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A Jet Engine Retraction System

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A JET ENGINE RETRACTION SYSTEM

By

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Date

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ABSTRACT

RETRACTION SYSTEM OF A JET ENGINE

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A high-altitude dynamic soaring unmanned aerial vehicle (UAV) called JetStreamer has been designed and built in the Composites Lab of Lehigh University. A small jet engine will be used to bring this UAV up to the jet stream. The small jet engine is lighter than a piston engine and may be more efficient at high altitude. This makes it particularly attractive for Jet Streamer flying over 10,000 m. However, the installation of the jet engine could be a challenge due to the limited space and complicated structure reinforcement especially when there is retractable motion involved to reduce the drag. The purpose of this work is to design and manufacture a retractable jet system which can be installed inside the fuselage. A parallelogram mechanism was used for achieving the retractable motion. It is driven by a worm and gear with power from a 6 rpm motor and automatically locks in position when the motor stops. The main structure of the system was fixed on two bulkheads mounted inside the fuselage. The whole system has been made and installed inside a simulated carbon fiber fuselage right on the target location. The shift between retracted and extended position was steady even when the load factor was up to 10 caused by gusts. The results indicate that this retraction system satisfies the design requirements.

1 INTRODUCTION

1.1 Background

Sea birds such as albatross can draw energy from the differentials in wind speed by a method called dynamic soaring. It allows them to keep aloft without beating a wing.

In order to verify that the same method can be applied on large aircraft flying in jet streams Lehigh University's Composites Lab lead by Professor Joachim Grenestedt has built an unmanned glider, the "JetStreamer" which has a wing span over 6 meters. Although the glider is designed to take energy to from the wind, it does need the power to take it to a proper altitude as a start. And to have the best performance, the JetStreamer tends to fly in jet stream which means the altitude could be well above 6000 m. To send it to that altitude a jet engine with 230N thrust needs to be installed on the glider. Once the glider reaches the desired altitude, the jet can be shut down and then retracted into the fuselage to reduce drag. If the wind gradient is not sufficient to maintain powerless dynamic soaring, on the other hand, the JetStreamer can still take advantage of the wind gradient to reduce fuel consumptions by performing powered dynamic soaring flights with the same jet engine [1].

This thesis focuses on designing and manufacturing a retraction system for the jet engine which meets the following requirements:

- Move back and forth from retracted position to extended position and self-lock at both positions.
- The motion is smooth and steady

- Withstand high loads.
- The system not overly heavy.

The relative position of the jet engine is shown in figure 1.

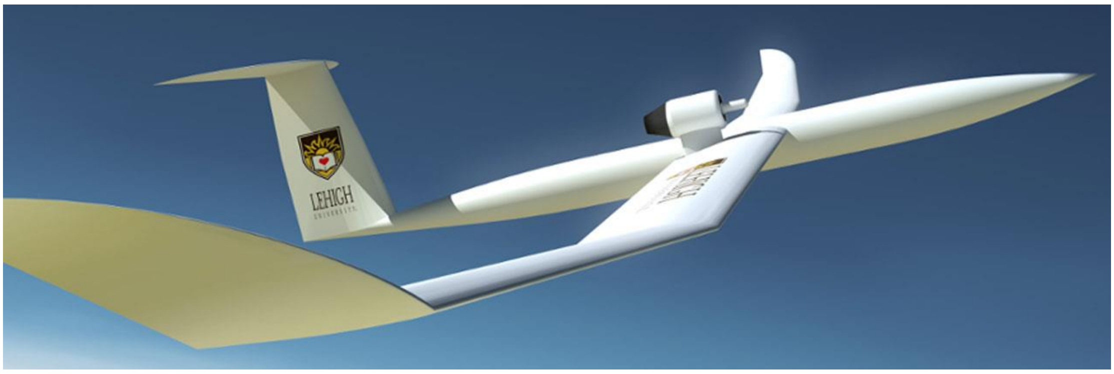


Figure 1: JetStreamer Concept Rendering

1.2 Design Specifications

Since the key has been raised, the basic conception of the design need to be established. When it comes to aircraft design, it is in general crucial to minimize the weight in order to increase the performance. In this case the thin wall steel tubing and thin aluminum plate are good choices for holding the engine. Composite sandwich will be used to attach the system to the internal surface of the carbon fiber fuselage. It is expected that during the flight the aircraft will encounter strong gusts or need to take steep turns both of which can cause load factor as high as 10 G. So it is important that the whole structure for the engine can take 10 G loads. Moreover because of the high temperature exhaust gas from the jet engine, the operating position of the engine needs to be at least 100mm above the top of the fuselage. Another important factor is the limited space. The total space for the system will be the cross section whose diameter is 180mm with length of 500mm.

A summary of the design specifications is:

- Thin wall steel tube structure
- Composite sandwich bulkheads
- Withstand 10G loads along the vertical axis of the engine
- 100mm clearance from the top of the fuselage at extended position
- Whole system can be fitted in a OD 180mm OD ×500mm long cylinder

2 INITIAL DESIGN

2.1 Basic Mechanism

The first step is to design a mechanism that can achieve the transition between retracted and extended positions. Although the length of the glider is over 5 m the diameter of the cross section is only 180mm while the diameter of the engine itself is already 130mm. The comparison of the engine and the cross section is shown in figure 2 below.

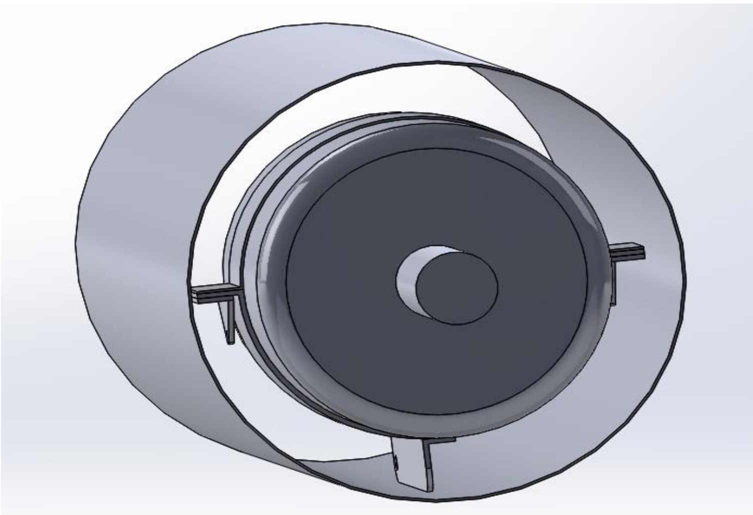


Figure 2: Engine Inside the Fuselage

The engine can only be horizontally put inside the fuselage. In this situation, a parallelogram mechanism may be the best solution. The same type of mechanism has been applied on the PSR Jet System used by manned sailplanes [2]. Figure 3 shows the details of the PSR Jet System.

