Conceptual Design of A Personal Flight Vehicle
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Abstract

The purpose of this E90 project is to develop a conceptual design for an Octocopter personal transportation aircraft. Building on prior knowledge, the student gained relevant mechanical engineering design experience through this project, especially the use of the CAD design tool Autodesk Fusion 360. The result is a pilot-focused aircraft design for short-distance transportation, with a human-integrated control system and user-friendly accessories.
Introduction

Humans have always been interested in flight. From the Wright Brothers testing aircraft to the models we have of Jetpacks today, we can confidently state that flying freely is a treasured goal for many. Currently, there are numerous models of personal flying vehicles in development. Some are created for recreational uses, like the Zapata flying board; some are created for industry use, like the Martin Jetpack for first responders; and some are created for short-distance transportation, like the Kitty Hawk electrical aircraft. The author of this paper wishes to pursue a career as a mechanical engineer in sustainable aeronautics. She has also been a personal aircraft enthusiast from a young age. As such, given the opportunity to design a mechanical system, she chose to design an aircraft for short-distance transportation that included user-focused elements for improved human integration.

Swarthmore College students’ Engineering Design projects aim to satisfy two requirements: a comprehensive culminative activity for the Swarthmore Engineering major, and a design project for the Engineering ABET accreditation. The student completed her E90 project, having satisfied these goals. This report provides an overview of the design process. First, we introduce the inspiration and purpose of the project. Next, we discuss the design and CAD drawing process of the Octocopter. In the results section, we present the CAD drawing. In the discussion, we give the specifications of the aircraft and highlight challenges faced in the design process. Finally, we identify possible future areas of research.

The initial vision was to design and build an aircraft that would fly. Previous work by Billy Yang ’19 in a 2017 summer project sponsored by the Halpern Family Fund outlined a design and afforded physical testing of an electrically-driven propeller system for a personal flying craft. After reading the project report and taking note of the future areas of work identified, the author aimed to create a two-way control system for a multi-copter (likely six to eight propellers) and if time permitted, to build a smaller scale of Billy Yang’s design to test the feasibility of the new control system. COVID-19 interrupted the semester dedicated to fabricating the E90 project design; access to a workspace and shop support staff became unavailable, and the initial project conception was no longer viable. As such, the focus of the project on the control system was immediately adapted to focus on designing a manned multi-copter and showcasing it through CAD software. The final vision is to design a theoretically buildable VTOL Octocopter. Next, we delve into the specifications of the aircraft.
Theory

This section is an overview of the components in this transportation aircraft with focus on user-friendly operations. First, we review the relevant physics concepts considered and the calculations undertaken. Then, the subsystems in the aircraft are outlined—essentially any component that is not the frame. Finally, we consider the “human container” part of the design. Safety is essential for manned aircraft and is considered throughout this section.

The physics concepts and calculations relevant in this design include two types: 1) consideration for the whole aircraft and its ease of movement through the air, and 2) the power source providing lift. The physical components on the aircraft derived from calculations are italicized.

I) For the calculation pertaining to the whole aircraft:

I. Center of Gravity- The location of the center of gravity should remain below the fans at all times for stability. A center of gravity above the axis of the fans would result in an inverse pendulum problem in flight, requiring a sophisticated control system for stabilization. Since the control system is envisioned as more human-integrated, the craft needs to be easily maneuverable in flight, but also stable for safety reasons.

II. The weight- The aircraft needs to weigh as little as possible, while still satisfying structural standards. Billy Yang reported an initial weight vs. strain study of the aluminum arm of his aircraft design. His study on one Aluminum arm beam of 30x1x1 in. showed that his dual-motor hex-copter allows for 81.9kg-force in take-off (803 N). This is within the consideration of the safety requirement of a drone’s maximum take-off weight to be at half its maximum thrust\(^1\). An average adult female weighs about 60kg-force (588 N). For his design, the total frame can only weigh 21.9kg-force (215 N). For an aluminum frame, that is not possible. Studies of other manned aircraft with successful flights such as the Martin Jetpack Series \(^2\), DCL racing craft\(^3\),

