SAE Aero (Regular) Competition Capstone Team

"Ponderosa Pilots"

Aircraft Operation Manual

"Pine Patrol One"

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Introduction

With hopes of competing in SAE's Annual Aero Design Competition, our team constructed a small-scale, payload carrying aircraft. This aircraft features: an all-aluminum frame, EPS foam aerodynamic bodies, taildragger-style landing gear, and servo-actuated control surfaces. A photo of this product can be seen below:

Figure 1: Pine Patrol One

The Ponderosa Pilots aircraft, Pine Patrol One, is an all-electric, remote-controlled aircraft constructed from foam and aluminum members. This document will detail how such a craft is constructed, operated, and maintenanced. Our team hopes to shine a light on our process and put forth a guide that will assist future Capstone teams in understanding our aircraft. Some key highlights of this document include: manufacturing processes for the aircraft frame, the aerodynamic surfaces, and the landing gear; a guide to the remote-controlled operation of our product; a maintenance guide for anyone using our design or a similar design; and a list of recommended future work that can be done to improve a design like Pine Patrol One.

Manufacturing

Manufacturing was conducted entirely by the team at their personal residences or at Building 98C with minimal assistance from shop managers. The design of the craft revolved around the idea that it should be simple to construct and feature parts that are easily replaceable or mendable during the event of a crash- all while still being inherently durable. Materials include aluminum for structure, foam for lifting bodies, and 3D printed objects.

Frame

Main Spar

Square hollow aluminum tube was used as the main structural members. A one-inch tube was used for the main frame with 1/16” wall thickness and was weight relieved on the mill at 98C. It spanned from the motor in the front to the rear end of the Ballfoil where the rear steering gear was mounted.

Figure 2: Aluminum Square Tube

Wing Spar

The inner wing spar was constructed of ½-inch aluminum hollow square tube and 1/8th-inch wall thickness. This member was not weight relieved as its weight was low and proved less rigid than the main spar. The wing spar spanned the entire wingspan of 60 inches.

Frame Connection Block

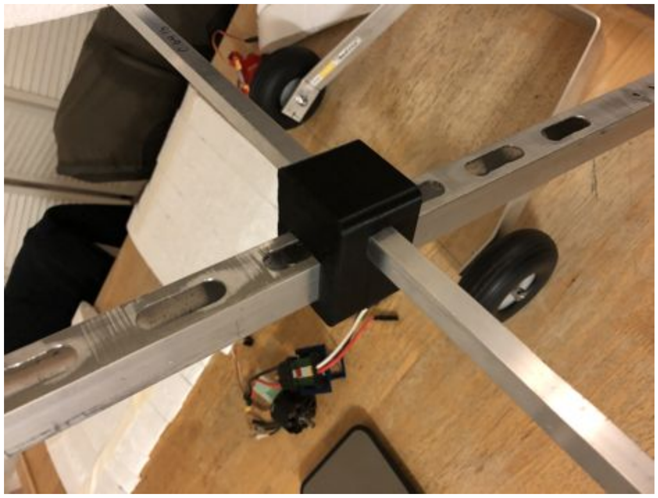


Figure 3: 3D Printed Connection Block

Both of the aforementioned frame spars were connected via a 3D printed block of 30% infill. Although this members structural capacity is much less than the two members it joins, testing proved this to be a worthy connection. Consider that the landing gear is not attached at this connection point, so it receives no landing forces. This member allows the wing spar to slide out for transport. The friction of 50 inches of wing foam fit snug to the wing spar keeps the wing spar in place.

Aerodynamic Surfaces

Process Overview

To manufacture wing segments, our team procured 2-inch-thick insulation EPS from Home Depot, created solid wooden templates in the shapes of the desired airfoil profile, and bolted two of these on either side of the foam (aligning them in rotation and x,y position). Then we ran a hot wire over the template to obtain 2-inch-thick pieces of a wing which were later glued together. This section will go into the details of manufacturing templates and wings.

Templates

Two types of templates were manufactured: wooden, and 3D-printed PLA templates. We will discuss how to manufacture these templates and how to attach them to foam to prepare them for hot wire cutting in this section.

Figure 4: Wooden Templates (left) and 3D-Printed Templates (right)

Wooden Templates

The wooden templates were manufactured by hand. First we printed a CAD drawing of our airfoil. However our airfoils were 52 or 18 inches in chord, they would not fit on a single piece of paper. Therefore grid lines were added to the CAD drawing and the airfoils were printed on multiple sheets and then taped together. Then the outline of the airfoil was cut by hand.

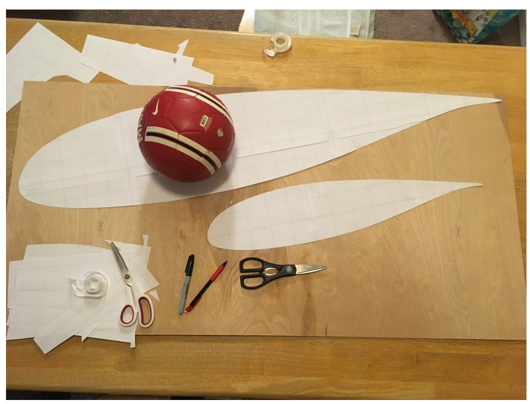


Figure 5: Paper Templates Cut Out

This profile was then traced onto a wooden board. Next, a router was used to cut very close to the drawn profile on the wood. Finally the profile was sanded down to fine-shape the wood to get it to match the profile perfectly.

