Implementation of Active Flow Control using Microjets on an RC Aircraft

A Project Report

Presented to

The Department of Mechanical Engineering

At Florida State University

In partial fulfillment

Of the requirements for

The ME Senior Design Program

At FAMU-FSU College of Engineering

By

Phillip Kreth

Daniel Drake

Matt Tubtim

Hussein Nabulsi

April 1, 2007

Abstract

An active flow control system consisting of microjet-based actuators was implemented to a remote controlled airplane to test for positive flow reattachment during actual flight. An air supply system, using a compressed gas cylinder, high-pressure regulator, and remotely-operated valves, was designed to supply air, at 10 psig, to microjets located 4 in from the leading edge of the wing. This location was determined through the use of tuft testing in a wind tunnel. Designed using off-the-shelf components, the system added a total of 10.8 lbs to the aircraft and successfully demonstrated reattachment when the control was activated. This was visualized using tufts and a small video camera mounted to the vertical stabilizer of the aircraft.

Table of Contents

List of Figures

I. Introduction

Background

Active Flow Control (AFC) technologies have been explored in the lab for a number of years. One of these, the use of microjet-based actuators has shown substantial promise in a number of flow and noise control applications. For example, wind tunnel tests have shown that using these actuators can eliminate/delay separation and enhance lift for airfoils. In this project, the effectiveness of this technique on more realistic configurations/flows, using RC aircraft, will be explored. The microjets used in this project are 0.4 mm holes through which air is ejected at pressures from 5-10 psig (Fig. 1).

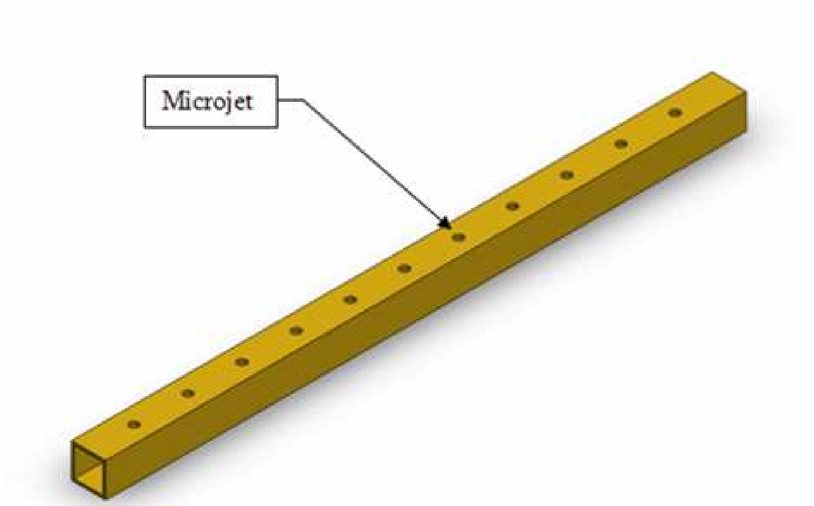
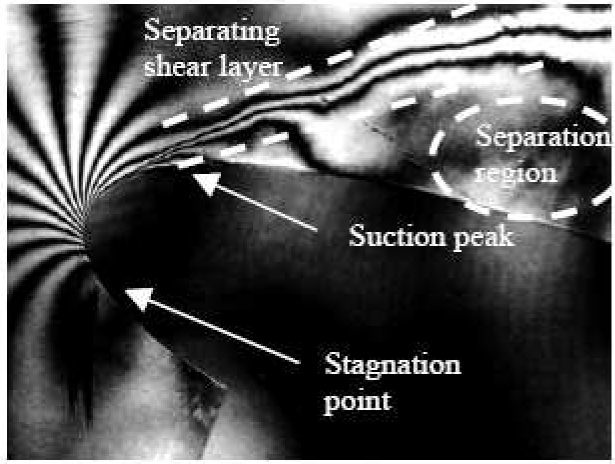


Figure 1: Microjets machined on 1/8" square brass tubing.

It is important to note that the air is not used as thrust to propel the aircraft; instead, the pressurized air is ejected perpendicular to the flow at the top surface of the airfoil. The air creates a vortex that enhances mixing in the boundary layer in the region where flow separates from the wing during flight at the critical angle of attack (AOA) (Fig. 2). When flow encounters an airfoil at a high AOA, it will "see" an increasing area as it travels from the leading edge to the trailing edge of the airfoil. This increase in area causes the flow to decelerate (as does friction), in turn increasing the pressure. This creates an adverse pressure gradient that, when the AOA is too high, will overcome the momentum of the flow causing the flow to separate. This also creates reverse flow on the airfoil's surface. Flow separation is the direct cause of stall on aircraft, since the pressure on the upper surface of the wing will be higher than that on the bottom, causing a drastic reduction in lift.



[1]

Figure 2: Flow separation on an airfoil beyond the critical angle of attack.

The placement of the microjets is crucial for the system to work efficiently. Previous research has indicated that the jets should be placed just before the point of separation on the airfoil. The microjets, once activated, should allow the flow to remain attached at higher AOA's. This means that the airfoil should still be producing lift at angles higher than the unmodified critical AOA. An increase in lift at higher angles of attack will give an aircraft more capabilities: lower minimum flying speed (shorter runway distance for landing), increased angle of attack (higher rate of climb), and improved lift characteristics on one wing at a time (roll control).

Project Scope

The expectation of the project is to have an aircraft with microjet arrays on the wings that will increase the overall lift and delay stall. After receiving a model aircraft, the group should become familiar with the flying characteristics of that aircraft by flying it without any AFC systems installed. Wind tunnel testing must be done on a wing section from the aircraft. These tests will determine the critical AOA and the separation point, thus determining an optimal location for the microjets. Using the data collected from the wind tunnel, the group should design an air supply system that will be contained within the aircraft and not exceed the maximum weight that can be supported by the model. Balance is also extremely important and must be taken into consideration when designing such a system. After the system has been implemented to the model, the group should demonstrate performance improvements on the aircraft.

II. Needs Assessment

1. Implement an active flow control (AFC) system, in this case microjet arrays, on a remote controlled (RC) aircraft
2. The system needs to be activated remotely
3. The system needs to operate for a long enough period of time to allow for testing and data collection

[1] C. Shih, J. Beahn, and A. Krothapalli. *Control of Compressible Dynamic Stall using Microjets*, Proceedings of FEDSM'03. 4th ASME_JSME Joint Fluids Engineering Conference. Honolulu, HI. July 6-11, 2003

4. The system should delay stall and increase lift
5. Only off-the-shelf items should be used
6. An analysis of the flight characteristics that are going to be improved will be conducted
7. A budget of $1500^{00} should be maintained

III. Wind Tunnel Testing

As stated before, wind tunnel testing must be conducted on a section of the wing of the model aircraft. This will allow the group to determine the critical angle of attack and the separation point. Various techniques were explored and are outlined in this section.

Paint Testing

Paint testing refers to using a paint-like mixture of oil and dye that when applied to the surface of a wing in small droplets will show the local flow direction. Paint tests have been used in other research to show reverse flow, caused by flow separation, and reattachment using microjet arrays (Fig. 3). Paint tests can be valuable in showing reattachment using microjet arrays, but they are very difficult to perfect. The group attempted conducting such a test but was not able to produce results similar to those below. This is because this testing method is both a science and an art form. The group simply lacked experience in this area to produce results worthy of pursuing further testing.

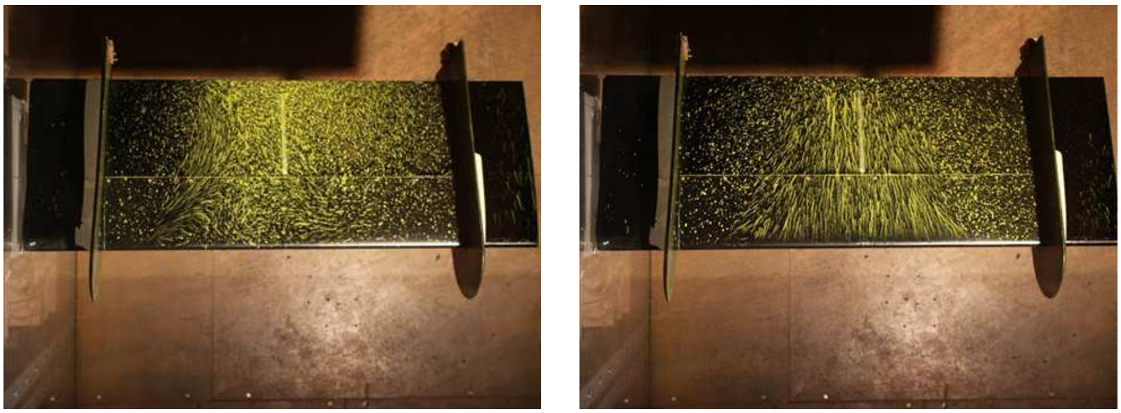


Figure 3: Research conducted at Université de Poitiers, France on an ONERA D airfoil (span 1 m, chord 0.35 m) shows flow separation and reattachment using microjets from a paint test. The wind tunnel's air flows from the bottom to the top ($U_\infty = 45$ m/s, $\alpha = 14°$). The picture on the left indicates separated flow (no streamlines in the direction of the flow) while the image on the right indicates reattachment using microjets that cover 40 % of the span.

C_P Measurements

Another method of testing airfoils in wind tunnels is through the use of pressure ports on the surface of the airfoil that will measure (through a simple calculation) the coefficient of pressure (C_P). The group disassembled a wing section and inserted pressure taps and conducted this test. The wind tunnel was run at 10 and 20 m/s for these tests and C_P was graphed (Fig. 4). When consulting with researchers at the Fluid Mechanics Research Lab, it was determined that there were a few possibilities for the location of the separation point. The group determined that it must perform another wind tunnel test that will help determine the actual separation point.

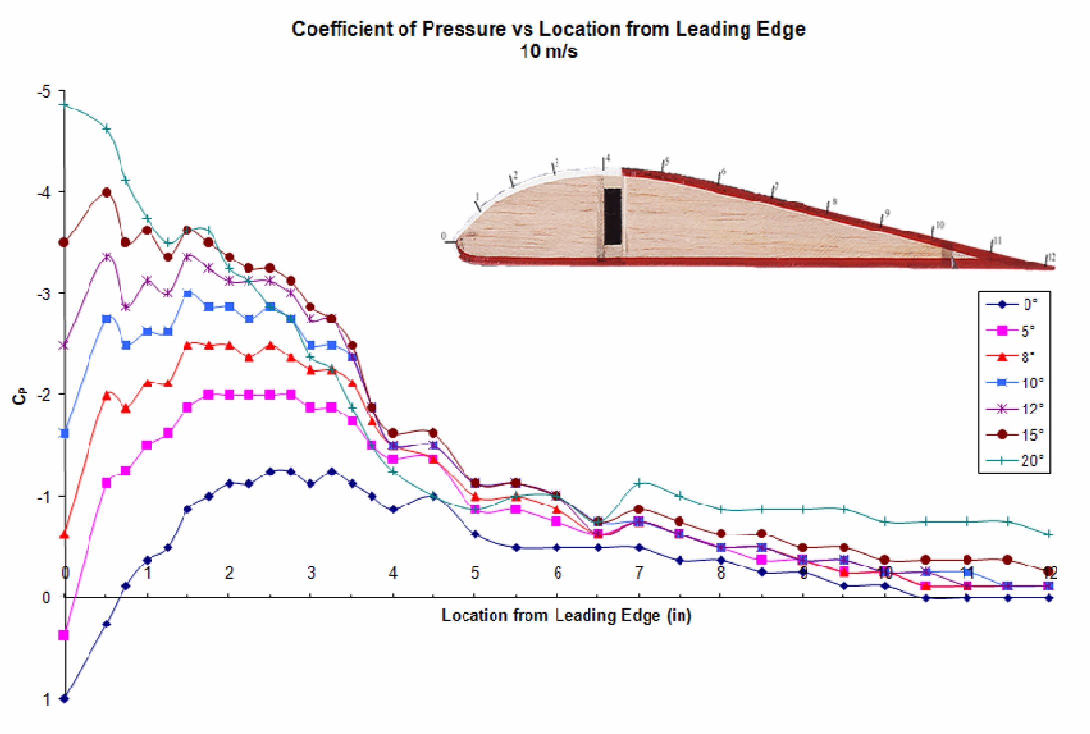


Figure 4: A graph of C_P (U_∞ = 10 m/s; α is varied) along the top surface of the wing.

Tuft Testing

Tuft testing refers to the use of small wool yarn strips attached to the surface of the airfoil (Fig. 5). These tufts, if they are of the right density, will align with the local flow direction, thus indicating separation and reverse flow. The group conducted tuft tests at 10 m/s and various AOA's to determine the critical angle of attack and the separation point. After performing these tests, the group determined that the critical AOA was approximately 16°. Also, a rough estimate of the separation point was determined.

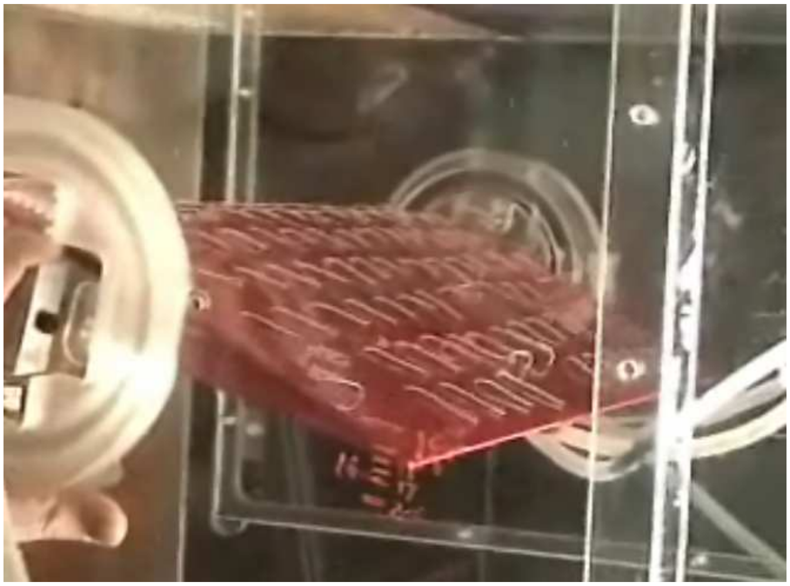


Figure 5: Test section mounted in the wind tunnel. This picture was taken during the test with 3 microjet arrays (notice the supply lines on the right). The tufts (in white) can be seen on the airfoil (in red).

The group determined that this was the best testing that had been conducted and could easily show reattachment and an increase in the critical AOA with microjet control applied; therefore, this testing method was pursued. Three arrays of microjets were mounted in the wing (all near the approximate separation point) and the wing was retested with control. Video was obtained showing separation without control and reattachment with the microjets activated. The video can be seen at the group's website (see link below).[2] An optimal location for the microjets was determined from reviewing the video. This method of testing could also be used on the actual RC model to demonstrate reattachment in real flight.

IV. Concept Generation, Analysis, and Selection

For this design project, there are two major requirements. The first is that the air supply method to the microjets should allow for 10 psig in the jets and should be able to supply that pressure to around 360 jets. The second is measuring the plane performance. Because of the weight, volume, and budget constraints, the systems must be selected in conjunction.

Air Supply Method

The air supply system must be able to output a pressure great enough that, after the losses through various tubes and fittings, will be 10 psig at the microjets. Also, considering that 100 % of the wingspan will be covered with microjets, the system should supply enough air to allow for testing. Two major supply methods were inspected: a pump or compressor and a high-pressure cylinder (Fig. 6).

[2] http://www.eng.fsu.edu/ME_senior_design/2008/team16/WT_Tuft_Reattachment.wmv

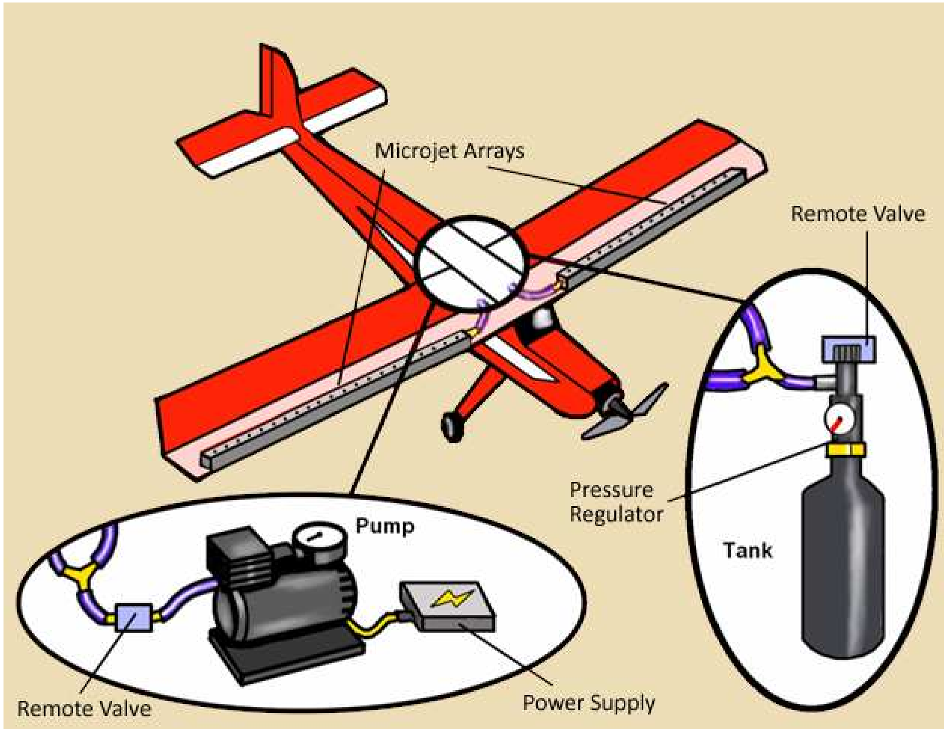


Figure 6: Two air supply concepts, one using an air pump and the other relying on a tank.

