April 2013

Design and Testing of a Flapping Wing Micro Air Vehicle

Daniel A. Pappas
Worcester Polytechnic Institute

James Vincent Nicolora
Worcester Polytechnic Institute

Lucas David Sorensen
Worcester Polytechnic Institute

Repository Citation
Pappas, D. A., Nicolora, J. V., & Sorensen, L. D. (2013). *Design and Testing of a Flapping Wing Micro Air Vehicle*. Retrieved from https://digitalcommons.wpi.edu/mqp-all/2586

Design and Testing of a Flapping Wing Micro Air Vehicle

A Major Qualifying Project to be submitted to the faculty of
Worcester Polytechnic Institute in partial fulfillment of the
requirements for the degree of Bachelor of Science.

Submitted By:

James Nicolora
Daniel Pappas
Luke Sorensen

Submitted To:

Project Advisors:

Prof. Michael Demetriou, Worcester Polytechnic Institute
Prof. Maria Chierichetti, Worcester Polytechnic Institute

April 30, 2013

ABSTRACT

The objective of this MQP is to design, test, and assess the feasibility of a flapping-wing remote controlled micro air vehicle (MAV). The group designed an MAV with a wingspan and total length of under one foot and a weight of under one ounce, similar to existing projects. The group then manufactured, assembled, and performed several tests on a prototype of the MAV. Finally, the group proposed design improvements and recommendations for future work at WPI.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Within recent years, interest in unmanned aerial vehicles (UAVs) has experienced a steady rise. In particular, micro air vehicles (MAVs) hold a special interest among engineers for both civil and military applications. MAVs that fly using flapping wings hold great potential for indoor reconnaissance and hovering observation.

The objective of this project is to build a small flapping wing vehicle that possesses a wingspan of approximately 1 ft. (30cm) and weighs approximately one ounce (28g). This vehicle should be capable of vertical takeoff and landing (VTOL) as well as high maneuverability for indoor environments.

1. 1 Background

Our team is far from the first group to take on this challenge. There have been numerous other attempts to replicate flapping bird and insect flight from a mechanical device. Notable projects that we examined were the RoboBee at Harvard University, the Mentor at University of Toronto, and the Delfly at TU Delft.

Professor Wood and his team at Harvard University have made great strides in developing a robot capable of hovering and flight that is of similar size and weight to a common insect. The University of Toronto's Mentor robot and Delft University of Technology's Delfly both use parts modeled on natural flapping wing animals as well as integrating parts similar to conventional aircraft. Both Delfly and Mentor are biplane MAVs utilizing four wings in what is known as a clap and fling method for obtaining lift and thrust.

1.1.1 University of Toronto Mentor

Mentor at the University of Toronto was among the first radio controlled MAV's to achieve hover using 4 wings in a clap and fling motion, as shown below in Figure 2.

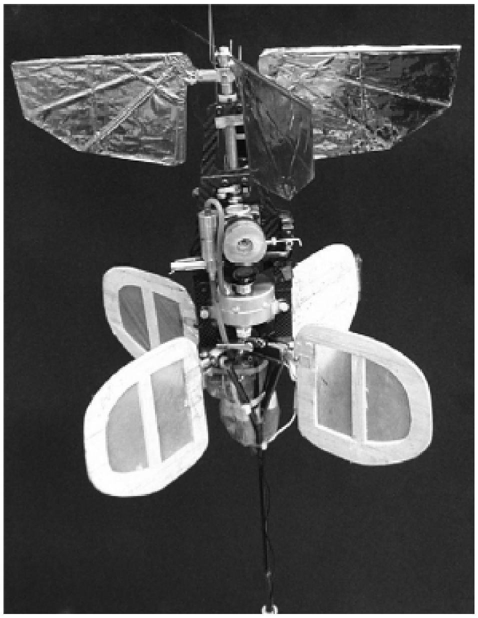


Figure 1: Toronto Mentor Project

Mentor proved the viability of the clap and fling method and the possibility that such a device could be stable while under remote control without any sort of autopilot. Mentor was designed to have a similar wingspan at 26cm but a much higher weight than our project calls for. Mentor had two configurations: one with an internal combustion engine (ICE) and another on battery power. The ICE method weighed 580g – a fourth of that being the fuel and motor. The battery powered method could not make use of relatively recently developed Lithium-Ion batteries but instead used much more inefficient Nickel Cadmium. This resulted in a weight of 440g – over half of which was allocated to the motor and batteries. Mentor was never intended to emulate any actual bird or insect. It was proof the clap and fling method could be used to achieve stable lift and hover even with a relatively heavy aircraft. This inspired the WPFly design as it pointed the group in the direction of clap and fling research.

1.1.2 TU Delft Delfly

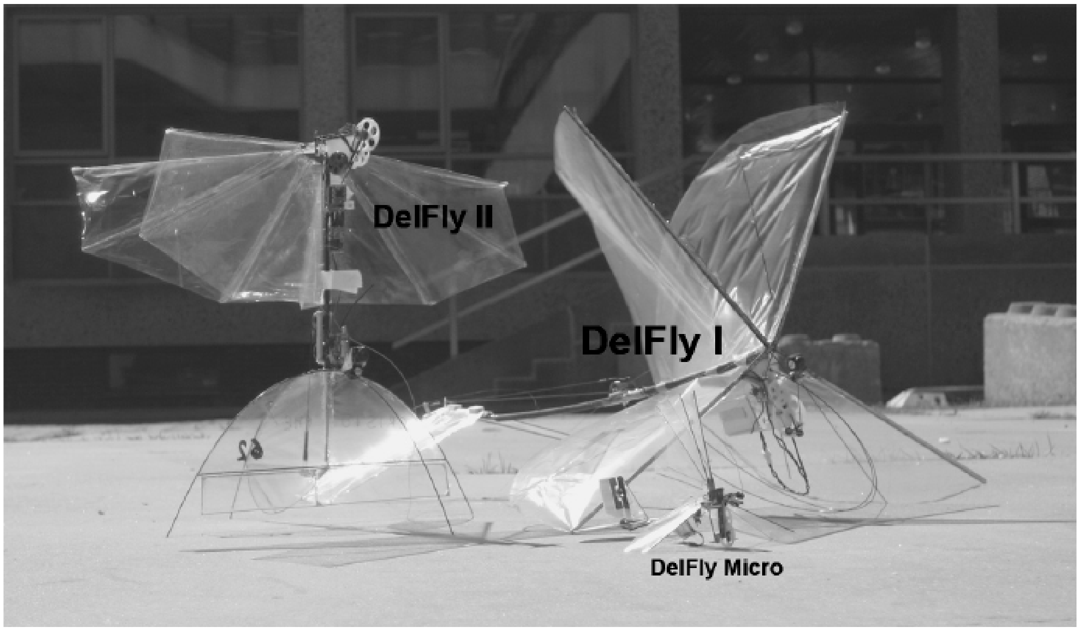


Figure 2: DelFly II (Left), DelFly I (Right), DelFly Micro (Front) ***(De Croon, G. 2009)***

Delfly has existed in three major forms. The first, Delfly I, is an MAV capable of forward flight as well as slow near-hovering flight. DelFly I weighed 21g with a wingspan of 50cm. Like all prototypes, Delfly I suffered from a number of problems relating to stability, control, and reliability. Its inverted V tail allowed for stable forward flight but created difficulty in controlling attitude changes. Delfly I's drive train was designed so that as the motor turned, a Z shaped crank would rotate causing the wings to move up and down. This method was difficult to sync and resulted in the craft experiencing slight rolling during flight. Also, the motor did not possess a high efficiency which, along with it not being brushless, caused it to build up heat during flight. This decreased reliability caused for frequent motor replacements.

Figure 3: Delfly I Drivetrain ***(Bruggeman, B. 2010)***

The project was later redesigned with many of these flaws corrected into the DelFly II. This model was smaller and lighter, weighing only 16g with a wingspan of 28cm. The drive train was completely redesigned to eliminate the rolling motion present in DelFly I. Additionally, the revamped design included custom-made high-performance components, such as a custom brushless motor capable of much higher efficiencies and a custom microcontroller for experiments with autonomous flight. The tail was redesigned to use a classic cruciform tail seen on most model aircrafts to allow for pitching and yawing motions which the vehicle was previously incapable of. This vehicle was capable of both indoor and outdoor flight, as well as maintaining the stability required to have a camera as payload. This design has been the subject of numerous research projects on optimizing the flapping motion and increasing lift as well as various controls and autonomous flight experiments.

1.1.3 Harvard University RoboBee

Robert Wood and his team at Harvard University recently developed a very small robot that very closely mimics a flapping insect. By making use of piezoelectric actuators, the wings have three degrees of freedom. The robot does not have a tail and makes its attitude adjustments through manipulating its wings. This is the same as how an actual insect flies and controls itself. The robot suffers from scaling issues and the device requires external power, for no commonly available power source is small enough to fit onboard. The lack of a tail and any sort of control sensor also results in unstable flight; most tests only run for a few seconds until the aircraft loses control. RoboBee is a marvel of engineering, using novel miniaturization and manufacturing techniques; however, with a wingspan of just one inch, its scale is smaller than the scope of this project and was not heavily considered in our design.

1.2 Clap and Fling

The clap and fling method is a method of flapping that generates more lift then conventional beating of wings. It can be seen being used in nature by sparrows and some species of fly. Mechanically the clap and fling works by rapidly bringing two wings together beginning with the leading edge. The leading edges touch and flexible wings will follow in a phenomenon known as feathering. As the wings come together air is pushed out the back generating thrust, which when angled properly will create lift. Once the wings are together they immediately begin to peel apart allowing air to rush in from the front. This suction also creates thrust, pulling the wings forward. From an outside perspective the air is being circulated around the wings, which creates lift under the Kutta condition. The wing is rapidly moving though air resulting in unsteady flow and vortices forming around the leading edge. These vortices will interact in ways not yet understood with the vortices coming off the edge of the wing creating additional lift. All of these phenomenon together are illustrated below.

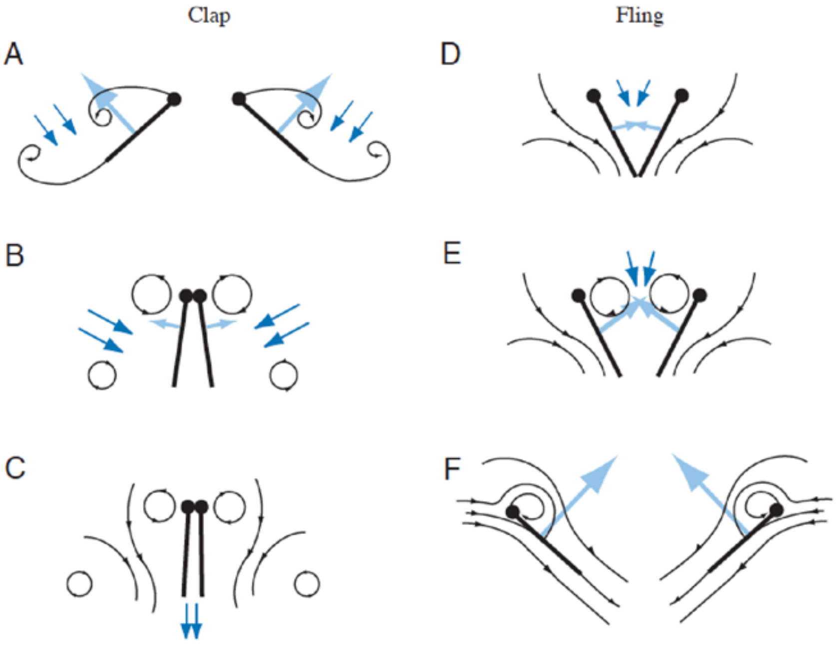


Figure 4: Clap and Fling Method ***(Sane, S.P. 2003)***

1.3 Organization of the Work

The following chapters will detail the design, manufacturing, and testing of this project's flapping wing MAV. The design section will explain the design objectives and material selection for each component of the MAV. The manufacturing section will detail the manufacturing processes associated with each component. The testing section will explain tests run on the components to ensure they will not fail.