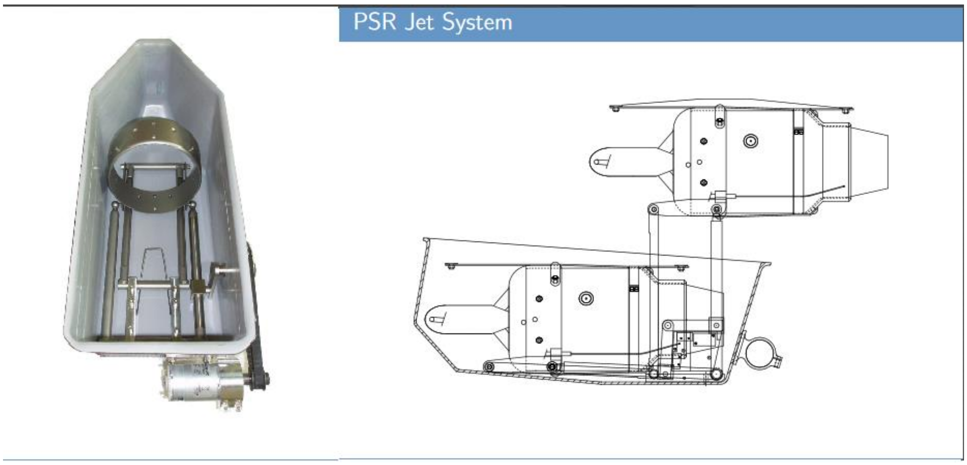


Figure 3: PSR Jet System [2]

With proper modification, it seems like the same kind of system can be used in our case.

2.2 Computer 2-D Modelling

Parallelogram mechanism is the foundation of the design. Using the dimensional parameters of the fuselage and the engine, a basic 2-D computer model was established to simulate the process of retraction. Figure 4 shows the simulation of the system. In order to increase the reliability of parallelogram since it is easy to go over center at the very beginning and to better arrange the space, the two arms of the parallelogram were fixed on different levels at the retracted position which is different from PSR system in figure 3.

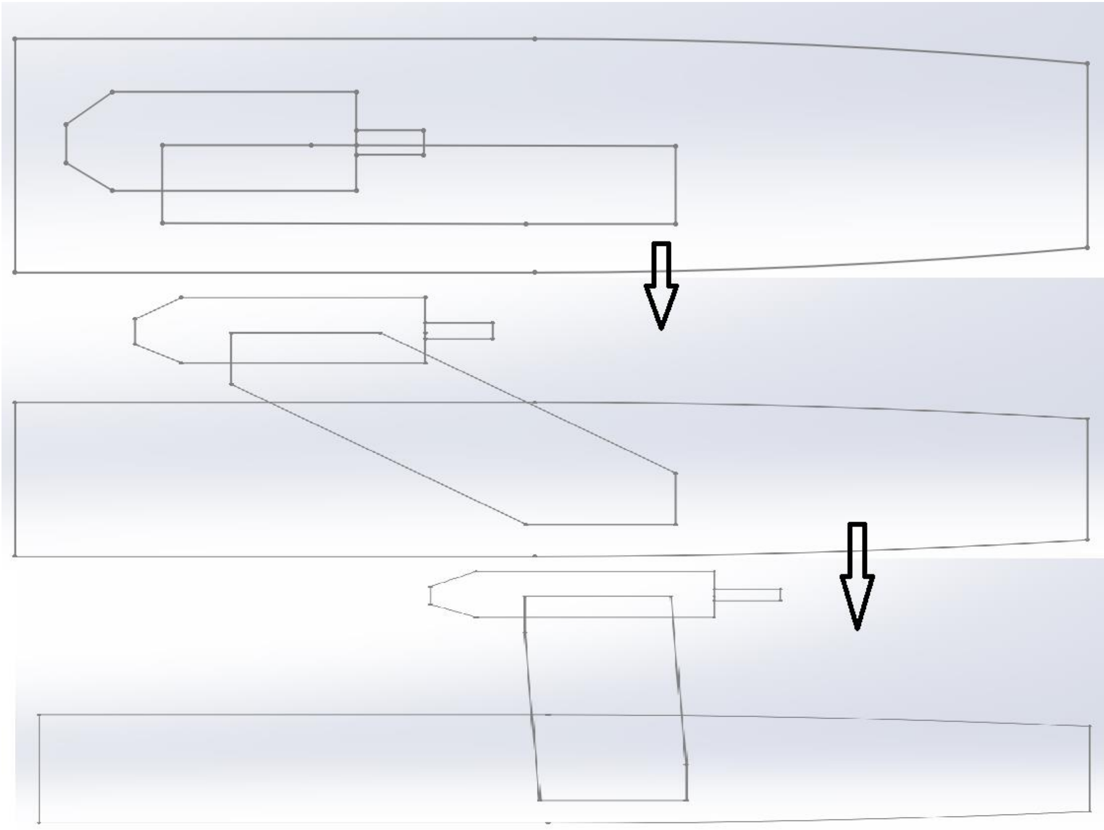


Figure 4: Simulation of Parallelogram Mechanism

2.3 Detail Design and Computer 3-D Modelling

The basic concept of the design has been established, the next step is to design each component of the system. The CAD software SOLIDWORKS was used for 3-D modeling the whole system

Structure of the Parallelogram

The parallelogram is accomplished by two parts:

- Two tubes hinged on both side of the engine mount connect to a third tube served as a fixed hinge on the bulkhead. They take most of the force in operation and control position of the jet.

- Another tube hinged on a tab attached to the bottom of the engine mount and the bulkhead to control the attitude of the jet and keep it parallel to the fuselage.

The two tubes in the front are bent to fit inside the fuselage. Figure 5 shows 3-D model of the parallelogram.