Pump/Compressor

Several pumps were inspected to supply compressed air. The weight of the system compared to the mass flow it can provide and size are major factors and have ruled out many pumps. The most suitable pump weighs 5.3 lbs, consumes 75 W at 12 V, and can supply at least 20% more mass flow than required for 1 row of microjets. This pump costs $320^{00} and has dimensions of 7.5 in x 5 in x 6.75 in. A pump would also require an electrical power supply. The power could be supplied by batteries but would add as much as ½ lb to the aircraft in order to supply power to the system for the duration of one flight. The major benefit of using a pump is its endurance: it can allow the system to run longer than any other proposed designs. However, its major drawbacks are weight and cost.

High-Pressure Cylinder

High-pressure cylinders are a great way of supplying air in multiple applications. Smaller sized cylinders are readily available since they are used commonly for recreational paintball. A tank for such an application can cost nearly $300^{00} and have dimensions of 4 in OD (outside diameter) and 10 in length. The most impressive quality of using a high-pressure cylinder is that the pressure can be adjusted using a pressure regulator connected directly to the tank. If the system actually experiences more losses than what were accounted for in the calculations, the pressure regulator can simply be turned up to increase pressure downstream. When considering using a high-pressure cylinder in an application like this, the group must investigate the best option for the contents of the cylinder.

Many different gases are available to fill these tanks with, as well as liquid forms of many gases. In some applications, liquid CO_2 is used. The main advantage of using a system with liquid CO_2 is that it has a large expansion value. For a small amount of liquid, a vast amount of gas is released: meaning that smaller tanks could be used in the airplane. However, liquefied gases are very cold and may cause freezing in the supply lines as well as other effects near the microjets. Also, since the gas is in a liquid form, the center of gravity of the tank will change during flight and could affect the balance of the airplane which, in some cases, may cause a crash. Liquefied gases were deemed too hazardous for our airplane and air supply system and have not been considered.

Compressed air is another common mean of supplying air in multiple applications such as SCUBA, cutting torches, and pneumatic tools. High pressure air (HPA) tanks in particular are light weight, small, and affordable. These tanks would be capable of supplying the necessary mass flow rate for around 50 seconds, depending on the capacity. Also, using compressed air does not lead to tank or line freezing. It is important to take safety into consideration when dealing with a compressed gas cylinder since the contents are under extremely high pressures. In the event of a crash, a HPA tank could rupture causing an explosion that would be hazardous to the group and the surrounding environment.

Air Supply Method Selection

Determined to be the best option, a high-pressure cylinder filled with a compressed gas has been chosen for the best method of supplying air to the microjets. The main considerations in choosing the method were the weight and volume, since some safety issues cannot be avoided. The pump or compressor would not be sufficient for our system since it has a large volume, requires external power (adding weight), and does not have a varying output. Considering the safety of a high pressure cylinder will be an issue in designing the modifications to the airframe that must be done in order to contain the system within the RC aircraft. Foam support should be used as well as some sort of metal to protect against any form of penetration in the event of a crash.

Performance Measurements

This section details the various methods of performance measurement that have been considered. This will be used once the entire system has been implemented to the aircraft. The group has chosen the following options to prove the concept of flow reattachment.

Radar Gun

Sports Radar Gun from Bushnell - $118.18

- Easy to use: the gun has a rubber handle and the design allows for “point-and-shoot” measurements
- Large, clear LCD output
- Both mph and kph speeds can be reported
- Fastest speed is displayed when the trigger is released
- Accuracy is very high (+/- 1 mph and +/- 2 kph)
- Safety depends on the measurements that are trying to be recorded:
    - If the climb rate is to be measured, a person will have to be on the runway directly underneath the airplane. This is a very risky situation and is also not allowed at the airfield used (Seminole RC Club Airfield).
    - The radar gun allows for measurements from 10 – 110 mph from 90 feet away.
- The weight and volume of this device does not have an effect on the airplane’s performance or weight and balance.

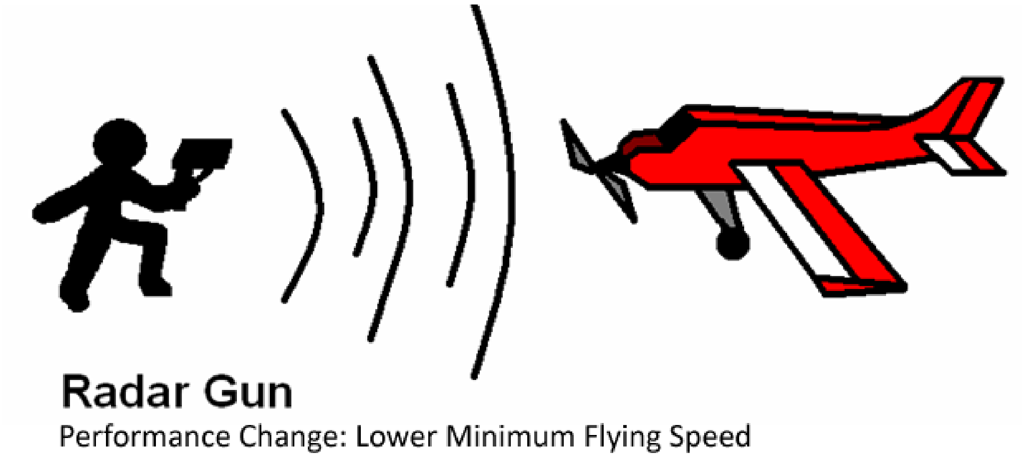


Figure 7: A radar gun can be used to measure the ground speed of the aircraft. Since the critical AOA should be increased, the plane should have a lower minimum flying speed.

Obstacle Course

- An obstacle course could be set up near the runway to measure an increased rate of climb (due directly to an increase in critical AOA).
- The supplies to build an obstacle course could probably be borrowed or made out of scrap. The price for the course is estimated to be very low.
- The setup of the obstacle course is debated:
  - Beams of varying heights may be set up parallel to the runway and when the airplane takes off, the distance to the objects may be measured. The airplane should climb over the obstacles in a measured time and the rate of climb is calculated.
  - Slow flight speeds could be measured by setting up the same beams parallel to the runway and inspecting video evidence of the airplane flying behind the beams if they are placed at certain distances apart.
- This is a very risky technique of measuring the performance of the aircraft since the airplane may run into the obstacles even if they are set up far from the runway.
- It would also be very difficult to obtain the correct location to place the obstacles since the wind direction and speed may change and cause the aircraft to take off at different locations from the same starting point.

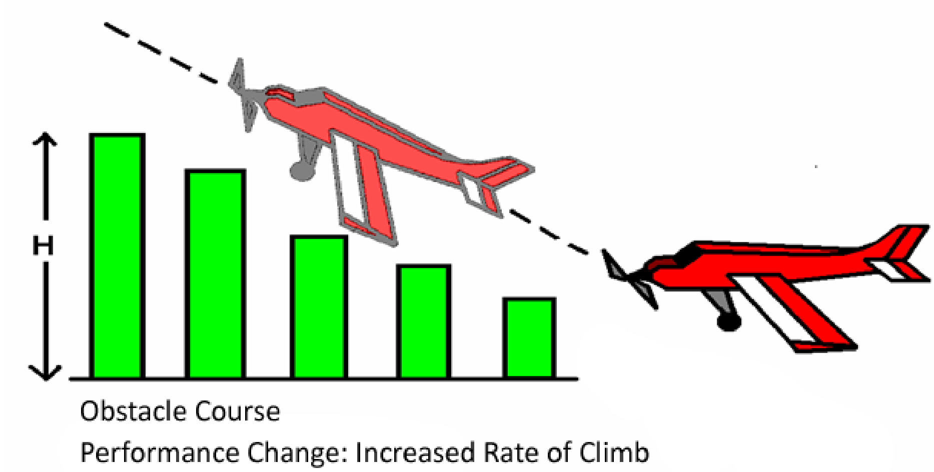


Figure 8: Measure rate and angle of climb using pylons placed in the background and video recording the flight with a camera mounted on a tripod. Angles can be compared with and without control.

Mounted Video Camera and Tufts

A video camera can easily be mounted to the airplane and pointed at the wing. Tufts, as tested in the wind tunnel, can be placed on the wing's upper surface and will indicate whether the local flow is separated or attached. The video can either be stored on a card in the camera or transmitted to a laptop set up at the airfield. Upon watching the video, the group should expect to see separation occurring on the wing and reattachment when the microjets are actuated. Another possibility for testing the system with a video camera is to observe reattachment over one portion of the wingspan at a time. For example, only the microjets at the tip of the wing can be activated during a stall allowing the airplane to maintain roll control (the ailerons are located at the tips) and video will show one portion of the wing with separated flow and the other with the flow reattached due to the microjet control.

Video cameras have been mounted to many remote controlled aircraft, and hence have been designed with weight and volume being the main concern. A video camera can be easily acquired through a number of hobby shops for around $\$100^{00}$. These video cameras are very small (3 in x 1.5 in x 0.5 in) and weight around 1 oz. A camera of this size will record the video to an SD card which will allow for 15 minutes of video per gigabyte of storage space. Transferring the video to a computer would be easy since many computers have slots that will read SD cards.

GPS, Pitot Probe, and Accelerometers

One option for measuring plane performance is a GPS system that is already commercially available for measuring the performance of model airplanes. This device mounts inside the airplane and can record data, or wirelessly send the data real time to a computer. This system can measure airspeed using a pitot probe; measure groundspeed, altitude, and rate of climb using GPS; and measure acceleration using an accelerometer. This system is also capable of measuring plane attitude using gyros but this add-on is considerably more expensive. This complete system weighs less than ¼ lb. The resolution for airspeed and altitude is 1 mph and 1 ft respectively. The angle resolution for the gyros is 1200 degree-seconds. The cost of the base unit which measures climb rate, airspeed, and groundspeed is \$449.99, the accelerometer for G measurements is \$79.99, and the cost for the gyros is $\$1,449^{00}$. The volume of the complete system is less than 10 in^2. Although the resolution of the GPS is good its accuracy may be poor. The sponsor of the project has used GPS on model aircraft and has found that the accuracy necessary for rate of climb measurements for this project is not possible using GPS.

Performance Measurement Devices Selection

When selecting a method of measuring the performance improvements of the aircraft, the group decided that the cost and safety of the airplane would be the two driving factors. The sports radar gun from Bushnell is a cheap way of measuring the ground speed of the aircraft and can be applied in a number of ways to measure the speed of the airplane in various orientations. The obstacle course is very cheap but could easily jeopardize the airplane if something were to go wrong. Using tufts and a video camera to obtain results similar to the wind tunnel testing conducted is the best option for performance measurements. This system does require adding weight to the airplane, but at only 1 oz, the video camera is of little concern to the overall weight of the aircraft. GPS and its accessories are too expensive for the budget given to the group and have also been observed to be inaccurate. During a visit to Eglin Air Force Base, the group was advised to not use GPS because of previous work conducted there on similar RC airplanes.

The best options for measuring the performance of the system are through the use of a radar gun and a mounted video camera with tufts on the wing. The radar gun will allow the group to test the flying speed of the airplane on landing with and without control. The group has calculated that a 7.2% reduction in minimum flying speed should be observed after control has been applied. Using a camera to record the movement of tufts is extremely beneficial to the group since they have conducted wind tunnel tests that demonstrate reattachment using a similar setup. The video would also be easy for anyone with a non-technical background to interpret and would help to market the system.

V. Proposed Design in Detail

Air Supply System

The air supply system for the microjet actuators must be designed carefully so that there are no critical points of choked flow ($M = 1.0$) in the system, unless it occurs at the microjet exit. Another consideration that must be taken into account is the pressure loss due to fittings, distribution manifolds, and length of the lines. The regulator selected must be able to supply a pressure to the main supply line such that the losses through the system to the microjets will still allow for 10 psig in the jets. With this in mind, the group has made the following diagram to design an air supply system using the selected method (high pressure cylinder) (Fig. 9).

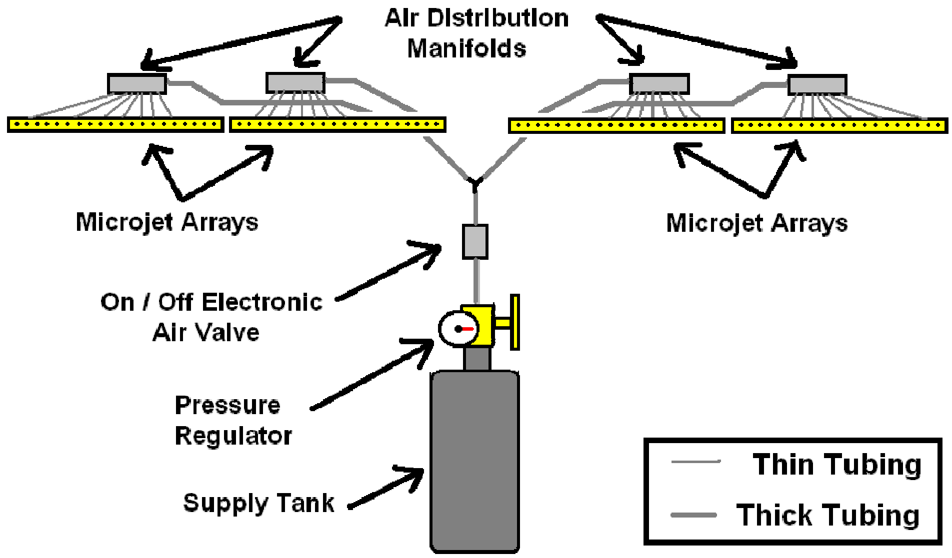


Figure 9: Diagram of air supply system. After the regulator, an electronic valve must be located to actuate the system as needed. Distribution manifolds must also be utilized to ensure that an even pressure and mass flow rate is supplied into the entire array of microjets.

The pressure losses for each of the supply lines were calculated and graphed as a function of their diameter; calculations are located in Appendix D. From the graphs, it was clear that the pressure losses rise asymptotically when the supply line diameter is reduced to a critical size. Utilizing this information, the group selected diameters that would keep the total loss in the supply system below 7.4 psia so that incompressible flow analysis would be valid. The other selection criterion was to minimize the diameter of the supply lines in order to minimize weight added to the aircraft.

Pressure losses in the distribution manifolds and at the microjets were also calculated and added to the losses in the supply lines (Fig. 10). The total loss for the air supply system was 3.53 psia. This lies within the 7.4 psia limit for incompressible flow analysis. The pressure ratio of the microjet pressure (10 psig) and the back pressure (14.7 psia) was calculated and ensured that choked flow was not occurring. This pressure ratio returned a mach number of M = 0.89 when looking at compressible flow tables. Also to keep the pressure drop from the tank to the microjets constant everywhere, the supply lines will all have to be the same length. Pressure ports have been incorporated into the microjet arrays in order to test the pressure of each array.

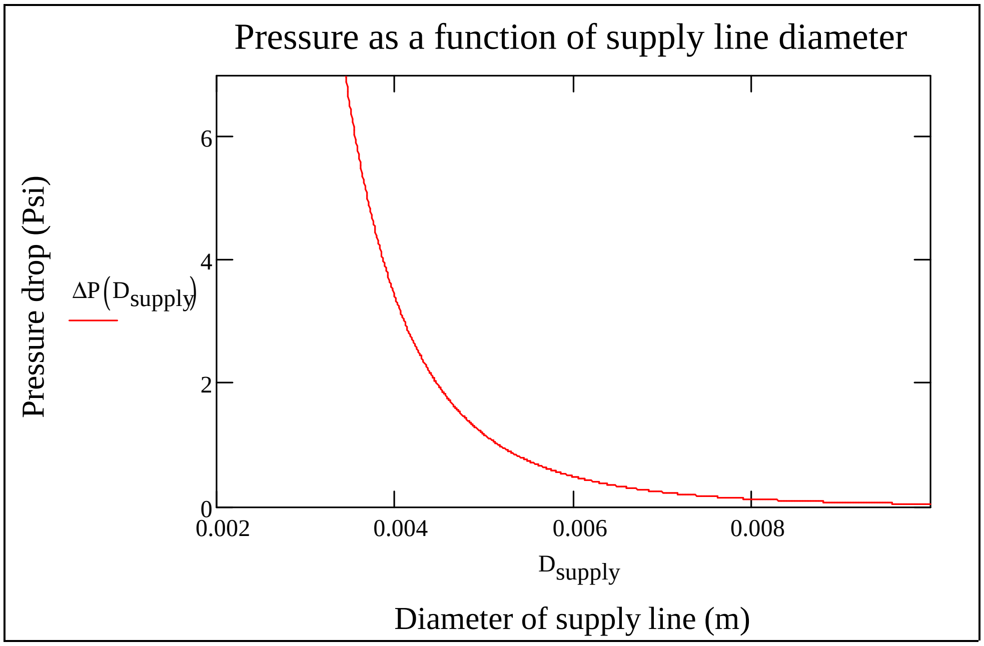


Figure 10: Pressure loss as a function of the diameter of the intermediate supply line. From the graph it is apparent that the pressure drop rises asymptotically near 4 mm. From this, a supply line diameter of 6 mm was chosen with a pressure drop of 0.489 psia over a 4 ft section.

