TRANSITIONAL FLIGHT-MODE UAV

by

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ABSTRACT

The purpose of this paper is to detail the research, design, and fabrication of a transitional flight-mode UAV proof of concept prototype. This prototype allows for exploration and development in a new and exciting branch of unmanned vehicle engineering by combining the positive attributes of vertical flight UAVs and horizontal flight UAVs. To complete this prototype, research was conducted to determine specific areas of interest and find the ideal means of construction. Then, as research was completed, the design process commenced and parts were either ordered or designed and fabricated to yield the final assembly. This prototype has all the necessary software and hardware capabilities to fly vertically and transition to and from horizontal flight, utilizing the gyroscopic control of the rotors as well as relying on a pair of actuated wings that create and control lift in horizontal flight. The research and development conducted for this phase of the project will supply inspiration and infrastructure for future development, research, and application by the TCU Department of Engineering.

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INTRODUCTION

This paper details the research, design, and fabrication of a transitional flight-mode UAV. UAV stands for unmanned aerial vehicle, but these devices are known more commonly as drones. The term UAV is used, though, because it more accurately describes the nature of the system that has been built because it is without a function to operate independent of direct human control, that is it is unable to be programmed to execute certain actions and must be operated by a person at all times the system is active. Most commercially available drones are like this, at least to some extent. Multirotor drones, which have become wildly popular, are almost exclusively controlled by a person using a radio control transmitter. However, some of these commercially bought multirotors are equipped with smart capabilities such as returning uncontrolled to the point of take-off, or holding GPS coordinates. For this reason, many use the terms UAV and drone interchangeably, but throughout this paper UAV will be used exclusively in describing the vehicle of interest. This vehicle is deemed a transitional flight-mode UAV because it is equipped with the necessary mechanisms and controls to change the nature of its flight while in the air. The primary transition of interest is that from a vertical thrust state, where the rotation of rotors is used directly to maintain lift, to a horizontal thrust state where the rotation of the rotors is directed in a forward direction and wing structures are used as the primary source of lift. The inspiration for this, as well as the benefits of such a system, are explored below.

BACKGROUND

Inspiration for the transitional flight-mode UAV was drawn from two main sources, the first being the capabilities and revolutionary nature of the Bell-Boeing V-22 Osprey, and the second being the ever-growing popularity and widespread use of UAVs and drones. The Bell-Boeing V-22 Osprey, pictured below in Figure 1, is a modern engineering marvel. The aircraft has two rotors on either side of the body attached to nacelles. These nacelles are attached to the main wing of the V-22, but rotate over 110° from past-vertical to below-horizontal orientations. This mechanism allows the aircraft to fly in a variety of unique ways. It has the ability to take off and land vertically as if it were a helicopter, and has the ability to perform almost any other function a pilot would expect out of a helicopter. The ability to rotate the nacelles in flight though gives pilots the ability to fly like a prototypical airplane, as well as nearly anywhere in between these two extremes. These brilliant capabilities allow the V-22 to accomplish missions otherwise impossible when using conventional aircraft because of constraints on space, range, or terrain. The main limitation of the V-22 is that it is a manned aircraft, and thus must maintain a constant orientation of the body so as not to induce impairment of the pilots and/or crew aboard. Drones and UAVs, on the other hand, are not constrained by this human limitation. With the recent boom of UAV technology advancement as well as commercial availability, a distinct market dichotomy has developed.

Figure 1 – Bell-Boeing V-22 Osprey (Photo Credit: bellhelicopter.com)

Typically, UAVs and drones are either of the multirotor variety (as seen in Figure 2) that use rotors to directly create lift, or of the airplane-style variety (seen in Figure 3) that use rotors for horizontal movement and wings for lift. Because of growing comfort and familiarity with the use of drones among the military and the general public, there is a growing desire among military organizations and corporations to utilize these devices for more diverse and complicated missions and thus an opportunity for engineering ingenuity to provide a useful solution. In seeing this opportunity, it was decided that this project would attempt to create a UAV prototype that would bridge the gap of the two basic drone styles in the way that the V-22 did for the United States' military divisions.

Figure 2 – Amazon PrimeAir Octocopter Drone (Photo Credit: amazon.com)

Figure 3 – AeroVironment RQ-11 Raven (Photo Credit: avinc.com)

In conducting research about the market for a UAV with the capability to use rotors for both vertical and horizontal flight it was discovered that there are a variety of organizations pursuing such a design. The most prominent of these is DARPA, who have dubbed their project TERN (Tactically Exploited Reconnaissance Node). TERN is a tail-sitter drone, seen in Figure 4, which means that its wing-shaped body sits vertically on what would be the tail and uses a rotor that is fixed in orientation to the wing to create thrust in the direction of motion only. Thus, TERN and other, less heralded, tail-sitters have essentially two modes: vertical take-off/landing and forward horizontal flight with little in between the two. The TERN concept meets some needs of the military, but it fails to fully exploit the opportunities afforded by an unmanned vehicle. Likewise, Amazon is experimenting with a dual flight-mode UAV to be used for ultra-rapid delivery. The Amazon PrimeAir, seen in Figure 5, uses one set of rotors to fly vertically and a different set of rotors to fly horizontally while using wings for lift. This concept is rather interesting, but the efficiency of having two sets of rotors for two distinct tasks raises concern. A benefit of this system for Amazon is that the body of the vehicle remains in a constant orientation to alleviate packaging concerns, but one couldn't help but to wonder whether a more efficient use of thrust could be used, while incorporating design features to accommodate packages to be transported.