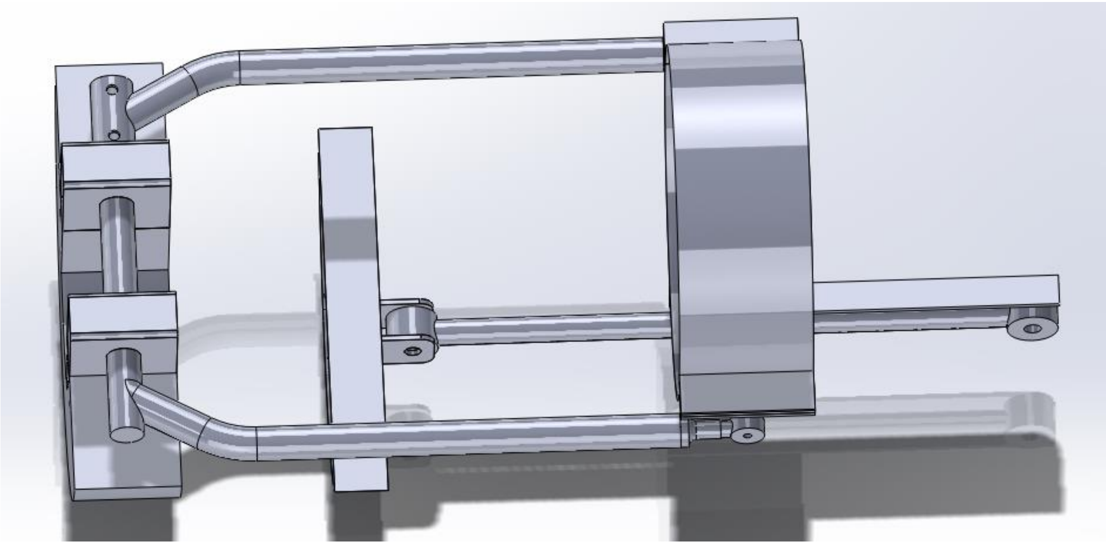


Figure 5: 3-D Model of the Parallelogram

Drive Mechanism

Because of the gusts the system needs to be designed to take 10 G loads which means the driving member of the system must provide a torque over 62.5Nm. The electric motor is a good choice. The size and the weight of electric motor is appropriate for this case but even for a 6rpm DC motor with a gear box the maximum output torque was only 6Nm which was a lot less than the required torque. In order to amplify the torque a worm screw and gear were installed with the motor. By virtue of their design, the positions of the worm screw and gear are locked when the worm is not driven which perfectly meets another design requirement. Figure 6 shows the assembly of the driving part.

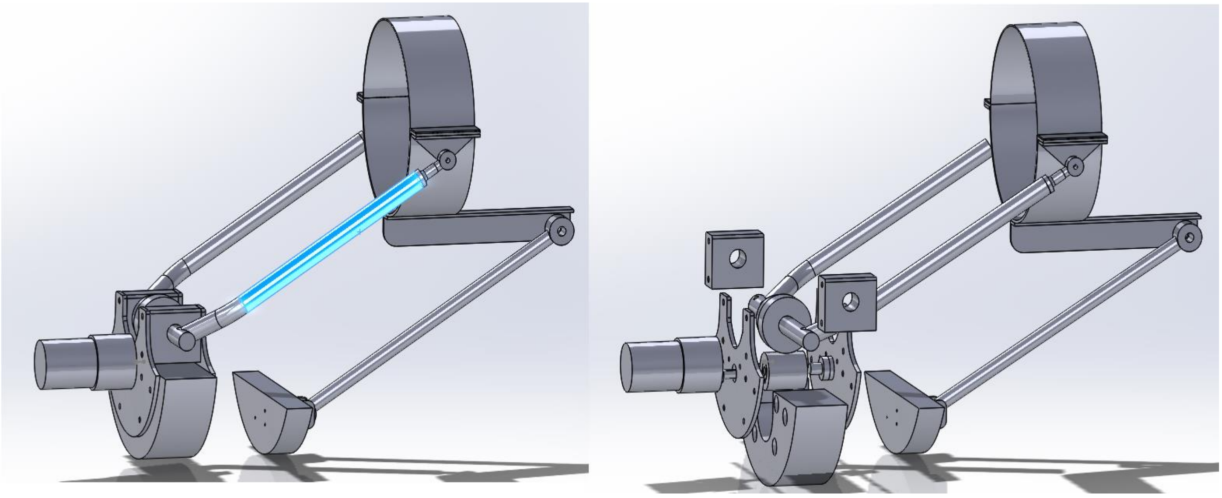


Figure 6: Motor with Worm Gear

Base for the Drive Mechanism

The next step is to put everything on a base which can be mounted inside the fuselage. The fuselage itself is made of carbon fiber with the thickness less than 1 mm. Due to the characteristic of the carbon fiber, it can take tremendous shear stress. Meanwhile a little poke on the surface can result in a significant deformation because the skin is really thin. So the crucial point of the base is to transfer any force from the system into shear force applied on the internal surface. A bulkhead is a good way to solve this problem. The bulkhead for the driving part is shown in figure 7. The bulkhead was made of a thick core and two aluminum plates one of which had the motor mounted on. And the transverse tube sits in two little blocks in between the plates. The bulkhead was then bonded inside the fuselage and served as a medium to transfer the thrust of the engine into shear on the internal surface.