Airframe Modification

Since the method of supply will be the use of a high pressure cylinder, the group must take careful measures to ensure that the risk of damage to the tank is very minimal. This means that some form of protection must surround the tank at all times during flight. The use of foam boards will help pad the tank in case of an impact and mounting the tank inside a sheet of metal should help protect it against any puncturing that could occur during a crash. The tank selected has a diameter of 3 in, so it was determined that mounting the tank on the inside of the fuselage would not be an option unless significant changes to the sides of the fuselage were made.

One proposed design is to mount the tank below the aircraft and protect it with sheet metal and a foam support core (Fig. 11). Some of the tank will be able to be recessed inside the aircraft, but it should be easy to remove for any maintenance and refilling. This location was selected keeping the airplane's balance in mind.

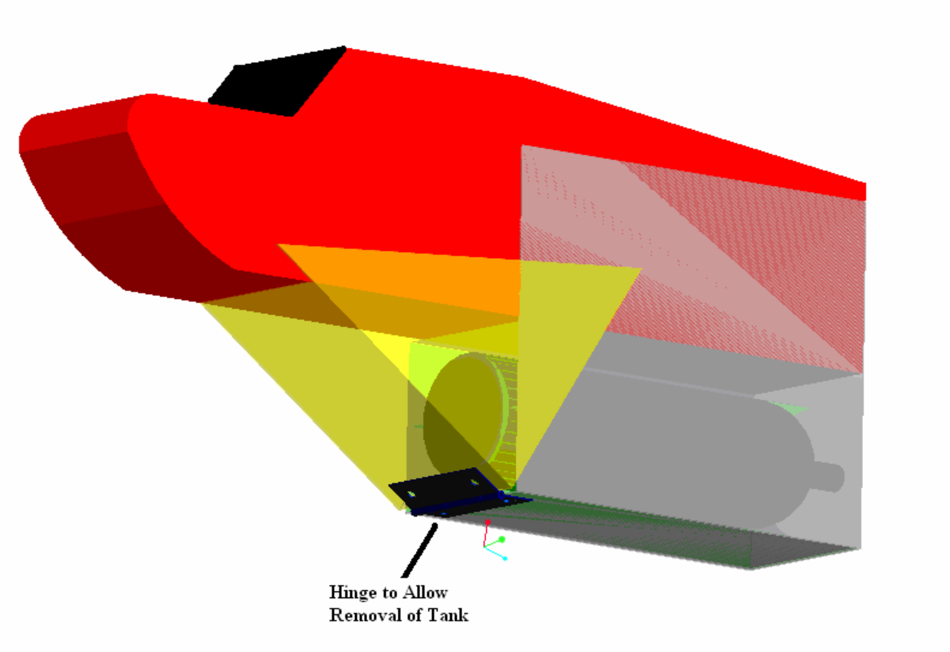


Figure 11: Placement of the compressed air tank.

The shield is composed of two parts, the nose and the support core. The support core, in green, will encase the tank with molded foam supports which will displace energy around the outside of the tank during impact. The sides of the shield will bolt to the airframe. Not only will the shield fully enclose the tank, but it will also add structural rigidity to the plane. The material for the shield will be aluminum sheet metal which should be sufficient to protect the tank and keep weight down. The nose, seen in yellow, will bolt partly to the plane and partly to the shield. The nose connects with the airframe near the front section of the fuselage at an angle such to reduce drag. A hinge can be placed at the connection point of the nose and shield to allow the tank to be removed from the system.

Another proposed design solution was to use a quick connect filling system to allow the tank to remain in the airplane once it has been placed. If the sides of the airplane are cut away on a small section approximately equal to 30% of the height of the fuselage, the tank could be completely recessed inside the fuselage. With this design, the use of foam padding and a piece of sheet metal will still be required since the tank will be exposed on the bottom side of the fuselage. The location for this design will require that the battery compartment and servo locations be moved. Also, the orientation of the tank will be opposite as the previous design suggests. This means that the regulator will be near the front of the airplane. This would allow the regulator to be connected directly to the tank, thus minimizing the weight of the previous design which would require a high pressure line to connect the two.

After careful considerations of safety, of the plane and the user, as well as the weight and balance of the airplane, it was determined that the high pressure cylinder be placed within the aircraft as much as possible. The tank should still be removable but also well protected in the event of a crash.

Wing Support Bars

Although the airframe used in this project will be able to support the added weight, it is necessary to support the weaker location of the aircraft: the wing's connection to the fuselage.

The kit for the aircraft has simple rubber bands used to hold the wings in place. These are not rigid and have failed during previous flights with increased weight. Struts will need to be used to increase the rigidity and strength of the connection. Struts are readily available at the local hobby vendor, HobbyTown USA. These struts have an airfoil-like cross-section to reduce any drag induced when added to the aircraft. The group will acquire these and fit them to the aircraft (Fig. 12).

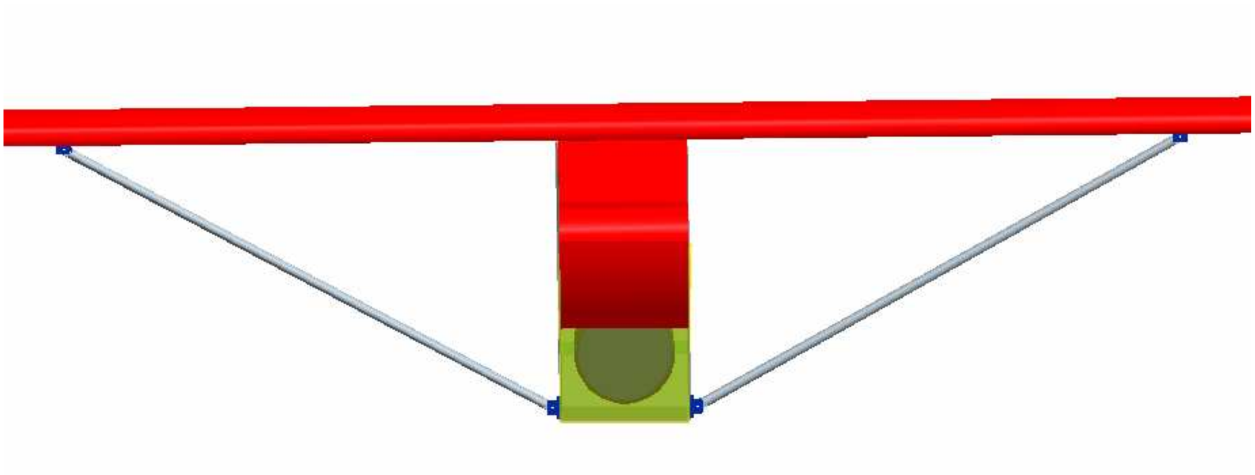


Figure 12: Frontal view of the wing support system proposed. The struts will make the connection between the wings and the fuselage rigid and also help distribute the loading due to the increase in weight amongst a more even surface of the wings. Note this is not the entire wingspan.

The struts must be able to attach to the shielding for the tank since it will be located directly underneath the wings (where the center of gravity is located). The struts should be able to be locked down to the wings and shielding and should allow the group to tighten this connection down so that the wings will see little displacement during flight. This connection will assist the rubber bands in securing the wings to the fuselage and should prevent failure from occurring at this connection again.

VI. Final Design Overview

Proposed Schematic

After the selection phase was finished, the group designed a system that should be implemented to the aircraft and made the following diagram (Fig. 13). All parts of this diagram are labeled to show the placement. The microjet location is shown in the figure and has been determined to be the optimal location for the best flow control. This schematic was made late in the fall semester and will be utilized during the actual design phase of this project which will take place in the spring semester.

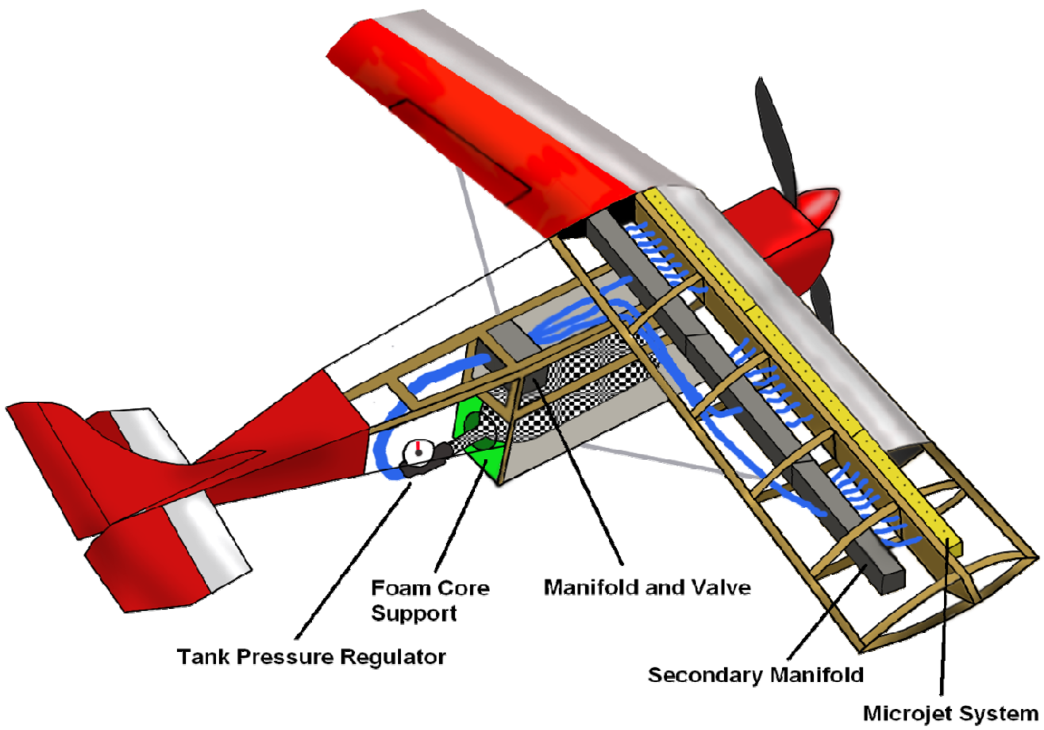


Figure 13: Final design schematic. The fuselage and wing sections have been cut away to show the detail of the system. The microjets will cover 100% of the wingspan. The tank will be housed within the fuselage and will be oriented in the opposite direction. Here it is shown facing the tail of the aircraft simply to show the regulator's location (connected directly to the tank).

Final Product Delivered

The final product delivered to the sponsor is seen in the following picture (Fig. 14). All of the components are self-contained in the aircraft, with the exception of the video camera used to measure the performance of the microjets. The final product is slightly different from the schematic in the following ways:

- The high pressure cylinder is oriented in the other direction (as stated in the description of Figure 13.
- The video camera was mounted to the tail of the aircraft allowing the video captured to contain 50% of the wingspan. Rudder control is affected only slightly.
- Tufts are installed on 50% of the wingspan.

Figure 14: Picture of the final product to be delivered to the sponsor. The microjet arrays cover 100% of the wingspan and can be seen in the darker color red. Tufts, seen on the right wing, will be used to visualize the flow during flight. The video camera, mounted on the tail, is aimed directly at the right wing.

Components of the Final Product

Pictures were taken during the design phase of this project to document progress as well as the actual locations of the systems installed into the aircraft. Each component was weighed and placed so that the center of balance of the airplane remained in the original location. The pictures taken are described in detail below.

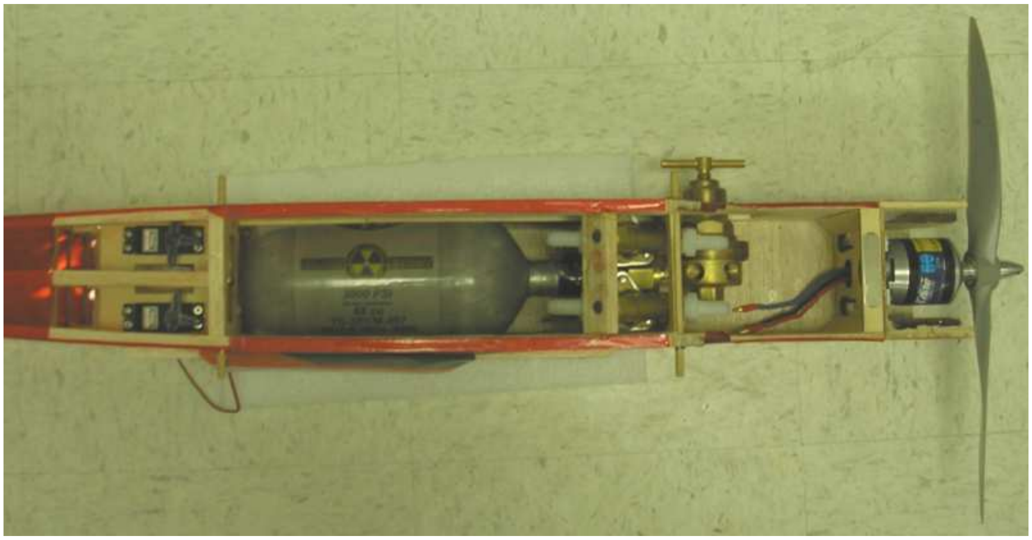


Figure 15: Overhead view of the air supply system placed within the fuselage.

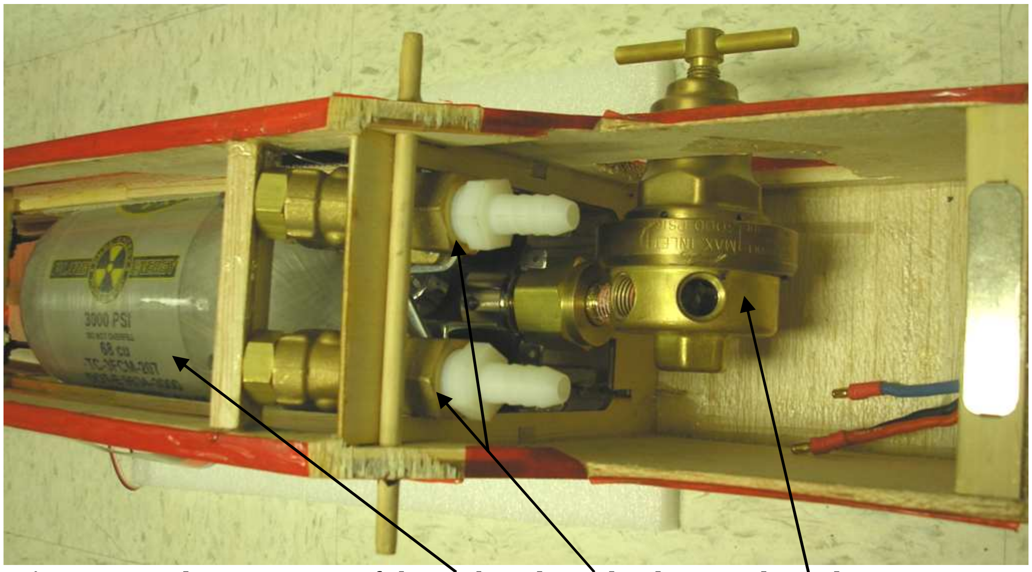


Figure 16: Close-up view of the tank, solenoid valves, and regulator.

Figure 17: Side view of tank location. As stated, it was recessed in the fuselage. The side of the fuselage is reinforced with an extra wooden support bar.

Figure 18: Bottom view of the tank. The location of the landing gear was not modified by its location. A foam support will be installed below the tank as well as a shielding made of sheet metal (Fig. 19).

Figure 19: Shielding made of sheet metal (tin) contains the foam support.