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and various homemade recreational manned multi-copters\textsuperscript{4,5,6,7} showed that the aircraft needs to be light, but not the absolute lightest possible. If sufficient thrust is provided by the motors, the weight limit can be lenient. However, the most sustainable aircraft will be one that is most efficient: lighter, so less power would be needed to provide the necessary thrust force. As shown by the Martin Jetpack Series 1, there exist materials in production that can be used for the frame, joints, and components that are very light. \textit{The seatbelt for the person is cloth, and the backboard can be carbon fiber. The arms and the cage are aluminum.}

2) For the calculations pertaining to the power source:

I. Power and thrust- We consider a multi-copter with 8 motors: an Octocopter. Billy Yang performed a study of Thrust versus Power in his report. From his results, we concluded that a dual-fan motor (two counter-rotating propellers on each fan) is not efficient enough to justify the additional weight. Thus, to add power, we will have 8 arms in our design each with one clockwise-rotating fan. For safety considerations, the maximum lift-off weight should be half of the maximum thrust force.

\[ P = Tv \]

\(P\) is the propulsive power in Watts, \(T\) is the thrust provided by the engine in N, and \(v\) is the speed in meters/second. \textit{A U15II KV100 motor}\textsuperscript{8}, combined with the \textit{G40x13.1 propeller}\textsuperscript{9} and operating at 50 V, 171 A, provides 8550 W of power at full throttle, or max thrust of 35.5kg-force (348 N) at 3473 RPM\textsuperscript{10}. Thus with 8 motors, we have 68.4 kW or a max thrust of 28.4 kg-force (2.79 kN). Since the maximum lift-off weight needs to be half of the max thrust force, there is sufficient power for 142kg (1.39 kN) in take-off. If we were to use all the weight allowance, calculations done indicate the motors will provide enough power for a max flight speed of 49 m/s or 176 km/hr, which is not assumed to be desired or reached in flight.


\textsuperscript{10} T-Motor. “U15II KV100”.
2. Power source- Batteries. Figure 1 is taken from the manufacturer’s website for our motor.

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\text{Efficiency } \eta = \frac{P_0}{P_l} = \frac{\tau \omega}{l V}
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Where \( \tau \) is torque, \( w \) is the rotational velocity, \( I \) is the current and \( V \) is the voltage. Figure 1 is taken from the motor manufacturer’s website and includes load testing data for various currents. It also includes efficiency in G/W (grams over watts).

Assuming the craft is flying constantly at 65% of throttle, drawing 60.3A, a battery capacity of 60,000 mAh will allow 59.7 mins of flight time, excluding variations. Such variations include take off, landing, and deviation from a speed of 15.2 m/s or 55k m/hr at this fixed 3015 W power, 20.3kg-force (199 N) thrust. From studies of other battery-powered, manned multi-copters, batteries have been used in the range of 25,000 mAh to 100,000 mAh. Our estimate of 60,000 mAh is reasonable. A specific battery has not been chosen. However, the mass of one Lithium Battery found by Antigravity provides a good estimate of the mass of such a battery system. One battery providing 32,000 mAh and is 2.1kg\(^{11}\). Two of such batteries would be 4.2kg and is included in total payload mass of 142kg.

The specifications of our subsystems are relevant in the design of a user-friendly aircraft. They are also outlined below for help with visualization as some, most notably the electrical systems, are not shown in the CAD file. First, we expand the fan system that provides the thrust

of the craft. This includes the blades, motors, batteries, and Electronic Speed Controllers (ESCs). This subsystem is located at various points in the aircraft. At the extremities of each arm, we have a motor screwed into the frame, and a propeller attached to that. We choose for the design specific blades and motors produced by T-Motor: \textit{U15II KV100 motor} and \textit{G40x13.1 propeller}. At the back of the person cage aircraft, between the backboard and the walls is a \textit{triangular prism cut out} in which we store some electrical components: 8 ESCs and batteries capable of 60,000 mAh. A specific type of ESC has not been considered. Any typical ESC should be able to read the fan speed to the controller, though we are considering the kind with more inputs so we would need a bit fewer electrical components. The manufacturer for our motor and propellers, T-Motor, sells the Flame 200A HV\textsuperscript{12} that is compatible with our motor and propeller.