Figure 6: Cutting Template With Router

Figure 7: Cut Out Wood Templates

Two of these would be manufactured, taped together to be collinear and holes were drilled through them to attach them to the foam block. Lining up the two templates to be identical in rotation and x,y coordinates is quite difficult. Two methods our team used were: measuring hole locations from the edge (if the edge is square), or using a drill press to cut perfectly orthogonal guide holes through the foam. Visual inspection of dimensional accuracy has proven to be sufficient to produce accurate enough wing segments.

An additional thing to note is that you should not use plywood. When plywood is cut it tends to have an uneven surface finish and the hot wire will get caught in the surface and it makes lower quality wing segments, often leaving large striations in the wing surface. Secondly a limiting factor of this method is it makes it very difficult to make internal features (like a square hole in the middle of the wing to hold a structural beam). Therefore in addition to this method of wooden templates, we used 3D-printed templates to add on internal features.

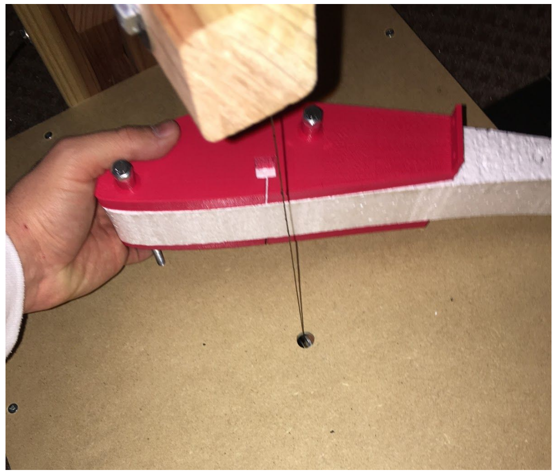


Figure 8: Cutting Internal Features With a 3D Printed Part

As we will see, PLA Templates have their own limitations. Another method used to drill the holes was simply using the hand to make sure the bit is normal to the foam block surface and twist it by hand (while it is not attached to a drill). For these templates this was likely the most successful method of drilling, though all of our team members drilled the holes a different way. The benefits of this method is you can increase the scale of the template without any real limitations unlike the 3D-printing method. Internal features are also possible but they are more difficult to make dimensionally accurate.

3D-Printed PLA Templates

The process of manufacture is fairly simple: make a CAD drawing, and add some extruded cylinders around the holes. These cylinders are to keep the drill straight when positioning the holes for the templates. The drill used to make these holes needs to be smaller than the size of the bolt by a significant margin. This is because when you drill the hole, it does not always cut the foam but rather pulls out small beads of the foam. Because of this if it catches a bead that is ½ inside the drill diameter and ½ outside it can pull the whole foam bead out, and the hole will be larger than the drill diameter, leaving you with a sloppy large hole. It is better to have a tight bolt hole as when threading the bolt in, it will tend to push the foam out of the way. To be able to accommodate the smaller drill and the larger bolt on the same template, separate concentric add-in cylinders were used to be added into the drill holes during drilling and then be removed to allow the bolt to go into the template. Once the model is complete, turn it into an .stl, and if it is a curved part you need many triangles to accurately interpolate the surface. So when saving the part, go into the settings in the save as window and make sure you turn up the tolerance value to the max for a cleaner surface finish. Send the .stl to a 3D printing lab and 3D print it. The benefits of this method are that the templates can have internal features.

There are a few down sides. One is that if the part is larger than a single print bed, you will need to glue or bolt them together. This will leave a seam where the hot wire can get caught and mess up your part surface finish. The second is that if you use a low temperature plastic like PLA, over a few uses the hot wire can slightly melt the surface and the template will develop dips and the wire will start to get caught. Included in the "Future Recommendations" section is a discussion on how to improve the use of 3D printing in regards to foam-cutting templates. The final benefit of this method is that because it takes less time to manufacture, you can make more of them, this means if you want to make a tapered section, this is by far the best way to go.

Figure 9: Varying Sizes of Wing Templates for a Tapered Wing

Hot Wire Cutting

Once the templates are lined up and bolted to the foam, turn on the hot wire power source and calibrate it to 11.8 volts and 3.68 amps or as instructed by the manual at the web link below. Then run the template and foam over the hot wire until all the excess foam has been removed.

[For more information on how to use the wire cutter, visit our website at https://www.ceias.nau.edu/capstone/projects/ME/2019/19F12_SAEAeroRegular/ and look for the "Hot Wire Foam Cutter Operation Manual."]

Compiling Wings Sections

Finally these wing sections will be glued together to form a longer wing. Put glue on the ends and clamp them together using your hand to align the edges.