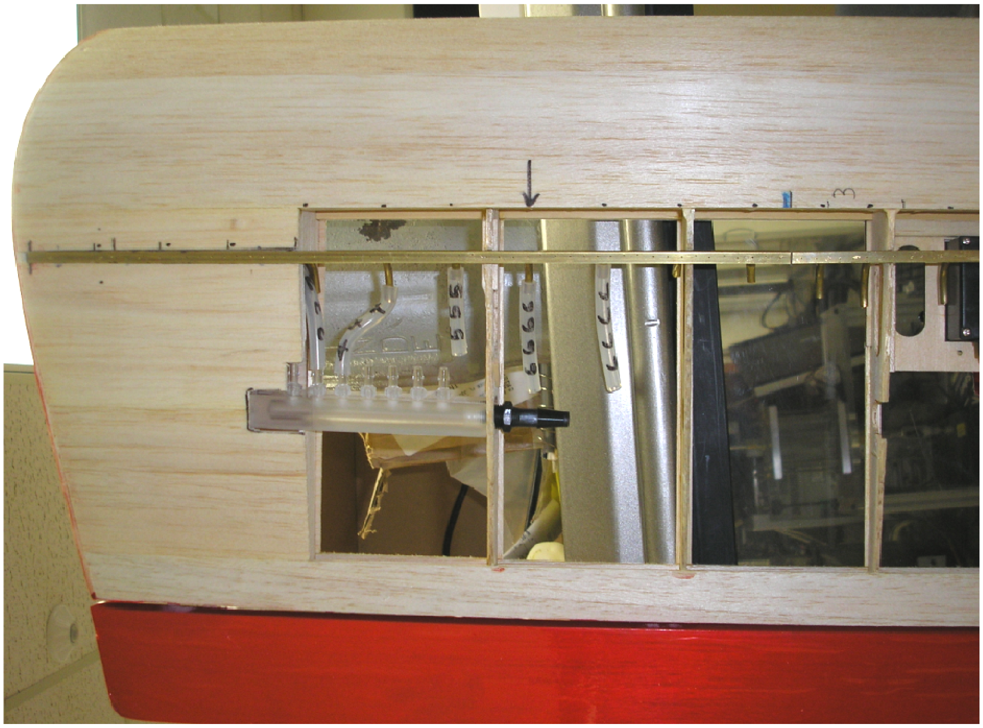


Figure 20: Tip of left wing with microjets and secondary manifold in place. A close-up view (Fig. 21) is also shown.

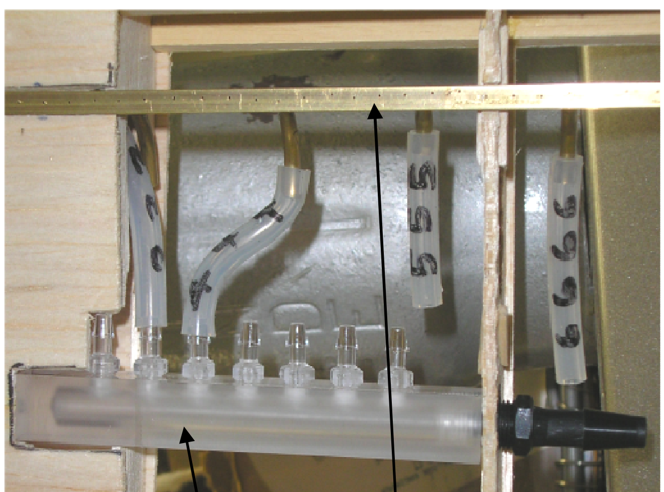


Figure 21: Manifold and microjet close-up.

VII. Testing Metrics

Performance Metrics

To demonstrate the increased performance from the use of the active flow control system the following flight parameters will be tested with the microjet system activated and compared to the flight characteristics without the jets. Operating the jets should actively attach the flow and increase the critical angle of attack of the aircraft. This will produce greater lift and lower drag than the unmodified airplane. The following flight maneuvers will be tested.

1. *Takeoff Distance and Touch Down Speed:* The plane should have a reduced takeoff distance with the microjets activated since lift should be improved and a higher critical angle of attack should be available (Eqn. 1.1). From the research of Michael Amitay, *Flight Control Using Synthetic Jets*[3], it was shown that an increase in lift of 16% is possible. Using that as the basis for velocity calculations and reference values for the coefficient of lift from *Theory of Wing Sections*[4], a 7.2% reduction of landing speed can be shown. For an aircraft weight of 8 lbs, this would be a reduction of 1.3 mph.

$$\text{Lift} = \frac{1}{2} \cdot V^2 \cdot A \cdot C_L \qquad (1.1)$$

V = Velocity
A = Wing Area
C_L = Coefficient of Lift

As can be seen from equation 1.1, increasing the critical angle of attack increases the lift coefficient. The lift value for takeoff corresponds to the airplane weight for non-accelerating flight. With the lift value fixed and the coefficient of lift increasing, the airspeed (V) decreases. However, the drag is also increased with increasing angle of attack, typically at an exponential rate. It is necessary that the plane produce sufficient thrust to overcome the additional drag force. Using a large coefficient of lift, the power necessary to overcome drag was calculated to be 11% of the available engine power. For the case of touchdown speed, engine power is not an issue. In this situation, the drag force works to reduce the kinetic and potential energy of the landing plane. As the landing plane dissipates its kinetic energy, it will pass through the point where the lifting force is less than the weight of the aircraft and the plane will touchdown in a stalled condition. This maneuver is common for landing planes. The touchdown speed will be reduced as the angle of attack is increased as described above. For both cases, the required runway length will be reduced, demonstrating a useful increase in performance. Also for a landing aircraft the microjet system can be powered with the surplus engine power that a landing plane has at partial throttle, with no adverse effect on thrust.

---

[3] M. Amitay and A. Glezer, "Separation Control using synthetic Jet actuators". Chapter in a book on Manipulation and Control of Jets in Crossflow. Series: CISM International Centre for Mechanical Sciences , Number 439. Editors: Ann R. Karagozian, Luca Cortelezzi and Alfredo Soldati, 2003, ISBN: 3-211-00753-9.

[4] Abbott, Ira H., and A. E. Von Doenhoff. Theory of Wing Sections. Dover Publications, 1959.

2. *Minimum Controllable Airspeed:* Positive roll control can be maintained at a lower airspeed with wing tip microjets activated delaying stall over the portion of the wing with ailerons. This can be demonstrated by measuring airspeed while simultaneously videoing tufts mounted on the wings. The wing roots should show flow separation while the flow over the wing tips remains attached. The velocity of the plane relative to the incoming air for this test is 7.8 m/s which is the same velocity for the first test.

3. *Maximum Angle of Climb:* During climb, the plane can maintain a steeper angle of attack with the microjets on, which will increase drag and cause reduced air speed for a given thrust (power setting). If the reduced lift, as a result of lower airspeed, is offset by the increase in lift from a higher angle of attack, the plane will have a greater angle of climb. This will result in improved obstacle clearing (trees or power lines at the end of runways).

4. *Roll Control using One Wing's Jets:* Activating the microjets on one wing should create asymmetric lift and cause the plane to bank. This is more likely to occur at AOA's greater than 5 degrees. At these angles, the mixing caused by the microjets will increase the flow velocity over the trailing edge of the wing, resulting in higher lift. This flow modification is not as effective at low angles off attack. For this control technique to work, the increased lift will have to be larger than the thrust produced by the microjets.

Test Plan

Since the budget constraints of this project will limit the group to obtaining simple results that flow reattachment has occurred, many of the above metrics will be left untested and proposed as future work. The following plan was assembled by the group to demonstrate that a system has been successfully implemented to an RC aircraft and that it produces results similar to those found using the wind tunnel.

1. *Video of Aircraft on Ground:* A video record of the aircraft on the ground should be kept. This should show that all systems implemented are in working order and have been implemented correctly such that everything is self-contained within the aircraft.

2. *Flight Test, No Control:* Since the airplane will have a large increase in weight, it is imperative that the group fly the airplane without testing the active flow control system. This flight will show whether or not the airplane will hold during normal flight and will also allow the group to trim all of the controls of the airplane.

3. *Flight Test, With Control:* Video should be obtained from the on-board camera showing the airplane being tested in a stall condition with control. This video should show separated flow and, with the microjet on, reattachment. For this test, the group has decided a simple modification will be made: wing tip jets will be activated only. This will allow the camera to capture one wing for the results needed. If the jets at the tip are activated during stall, the wing roots should show separation and the tips will show reattachment.

Test Results

The tests outlined in the previous section were conducted and successful, after a few attempts. Videos of the three tests can be seen online at the group's webpage[5]. The most important test, to the group, was to acquire video of the system working on the ground. From the wind tunnel testing section, one can see that the group demonstrated flow reattachment over the wing section of the aircraft chosen. This ground testing would also show that the group had successfully implemented an AFC system to an RC aircraft. Should the airplane crash during a flight, for whatever reason, the group would then have these two videos to show as evidence that the project could be seen as a success.

When attempting to fly the airplane with the system implemented, there was a small accident on takeoff. The airplane's landing gear was sheared off of the airplane during a steep turn and overcorrection. This is meant to happen if there are any problems with a landing; for example, if the airplane were to be traveling too fast on landing and hit some obstacle with the tires, they should be removed from the airplane to keep the rest of the airplane flying in a straight pattern, rather than tipping over. New landing gear had to be purchased because the previous tires were not stiff enough.

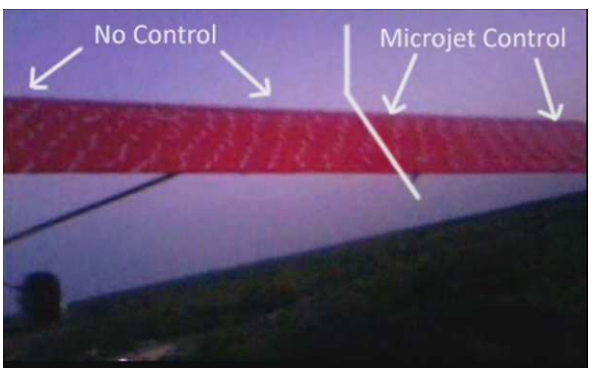
After installing the new landing gear to the airplane, the group decided to taxi the airplane around on the pavement for a while to make sure that the wheel were in working order. During this testing, the rear wheel (which had been modified originally) also sheered from the airframe. The group determined that the rear wheel should be replaced with one meant for larger airplanes. After the near wheels were put in place, and a few more runs on pavement, the airplane was in working order again and ready to fly.

After flying the airplane with the system, the group was relieved that the airplane did not crash due to the increased weight. This successful flight meant that the group was successful in considering the balance and weight of the airplane. With the help of an expert pilot at the Seminole RC Club Airfield (Fig. 22), the airplane was flown for the first time since the design phase started. That pilot assisted the group with trimming the controls of the airplane. After this flight, it was determined that the group should test the airplane under stall conditions with the control applied to the wing tips.

The video camera mounted on the tail of the aircraft was set to record and the test flight began. After successfully entering and recovering from a stall, the aircraft was landed and the video was taken from the camera. After reviewing the video with faculty advisor, Dr. Farrukh Alvi, the group determined that the project was a success and that separated flow was seen over the wing roots while flow was reattached over the wingtips due directly to microjet activation (Fig. 23).

[5] http://www.eng.fsu.edu/ME_senior_design/2008/team16/

Figure 22: A picture of the airplane just before the test with control activated. The Seminole RC Club Airfield is seen in the background. The video can be seen at the website[5].



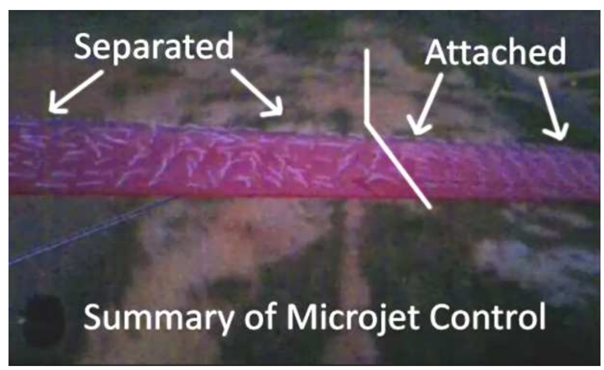


Figure 23: Screenshots of the test video; both views are of the right wing. The pictures show which microjets are activated and where reattachment occurred during the stall.

VIII. Conclusion

The preceding report shows that the use of microjet actuators is a successful method of controlling flow separation on a remote controlled aircraft. Utilizing various wind tunnel testing methods, it was determined that tuft testing would be the simplest means of demonstrating flow reattachment during actual flight. During this wind tunnel testing, the optimum location for the microjets was determined to be 4 in from the leading edge of the airfoil. A pneumatic system consisting of a high-pressure cylinder, regulator, remotely-operated pneumatic valves, and approximately 360 microjets (enough to cover 100% of the wingspan) was designed and implemented to the airplane. Successful flight testing was conducted, and video of reattached flow was captured by an on-board camera. This aircraft can now be used to conduct further, and more detailed, testing of active flow control. These tests include roll control, a lower minimum flying speed, and a higher angle of attack.

IX. Acknowledgements

We would like to thank several people for their assistance throughout the duration of the project. Dr. Farrukh Alvi, Advance Aero Propulsion Lab (AAPL), is our faculty advisor and has provided valuable feedback on all of our work and given us an in-depth view on this project and its correlations to larger scale applications. Some items were also bought under the research budget at AAPL, so we would like to especially thank Dr. Alvi for helping us acquire some other needed parts at the last minute. Dr. Gregg Abate, Eglin Air Force Base, is the corporate sponsor for this project. He helped steer us in the right direction during our on-site visit. Dr. Cesar Luongo is the professor in charge of the Mechanical Engineering Senior Design competition. He has been a motivation to us as well as a supplier of extremely valuable input. He is always available to answer all questions that we have. Mr. Jon Cloos is the person in charge of all purchasing that the group needs to do. He has to manage twenty-two groups this year and has been very busy with all groups. We appreciate the work that he has done to ensure that our project could be completed on time.

X. References

Abbott, Ira H., and A. E. Von Doenhoff. Theory of Wing Sections. Dover Publications, 1959.

C. Shih, J. Beahn, and A. Krothapalli. *Control of Compressible Dynamic Stall using Microjets*, Proceedings of FEDSM'03. 4th ASME_JSME Joint Fluids Engineering Conference. Honolulu, HI. July 6-11, 2003

Cengel, Yunus A., and Robert H. Turner. Fundamentals of Thermal Fluid Sciences. Boston: McGraw-Hill, 2005.

M. Amitay and A. Glezer, "Separation Control using synthetic Jet actuators". Chapter in a book on Manipulation and Control of Jets in Crossflow. Series: CISM International Centre for Mechanical Sciences , Number 439. Editors: Ann R. Karagozian, Luca Cortelezzi and Alfredo Soldati, 2003, ISBN: 3-211-00753-9.

Appendices

TeleMaster Electro,

With Flow control

Airplane flight manual

Contents

General

1.1 Introduction

The airplane flight manual is intended to provide the pilot with the necessary information to conduct safe and proficient operation of the airplane. This aircraft was designed as a research platform and is equipped with an active flow control system. When activated this system allows the plane to operate at increased angles of attack without the loss of flight controls. It accomplishes this by releasing pressurized air from microjets (orifices) located along the top of the airfoil, figure 1.

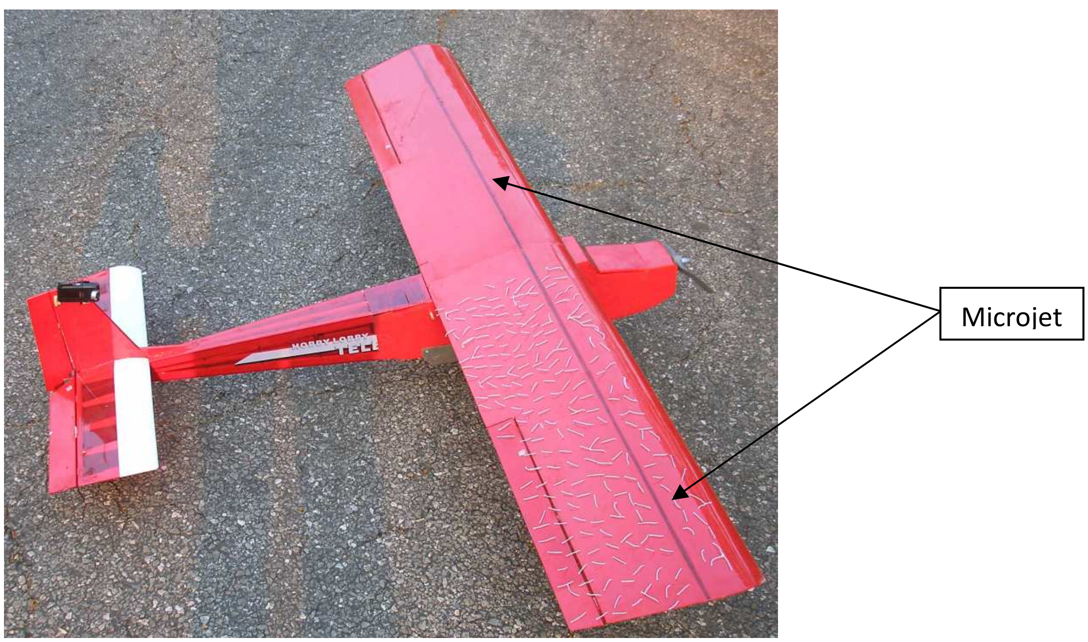


Figure 1, Microjet are located along the top surface of the wing. Compressed air is released through the Microjets at approximately 10psig.

1.2 Warnings, Caution, notes, and other definitions

The following definitions apply to warnings, cautions, and notes used in the light manual:

WARNING

means there exists a risk of serious injury to the operator or bystanders if the procedure/limitation is not observed.

CAUTION

means that damage to the aircraft or equipment may occur if the procedure/limitation is not observed.