Figure 4 – DARPA TERN (Photo Credit: darpa.mil)

Figure 5 – Amazon PrimeAir VTOL Drone (Photo Credit: amazon.com)

DESIGN

Given the desire for more versatile unmanned aircraft shown by both military and commercial entities, the goal of this project was established to create a transitional flight-mode UAV prototype to accomplish certain mission-related goals. Primarily, the UAV would be able to take off and land in a vertical fashion so as to allow access in more environments and reduce the difficulty and risk associated with recovering vehicles. Beyond that, the UAV would be able to navigate small spaces, such as caves or tunnels, or hold on a target position while in vertical mode. This required a design that ensured stability in the vertical flight mode. Being a transitional flight-mode UAV the prototype would be equipped, with mechanisms and software, to rotate approximately 90° to begin horizontal flight and then have the ability to rotate back to a vertical mode for small space navigation or landing. In researching current efforts to create UAVs with multiple flight modes, there appeared an opportunity to experiment with new capabilities in attempting to complete a transitional flight-mode prototype. The first major design opportunity is one that is exploited by many tail-sitter UAVs, being the rotation of the entire body of the vehicle to transition from vertical to horizontal flight. However, the distinction of this design when compared to tail-sitters is better stability in vertical flight to allow simpler and more controllable maneuverability in the vertical flight mode. This factor led to the decision of modifying a commercially available multirotor UAV to complete the prototype, as the multiple rotors spaced symmetrically about the center of mass provide inertial stability that is unmatched by the nearly two-dimensional tail-sitters. The other rather intriguing design opportunity that presented itself from this research as well as discussions with Dr. Williamson, was the desire to control the orientation of the lift structure of the UAV relative to the direction of thrust. To put it simply, the wings that were to be mounted to the UAV being modified would be able to rotate so that experimentation could be done with various angles of attack. The angle of attack is simply the angle of a wing relative to its velocity, and in comprehending this simple physical definition lies the fascinating prospect of this design consideration. A UAV equipped with rotatable lift structures allows an opportunity for not only testing the effectiveness of flying with the rotors perfectly horizontal while varying the angle of the wing. This capability allows the testing of a vast array of angles, not only of the wing relative to the velocity, but also of the rotors relative to the velocity of the craft with a corresponding angle of attack of the wings. For instance, one could rotate the craft 75° towards the horizontal flight mode and set the wing at a very shallow angle of attack to reduce drag. This is possible because some of the thrust from the rotors is still dedicated to vertical lift, so the wings do not need to produce as much. Intuition says that this setup would be less efficient than either extreme, but it may provide the handling ability of a typical multirotor traveling at a 45° pitch while also providing extra velocity capabilities. It was these possibilities that inspired the bevy of design considerations explored throughout the rest of this paper.

UAV Selection

The first design choice to be made in the development of this prototype was selecting a multirotor UAV to be modified. In the beginning of this selection process an H-shaped quadcopter, such as the Lumenier QAV500 pictured below in Figure 6, was the ideal target as the H-shape of the rotor arms provided a symmetrical axis along which the wings could be mounted. This was necessary because having the center of mass in this direction align with the center of lift creates a more stable aircraft. It also reduces complication in the transitionary angles of the aircraft associated with a moment created by the lift force at a given distance away from the center of mass.

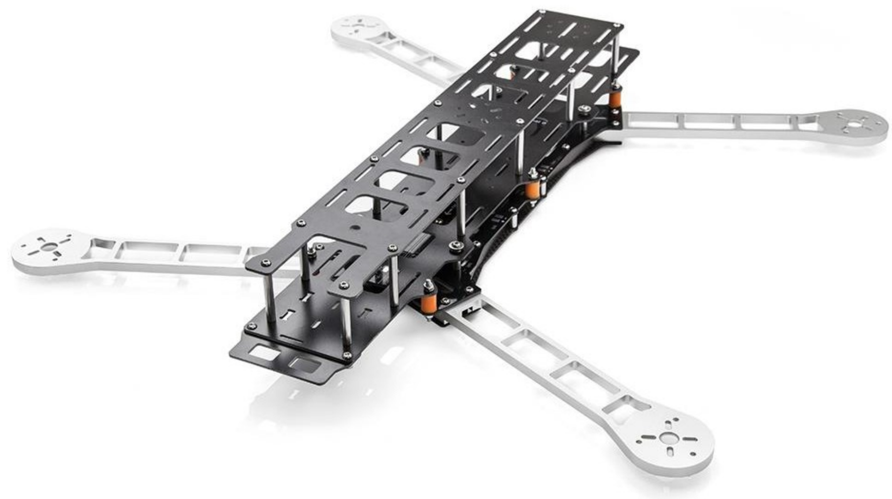

Figure 6 – Lumenier QAV500 Frame (Photo Credit: lumenier.com)

While, theoretically, a quadcopter of this kind would serve the purposes of the project well, they proved to be either too expensive or did not offer the software flexibility needed to accomplish horizontal flight. Thus, the search turned to aircraft that offered control software that was easily edited to disengage the angular limitations imposed upon most commercially available UAVs. These pitch limitations, often restricting flight of multirotors to within 45° of vertical, are useful in allowing beginners safety in operation but were obviously detrimental to creating a vehicle that can fly horizontally. Luckily, hours of scouring the internet and various hobby shops resulted in the discovery of the AersoSky 550 Hexacopter, shown below in Figure 7. This UAV was available as an almost-ready-to-fly kit that required a bit of assembly and the integration of a transmitter/receiver and a battery. This reduced the anticipated workload of having to research, coordinate, purchase, and integrate a control board, motors, electrical speed controllers, and all the associated wiring.

