time. This knowledge is also gained through working experiences with drones, which the attendees do not have. A summarized guidance line will be provided to the students so that they can learn by the experiences gained from the UAV club members of the Vaughn College.

V. Conclusion

This paper presented the development of a drone system as teaching and learning platform through workshops hosted at Vaughn College. Through these workshops the principles of the drone components and the design of a drone have been taught to high/middle students and drone hobbyists. These workshops also provided hands-on experience to the students who can implement the lessons that are being taught to them. The survey given to the attendees showed very positive results except for the student's confidence level to build his/her own drone. The future workshops are planned to provide more information on the building process. These series of workshops showed that is can be a great approach to teach students on how to self-design their own drones, which can be a great tool for students to understand engineering concepts and be interested in different engineering fields.

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