Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

High Altitude Research Return Vehicle (HARRV)
System Architecture White Paper

April 17, 2008

Document History

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Approval

Title	Name	Signature	Date
Customer			
Advisor #1			
Advisor #2			
CC			

System Architecture White Paper

Aerospace Senior Projects (ASEN 4018 & 4028)

1.0 Information

1.1 Project Title

High Altitude Research Return Vehicle (HARRV)

1.2 Project Customers

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2.0 System Architecture

2.1 Guided Free Fall Device

The guided freefall device is essentially an adaptation of the GPS ballistic concept. By employing a slender body, cylindrical airframe, the device will freefall at higher speeds compared to aircraft vehicle designs. Using a GPS receiver for position and altitude determination, control actuators will guide the device towards its target by deflecting control surfaces. The fins and control actuators will be located at the rear of the vehicle, as with most common rockets, so that the device will be statically stable. Avionics and payloads will be placed as close to the nose as possible in order to increase the vehicle's static margin. In order to slow the device to a safe landing speed, a parachute will deploy near the ground. It will be necessary to design this system in such a way that the parachute does not rapidly inflate; otherwise the shock encountered on deployment will destroy the vehicle, payloads, and/or parachute.

2.2 Parafoil

This design concept is to use a deployable parafoil, or ram-air parachute, to glide the vehicle to a designated target area. A parafoil is typically constructed from rip-stop nylon material and a line material (i.e. Dacron, spectra, or Vectran) which connect the parachute to its payload. A ram-air parachute is configured with a bottom skin and a top skin with vertical ribs sandwiched between the two skins. Parachute fabric weighs a maximum of 4.75 ounces per yard.[i] The parachute would contain no more than four yards of fabric making the parachute weigh about 19 ounces plus the weight of the lines. If a high performance fiber – like Vectran with a density of 1.4 g/cm^3 – is used for the lines, it would weigh less than an ounce.[ii]

The ribs of the canopy form cells which are open on the nose of the canopy and closed on the tail. The suspension lines of the parafoil trim it in a nose down attitude so that air is forced into the cells of the parachute through the nose, causing the parachute to inflate into an

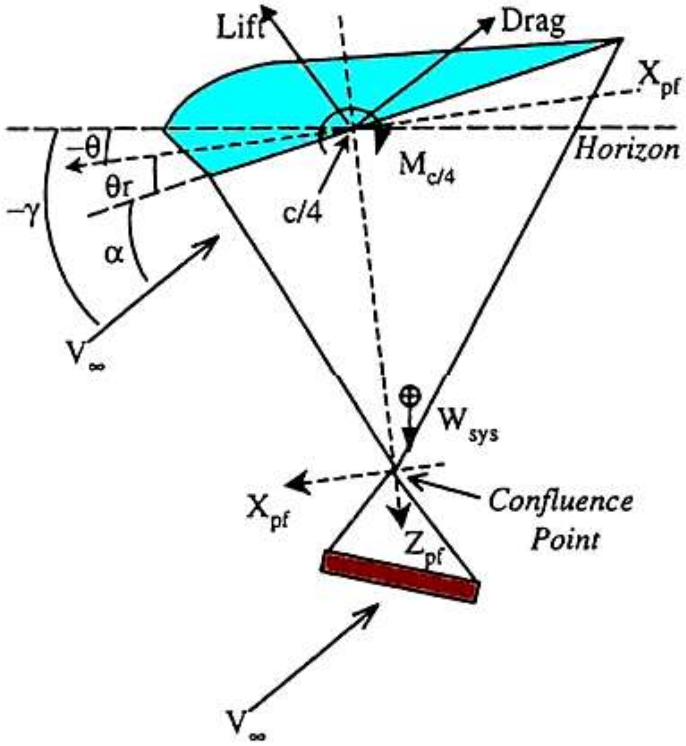


Figure 1- Parachute forces and aerodynamic angles (Yakimenko, 7).

airfoil shape. This configuration allows the parafoil to produce lift and a forward glide. Typical ram-air parachutes have a forward velocity of 20 to 25 mph in full glide and lift to drag ratios of about 3:1.[iii]

Parachutes typically open with shock loads of about 5 g to 8 g with the assistance of a slider device that slows the opening. High altitude openings experience much higher shock loads, with the opening shock being 400 percent higher at 40,000 feet than at 10,000 feet.[iv] This phenomenon has not been sufficiently explained or tested. For this reason, the parachute must not be deployed until the vehicle reaches a lower altitude.

A parachute is controlled with two control lines (also called brakes) that are connected to the tail of the parafoil. These control lines are used to steer the parafoil by deflecting the tail on the side of the desired turn. The control lines can also be simultaneously used to alter the pitch of the parafoil in order to adjust glide or perform maneuvers such as a landing flare. This two-surface control system would allow for two actuators to pull the control lines for full control of the parafoil through its descent and landing.

A GPS receiver would be sufficient to effectively navigate the parafoil, but a heading direction detector could be used to find the heading quicker. A heading detector could also be used to infer wind direction so that the parafoil could land into the wind allowing for a slower, softer landing. A feed-back control system would be used to manipulate the parafoil's controls in order to guide the parafoil to a desired landing target.