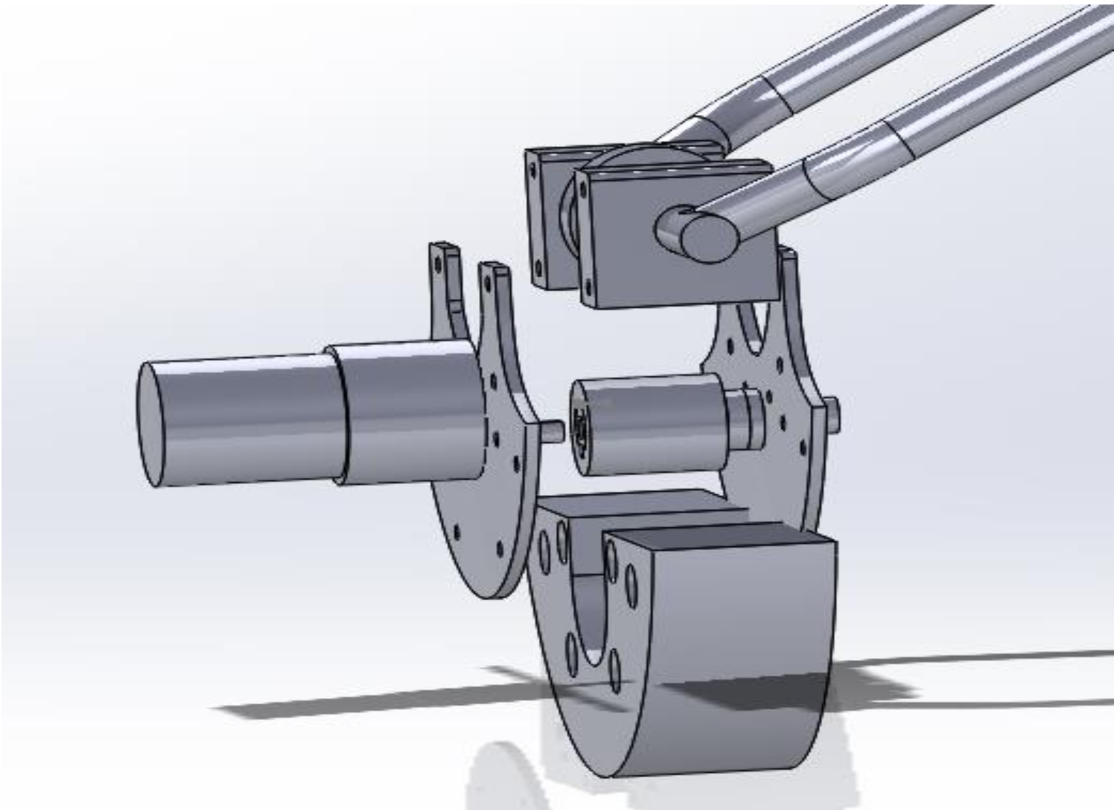
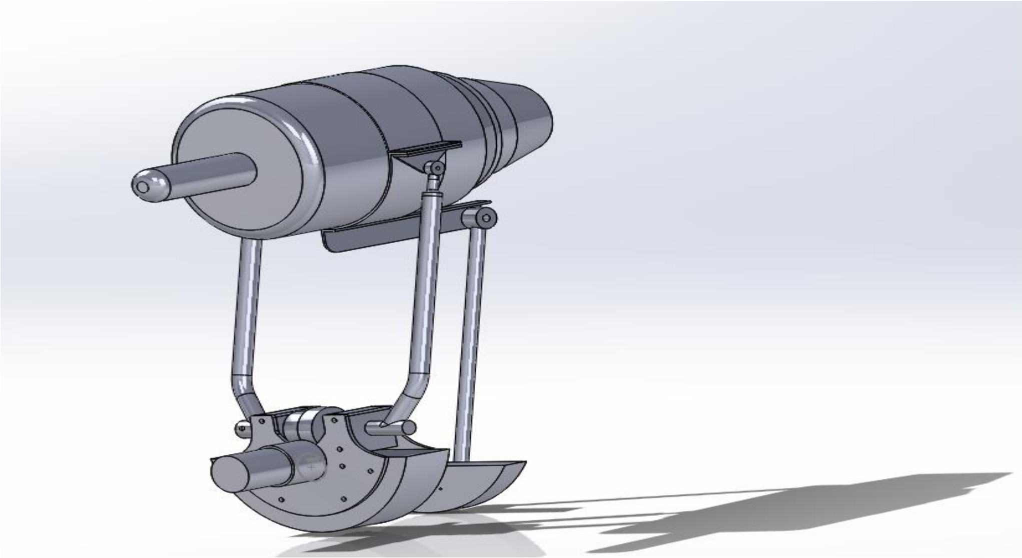


Figure 7: Bulkhead Base

Base for the Attitude Rod

The rod in the back is to prevent the engine from pitching. This is a two force member and is attached at one end to the lower portion of the engine mount while the other end attaches to the rear bulkhead.

Final Design



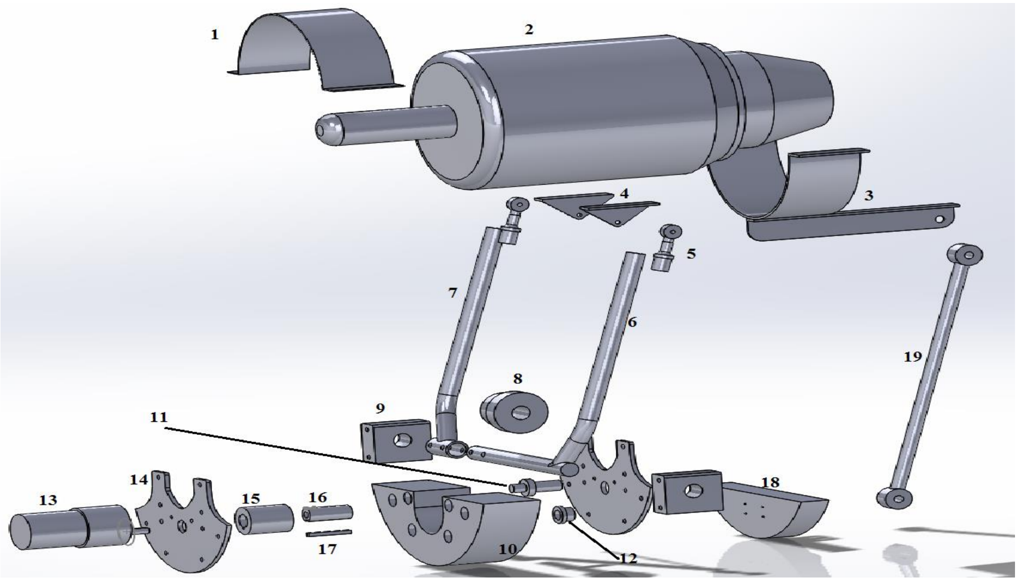


Figure 8: Final Design

1----top of engine mount 2----jet engine 3----bottom of the engine mount 4----hinge for the rod end 5----rod end 6----tube part 1 7----tube part 2 8----worm gear 9----block for the tube 10----bulkhead sandwich 11----shaft for the bushing 12----bushing 13----electric motor 14----aluminum plate for the motor 15----worm 16----transmission shaft 17----key 18----rear bulkhead 19----attitude rod

3 Basic Analysis

The basic parameters of the jet engine are shown below:

- Nominal thrust: 230 N
- Engine weight:2.5 kg
- Diameter: 130 mm
- Length: 350 mm
- RPM range: 33,000 to112,000
- Max temperature: 750 °C

3.1 Tube Structure

Length of the Arm

In order to protect the fuselage from the exhausted gas which can reach 750℃ at the end of the engine when it is working the engine at extended position need to be 100mm to 150mm above the fuselage. The diameter of the fuselage D_{fuse}=180mm. The length of the arm is at least $\frac{1}{2}D_{fuse} + 100 + \frac{1}{2}D_{engine} = 250mm$

Strength of the Tube

The structure of the tubes is shown as figure 8. Since the dry weight of the engine is 2.5kg and the L_{arm}=250mm, considering the 10G loads **the biggest moment at retracted position** is $M_{idle} = 250N \times L_{arm} = 62.5Nm$. Considering the tube structure as cantilever and the attaching points between the tube and the engine mount pass right through the center gravity of the engine, the largest stress is generated at the root of the tube with $M_{idle} = 62.5Nm$ and the moment on each tube is 31Nm.

$$\sigma_{max} = \frac{MR_{tube}}{I}$$

$$I = \pi R_{tube}^3 t \quad t\ stands\ for\ the\ thickness$$

After choosing the 4130 tube with OD 12.7mm and thickness 0.711mm, the $\sigma_{max} =$ 345Mpa. The properties of the 4130 steel are:

- Tensile Strength, Yield 435 MPa
- Modulus of Elasticity 205 GPa

The safety factor $n = 1.26$

The biggest moment at extended position is $M_{working} = 230N \times L_{arm} = 57.5Nm$ when applying full throttle. The safety factor is slightly bigger in this case.