The second subsystem we will outline is the new feedback system, designed to involve the pilot in maneuvering the aircraft more than most existing aircraft. Current aircrafts implement control systems designed to stabilize the aircraft through computer algorithms. Martin Jetpack optimized its control system so the aircraft can hover in the air while the pilot goes hands-free. Our subsystem aims to integrate the human more in piloting the aircraft. In this system, each finger of the pilot (excluding the thumbs) can control the speed of 1 blade. The controller and transmitter module (\textit{Arduino Nano}) will be close to the person’s hands, and the receiver module (\textit{Arduino Nano} or another Arduino model) will be in the cut-out. There are currently two working models for this system. In both models a built-in electronic control system works as a back-up in case the pilot cannot react quickly enough to large and sudden aircraft swings. The first involves one finger attached to a spring that is then attached to a circuit similar to that shown in figure 2 below. This is an easily buildable mechanical system where one would curl/pull the finger towards the palm to indicate a faster blade speed. A faster blade speed will also result in greater tension in the spring and the finger being pulled on.

The second model for the systems involves a haptics feedback glove, easily makeable with a strip of sensors attached to a glove, where a movement along the finger will indicate a large electrical current and will be read by the Arduino controller module. This would then be sent to the Arduino receiver and the voltage will non-linearly scaled to represent different fan speeds. In reverse, the system has not been considered in its entirety. However, a change in fan speed has to result in a tangible difference felt on the finger. This subsystem aims to integrate the human more, to feel the aircraft more as an extension of the person instead of a casing.

Lastly, we consider the Human container or cage and safety considerations. This craft is designed for short-distance travel (<40km in a single trip). The human cage was designed for comfort. The standing position is a reflection of the fact that this is a transportation craft. With short flight times, a seated position is not needed. This standing position also improves visibility, as the line of sight is not blocked by the propellers. Having part of the torso above the propeller arms may also increase the pleasure of flying, as one can feel less “restriction” from the metal casing. Accessories are currently included in the design, though more should be added. A seatbelt is necessary in case of an accident. It will also help the pilot feel more secure with the pitch and yaw of the aircraft. The parachute is envisioned to be inside the seatbelt. A firm bottom of the craft is also included to help make the user feel more grounded/safer in the air. The two hooks at the two front walls of the craft can hold bags, grocery bags, a backpack, or a briefcase. Lastly, a small screen is attached to the front walls of the cage and will display movement and aircraft information much like a typical dashboard in a car.

The craft “locks” by removing access to the control system when not in use. This means either a lock for the triangular prism component that holds the mechanical feedback system or
bringing the gloves with you in the wireless haptic feedback system. We looked to the Martin Aircraft for safety guidance as it is a company designed craft made for first responders. Safety is the most important aspect of that design and many redundancies were implemented to minimize accidents. Additional safety accessories needed were not considered beyond that stated above and further needs are discussed in the discussion section.

With the above ideas in mind, we set about executing the project. Below we will outline the methods used to realize the project.

Methods

The design for the aircraft was formulated by studying previous models of flying vehicles. Various models were analyzed including ones that do not have the same function or components as the aircraft in question. We did, however, limit the investigation to mainly VTOL vehicles because a multi-copter’s structure is very different from that of a typical non-VTOL aircraft. Models with electrical motors and turbo engines (jetpacks) were studied. Models that were manned and unmanned were studied. Company-sponsored professional industry designs were investigated as well as amateur models.

The design of the aircraft is shown in a CAD model. Using Fusion 360’s top-down design model, we constructed the craft, starting with the human container, proceeding to the arms and the motor and blades attached. Lastly, joints were added, cut-outs were made, and accessories added in. This model is made to the best of the ability of the designer but is not meant to be manufacturable from the CAD file. It is a conceptual design that will need further engineering modeling and testing prior to construction.
Results

Figure 3. First sketch of aircraft. Top view and side view

The Fusion 360 file can be found here: https://a360.co/2RM2sMe

Figure 4. Top-down view of the craft. Front of craft to the right. Person cage in the middle with eight arms, motors, and blades visible.
Figure 5. Side view of the craft. Back of craft to the right. Backboard and seatbelt visible. Cage height visible.

