ABSTRACT

This paper discusses the design and development of a Micro Air Vehicle (MAV) platform focusing on aerodynamic design; material durability and precision; and propulsion system integration. The purpose of the MAV is to compete in the surveillance mission at the 2006 International Micro Air Vehicle Competition (IMAVC). A low Reynolds number airfoil and planform was designed and validated through wind tunnel testing. Methods of manufacturing were developed to ensure a highly durable platform with precise tolerances. A propulsion system optimized by the MAV propulsion team was integrated into the platform. Furthermore, a super lightweight camera and transmitter were found that allow live video to be streamed to the ground station.

INTRODUCTION

The development of micro-scale platforms in the past decade has proven to be a very useful for many applications including military surveillance. DARPA defines an MAV as an aircraft that weighs less than 100g having a maximum linear dimension less than 15cm [1]. The IMAVC has promoted MAV development and universities around the world. The 2006 MAV team is focusing on developing an MAV platform capable of completing the surveillance mission at this competition. This surveillance mission consists of flying the smallest possible MAV 600 meters to a symbol on the ground and returning an image of the symbol to the ground station.

This year two separate design teams are working together to develop an MAV platform with an optimized propulsion system to demonstrate the 2006 IMAVC. The MAV platform team was responsible for developing a precise and durable platform that is aerodynamically stable and controllable. The platform will house the propulsion system developed by the MAV propulsion team as well as a color video camera and transmitter.

NOMENCLATURE

\[ AOA \] = angle of attack  
\[ AR \] = aspect ratio  
\[ C_D \] = coefficient of drag  
\[ C_{D,max} \] = maximum coefficient of drag  
\[ C_l \] = coefficient of lift  
\[ C_T \] = coefficient of thrust  
\[ D \] = drag  
\[ J \] = advance ratio  
\[ LE \] = leading edge  
\[ MLD \] = maximum linear dimension  
\[ mph \] = miles per hour  
\[ Re \] = Reynolds number  
\[ RPM \] = revolutions per minute  
\[ T \] = thrust  
\[ TE \] = trailing edge  
\[ U_\infty \] = flight speed
A. Overall Design Considerations

The design of the MAV was broken down into three main areas: aerodynamics; materials and manufacturing; and electronics and propulsion system integration. Subgroups of the team were created to focus on each of these areas as well as the seamless integration into the final product. The aerodynamic group was responsible for creating an airfoil and planform that will provide sufficient lift while being both stable and controllable. The materials and manufacturing group was responsible for researching and developing materials and manufacturing processes that will ensure a super light weight yet durable platform. The platform must conform to the tolerances of the airfoil and planform shapes and be able to protect all of the on-board electronics. The electronics group was responsible for finding a camera, transmitter, and servos, as well as supporting the integration of the propulsion system into the platform.

B. Aerodynamic Design

It was the focus of the aerodynamics group to design and develop a wing/pod configuration that would maximize lift, minimize drag, insure aircraft stability, and be maneuverable. The aerodynamics group also recognized that scalability and adaptability were favorable design characteristics and made efforts to ensure the design incorporated aspects to address both. The design was broken into 5 major aspects: airfoil, planform, wing, pod, and control surfaces. The specific goal of the airfoil design effort was to establish a group of airfoils that had high $C_l/C_{d_{max}}$ values that occurred at or near the projected cruise angle of attack (AOA). The design of the planform was focused on effectively converting the 2-D lift generated by the airfoil into 3-D wing generated lift. The wing design refers to the exact spanwise airfoil distribution, chosen to maximize lift while minimizing drag. The pod aerodynamic design addresses drag, directional stability, and thrust line implementation.

MAV airfoils operating at low Re numbers experience laminar separation bubble formation which degrades overall airfoil performance through loss of lift and increased drag. Previous research\textsuperscript{5} has shown that airfoils that have thickness to chord ratios greater than 10% are more prone to laminar separation bubble formation. To address the poor performance of thick airfoils many researchers used thin airfoils with thickness to chord ratios in the range of 2-12%. In a study done by Kellogg\textsuperscript{5}, five airfoils of various thicknesses were tested at Re numbers of 60,000, 100,000, and 150,000. The results of the testing showed for laminar flow the thinner airfoils had 9% higher lift to drag (L/D) values and for turbulent conditions thin airfoils had 22% higher L/D values. The results of this study, as well as others like it\textsuperscript{4} have driven MAV airfoil towards thin cambered plate airfoils.