NOTE

Draws attention to an item that is unusual of important.

1.3 Engine

Power 60 Brushless Outrunner, Electric motor

Specifications;
Diameter: 50mm (2 in)
Case Length: 62mm (2.4 in)
Weight: 380g (13 oz)
Maximum Operating Temperature: 220 degrees Fahrenheit
Maximum Burst Current duration is 30 seconds
Shaft Diameter: 6mm (.24 in)
Kv: 400 (rpms per volt)
lo: 2.7A @ 10V (no load current)
Ri: .06 ohms (resistance)
Continuous Current: 40A
Max Burst Current: 60A
Watts: up to 1200
Cells: 16-24 Ni-MH/Ni-Cd or 5-7S Li-Po
Recommended Props: 14x8 to 16x10
Brushless ESC: 80-Amp

1.4 Batteries

Lithium Polymer Batteries,

Number of Batteries: 2
2400 mAh, 3 cell Batteries
Connected in series
Total voltage 25.2V (24.96-25.32)

1.5 Motor Controller

Jeti, Advanced 70 Plus

Weight: 38g
Max Current: 70A
Size: 52mm x 25mm x 12mm

1.6 Radio

Futaba 7CAP, 7 channel radio

Specifications;

T7CAP

I system: 2-stick, 7 channels

Frequency: 50 or FM/PPM or PCM

Switchable 9.6V NT8S600B Ni-Cd battery 250mA

Servo S3151 (Standard, digital)

Control system: Pulse width control, 1.52 ms neutral

Power requirement: 4.8V (from receiver)

Output torque: 43.0 oz-in(3.1 kg-cm) at 4.8V

Operating speed: 0.21 sec/60 at 4.8V

Size: 1.59 x 0.79 x 1.42 (40.5 x 20 x 36.1 mm)

Weight: 1.48oz(42g)

1.7 Battery Charge

Micro Control Balance charge, Model # DBC-14

Specifications;

Power input: 11V-15V

Maximum working current: 6 Amp

Number of Cells: 4

1.8 Supply Tank

Luxfur 6 Composite tank

Maximum pressure: 3000psi

Internal Volume: 68ci

1.9 Pressure regulator

Victor

Maximum pressure: 3000psi

1.10 Valves

Solenoid Valve model 442P

Specifications;

Operating voltage: 24V

Minimum orifice size: ¼ in

1.11 Propeller

15in x 10in composite propeller

1.12 Airplane weight

Maximum takeoff weight 14.9lbs

Normal operating procedures

This section describes how to operate the airplane and its systems. All of the following procedures should be followed In order to conduct a safe and productive flight. This section begins with the preflight groundwork and continues step by step through all aspects of a flight.

2.1 Charging The Batteries

To ensure adequate battery power for the remote and receiver the batteries should be charged for 15 hours. Figure 2 shows the charging setup. This should allow several flights before the radio indicated that the battery is low. The batteries should be discharged at least every 8 weeks to prevent a condition called memory. This can be accomplished by operating the plane's servos on the ground until the system turns off from a low battery condition. The radio and receiver batteries may be charged unattended.

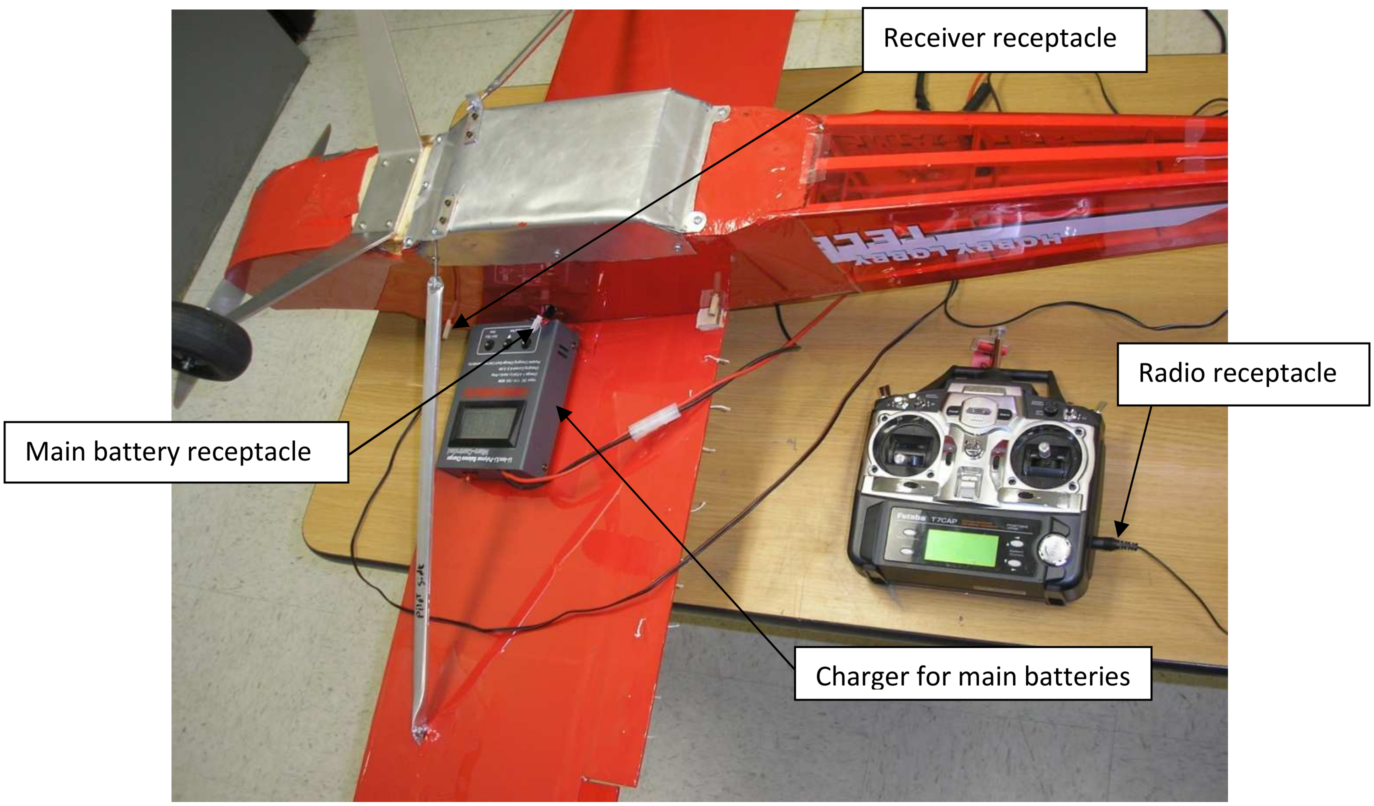


Figure 2, Charging setup. The main batteries must not be charged unattended. However, the radio and receiver batteries may be charged unattended.

The main batteries can be charge at the same time as the radio batteries, Figure 2. The main batteries are Lithium Polymer and are located under the wing just above the compressed air tank.

WARNING

Lithium polymer batteries are prone to catch fire. For this reason these batteries should not be charged unattended. The plane should not be charged in a place where a fire could cause death or injury. For this reason it is recommended that the plane be charge outdoors on a large piece of concrete.

To charge the main batteries place the plane inverted on a soft surface such as carpet or blanket. Connect the battery charger to one of the battery pack receptacles. These receptacles have 5 pins and should be connected to the five pin connector on the charger, figure 2. Once connected ensure that the batteries cells read greater than 2.7 Volts on the L.E.D. display. One charging port will read 0 because there are only three cells per battery and the charger is capable of charging a four cell battery. If a cell reads less than 2.7 Volts the charger will not charge that cell and no attempt should be made to charge the cell using another method. Lithium Polymer batteries become unstable when discharged below 2.7 Volts. Batteries that have been discharged below 2.7 should be removed from service.

NOTE

The main batteries should not be discharged bellow 3.0Volts. The most effective way to avoid this is to monitor the battery level after every flight and correlate this to the duration of the flight. When fully charged the batteries will last for ten minutes or more.

The main batteries should also be visually inspected to ensure flight worthy condition. There should be no evidence of wire shorting or overheating. Additionally, the batteries should not be deformed or look enlarged as if inflated. If any of these conditions exist properly dispose of the batteries immediately.

2.2 Weight And Balance

If the plane has been modified in any way such as adding any weight of moving internal components around the weight and balance should be checked. Check the weight by placing the plane on a scale capable of measuring 16lbs ±0.5lbs. The plane should weigh less than 14.9lbs.

CAUTION

The airplane must be balance properly to ensure stable flight characteristics. If the plane is not within the prescribed limits do not fly it.

When properly balanced the plane will sit level when placed on the plane balance. A level condition exists when the horizontal stabilizer is at the same height above the ground as the main wing, figure 3. The balance point of the plane should be between 4.25 inches to 5 inches behind the leading edge of the main wing. This region is known as the balance box.

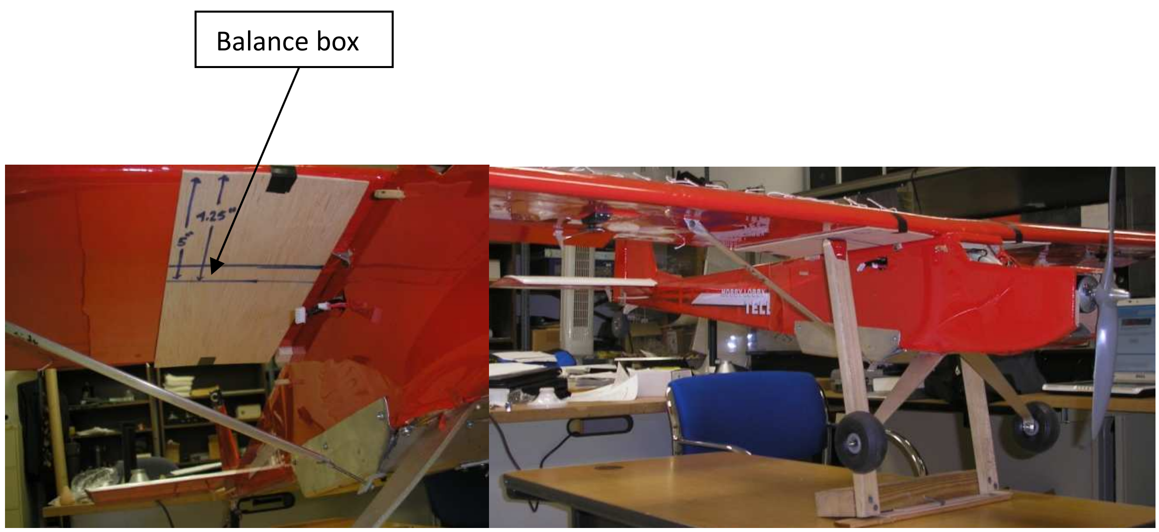


Figure 3, Ensure proper balance by lifting the plane from its wing. Determine the location of level balance. This should reside in the designated balance box.

2.3 Range Testing

Before each flight the plane radio and receiver should be checked for range. With the radio antenna RETRACTED have one person monitor the plane while another person walks away from the plane while operating the servos. A distance of 100ft must be reached before the receiver loses signal. Repeat this test, this time hold the airplane and test the engine for proper range control.

2.4 Flight Conditions

The plane has demonstrated landing and takeoff with a 8 mph cross wind. However, maximum safe crosswind component will depend on the experience of the pilot. The plane should not be operated in rain. The plane should also be operated when there is sufficient light.

2.5 Filling The Compressed Air Tank

The tank is filled by connecting the compressed air hose to the tank inlet, figure 3.

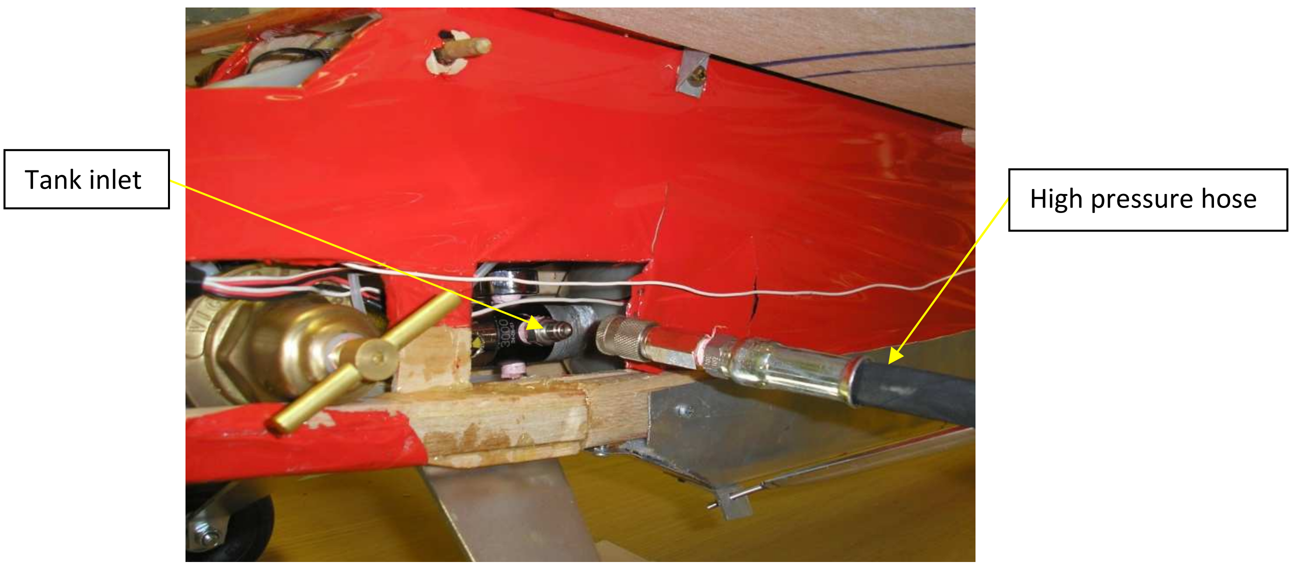


Figure 3, to fill the compressed air tank connect the high pressure hose to the tank inlet.

WARNING

Fill the tank at no more than 100 psi per second. Do not exceed 3000psi.

2.6 Preflight

When the preceding procedures have been completed the plane is ready for preflight. First the plane should be visually checked for damage missing parts. Next check the wheels to ensure free rotation. Once this is done the plane is ready to be turned on.

WARNING

The plane must be activated in the following order. First turn the remote on. Then place the receiver switch located on the plane in the on position. Before connecting the main batteries make certain the throttle is in the cut off position. Connect the main batteries while staying clear of the propeller, figure 4.

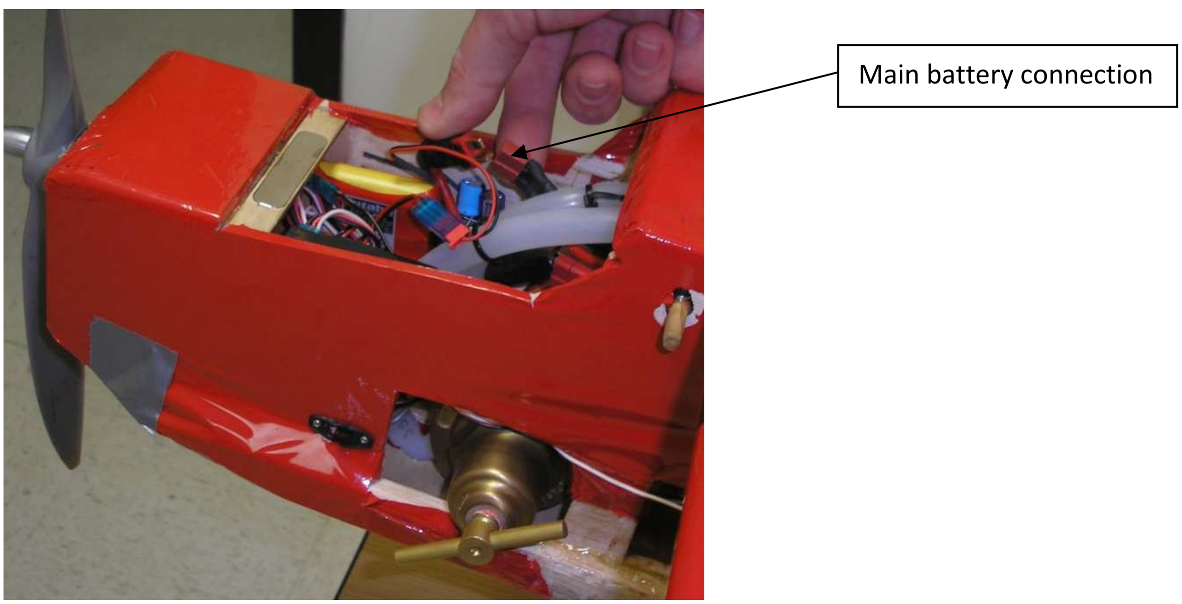


Figure 4, Connect the main battery last. Stay clear of the propeller.

The plane is now activated. Check that the flight controls are free and correct. Then hold the plane and apply full power to check for proper operation, close the throttle. Turn the air supply system on and quickly turn it off. Any irregularities warrant further investigation. If all systems operate normally the plane is ready to fly.