2. DESIGN

The group sifted through the literature to gain insight into the motion of flapping wings and how they generate lift. Previous projects involving flapping wing MAVs inspired the group and provided a foundation from which to base the WPFly.

The modeling process began with a basic idea of what the group was hoping to achieve with this project – a relatively small flapping wing vehicle capable of vertical takeoff and landing, hover, and horizontal flight. Through research, that it was decided that mimicking a two-wing bird or insect would be rather difficult and unreasonable, for these animals move in a very complex manner. Through more research and the discovery of the clap-and-fling method of flight, the group decided upon a four-wing vehicle with tail surfaces to provide stability and control. This would be easier to model and manufacture than the motion required for a two-wing vehicle to take flight.

As the group continued to model the MAV, the next step was to choose which components and materials would be used in the design. In the development of the body, and wings, the group researched materials that were lightweight, yet durable enough to withstand impact and rapid movement. The group also researched materials that could be manufactured on the WPI campus to conserve the financial budget. Also involved in the design are several electronic components: a battery and adapter, a motor and speed controller, three actuators, a receiver, and a transmitter. These components must power the MAV, flap the wings, and control the tail surfaces, while still fitting within the proposed weight budget. Detailed descriptions of these components and their purpose, as well as why the group chose each specific item, will be included in this section. An isometric view of the current design is seen in Figure 5.

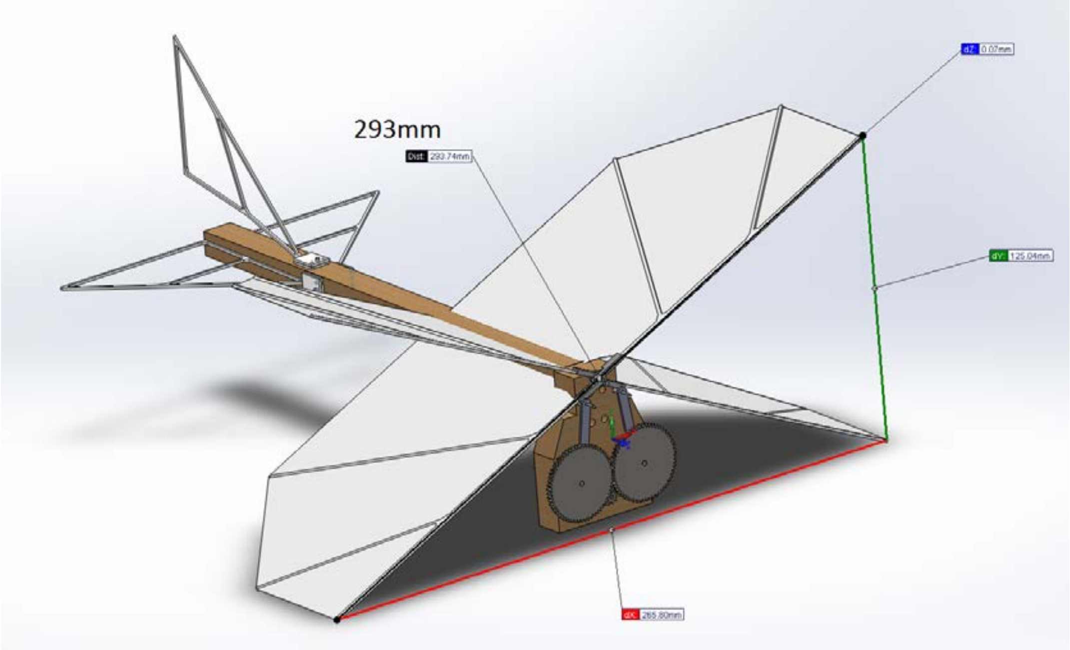


Figure 5: Isometric View of the SolidWorks Model

2.1 Body

Because weight is a significant design constraint, the group eliminated metals as an option for the body material and instead decided to research composites and polymers. The group eventually narrowed the field to two different materials. The first, balsa wood, had been used in previous flapping wing MAVs. The group also found a polymer, Polymethacrylimide foam, that is often used in sandwich construction and less dense than balsa wood. This foam is easy to shape, as it can be sliced with a hot-wire foam cutter, and also adhesive to epoxy, which would aid in the construction of the MAV. However, this foam is less widely available than balsa wood, and thus more expensive. Balsa wood would be easy to customize in-house, for it can be easily cut and sanded to the desired size and shape. Although balsa is denser than the polymer foam, the body is small enough for this weight difference to be minimal. Because balsa wood is cheap, customizable, and durable, the group selected it to build the body of the MAV.

The shape of the body was designed to be simple and lightweight. There is a solid piece running from the tail to the nose, where there is another section designed to mount the drive train and hinge. The length of the body was designed to match the wing span, thus keeping the MAV as small as possible while making control feasible as well.

The body shape was finalized for ease of manufacturing and for simplicity as well. The finalized drive train was used to design the front part of the body, and a very simplistic final design was chosen. Minimizing the frontal area mitigates drag losses due to the frontal profile. To connect the slim body structure to the front portion, a simple approach was taken. Milling out a section on the front piece that the back section could be slotted into and glued gave the body stability and strength. The finalized body was rather simplistic, and its design can be seen in Figure 5.

2.2 Wings and Tail

For a design involving four wings, it is crucial for each wing to be as lightweight as possible. For this purpose, the group decided to research thin polyester films to comprise the wing, and lightweight spars to provide support and allow for the clap and fling effect.

While researching different wing shapes, the group took previous MAVs and manufacturing techniques into consideration. The design, mostly rectangular in shape, was selected to mimic that of the DelFly. This design will prevent the wing spars from being overly complicated and flimsy, while still keeping much of the surface area necessary for lift. The design is tapered at the outer edge of the trailing edges, allowing for the support spar to bed closer to the leading edge and preventing the backside corners of the wings from being unstable during flapping.

The group also researched multiple designs for the tail structure. The first option considered was an inverted V-tail. This requires only two control surfaces, however the MAV would not be highly maneuverable. This is demonstrated by the DelFly, where the V-tail was abandoned due to inadequate control of longitudinal motion in wake of the flapping wings (De Croon, G. 2009).

Because maneuverability is a primary objective of this project, the group researched traditional cruciform tails. The use of a rudder and two unlinked elevators allows for higher maneuverability than an inverted V-tail. Three servos are used to control each surface and allow the MAV to yaw, pitch, and roll. Although the group originally selected this style as its final tail design, it was later discovered that a redesign was necessary for manufacturing purposes. The group realized the design was slightly too complicated to manufacture on campus, especially given its small scale and delicacy.

The new tail still consists of two elevators and a rudder, however the entirety of each surface is a movable control surface. This design is simpler to manufacture than attaching elevators onto the horizontal tail, and is expected to allow for more control during flight. The tail redesign, including the control disks and actuators, is shown in Figure 6. The control devices for the tail were designed so the controllers could be created using a sandwich method of a cheaper plastic, to make manufacturability easier, and to make a stronger controller than the original design. These discs can be seen in Figure 6.

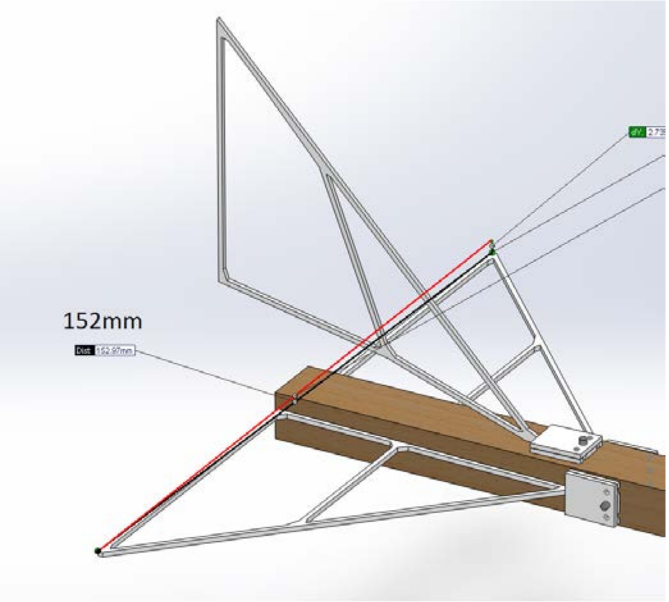
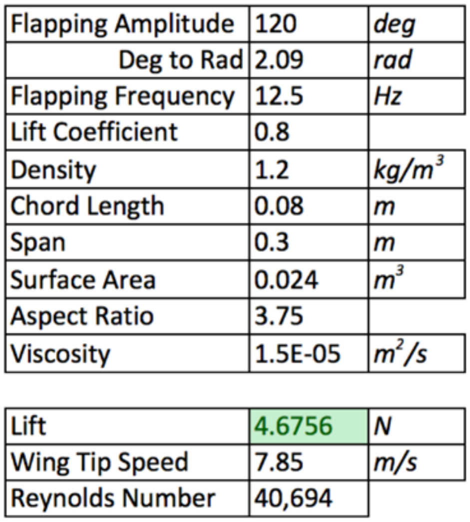


Figure 6: SolidWorks CAD Model of Tail Structure

To finalize the size of the wings, the group used a lift equation found through literature. This equation is an estimated equation derived through testing of rectangular flapping wings. Although this wing shape is not rectangular, the group used the equation shown below as a preliminary estimate.

$$L_{rect} = \varphi_0^2 \cdot \pi^2 \cdot f^2 \cdot C_L \cdot \rho \cdot c_0 \cdot l \cdot \frac{1}{3}$$

In this equation, φ is the flapping amplitude, f is the flapping frequency, C_L is the lift coefficient, assumed as 1, ρ is the air density, c_0 is the chord length, and l is the wing span. Implementing our values into this equation yields a lift value high enough to provide lift to our vehicle. This equation is summarized in the table below.