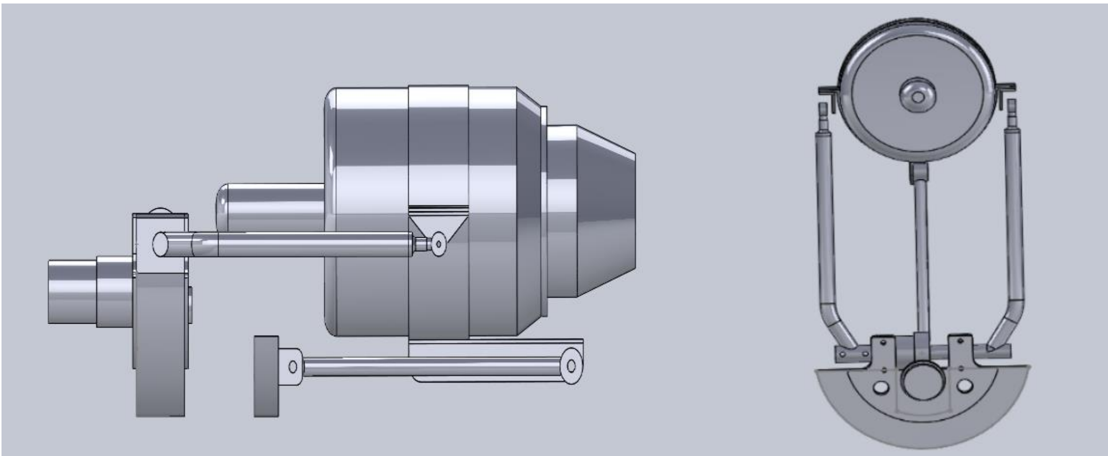


Figure 9: 3-D Model of the System

Since the RPM of engine can reach 112,000, the gyroscopic moment need to be considered. Assuming the pitching angular velocity around lateral axis is 60° per second and the blades are considered as a 100g thin disc plate with the radius of 50mm the following results can be derived:

Moment of inertial $J = \frac{1}{2}mr^2 = 1.25 \times 10^{-4} kg * m^2$

Blade spin velocity $\omega_1 = 112000 \times 2\pi \div 60 = 11722 rad/s$

Pitching angular velocity$\omega_2 = \frac{1}{3} rad/s$

Gyroscopic moment $M_g = J\omega_1\omega_2$=0.49Nm

The distance between the tubes is 130mm, so the force added on the top of the tube due to the gyroscopic moment is 3.8N. It won't be a threat to the structure.

3.2 Aluminum Plate

The aluminum plates are used in the system for hinge point, engine mount, motor mount and so on. The yield strengths of aluminum are shown below:

- Shear stress 220 MPa
- Tension stress 410 MPa

For an engine with 230N thrust, if the maximum stress allowed is 220Mpa then the minimum cross section is $\frac{230N}{220Mpa} = 1.04mm^2$. Theoretically a plate with 2mm^2 cross section will be strong enough to take the force with safety factor $\frac{2}{1.04} = 1.9$. So aluminum plates with thickness of 2-3 mm will be enough for the whole system. Figure 10 shows one of the plates for the engine mount.

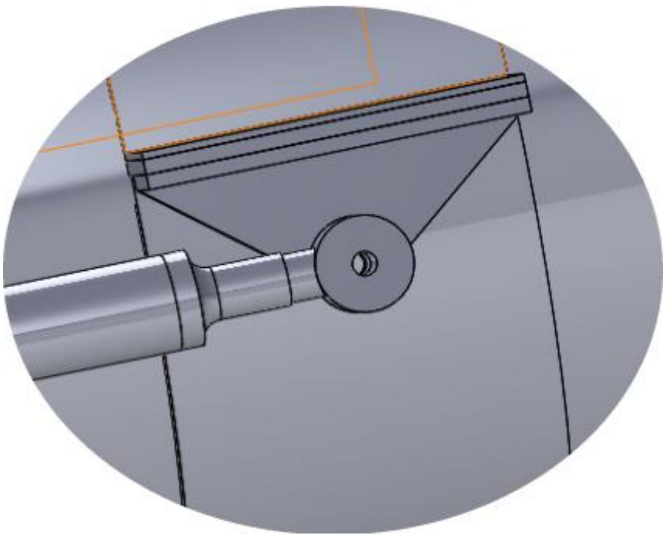


Figure 10: Plate for Engine Mount

3.3 Power Source and Drive Mechanism

The work for taking the engine to the work position is $W = m_{engine}. g. L_{arm} = 6.25Nm$. If the whole process takes 60seconds then the input power need to be at least 0.1 watt. On the other hand, the peak torque has to reach 62.5Nm in case of the 10G loads.

3.4 Bulkhead Sandwich

The bulkhead for the driving member consists of two aluminum plates and the core is made of composite material. Assuming the torque at working position is 57.5Nm as calculated before, the thickness of the core is 40mm and the bulkhead is bolted by six 8-32 screws, the thickness of the carbon fiber wrapping the core can be calculated as follows:

The force added on each side of the core $F = 57.5Nm \div 0.04m < 1500N$

The force on each screw $F_{screw} = 1500N \div 6 = 250N$

The pressure on the fiber assuming all the loads is taken by the screws

$$P = \frac{F_{screw}}{\emptyset_{screw} * thickness} = \frac{250N}{0.004m \times thickness}$$

For carbon fiber P_{max}=200Mpa

The thickness of the fiber should be 0.3mm. One Layer of 100g/mm^2 carbon is approximately 0.1 mm thick, thus the bulkhead needs at least three layers.

