Unmanned Aerial Systems Solutions (UASS)

S900 and Stalker Improvement Program

Engineering Analysis Package

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This EAP is presented to show the analysis performed by UASS to ensure that the Unmanned Aerial Systems are able to meet the prescribed operational and design requirements for all subsystems, namely Propulsion, Payload, Power, Communications, and Ground Station including the autopilot. The S900 UAS is built upon the DJI S900 airframe, which includes the physical structure itself. The

Stalker UAS is built upon the Lockheed Martin Stalker airframe, which includes the physical structure itself. Both UASs include the motors, speed controllers, and propellers, as well.

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Purpose

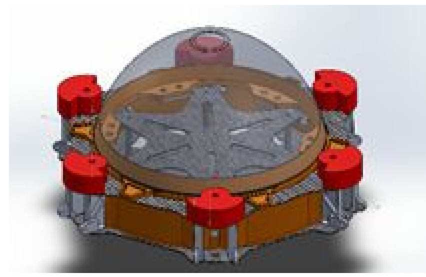
This Engineering Analysis Package (EAP) is presented to show the analysis performed by Unmanned Aerial Systems Solutions (UASS) to ensure that the modified UASs are able to meet prescribed operational and design requirements. When working with any system, notably a commercial product, the engineer must make some decisions of how far to reverse engineer the existing system before moving forward. This could involve study to the point of total recreation and intrinsic design improvement, or simply end at understanding and confining to physical limits of the system. This EAP focuses mainly on analysis of the subsystem changes and innovations made by UASS. However, a light analysis and discussion of the existing platforms is made in the interest of ensuring that the functions provided by the commercially purchased components are capable of fulfilling the requirements set forth in the Statement Of Work (SOW), class discussion, and design reviews.

“Aviation is the branch of engineering that is least forgiving for mistakes”

-Freeman Dyson

DJI S900: Summary of System

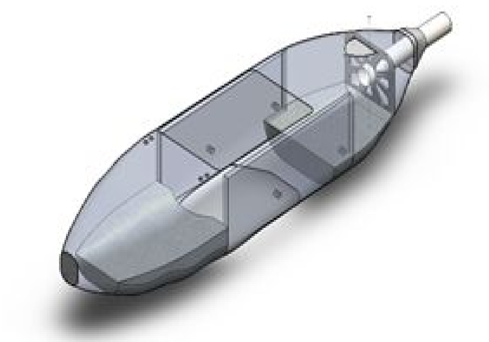




Da-Jiang Innovations, (DJI) a China based company founded in 2006, is said to be "at the forefront of the civilian drone industry". DJI may be best known for its' consumer "Phantom" quad-copter, but it also manufactures UAS for use as commercial platforms. The S900 as shown in figure 1, is a 6 bladed copter that is part of the company's "spreading wing series". In a family with the S800, S800 EVO, and S1000, the S900 is designed to be a heavy lifting UAV fit for purposes from cinematography to farming. A product manufactured by a company with over a decade in the field, The S900 carries with it over a decade of improvements and innovations. That said, the industry is developing and the S900 is not necessarily the face of perfection.

UASS has taken an S900 Airframe and outfitted it with non-stock electronics, mounts, and cladding. The Modified S900 UAS is built upon the DJI S900 airframe, which includes the physical structure itself as well as the motors and speed controllers. It will be powered by several six cell lithium polymer batteries in parallel. The UAS control system will consist of a 3DR Pixhawk autopilot system supported by a ground station laptop or tablet running the Mission Planner UAS control software. The communications package will consist of three distinct parts; the telemetry system supported by an XBEE PRO-XSC 915 MHz transceiver, a 2.4 GHz manual RC controller, and a 2.4 GHz DJI Lightbridge HD video feed. There will be custom designed cladding to provide weather resistance to the critical electronics as well as a custom payload integration that will provide physical and electrical connections to the various supported payloads.

Stalker: Summary of System

Lockheed Martin (L.M.) is perhaps a name synonymous with military aviation technology. With over century old roots through the Loughead Aircraft Manufacturing Company founded in 1912, design and production of aircraft such as the p-38 and SR-71, and a merger in 1995 the Martin Marietta Corporation, L.M. works on the leading edge of aerospace technologies. The Stalker was developed to be a robust, silent military platform for purposes from surveillance to payload delivery. In a similar stride to the S900, UASS has taken an existing airframe and fitted it with alternate control systems and flight hardware. Building upon a Stalker airframe, including the motor and propeller, the aircraft will be powered by several six cell lithium polymer batteries in parallel. The UAS control system will consist of a 3DR Pixhawk autopilot system supported by a ground station laptop or tablet running the Mission Planner UAS control software. The communications package will consist of three distinct parts; the telemetry system supported by an XBEE XTEND 915 MHz transceiver, a 2.4 GHz manual RC controller, and a 2.4 GHz DJI Lightbridge HD video feed. Twin mounting rails will be added for a semi-universal payload attachment system.

I. Propulsion

A. Summary of Results

1. Calculations involving DC motor operations are of concern. Electric motor parameters are of primary interest so that performance standards can be established and consistent UAS operation can be achieved.

B. Results

1. Propeller Thrust
    a) Thrust developed by an electric motor.
    b) $T = \frac{1}{2}\rho * A_{\rho} * \Delta V * (2V + \Delta V)$
    c) ρ = air density, $A\rho$ = Area of propellor, ΔE = change in air velocity, V = initial air velocity
    d) Thrust Equation, Chapter 8, pg. 289, Eq. 8.2, Designing Unmanned Aircraft Systems: A comprehensive approach; 2nd edition, Jay Gundlach
2. Shaft Speed
    a) Speed of the shaft on the electric motor.
    b) $RPM_{Mot} = K_{V} * V_{Mot}$
    c) K_{V} = voltage constant, V_{Mot} = motor voltage
    d) Relationship between motor shaft, voltage constant and the voltage across the motor leads, Chapter 8, pg. 317, Eq. 8.54, Designing Unmanned Aircraft Systems: A comprehensive approach; 2nd edition, Jay Gundlach
3. Current Drawn
    a) Current across motor leads
    b) $I_{Mot} = P_{Mot} * \frac{K_{V}}{RPM_{Mot}} * I_{OL}$
    c) P_{Mot} = motor power, K_{V} = voltage constant, I_{OL} = Current to turn shaft from rest, RPM_{Mot} = shaft speed
    d) Current across the motor leads, Chapter 8, pg. 318, Eq. 8.59, Designing Unmanned Aircraft Systems: A comprehensive approach; 2nd edition, Jay Gundlach
4. Voltage Produced
    a) Voltage across motor leads
    b) $V_{Mot} = \frac{RPM_{Mot}}{K_{V}} + (I_{Mot} * R_{Mot})$

c) RPM_{Mot} = shaft speed, K_V = voltage constant, I_{Mot} = current across motor leads, R_{Mot} = motor

d) Voltage across motor leads, Chapter 8, pg. 318, Eq. 8.60, Designing Unmanned Aircraft Systems: A comprehensive approach; 2nd edition, Jay Gundlach

5. Motor Efficiency

a) Resistance and efficiency of electric motor

b) $\eta_{motor} = \frac{P_{Shaft}}{I_{Mot} * V_{Mot}}$

c) P_{Shaft} = power delivered to shaft, I_{Mot} = current drawn, V_{Mot} = motor voltage

d) Motor Efficiency, Chapter 8, pg. 318, Eq. 8.61, Designing Unmanned Aircraft Systems: A comprehensive approach; 2nd edition, Jay Gundlach

C. REFERENCES

1. Textbook; included in main bibliography
2. Motor Specs
   a) S900 User Manual
      - Stator Size: 41×14mm
      - KV: 400rpm/V
      - Max Power: 500W
      - Weight(with Cooling Fan): 158g