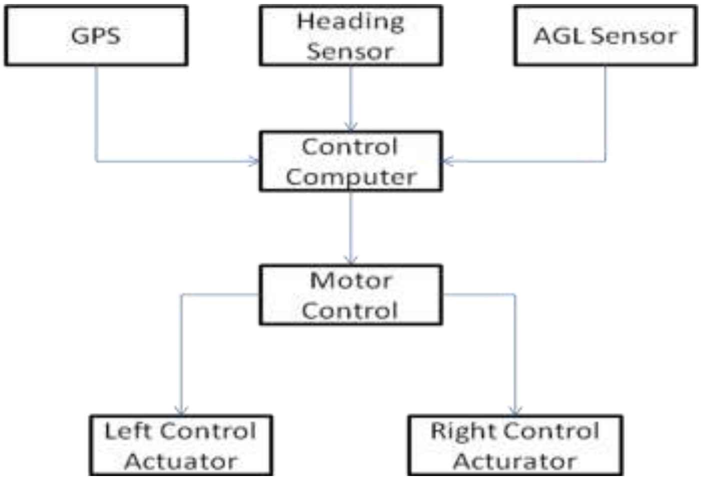


Figure 2- Navigation and Control System of Parafoil

A parafoil will be unconstraining to the payload configuration since the center of gravity of the payload will always hang under the confluence point. This would allow the parafoil and parafoil control system to operate independently of the cargo. A parafoil could also be considered for a final stage recovery system to guide a separate system – such as a UAV or ballistic freefall device – during landing.

2.3 Glider/Powered UAV

The glider design is a rigid, unpowered aircraft, which will rely on an efficient aerodynamic structure to produce the necessary lift to drag ratio required for the vehicle to travel to its destination. The vehicle will incorporate rigid control surfaces to produce the aerodynamic loads necessary for control in pitch, yaw, and roll. The glider will use its weight to generate the thrust necessary to travel against the wind. A major advantage to the glider design is the extensive amount of empirical data collected through similar vehicle designs in the past. A disadvantage of this design would be the structure weight.

3.0 Requirements

Table 1: Top-Level Project Requirements

Requirement	Description	Parent Requirement	Verification Method
0.PRJ.1	Vehicle must carry at least 5 BalloonSats	All of the payloads can be launched in 2 missions	Fit the payloads inside the bay, then measure the total weight of the vehicle
0.PRJ.2	Vehicle shall autonomously navigate to a designated landing zone	Mission profile	Flight testing of the autopilot program with a scaled model
0.PRJ.3	Vehicle shall land within a 1/4 mile of the target landing site	Customer requirement	Flight testing of the autopilot program with a scaled model
0.PRJ.4	Upon landing, the vehicle shall be in a condition such that no systems have suffered failure	Customer requirement	Recovery system testing and analysis; post-flight inspections
0.PRJ.5	Vehicle shall allow each payload a view to the atmosphere*	Payloads' science instruments must function as intended	Design analysis and flight tests
0.PRJ.6	Vehicle shall operate in a manner compliant with all applicable local, state, and federal regulations	Flights must be approved by FAA	Obtain FAA approval for flight

*Awaiting specific payload requirement from customer

Table 2: Top-Level System Requirements

Requirement	Description	Parent Requirement	Verification Method
0.SYS.1	Combined vehicle/payload shall weigh equal to or less than 26 lbs if a beacon/transponder is incorporated. Otherwise, it shall weigh equal to or less than 20 lbs	0.PRJ.1	Weigh the vehicle with the payloads
0.SYS.2	Vehicle shall be able to accommodate at least 5, 5" cube payloads	0.PRJ.1	Fit the payloads inside the bay
0.SYS.3	All subsystems shall survive in a temperature range of -80°C to 40°C	0.PRJ.2	Thermal testing (Subsystems' functionality inside a freezer)
0.SYS.4	All subsystems shall withstand partial	0.PRJ.2	Vacuum testing (Subsystems'

	vacuum conditions down to 1.0 kPa		functionality inside a vacuum chamber)
0.SYS.5	Vehicle shall be capable of operating without user input	0.PRJ.2	Flight testing (Have a scaled model fly and land with the autopilot program)
0.SYS.6	Vehicle shall employ a recovery system which will return it to the ground with a vertical velocity no greater than 20 ft/s	0.PRJ.5	Recovery system testing and analysis (Have a scaled model land from hot air balloon drops and record the impact speed with accelerometers and timers)
0.SYS.7	Vehicle shall be capable of radio communications with a ground station in a 20 mile line-of-sight range	0.PRJ.7	Communication system testing; flight testing (Place a model within the line-of-sight range and try establishing radio communication)
0.SYS.8	Redundant systems shall return the vehicle safely to the ground if the primary navigation system fails	0.PRJ.5	Flight testing (Intentionally turn off the main systems and have the vehicle operate on back-up systems)
0.SYS.9	Autonomous operation can be overridden from the ground station	0.PRJ.7	Flight testing and ground testing of the manual system (Intentionally cut into the autopilot's program and manually control the vehicle)
0.SYS.10	Once autonomous control is engaged, the vehicle shall be capable of traveling at least 10 miles, in a direction parallel to the mean surface of the earth, to a pre-defined landing site	0.PRJ.2	Design analysis and flight testing

3.1 Guided Free Fall Device

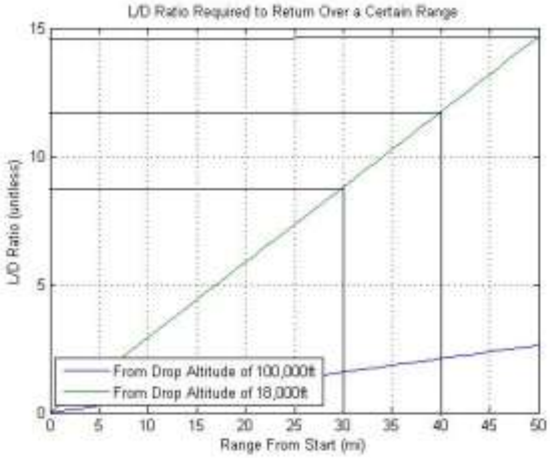
An approximate weight could not be determined at present for two reasons: 1) there are no similar projects (e.g. payload return from high altitude) that use this vehicle structure, 2) the only applications of this vehicle platform have been military ballistics carrying warheads.