Figure 7 – AeroSky 550 Hexacopter Fully Assembled

The main feature that drove the decision to purchase the Aerosky 550 was its control software. It runs using an Arduino board loaded with an open source software called MultiWii. It is so named because its original iteration was utilizing gyroscopic measurement devices from Nintendo Wii controllers, and has since evolved into the primary open source control software for multirotor UAVs. With MultiWii loaded onto the UAV, a bevy of settings can be altered by linking the UAV and a computer through the use of a USB cable and an extremely intuitive GUI (Graphic User Interface). The GUI for MultiWii is shown below in Figure 8 and allows for easy control of angle limitation, thrust curves, and control stick sensitivity.

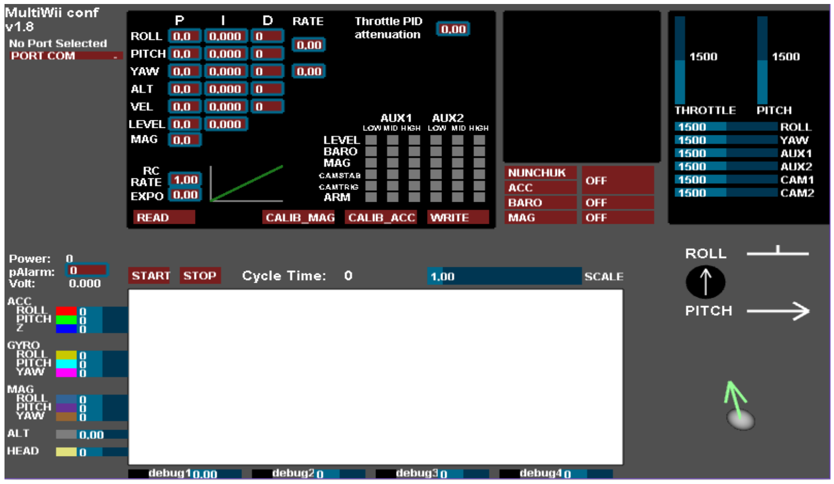

Figure 8 – MultiWii GUI

The added benefit of selecting the Aerosky 550 Hexacopter is simply the structure that the hexacopter provides. Because it has six arms instead of four, it provided the symmetrical axis desired from an H-frame quadcopter, but the arms along the symmetrical axis provided adaptable infrastructure that could be used to more simply incorporate the lift structures.

Lift Structure Mounting

To enable the UAV to fly in a horizontal manner, lift structures had to be mounted to the body of the vehicle. Given the geometry of the hexacopter, it was determined that the best way to accomplish this would be by mounting a wing section on either side of the body. To determine the sizing of the components needed to mount these wings, the size of the wings had to first be selected. A foam-core wing with a balsa wood exterior was selected because of its excellent strength-to-weight ratio, which is an essential design component in any aeronautical application. To ensure that the craft could be flown horizontally after rotating in either direction, a symmetrical airfoil shape was selected, specifically a NACA 65-006 wing. A diagram of the cross section of the wing is shown below in Figure 9.

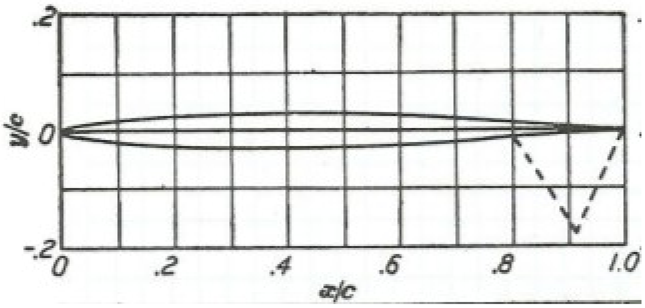

Figure 9 – NACA 65-006 Airfoil Cross Section (Photo Credit: Anderson Jr., Introduction to Flight 8th Edition)

The solid foam core provided a blank slate to incorporate the structure that the wing would attach to. Because the wing needed to rotate, it was necessary to use a cylindrically shaped support. To accomplish this rotation in a manner that would maintain the lightweight nature of the aircraft and that would maintain the rigidity of the structure, carbon fiber composite tubing was selected as the support structure. Carbon fiber composite is a material widely used in the aerospace industry that combines amazing strength and rigidity with exceedingly low weight. To allow the rotation of the wing, two diameters of tubing were purchased from Clearwater Composites. These diameters were selected to allow a rotational clearance between the inner diameter of the larger tube and the outer diameter of the smaller tube, and this fit is shown below in Figure 10. Thus, the smaller tube would serve as the primary load-bearing structure that would connect to both the central body of the UAV and to the rotor, while the larger tube would be mounted to the inner structure of the wing to act as a stiffening spar and facilitate the rotation of each wing.

Figure 10 – Carbon Fiber Tube Rotational Fit

With the support structure of the wings decided, it was then necessary to determine the span of each wing. To maintain the structural integrity of the carbon fiber support tubes, the shortest possible span of the wing was desirable. However, it was important to ensure that the wing would not be so small as to not create enough lift to keep the vehicle airborne. Thus, a quick analysis comparing the total wingspan of the vehicle to the necessary velocity to maintain level flight was performed using the basic equation for lift displayed below in Equation 1.