2.7 Setting the microjet pressure

To set the desired microjet pressure attach a pressure gauge to the pressure port tubes located next to the tank fill port. After attaching the tubes to the ports and turn on the microjets from the radio, switch C or E depending on setup. Next adjust the regulator for the desired pressure.

2.8 Takeoff And Landing

The plane requires significant takeoff distance so all of the runway should be utilized. The plane should takeoff against the wind to reduce takeoff distance. During the takeoff roll full down elevator should be applied to keep the tail wheel firmly on the ground. Full power should be used for takeoff and climb out if clearing an obstacle. For added safety discharge the compressed air tank before landing.

WARNING

Do not fly the airplane above or near any person or property.

2.9 After Landing

Immediately after landing disconnect the main batteries. Then turn the receiver switch off. Last turn the remote off.

Checklist for Telemaster Electo, with flow control

Preflight

Main batteries-Charged
Radio batteries-Charged
Receiver batteries-Charged
Weight and balance-Check
Range test-Check (at least 100ft with antenna down)
Compressed air tank-full (max 3000psi)
Camera (if installed) securely mounted-Check
Engine securely mounted-Check
Wing attachment-Check

Run up

Flight controls free and correct-Check
Microjets activation-Check
Engine (full power)-Check

Before Takeoff

Wind Direction and speed-Check
Traffic-Check

Takeoff

Use full elevator deflection (down) until liftoff
Use full length of the runway
Take off speed approximately 26 mph

Landing

Ensure compressed air tank is empty
Use full length of the runway

B: Product Specifications

General Description:

The product will use microjets installed on the wing of a remote controlled scale aircraft to actively control flow separation over the wings. The system must supply air or a gas with similar properties to the microjet arrays.

Design Constraints:

1. Total weight of supply system and jets - 10 lbs or less
2. Microjet run time - 30 seconds or greater
3. Gauge pressure at the microjets - 10 psi+
4. Microjet size – 0.4mm
5. Microjet spacing – 5mm
6. Number of rows of microjets along wing – 2 or less
7. Mass flow to the microjets - $4.4(10)^{-5}$ kg/s
8. Microjets activation- remotely, wireless for each wing individually
9. Volume of system – 6in × 6in × 15in or less

Aircraft Operating Parameters:

1. The airplane shall be able to land and takeoff unassisted, as it would in an unmodified state, with the exception of takeoff distance.
2. The plane shall be capable of recovering from a spin.
3. The plane's endurance will be at least 10 minutes.

In the event of a crash the systems on the aircraft will not pose a danger to the operator or spectators standing a distance of 100 ft from the impact.

C: Calculation: Jet Duration at 10 psig

Calculating Jet Duration at 10 psig

$kJ := 1000J$

Gas Constants $R := .2870 \frac{kJ}{kg \cdot K}$

Temperature $T := (25 + 273)K$

Volume of Tank $V := 68in^3$

Tank Pressure $P := 4500psi$

Mass of air in tank $m_{tank} := \frac{P \cdot V}{R \cdot T}$ $\boxed{m_{tank} = 0.404\,kg}$

Pressure to the Jet $P_t := 1atm + 10psi$

Constant for Air $\gamma := 1.4$

Mass Flow Rate Per Micro jet assuming the jet is choked

$$P_b := \frac{P_t}{\left(1 + \frac{\gamma - 1}{2}\right)^{\frac{\gamma}{\gamma-1}}}$$

$P_b = 8.995 \times 10^4\ Pa$

$\frac{P_b}{P_t} = 0.528$

Velocity of Jet exit $M_1 := \sqrt{\gamma \cdot R \cdot 273K}$ $M_1 = 331.197 \frac{m}{s}$

Radius of jet $r := \frac{.4mm}{2}$

Cross Sectional area of jet $A_{cross} := \pi \cdot r^2$

Calculated Mass Flow Rate per jet @ 24.7 psia $m_{dot\_calculated} := \frac{P_b \cdot M_1 \cdot A_{cross}}{R \cdot T}$

$$\boxed{m_{dot\_calculated} = 4.377 \times 10^{-5} \frac{kg}{s}}$$

Mass Flow Rate Per Micro jet from Dr. Shih Reasearch www.eng.fsu.edu/departments/mechanical/labs/hilites/presentations/fmrl/dynstall.pdf

$$m_{dot} := \frac{.03}{500} \frac{kg}{s}$$

$$m_{dot} = 6 \times 10^{-5} \frac{kg}{s}$$ @ 22 psia .4mm jet

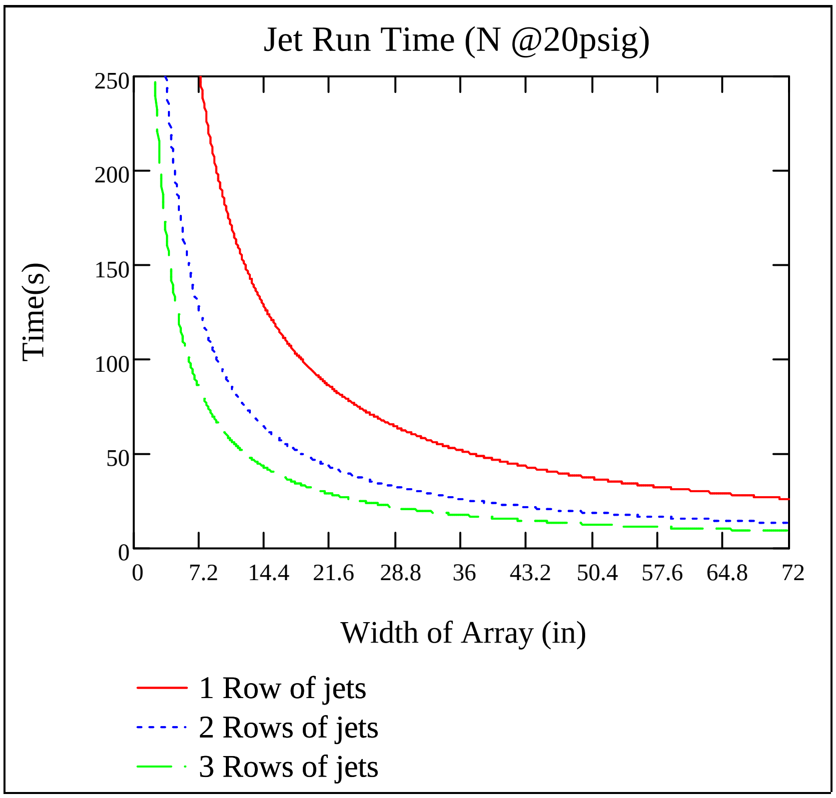
Jet Run Time as a function of the number of jets

$$Run(rows_{of\_jets}, array_{width}) := \frac{m_{tank}}{m_{dot\_calculated} \cdot rows_{of\_jets} \cdot array_{width} \cdot spacing} \cdot \frac{1}{.025}$$

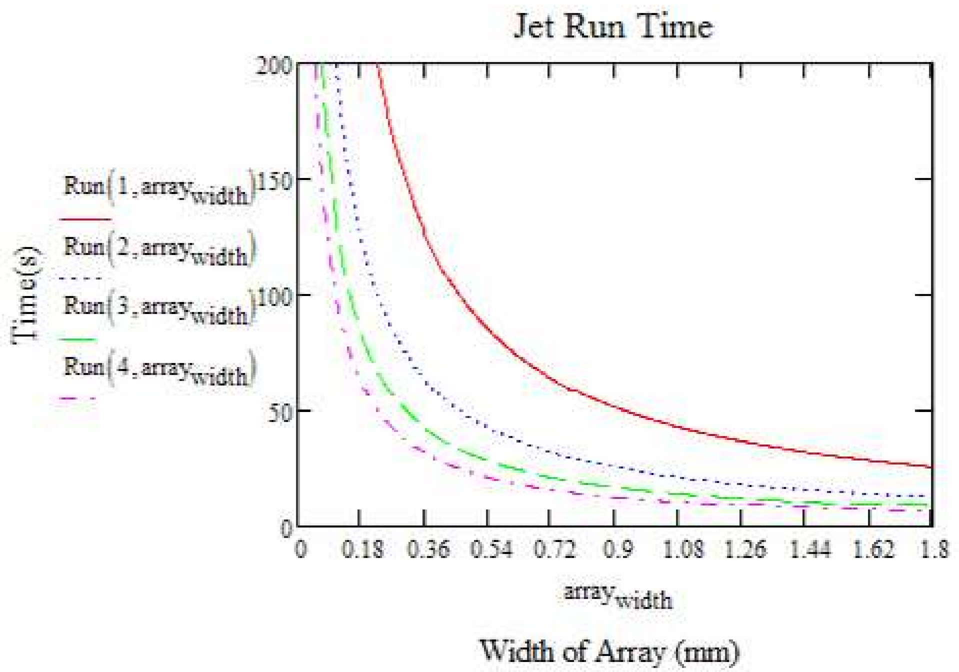
$$jet \equiv 1$$

Jets per width of wing

$$spacing \equiv \frac{1 jet}{5 mm}$$



$$Run(rows_{of\_jets}, array_{width}) := \frac{m_{tank}}{m_{dot\_calculated} \cdot rows_{of\_jets} \cdot array_{width} \cdot spacing}$$

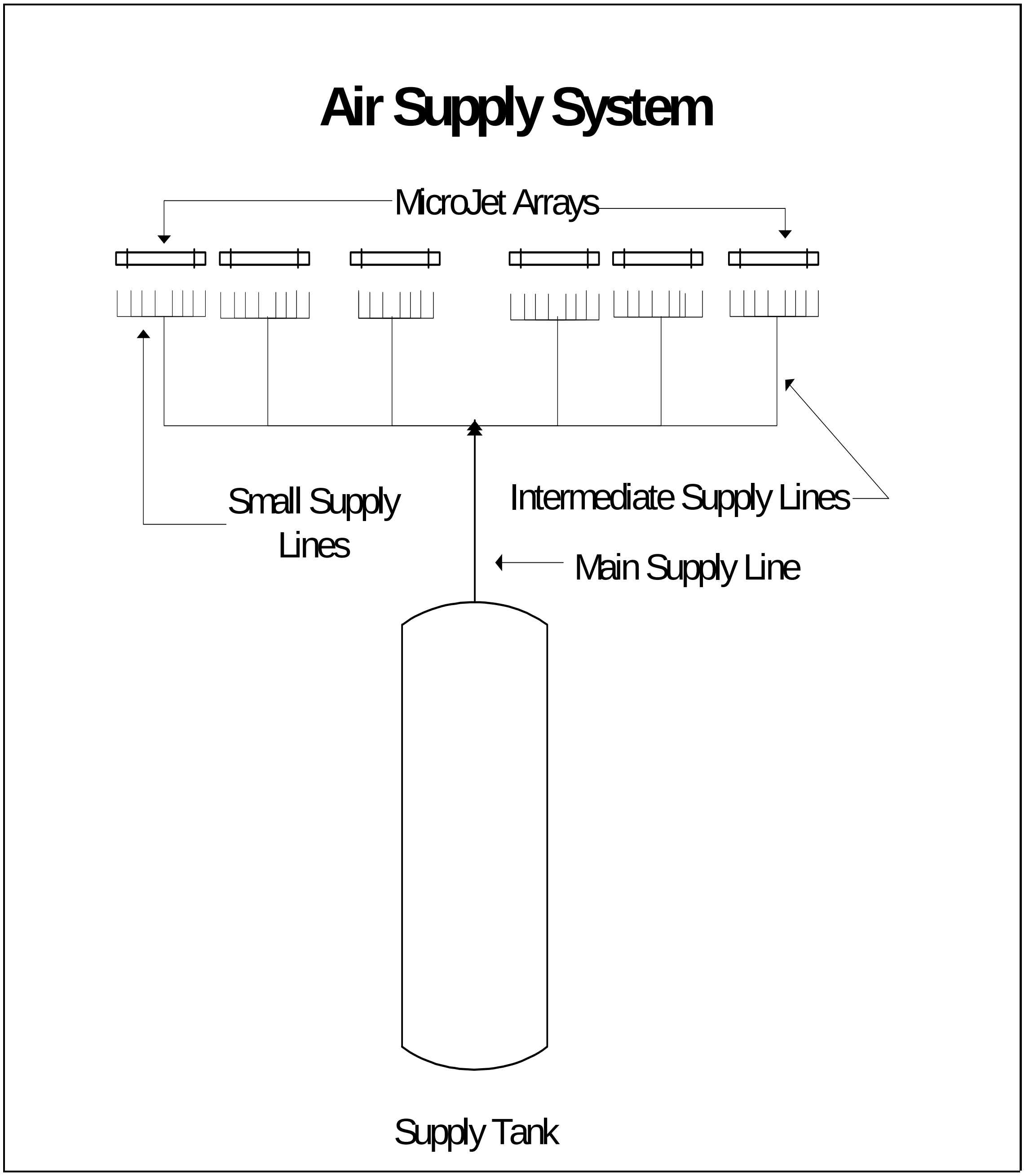


Volumetric flow through pressure regulator.

$$\frac{m_{dot\_calculated_{365}}}{\frac{P_t}{R \cdot T}} = 17.004 \frac{ft^3}{min}$$

D: Calculation: Pressure Drop through the Supply System

Design Calculations for Air Supply System



Pressure Drop Calculation

Given Values

Color Code for worksheet	Design Variable	Results
Temperature of air from supply Tank	$T_1 := 298K$	
Gas Constant (air)	$R := \frac{287J}{kg \cdot K}$	
Dynamic Viscosity of Air, (small error up to 7atms)	$\mu_{air} := 1.849 \times 10^{-5} \cdot \frac{kg}{m \cdot s}$	
Jet pressure	$P_{jet} := 10psi + 101kPa$	$P_{jet} = 24.649psi$
Jet Spacing	$jet_{spacing} := \frac{1 \cdot jet}{5mm}$	$jet_{spacing} = 0.2\frac{jet}{mm}$
Wing length (actual wing length will be 5'9")	$L_{wing} := 6ft$	
Total number of jets	$N_{jet} := L_{wing} \cdot jet_{spacing}$	$N_{jet} = 365.76$
Number of Jet arrays	$N_{array} := \frac{L_{wing}}{1ft}$	$N_{array} = 6$
Density of Air at 10 psig	$\rho_{air} := \frac{P_{jet}}{R \cdot T_1}$	$\rho_{air} = 1.987\frac{kg}{m^3}$
Mass Flow per Jet at 10psig	$M_{jet} := 4.377 \times 10^{-5} \frac{kg}{s}$	
Total Mass flow from tank	$M_{total} := M_{jet} \cdot N_{jet}$	$M_{total} = 0.016\frac{kg}{s}$
Mass flow per array	$M_{array} := \frac{M_{total}}{N_{array}}$	$M_{array} = 2.668 \times 10^{-3} \frac{kg}{s}$
Maximum pressure drop to allow for incompressible flow analysis.	$P_{jet} \cdot 30\% = 7.395psi$	
Approximate length of intermediate the supply	$L_{supply} := 4ft$	
Approxmate length of small supply lines	$L_{small} := 8in$	
Diameter of small supply line	$D_{small} := 1.6mm$	
Length of main line	$L_{main} := 1ft$	

Determining the diameter of the Intermediate supply line

Laminar Flow Analysis

The pressure drop across the large supply line is as followed

$$\Delta P = f \cdot \frac{L_{supply} \cdot \rho_{air} \cdot V_{supply}^{2}}{2D_{supply}}$$

Where

$$f = \frac{64}{Re} \quad \text{Assuming laminar flow.} \qquad Re = \frac{\rho_{air} \cdot V_{supply} \cdot D_{supply}}{\mu_{air}}$$

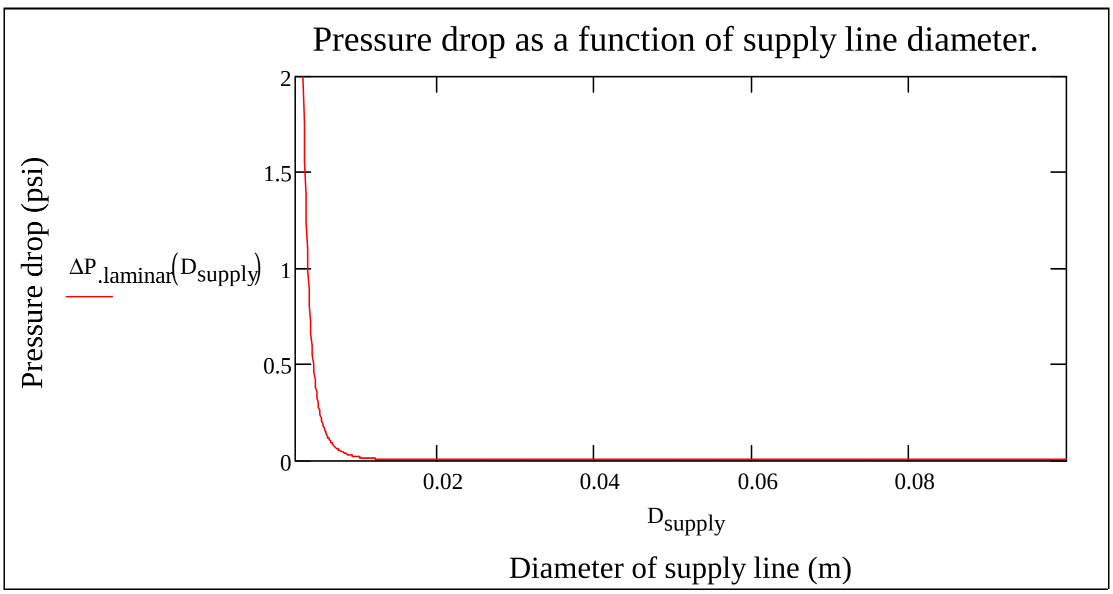
And

$$V_{supply} = \frac{M_{array}}{\rho_{air} \cdot A_{supply}} \qquad A_{supply} = \frac{\pi}{4} \cdot D_{supply}^{2}$$