It was determined that extrapolating weight data from relevant military ballistics would be possible, but inaccurate and irrelevant because of the large diversity between the design objectives of the military and of HARRV. However, because this vehicle platform provides significant benefits, a more thorough analysis will be completed prior to PDR. This will provide a possible weight range for several platforms along with a range of possible materials.

Since the vehicle will have characteristics similar to a glider, it is entirely feasible to use the same aerodynamic model to feed an autopilot the necessary control derivatives and stability information to allow it to be controlled using an off the shelf autopilot or a HARRV assembled one. The autonomous control device will need to send and receive information to and from the yaw, pitch, and roll control surface actuators.

This equation was used to create a plot of range with respect to L/D for the two possible altitudes.

$$\frac{L}{D} = \frac{\Delta s}{\Delta h}$$



The nose-heaviness eliminates concerns regarding stall recovery because the vehicle will automatically point its nose down upon stall and will regain flow attachment. This will result in controllability reestablishment.

This design also reduces the possibility of a mid-air collision with another aircraft because it will travel through a very small volume of Class A airspace in a very short amount of time (79 sec [see BOTE calculations]), and its path will be completely predictable. This path is easily verifiable prior to testing because of the massive military and civilian ballistics databases.

Finally, this design's agility reduces risks because of increased maneuverability; this is demonstrated in many similar ballistic vehicles such as HOPE/HOSBO[v], SDB[vi], and Walleye (I & II)[vii]. These vehicles are designed to hit static installments and also moving vehicles.

There are large military and civilian ballistics databases with trajectory predictions and verification, aerodynamic control surface development and implementation, and mainly, of failures and corrective measures for those fail modes. Two such online ballistics databases are Designations Systems[i] and Global Security[iii].

Also, because lift/drag surfaces exhibit similar characteristics for guided ballistics and wings, NACA, NASA, and other aerodynamic research center databases would be applicable.

This vehicle platform will travel through the jet stream with a higher velocity for a shorter duration of time, so it will be pushed by the winds a lesser distance than other vehicle platforms.

BOTE (Back of the Envelope Calculations)

Airspace Time of Travel

Assuming the vehicle enters Class A airspace at its terminal velocity of 531.18 ft/s, and using a total airspace distance of 60,000ft-18,000ft, the time of travel is

t = distance/velocity = 42,000 ft/(531.18 ft/s) = 79.07 s

3.2 Parafoil

Requirement 0.PRJ.1, the project payload requirement, can be met because the parafoil payload would be configurable in a variety of ways to hold the necessary payload. A parafoil is desensitized to payload C.G. and could perform with a range of suspended weights, making the payload requirement easily met.

Requirement 0.PPJ.2 can be met since the parafoil could be controlled with a simple two-actuator system. Because commercial autopilot systems are not designed to control parachute systems, there will be difficulty modifying a commercial autopilot or building a custom autopilot from scratch.

The requirement 0.SYS10, regarding the vehicle’s range, can only be met by the parafoil if the vehicle was allowed to fly with the wind. Due to the low speed and low lift to drag ratio of the parachute, it would be highly susceptible to being pushed by the wind. If the parafoil were to open 12,500 feet above the ground (just below class A airspace in Boulder) with no wind, it could only fly a maximum of about six miles assuming a lift to drag ratio of 3:1. Any effort by the system to fly into the wind or cut across the wind would greatly reduce the already limited range of the parafoil.

3.3 Glider/Powered UAV

One of the major advantages of the glider design is historical records of similar successful vehicle designs. Through empirical data, the glider option has proven its ability to fulfill all of these requirements. Additional pros of the glider design option is technical experience among the team, proven potential for success, and long range potential through a high glide ratio. The major disadvantage of the glider design option is the vehicle weight. Large lift surfaces and a rigid structure increase the weight significantly. Another con of the glider design option is the little to no altitude recovery, which places a large dependency on the vehicle's glide ratio.

Weight is one of the most difficult requirements to satisfy. The flying wing design implemented for last year's vehicle had an empty weight of 15.4 lb. The low weight of the vehicle was accomplished through the use of modern weight-saving materials, such as composites. The weight can be further reduced through its design and fabrication. The design of the vehicle itself will be improved through reevaluated aerodynamics and consideration of different glider options beyond the flying wing design. This will improve the aircraft's efficiency and reduce the size. Analysis of the materials utilized in last year's vehicle might identify weight-reducing improvements to be applied to this vehicle.

Range depends on the glide ratio of the vehicle. Modern sailplanes have a glide ratio between 30 and 55, which would allow the aircraft to travel a maximum of 125 miles within the range of altitude from 18,000 ft to 6,000 ft. Last year's vehicle maintained a glide ratio of 9.8 to 12.2, which would allow it to travel a maximum of nearly 28 miles within the same altitude range. Aerodynamic analysis will shape the design more toward sailplanes and similar aircraft to the extent that the vehicle would still satisfy all the other top-level requirements. The empirical data from a sailplane and similar aircraft would help to improve the glide ratio.

Control can be established through control surfaces on the wings. This is the method implemented on most modern airplanes. It is a heavily used and proven reliable method throughout the world. Control and navigation devices for this control option are widely available as commercial off the shelf products. Last year's vehicle incorporated a COTS autopilot systems that autonomously navigated and operated the control surfaces to guide the vehicle to the target destination. This autopilot system is available for use at no additional cost.