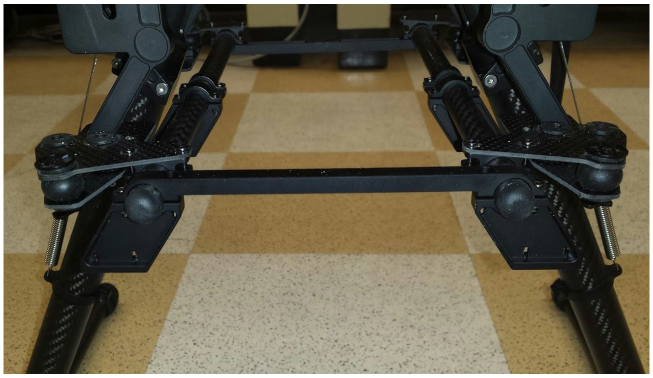
   b) Equivalent Stalker motor (http://hobbyking.com/hobbyking/store/__32819__Turnigy_GliderDrive_SK3_Competition_Series_3858_4_6_1120kv.html)
      - Turns: 8T
      - Voltage: 3~4S Lipoly[1]
      - RPM/V: 1120kv
      - Motor Poles: 14
      - Internal resistance: 0.021 Ohm
      - Max Loading: 58A
      - Max Power: 860W
      - Shaft Diameter: 5mm
      - Shaft Length: 20mm
      - Mounting screw Spacing: 25mm (M3x4)
      - Connector: 3.5mm bullet
      - Weight: 180g
3. ESC Specs
   a) S900 (User Manual)
      - Working Current: 40A
      - Working Voltage: 6S LiPo

- Signal Frequency: 30Hz ~ 450Hz
- Drive PWM Frequency: 8KHz
- Weight(with Radiators): 35g

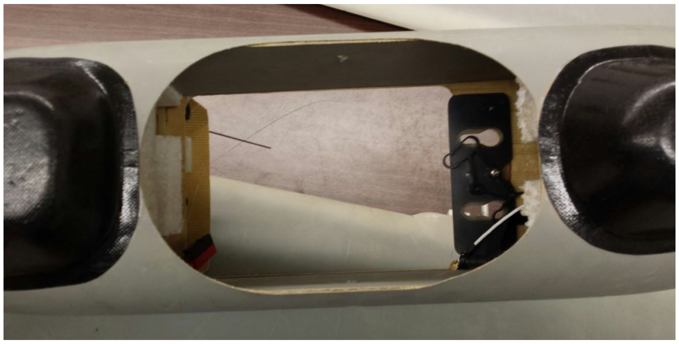
b) Stalker (http://hobbyking.com/hobbyking/store/__28888__Turnigy_AE_100A_Brushless_ESC.html)

- Output: Continuous 100A, burst 115A up to 10 seconds
- Input Voltage: 2-6 cells lithium battery
- BEC: Linear 4A @ 5V
- Control Signal Transmission: Optically coupled system
- Max Speed:
  - 2 Pole: 210,000rpm
  - 6 Pole: 70,000rpm
  - 12 Pole: 35,000rpm
- Size: 71mm (L) * 34mm (W) * 17mm (H)
- Weight: 79g

II. Payload



(a)



(b)

Figure 3. Payload bay for (a) S900 and (b) Stalker.

A. Summary of Results

1. The main concern regarding the payload subsystem is the ability of the two UASs to securely hold the payload in place. Of the locations of possible fractures that would cause the payload to detach, the material, most likely PLA or some other plastic, holding the payload to the payload rails would be the most likely. If the systems are not properly balanced to the appropriate center of gravity (CG), then the UASs will not be able to fly optimally or at all in some cases. An inappropriate CG could lead to a severe failure resulting in damage to the aircraft or payload.

B. Results

1. Tensile Loading at Attachment Points
    a) Setup:

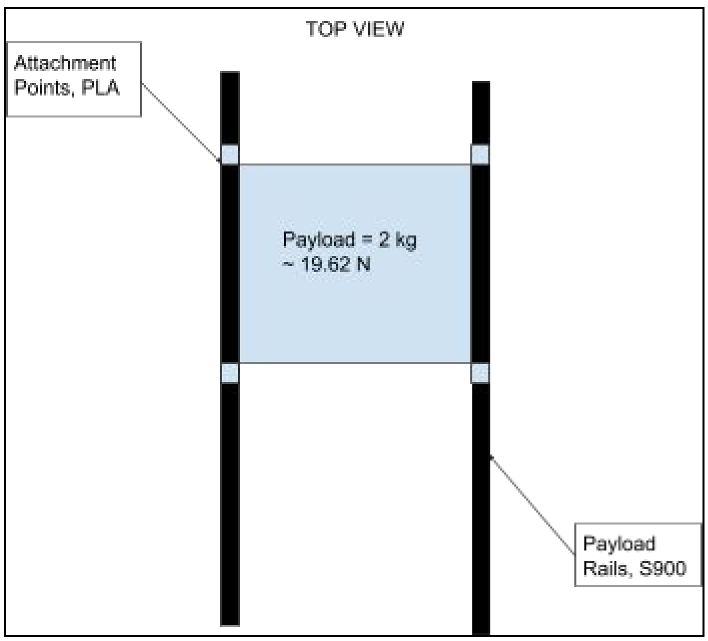


Figure 4. Top view of a theoretical payload of maximum allowable mass on the S900 rails.

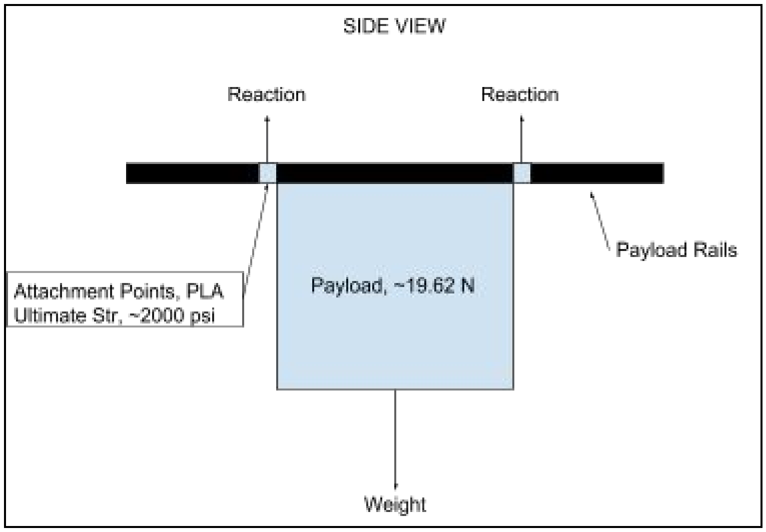


Figure 5. Side view of a theoretical payload of maximum allowable mass on the S900 rails.

b) The lowest ultimate stress of PLA found in the below reference is represented as $\sigma_U = 2000psi \approx 13789.5kPa$
c) Stress is calculated by force divided by the affected cross-sectional area, or $\sigma = \frac{F}{A}$
d) The weight of the payload is the force in this case, so F_{tot}=19.62 N and the force supported by each attachment point is this weight divided by the total attachment points, or F/4=4.905 N
e) Taking a cross-sectional area of (6mm)*(3mm)*2 = 36 mm^2 due to the estimated geometry of one attachment point, shown below in Figure 6.