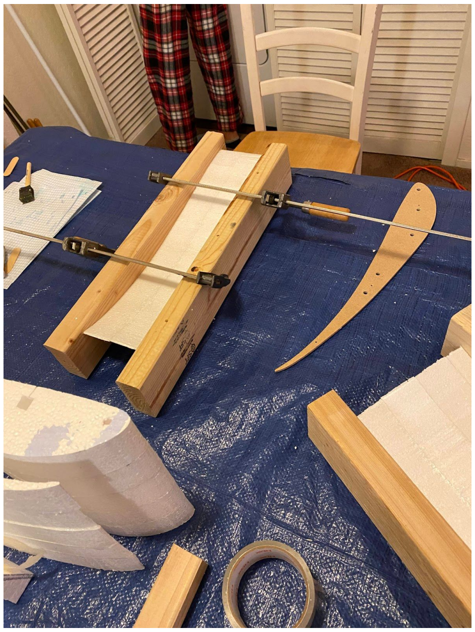


Figure 10: Clamping Together Cut Foam Wing Sections.

Landing Gear

The next major component to discuss is the landing gear. The landing gear of our aircraft is in the "tail-dragger" style. This means that there is a single steering wheel in the rear of the plane, and two, elevated, tandem wheels nearer the front of the plane. The manufacturing processes for these two items were similar, but the designs of each were very different. The following two sections will discuss each in further detail.

Rear Gear

The rear landing gear was the steering wheel. Over the course of our design process, the steering wheel took on many different shapes and sizes, but this report will discuss the final state of the design. Improvements to the design that the team was not able to implement before the COVID19 situation will be discussed in the Future Recommendations section.

Construction:

1. First, using a vice, bend a 3/4-inch aluminum flat-beam into a U-bracket shape. This bracket will wrap around and mount the wheel (See CAD: Figure 18 for dimensions).
2. Drill a quarter-inch hole through both sides of this bracket. This will support the wheel axle.

3. Cut a seperate 4-inch section of the half-inch aluminum flat-beam. Attach this to the U-bracket with two (2) size #6 bolts. This flat will act as a lever arm for the servo motor to actuate.
4. Drill small, 1/16th-inch holes across the span of the lever arm. These holes will be mounting points for the servo clevis. When calibrating the steering system, the user can select which mounting point to use for different ranges of steering motion.
5. Drill a large, half-inch hole through the center of the U-bracket and flat-beam system.
6. Attach the system to the aircraft's main beam using a half-inch, aluminum bolt. Place plastic washers between the system and the main beam and do not tighten the nut completely. This will ensure that the system can rotate smoothly.
7. Finally, attach the wheel using a quarter-inch bolt as the wheel axle. Use plastic spacers to ensure that the wheel is centered on the axle and not in contact with the walls of the U-bracket.

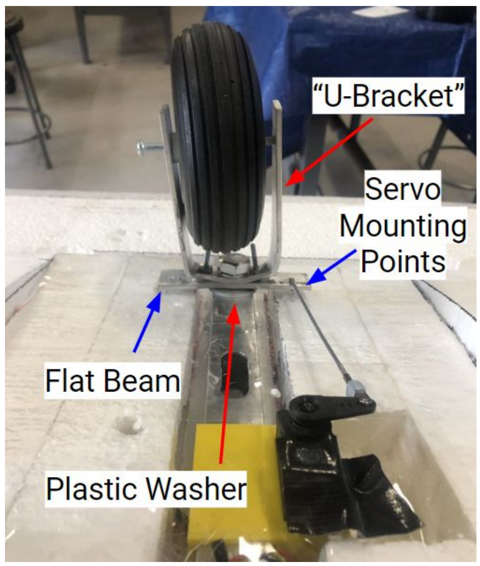


Figure 11: Rear Landing Gear

Front Gear

The front gear was a stationary, two-wheel system fashioned once again from bent aluminum. Later analysis found that a more successful front gear would be an off-the-shelf carbon fiber model, but this was never implemented (See "Future Recommendations"). The gear that was implemented, however, was very simple to construct. It features a single, aluminum flat-beam bent into a shape to provide both strength and shock absorption.

Construction

1. First, cut a 1.5-inch aluminum flat plate and bend it to shape using a vice. These dimensions can be seen in CAD: Figure 19.

2. Next, drill quarter-inch holes in the bottom sections of the landing gear for the wheel axles. These axles are an off-the-shelf product similar to the Du-Bro set shown below.

Figure 12: Du-Bro Wheel Axles

3. Attach the axles and mount the wheels on them using collets.
4. Drill small, eighth-inch holes in the bottom section of the landing gear.
5. Tie a metal cable through each of these holes. Our team used picture-hanging wire. Connect the two ends of the wire with a small spring.
6. Mount the landing gear to the main beam using two (2) size #8 bolts.

Figure 13: Front Landing Gear

Electronics Mount

The central electronic components are primarily housed in a 3D-printed enclosure at the front of the main spar. This includes the 3000mAh LiPo battery, the Electronic Speed Controller (ESC), and a 1000w power limiter mandated by the competition. The battery leads to the 1000w limiter, followed by the ESC. From there, it is dispersed to the motor and to servos. This mount slides over the main spar and is interference-fitted to prevent translation along the spar. *See Figure 17: Exploded View in the CAD section for this component.*

Servos

Figure 14: Hitec Servo

The aircraft uses six Hitec RCD HS-5625MG digital high-speed metal gear servos to achieve control. One for each aileron, two for the elevator, one for the rudder, and one for the rear steering gear. They are linked to the receiver that is mounted on the underside of the Ballfoil. The servos were mounted in place by cutting tolerance fitted slots into the foam. Additionally, a dollop of silicon was placed under each servo to ensure movement was not allowed.