Figure 6. View of the craft from front-right. Door to cage open.
Figure 7. Detail of one motor with blade.
Screws attaching the bottom of the motor to the plates are not shown.

Figure 8. Detail of inside of cage.
Two hooks at the front, and Seatbelt visible.
The dimensions and specification of aircraft are as follow:

The cage in total is 58cm across and 125cm high. The wall, comprised of eight pieces making an octagon, is 3cm thick [imagined to be made of corrugated carbon-fiber board. Each of those sections is 22cm across on the outside and 19.9cm across on the inside. The bottom octagonal standing plate is 10cm high. The backboard is 165cm tall and 0.75cm thick. The cover for the triangular prism compartment is 4cm thick and swings upwards from the attachment to the backboard. When open, the top of the cover touches the back of the backboard. The entire cage structure aside from the seatbelt and the hooks is made of a sturdy but lightweight material. Perhaps corrugated carbon-fiber board.

The eight arms are each 100cm long, from attachment point at the cage to extremity (tip of semi-sphere), and 4cm in diameter. They are attached to the cage at a distance of 10cm from the top edge of the cage to the center of the arm face. The arms are made of Aluminum.

The eight motors are U15II KV80 motors from T-motors. The dimensions are shown below in figure 9. They have a mass of 1.74kg each. They are attached to the arm via screws in plates all with centroid at 4cm from the edge of the cylindrical portion of the arm. The plates themselves come equipped with the motor. The motors have dust preventative and water-resistant capabilities. They also have added cooling capabilities.

The propeller blades are T-motor’s G40x13.1 propeller. They are 40 inches or 101.6 cm in diameter and 13.1 inches or 33.27cm in pitch (height). They screw into the U15 Motor with 4 screws and a cover plate, which are included. They are made of CF + Epoxy. Each has a thrust limitation of 60kg.

Figure 9. Dimensions of the U15II KV80 motor in mm\(^7\).
The seatbelt is 43cm tall 18.3cm wide and at the extreme can be 25cm away from the backboard. It is attached at the higher end at 19cm from the top edge of the backboard. It is made of non-flammable cloth material. It is displayed as 1.5cm in diameter and of cloth canvas in this CAD drawing.

The hooks are 0.75cm thick and about 12cm long. At the extreme, it is 4.2cm away from the wall of the cage. The material specifications are not set, perhaps made of fiber carbon or light composite metal. In this design it is represented as a fiber carbon material.

**Discussion**

From the figures shown above, it is clear we have successfully designed a VTOL manned vehicle. This new design tries to resolve some previous concerns in VTOL manned vehicles as identified by the designer, including what is needed to increase the pleasure of flying and to make it a “good” short-distance transportation craft. In this section we will also elaborate on why this model is not complete, thus only conceptual, and what future models may require.

The addition of two-way feedback for the control system, though not shown in the CAD file, is an integral part of this design. It aims to integrate the pilot more with the aircraft, to minimize a feeling of being protected from nature while in flight. It can also increase the pleasure of flying. One can compare this to driving stick shift (manual transmission) automobile instead of automatic to enhance the pleasure of driving. This optimization of the feeling of flying through the air does, however, make this aircraft less accessible. Increased skill needed to maneuver the craft could result in long periods of training prior to the first flight and long adjustment periods before controlling the craft with ease. I believe this tradeoff is “worth it” for a better integrated flying experience. There are also many commercial and regulatory concerns with flying a short distance transportation craft. With current regulations, this aircraft design can be built but not used for its design purpose. However, this aircraft design is intended for when frameworks and infrastructure exist for personal transportation via air.