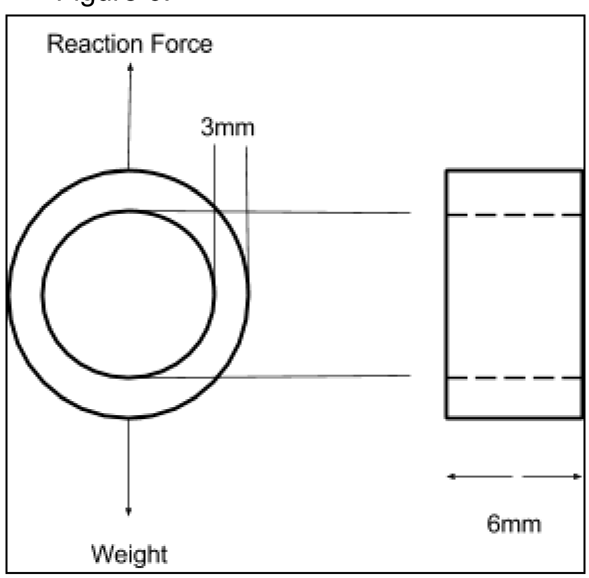


Figure 6. Estimated size and shape of an attachment point.

f) A = 36 mm^2 = 3.6 x 10^{-5} m^2

g) $\sigma = \frac{F}{A} = \frac{4.905N}{3.6\times10^{-5}m^2} = 136250\ Pa = 136.25\ kPa$

h) This shows that the estimated stress is a lot less than the ultimate stress of 13789.5 kPa. In fact, $\frac{\sigma_U}{\sigma} = 101.2$

i) The yield strength is greater than the ultimate strength, and thus it is unlikely that the attachment points will break under the maximum payload weight.

j) If the material used is not PLA, so long as the Ultimate Tensile Strength and the Yielding Strength are greater than that of PLA, it will not fail due to the tensile loading. In current configuration, the PLA parts are not load bearing, and serve solely as weather cladding. Cold temperature testing is to be done to investigate effects from thermal expansion/contraction.

Center of Gravity and Flight Stability

There are intrinsic performance and stability characteristics between a hex-copter and a fix winged aircraft. However, a parallel can be drawn between the two when it comes to analysis in the sense of consolidating forces.   A fixed wing plane for example, attains flight via different net pressure distributions between the top and bottom of the craft. These lifting forces vary from point to point on the wing and fuselage, and for analysis purposes it is easier to condense them all to one force acting on one point of the aircraft with an associated moment. The same goes for a hex copter; lift distributions from the spinning propellers can be individually centralized on the motor shafts, and further into a net force and moment around the center of the fuselage. The following discussion carries minimal numerical values, as minimal aircraft data is available. Rather, it details the phenomena that the existing system has been engineered around so that we are aware of the envelope in which we are free to safely make modifications.

S900

Whether 3 rotors or 8 rotors, a characteristic that all multi rotors share is that they possess some form of symmetry. A center can be found that is equidistant from all propellers. This point is essentially the center of lift, and it makes sense that to prevent tipping, the center of gravity of the craft should be at the same point. Configurations in both hardware and software may allow for the center be designed sit off of this equidistant point, but this is not the case with the S900. A design issue faced when incorporating removable weight such as a payload or battery is the balancing of every configuration of load. An elegant way around this problem is to mount things on different vertical planes. Doing so allows the removal of a fraction of the components without unbalancing the craft. It also may be worth noting that the S900's propellers do not all spin on the same plane.

As shown above, the propellers are angled slightly inward. Doing so provides both a stability effect, and performance enhancement. A stability gain is seen in the sense that the acting force of lift is raised higher above the CG. Akin to a keel stabilizing a sail boat, this configuration places forces in such a way that gravity is satisfied. Dead weight low, lift high. In addition, angling the propellers gives a slight lateral thrust vector. In static flight, all the lateral force vectors from each propeller will cancel. When movement is desired, the system will respond more lively than one with all propellers spinning on the same plane, as the system is already generating the force to move sideways and all it must do to strafe is cancel the proper negating force. No mention is made of moment cancelling and counter rotation of propellers, as it is beyond the scope of modifications. A day long discussion in itself could be made out of multi-rotor control algorithms.

Stalker

A fix winged aircraft is a more complicated balancing act than a multi-rotor when it comes to load placement and physical design.

If an airplane is “stable” it will naturally tend towards a stable flight path if disturbed. On the other hand, an unstable aircraft may gain a few degrees of angle of attack and continue to uncontrollably do so until stall.

Major players in longitudinal control and stability of a fixed wing airplane include center of mass, center of lift, aerodynamic center, and the moment generated from the tail’s lift. As can be seen in figure 7.10 below, the lift from the wing and tail cancel moments around the CG to prevent pitching. If the aircraft increases velocity, it must decrease its’ angle of attack in order to not increase the moment generated by the increased lift from the wing. The opposite holds for a decrease in velocity.

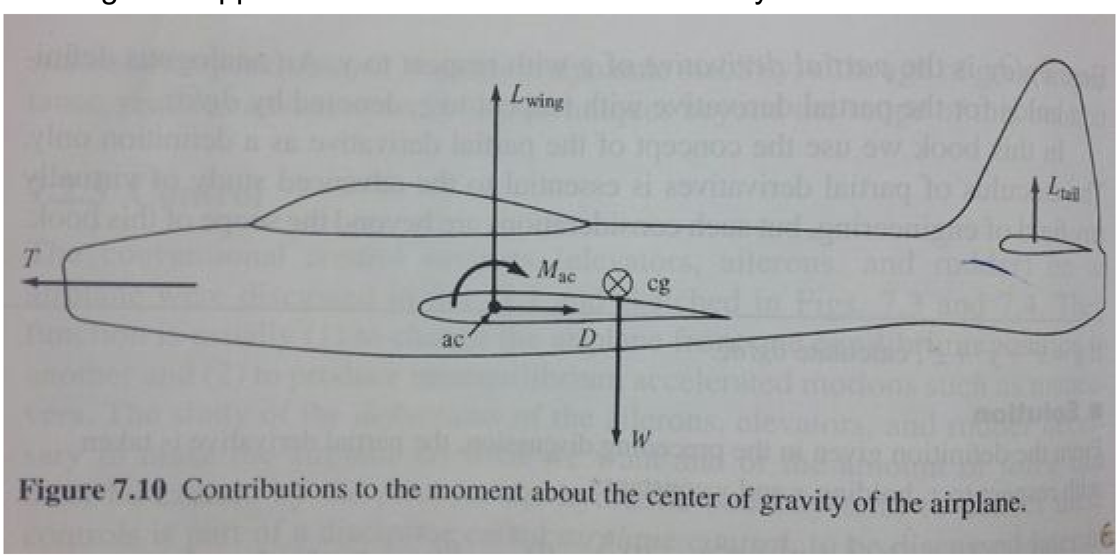
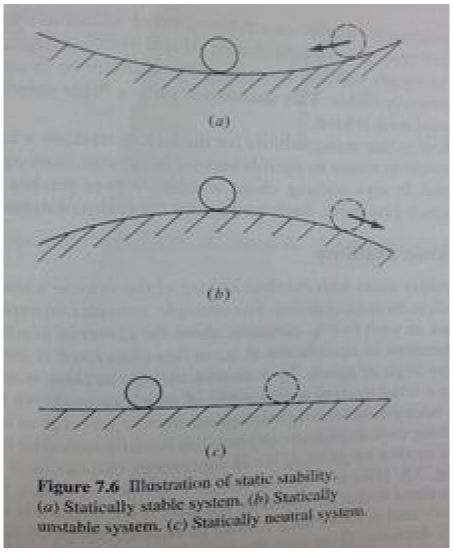
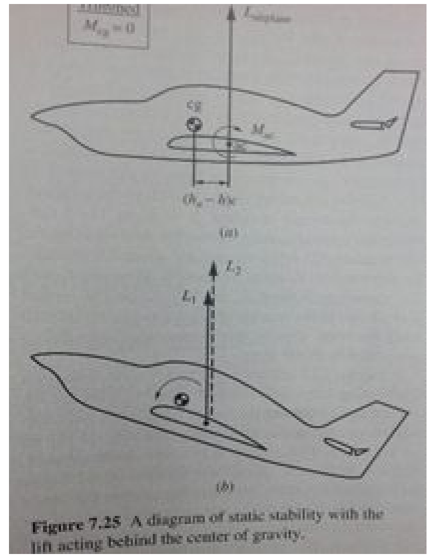


Figure 7.10 Contributions to the moment about the center of gravity of the airplane.

While a pilot has control over flight characteristics of the wing, the angle of attack, and in some cases even the CG, It should not fall on the pilot to ensure that the airplane is constantly balanced. Rather, it should be intrinsic in the design.

Figure 7.6 below illustrates the notion of stability. A stable aircraft will return to level flight if disturbed by a gust of wind or slight pilot error. An unstable aircraft on the other hand is just waiting for the opportunity to slip into an uncontrollable stall.