Flapping Amplitude	120	*deg*
Deg to Rad	2.09	*rad*
Flapping Frequency	12.5	*Hz*
Lift Coefficient	0.8	
Density	1.2	*kg/m^3*
Chord Length	0.08	*m*
Span	0.3	*m*
Surface Area	0.024	*m^3*
Aspect Ratio	3.75	
Viscosity	1.5E-05	*m^2/s*

Lift	4.6756	*N*
Wing Tip Speed	7.85	*m/s*
Reynolds Number	40,694	

Figure 7: Lift Equation Results

After finalizing the size and shape of the wings and tail, the group researched materials to form the spars and membrane. These materials would need to be as lightweight as possible, but strong enough to flap without failing.

Upon investigating WPI's 3D printers, the group discovered that the available plastics were not strong enough to withstand the rapid movement and clapping of the wing spars. Taking these demanding applications into account, the group researched common durable materials such as titanium alloys, carbon fiber, and Polyether ether ketone (PEEK). All three materials would be strong enough to support the wings, but the group chose PEEK, the least dense of the three. PEEK, a thermoplastic, is known for its robustness and high performance, and is often used in applications requiring movement, such as pistons and bearings. PEEK's only downfall is its price; however, after reviewing the budget, the group decided it would be worth it for its strength and reliability. Once the group chose PEEK as the spar material, it was time to focus on a membrane that could be effectively bonded to it.

Through literary research, the group discovered that a polyester film, commonly referred to as Mylar, has been successfully used to create wing membranes in other MAVs. Mylar is widely available and can be manufactured into extremely thin sheets. Although only fractions of a millimeter thick, these sheets have proven to be tear-resistant when used on flapping wing MAVs, such as the DelFly (De Croon, G. 2009). Mylar also adheres well to epoxies, and holds well long after drying. For these reasons, the group purchased a roll of 26 micron (0.026mm) thick Mylar.

2.3 Hinge

A hinge is necessary to hold the four wings together and allow a flapping motion that brings the leading edges together. The group originally chose aluminum 6061 as a material. This would withstand the rapid movement without failure, and because the hinge is so small, would not add a considerable amount of weight to the MAV. The symmetry of the hinge allows for the same part to be manufactured twice and pinned together. The original design was intended to be easy to manufacture, but due to its tiny size, the group had to further simplify the design.

This simpler hinge, although more angular than the original, was not as practical to manufacture as we hoped. We discovered through talking with shop supervisors in Higgins that this design would be impractical to manufacture out of aluminum, and a 3D printed version was creating using WPI's 3D Objet printer.

2.4 Drive Train

The motion of the hinge will be created by a drive train connected to the motor. The group considered two different drive train options. The first contained gears that would spin parallel to the axis of forward movement (with their axels perpendicular). Although this design has been successfully implemented onto previous MAVs, it was dismissed due its complicated drive train and the effect that gyroscopic forces would have on flight.

Instead, the group chose a method involving two counter-rotating gears, spinning perpendicular to the forward movement of the MAV (with their axels parallel). Mechanically, this design is more simple and easier to construct, and due to the counter-rotation, the gyroscopic forces would be minimized.

From our motor tests we discovered that a drive train ratio of 6-66 would be desirable, and we ordered gears to match this design. This would give us an acceptable drive train assembly, and this drive train can be seen in Figure 7. This drive train is simplistic and secure, so we are anticipating minimal issues with its assembly.

For the design of the drive bar and the other design parameters, we used SolidWorks to created and test the kinematics of the drive train. This process can be seen in Figure 8.

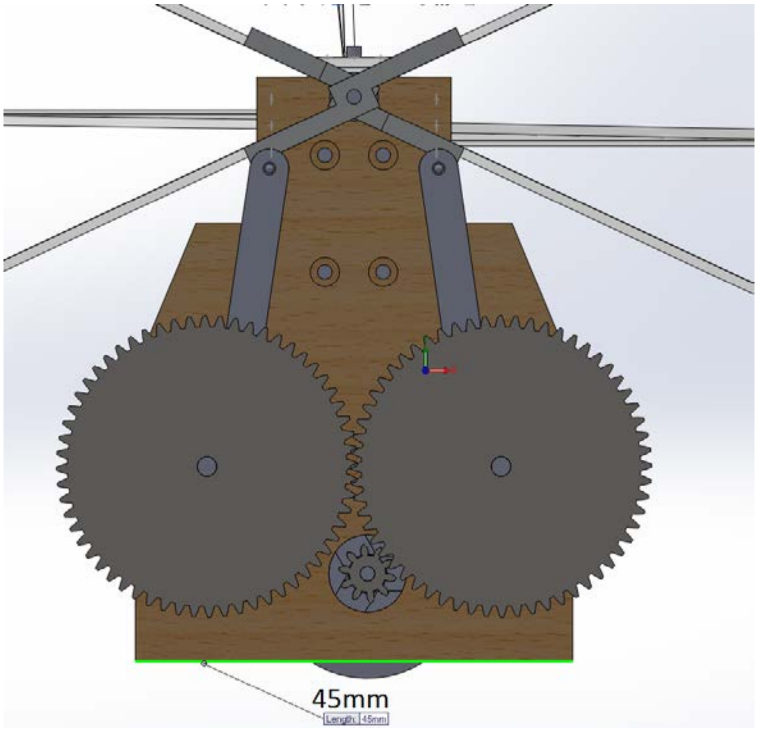


Figure 8: Finalized Drive Train

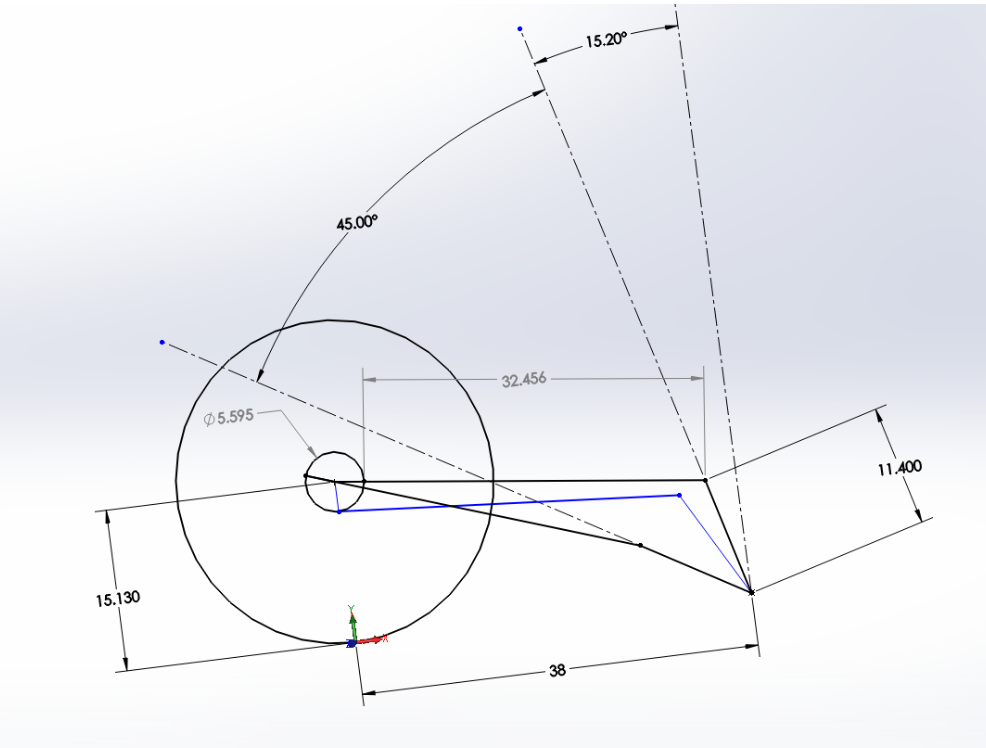


Figure 9: Kinematic Model of the Drive Train Used for Parameter Determination

2.5 Battery

Lithium polymer batteries are commonly used in remote controlled planes and MAVs. These batteries are fairly cheap and lightweight, which allows for longer and smoother flights. After researching many lithium polymer batteries, the group settled on a one cell, 160 milliampere-hour, 3.7 volt battery from the vendor DraganFly (rctoys.com). The group researched both batteries and motors together, for the battery must have the ability to run the motor. The battery voltage is crucial, for if it is below the nominal voltage of the motor, the motor will not start. The electrical charge of 160 mAh is comparable to batteries used in other small ornithopters. This battery was also selected for its small mass of 4.1 grams and slender profile that will allow it to fit nicely into the body of the MAV.

2.6 Motor

The group researched different types of motors and decided that a brushless DC motor would be most appropriate for this project. Brushless motors have several advantages over brushed motors. They have more torque per weight, and more torque per watt, making them more efficient. Brushless motors have increased reliability, leading to a longer lifetime. The group narrowed the motor selection down to two: the Hobby King AP-02 Brushless Micro Motor, and the Micromo Series 1307 004 BH brushless geared motor, each of which weigh less than 2.5 grams.

The group initially selected the 1307 Series motor. The 1307 motor includes an integrated gear head. There are several ratios available, ranging from 6:1 to 659:1. With a 6:1 ratio, the output speed is estimated at 1639 rpm. Once loaded, this ratio would be appropriate for the projected flapping frequency of ~13 Hz.

This frequency was selected through an analysis run in SolidWorks on the modeled wing spars. Animating the spars to flap at various amplitudes, the group discovered that the PEEK spars have a natural frequency of ~13 Hz. Matching this frequency allows for the maximum amount of lift.

This motor also includes built-in hall sensors (tachometers) that can measure the true rpm of the loaded motor. The integrated gear head and hall sensors would conveniently spare the group from purchasing and assembling its own gears and tachometer. Even with these extra components, this motor weighs an impressive 2.1 grams.

However, after a review of the financial budget and further research into power requirements, the group decided that the 1307 motor would not suffice. The output power of this motor is a trifling 0.157 Watts, whereas the AP-02 can reach up to 7 W. Although the AP-02 does not have an integrated gear head or built-in tachometer, it is almost equally lightweight (2.3g) and will provide the power necessary to flap the wings. The AP-02 is also less than one quarter of the price of the 1307, which helped the group finalize its decision.

2.7 Actuators and Receiver

Because the tail will have three separate control surfaces, it will require three actuators to control these movements. The group initially settled on the Toki Biowire servos from HobbyKing. Weighing only 1 gram each, these servos are fairly light, and their slender shape would allow for easy integration with the rear end of the fuselage. These servos would be able to rotate the elevators and rudders 30° in both directions. However, after further research, the group discovered Plantraco Microflight's 1.1 gram magnetic actuators. With the same range of motion and weight, this became the group's primary choice. These actuators also cost half as much as the Biowire servos, which will make an effective difference when purchasing three. Because these actuators are magnetic, the original plan to use small metals brads to fasten them to the body was replaced with the design of three actuator mounts. These mounts, made from PEEK, could be cut using the Washburn Shops laser cutter.

The Plantraco website recommends the Micro9 3 Channel PlugnPlay 0.9g Receiver as a compatible receiver option. The Micro9 is designed to work specifically with the selected actuators, simplifying installation and control. With 4 channels, a range of 100 meters, and a weight of 0.95 grams, this receiver is ideal for the group's design intentions.