Equation 1

$$L = \frac{1}{2}\rho v^2 S C_L$$

$$\rho = air\ density, v = air\ speed\ S = wing\ surface\ area, C_L = Lift\ coefficient$$

This analysis created a matrix with the inputs of wingspan and lift coefficient (which is driven by attack angle) with the result being level flight velocity which is obtained by setting lift from Equation 1 equal to the weight of the UAV. This data is shown below in Table 1.

		Lift Coefficient														
		0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	
Total Wing Span (ft.)	2	100.4846481	82.04537163	71.05338	63.55207	58.01484	53.7113	50.24232	47.36892	44.9381	42.8468	41.02269	39.41332	37.97963	36.69180564	Velocity (ft/s)
	2.25	94.73783479	77.35311819	66.98977	59.91747	54.69691	50.6395	47.36892	44.65984	42.36805	40.39635	38.67656	37.15924	35.80754	34.59336611	
	2.5	89.87620156	73.38361128	63.55207	56.8427	51.89005	48.04085	44.9381	42.36805	40.19386	38.32334	36.69181	35.25235	33.97001	32.81814865	
	2.75	85.69359585	69.96852802	60.59452	54.19739	49.47522	45.80515	42.8468	40.39635	38.32334	36.53987	34.98426	33.61179	32.38913	31.29087699	
	3	82.04537163	66.98976542	58.01484	51.89005	47.36892	43.8551	41.02269	38.67656	36.69181	34.98426	33.49488	32.18084	31.01024	29.95873385	
	3.25	78.82664333	64.36168476	55.73885	49.85435	45.51058	42.13461	39.41332	37.15924	35.25235	33.61179	32.18084	30.91835	29.79367	28.78342045	
	3.5	75.95925415	62.0204713	53.7113	48.04085	43.8551	40.60193	37.97963	35.80754	33.97001	32.38913	31.01024	29.79367	28.7099	27.73639797	
	3.75	73.38361128	59.91746771	51.89005	46.41187	42.36805	39.22519	36.69181	34.59337	32.81815	31.29088	29.95873	28.78342	27.7364	26.79590617	
	4	71.0533761	58.01483865	50.24232	44.9381	41.02269	37.97963	35.52669	33.49488	31.77604	30.29726	29.00742	27.86943	26.85565	25.94502458	
	4.25	68.93189993	56.28266061	48.74221	43.59636	39.79785	36.84565	34.46595	32.49481	30.82728	29.39266	28.14133	27.03732	26.05381	25.17037102	
	4.5	66.98976542	54.69691442	47.36892	42.36805	38.67656	35.80754	33.49488	31.57928	29.95873	28.56453	27.34846	26.27555	25.31975	24.46120376	
	4.75	65.20304968	53.23806713	46.10552	41.23803	37.645	34.8525	32.60152	30.73701	29.15969	27.80267	26.61903	25.57474	24.64444	23.80878742	
	5	63.55207159	51.89004917	44.9381	40.19386	36.69181	33.97001	31.77604	29.95873	28.42135	27.09869	25.94502	24.92717	24.02043	23.20593546	
		Velocity (ft/s)														

Table 1 – Wing Span Determination Matrix

The intuitive design thought was to utilize a one foot span for each wing and in looking at the results of Table 1, with input from Dr. Williamson, this design thought was found to be within the bounds of reason for use. This span is shorter than those used in many radio-controlled airplanes of the same relative size; however, the use of six rotors as compared to the single rotor that an airplane uses provides the requisite power needed to achieve the velocities outlined in Table 1.

As stated earlier, the support for the wings and rotors would be the smaller diameter composite tube. This tube had to be mounted securely to the body, preferably by using the existing connection points that were utilized to fasten the existing arms to the body. The initial design thought to accomplish this would be to purchase and modify a pair of arms, seen below in Figure 11.