The aerodynamic center of an aircraft is this magic point where a moment of zero is maintained at all angles of attack. For stable flight, the CG must be placed in front of the aerodynamic center. This configuration is self righting, as an increase in angle of attack results in a moment forcing the nose back down. (illustrated in figure 7.25 above) With all that said, we must place batteries and payloads in appropriate places so that the center of gravity is in its' proper place. Fortunately for us, the folks at L.M. have marked this spot on the bottom of the wing.

Figure 7. Stalker center of gravity indicated on wings.

What we can conclude from this is that a mal-placed center of gravity will most probably lead to a crash. More importantly however, we have the knowledge that if we cannot perfectly balance the load over the CG, it is not the end of the world. If at all possible, it would be preferable to have the CG forward from where it should be rather than rear. There may be a small envelope in which the CG could be moved rear, but the window of safe angles of attack quickly narrows with rear CG deviation. Forward placement of weight from the designated CG would result in stable flight with lower efficiency as the tail would have to be trimmed heavily to compensate for the increased moment around the center of lift.

C. REFERENCES

1. http://plastics.ulprospector.com/generics/34/c/t/polylactic-acid-pla-properties-processing
2. figures 7.6, 7.10, and 7.25 are pulled from John D Anderson's "Theory of Flight" Mcgraw-Hill, 2012.

III. Power

A. Summary of Results:

1. The power system's main issue is fulfilling the battery energy requirements. This is determined by finding the required power used for the system with the battery voltage and determining the required Ah of the battery system. In addition to finding the proper battery is the problem of appropriately sizing the wire and noting the voltage drop from source to load. In order to find the wire size, we use a developed estimation that is explained in the subsequent calculations.

B. Results

1. Battery Sizing Calculations:

In this set of calculations, we will use the batteries we have selected based on preliminary calculations. In this case, we will show the calculations for the 20 minute flight time and the 30 minute flight time of the S900.

S900: 20 Minutes with 1.5 kg Payload

In order to determine the flight time, a number of battery quantities and system requirements must be known. First, we will be assuming for these calculations that the power draw and current requirements are the same as listed for hovering the S900. In this case, that means that the working current I_{hover} = 40 A and the power in the motors P_{hover} = 1 kW. From this we know the flight time is given by

$$t_{flight} = \frac{16\ A*hours}{40A} = 0.4\ hours = 24\ minutes$$

Now that we have verified that it meets our timing requirements, we need to check our weight. The 16 Ah battery we have selected weighs 1920 grams. Since our maximum takeoff weight is 15 lbs, and we know the weight of the frame is 3.3 kg, we can find out how much weight we have for the battery. Converting the weight to kilograms, we see then that

$$W_{battery,max} \leq W_{takeoff,max} - W_{frame} - W_{payload} = 6.8\ kg - 3.3\ kg\ - 1.5\ kg\ =\ 2\ kg$$

Since our battery weighs less than 2 kg, we have verified our design.

S900: 30 Minutes with 1 kg Payload

Using the same quantities from the above calculations, we know the flight time for the 20 Ah battery is given by

$$t_{flight} = \frac{20\ A*hours}{40A} = 0.5\ hours = 30\ minutes$$

Now that we have verified that it meets our timing requirements, we need to check our weight. The 20 Ah battery we have selected weighs 2405 grams. Since our maximum takeoff weight is 15 lbs, and we know the weight of the frame is 3.3 kg, we can find out how much weight we have for the battery. Converting the weight to kilograms, we see then that

$$W_{battery,max} \leq W_{takeoff,max} - W_{frame} - W_{payload} = 6.8\ kg - 3.3\ kg\ - 1.0\ kg\ =\ 2.5\ kg$$

Since our battery weighs less than 2.5 kg, we have verified our design.

Stalker: 2 Hours with 2 kg Payload

It is important to note that we were not able to find a battery setup to give us a flight time of 2 hours without exceeding our weight requirements. For the shorter time, we are going to make use of two 16 Ah batteries. To determine the flight time, we are assuming that once the stalker is in the air, we will only require 30% power to maintain flight throughout the mission. From motor tests, we assume the motor's rated current is 80 A. So, we see the flight time is given by

$$t_{flight} = \frac{2(16\ A*hours)}{0.3(80A)} = 1.333\ hours = 80\ minutes$$

Now that we have verified that it meets our timing requirements, we need to check our weight. The 16 Ah battery we have selected weighs 1290 grams. Since our maximum takeoff weight is 22.5 lbs, and we know the weight of the frame is 14.5 lbs, we can find out how much weight we have for the battery. Converting the weight to kilograms, we see then that

$$W_{battery,max} \leq W_{takeoff,max} - W_{frame} - W_{payload} = 10.2\ kg - 6.6\ kg\ - 2\ kg\ =\ 1.6\ kg$$

Since our battery weighs more than 1.6 kg, we would be able only to fit one in the stalker and attain a flight time of only 40 minutes.

Stalker: 4 Hours with 2 kg Payload

It is important to note that we were not able to find a battery setup to give us a flight time of 4 hours without exceeding our weight requirements. For the shorter time, we are going to make use of two 20 Ah batteries. To determine the flight time, we are assuming that once the stalker is in the air, we will only require 30% power to maintain flight throughout the mission. From motor tests, we assume the motor's rated current is 80 A. So, we see the flight time is given by

$$t_{flight} = \frac{2(20\ A*hours)}{0.3(80A)} = 1.667\ hours = 100\ minutes$$

Now that we have verified that it meets our timing requirements, we need to check our weight. The 16 Ah battery we have selected weighs 1610 grams. Since our maximum takeoff weight is 22.5 lbs, and we know the weight of the frame is 14.5 lbs, we can find out how much weight we have for the battery. Converting the weight to kilograms, we see then that

$$W_{battery,max} \leq W_{takeoff,max} - W_{frame} - W_{payload} = 10.2\ kg - 6.6\ kg\ - 2\ kg\ =\ 1.6\ kg$$

Since our battery weighs more than 1.6 kg, we would be able only to fit one in the stalker and attain a flight time of only 50 minutes.

2. Wire Sizing

When looking into wire sizing, the resource used is the table of AWG wire sizes, Table A1 in the Appendix.

The problem with most of the wire sizing provided in the AWG tables is that they are designed for wiring a house or larger operations. Thus, they require at least 300 circular mills of copper per amp of current. In our application we have developed an estimate that allows for lower standards. This assumption is based on the notion that we are powering brushless motors and do not run our system for truly long periods of time. So, we note that we estimate about 100 circular mills per amp. Thus, we can find the values for the S900 and the Stalker.

For the S900, we note the ESC requires 40 A. Thus, we see that would lead us to a wire with

$$100\frac{cmils}{A}(40\ A) = 4000\ cmils \approx 14\ gauge\ wire$$

For the Stalker, we note that we have been told the motor should draw at maximum 80 Amps. Thus, we must use wire corresponding with the following approximation:

$$100\frac{cmils}{A}(80\ A) = 8000\ cmils \approx 11\ gauge\ wire$$

C. REFERENCES

1. http://electronicdesign.com/boards/efficient-tool-sizes-high-current-pcb-traces
2. http://www.rcgroups.com/forums/showthread.php?t=515819&highlight=an+electrician+but+close
3. http://www.rcgroups.com/forums/showthread.php?t=1400431
4. https://en.wikipedia.org/wiki/American_wire_gauge

IV. Communications

Figure 8. RC Manual Controller, Spektrum DX8 2.4GHz

A. Summary of Results

1. The main issue when considering the communication links is maintaining adequate power at the receiver. This depends on a number of things, including the rain fade, transmit power, receiver sensitivity, path loss and various other values related to the attenuation or amplification of an RF signal. In the following calculations, link budget tables are made for telemetry, video and RC communication systems. These tables are made to find the theoretical maximum range of each communication system and still maintain a 10 dB fade margin. In addition to this, the rain fade will be considered by finding a reliable source, using the knowledge that we need to ideally operate at 1 inch/ hr.