Motor Mount

The motor mount is a simple 3D print of 100% infill that features a flat circular mounting plate, backed by a hollow rectangular section that inserts into the main spar. It is affixed to the main spar by tolerance fit and one machine screw that passes through perpendicular to the spar. The 3D-printed motor mount proved effective during testing because crashes tend to be nose-first and the expensive motor is spared when the 3D-printed mount breaks free with impact force. This is a sacrificial piece and spares are needed.

Control Surface Hinges

The control surfaces are produced from the completed wings. The trailing edge is cut and then both of the mating edges are angle-trimmed to allow 20% of downwards rotation of the control surface. The hinge is produced with a strip of clear packing tape along the mating edge with dollops of epoxy under the tape at intervals. The epoxy ensures that the tape will not free itself from the EPS foam if adhesion is low.

General Assembly

The above sections have detailed how to manufacture individual components of Pine Patrol One. This next section will detail how those components are assembled together to form a singular, final product. Because our design's primary construction is from EPS foam, the team had to experiment with several different adhesives to find one that didn't melt the material. Epoxy was found to be a successful means to attach components, and very few attachments were made with other means.

Adhesives: (Epoxy, Silicone)

The primary adhesive constituent used in manufacturing and repairs is quick-set Epoxy. This is one of the few adhesives that do not melt EPS foam. It was used for places where permanent connections were desired. Additionally, silicone was employed when affixing servos, as it allowed them to be removable for maintenance.

Fasteners

As mentioned earlier, very few fasteners were used in the construction of Pine Patrol One. Most connections were made using epoxy adhesive. The following table will detail all fasteners used in the construction of the aircraft.

Table 1: Fasteners

Subsystem	Fastener Type	Quantity	Use
Front Landing Gear	#8 Bolt	2	Fasten Landing Gear to Frame
Rear Landing Gear	#6 Bolt	2	Fasten Bracket to Lever Arm
Rear Landing Gear	1/2" Bolt	1	Axis of Rotation (Steering)
Motor	#6 Bolt	1	Fasten Motor Mount to Frame
Motor	#6 Machine Screw	4	Fasten Motor to Motor Mount
Wings	#6 Bolt	2	Fasten Wing Mount to Frame

Other

Aside from adhesives and fasteners, there were a few other means of attachment/connection that must be mentioned. Below is a succinct list of these "miscellaneous" methods of attachment.

- ⅝-inch wooden dowels were used to "pin" the Fuselage to the Main Beam
- Magnetically attached panel used to close the cabin (due to COVID19 halting our progress, a duct-tape-sealed cabin was used in final implementation)

Operation

Operation requires practice but in principle it is very simple.

Connect the battery to the ESC and turn on the Controller. Wait for the motor to make a series of tones. The system is ready for motor and servo input signals.

Figure 14: The Remote Controller

Inputs:

All the inputs have reactions in flight. The control inputs, outputs, and reactions will be listed here. Note that all the reactions will be noted in the coordinate system of a pilot in the cockpit of the aircraft.

- Moving the right stick right will move the right aileron up and the left aileron down. This will result in the aircraft rolling clockwise.
- Moving the right stick left will move the right aileron down and the left aileron up. This will result in the aircraft rolling counter clockwise.
- Moving the right stick down will result in the elevator moving up. This will result in the aircraft pitching up.

- Moving the right stick up will result in the elevator moving down. This will result in the aircraft pitching down.
- Moving the left stick up will increase the throttle and thus the thrust.
- Moving the left stick down will decrease the throttle and thus decrease the thrust.
- Moving the left stick left will move the rudder left and result in the craft yawing left and will move the rudder wheel left as well and turn left if on the ground.
- Moving the left stick right will move the rudder left and result in the craft yawing right and will move the rudder wheel right as well and turn right if on the ground.
- As set up moving the top right switch toward the user will turn on the throttle safety and pushing it away will arm the throttle stick.