3.5 Connections

Worm Gear and Tube

The worm gear is bolted to the transverse tube that sits between the two blocks as shown in figure 6 with an 8-32 screw. The torque on the tube 57.5Nm and the OD of the tube is 15.8mm so the force on the screw will be

$$F = \frac{57.5Nm}{0.0158m} = 3600\text{N}$$

If the yield stress for steel is 435Mpa, then the thickness of the tube is at least 2mm.

Rivet

The stainless steel rivet can take at least a 1000N load which is even more than the thrust of the engine itself. So the rivet can be used fix the rod end on the tube and the tabs on the engine mount.

Rod Ends

The 6-32 steel ball joint rod ends can take more than 3000N static radial load and the loads on the rod ends are no more than the thrust which is 230N. So it is strong enough to serve as the hinge for the engine mount.

4 Manufacturing

4.1 Tube Structure

The main structure of the parallelogram was made of three tubes. For maintenance purposes it is detachable. A wooden jig cut by water jet was made for the welding. Two aluminum sleeves were made to keep the longitudinal axis of all three tubes in the same plane. The picture of the tubes in the jig is shown in figure 11. The left tube was welded to the transverse tube while the right tube was welded to a short tube bolted to the transverse one. A hole was drilled in the middle of the bottom tube so the worm gear later could be later bolted on.

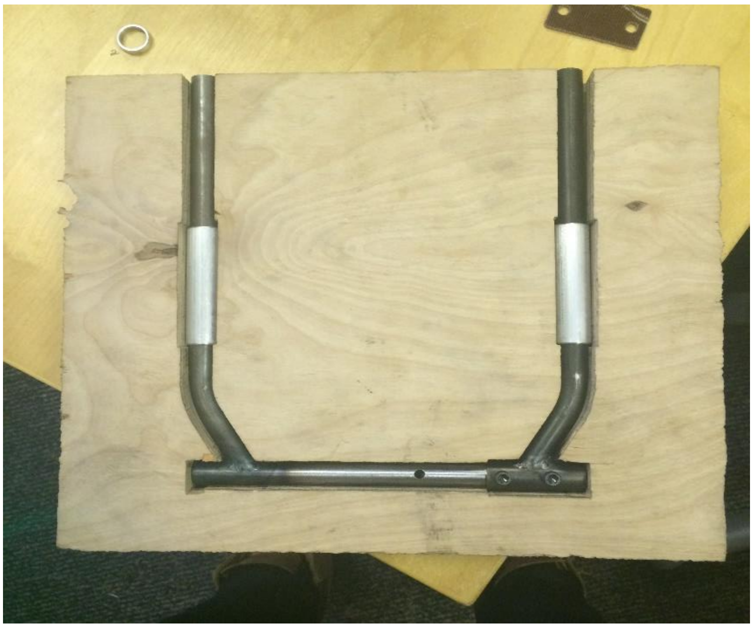


Figure 11: Welding Jig

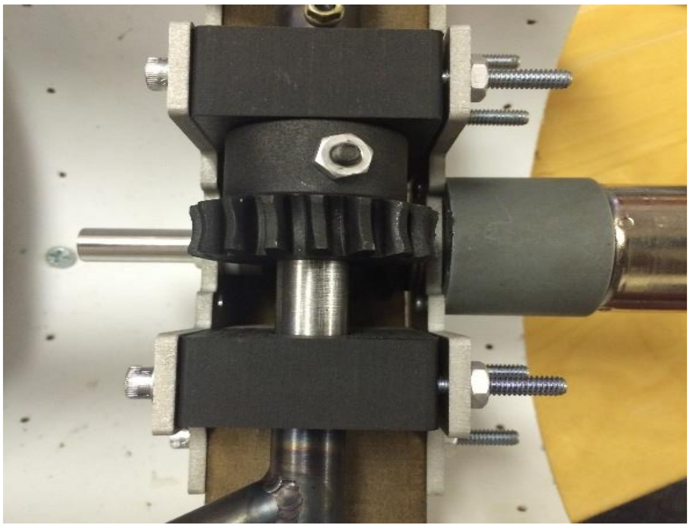
4.2 Engine Mount

The figure 12 below shows the engine mount. Two strips of aluminum cut by the water jet were bent to fit the surface of the engine and later clamped together with bolts. Two bent plates sit under each end of the strip to attach the mount to the rod ends on the tube. Another aluminum plate served as an attaching point for the attitude rod and was connected to the bottom of the mount via rivets. An extra aluminum strip was clamped around the engine connected to the plate to reinforce the structure.

Figure 12: Engine Mount

4.3 Drive Mechanism

The motor was bolted to a 3mm thick aluminum plate. An extra shaft with a keyway was connected to the original shaft of the motor by set screw. The worm sat on the extra shaft with a key. The bushing for the shaft sat on an identical aluminum plate. There were ten holes on both plates so they could later be attached by bolts. The tube rested in the center of two little Delrin blocks. Figure 13 shows the assembly of the drive mechanism.