In addition to generating lift the airfoil must also provide a margin of static pitch stability. It was determined through initial concept development that the primary choice for the MAV’s configuration was a flying wing. Flying wing configurations require the wing to have a negative pitching moment slope and a positive intercept\textsuperscript{56}. This is achieved through the addition of reflex to the airfoil.

With the positive benefits of thin airfoils and the requirements of reflex for stability, the aerodynamics group developed a method for designing thin-cambered-reflexed airfoils. Previously efforts have been pioneered using an n\textsuperscript{th} order polynomial to define the airfoil’s mean camber line\textsuperscript{7}. The disadvantage of this method is an inability to smoothly connect all possible airfoil parameters without requiring a large number of higher order terms. In an effort to design a range of airfoils a method for creating airfoils based on max camber, position of max camber, max reflex, position of max reflex, and thickness values was developed. The method utilizes a Bezier curve to create the mean camber line of the airfoil to which a constant thickness distribution is applied. Bezier curves were chosen because of their flexibility and reliability in producing a smooth curve. An example of a Bezier airfoil with its defining control points is shown in Figure 1.

![Figure 1. Bezier airfoil.](image)

Previous research\textsuperscript{3,8,9} suggests that max camber near the $\frac{1}{4}$ chord point provides favorable lift production so all airfoils analyzed have max camber at the $\frac{1}{4}$ chord point. In addition, it was determined through primary analysis that max reflex and position of max reflex of 1% and 85% chord respectfully provides the required pitching moment characteristics without substantial loss of pressure on the aft portion of the airfoil resulting in lower lift. Using these baseline parameters the max camber was varied from 1% to 9% and evaluated using XFOIL\textsuperscript{10}. For low Re number airfoil analysis, XFOIL provides a sufficient tool for
modeling laminar separation bubble formation, as well as providing acceptable results for lift and drag. XFOIL has been reported to over-predict lift and under-predict drag; however this trend has been found consistently and will not affect general trends. Figure 2 and Figure 3 show the results for maximum $C_l$ and maximum $C_l/C_d$ for the various camber values at 3 Reynolds numbers.

![Figure 2. Maximum $C_l/C_d$.](image)

![Figure 3. Maximum $C_l$.](image)

It is clear that camber values in the range of 4% to 6% represent maximum $C_l/C_d$ performance. However the 6% airfoil has the disadvantage of being highly dependent on Reynolds number. Figure 3 shows how maximum $C_l$ behaves as camber increases. Camber values between 3% and 7% represent the steady increase of $C_{l,max}$. From this data the aerodynamics group identified the 4 , 5, and 6 percent airfoils as forerunners in performance.

The development of the planform was driven by the aerodynamic need to maximize lift production and the need to minimize the largest linear dimension of the aircraft. The planform was chosen from eight possible types: Circular, Modified Circle, 3-Circle Design, Zimmerman, Inverse Zimmerman, Tapered, and Elliptical. The primary requirements of the planform are aspect ratio (AR), surface area, and maximum linear dimension (MLD). Secondary requirements are control surfaces, control integration, and stability. A preliminary feasibility assessment eliminated the circular, elliptical, and Zimmerman because of poor tip vortex properties as well as control surface implementation concerns because of a trailing edge shape. The tapered planform shape was not further investigated because of poor MLD to surface area characteristics. A comparison between the Modified Circle, 3-Circle, and Inverse Zimmerman planforms was performed. In this analysis, primary and secondary requirements were assigned to the planform that most reflects the associated characteristics. The modified circle has an area similar to that of a circle therefore its MLD will be smaller than the others, while still achieving similar surface area. For the 3-Circle and Inverse Zimmerman planforms, CAD models were created, keeping MLD constant across planforms. The 3-Circle planform had the largest surface area while the Inverse Zimmerman had the largest AR. The difference between the AR of the 3-circle and the Zimmerman was minor. The results of the feasibility assessment showed the 3 Circle planform as the best choice. The 3-circle planform was designed so that a ratio between the leading edge (LE) and the trailing edge (TE) is specified along with a ratio between LE and distance between the LE and TE. This configuration allows for a specific AR to be specified independent of MLD. This allows for full scalability and flexibility without changing AR.