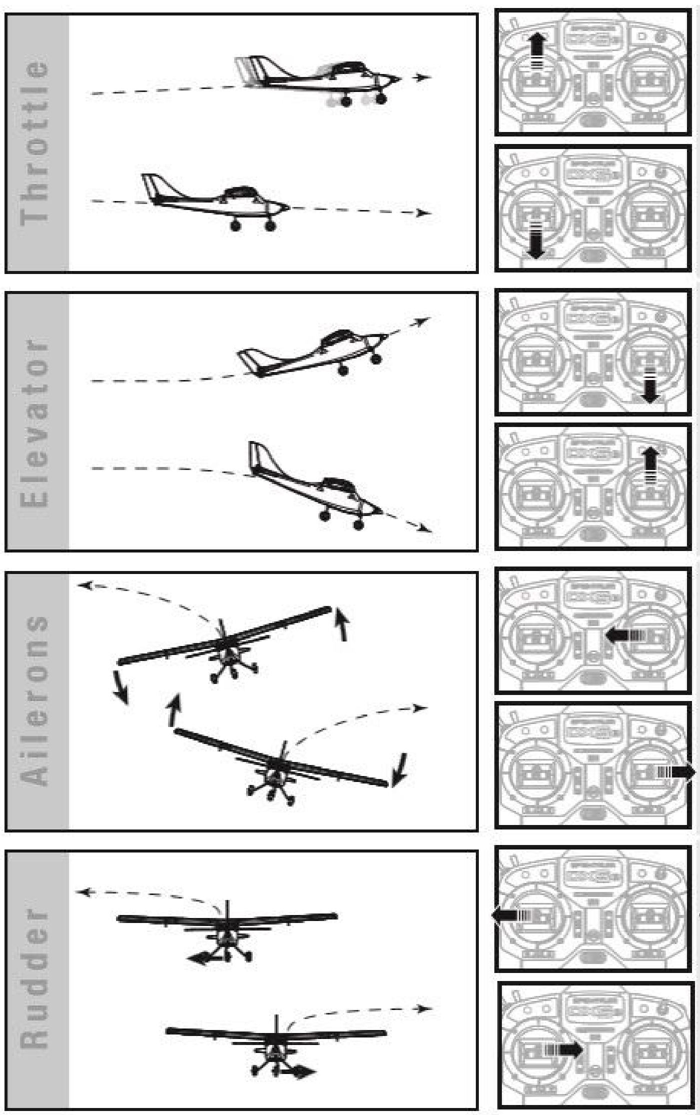


Figure 15: Transmitter Control Surface Correlation Sheet

We will now briefly describe flight control procedures.

Take off:

To take off, place the craft on a flat long runway with at least 100 ft of flat ground. Turn the thrust to 100%. Then wait for the tail to lift off the ground. Next pitch up lightly until the craft leaves the ground. Use the other controls at your discretion to steer the aircraft.

Landing:

Use the controls to get the aircraft far from the runway but on the side of the runway you intend to land from. Then decrease the throttle to about 80% to lose altitude and speed as you start to approach the runway. Note the rate of altitude loss versus the ground speed and adjust throttle so that the craft will touch the ground as it reaches the start of the runway. Turn off the throttle as it touches the ground. Allow the craft to stop and unplug the battery before manually transporting the aircraft once you are done.

Maintenance/Repair/Troubleshooting

Maintenance (Wear and Tear)

Most components on the aircraft should function for the life of the aircraft barring the event of a crash. Some components that may need to be replaced after excessive use are as follows:

- Batteries
  Replace if there is any sign of expansion or puffiness
- Landing gear
  Aluminum version - Replace every 70 soft landings or 30 hard landings
  Carbon Fiber version - Replace if angle of attack drops below 15 degrees
- Wheels
  Replace if foam tread is worn down to polymer wheel
- Wires
  Replace if servos are actuating without controller input
- Cabin cover
  Replace if there is any play when installed

Repair

Design of the plane was made exceptionally modular. All sections of the aircraft are fairly easy to repair and can be done with simple hand tools and epoxy adhesive. Aerodynamic surfaces such as the main body, stabilizers, and wings need to be completely reconstructed upon damage. All other structural members and components can be serviced on site to get the plane ready to fly again.

<u>Motor Mount Removal:</u>
The motor mount is 3D printed and designed to fail in the event of a crash in an effort to save the more expensive motor and propeller. Disconnect the three power cables from the motor to the ESC. The mount is attached to the frame by a single #6 bolt and nut through the top of the frame a few inches from the front of the aircraft. Once the bolt is removed the mount will slide out of the frame. To remove the mount from the motor, four small bolts must be removed.

<u>Motor Mount Installation:</u>
To install the motor mount, four small bolts should be fed through the mount and into the back of the motor. These bolts should be tightened in a criss-cross pattern to avoid bending the motor mount or cracking the 3D printed plastic. Once tight, the whole assembly slides into the main

beam, ensuring that the bolt hole is oriented correctly to feed a bolt though the mount from the top. Tighten the #6 nut and bolt. Reconnect the three power cables from the ESC to the motor.

Wing Removal:

The wings are commonly damaged in small crashes. The foam sections are attached to the body via one square tube spar located about one-third of the chord length of the wing. To remove the wings, the foam section must be unattached from the main body on the underside of the aircraft. Then, the servo wires that run into the main beam from the wings must be disconnected. The entire wing can then be slid off of the spar and set aside. Moving to the opposite wing, the wing along with the spar can be pulled directly out of the main beam.

Wing Installation:

To install the wings, a new level spar should be inserted levelly into the 3D printed mount attached to the main frame. Once the spar is in wing sections can be slid onto the spar until they touch the main body. There will be wooden alignment dowels on the top and bottom side of each wing to ensure correct angle of attack upon mounting. Reconnect servo wires from wings to female connectors coming out of the main frame.

Landing Gear/Wheel Removal:

To remove the landing gear and wheels the aircraft should be flipped over so that the wheels are facing up. Two #8 nuts and bolts hold the main landing gear to the frame. The main landing gear can then be removed. To remove the secondary gear, disconnect the steering linkage from the servo. One ½-inch nylon-locking bolt holds on the secondary landing gear from the top of the aircraft. To remove the wheels, small hex keys must be used to loosen the collars that hold on each wheel. On the main gear, the tensioner spring can be removed by cutting the wire.

Landing Gear/Wheel Installation:

When installing the landing gear, dimensions of the main gear should be checked against drawings to ensure correct angle of attack when mounted. Small hex keys should be used to attach all wheel collars facing outwards. To install tensioning spring on the main gear, picture hanging wire should be tied to each end of a spring, and fed through the holes just under the wheel axle mounts. Tie the wire so that at rest there is a very small amount of tension on the spring. To mount main gear, apply thread locking fluid to the #8 bolts and tighten them in place. To attach the steering gear, insert the axle through the frame and tighten the new ½-inch bolt until it engages the nylon thread. Reattach the servo linkage.