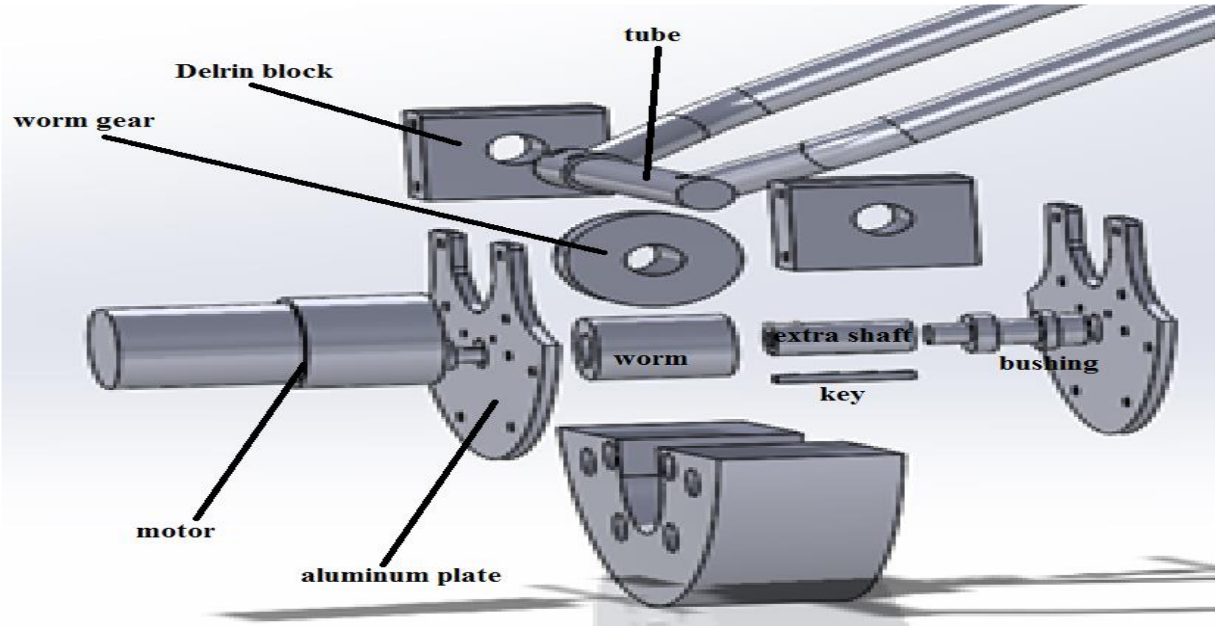


Figure 13: Drive Mechanism

4.4 Sandwich for Bulkhead

The whole system was mounted inside the fuselage with the bulkheads. Fiber-reinforced sandwich is light yet strong enough and a good choice for the material of the bulkhead.

In order to make the sandwich, six 12.7mm thick pieces of foam is cut by the water jet. Figure 14 shows the foam for the sandwich. The bulkhead in the front takes most of the thrust and was made 40mm thick. To begin, four pieces of foam were glued together by epoxy. The foam is easy to collapse under the pressure of the bolts, so spacers made of Garolite were inserted into the position of the holes. After putting in the spacers the foam was bonded together under a vacuum bag and squeezed together by air pressure under room temperature. When the epoxy was cured, the holes for the bolt were drilled on the spacer.

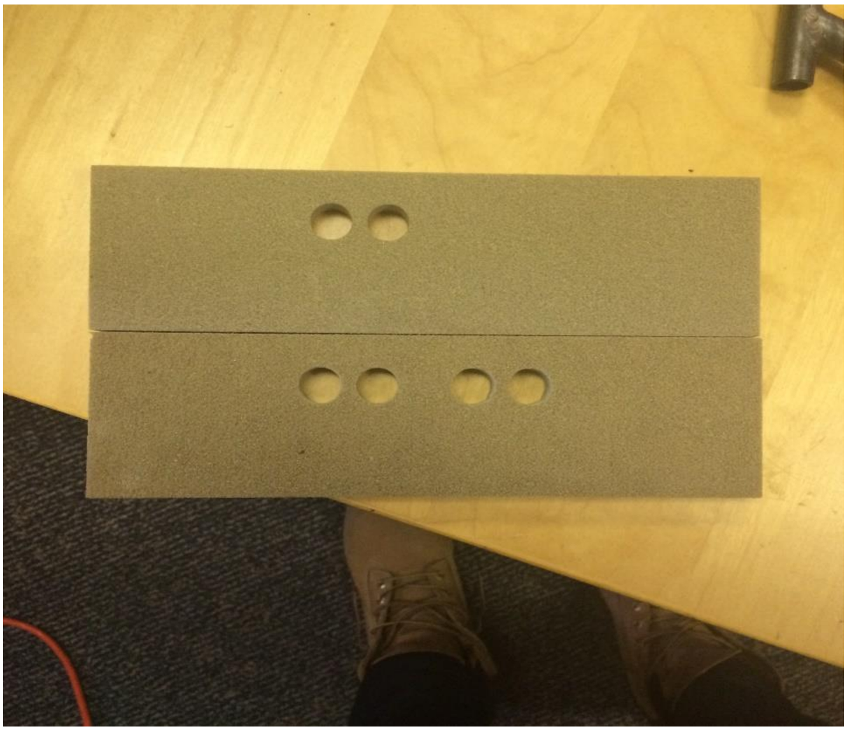


Figure 14: Foam

To achieve the high strength for the light weight sandwich, carbon fiber prepreg was used since it has high stiffness, high fiber content and consistent mechanical properties. According to the calculation each sandwich needs 3 layers of carbon fiber which are $[\pm 45°], [0° \ \ 90°] \ \ and \ \ [\pm 45°]$. The fiber along the edges were tailored so it could fit in the corner. An extra strip of fiber was used in the gap to make sure the whole piece of foam was fully covered by the fiber. The sandwich was put into a vacuum bag and cured in an oven at $100℃$ for 6 hours. The sandwich after curing is showed in figure 15. After the sandwiches were cured, they were cut to fit the curve of the fuselage.

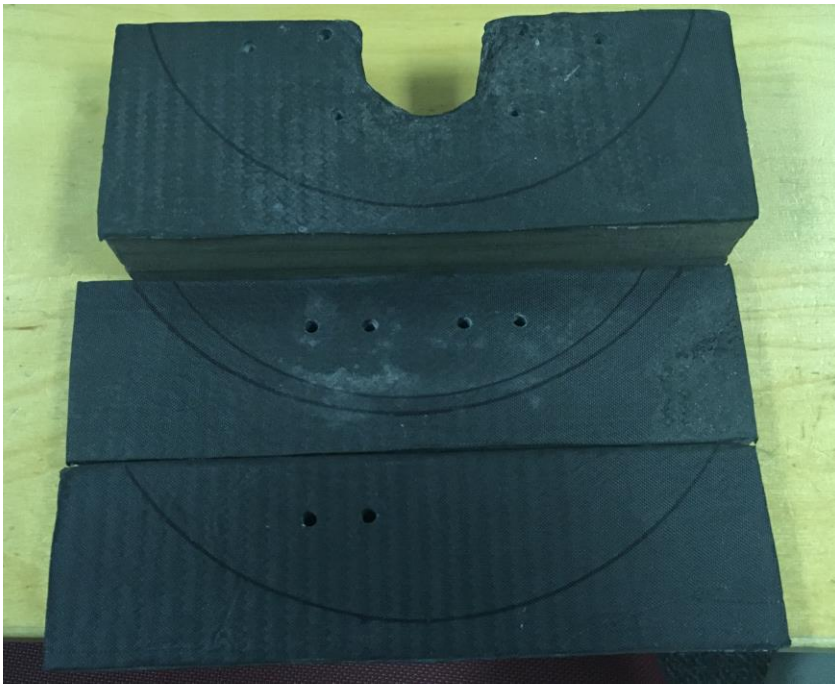


Figure 15: Sandwich for Bulkhead

4.5 Assembly

In order to simulate the system inside the Jet Streamer, part of the fuselage was built in the same way from the mold of the JetStreamer. There are two halves of the mold. Three layers of carbon fiber prepreg were laid down on the internal surface of each part following the sequence $[\pm 45°], [0° \;\; 90°] \;\; and \;\; [\pm 45°]$. Extra prepreg was left on the edges of each mold half so the bonding layer of the two halves could be reinforced. After the layup was done the two halves of the mold were put together and two vacuum bags were set for the curing. One bag sat inside the mold while the other one sealed the fuselage from the outside atmosphere. When the vacuum pump was working the bag inside still had room air pressure while the rest of the mold was vacuum because of the bag outside. The air pressure of the inside bag pushed the layers against the mold to achieve a better surface quality. The fuselage section was then cured inside the oven under $100℃$ for 6 hours with the vacuum pump on. When the fuselage was finished the middle part of it was cut open for installation of the retraction mechanism and the jet.