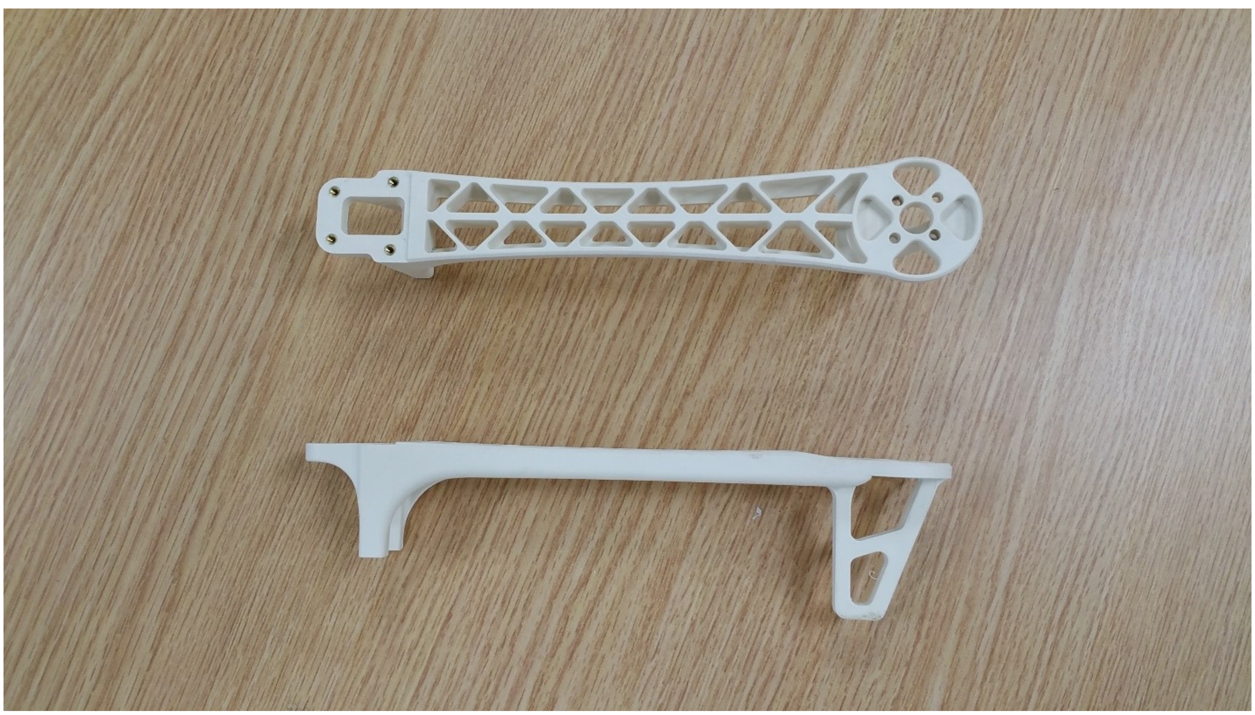

Figure 11 – Original Rotor Arms

When assessing the ability of these arms to accommodate the composite tube it became apparent that the modifications would be too complex to validate using such a method. Thus, it was determined that the mounts for the composite tube would be designed from scratch and fabricated. To allow for rapid fabrication and developmental design, the facilities in the TCU Fab Lab were used to 3D print these mounts. These decisions allowed for precise control of tolerances, as well as complicated geometry to facilitate better support of the wing, rotor, and all other associated components. The material used to fabricate the mounts was ABS plastic, which is a commonly used filament in 3D printing applications that require lightweight strength. After a few iterations of the design for the tube mount, the final design is displayed below in Figure 12.

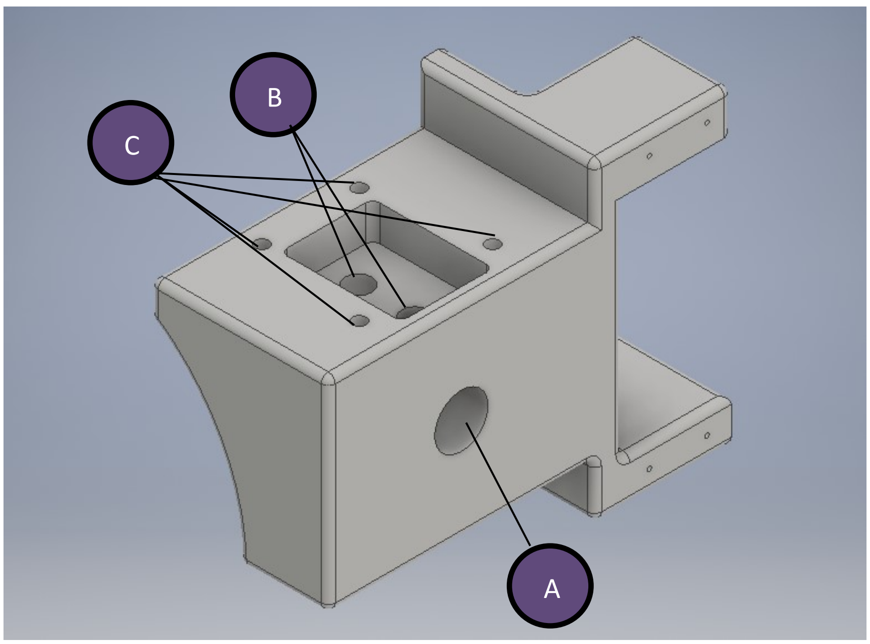

Figure 12 – Arm Tube Mount Final Design

Hole A of Figure 12 is the entry point of the composite tube. This hole is sized to provide a snug fit to maintain support of the tube and distribute load to the mount. The two vertically oriented holes labeled by B in Figure 12 coordinate with holes drilled into the tube. These holes allow fastening of the tube to the mount through the use of bolts and nuts. This fastening system maintains a constant orientation of the tube, the importance of which will be discussed in a following section. Finally, the four holes labeled with C in figure 12 correspond to the threaded holes of the arms in Figure 11 and provide four of the six mounting points to the main body. The other two mounting points also mimic the arms of Figure 11 and are not visible in Figure 12 as they are on the bottom side of the mount. These six mounting points replicate the dimensions of the arm mounting points exactly for seamless installation onto the main body without modification. The primary difference between these holes is that the 3D printed mount did not have pre-threaded holes, but used the threads of the machine screws to tap the ABS and provide a secure connection.

Once the arm tube mount was securely fastened to the body, and the composite tube placed and fixed inside the mount, it was possible to affix the wings and rotors. The installation of these components is shown below in Figure 13.