Wing development was dependent on the correct implementation of different airfoil shapes along the span of the wing. The goal is to achieve an elliptical lift distribution and to take advantage of the propeller slip stream. The section of the wing that is directly aft of the propeller experiences higher flow velocities than the rest of the wing. It also has the largest chord which results in the highest local Reynolds number. Utilizing this aspect the aerodynamics group chose the 6% airfoil for the center section of the wing. The 6% airfoil has good $C_{l}/C_{d,max}$ values at higher Reynolds numbers as well as a higher $C_{l,max}$ value. Also the 6% airfoil has higher $C_l$ values in general which fits well for the center section of the elliptical lift distribution. Outboard of the center section the airfoil transitions to a 5% cambered airfoil. The 5% has the best $C_{l}/C_{d}$ values over the flight Reynolds number range at a lower AOA than the 6%. Performance at a lower AOA is necessary for airfoils near the wing tips because downwash results in a lower local AOA. The reduced camber also results in lower $C_l$ values which also adds to the elliptical lift distribution. The wing is also designed so that the upper surface at the airfoil’s max camber location was at the same location across the wing. This resulted in a slight dihedral which adds to roll stability.

The basic control surface configuration for a flying wing design implements the use of elevons. Elevons are dual function control surfaces that can deflect symmetrically to create pitching moment changes on the wing and asymmetrically to create rolling
moments on the wing. In addition to creating a rolling moment, asymmetric elevon deflection causes adverse yaw. Adverse yaw refers to the yawing moment caused by the drag differential that is caused by increased lift induced drag on one wing and decreased lift induced drag on the other. This yawing moment acts in the direction away from the turn, which prohibits proper control. To combat adverse yaw, an asymmetric elevon deflection is required to ensure equal drag in produced on both wings. Analysis was done in XFOIL to estimate the adverse yaw assuming a 2-D airfoil and neglecting 3-D wing effects which simplified the analysis however detailed flight testing is still necessary to establish if the control surfaces provide sufficient and effective control. The adverse yaw effect can be seen in figure ($C_d/\delta e$). If drag was symmetric, the average value for an elevon effectiveness parameter, $\delta C_d/\delta e$, should be close to 0. However, in this case it is slightly greater than 0. For this simulation we know that we will have only a small amount of adverse yaw.

The primary goal of the pod aerodynamic design was to ensure directional stability through proper sizing of the vertical tail portion of the pod. In addition, the pod could add a substantial amount of drag is improperly designed. Drag was addressed by simply reducing the frontal area of the pod. Creating smooth transitions between any differences in thickness ensured there would be few stagnation regions that rob flow momentum and cause drag. The foundation for directional stability is greatly simplified because of the general flat shape of the pod. To ensure static directional stability the center of pressure must be aft of the center of gravity (CG), and because the effect of the wing is assumed to be destabilizing, a slight margin was factored in. This resulted in a pod that has 35% more area aft of the CG than forward. The pod also incorporates a motor mount that is at 3° down from the chord line of the wing. This is to align the motor closer to forward while flying at cruise angle of attack which creates a more efficient cruise flight condition.

C. Materials and Manufacturing

The materials and manufacturing team was tasked with designing an efficient way to manufacture a durable platform to hold all of the components. It must also protect the components necessary to accomplish the competition task and the processes involved must allow for consistency in production. With these goals in mind, the logic was to use all of the tools at the team’s disposal to create a viable platform to the designed specifications as quickly as possible. These logistics are driven by the assessed need for precision and accuracy for each element or process by understanding its independent impact on the overall system. These elements were heavily focused on to ensure process design efforts were justified. This feat entails creating tooling such as integration jigs and fixtures, component molds, and manufacturing plans that would allow for seamless flow to a completed MAV.

Since the manufacturing plan is defined by a hierarchy of precision, it will be broken down into three subgroups according to their needs assessment. To ensure that this classification is upheld, it is important that these elements be fabricated in the earlier stages of the build, if possible, to ensure that careful consideration and proper time is allotted. This will also decrease the chances of stoppages due to tier one elements being more automated; therefore less human error will be introduced. This methodology eliminates excess manufactured parts and allows for efficient use of the production system time schedule. If the tier one elements are not fabricated correctly it does not make sense to continue with the process of making elements with less critical tolerances which reduces manufacturing time.