Combining Equations and simplifying Gives

$$\Delta P_{laminar}(D_{supply}) := \frac{128 \cdot \mu_{air}}{M_{array} \cdot \rho_{air} \cdot \pi} \cdot L_{supply} \cdot \left(\frac{M_{array}}{D_{supply}^{2}} \right)^{2}$$

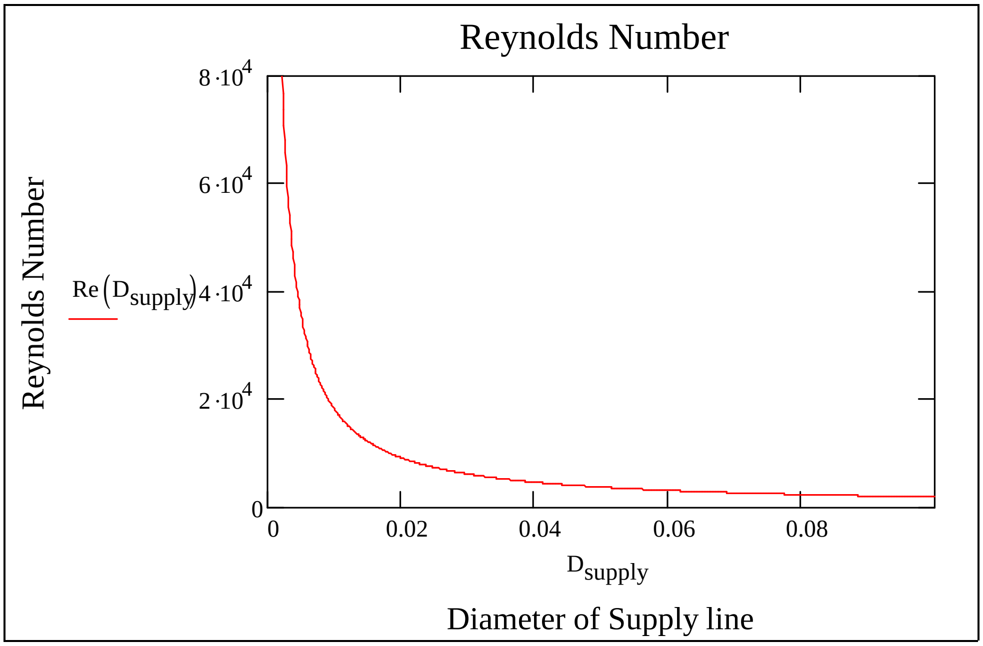
$$\Delta P_{laminar}(8cm) = 4.367 \times 10^{-6} \, psi$$



The Graph above is relevant for laminar flow only. For this condition the Reynolds number must be less than 2300. This occurs for diameters greater than 8cm.

$$Re(D_{supply}) := \frac{\rho_{air} \cdot \frac{M_{array}}{\rho_{air} \cdot \left(\frac{\pi}{4} \cdot D_{supply}^{2}\right)} \cdot D_{supply}}{\mu_{air}}$$

$$Re(8cm) = 2.297 \times 10^{3}$$



The figure above shows the Reynolds number as a function of the diameter of the intermediate supply line. Laminar flow is valid at about 8cm which is impractically large for the current application.

Turbulent flow analysis

This analysis is valid for Reynolds numbers greater than 4000. This occurs at a diameter of approximately 4.5cm. To maintain incompressible flow analysis the pressure drop should be less than 7.4 psi for this supply line.

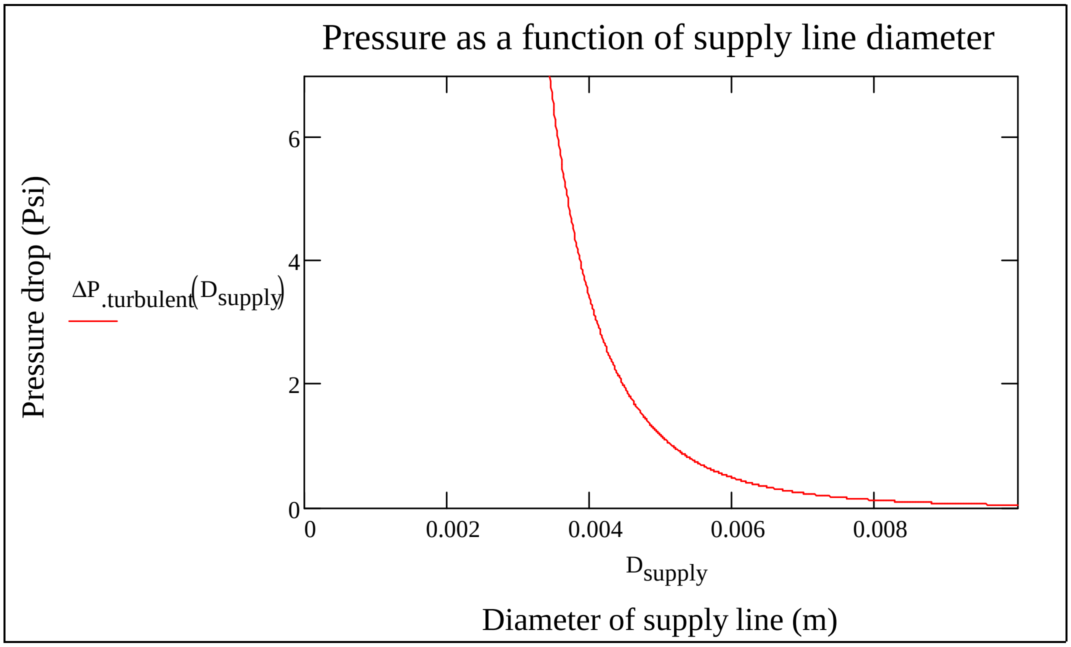
Assuming Turbulent flow in the supply line changes the friction factor to the following,

$$f = \left(0.790 \cdot \ln(Re - 164)\right)^{-2}$$

From Thermal fluid Sciences second edition, Cengel p. 883

$$\Delta P_{turbulent}(D_{supply}) := \left(0.790 \cdot \ln\left(\frac{M_{array}}{\frac{\pi}{4} \cdot D_{supply} \cdot \mu_{air}} - 164\right)\right)^{-2} \cdot \frac{L_{supply} \cdot \rho_{air} \cdot \left[\frac{M_{array}}{\rho_{air} \cdot \left(\frac{\pi}{4} \cdot D_{supply}^{\ 2}\right)}\right]^2}{2D_{supply}}$$

$\Delta P_{turbulent}(6mm) = 0.489\,psi$ Pressure drop for intermediate supply line.



The figure above shows the drop in pressure for the intermediate supply line. This graph is valid for diameters less than 4.5 cm. Notice how the pressure drop increases asymptotically for diameter less than 4mm. From this a diameter of 6mm was chosen.

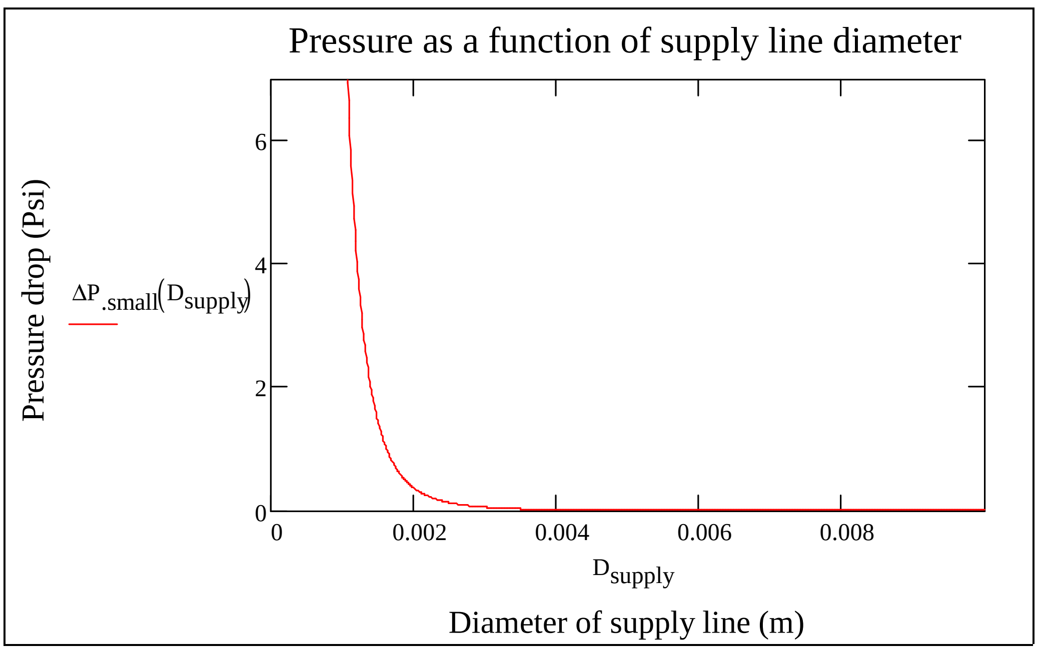
Calculate the Number of the small supply lines.

Number of Supply Lines $N_{small} \equiv 8$

Assuming Turbulent flow,

$$\Delta P_{small}(D_{supply}) := \left(0.790\cdot\ln\left(\frac{\frac{M_{array}}{N_{small}}}{\frac{\pi}{4}\cdot D_{supply}\cdot\mu_{air}}\right) - 164\right)^{-2}\cdot\frac{L_{small}\cdot\rho_{air}\cdot\left[\frac{\frac{M_{array}}{N_{small}}}{\rho_{air}\cdot\left(\frac{\pi}{4}\cdot D_{supply}^{2}\right)}\right]^{2}}{2D_{supply}}$$

$\Delta P_{small}(D_{small}) = 1.102\,psi$ Pressure drop across the small supply lines

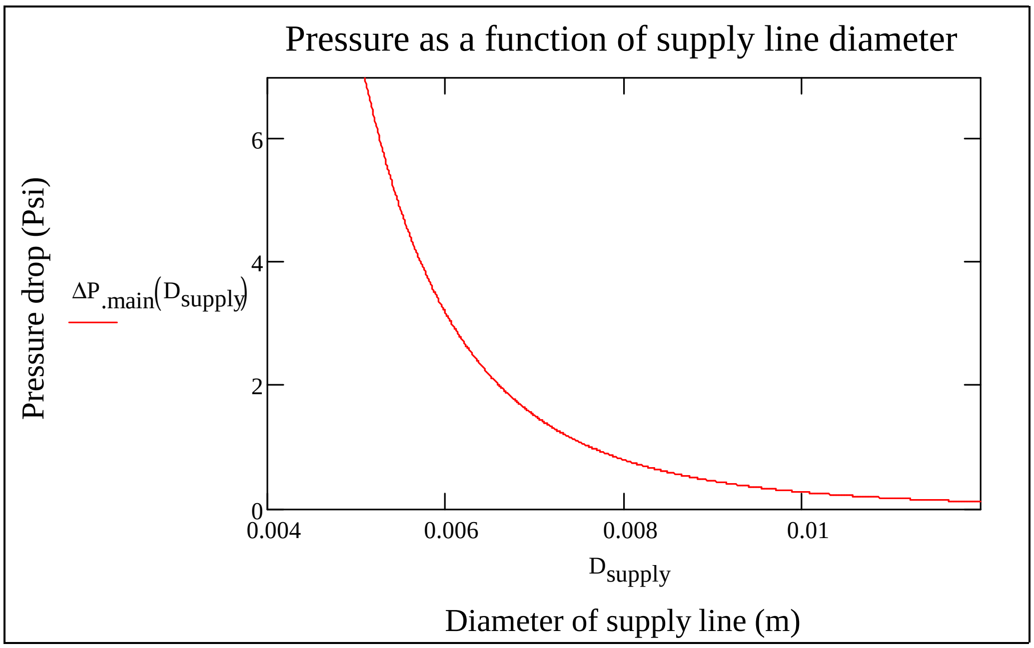


The figure above shows the diameter of the small supply lines is fixed because the microjets are 2.3mm square and a supply lines of 1.6mm is the largest that will physically connect to the microjets. Iteratively increasing the number of supply lines feeding each microjets a value of 8 supply line per microjet array is found.

Losses in the main supply line

$$\Delta P_{main}\left(D_{supply}\right) := \left(0.790 \cdot \ln\left(\frac{M_{total}}{\frac{\pi}{4} \cdot D_{supply} \cdot \mu_{air}}\right) - 164\right)^{-2} \cdot \frac{L_{main} \cdot \rho_{air} \cdot \left[\frac{M_{total}}{\rho_{air} \cdot \left(\frac{\pi}{4} \cdot D_{supply}^{\;2}\right)}\right]^{2}}{2 D_{supply}}$$

$\Delta P_{main}(1cm) = 0.271\,psi$



Calculating losses at various fittings, "Minor Losses.

Basic Loss equation

$$\Delta P = K_L \cdot \frac{V^2 \cdot \rho_{air}}{2}$$

Minor loss coefficient for connection to microjets

$$K_{L\_jet} := 1$$

Losses at the connection to microjets

$$\Delta P_{minor\_a} := \frac{K_{L\_jet} \left[\frac{\frac{M_{array}}{N_{small}}}{\rho_{air} \cdot \left(\frac{\pi}{4} \cdot D_{small}^2 \right)} \right]^2 \cdot \rho_{air}}{2}$$

$$\Delta P_{minor\_a} = 1.004\,psi$$

Minor loss coefficient for connection to the manifold

$$K_{L\_man} := .5$$

$$\Delta P_{minor\_b} := \frac{K_{L\_man} \left[\frac{\frac{M_{array}}{N_{small}}}{\rho_{air} \cdot \left(\frac{\pi}{4} \cdot D_{small}^2 \right)} \right]^2 \cdot \rho_{air}}{2}$$

Minor loss for the manifold connecting the small lines to the intermediate lines.

$$\Delta P_{minor\_b} = 0.502\,psi$$

Minor loss for the manifold connecting the intermediate lines to the main line.

$$\Delta P_{minor\_c} := \frac{K_{L\_man} \left[\frac{M_{array}}{\rho_{air} \cdot \left[\frac{\pi}{4} \cdot (6mm)^2 \right]} \right]^2 \cdot \rho_{air}}{2}$$

$$\Delta P_{minor\_c} = 0.163\,psi$$

Total Pressure Drop For Air Supply System

$$\Delta P_{total} := \Delta P_{turbulent}(6mm) + \Delta P_{small}(D_{small}) + \Delta P_{main}(1cm) + \Delta P_{minor\_a} + \Delta P_{minor\_b} + \Delta P_{minor\_c}$$

Total Pressure Drop

$$\Delta P_{total} = 3.532\,psi$$

Comparing Area Ratios For the small Supply line and the microjets they supply.