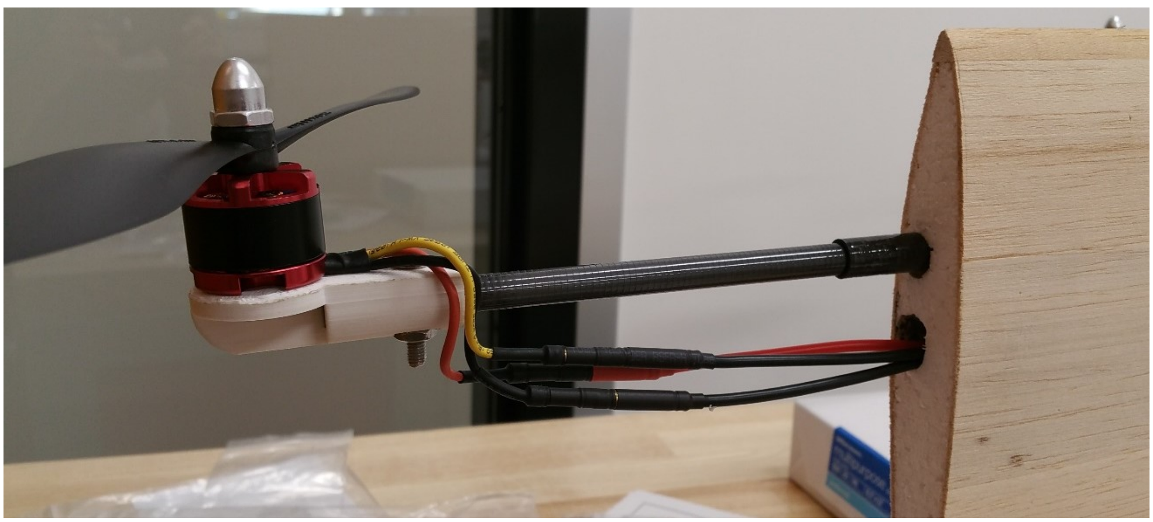

Figure 13 – Wing and Rotor Installation

First, to install the wing the larger diameter tube was cut into 14-inch segments and bonded to the inside of the wing using Gorilla Glue Adhesive. The hole for this bonding was created through a melting process using a heated steel rod. Seen near the bottom of Figure 13 is a series of wires running through another hole created in the same manner as the one utilized to bond the larger carbon fiber tube. This was necessary because the inner diameter of the smaller arm tube could not fit the three wires required to transport current to the DC rotor, and running the wires along the wing would disrupt the airflow thus negatively impacting the lift capabilities of the UAV. The rotor is mounted to the arm tube in a similar fashion to the mounting of the arm tube to the body of the aircraft. The rotor mount, seen below in Figure 14, was also fabricated using 3D printed ABS plastic.

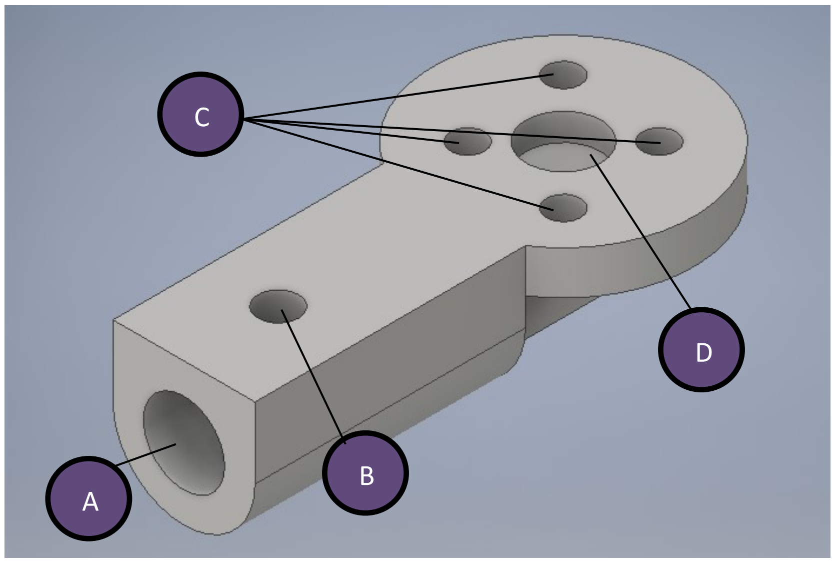

Figure 14 – Rotor Mount Final Design

The rotor mount's primary mounting mechanism mimics that of the arm mount very closely as shown by elements A and B in Figure 14. Once again, hole A provides the entry point of the arm tube with a snug fit. Hole B coordinates with another hole on the arm tube that was drilled along the same plane as the two holes used to mount to the body. This ensures that the rotors will maintain level orientation with the body, and thus all of the other rotors. The holes denoted as element C are through-holes that accommodate the machine screws used to affix the rotor to the rotor mount. Finally, element D provides clearance for a small piece of the rotor that extends below its primary surface. This was an important element as that small rotor piece spins at the same elevated RPM as the rotor and blades.