4.0 Feasibility

The glider concept is a very feasible solution for this problem because it is the most tested and proven platform for autonomous unmanned aerial flight. The major point that makes this project feasible, more so than the other concepts, is that the commercially available autopilot navigation systems have been programmed/designed for an airplane-like platform. Furthermore, this was the design chosen by last year's team, therefore the range and performance of the vehicle should satisfy the requirements. Some basic kinematics calculations paired with simple aerodynamics and conservative estimations for coefficients of lift and drag were used to verify this assumption. The first concern is that the aircraft would have to fall a long way before picking up enough speed to get sufficient lift to pull out of the dive. Therefore the speed of the craft, using a C_D estimate for last year's design, 0.3[viii], was found for a freefall through the atmosphere. The speed at which the aircraft would have enough lift to support its own weight at the altitude of 100,000 ft is 184.5 mph. It would reach this speed in a free fall in 1,329 feet. These calculations were made using an extremely conservative lift to drag ratio of 5. The calculations were also done for a lift to drag ratio of 7 with little difference as illustrated below.

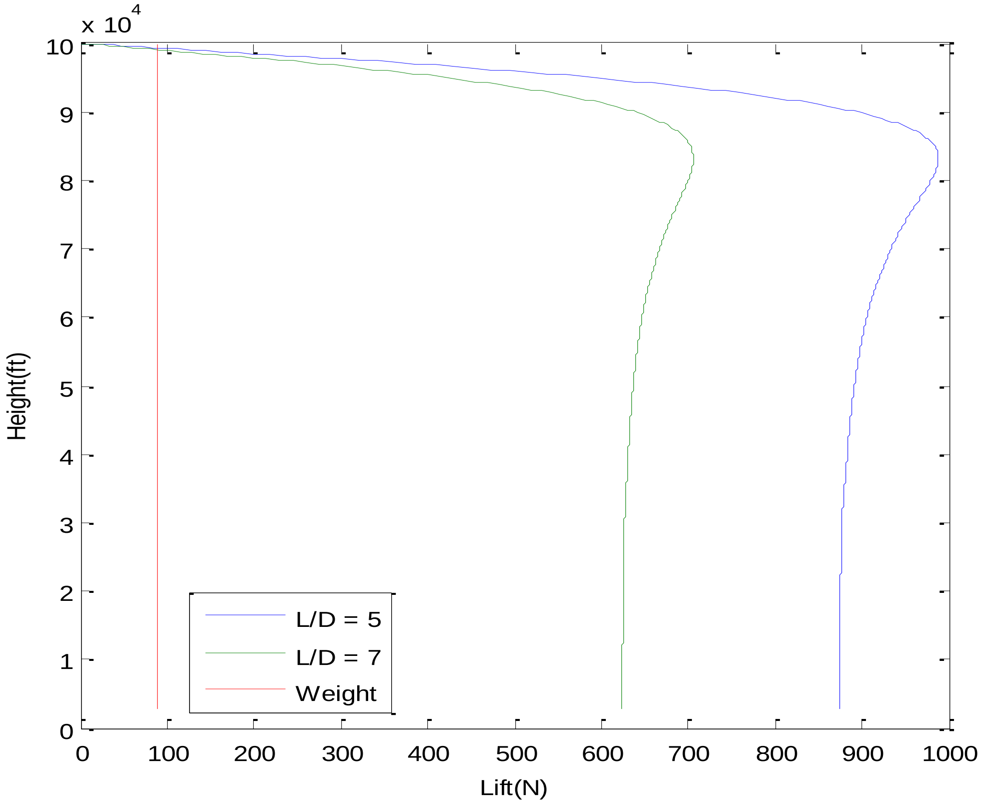


Figure 3: Pull-up Speed for Different L/D Ratios

The above plot was created using a simple model for the system using the following free body diagram and equation:

$$\sum F_y = F_D - F_g = \frac{1}{2}\rho \cdot v^2 \cdot C_D \cdot S - m \cdot g = m \cdot a$$

Assuming that the aircraft has performed the pull up maneuver and that it is flying horizontally at this height and speed, simplified aerodynamic equations were used in cooperation with a simulated proportional derivative (P.D.) controller to control pitch to determine the effective range of the glider neglecting wind. This range can be accurate if the glider is programmed to fly with a crosswind and can be increased if the glider flies with a tail wind. The following is an estimation of the range possible by a glider with a C_D of 0.3 and an L/D ratio of 5.