Tier one elements are comprised of the wing structure and propeller. These elements hold precise tolerances on all dimensions and relations and will require molds with minimal hand work. Tier two elements consist of the component bay structure, electrical component location, electrical component fastening, vertical tail, motor mount and structure integration. These elements have specific dimensions that need to be adhered to and are mostly relative to a location on the platform that will require location or integration jigs. Tier three elements are the control surface actuation system (CSAS) and skin application. These are elements that require mostly hand construction with constraints that are purely relationally based.

The first tier one element is the wing structure. Based upon our material needs assessment, 5.5 osy carbon fiber satin weave is used for the leading edge and control surface structure while IM7 carbon fiber tow is used for the wing spars. From the wing aerodynamic data specifications, the first step is to create a precise and accurate 3D model of the mold using SolidWorks 2006. This mold file is then sent to a fusion deposition molding machine that will layer an ABS plastic mold while holding tolerances of up to five thousandths of an inch. This mold is designed to incorporate grooves for the proprietary custom contoured carbon rods to sit into and give the contour to the rest of the wing as seen in Figure 4. The mold is then retro-fitted on the bottom surface with a tensioning and locking cleat for the carbon rods. The setup is then wrapped in a thin plastic film to act as a release agent. After laying fabric and epoxy on the mold it can be placed in the vacuum bag to properly cure. If the resolution of the mold is undesirable, a
thin coat of joint compound can be applied and sanded smooth.

The vacuum bag will need to be prepared prior to the composite lay-up. The carbon fiber wing material is cut, using templates, from a stock piece of 5.5 osy carbon fiber satin weave. The proprietary carbon fiber rods are constructed with IM7 carbon tow at 200 fibers per strand on the same mold. This allows for direct incorporation to the wing surface material during vacuum bagging. Once the rod lay-up is secured, the previously cut carbon fiber weaves, are laid on top of the rods, and impregnating with epoxy. The epoxy should be allowed a minimum of twelve hours to fully cure. Once the assembly has fully cured and is taken out of the vacuum bag it can be released from the mold as seen in Figure 4. The wing is then cut to the specified shape using rotary and shear tools.

The propeller is also constructed of 5.5 osy carbon fiber satin weave in a similar fashion to the wing structure. A SolidWorks model for a mold will be created based on aerodynamic propulsion specifications and rapid prototyped using ABS plastic. This mold will not only be used to create the contour of the prop but also to act as a locating jig for drilling out the concentric mounting hole for accuracy, balancing of the prop, and cutting down on unnecessary vibrations.

Upon completion of the curing process it is necessary to use a rotary tool to gain access to the mounting hole for drilling. This should be done before the prop is taken off of the mold to insure that the hole is located correctly. Once the hole is drilled, the prop can be cut to size, similar to the wing structure.

Once the bay has cured, it can be removed from the jig and placed onto the locating and mounting jig specifically made for the bay electrical components. The bay structure is laid onto the jig locations for the receiver, camera, and transmitter cut-outs. Using aryaacynate glue, components are tacked in place. The electrical components can be wired being sure to have a “soft connection” to the batteries as not to drain the power supply.

Once the bay assembly is complete, it is necessary to mount the bay to the wing structure. This will be done with a locating fixture. The wing and bay are aligned upside down in the vertically constraining fixture. Once insured that it is located correctly, run a bead of epoxy along the length of the bay and attach small fiberglass reinforcement L-brackets at the leading and trailing edge; connecting the bay to the centerline rod. Once cured the platform structure is completed.

The wing skin chosen is 0.75mm thin a plastic film. Both wing and bay assemblies will be wrapped by hand starting from the leading edge using spray adhesive and ending at the trailing edge as tightly as possible to the surfaces without distorting the structure. After the glue has cured the excess plastic can be trimmed using a shear tool.

This system utilizes a pull-pull, cable/sheath technology for the controls actuation system. For a successful system both ends of the sheaths need to be fully secured to the structure and constrained. The cables are mounted to the aft of the control surfaces by tacking with epoxy. Once the system is routed it is ready for flight.

D. Surveillance System

To obtain a picture of the target a color video camera and transmitter must be used to stream video to the ground station. Since it was common to see camera and transmitter combinations, it was necessary to select the components as a group. The camera selection was chosen based upon weight, power consumption, and resolution. Weight, power consumption, transmission frequency, and transmission power were the four specifications that were looked at in deciding upon a transmitter. Based on past MAV teams’ successes, a minimum resolution of 300 lines is necessary. A transmitter frequency of 2.4 GHz was chosen because of its long range and vast

Figure 4. Tier one elements shown with molds.