As mentioned above, both the arm mount and the rotor mount were fabricated using 3D printed ABS at the TCU Fab Lab. This, thankfully, allowed for rapid prototyping and development of designs. However, these benefits did not come without drawbacks; 3D printing is a rather fickle process, especially when using a material such as ABS. This is due in part to the elevated melting temperature of ABS as compared to resins more commonly used for modeling and artistic ventures. The temperature required to melt the ABS filament, and thus deposit it to create the parts, was near the upper limit of the machines used at TCU. This led to two main issues that frustrated and delayed progress. The first problem is associated with the primary layer of material deposited onto the buildplate of the 3D printer. Because it is barely reaching the melted state, the ABS solidifies quickly and will often not stick properly to the buildplate. This led to misprinted parts because the base layer affects all layers above it. Similarly, the second issue is also caused by rapid cooling of the material. As a part is built up, it is ideal for the material to cool at an even rate. However, the ABS has a tendency to cool at uneven rates, once again due to the fact that the deposited material is not well above its melting point. Due to this uneven cooling, seen particularly along corners and in large hole features. This uneven cooling rate leads to warping of the material which can either modify the entire shape of the part, or lead to delamination of individual layers resulting in structurally dangerous cracks. As a result of these common printing failures, the fabrication process was developed concurrently with the design of the parts, leading to a vast collection of failed parts displayed below in Figure 15.

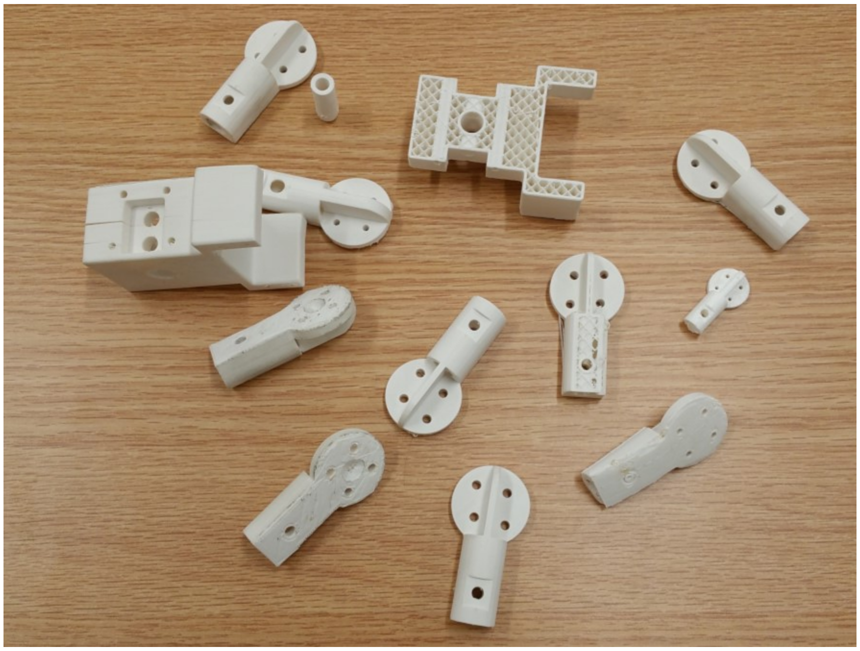

Figure 15 – Failed 3D Printed Part "Graveyard"

Wing Rotation/Actuation

To fully unlock the potential on the capabilities of this UAV, the design goal was set out to not only affix wing structures, but to be able to control the orientation of these structures relative to the orientation of the vehicle. To accomplish this it was determined early on in the design process that a pair of RC servos would be used to actuate each wing. Initially, they were going to be mounted to the body of the vehicle using their own separate mounts either on the top or bottom surface so as to maintain the position of the center of gravity. However, with the discovery of the ability to 3D print the arm mounts the decision was made to incorporate mounting the servos into this mount design. This decision is the reason for the C-shaped structure on the right side of the mount in Figure 12. Before this installation decision was made, though, the servo had to be selected and purchased. This was an extremely important decision as the servo had to provide enough torque to maintain the position of the wing as it supported the entire weight of the UAV, and the servo could not be too physically large or heavy so that it would not adversely affect the capabilities of the vehicle. Thus, the Hitec D645MW servo which is seen below in Figure 16 was selected as it exceeds the above criteria. The D645MW is rated to a torque of 180.1 oz-in. This gives a comfortable factor of safety as the weight of the UAV is approximately 4.4 lbs (70.4 oz), the wings are mounted through their aerodynamic center so as to reduce the amount of moment created about the wings, and the load of the body is distributed across two servos. The added benefit of these servos is that they offer the ability to be programmed through the use of a simple adapter and computer program, allowing control of positive input rotation direction and total angle travel.

Figure 16 – Hitec D645MW Servo, placed in arm mount

Once the servo was selected and attached to the arm mount via the four screw holes seen in Figure 16, the mechanism of connection between the servo and the wing structures had to be fabricated. To assure that this mechanism would not be a source for failure, a different servo attachment than the one seen in Figure 16 was used. Instead of extending in one direction, the new servo attachment extended in two, allowing for symmetrical actuation of the wing. Steel pushrods were attached to the servo arm using standard screw-lock connectors. To attach these pushrods to the wing, so that when the servo was rotated by the radio transmitter the wing would also rotate, two ball link control horns were bonded to the face of the airfoil closest to the body of the aircraft. These control horns were selected because they extend away from the surface and include a connection point through a ball bearing press fit into the control horn. This allowed rotation of the connection point, so that the pushrods would remain constantly oriented maintaining the center of rotation of both the servo and the wing. Initially, the pushrods were connected to the control horns using a clevis attached to the end of the pushrod. This is displayed below in Figure 17.