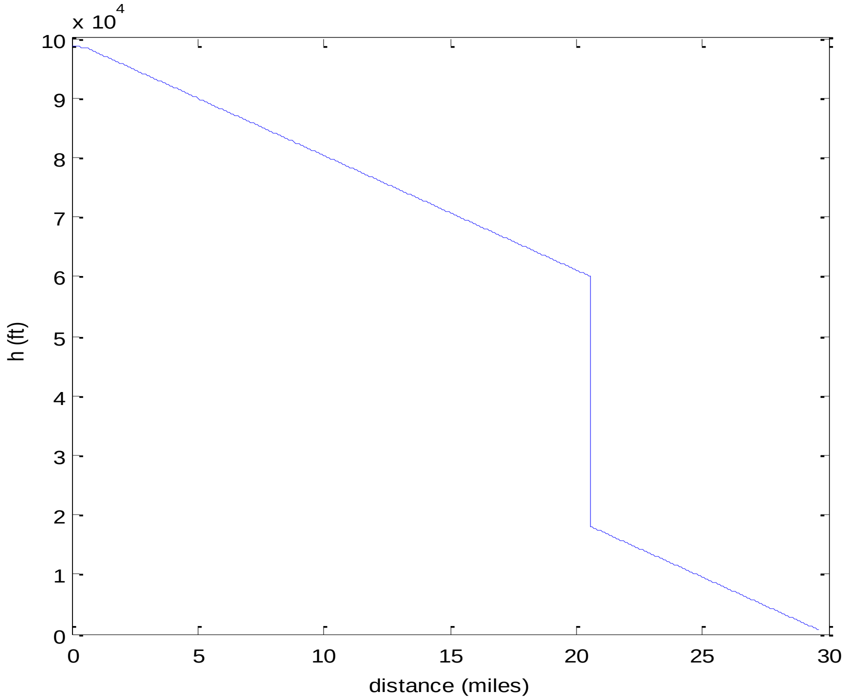
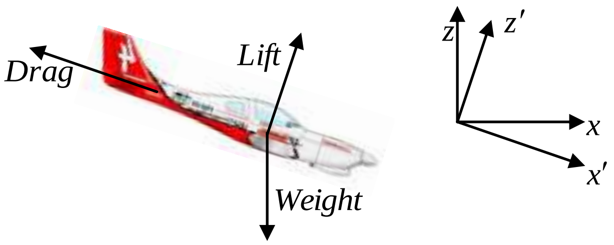


Figure 4: Range of a Glider with an L/D Ratio of 5

The equations and force balance used for the above simulation are as follows.



$$\sum F_{z'} = Lift - Weight \cdot \cos(\alpha) = \frac{1}{2}\rho \cdot v^2 \cdot C_L \cdot S - m \cdot g \cdot \cos(\alpha) = m \cdot a_{z'}$$

$$\sum F_{x'} = Weight \cdot \sin(\alpha) - Drag = m \cdot g \cdot \sin(\alpha) - \frac{1}{2}\rho \cdot v^2 \cdot C_D \cdot S = m \cdot a_{x'}$$

The P.D. controller was simulated by adding or subtracting 1^o to α when $a_{z'}$ is not equal to zero. This maintains the speed so that lift is always equal to the portion of the weight that acts along z'.

From this it is seen that the range of such a glider, assuming a landing altitude of 3500 ft, is 29.61 miles. The upper section of this flight is most productive, producing a range of 20.6 miles. Another advantage to the feasibility of this concept is that this is the concept in which our team has the most experience, both with design and fabrication.

5.0 Testing and Verification

For the project to be considered a success, its minimum requirements must be met, and in order to do so, tests shall be performed on those individual constraints. To verify project requirement 0.PRJ.1, the vehicle and the payloads shall be weighed together to confirm that the system does not exceed the weight limit. This can be done by weighing the payloads and the vehicle separately then combine their measurements or weigh all the components at once. Proving this requirement would probably be one of the simpler verification methods of the project.

To validate the vehicle's autonomous navigation, flight testing of autopilot program with scaled model and/or actual vehicle is necessary for requirement 0.PRJ.2. With the auto pilot mounted on the vehicle, it can be dropped from an aircraft fly-by or a hot air balloon ride, and if the vehicle can safely land then the requirement is met. Safe can be defined as no subsystem failures during landing. Even before the actual flight tests, simulations of flight conditions could be input into the autopilot to see its reactions; this would be a good prediction of the vehicle's actual performance before actual field tests.

Another important requirement for success is that the vehicle must land in a predetermined site as system requirement 1.SYS.10 stated. To test this condition, the vehicle's design will be thoroughly analyzed. This will be done through knowing all of its aerodynamic properties as well as aerodynamic forces to act on the vehicle while in the air. From that, a reasonably accurate prediction of where the vehicle will land can be calculated. Besides this, the vehicle and autopilot program would also need to be in actual field tests, just as mentioned for requirement 0.PRJ.2

6.0 Risks

6.1 Catastrophic Failure of Glider or Subsystems

A catastrophic failure of the glider would be any sudden and total failure of some system from which recovery of the vehicle is not possible. The loss of structure, such as a wing, and control surface failure due to: loss of structure, sticking, or servo malfunction would be considered an unrecoverable failure. In addition, loss of stability, were the gilder is unable to regain control, loss of the autopilot, or power failure would result in a catastrophic failure. In the event of these failures a parachute deployment system would be designed to trigger at a certain altitude above ground level. The parachute deployment system would be independent of all other systems to insure that the deployment system would not be affected by the failure and would deploy consistently. This parachute would slow the vehicle to a touchdown velocity of 20 ft/s to confine to 0.SYS.6 of the requirements to prevent destruction of payload. Based on terminal velocity calculations a round parachute with of $C_D = 1.5$ will be approximately 8.2 feet in diameter and would be sufficient to slow the glider to a touchdown velocity of 20 ft/s.

6.2 Loss of Navigation or Radio Communication

Navigation, provided by GPS, and radio communication are critical for the gilder autopilot to locate the specified landing target. Loss of navigation and radio communication is a definable error that is included in most commercial autopilots.

The autopilot, depending on altitude, would wait a certain amount of time until it reacquires the signal. During this time the autopilot could be programmed to trim the aircraft for straight flight with little altitude loss. If the autopilot does not regain the signal the parachute deployment system will trigger when the glider drops below a certain altitude.