Control surfaces:

Ailerons, elevator, and rudder are to be attached by meticulously lining the edge up with the wings, horizontal stabilizer, and vertical stabilizer respectively. Then three drops of epoxy should be put along the length of the edge on each of the mating surfaces. Packaging tape is then applied across both surfaces while covering the epoxy. Ensure that the surface has full actuation and let set for 20 minutes. Attach servo linkages.

Wiring Removal:

To remove wires, disconnect the battery, and disconnect wire in question from the receiver and any affected servos. Feed wire through weight relief holes in the main beam.

Wiring Installation:

To install wires, disconnect the battery, choose a wire with correct length and number of connectors for application. Feed wire through weight relief holes in the main bar ensuring the correct end (male/female) is facing the right way. Connect loose ends to servo(s) and receiver or power limiter. Test all servo functions before attempting to fly.

Attaching EPS sections:

To attach foam sections, one-minute epoxy should be conservatively applied to a single section, then pressed against a dry section. A small amount of pressure should be applied while ensuring a continuous edge around the two sections. Let set for 20 minutes before further assembly. This technique is also used to attach horizontal and vertical stabilizers.

Troubleshooting

Safety when operating the device is of paramount concern. If something does not seem right in pre-flight runs, do not attempt to take off the plane. Common issues ran into were related to servo connections. All connections were made to be accessible, so if a control surface is not actuating, check all wire connections, including servo connection, power limiter connection, and receiver connection. Further check controller power and if it is operating normally. Battery issues also arise after extended operation. Replace battery if control surfaces do not actuate fully, and if the issue persists replace receiver. Propeller issues are generally attributed to incorrect connection of the three power wires. If take off does not take place in a very short distance when throttle is above 80% (less than 100 feet) measure aircraft angle of attack, and adjust main landing gear as necessary. If the plane is very erratic in the air, check payload placement, small variations in location result in large center of gravity changes that detrimentally affect in flight controllability.

Future Recommendations

As mentioned several times in the text above, there were some aspects of this product or the manufacturing processes that we hoped to improve before we were forced to abandon manufacturing in the wake of the COVID19 crisis. This addended section will briefly discuss the improvements that we hoped to make, in hopes that future Capstone teams take them into consideration.

Improved Foam-Cutting Templates

As mentioned in the Aerodynamic Surfaces Manufacturing section, 3D-Printed templates are great for complex geometry and unique features, but they fall short when it comes to temperature resistance. Therefore if higher temperature plastics can be used on a large enough print bed these issues can be mitigated. If a large high temperature 3D printer can not be found high temperature adhesives may be useful. To find a better high temperature plastics calculate the wire temperature with an online nichrome wire temperature calculator tool and compare it to other high temperature plastics like PETG, ABS, or PEEK.

Landing Gear Improvements

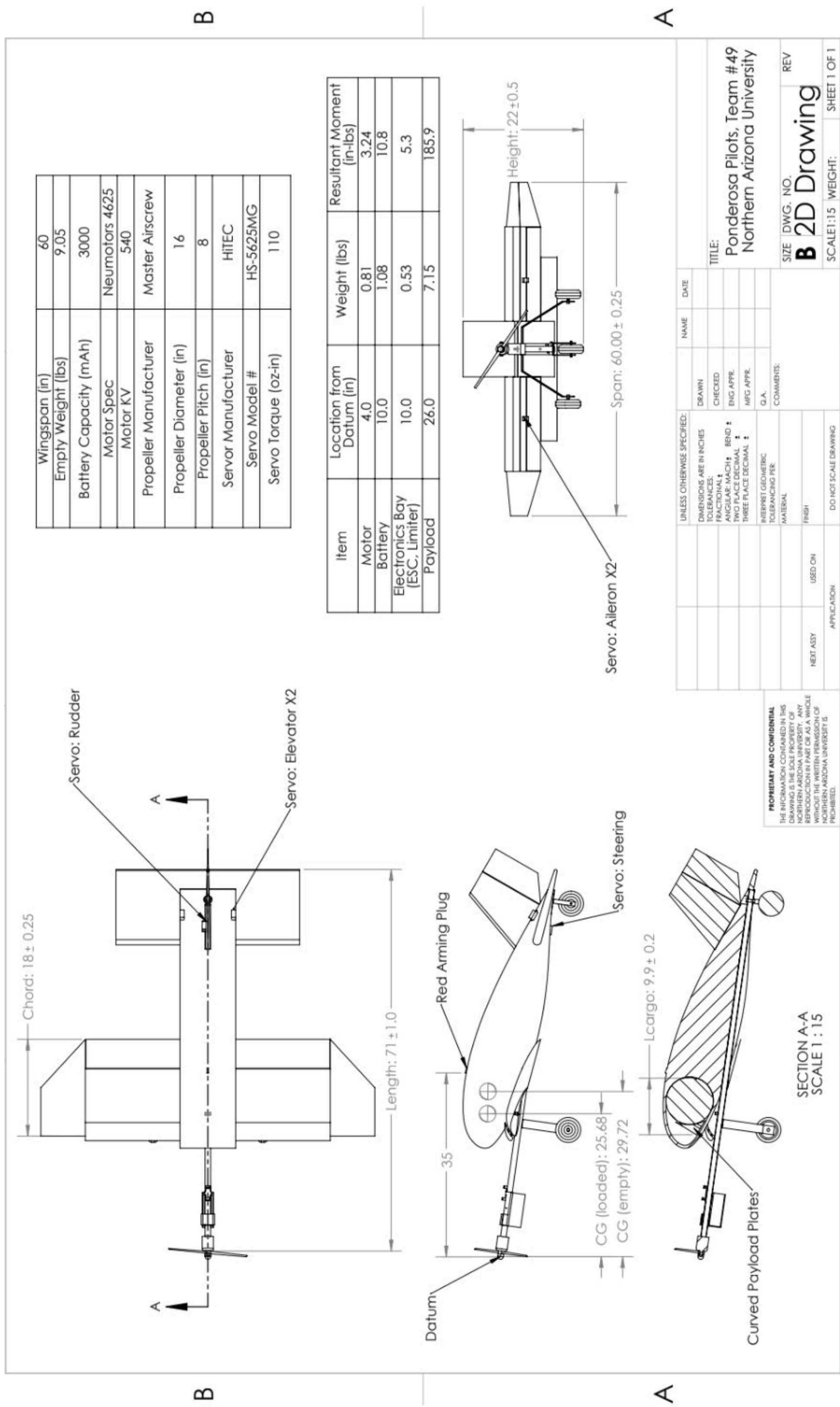
There are a few improvements that the team hoped to implement in a final product. First, the design of the rear landing gear is cumbersome and contains many small parts. If the bracket and the lever arm could be integrated into one solid piece via welding, one could eliminate all the excess parts back there. Second, a materials analysis revealed that a carbon-fiber front landing gear would fare much better than the aluminum one that we're currently using. These carbon-fiber parts can be found off-the-shelf for RC aircraft use, and would be able to withstand much more impact than the current landing gear.