B. Results

1. Rain Fade Calculations
   a) The rain fade calculations were not made directly, but extracted from reliable sources that have performed the calculations themselves. Most of these include universities and companies that require these values for their own jobs. As can be seen in the figure below, the rain fade chart fails to even extend to 2.4 GHz. Assuming the rain is falling at 25 mm/hour, which is just above the 1 in/hour mentioned in the SOW, the attenuation is only .01 dB/km at 3 GHz and only decreases as the frequency decreases. This amounts to only 1dB of attenuation after 100 km, at which point you run into different problems involving the curvature of the earth.

This figure provides the upper limit on the rain attenuation at 2.4 GHz and 900 MHz and we are able to assume that the attenuation is no more than 1 dB for any distance that the UAS is from the ground station.

b) The figure used to extract the information is given below.

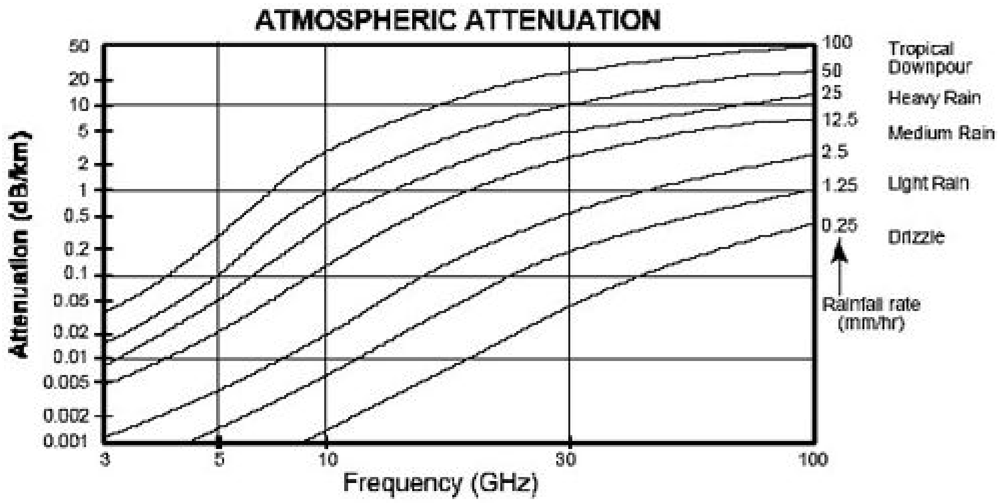


Figure 9. Graph of Atmospheric Attenuation

2. Link Budget Analysis

a) The link budget indicates whether or not the receiver will be able to hear the transmitter after all gains and losses are taken into account. The result of this is given in terms of margin, which is how many dB's the received power is above the receiver sensitivity. The results for each of the communication systems is presented below. Each analysis is conducted assuming heavy rain and a desired 10 dB of gain margin, to allow for miscellaneous

b) The tables below outline the link budgets for the telemetry, video and RC communication links. Values for transmit/receive powers, antenna gains and receiver sensitivity are all taken from respective datasheets. The rain fade is taken from Figure 1 above. Path loss is calculated using the free space path loss equation given in Equation 1 below. Miscellaneous losses are used as a worst case scenario for the link budgets and represent any interference, multi-path losses, obstructions or anything else that might inhibit the communication link.

$$Path\ Loss = 20log\left(\frac{4\pi d}{\lambda}\right)$$

Equation 1: Free Space Path Loss

Fade margin is calculated using each of the gain terms and loss terms and finding how many decibels over the receiver sensitivity the received power is. The Fade margin for this analysis is calculated in the Equation below. Matlab code was used to determine what the maximum distance was by solving for the parameters in the gain margin equation that have a dependency on distance (Path Loss and Rain Attenuation).

$$FM = TX_{Power} + ANT_{TX} + ANT_{RX} - PathLoss - MiscLoss - RadeFade - RX_{Sensitivity}$$

Equation 2: Fade Margin Calculations

$$TX_{Power} = Transmission\ Power$$
$$ANT_{TX} = Gain\ of\ Transmission\ Antenna$$
$$ANT_{RX} = Gain\ of\ Receiver\ Antenna$$
$$PathLoss = Free\ Space\ Path\ Loss$$
$$MiscLoss = Losses\ That\ Are\ Not\ Accounted\ For$$
$$RainFade = Losses\ Due\ to\ Rain$$
$$RX_{Sensitivity} = Receiver\ Sensitivity$$

Each calculation is for the UAS to ground station link. The reason for this being that each communication link is either one way or symmetric with the same antenna and radio on each side. The Telemetry link is symmetric since the same radio is being used on the ground station as in the air, the antennas are also going to be the same though the calculations will be symmetric since if the gain is not on the transmit side, it will be on the receive side. For the systems designed, the Lightbridge is a one-way link since we only care about getting the video down to ground and are not sending signals up to the UAS. The controller is also a one-way data link from the ground station to the UAS.

Table 1: Telemetry Link Budget

Link Budget Analysis - Telemetry		
Parameter	Power/Gain/Loss in dBm	Note
Tx Power	30	1 Watt
Tx Antenna Gain	2.5	Dipole Antenna
Free Space Loss	114.85 dB	
Rain Attenuation	< 1dB	
Rx Antenna Gain	2.5	Dipole Antenna
Misc. Losses	10	To account of everything else
Rx Sensitivity	-100	Datasheet sensitivity assuming AWGN
Margin	10 dB	Total dB above Rx Sensitivity
Max Distance	14.42 km	Maximum Distance

Table 2: Video Communication Link Budget

Link Budget Analysis - Video		
Parameter	Power/Gain/Loss in dBm	Note
Tx EIRP	20	Includes Antenna Gain
Free Space Loss	105.98	
Rain Attenuation	< 1dB	
Rx Antenna Gain	5	On Ground Station
Misc. Losses	20	To account for everything else

Rx Sensitivity	-101	Datasheet sensitivity assuming AWGN
Margin	10 dB	Total dB above Rx Sensitivity
Max Distance	1.97 km	Maximum Distance

Table 3: RC Controller Link Budget

Link Budget Analysis - Remote Controller		
Parameter	Power/Gain/Loss in dBm	Note
Tx Power	23	200 mW
Tx Antenna Gain	15	Higher Gain Option Shown
Free Space Loss	114.44	
Rain Attenuation	< 1 dB	
Rx Antenna Gain	2.5	Dipole Antenna
Misc. Losses	20	To account of everything else
Rx Sensitivity	-100	Datasheet sensitivity assuming AWGN
Margin	10 dB	Total dB above Rx Sensitivity
Max Distance	10.4 km	Maximum Distance

C. REFERENCES

1. DJI, 'DJI Official - DJI The World Leader in Camera Drones/Quadcopters for Aerial Photography', Dji.com, 2015. [Online]. Available: http://www.dji.com/product/compare-lightbridge.

2. Spektrum, 'DX8 System with AR8000 + TM1000 No SX MD2 (SPM8800): Spektrum - The Leader in Spread Spectrum Technology', Spektrumrc.com, 2015. [Online]. Available: http://www.spektrumrc.com/Products/Default.aspx?ProdId=SPM8800.

3. Purelink, '5.8 GHz, The Best Choice for RLTS', Purelink.ca, 2015. [Online]. Available: http://www.purelink.ca/en/technologies/real-time-location-system.php.

4. Digi, 'XBee Pro XSC', Digi International, 2015. [Online]. Available: http://www.digi.com/products/xbee-rf-solutions/modules/xbee-pro-xsc.