6.3 Performance in a High Altitude Environment

The glider will travel to an altitude up to one hundred thousand feet where pressure and temperatures will reach extreme lows. System requirements 0.SYS.3 and 0.SYS.4 state that the glider and its subsystems must withstand temperatures down to -80°C and pressures down to 1.0 kPa. All electronic sensors, batteries, and other electronic components, such as the autopilot, may malfunction due to the low pressures and temperatures experienced at this altitude. Electrical systems will be critical to the functionality of the glider and need to be protected. A thermal protection system will have to be added to ensure proper function of these electronics. Lightweight insulation, a thermal heater, and heat generated for electronic components can all be utilized to insure the survival of the electronics. A basic thermodynamics analysis was performed to estimate the amount of heat required to keep a small electronics bay, insulated with low density polyethylene foam, above -40°C, see Figure 1. The analysis did not take into account heat generated by the electronics. Based on this analysis 0.217 Watts of heat would be necessary to keep the electronics above -40°C at 100,000ft. The risk electronic failure due to a high altitude environment can be further mitigated by testing the electronic systems and thermal protection system in vacuum testing facilities and low temperature freezers. This would be done to prove the reliability of these systems before flight.

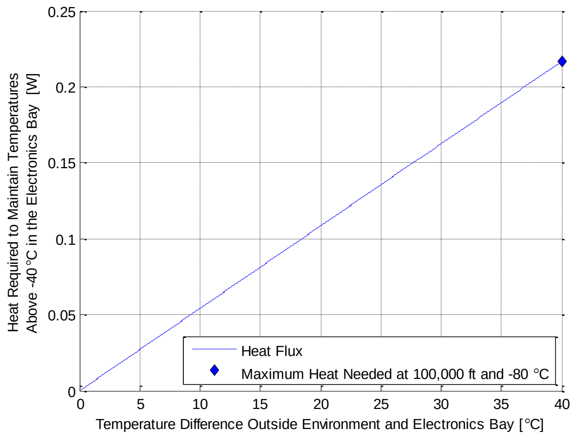


Figure 5: Heat Required to Maintain Electronics Above -40°C

Table 3: Risk Analysis

Risk	Description	Mitigation
0.RSK.1	Catastrophic Failure of Glider or Subsystems	Parachute Deployment System
0.RSK.2	Loss of Navigation or Radio Communication	Autopilot Programming/ Parachute Deployment System
0.RSK.3	Performance in a High Altitude Environment	Thermal Protection system/ Testing the Electronic Systems and Thermal Protection System in Vacuum Testing Facilities and Low Temperature Freezers

7.0 Team Qualifications

Table 4: Team Qualifications

Technical Area	Team Member Responsible	Level of Expertise
Aerodynamics	Mitchell	4
Structures	Chris	4
Control Systems	Aaron	4
Thermal Modeling	John	3
Electronics Design and Fabrication	Eric	5
Software	Matt	4
Propulsion (if applicable)	Eric	2
Fabrication	Mark	5
Testing and Verification	Chris	3

8.0 Response to PDD feedback from PAB

Table 5: Response to PDD Feedback

PAB Comment	Response
Changing a required format is not advised	Returned the Project and Top Level System Requirement tables to the correct format.
Lack of Clarity of Requirements and Testing Methods	Requirements and Testing Methods were revisited and rewritten to be clearer and better defined. Testing Methods were rewritten to the best of our ability. Until the design is more accurately defined, testing methods will be unknown to a certain degree.
Ambitious wording through the report	Each use of a ‘weasel word’ was visited and reworded to be more quantitatively defined.
Deliverables did not mesh with the requirements	Deliverables were rewritten to better match the requirements.
Facilities locations not defined	Possible locations for necessary facilities researched and included in revised edition.

9.0 Resources and References

9.1 Facilities

Table 6: Facilities

Facility	Comment
Sun Microsystems Thermal Testing Facility Bio Serve Facilities	Thermal Testing Facilities for project survival at extreme temperatures No point of contact yet, still looking into possibilities Thermal Facilities and possible Vacuum Testing facilities Point of Contact: Dr. David Klauss
Senior Design Room	Load Testing on any structural system that does not require large areas or any large destructive testing. Point of Contact: Matt Rhode
MileHi Sky Diving Inc.	Possible drop tests versus last year's hot air balloon test Point of Contact: Aaron Okken
University of Kansas Air Force	Wind Tunnel testing No point of contact yet Wind Tunnel testing No point of contact yet
Aero Machine Shop	For any machining needs Point of contact: Matt Rhode
Aero/Mechanical Composites Shop	For simple composite work Point of contact: Matt Rhode
EBS Carbon Inc.	For any Advice on Composite work and minor use of facilities Access to Vacuum pumps and autoclaves Point of Contact: Eric Strauss

9.2 References

See Appendix B

10.0 Acknowledgements

10.1 Customer contacts

Chris Koehler contributed to the development of our requirements and goals of the project.

10.2 Faculty members

The PAB members :Scott Palo, Robert Culp, Jean Koster, Donna Sue Gerren, Lakshmi H. Kantha, Dennis Akos, Mahmoud Hussein, Ryan Starkey, Matt Rhodes, and Trudy Schwartz for their inputs regarding the requirements and objectives of the project.

10.3 Others

Benjamin Reese provided the PDD of the previous year when it was not available from the senior design webpage.