2.8 Transmitter

The team encountered issues with finding a transmitter suitable for this project. The receiver is designed to operate on a 900Mhz frequency. The group sought to find a 900Mhz transmitter on campus, however all of the transmitters owned by WPI professors unfortunately operate on either 2.4Ghz or 72Mhz. These are the most common frequencies for RC aircraft in the US and 900Mhz is hard to find. This is because in the USA, 900Mhz is right on the edge of the cell phone band, so amateur radio applications like RC planes stay away from that range. However, our receiver was manufactured in Canada where the cell phone band ends at 850Mhz, allowing RC applications to extend further.

Some older transmitters made for robotic applications have been made to operate on the correct frequency. One such transmitter was obtained by the team from the local FIRST robotics chapter. This transmitter was designed to plug into a computer and simply serve as a transmitter for a ground station. Finding documentation for the controller, a cable to attach to a computer, and programming a ground station would have been very difficult for the limited time available to our group. The team decided to pursue other options.

The team decided to purchase a transmitter from plantraco, the same vendor for the actuators and receiver. This circumnavigated the problem entirely as this transmitter is 900Mhz and designed to work specifically with Plantraco products. The transmitter has controls for throttle, rudder, elevators, and ailerons. Since this design calls for two seperatly moving elevons and a rudder the aileron and elevator control will both be used to control the flaps.

2.9 Microcontroller

The group originally planned on programming the MAV to run autonomously. If this is the case, a microcontroller is necessary. However, the group determined autopilot is not a primary objective of this project, and using a transmitter to control the MAV remotely is a much more practical option. In future developments and experiments with autopilot, the group recommends a microcontroller such as the Arduino Pro Mini, which has several analog and digital inputs and has been widely used at WPI. This MAV, however, will not contain a microcontroller as it is outside the scope of this project.

3. MANUFACTURING

3.1 Wing Spars

The wing spars, tail spars, and actuator mounts are cut using the laser cutter in Washburn Shops. Because the final material is rather expensive, the group test cut the polystyrene first to ensure the final design would be successful on the first attempt. The first cut proved the wing spars were much too thin, and needed to be reinforced before final cutting. The tail structures were successful, but they too were chamfered at the corners to keep them from failing under unforeseen circumstances. After this slight redesign to strengthen the joints, the group ran another test cut with improved results. The wing spars manufactured successfully and are much stronger than the first cut. The strengthening on the tail is also noticeable from the previous cut. Because there is PEEK remaining after the completion of the wing spars, it is also used to manufacture the drive train bars and the actuator mounts. Because the drive bars move rapidly and experience both tension and compression during each rotation, PEEK's strength and durability make it an ideal material. This also makes PEEK a prime candidate for the actuator mounts, as they must be strong enough to hold the actuators in place in case of a flight mishap or crash.

Although the PEEK is very strong and durable, the laser cutter is able to make clean cuts through it with the proper settings. With these settings, every piece needed is manufactured using only one 12" x 12" sheet of PEEK. Additionally, there is a sizeable difference between the quality of the plastics; the wing spars performing much better than their counterparts did. The difference in quality is evident though examination of the settings used to laser cut the parts. To cut through the PEEK, the machine requires maximum power at a very low speed, whereas the HIPS can be cut much faster at a lower power.

	Power	Speed	PPI	Depth
PEEK	100%	12%	1000	0.04 “
HIPS	75%	40%	500	0.04 “

Table 1: Laser Cutter Settings - PEEK vs. HIPS

3.2 Body

The body was designed so that it could be easily manufactured using the laser cutter and then finalized on a milling machine. A sturdy design for the body was achieved using this method and was glued together to create a very solid base for the MAV. Two iterations of the body were created however, because on the first iteration the laser cutter’s power settings were set too high and the holes became too large. On the second attempt only the outline was done on the laser cutter and the holes were put in afterwards by hand with the milling machine.

3.3 Control Discs and Washers

The control discs, as shown in Figure 6, and washers were manufactured from High Impact Polystyrene (HIPS). Because the control discs have a small gap in them, for the attachment of the PEEK tail frame, a sandwich method was used to allow for manufacturing with the laser cutter.

The HIPS was also used to manufacture washers for the rotating parts, such as the motor. These washers protect the body of the MAV and also help these parts spin smoothly.

3.4 Final Assembly

After manufacturing the individual parts, assembly was rather straightforward. The hinge, gears, drive bars, and control discs could all be fastened to the body with small metal brads. Super glue is very effective in attaching the spars to the hinge, as well as the actuators to the mounts and subsequently, the mounts to the body. A photograph of this assembly is shown below in Figure 10.

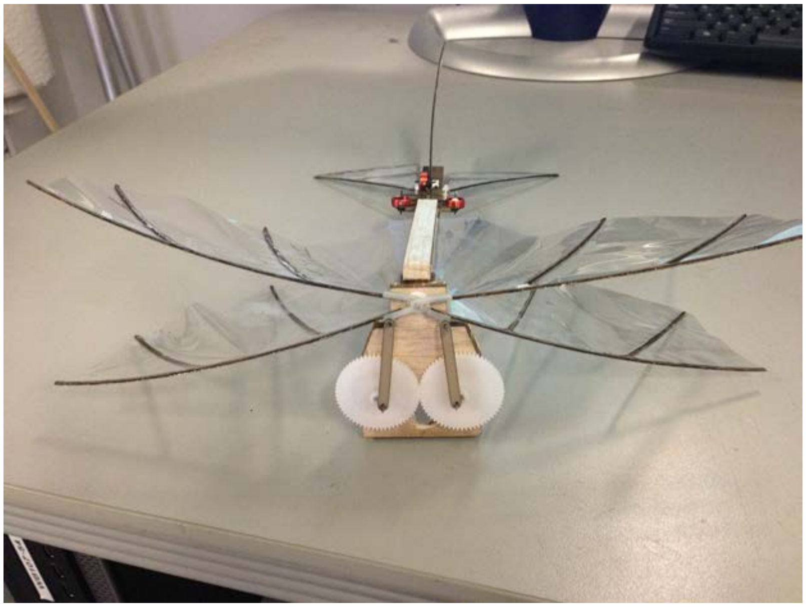


Figure 10: Photograph of the complete assembly.

4. TESTING

4.1 Motor Testing

The team performed a test on the motor to verify that it operated as intended and its power output was as stated by the manufacturer. For ease of testing, the receiver/transmitter was replaced with an Arduino Uno board. This allowed for far greater throttle control over the motor. Based on documentation for the motor controller, it was established that the correct duty cycle at full throttle had a pulse duration of 2ms and the low throttle was 1.1ms. This was programed into the Arduino and an oscilloscope was used to verify the signal clarity. Because the Arduino nominally outputs 5V, a voltage divider was created to lower the voltage to 3.7V. A 4kΩ and a 3kΩ resistor were used to reduce this voltage while still maintaining a clear signal to the motor. In order to start a brushless motor, the throttle must first be set at full, then zero, then some middle throttle. The board was programed to output this and then run at 80% throttle continuously. To test the total output of the motor system, enough torque was applied to stall the motor while the total current draw was measured, based on the formula $W=A\times V$

The group was able to determine at 3.7V and full throttle the motor draws .3A, giving a total of 1.1W of power.

4.2 Drive Train Testing

After assembling the drive train, a test was performed to ensure that the gears and drive bars would perform properly. Because the motor had not yet been mounted to the body, this was done through the use of a drill. The drill, with the smallest gear attached to the drill tip and locked into one of the larger gears, was spun at increasing speeds. The drive train functioned properly, moving the hinge so that the wings flapped in a symmetrical manner.

4.3 Electrical Component Setup and Testing

The electrical components operate in two basic control loops that are then connected together. The first control loop is the actuators, transmitter and receiver working together to provide stability and control. The actuators are "plug and play" with the receiver and respond well to controls from the transmitter. The receiver has magnetic points where a power supply can be attached. At rest the receiver draws 40 mA of current and when the actuators are moving the current draw peaks at 200mA. The second control loop involves the motor and electronic speed controller or ESC. All brushless motors require an ESC to function. The ESC takes signals from the receiver and coverts them into a pulse with modulation signal (PWM). A PWM signal is an analog signal that behaves similar to a digital signal. It fluctuates between high and low voltages and the ratio between the time it is high and the time it is low is known as the duty cycle. Our receiver outputs a signal known as Pulse Position Modulation. This signal is very similar to a PWM signal except it outputs a larger magnitude of voltage. The ESC is capable of converting between the two automatically and the motor will be directly connected to the receiver.

4.4 Actuator Testing

Before mounting the actuators to the body of the MAV, tests are conducted to ensure that the actuators function properly and can be controlled in tandem by the dual joystick transmitter. Each of the three actuators is wired into the receiver so that the two actuators corresponding to the left and right elevators could be controlled with horizontal movements of the left and right joystick, respectively, and so the rudder's actuator could be controlled with vertical movements of the right joystick. This would leave the vertical axis of the left joystick to interact with the motor's speed controller. Because this test was successful, the group attached the actuators to the body using the PEEK mounts. Next, a test is performed to ensure that the actuators were powerful enough to move the tail structure. Unfortunately, with the current design, the actuators were unable to spin the control discs and move the tail. A solution to this is to design control discs with larger moment arms, thus allowing for the same actuators to move the tail.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The design process detailed by this report began with an examination of the project objective. This is to build a flapping-wing micro air vehicle capable of vertical takeoff, hover, and forward horizontal flight. After a thorough literary review, it was decided that the wing movements of most birds and insects is very complex with twists and other motions that are not yet fully understood by experts. Because of this a four-wing design, utilizing the clap-and-fling effect, was selected. This allows for the design of a vehicle capable of flight with a simplified wing motion. These wings are attached to a symmetric hinge that is powered by a motor. A battery powers the motor, allowing for free flight with an onboard power source. Aside from the main wings, the design also includes a tail structure, composed entirely of two elevators and a rudder. Allowing full movement in each component of the tail structure simplifies both the design and manufacturing processes.

5.2 Recommendations

For future improvements on this project, the group recommends a more careful selection of electronic components. Focused mainly on the weight and financial budget, the group ordered the electronic components from multiple manufacturers. This led to a compatibility gap between the components, which slowed the manufacturing and assembly processes considerably. In future years, teams must continue to focus on their budget, but must place more emphasis on compatibility before placing orders for electronic components.

One improvement that may alleviate this problem would be the inclusion of a robotic expert, either within the MQP team or as a co-advisor. This may allow the team to predict design flaws and take measures to prevent them in advance.

Another area for improvement may be the wing spar material. Originally it was a struggle to manufacture the durable PEEK, however the group eventually found the proper laser cutter settings to cut it with ease. PEEK is a good selection for wing spar material, because it is extremely strong and durable, and its flexibility allows for the motion necessary to achieve the clap-and-fling effect. However, PEEK is a very expensive material for the amount obtained. In future years, teams may seek a cheaper material with similar material properties as PEEK. An additional area for design improvement is in the hinge. The hinge the group manufactured was structurally too weak for the frequency required for lift, but a simple increase in size and thickness should make a printed hinge feasible for this application.

These are some improvements that future MQP teams should take into consideration. It is important to design the vehicle with respect to the weight and financial budgets, but also to avoid the budgets from hindering the success of the design.