D. Matlab Code for Finding Maximum Distance

```
%Telemetry Link Budget

TX = 30;                    %Transmit power in dBm
TX_ANT_GAIN = 2.5;          %Transmission antenna gain
RX_ANT_GAIN = 2.5;          %Receiver Antenna Gain
RX_SENSE = -100;            %Receiver Sensitivity
MISC_LOSS = 10;             %Miscellaneous Losses

RAIN_ATT = .01;             %Rain Attenuation per 1 km
freq = 915*10^6;            %Operating Frequency
lambda = 299792458/freq;  %Wavelength
syms d                      %Distance in km
PATH_LOSS = 20*log10(4*pi*d*1000/lambda);   %Path Loss in Free Space
%Equation for Link budget
RAIN_ATTENUATION = RAIN_ATT*d;  %Total Rain Attenuation

GAIN_MARGIN =
TX+TX_ANT_GAIN+RX_ANT_GAIN-PATH_LOSS-MISC_LOSS-RX_SENSE-RAIN_ATTENUATION;

Max_Distance_Telemetry = double(solve(GAIN_MARGIN == 10,d))        %Return
Max Distance with this linka and Given Gain Margin
20*log10(4*pi*Max_Distance_Telemetry*1000/lambda)

%Video Link Budget

TX = 20;                    %Transmit power in dBm
TX_ANT_GAIN = 0;     %Transmission antenna gain
RX_ANT_GAIN = 5;     %Receiver Antenna Gain
RX_SENSE = -101;            %Receiver Sensitivity
MISC_LOSS = 10;       %Miscellaneous Losses

RAIN_ATT = .01;             %Rain Attenuation per 1 km
freq = 2400*10^6;           %Operating Frequency
lambda = 299792458/freq;  %Wavelength
syms d                      %Distance in km
PATH_LOSS = 20*log10(4*pi*d*1000/lambda);   %Path Loss in Free Space
%Equation for Link budget
RAIN_ATTENUATION = RAIN_ATT*d;  %Total Rain Attenuation

GAIN_MARGIN =
```

```
TX+TX_ANT_GAIN+RX_ANT_GAIN-PATH_LOSS-MISC_LOSS-RX_SENSE-RAIN_ATTENUATION;

Max_Distance_Video = double(solve(GAIN_MARGIN == 10,d))      %Return Max
Distance with this linka and Given Gain Margin
20*log10(4*pi*Max_Distance_Video*1000/lambda)
%Controller Link Budget

TX = 23;                   %Transmit power in dBm
TX_ANT_GAIN = 15;   %Transmission antenna gain
RX_ANT_GAIN = 2.5;         %Receiver Antenna Gain
RX_SENSE = -100;           %Receiver Sensitivity
MISC_LOSS = 10;            %Miscellaneous Losses

RAIN_ATT = .01;            %Rain Attenuation per 1 km
freq = 2400*10^6;          %Operating Frequency
lambda = 299792458/freq;  %Wavelength
syms d                %Distance in km
PATH_LOSS = 20*log10(4*pi*d*1000/lambda);   %Path Loss in Free Space


%Equation for Link budget
RAIN_ATTENUATION = RAIN_ATT*d;  %Total Rain Attenuation

GAIN_MARGIN =
TX+TX_ANT_GAIN+RX_ANT_GAIN-PATH_LOSS-MISC_LOSS-RX_SENSE-RAIN_ATTENUATION;

Max_Distance_Controller = double(solve(GAIN_MARGIN == 10,d))       %Return
Max Distance with this link and Given Gain Margin
20*log10(4*pi*Max_Distance_Controller*1000/lambda)
```

V. Ground Station & Autopilot

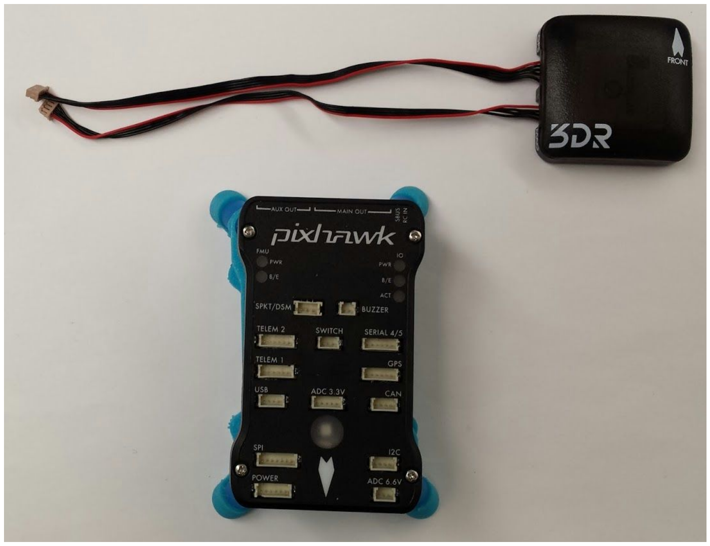


Figure 10. Pixhawk autopilot on vibration damping mount and GPS

A. Summary of Results:

1. The main concern for the Ground Station and Autopilot is if we can monitor the battery with Mission Planner. At a certain battery level, we would want the UAS to return to the start position from where it took off.

B. Results

1. Mission Planner
    a) We found that the battery system, as long it can be tracked by the autopilot, can be tracked by Mission Planner. Mission Planner can even go as far as setting a bingo battery level for the UAS to know when to come back to base.
    b) Patrick Steckman’s work and documentation can be seen at the Mission Planner website underneath Optional Hardware > Power Modules > 3DR Power Module

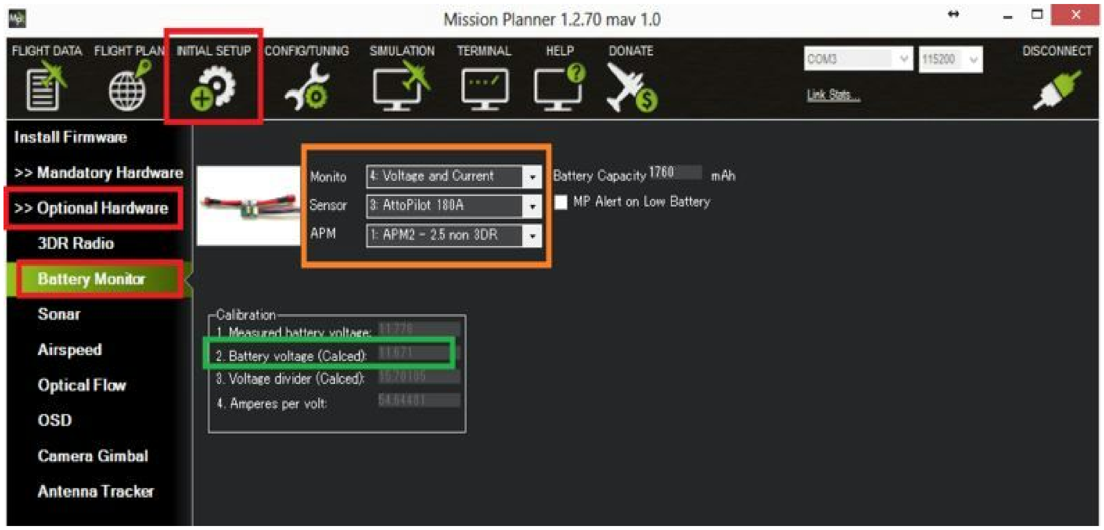


Figure 11: Shows the Battery Monitoring in Mission Planner.