The tier 2 elements include the component bay structure, vertical tail, and motor mount. The component bay structure is the portion of the vehicle that will house and protect the expensive and fragile electrical components such as the camera, transmitter and receiver. The bay will also act as a mounting location for the propulsion system and servos, used to actuate the control surfaces. The structure of the bay will be constructed of two layers of flat vacuum bagged 5.5osy carbon/Kevlar hybrid twill weave with incorporated vertical tail, battery bay and motor mount. A preformed location jig will specify the propulsion angle with respect to the mean camber line.
availability of transmitters to choose from. Based on these specifications, the CM-588 camera and SDX-22 receiver were chosen due to their extremely light weights.

For the ground station an antenna and a receiver must be chosen. The antenna was judged based on gain and beam width, and all of the antennas that were compared worked with a 2.4 GHz signal. Next, the required sensitivity of the receiver had to be calculated. A value for the free space and cable loss is necessary to calculate the required sensitivity. The cable losses in this setup will be small since the length of cable is short and there is only one connector. To account for cable loss the FCC budgets a negative 2 dB loss for this type of setup. With all of the unknowns determined equation 1 can be used to determine the receiver sensitivity.

\[ \text{Receiver Sensitivity} = \frac{\text{FSL} + \text{Cable losses} + \text{transmit antenna power}}{\text{Gain of receive antenna}} \] (1)

Figure 5 shows how the required sensitivity for our system changes with distance. For the competition a range of 600 meters is required and it is conservatively assumed 30% error in data transmission. Therefore the receiver must have a sensitivity of less than or equal to -71 dBm. The transmitter that was selected was sold with a receiver having a sensitivity of -92 dBm, so it will be more than sufficient. It is also important to note that both the receiver and antenna have an impedance of 50 ohms, which is necessary for the system to work correctly.

The SDX-22 transmitter and accompanying receiver were tested with an omni-direction antenna that was provided with the camera and transmitter. Testing showed that the dish antenna suggested in the preliminary design was not necessary and the omni-direction antenna assured us the 600 meter range without the worry of staying within the beam that is a large concern if the dish is used. Camera resolution testing was also completed and concluded that the target can be easily distinguished at distances of over 60 meters.

**E. Electronics**

In the preliminary design, the BMS-303 Blue Bird Ultra Servo was chosen for control surface actuation. Since then, Blue Arrow servos were found that are 0.5 grams lighter and had similar specifications. Resolution testing showed that both servos respond every time to a change in pulse width of 0.00001 seconds, which was more resolution that is necessary for the MAV to fly well. In addition, during flight testing it seemed like the Blue Arrow servos responded more precisely to control input. Because of this, and their lighter weight, Blue Arrow servos were used instead of Blue Birds.

To test the MAV’s endurance, the plane was run at full throttle with all of the electronic components running. Using a conservative estimate of flight speed of 15 mph, target acquisition will occur in approximately 1.5 minutes. Testing showed that the MAV should be capable of flying for at least 9 minutes, showing that the MAV has more than enough endurance to complete the surveillance mission.

The MAV Propulsion team determined two R/C receivers that could be used: the M5v2 Sub Micro Receiver and the GWS R-4P2H. Through testing it was determined that the R-4P2H did not have the necessary range of 600 meters and was therefore disqualified. The M5v2 worked at 600 meters and had a maximum range of approximately 850 meters; however, its size and weight were undesirable. A new receiver was found, the Hitec RCD Micro 05S, which weighs 9.1 grams compared to the M5v2 at 12.4 grams. The Micro 05S was found to have a range of at least 650 meters, meeting the necessary criterion. Therefore, the Micro 05S was used in the final design.

**F. Results**

Flight testing had to be performed to validate the planform and airfoil as well as work out any aerodynamic issues that may exist. It was decided very early that due to manufacturing time constraints it would be very beneficial to do flight testing with a solid carbon fiber wing rather than the carbon rod and plastic film discussed earlier. The wing will have an identical shape but will be able to be manufactured in less than ¼ the time. The downside is that it weighs almost twice as much, but after aerodynamic validation the weight reduction will only improve flight performance.