A. Appendices

a. MATLAB

```
clc
clear all
close all
%%
%http://www.basd.net/technology/STEEP/Technology/3.6/Para%20Design%20is.htm

%% Sizing for a Parachute

W = 20;  %weight of glider [lbs]
rho = 1.927e-3; %7000ft [slugs/ft^3]
Cd = 1.5 %Coefficient of Drag - Parachutes have a drag coefficient (Cd) of approximately 1.50, parasheets have a Cd of approximately .75.
V =20 %0.SYS.6 [ft/s]
D = sqrt((8*W)/(pi*rho*V^2)) %Equation for Terminal velocity

%% Amount of the Heat Needed to Electronics -40C and above

T1 = [-40:0.1:40] %Temp in electronics bay [C]
T2 = [-80:0.15:40] %Temp in electronics bay [C]
dx = 0.25 % [in] foam thickness
A = (2*12 + 2*7 + 2*2)*0.00064516 %[m^2] area of an estimated electronics bay
k = .05; %thermal conductivity of low density Polyethylene Foam 0.43 btu/in/hr/sq.ft/oF
dT = T1-T2;

Q = k*A*(dT/dx);
hold on
plot(dT,Q)
xlabel('Temperature Difference Outside Environment and Electronics Bay [\circC]')
ylabel({'Heat Required to Maintain Temperatures','Above -40 \circC in the Electronics Bay  [W]'})
grid on
plot(40, 0.2168,'d','MarkerFaceColor','b','MarkerEdgeColor','k')

hold off
legend('Heat Flux','Maximum Heat Needed at 100,000 ft and -80 \circC','Location','SE')
```