2. Stalker UAS Bungee Calculations
   a) The Stalker can be launched either using bungee cord or by hand. Bungee cord is a elastic material used to provide the line tension. It is type of tensioned line launch in which the line is fixed to a platform on one end and the UAV is hooked to the other end of the platform. The net force acting on the tensioned line launch:
      $F_{Net} = T_{Line} + T_{Propulsion} + W_{TO} + D_F + L_F$
      Where T_{Line} - Line Tension, $T_{Propulsion}$ - Propulsion Thrust, W_{TO} - Gross Weight during Take Off, D_F - UAV Drag Force, L_F - Lift Force
   b) Max W_{TO} = 22.5 lbs
   c) In most of the cases the drag and lift force are neglected. As they both try to cancel out each other.
   d) Below Figure shows the forces acting on the UAV during the Bungee Launch

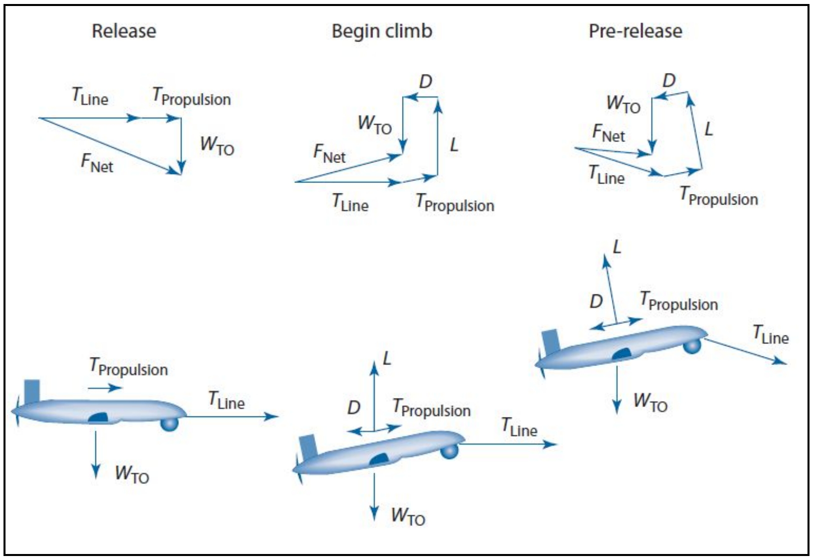


Figure 12. Launch Forces on the Aircraft [2]

e) Calculating the line tension:
General rule is to use 5 lbs of bungee tension per lbs of aircraft.

f) Maximum takeoff weight(gross weight) for stalker = 22.5 lbs

g) So we need 22.5*5 = 112.5 lbs (of tension)

h) Tension = [Spring Constant] X [Stretched Length] = Mass X Gravity = 112.5*0.45*9.8 = 496.125 N (1 lbs = 0.45 Kg approx.)

i) Stretched length = Length of Stretched Cord - Length of Unstretched Cord

j) Calculating the energy required during launch:

k) $\triangle E_{Line} + \triangle E_{Propulsion} + \triangle E_{Losses} = W_{TO} \cdot [(|\triangle V|^2/2*g) + \triangle h] + \triangle E_{Stored}$

l) $\triangle E_{Line}$ = Energy provided by the tensioned line = $k*\triangle X^2/2$

m) k - Spring Constant, $\triangle X$ = Stretched Length = Length of Stretched Cord - Length of Unstretched cord, W_{TO} - Gross weight during takeoff, g - Earth Gravity = 9.8m/s, $\triangle h$ = Launch Altitude - Release Altitude, $\triangle V$ = Airspeed Velocity

n) As we know the drag is neglected the losses will be set to zero and assuming there is no propulsion(just to make calculations simpler), the energy will be equal to the energy produced by the tensioned line.

o) $k*\triangle X^2/2 = W_{TO} \cdot [(|\triangle V|^2/2*g) + \triangle h]$

p) In order for the motors to engage stalker should achieve at least 20m/s airspeed and 20m altitude. Assuming the maximum takeoff weight = 22.5 lbs(100.084N)

q) Total Energy $k*\triangle X^2/2$ = 100.084 *[(800/2*9.8) + 20] = 6086.741 J

Figure 13: 6 kJ Portable Pneumatic Catapult [6]

r) We know Tension = k*△X = 496.125 N
s) Using the two equations, △X = 24.54 m; k= 20.22 N/m
t) Calculating the Bungee Stiffness : $k = (E * A_0) / L_0$
u) E - Young's Modulus, a Material Constant(N/m^2); A_0 - Cross Sectional Area of the material(m^2); L_0 - Length of unstretched cord(m)
v) Since most of the bungees available in market do not sell by a specific 'k' values. From the above equation, we know that it depends on the bungee as well. So, we need a bungee that produces the required tension at the given elongation.

Force(N)	Unstretched Length (m)	Elongated Length(m)	Stiffness Constant k(N/m)
200	0.5	3.2	75
400	1	6.5	72
100	0.2	1.56	74
500	1.2	7.8	75

Table 4: Bungee Stiffness Constant [4]

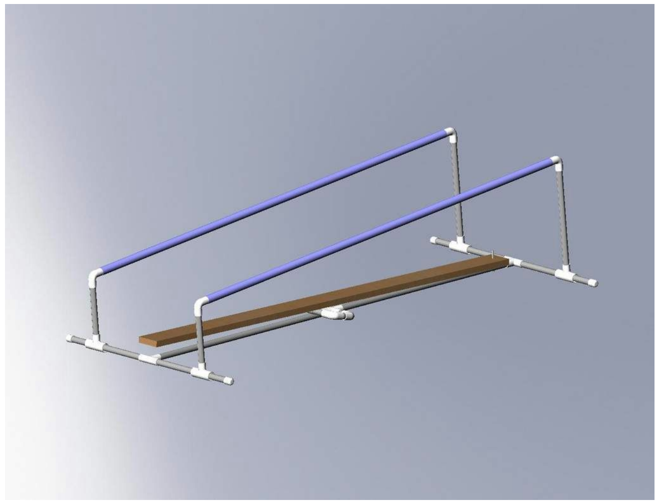


Figure 14: Design of Simple Bungee Launcher [3]

C. REFERENCES

1. http://copter.ardupilot.com/wiki/common-3dr-power-module/
2. Designing Unmanned Aircraft Systems (Page 444, Fig 11.15)
3. http://www.rcgroups.com/forums/showthread.php?t=1022950
4. http://urst.org/siteadmin/upload/4918U1015121.pdf
5. http://www.vti.mod.gov.rs/ntp/rad2013/3-13/6/6.pdf
6. http://www.uavfactory.com/product/21