CAD

The following section will include Solidworks CAD models and drawings of the aircraft. These are intended to assist the user in envisioning and assembling the aircraft. Included will be: full-assembly drawings, full-assembly exploded view, and any individual component drawings that were referenced in the above text. Fully-detailed CAD files will be submitted to the class in a separate assignment, but can be provided upon request.

Full-Assembly Drawing

The figure on the following page contains the full-assembly drawing of Pine Patrol One. This was the technical drawing that we submitted to SAE per competition requirements, so the figure will also contain specifications for electronics and annotations for the center of gravity.



Wingspan (in)	60
Empty Weight (lbs)	9.05
Battery Capacity (mAh)	3000
Motor Spec	Neumotors 4625
Motor KV	540
Propeller Manufacturer	Master Airscrew
Propeller Diameter (in)	16
Propeller Pitch (in)	8
Servor Manufacturer	HiTEC
Servo Model #	HS-5625MG
Servo Torque (oz-in)	110

Item	Location from Datum (in)	Weight (lbs)	Resultant Moment (in-lbs)
Motor	4.0	0.81	3.24
Battery	10.0	1.08	10.8
Electronics Bay (ESC, Limiter)	10.0	0.53	5.3
Payload	26.0	7.15	185.9

Figure 16: SAE Technical Drawing

Exploded View

The "Exploded View" pictured below nicely illustrates the different subsystems of the aircraft. Separated at the top are the aerodynamic surfaces. Under that is the aluminum frame, and under that are the two landing gear systems.