The addition of the hooks is meant to represent a greater focus on the comfort and usability of a transport aircraft. Additional accessories are needed to render a flight comfortable. However, the most useful improvements would only be imaginable with flight tests where the craft can be used for its imagined purpose. A varied number of flight purposes should be tested, such as a commute to work, to the grocery store, or from house to house. Perhaps the addition of foldable arms at the touch of a button for easier parking would be possible, or maybe even a cup.
holder for the morning coffee. It is important to note that this is not an entertainment craft, so these accessories should not correspond to long times in the craft for pleasure. There are other aircrafts for sale and in development for entertainment purposes, so this aircraft needs to be the best in meeting transportation needs.

Furthermore, added safety failsafe measures are required before this aircraft is flyable. The safety mechanisms added should make it so the consequences of a small or big occurrence are not fatal and injuries are minimal. Additionally, thrust distribution via connecting arm/truss, materials, sustainability, and what is displayed on the computer screen (not shown in CAD rendering) should all be considered before this model is complete. The cylindrical arm in the CAD model represents an attachment system to distribute the thrust from the motor and propellers to the human cage. The final design for building should not just be an aluminum cylindrical arm, but an integrated truss design of carbon fiber. Sustainability of this aircraft in its first conception is important. Aerial transportation will only be the future if the benefits outweigh the environmental costs. We need to conduct a full life cycle analysis, noise pollution modeling, battery charging/replacement and others and alter the design as needed.

Throughout the project, the researcher faced many challenges, some were due to lack of experience and others due to situational circumstances. The student gained invaluable project design experience as a mechanical engineer. She has no previous experience of working on a multi-component CAD object or working on a CAD project for an extended length of time. Additionally, previous to designing the feedback system, she has had no experience in conceptualizing and making an electrical system with more than 2 components. The situational challenge of COVID-19 quarantine starting March 2020 rendered the initial project proposal unachievable. The lack of lab space or shop support in quarantine meant no physical system could be built. Switching focus halfway through the allotted project period had ramifications for the hours allotted for different parts of the project. Initially, a great deal of time was devoted to understanding the electrical components of a multi-copter. This was so the parts needed for the feedback system could be identified correctly, the configuration knowledge would be present, and the building could commence as soon as parts arrived.

However, after switching to designing a whole aircraft, additional expert knowledge was acquired. This resulted in less time considering various aspects of the craft before settling on a design and starting to draw it in Fusion 360. More time was needed for comprehensive propulsion and thrust calculations and comparison of currently available motors and blades. Additional time was also needed to research solutions to the two main concerns in previous
models that this design wished to address. In the previous parts of the discussion, we identified particular problems that should be resolved before this model can be built and tested. The researcher improved her CAD skills, to an extent that redrawing the project would most likely remedy all drawing errors in the current design. Most of the drawing errors are in joints and alignment where the corresponding skill was not learnt till late in the drawing process.

The one advantage of solely conceptualizing an aircraft is that no money has to be spent in buying components for testing and building. As such, the cost of a blade and motor were no longer a concern, and the best in the market could be considered in the design of the aircraft.

There are many possible future areas of research. The most important future areas that will complete this current version include study of safety, of truss arm attachment system, of materials, of further user-friendly add-ons, and sustainability. After the aforementioned research is conducted and alterations are made, a logical next step would be building and testing. Other possible areas of research for version two of the aircraft could be a more extensive comparison for the best thrust system. For example, calculations could be made with other motor and propellers available for purchase. A bottom section with more elasticity could be considered for safer landings. Cost and manufacturability could also be an area of research for the future version.

Conclusion

Employing a CAD design software, we have shown a new design for a VTOL personal transportation system. Many aspects of aircraft design were considered, such as thrust power and safety requirements. Various design choices such as a human integrated control/piloting system were chosen for the purpose of making a user focused short distance transportation aircraft. The current CAD design is not manufacturable, and possible future areas of research are highlighted. Most importantly, research and development skills relevant to aerospace mechanical engineering were practised in the conceptualization of an aircraft. The purpose of the E90 project is thus met with this design project. The researcher invites everyone to imagine flying such an aircraft home from work or school after a long day and the freedom such a commute can bring.

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