APPENDIX

Table A1: AWG Wire Sizes

Paul L. Schimel
rev 3/3/2003

COPPER WIRE

AWG #	Solid Wire Diameter (mil)	Cross Section Cir mil	Cross Section Square mil	Cross section Square mm	Equivalent Cross section in 1/2 oz copper 1/2oz Cu=.7 mil Width (mil)	Equivalent Cross Section in 1 oz copper 1oz cu=1.4 mil Width (mil)	Equivanlent Cross Section in 2 oz copper 2oz cu=2.8 mil Width (mil)	Equivalent Cross Section in 4 oz Copper 4oz cu=5.6 mil Width (mil)	Equivalent Cross Section in 6 oz copper 6oz cu=8.4 mil Width (mil)	30 cir mil/A Current	100 cir mil/A Current	300 cir mil/A Current	500 cir mil/A Current	1000 cir mil/A Current	ohm/foot 25 deg C	ohm/foot 105 deg C
40	**3.15**	**9.9**	**7.78**	**0.0050**	**11.11**	**5.55**	**2.78**	**1.39**	**0.93**	0.33	0.10	**0.03**	**0.02**	**0.01**	**1.0679787990**	**1.3947772249**
39	3.54	12.5	9.82	0.0063	14.02	7.01	3.51	1.75	1.17	0.42	0.13	0.04	0.03	0.01	0.8458392088	1.1046635621
38	3.96	15.7	12.33	0.0080	17.62	8.81	4.40	2.20	1.47	0.52	0.16	0.05	0.03	0.02	0.6734388605	0.8795092055
37	4.45	19.8	15.55	0.0100	22.22	11.11	5.55	2.78	1.85	0.66	0.20	0.07	0.04	0.02	0.5339893995	0.6973886124
36	5.00	25.0	19.63	0.0127	28.05	14.02	7.01	3.51	2.34	0.83	0.25	0.08	0.05	0.03	0.4229196044	0.5523317810
35	5.61	31.5	24.74	0.0160	35.34	17.67	8.84	4.42	2.95	1.05	0.32	0.11	0.06	0.03	0.3356504797	0.4383585564
34	6.31	39.8	31.26	0.0202	44.66	22.33	11.16	5.58	3.72	1.33	0.40	0.13	0.08	0.04	0.2656530178	0.3469420735
33	7.08	50.1	39.35	0.0254	56.21	28.11	14.05	7.03	4.68	1.67	0.50	0.17	0.10	0.05	0.2110377267	0.2756146612
32	7.95	63.2	49.64	0.0320	70.91	35.46	17.73	8.86	5.91	2.11	0.63	0.21	0.13	0.06	0.1672941473	0.2184856729
31	8.93	79.7	62.60	0.0404	89.42	44.71	22.36	11.18	7.45	2.66	0.80	0.27	0.16	0.08	0.1326598508	0.1732533818
30.00	**10.05**	**101**	**79.33**	**0.0512**	**113.32**	**56.66**	**28.33**	**14.17**	**9.44**	3.37	1.01	**0.34**	**0.20**	**0.10**	**0.1046830704**	**0.1367157874**
29	11.27	127	99.75	0.0644	142.49	71.25	35.62	17.81	11.87	4.23	1.27	0.42	0.25	0.13	0.0832518906	0.1087267286
28	12.65	160	125.66	0.0811	179.52	89.76	44.88	22.44	14.96	5.33	1.60	0.53	0.32	0.16	0.0660811882	0.0863018408
27	14.21	202	158.65	0.1024	226.64	113.32	56.66	28.33	18.89	6.73	2.02	0.67	0.40	0.20	0.0523415352	0.0683578937
26	15.94	254	199.49	0.1287	284.99	142.49	71.25	35.62	23.75	8.47	2.54	0.85	0.51	0.25	0.0416259453	0.0543633643
25	17.89	320	251.33	0.1621	359.04	179.52	89.76	44.88	29.92	10.67	3.20	1.07	0.64	0.32	0.0330405941	0.0431509204
24	20.10	404	317.30	0.2047	453.29	226.64	113.32	56.66	37.77	13.47	4.04	1.35	0.81	0.40	0.0261707676	0.0341789468
23	22.56	509	399.77	0.2579	571.10	285.55	142.77	71.39	47.59	16.97	5.09	1.70	1.02	0.51	0.0207720827	0.0271282800
22	25.34	642	504.23	0.3253	720.32	360.16	180.08	90.04	60.03	21.40	6.42	2.14	1.28	0.64	0.0164688319	0.0215082469
21	28.46	810	636.17	0.4104	908.82	454.41	227.20	113.60	75.73	27.00	8.10	2.70	1.62	0.81	0.0130530742	0.0170472772
20	**31.94**	**1020**	**801.11**	**0.5168**	**1144.44**	**572.22**	**286.11**	**143.05**	**95.37**	34.00	10.20	**3.40**	**2.04**	**1.02**	**0.0103656766**	**0.0135375437**
19	35.92	1290	1013.16	0.6537	1447.38	723.69	361.84	180.92	120.61	43.00	12.90	4.30	2.58	1.29	0.0081961164	0.0107041043
18	40.25	1620	1272.34	0.8209	1817.63	908.82	454.41	227.20	151.47	54.00	16.20	5.40	3.24	1.62	0.0065265371	0.0085236386
17	45.28	2050	1610.06	1.0387	2300.09	1150.05	575.02	287.51	191.67	68.33	20.50	6.83	4.10	2.05	0.0051575562	0.0067357534
16	50.79	2580	2026.33	1.3073	2894.75	1447.38	723.69	361.84	241.23	86.00	25.80	8.60	5.16	2.58	0.0040980582	0.0053520521
15	57.10	3260	2560.40	1.6519	3657.71	1828.85	914.43	457.21	304.81	108.67	32.60	10.87	6.52	3.26	0.0032432485	0.0042356732
14	64.11	4110	3227.98	2.0826	4611.41	2305.70	1152.85	576.43	384.28	137.00	41.10	13.70	8.22	4.11	0.0025725037	0.0033596824
13	71.97	5180	4068.36	2.6247	5811.94	2905.97	1452.99	726.49	484.33	172.67	51.80	17.27	10.36	5.18	0.0020411178	0.0026656939
12	80.81	6530	5128.65	3.3088	7326.64	3663.32	1831.66	915.83	610.55	217.67	65.30	21.77	13.06	6.53	0.0016191409	0.0021145933
11	90.72	8230	6463.82	4.1702	9234.03	4617.02	2308.51	1154.25	769.50	274.33	82.30	27.43	16.46	8.23	0.0012846890	0.0016778001
10	**101.98**	**10400**	**8168.13**	**5.2698**	**11668.76**	**5834.38**	**2917.19**	**1458.60**	**972.40**	346.67	104.00	**34.67**	**20.80**	**10.40**	**0.0010166337**	**0.001327720**
9	114.46	13100	10288.71	6.6379	14698.15	7349.08	3674.54	1837.27	1224.85	436.67	131.00	43.67	26.20	13.10	0.0008070985	0.0010540683
8	128.45	16500	12959.06	8.3607	18512.94	9256.47	4628.24	2314.12	1542.75	550.00	165.00	55.00	33.00	16.50	0.0006407873	0.0008368663
7	144.22	20800	16336.27	10.5395	23337.53	11668.76	5834.38	2917.19	1944.79	693.33	208.00	69.33	41.60	20.80	0.0005083168	0.0006638603
6	162.17	26300	20655.95	13.3264	29508.51	14754.25	7377.13	3688.56	2459.04	876.67	263.00	87.67	52.60	26.30	0.0004020148	0.0005250302
5	181.93	33100	25996.66	16.7720	37138.08	18569.04	9284.52	4642.26	3094.84	1103.33	331.00	110.33	66.20	33.10	0.0003194257	0.0004171690
4	204.21	41700	32751.08	21.1297	46787.25	23393.63	11696.81	5848.41	3898.94	1390.00	417.00	139.00	83.40	41.70	0.0002535489	0.0003311342
3	229.35	52600	41311.91	26.6528	59017.01	29508.51	14754.25	7377.13	4918.08	1753.33	526.00	175.33	105.20	52.60	0.0002010074	0.0002625151
2	257.68	66400	52150.39	33.6453	74500.56	37250.28	18625.14	9312.57	6208.38	2213.33	664.00	221.33	132.80	66.40	0.0001592318	0.0002079562
1	289.31	83700	65737.77	42.4114	93911.10	46955.55	23477.78	11738.89	7825.93	2790.00	837.00	279.00	167.40	83.70	0.0001263201	0.0001649737
ought (0)	**325.58**	**106000**	**83252.14**	**53.7109**	**118931.62**	**59465.81**	**29732.91**	**14866.45**	**9910.97**	3533.33	1060.00	**353.33**	**212.00**	**106.00**	**0.0000997452**	**0.0001302669**
2ought (00)	364.69	133000	104457.87	67.3920	149225.53	74612.76	37306.38	18653.19	12435.46	4433.33	1330.00	443.33	266.00	133.00	0.0000794962	0.0001038218
3ought (000)	409.88	168000	131946.78	85.1268	188495.40	94247.70	47123.85	23561.93	15707.95	5600.00	1680.00	560.00	336.00	168.00	0.0000629345	0.0000821922
4ought (0000)	460.43	212000	166504.27	107.4219	237863.24	118931.62	59465.81	29732.91	19821.94	7066.67	2120.00	706.67	424.00	212.00	0.0000498726	0.0000651335

1.) FOR THE SAME RUN IN ALUMINUM WIRE, TO GET THE SAME CONDUCTOR RESISTANCE REQUIRES 160% OF THE CROSS SECTION OF COPPER. (Al=(CuAWG-2))
2.) THE TEMCO FOR Al AND Cu ARE VERY SIMILAR, SO THIS APPLIES OVER ALL TEMP

Temperature Classifacation		(per UL1446)
Designator	Hot spot temp	
B	130	(deg C)
F	155	
H	180	
N	200	
R	220	
S	240	

Additional Notes:
Resistivity of Cu:
S(T)=(1.7241*10^--6)*(1+.0039*(T-20))
T is temp in deg C
S is Resistivity in OHM*centimeters (cm)
Resistance= [S(Tx)*Length(cm)]/Cross Section(cm^2)

Current Density:
1000 cir mil per amp is reserved for absolute worst case conditions. IE: high ambient temp, no air circulation around conductors, minimal self heating

500 cir mil per amp is a good starting point. With a little airflow, reasonable max ambient temp (say 85 deg C), and conductor thickness thinner than the depth of penetration for the ac frequencies through the conductor, this is a reasonable starting point.