Area of microjets per supply line. $A_{jet} := \frac{\pi}{4} \cdot (.4mm)^2 \cdot 7.62$ $A_{jet} = 9.576 \times 10^{-7} m^2$

Area of Small supply lines $A_{small} := \frac{\pi}{4} \cdot (1.6mm)^2$ $A_{small} = 2.011 \times 10^{-6} m^2$

Weight Of tubing

Small tubing $W_{small} := 1.5gm$

Number of small tubes $N_{.small} := 8 \cdot 6$

Intermediate tubing $W_{intermediate} := 36gm$

Number of intermediate tubes $N_{intermediate} := 6$

Mass of main line $W_{main} := 13gm$

Total mass of supply lines

$$W_{total} := W_{small} N_{small} + W_{intermediate} N_{intermediate} + W_{main}$$

$$W_{total} = 0.531\,lb$$

E: Calculation: Velocity with respect to Weight

Velocity Calculations

$C_L := 1.7$ form theory of wing sections, Ira page 3

$M_{plan} := 8\text{lbf}$ weight of plane

$\rho_{air} := 1.184 \frac{kg}{m^3}$

velocity of plane $V_1 := \sqrt{\frac{M_{plan} \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_L}}$

$V_1 = 17.816 \frac{mile}{hr}$

$V_1 = 7.965 \frac{m}{s}$

From Flight Control using synthetic jets, Amitay

16 % increase in lift

$C_{L2} := C_L \cdot 1.16$ coefficient of lift

$V_2 := \sqrt{\frac{M_{plan} \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_{L2}}}$

$V_2 = 24.262 \frac{ft}{s}$

$\Delta V := V_1 - V_2$ Reduction in velocity with the jets activated

$\Delta V = 1.869 \frac{ft}{s}$ $\Delta V = 1.274 \frac{mile}{hr}$

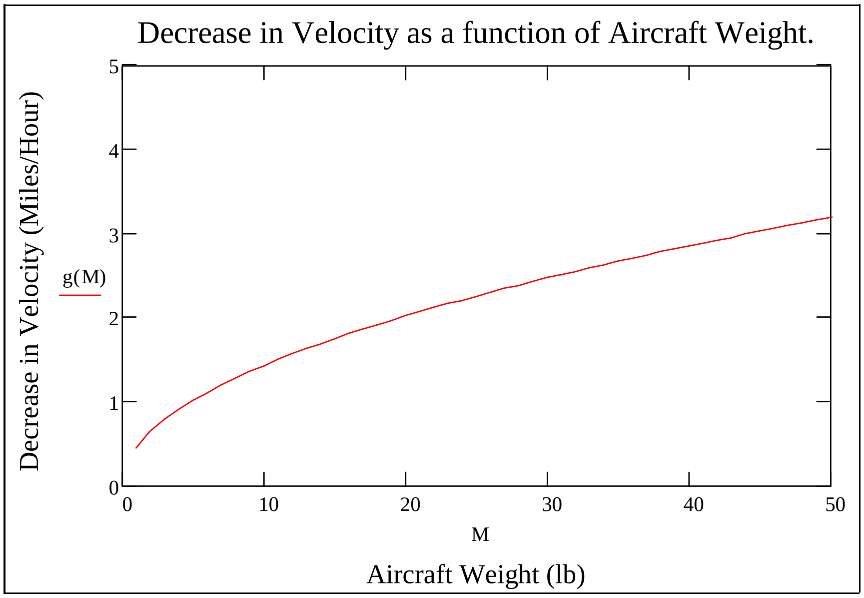
$\frac{\Delta V}{V_1} = 7.152\,\%$ % reduction

Change of velocity as a function of weight

$$f(M) := \left(\sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_L}} - \sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_{L2}}}\right)$$

$M := 1 .. 100$

$$g(M) := \left(\sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_L}} - \sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_{L2}}}\right) \cdot \frac{1}{5.28 \times 10^3} \cdot 3600$$



$$P(M) := \frac{\sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_L}} - \sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_{L2}}}}{\sqrt{\frac{M \cdot lbf \cdot 2}{6 \cdot ft \cdot 1 \cdot ft \cdot \rho_{air} \cdot C_L}}}$$

Drag Calculations

$A_{wing} := 6ft \cdot 1ft$

$C_D := .48$

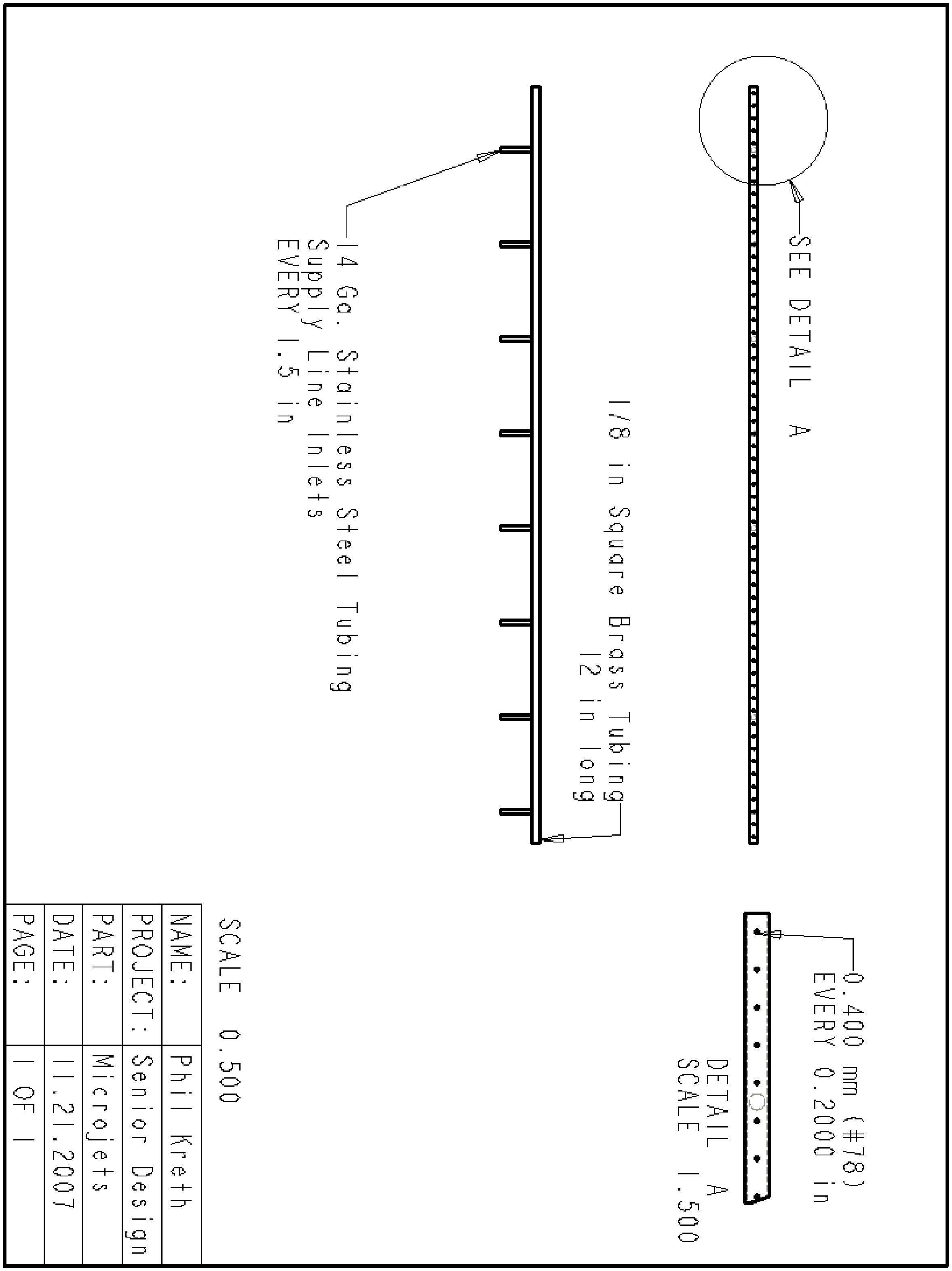
Drag at 30 deg. Angle of Attack.

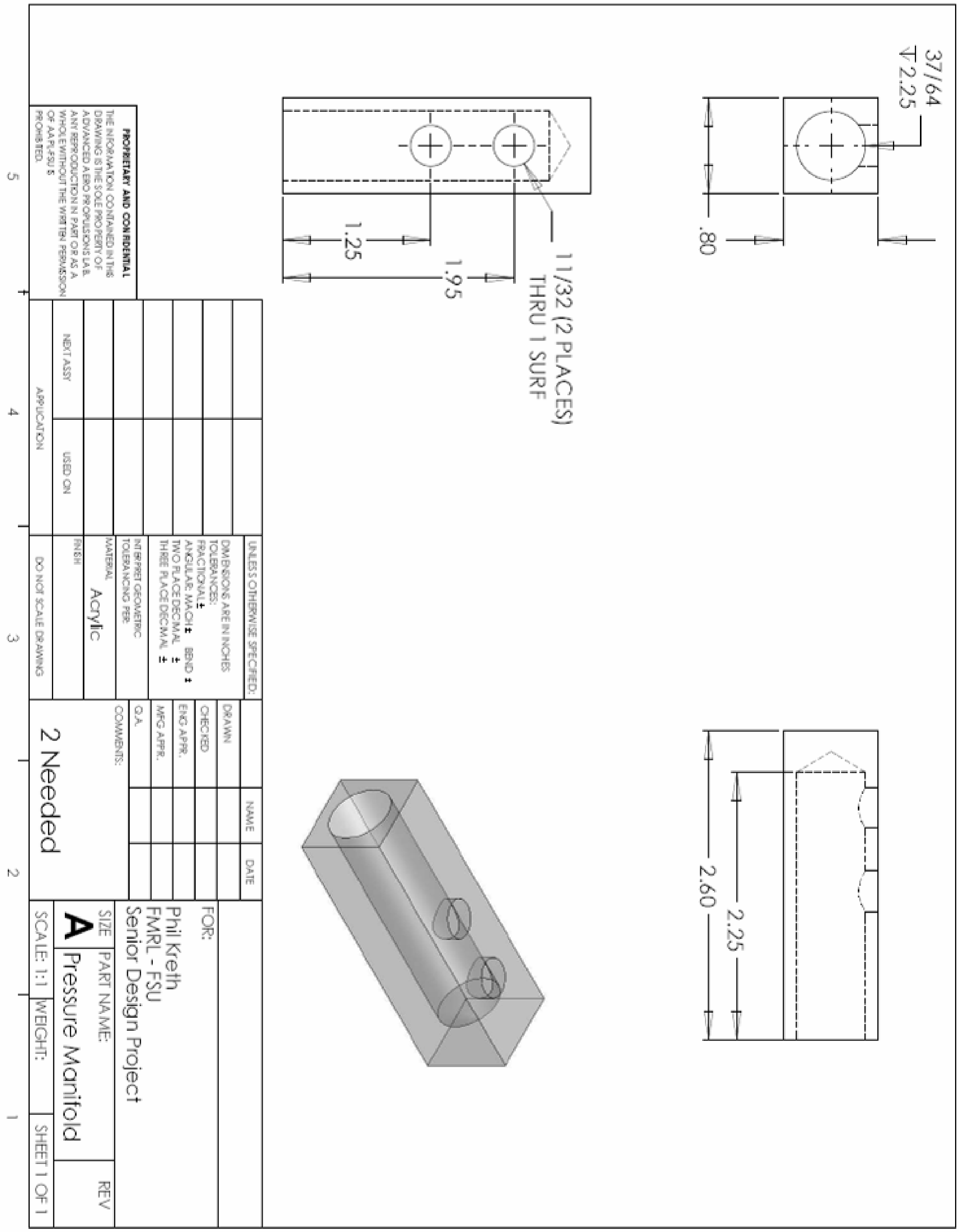
$F_D := C_D \cdot .5 \rho_{air} \cdot V_1^{\,2} \cdot A_{wing}$

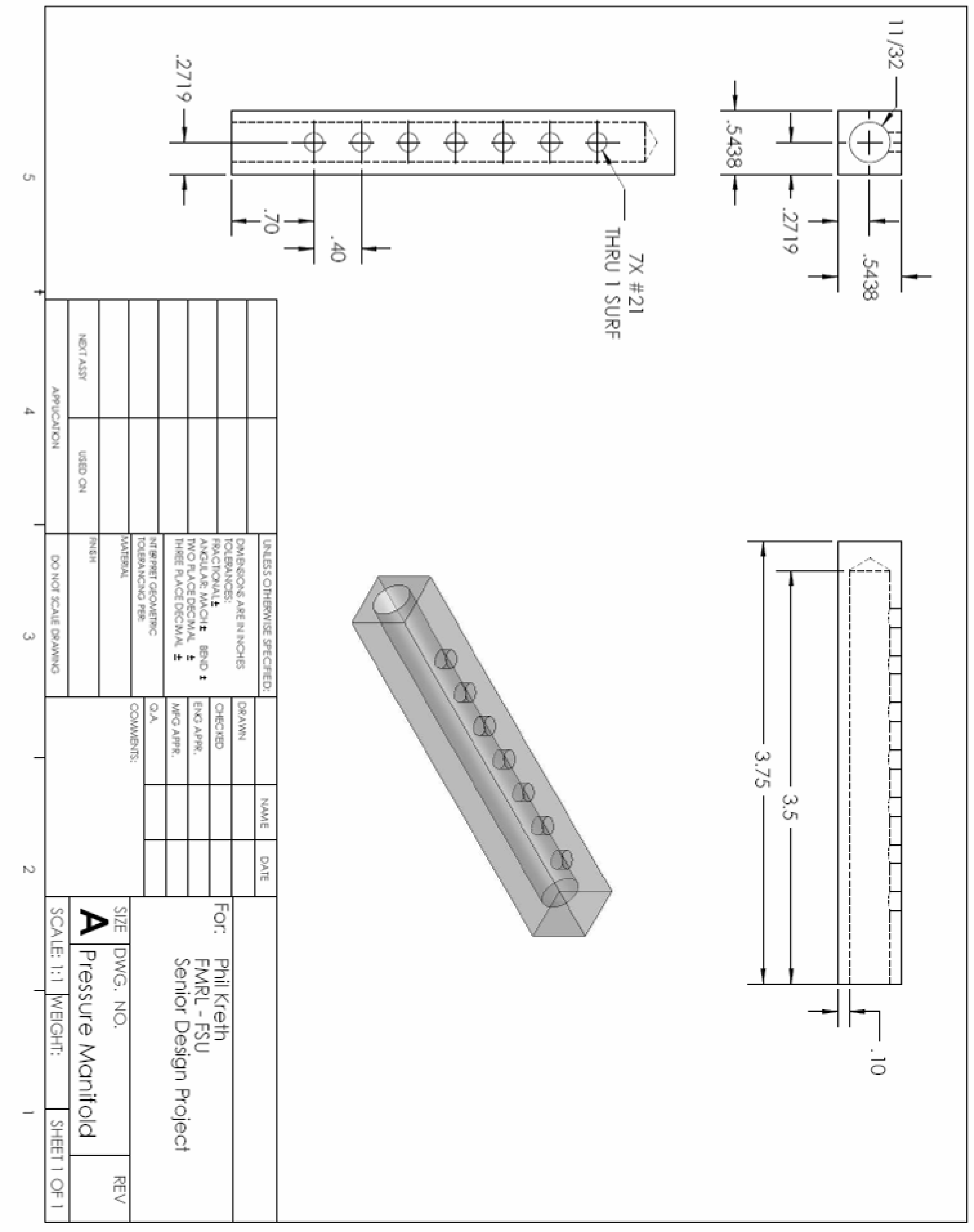
$F_D = 2.259\,lbf$

$F_D = 10.048\,N$

F: CAD Drawings




37/64
⊽2.25
.80
11/32 (2 PLACES)
THRU 1 SURF
1.25
1.95
2.60
2.25
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF ADVANCED AERO PROPULSIONS LAB. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF AAPL-FSU IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
2 Needed
FOR:
Phil Kreth
FMRL - FSU
Senior Design Project
SIZE
PART NAME:
A
Pressure Manifold
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5


11/32
.5438
.2719
.5438
.2719
.70
.40
7X #21
THRU 1 SURF
3.75
3.5
.10
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
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
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
For: Phil Kreth
FMRL - FSU
Senior Design Project
SIZE
A
DWG. NO.
REV
Pressure Manifold
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5

G: Weight added to Aircraft

Weight - Team 16 - Implementation of AFC on RC Aircraft

Item	*Weight (lbs)*	*Quantity*	*Total Weight (lbs)*
Solenoid Valves	0.70625	2	1.4125
Switch	0.01875	2	0.0375
High Pressure Cylinder	2	1	2
Actuators	0.0375	6	0.225
Manifolds	0.04375	6	0.2625
Regulator	2	1	2
T-bar	0.08125	1	0.08125
Camera	0.0625	1	0.0625
Added wood supports	0.905	1	0.905
Hoses	1.02	1	1.02
Cylinder Protection	0.802	1	0.802
Struts	0.2333	1	0.2333
Miscellaneous(Zip ties, Screws,etc)	0.8555	1	0.8555

Overall Weight	4.8875		9.89705

H: Project Budget

Budget - Team 16 - Implementation of AFC on RC Aircraft

Vendor	*Item*	*Unit Price*	*Quantity*	*Total Price*
HobbyTown USA	Brass Square Tubing	$2.09	10	$20.90
HobbyTown USA	Monokote Wing Covering	$13.99	1	$13.99
HobbyTown USA	Sheet of Balsa Wood	$4.48	2	$8.96
Hobby-Lobby Int.	Video Camera & SD Card	$135.81	1	$135.81
Airgas South	High Pressure Cylinder Adapters	$21.58	1	$21.58
Compressed Gas Supply	Quick Connect Fitting	$65.00	1	$65.00
Max Rubber	High Pressure Hose	$23.18	1	$23.18
HobbyTown USA	Pico Electric Switch	$25.95	2	$51.90
HobbyTown USA	On/Off Toggle Switch	$9.95	1	$9.95
HobbyTown USA	Miscellaneous Airplane Supplies	$68.10	1	$68.10
McMaster-Carr	Miscellaneous Airplane Supplies	$43.84	1	$43.84
McMaster-Carr	High Pressure Cylinder	$290.06	1	$290.06
McMaster-Carr	24V Brass Solenoid Valve	$43.69	2	$87.38
Transducer Techniques	10lb Load Cell	$265.00	1	$265.00
McMaster-Carr	Tubes & Fittings 1	$75.25	1	$75.25
McMaster-Carr	Tubes & Fittings 2	$71.47	1	$71.47
McMaster-Carr	Digital Speed Gun	$118.18	1	$118.18
Seminole RC Club	Membership	$29.00	1	$29.00
	Eglin Trip - Fall	$293.30	1	$293.30
	Total			$1,692.85