The next step was to use epoxy to attach the sandwich made previously to the internal surface of the fuselage. Both surfaces of the sandwich and the fuselage were sanded for better adhesive performance.

After the epoxy cured, two layers of fiber glass were laid on the edges between bulkheads and internal surface to reinforce the structure. Figure 16 and 17 show the Bulkheads after laying the fiber glass and the final state of the whole system.

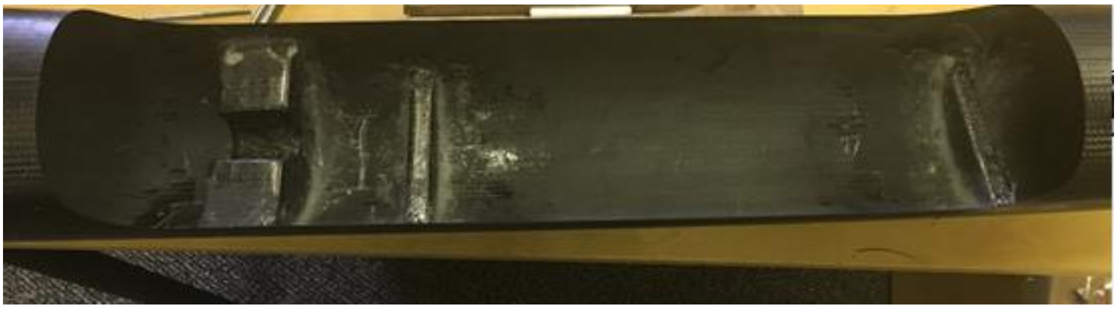


Figure 16: Bulkhead with Fiber Glass

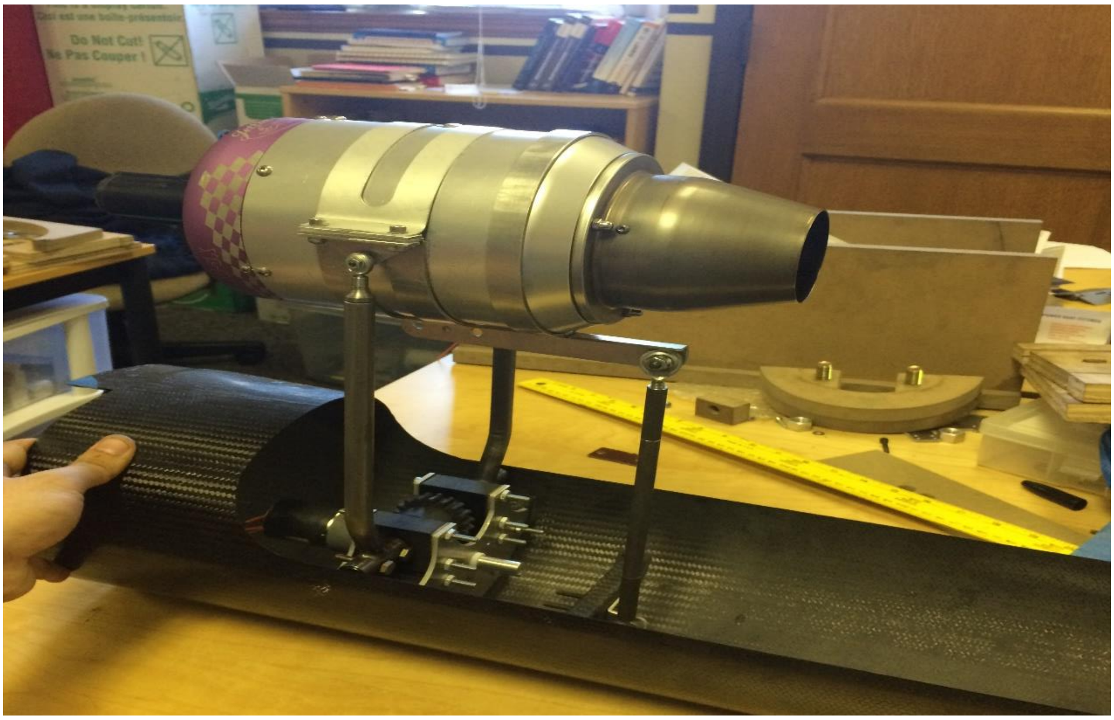


Figure 17: Final Version of Retraction System

5 Future Work

While substantial progress has been made on the retraction system, there is still considerable work that needs to be done before it's installed on the real Jet Streamer for flight testing.

5.1 Engine On Testing

The retraction system has yet to be tested with the jet running. Field test need to be done when the engine is under full power to test the strength of the retraction system. Meanwhile, all the accessories of the engine system need to be installed with the retraction system inside the fuselage to make sure there is no interference. A remote control system needs to be connected to the whole system in the end.

5.2 Testing Under Extreme Weather Condition

Because the operating altitude of the Jet Streamer can be as high as 18000m. The temperature at that altitude can be as low as -30℃. The whole system especially the electric parts need to tested under similar conditions to prove the reliability at high altitude.

5.3 Hatch for the Fuselage

The jet engine will be in and out of the fuselage during the flight so there needs to be a hatch installed on the fuselage to make sure that the it is open when engine is out and sealed when engine comes in.

Reference

[1] Yiyuan J. Zhao and Ying Celia Qi, “Minimum fuel powered dynamic soaring of unmanned aerial vehicles utilizing wind gradients,” University of Minnesota, Minneapolis, 2004

[2] Eike Schramek, “the Turbine-Better Than Its Reputation,” Segelfliegen, 1/2012

Vita

Yushi Mi was born in Hangzhou, China on October 16th,1991 to Honglie Mi and Daiping Zhang. After graduating from Hangzhou No.2 High School he attended University of Science & Technology Beijing and completed a Bachelor of Science in Mechanical Engineering. He then went to Lehigh University in Bethlehem, Pennsylvania to pursue a Master of Science in Mechanical Engineering.