REFERENCES

Agrawal, S. K., Madangopal, R., & Khan, Z. A. (2004). Biologically inspired design of small flapping wing air vehicles using four-bar mechanisms and quasi-steady aerodynamics. *Journal of Mechanical Design,* , 1-8.

Bruggeman, B. (2010). Improving flight performance of DelFly II in hover by improving wing design and driving mechanism. *Delft University of Technology M.Sc.Thesis,*

De Croon, G., De Clercq, K., Ruijsink, R., Remes, B., & De Wagter, C. (2009). Design, aerodynamics, and vision-based control of the DelFly. *International Journal of Micro Air Vehicles, 1*(2), 71-97.

GAJBHIYE, S., UPADHYAY, S., & HARSHA, S. (2012). FREE VIBRATION ANALYSIS OF FLAT THIN MEMBRANE. *International Journal of Engineering Science, 4*

Groen, M. (2010). PIV and force measurements on the flapping-wing MAV DelFly II. *Delft University of Technology M.Sc.Thesis,*

Hara, N., Tanaka, K., Ohtake, H., & Wang, H. O. (2009). Development of a flying robot with a pantograph-based variable wing mechanism. *Robotics, IEEE Transactions on, 25*(1), 79-87.

Harmon, R. L. (2008). *Aerodynamic modeling of a flapping membrane wing using motion tracking experiments* ProQuest.

Krashanitsa, R. Y., Silin, D., Shkarayev, S. V., & Abate, G. (2009). Flight dynamics of a flapping-wing air vehicle. *International Journal of Micro Air Vehicles, 1*(1), 35-49.

Maxworthy, T. (1981). The fluid dynamics of insect flight. *Annual Review of Fluid Mechanics, 13*(1), 329-350.

Michelson, R. C. (2004). Novel approaches to miniature flight platforms. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 218*(6), 363-373.

Miller, L. A., & Peskin, C. S. (2005). A computational fluid dynamics ofclap and fling'in the smallest insects. *Journal of Experimental Biology, 208*(2), 195-212.

Mueller, D., Bruck, H., & Gupta, S. (2010). Measurement of thrust and lift forces associated with drag of compliant flapping wing for micro air vehicles using a new test stand design. *Experimental Mechanics, 50*(6), 725-735.

Pornsin-Sirirak, T. N., Lee, S., Nassef, H., Grasmeyer, J., Tai, Y., Ho, C., & Keennon, M. (2000). MEMS wing technology for a battery-powered ornithopter. Paper presented at the *Micro Electro Mechanical Systems, 2000. MEMS 2000. the Thirteenth Annual International Conference on,* 799-804.

Sane, S. P. (2003). The aerodynamics of insect flight. *The Journal of Experimental Biology, 206*(23), 4191-4208.

Shyy, W., Aono, H., Chimakurthi, S., Trizila, P., Kang, C. K., Cesnik, C., & Liu, H. (2010). Recent progress in flapping wing aerodynamics and aeroelasticity. *Progress in Aerospace Sciences, 46*(7), 284-327.

Taylor, G. K. (2001). Mechanics and aerodynamics of insect flight control. *Biological Reviews, 76*(4), 449-471.

Whitney, J., & Wood, R. (2012). Conceptual design of flapping-wing micro air vehicles. *Bioinspiration & Biomimetics, 7*(3), 036001.

APPENDIX

Weight and Financial Budget

MATERIALS LIST				
Component	**Weight (g)**	**Cost ($)**	**Vendor**	**Item**
Transmitter	--	$77.58	Plantraco Microflight	HFX900 M2 Transmitter with 10mm Bahoma
Battery	4.10	$33.98	rctoys.com	160mAh 1-Cell 1S 3.7V
Motor	2.30	$39.98	Hobby King	AP-02 7000kv Brushless Micro Motor
Speed Controller	0.70	$23.71	Hobby King	XP 3A 1S 0.7 g Brushless Speed Controller
Actuator	3.30	$44.97	Plantraco Microflight	MiniAct Magnetic Actuator - 1.1g
Receiver	0.95	$73.04	Plantraco Microflight	Micro9 4 Channel PlugnPlay Receiver
Wing/Tail Membrane	--	$39.50	Professional Plastics	.001 X 48in X 96in Clear Mylar
Wing/Tail Spars	4.63	$130.00	Ultimate Plastics	PEEK
Drive Train Bars	0.34	--	Ultimate Plastics	PEEK
Actuator Mounts	0.45	--	Ultimate Plastics	PEEK
Body	9.00	$12.73	A.C. Moore	Balsa Wood
Hinge	Unknown	$0.00	WPI	Objet 260 Connex: VeroWhite
Gears	Unknown	$17.45	Gizmoszone	3 8-tooth, 3 60-tooth, 4 2mmx30mm shaft
Miscellaneous	Unknown	$17.21	Various	Fishing Line, Gorilla Glue, Brads
TOTAL:	25.77	$510.15		
ACTUAL:	34.50			

Table 2: Weight and Financial Budget.

Prototypes

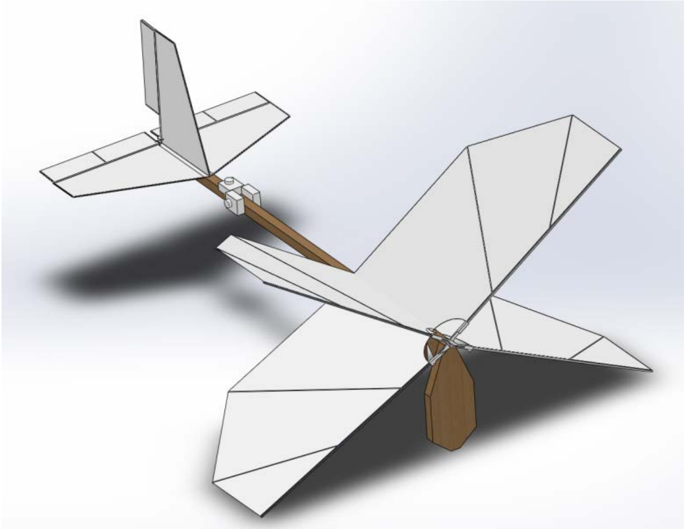


Figure 11: Isometric Drawing of First Prototype

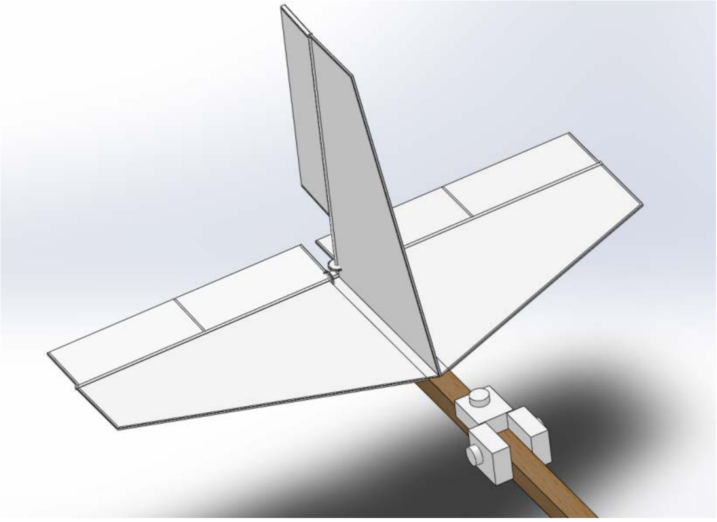
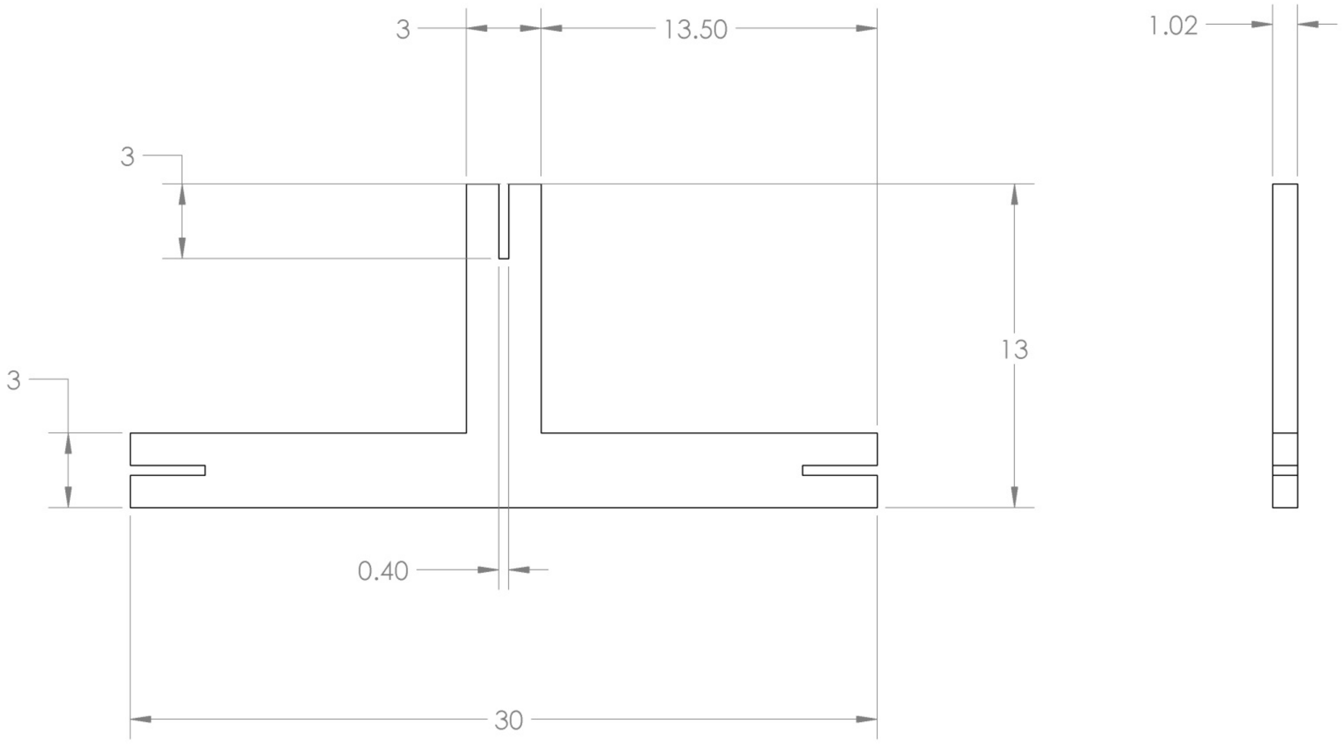


Figure 12: Isometric Drawing of First Prototype Tail

Drawings

The following drawings are of all components designed by this group. The units are in millimeters and angles in degrees.