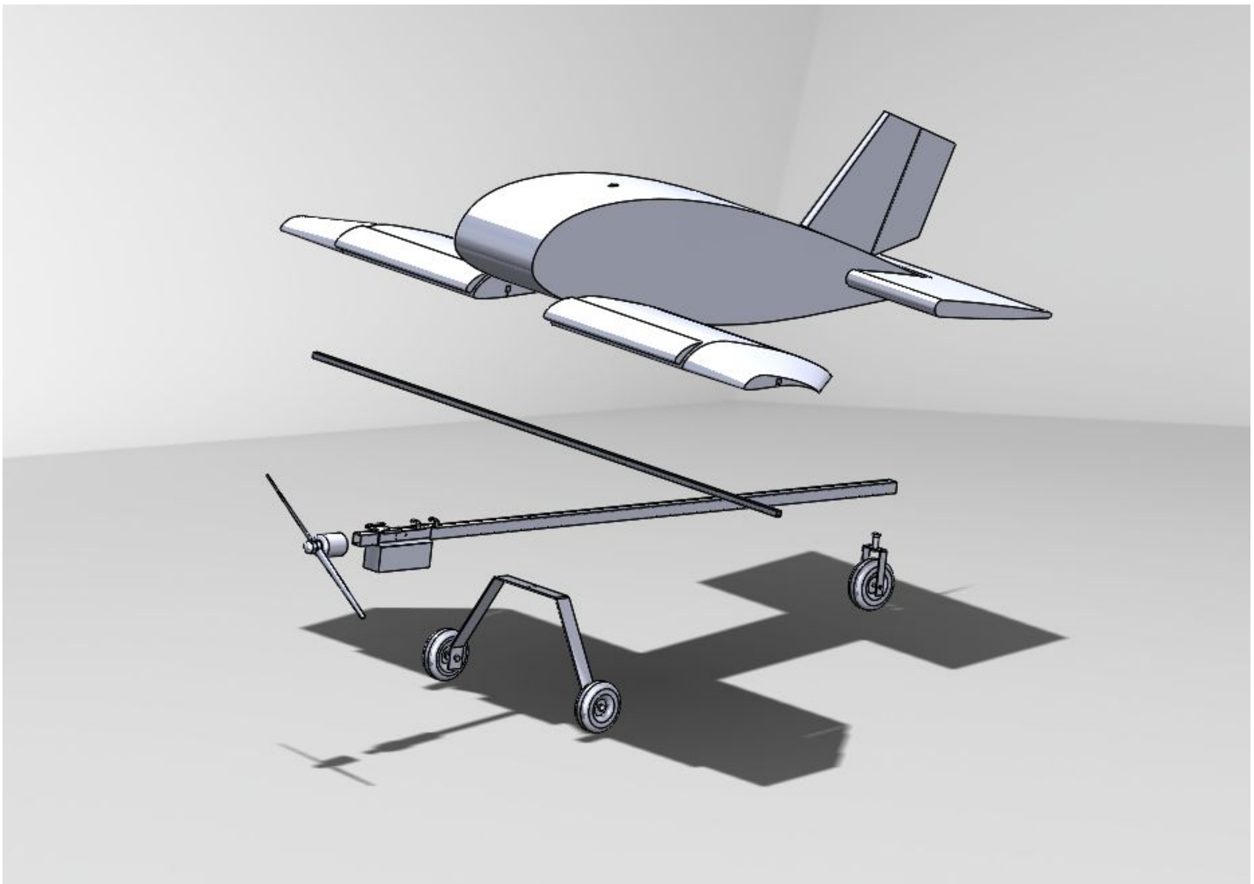


Figure 17: Exploded View

Individual Parts Referenced in Text

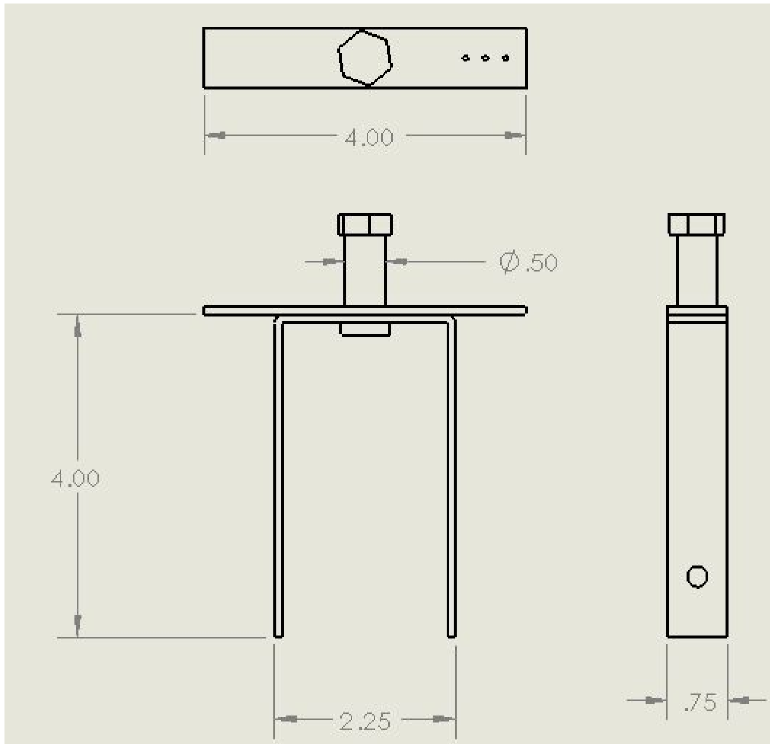


Figure 18: Rear Landing Gear Dimensions

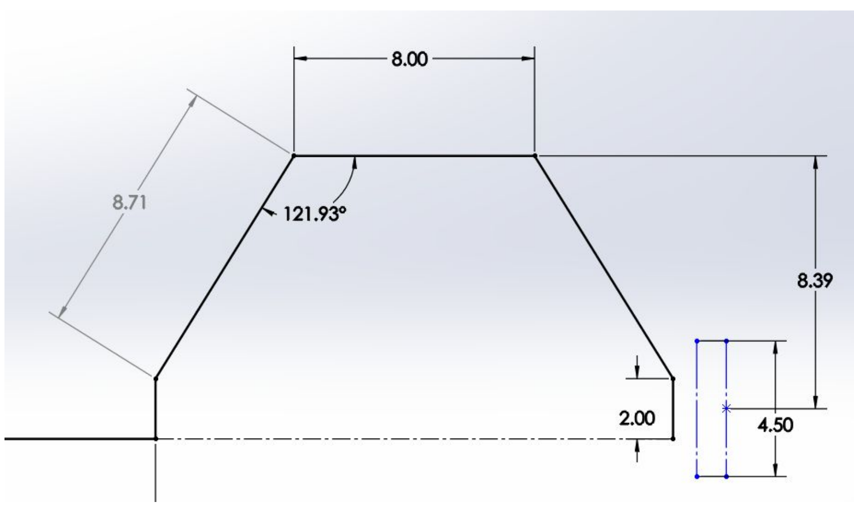


Figure 19: Front Landing Gear Dimensions