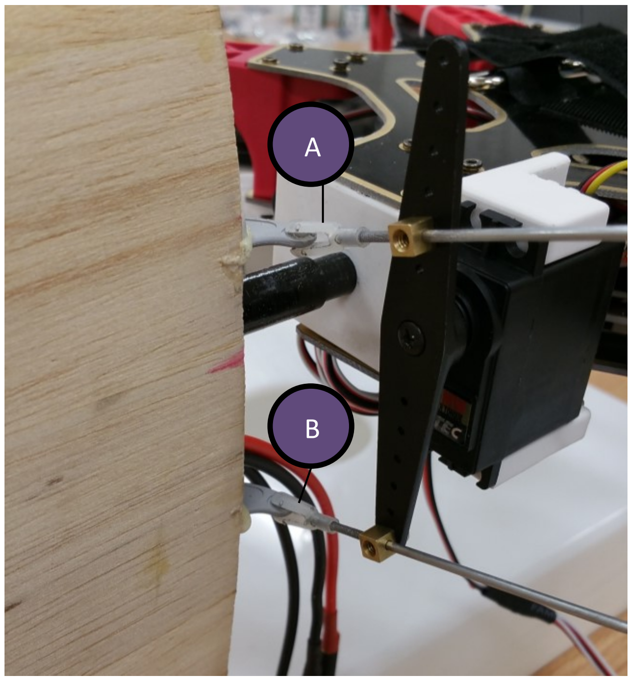

Figure 17 – Pushrod/Clevis Connection to Control Horn

Ultimately, this design provided more frustrations than successes. First, the length of the clevis, indicated as parts A and B in Figure 17, made bending the pushrod to an angle that would allow the clevis to be normally horizontal impossible. This issue accentuated the second problem in that the faces of the clevis created an interference with the control horn at any angle greater than ±5°. This interference cause the clevis to open or caused the wing to simply stop rotating. While this problem was maddeningly simple, overcoming it proved much more difficult. There were attempts to find wider spaced clevises as well as pushrods that were small enough in diameter to be run through the ball link, but both of these proved fruitless. Ultimately, and almost out of desperation, the decision was made to expand the hole in the plastic ball links to accommodate the existing pushrod, despite fears of destroying the ball link entirely. Luckily, this last ditch effort resulted in success with a much more operational rotational wing system. The pushrod was secured into the ball link control horn by using a U-bend, which is shown below in Figure 18.

Figure 18 – Operational Wing Rotation System

The solution of a pushrod secured into the ball-link control horn using a U-bend, shown as elements A and B in Figure 18, is operational to angles of approximately 35° either way; however, at any greater angles the ball link has a tendency to dislocate from the control horn. Due to the time constraints of this project, this system was not flight-tested and the occurrence of this issue is worrisome moving into flight testing. Thus, additional research was conducted, and it has been recommended to whomever continues development of this project that the control horns be replaced with a ball and socket joint such as the one shown below in Figure 19. This joint should allow a more simple connection that allows all of the rotation and strength necessary to rotate the wing. The main issue with a system like this is incorporating the threaded ball section into the wing, but this can be done by bonding a 3D printed plug with a threaded hole into the wing in a similar manner to the mounting of the larger diameter composite tube.

Figure 19 – Proposed Ball and Socket Joint for Wing Rotation

Full System Design

The culmination of all of these individual design decisions resulted in an operational UAV, displayed below in Figure 20, that accomplishes many of the goals set at the outset of the project. Disappointingly, as stated in the above section, the full system was never subjected to flight testing; however, the UAV has all of the operational systems necessary for vertical, horizontal, and transitionary flight. First, the control software and hardware allows for the rotation of the vehicle from vertical orientation 90° or more into a horizontal flight mode.

Second, lift structures in the form two symmetrical wings were affixed to the body to provide adequate lift to support the weight of the vehicle. Third, the ability to rotate and control these lift structures was successfully incorporated with safely sized control equipment and mechanisms. This allows future users of this transitional flight-mode prototype to ask and test unique research questions. Finally, all flight systems were maintained and the overall vehicle weight was actually reduced slightly from the initial system at 4.8 lbs to 4.4 lbs.

Figure 20 – Full System Transitional Flight-Mode UAV Prototype

FUTURE

While merely completing construction of a transitional flight-mode UAV is an accomplishment, it was not done simply for the sake of being done. The hope for this project is that it continues to be developed and used for the foreseeable future. The next step for this prototype is to be flown by an experienced drone/UAV pilot to test the aerial performance of the vehicle and identify any improvements to be made. Before doing this, it would be ideal to incorporate the ball and socket joint solution for wing rotation as well as coating the wing in a heat-shrink film to improve the airflow and thus maximize performance. After these small improvements and initial flight testing are completed, the door will be opened to a variety of interesting opportunities. First, there is the opportunity for in-depth exploration of a question posed at the outset of this paper, that being how do different angles of thrust combined with angles of attack affect the performance of this transitional flight-mode UAV? This would really bring the focus into the transitional part of this device, which can be a piece of remarkable interest because of the comparably immense depth of knowledge available concerning the two extremes of this vehicle: vertical and horizontal flight. Second, there are opportunities to tailor this technology to specific applications. This could be development of package transporting equipment that accommodates the transitional motion, or incorporating various sensors of military interest into the performance of the UAV. Finally, the largest opportunity available is to take any lessons learned from this prototype and the flight testing that will occur using it to develop a clean-sheet design of a transitional flight-mode drone. The drone distinction is used here because this iteration would ideally include the ability to automate the control system. Regardless, the future paths that this device offers are exciting to ponder and will hopefully inspire tremendous ingenuity and solutions that are beneficial to society.