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

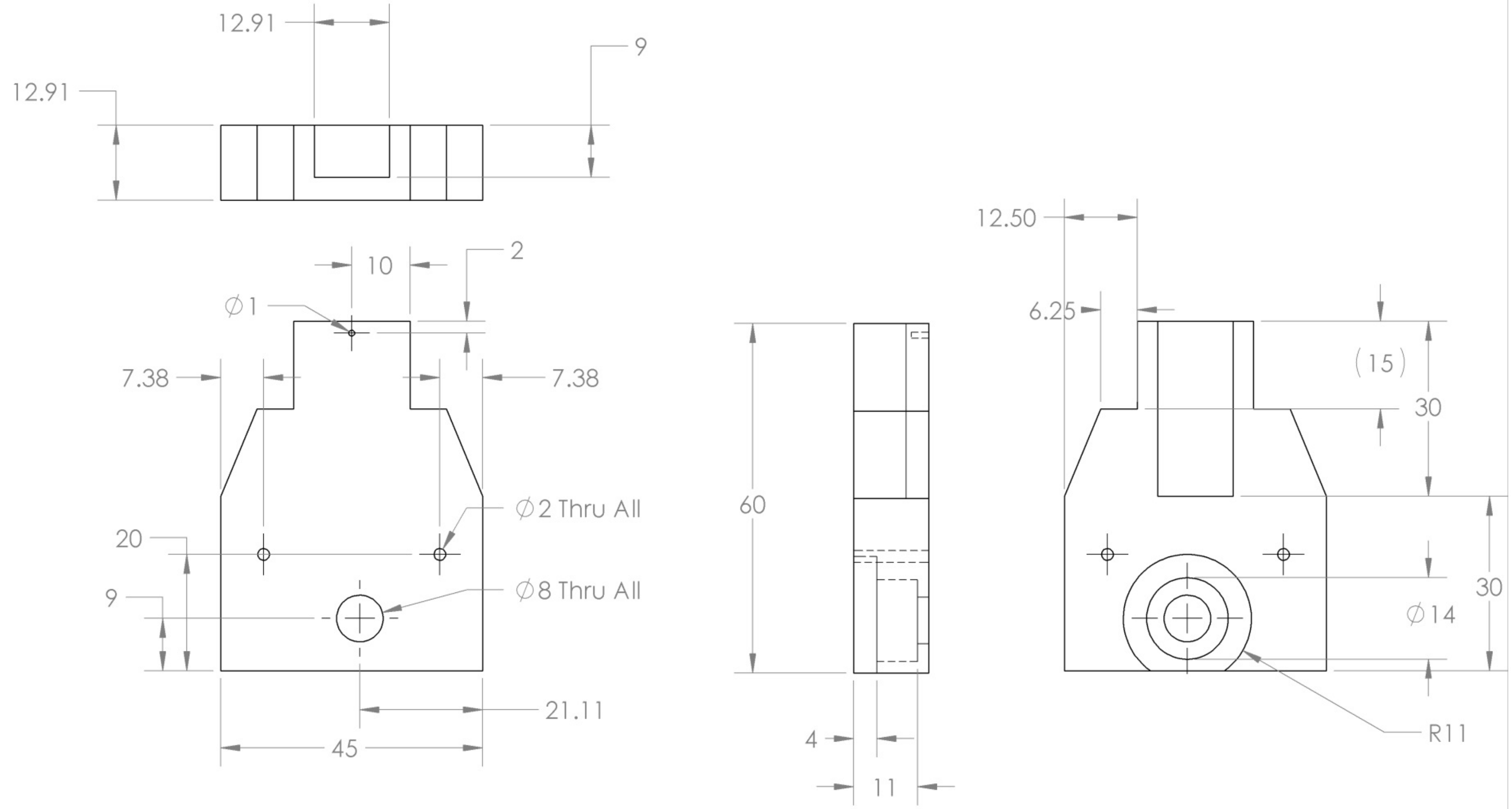
COMMENTS:

TITLE:

SIZE A
DWG. NO. Act-Mount
REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

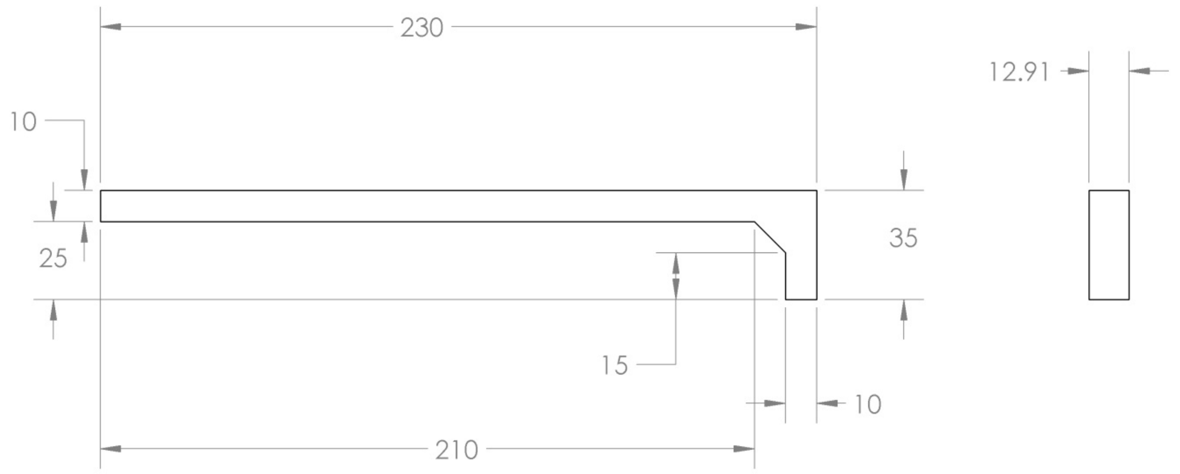
	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE **A** DWG. NO. Body-Front REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL

FINISH

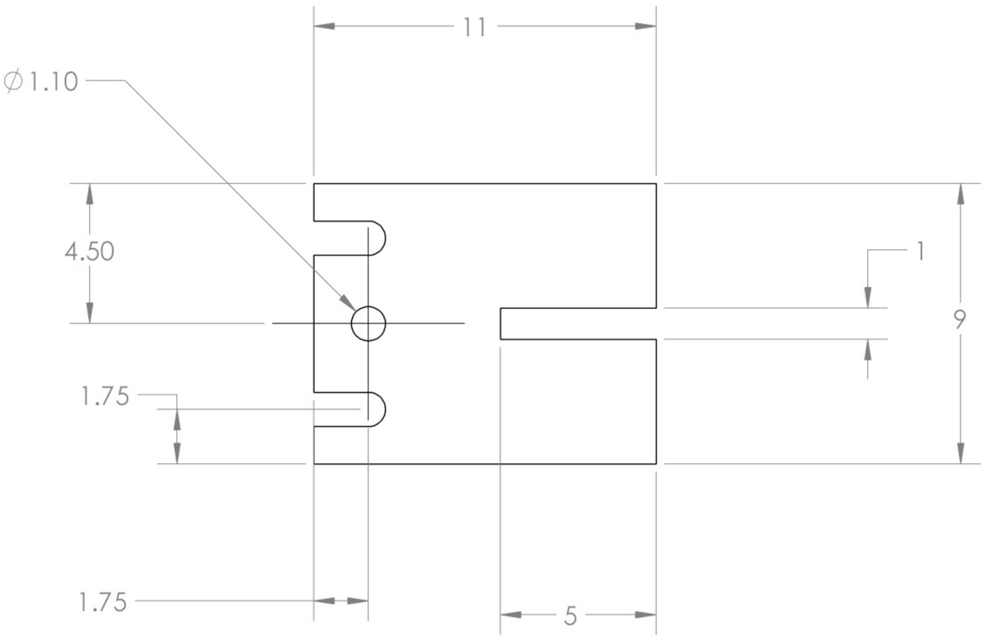
DO NOT SCALE DRAWING

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE A
DWG. NO. Body-Tail
REV
SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



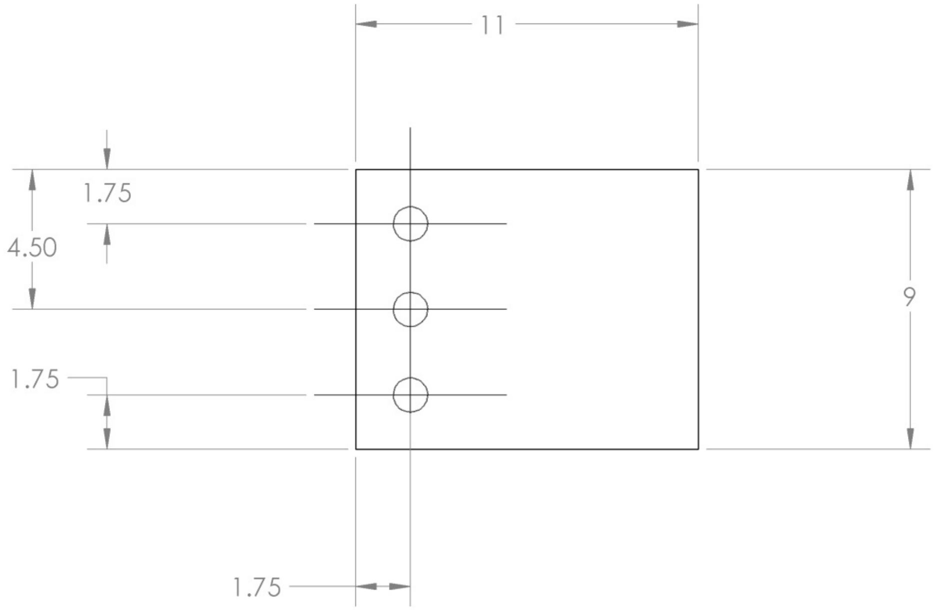
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LDS	3/21	TITLE:
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE DWG. NO. REV A Control-Down
FINISH				
DO NOT SCALE DRAWING				SCALE: 5:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