The foundations of the aerodynamic and flight characteristics of the MAV design were built upon
static stability requirements with margins applied to address dynamic stability. It was determined at the start of the design process that the flight testing phase of the project would be crucial in refining the design. With this in mind, an iterative test plan was developed to sequentially test the static and dynamic stability contributions of the vertical tail, center of gravity location, the motor thrust line, and most importantly the airfoil and planform design. All phases of flight testing followed the same sequence of steps. First, straight and level flight was achieved through trim. Second, an un-powered controlled left turn and controlled right turn were executed. Third, a powered straight and level flight was achieved through trim. Fourth, a powered controlled left turn and controlled right turn were executed. It was after these four steps that a plane was deemed ready for flying maneuvers and a mission.

Design flight testing began with a sequence of partial load glide scenarios, where the load mass was incrementally increased to the total flight mass and the flight characteristics were recorded. It was discovered from initial tests that if the center of gravity was located forward of ¼ chord point that aircraft would exhibit neutral longitudinal stability. The glide angle of attack also slightly increased as mass was added. For uncontrolled glide testing no roll or yaw dynamic instability was noted, however the lateral location of the CG was determined to be very important. A test apparatus was developed that balanced the MAV by a point on the tip and tail to determine the lateral location of the CG. This device was crucial in trimming the aircraft to glide straight.

For controlled glide testing the initial control surfaces proved to be ineffective, due to small size. The control surfaces were increased to 115% of their original size and effective pitch and yaw control was achieved. Control surface effectiveness was determined through glide testing because under powered flight the additional flight speed and subsequent increase in dynamic pressure would only increase control, so glide testing was seen as a conservative method for determining control surface size, however a buffer was designed in to account for known effects such as the gyroscopic force due to the spinning motor and propeller. It was also shown that small deflections in the control surfaces provided substantial control force as the XFOIL model predicted.

Powered flight testing followed controlled glide testing. The major goal of powered glide testing was to determine the effect of counter torque from the propulsion system on roll stability. This was done through a sequence of partial throttle powered glides where only a small fraction of the total thrust was used and counter weight was added the wing tip to account for the counter torque of the propeller. Various propellers were tested at various speeds and weight was added until the MAV flew at straight and level flight. A detailed analysis of counter torque was not preformed but the general rule of thumb was developed that for every inch of diameter ¾ of a gram should be added to the wing tip of the MAV. It is the recommendation that future teams devise a system to measure counter torque in a more controlled environment.

Maneuvering in powered flight followed, once counter torque was addressed. Initially, powered flight tests of maneuverability were conducted in the various gyms on campus, however it was found that the aircraft could not achieve flight speed in the small space provided and therefore was difficult to control. In addition, because the aircraft did not have an excessive amount of thrust and the pilot had limited experience, it was very difficult to perform flight maneuvers indoors. Outdoor testing provided the additional variable of wind however it was easily accounted for as pilot skill increased; in addition the ability to achieve flight speed resulted is sufficient control for maneuverability.

There were a few additional design changes that came about through flight testing. The leading edge lower surface of the wing was thickened using foam to help keep flow attached to the lower surface of the airfoil. The sharp leading edge of the composite wing cause unsteady shedding and flight instability. Porosity caused by loose weave in the carbon fiber wing was thought to reduce lift by allowing lower surface pressure to escape through the wing, so a layer of tissue paper was added to the wing that sealed all holes. In general, the durability of the pod was superb. However, the propeller, being in the front of the pod, takes a majority of every impact and has low durability. There were composite propellers available that could take the impact without breaking, but they bent the motor shaft which is much more expensive. It was determined that an additional layer of epoxy would be added at the small radius where the propeller blade meets the housing to reduce stress but it is the recommendation to any future team that they investigate propellers that are meant to bend at the hub to limit damage from impact.

G. Final Design

The final design has a 7.5” planform and was successfully flown for over 2000 meters. A competition mission simulation has not yet been completed due to lack of a good location to fly 600 meters.
Due to project time constraints it was necessary to build the final designs using a solid carbon fiber wing. Because of this, traditional control surfaces had to be used rather than the morphing control surfaces used in the carbon rod skeleton design. Furthermore, standard push-pull rods were used to actuate the control surfaces instead of the cable and sheath method designed for the morphing control surfaces.

Despite these minor shortcomings, all initial objectives were successfully completed. The final breakdown of parts and their corresponding weights is shown in Figure 6.

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**Total Weight** 96.9

**Figure 6. Final design component summary.**

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**REFERENCES**