5 4 3 2 1



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

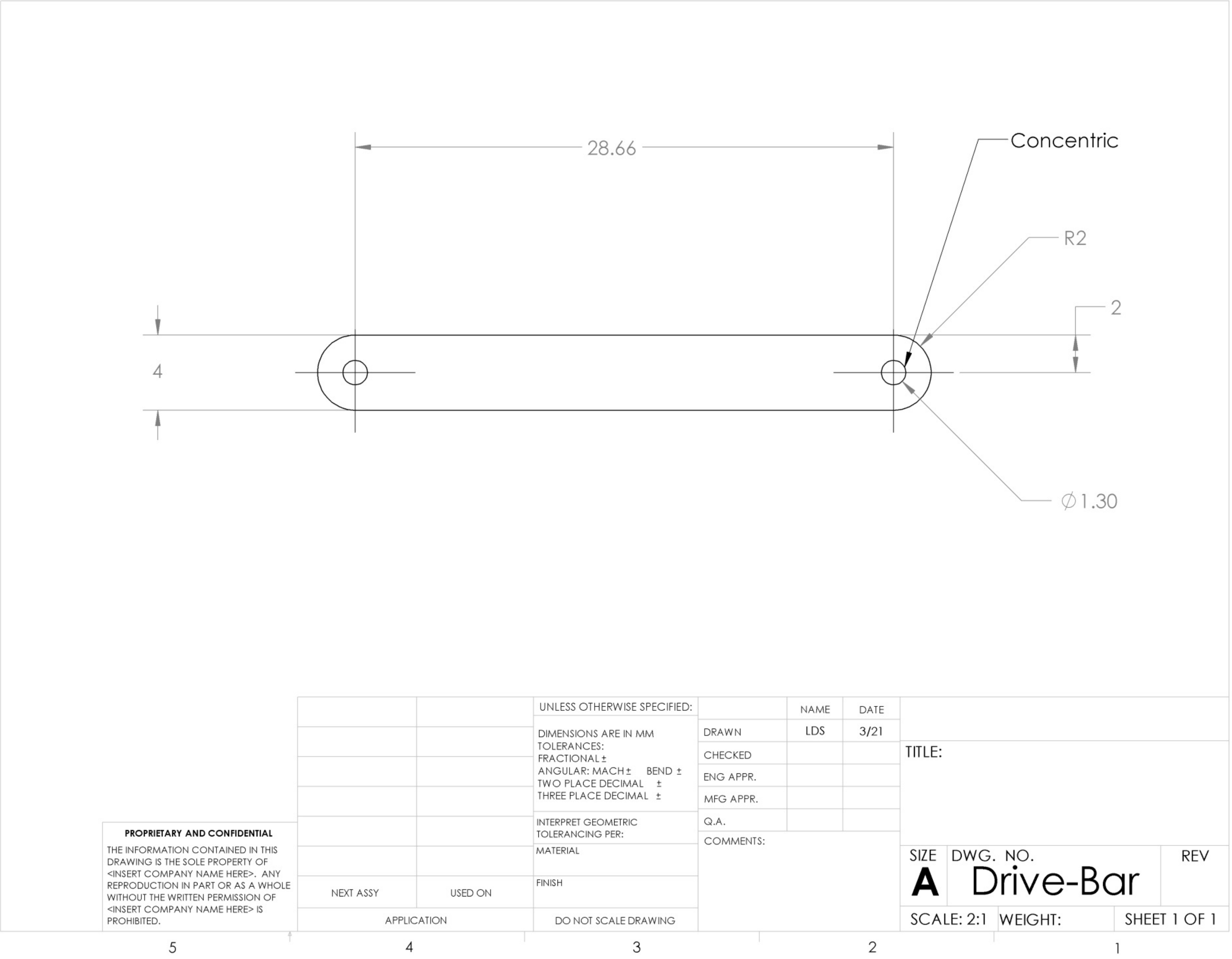
TITLE:

SIZE DWG. NO. REV

A Control-Up

SCALE: 5:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY
USED ON
APPLICATION

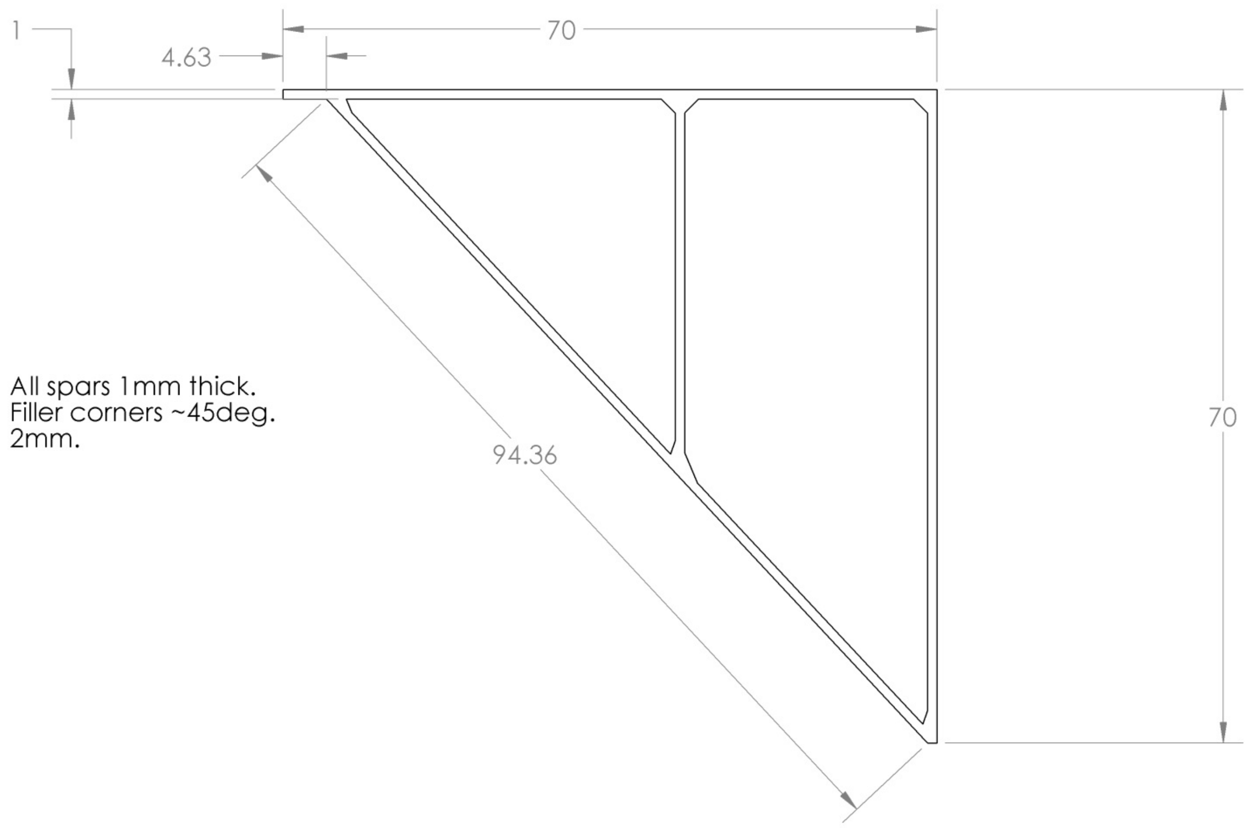
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE A
DWG. NO. Drive-Bar
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1



All spars 1mm thick.
Filler corners ~45deg.
2mm.

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

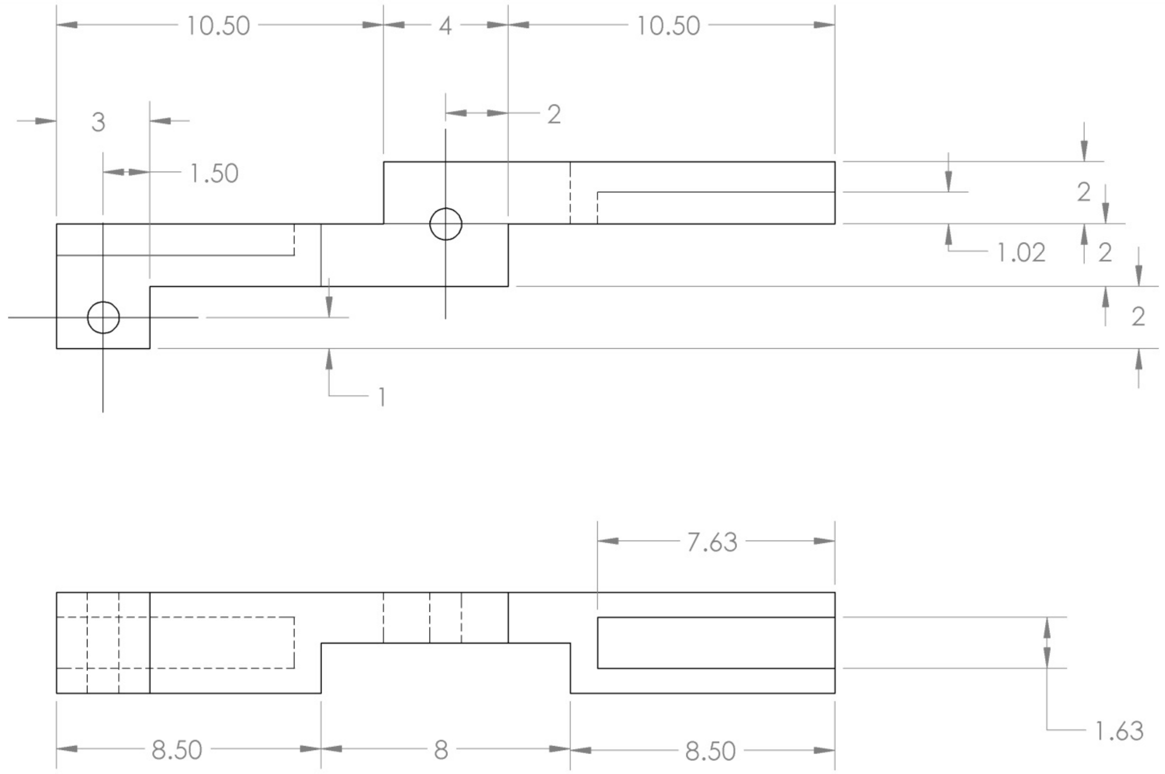
COMMENTS:

TITLE:

SIZE **A** DWG. NO. Elevators REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



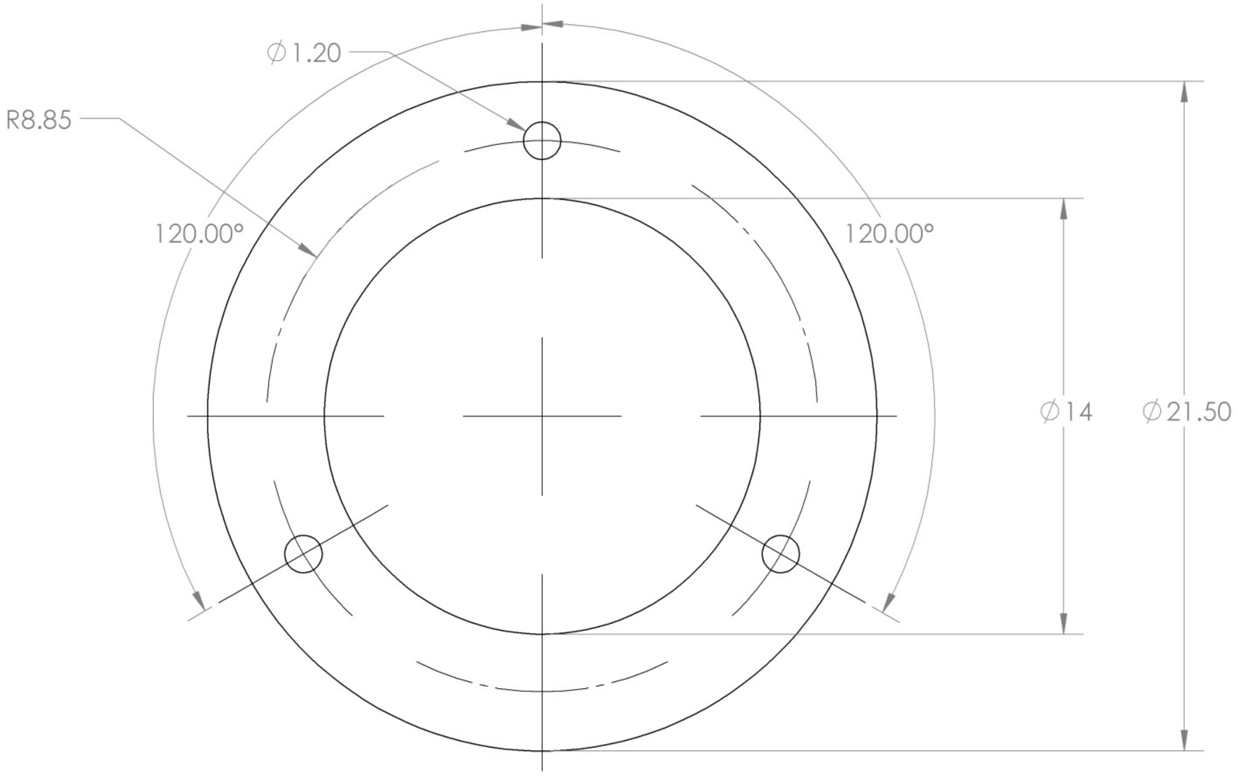
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LDS	3/21	TITLE:
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE A DWG. NO. Hinge REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 5:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LDS	3/21
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

SIZE A

DWG. NO. Motor-Ring

REV

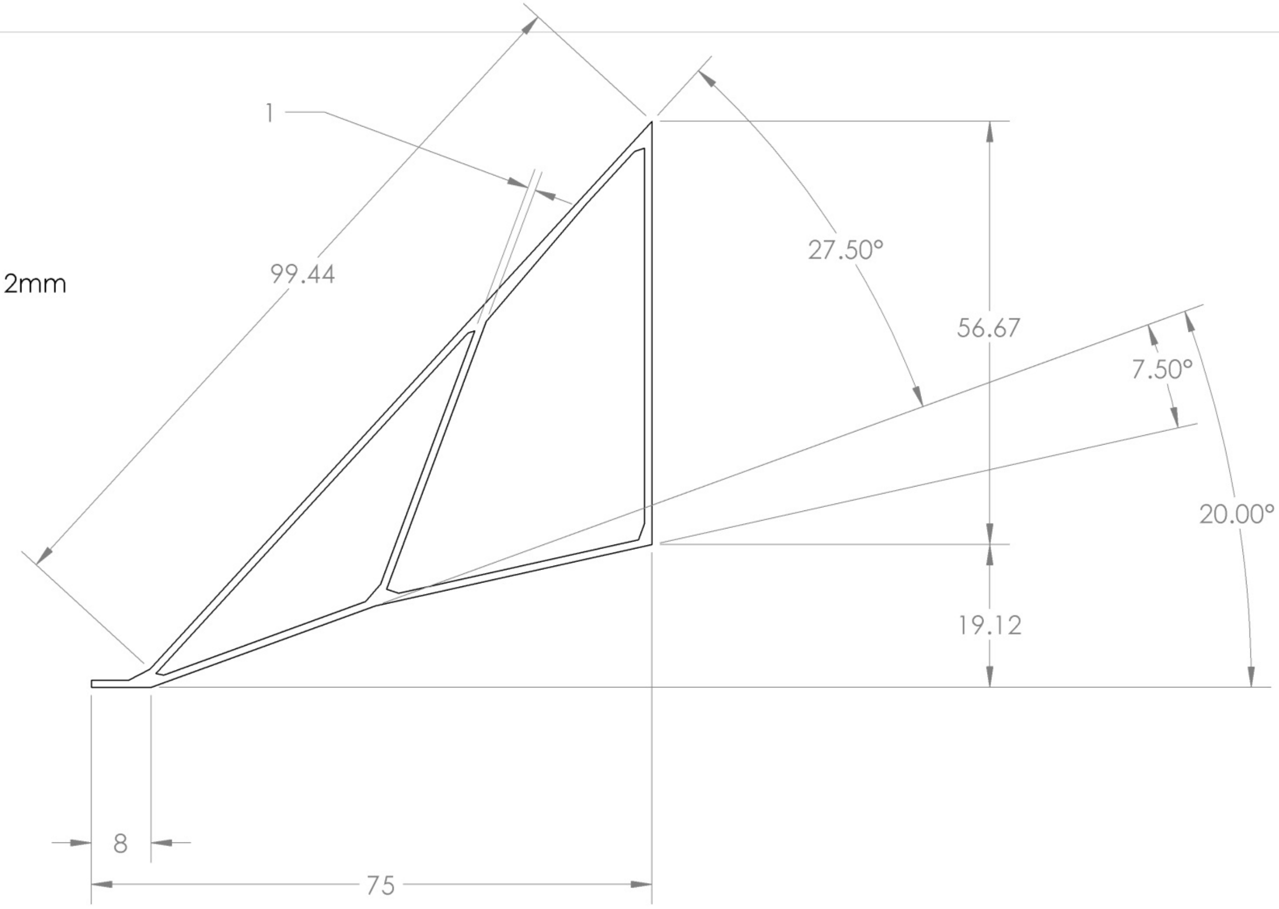
SCALE: 5:1 WEIGHT: SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

5 4 3 2 1

1mm thick spars
filler corners 45deg 2mm



	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

TITLE:

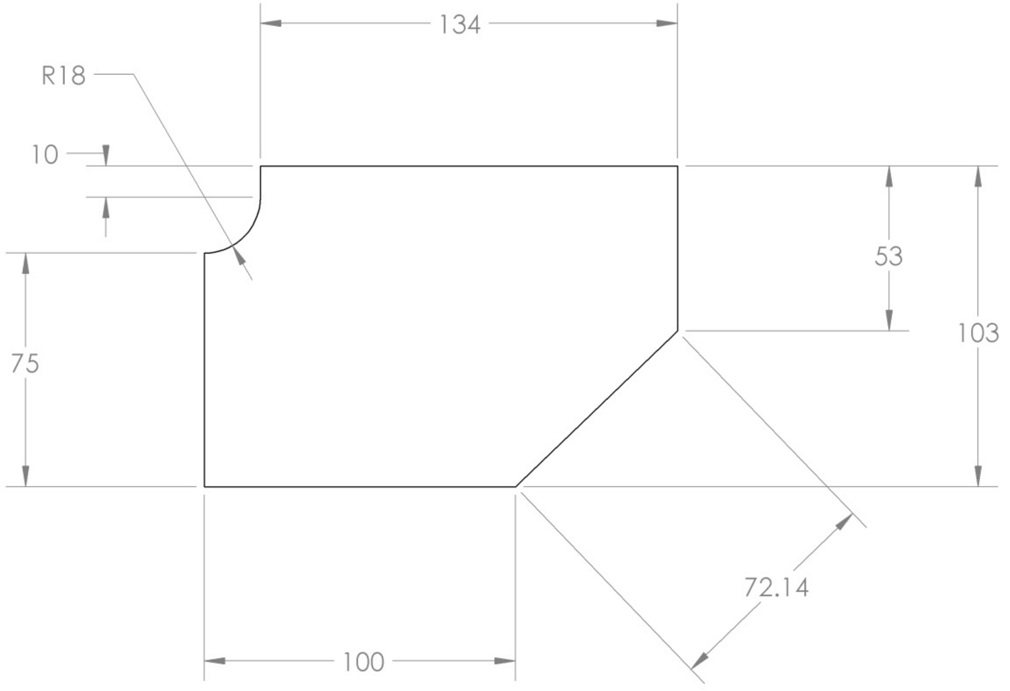
SIZE
A

DWG. NO.
Rudder

REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	LDS	3/21
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

TITLE:

SIZE A

DWG. NO. Wing-Membrane

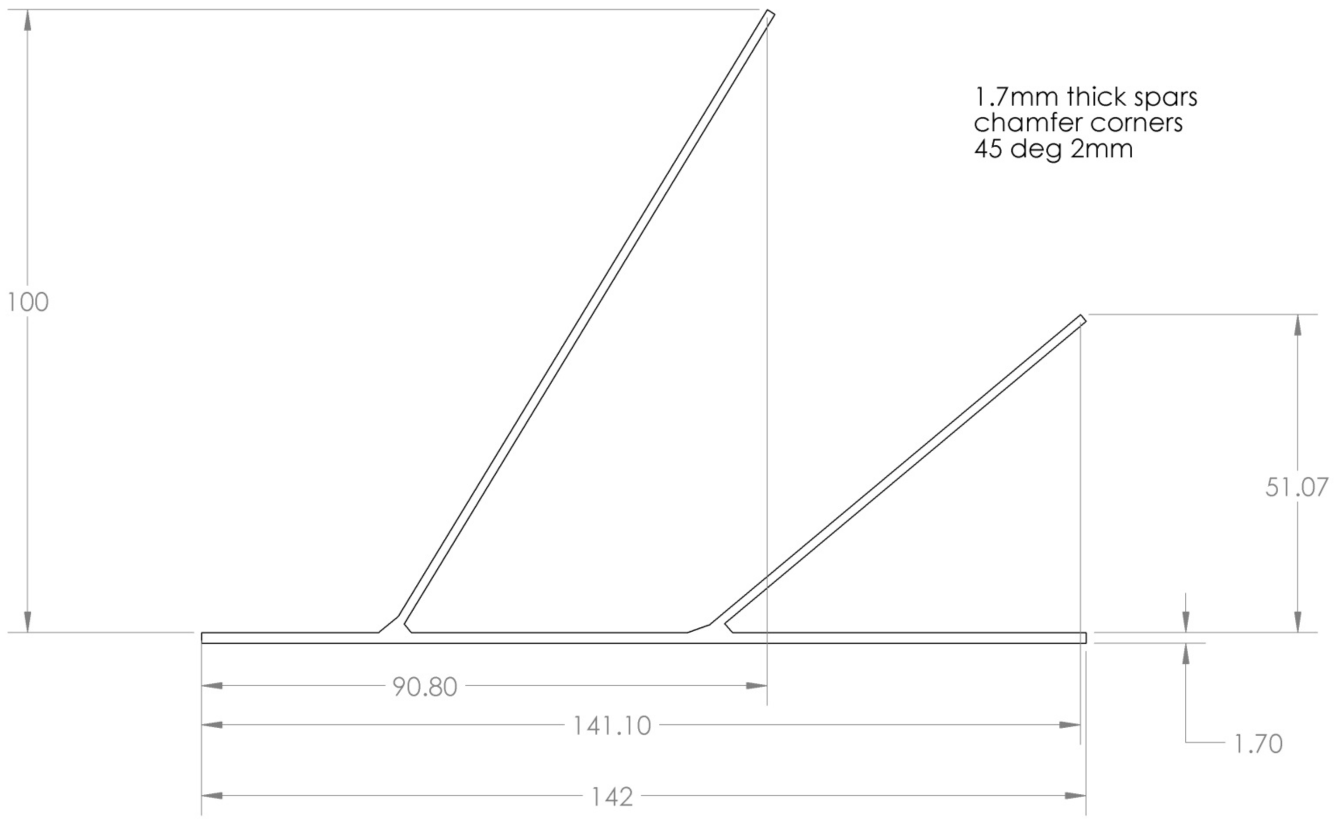
REV

SCALE: 1:2

WEIGHT:

SHEET 1 OF 1

5 4 3 2 1



1.7mm thick spars
chamfer corners
45 deg 2mm

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LDS	3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE A
DWG. NO. Wing-Skeleton
REV

SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1