dive_model.m

```
clc; clear all; close all;
C_D = 0.3;
L_D_MIN = 9.8;
L_D_MAX = 7;

g=-32.174; % ft/s
g_sci=-9.81; % m/s

C_L_MIN = L_D_MIN*C_D;
C_L_MAX = L_D_MAX*C_D;

weight = 20; %lbs
m=weight*0.45359237; %kg

AR = 4.51;
b = 84.39; %in
b=b*0.0254; %m
S=(b^2)/AR; % m^2

m_ft = 3.2808399;
```

```
dt = .5;
h_PLANE(1)=100000; % ft
v_PLANE(1)=0; % m/s
a_PLANE(1)=-g_sci; % m/s^2
t_PLANE(1)=0; % s
[T(1), a(1), P(1), rho(1)] = atmoscoesa(h_PLANE(1) / 3.2808399);
i=2;
for t=0+dt:dt:600
    [T(i), a(i), P(i), rho(i)] = atmoscoesa(h_PLANE(i-1) / 3.2808399);
    F_D = .5 * rho(i) * v_PLANE(i-1)^2 * C_D * S; % N
    F_g = g_sci*m; % N
    a_PLANE(i) = (F_D + F_g)/m; % m/s^2
    v_PLANE(i) = v_PLANE(i-1) + a_PLANE(i)*dt; % m/s
    h_PLANE(i) = h_PLANE(i-1) + v_PLANE(i)*m_ft*dt; % ft
    t_PLANE(i) = t;
    i=i+1;
end

figure
plot(t_PLANE,h_PLANE);
xlabel('Time(s)');
ylabel('Height(ft)');

figure
plot(t_PLANE,v_PLANE);
xlabel('Time(s)');
ylabel('Velocity(ft)');

Lift_MIN = (C_L_MIN *.5 * S) .* rho .* v_PLANE.^2; % N
Lift_MAX = (C_L_MAX *.5 * S) .* rho .* v_PLANE.^2; % N

weight_PLANE = -g_sci * m; % N
weight_array = ones(length(h_PLANE),1)*weight_PLANE;


figure
plot(Lift_MIN, h_PLANE, Lift_MAX, h_PLANE, weight_array, h_PLANE);
xlabel('Lift(N)');
ylabel('Height(ft)');
legend('L/D = 5','L/D = 7','Weight');

%% find time to pull up
for i=2:t_PLANE(end)
    if Lift_MIN(i-1) <= weight_PLANE && Lift_MIN(i) >= weight_PLANE
        t_pullup_MIN = t_PLANE(i) % s
        v_pullup_MIN = v_PLANE(i); % m/s
        v_pullup_MIN_mph = v_pullup_MIN * 2.23693629 % mph
        h_pullup_MIN = h_PLANE(i) % ft
        rho_pullup_MIN = rho(i); % kg/m^3
        P_pullup_MIN = P(i); % N/m^2
        speed_of_sound_pullup_MIN = sqrt(1.4 * P(i) / rho(i)) % m/s
    end
    if Lift_MAX(i-1) <= weight_PLANE && Lift_MAX(i) >= weight_PLANE
        t_pullup_MAX = t_PLANE(i) % s
        v_pullup_MAX = v_PLANE(i); % m/s
        v_pullup_MAX_mph = v_pullup_MAX * 2.23693629 % mph
        h_pullup_MAX = h_PLANE(i) % ft
        rho_pullup_MAX = rho(i); % kg/m^3
        P_pullup_MAX = P(i); % N/m^2
        speed_of_sound_pullup_MAX = sqrt(1.4 * P(i) / rho(i)) % m/s
    end
end

%% CRUISE CALCS
dt = 1;
t_cruise = 0:dt:847;
F_g = g_sci*m; % N
alpha_cruise(1) = 0; % rad
F_D_cruise(1) = .5 * rho_pullup_MIN * v_pullup_MIN^2 * C_D * S; % N
F_L_cruise(1) = .5 * rho_pullup_MIN * v_pullup_MIN^2 * C_L_MIN * S; % N
h_cruise(1) = h_pullup_MIN; % ft
rho_cruise(1) = rho_pullup_MIN;
```

```
P_cruise(1) = P_pullup_MIN;
v_cruise(1) = -v_pullup_MIN;
a_x_cruise(1) = 0;
a_y_cruise(1) = 0;
distance(1) = 0;
for i = 2:length(t_cruise)
    C_D_o = abs(1.28 * sin(alpha_cruise(i-1)));
    C_L_o = 2 * pi * alpha_cruise(i-1);
    F_D_cruise(i) = .5 * rho_cruise(i-1) * v_cruise(i-1)^2 * (C_D+C_D_o) * S;
    a_x_cruise(i) =  (F_g*sin(alpha_cruise(i-1)) - F_D_cruise(i))/m;
    v_cruise(i) = v_cruise(i-1) + a_x_cruise(i)*dt;
    [T(i), a(i), P_cruise(i), rho_cruise(i)] = atmoscoesa(h_cruise(i-1) / 3.2808399);
    F_L_cruise(i) = .5 * rho_cruise(i) * v_cruise(i)^2 * (C_L_MIN+C_L_o) * S;
    a_y_cruise(i) =  (F_L_cruise(i) + (F_g*cos(alpha_cruise(i-1))) )/m;
    h_cruise(i) = h_cruise(i-1) - v_cruise(i)*dt*m_ft*-sin(alpha_cruise(i-1));
    distance(i) = distance(i-1) + v_cruise(i)*dt*cos(alpha_cruise(i-1));
    if a_y_cruise(i) <= 0 && alpha_cruise(i-1) >= -(20*pi/180)
        alpha_cruise(i) = alpha_cruise(i-1)-(1*pi/180);
    elseif a_y_cruise(i) >= 0 && alpha_cruise(i-1) <= (20*pi/180)
        alpha_cruise(i) = alpha_cruise(i-1)+(1*pi/180);
    else
        alpha_cruise(i) = alpha_cruise(i-1);
    end
    %output = [a_y_cruise(i) F_L_cruise(i) (F_g*cos(alpha_cruise(i-1))) alpha_cruise(i-1)];
    %sprintf('a_y = %d\tF_L = %d\tF_g_j = %d\talpha = %d', output);
end
sprintf('d_stage1 = %d miles', distance*0.000621371192)
%%
dt2 = .5;
h_PLANE2(1)=18000;
v_PLANE2(1)=0;
a_PLANE2(1)=-g;
t_PLANE2(1)=0;
[T2(1), a2(1), P2(1), rho2(1)] = atmoscoesa(h_PLANE2(1) / 3.2808399);
i2=2;
for t2=0+dt2:dt2:100
    [T2(i2), a2(i2), P2(i2), rho2(i2)] = atmoscoesa(h_PLANE2(i2-1) / 3.2808399);
    F_D2 = .5 * rho2(i2) * v_PLANE2(i2-1)^2 * C_D * S;
    F_g2 = g_sci*m;
    a_PLANE2(i2) = (F_D2 + F_g2)/m;
    v_PLANE2(i2) = v_PLANE2(i2-1) + a_PLANE2(i2)*dt2;
    h_PLANE2(i2) = h_PLANE2(i2-1) + v_PLANE2(i2)*m_ft*dt2;
    t_PLANE2(i2) = t2;
    i2=i2+1;
end

figure
plot(t_PLANE2,h_PLANE2);
xlabel('Time(s)');
ylabel('Height(ft)');

Lift_MIN2 = (C_L_MIN *.5 * S) .* rho2 .* v_PLANE2.^2;
Lift_MAX2 = (C_L_MAX *.5 * S) .* rho2 .* v_PLANE2.^2;

figure
plot(Lift_MIN2, h_PLANE2, Lift_MAX2, h_PLANE2, ones(length(h_PLANE2)).*weight_PLANE, h_PLANE2);
xlabel('Lift(N)');
ylabel('Height(ft)');

% find time to pull up
for i=2:t_PLANE2(end)
    if Lift_MIN2(i-1) <= weight_PLANE && Lift_MIN2(i) >= weight_PLANE
        t_pullup_MIN2 = t_PLANE2(i)
        v_pullup_MIN2 = v_PLANE2(i);
        v_pullup_MIN_mph2 = v_pullup_MIN2 * 2.23693629
        h_pullup_MIN2 = h_PLANE2(i)
        rho_pullup_MIN2 = rho2(i);
        P_pullup_MIN2 = P2(i);
        speed_of_sound_pullup_MIN2 = sqrt(1.4 * P2(i) / rho2(i))
    end
    if Lift_MAX2(i-1) <= weight_PLANE && Lift_MAX2(i) >= weight_PLANE
        t_pullup_MAX2 = t_PLANE2(i)
```

```
        v_pullup_MAX2 = v_PLANE2(i);
        v_pullup_MAX_mph2 = v_pullup_MAX2 * 2.23693629
        h_pullup_MAX2 = h_PLANE2(i)
        rho_pullup_MAX2 = rho2(i);
        P_pullup_MAX2 = P2(i);
        speed_of_sound_pullup_MAX2 = sqrt(1.4 * P2(i) / rho2(i))
    end
end
%-------------------------------------------------------------------------
t_cruise2 = 0:dt:2500;
alpha_cruise(length(t_cruise)+1) = 0;
F_D_cruise(length(t_cruise)+1) = .5 * rho_pullup_MIN2 * v_pullup_MIN2^2 * C_D * S;
F_L_cruise(length(t_cruise)+1) = .5 * rho_pullup_MIN2 * v_pullup_MIN2^2 * C_L_MIN * S;
h_cruise(length(t_cruise)+1) = h_pullup_MIN2;
rho_cruise(length(t_cruise)+1) = rho_pullup_MIN2;
P_cruise(length(t_cruise)+1) = P_pullup_MIN2;
v_cruise(length(t_cruise)+1) = -v_pullup_MIN2;
a_x_cruise(length(t_cruise)+1) = 0;
a_y_cruise(length(t_cruise)+1) = 0;
distance(length(t_cruise)+1) = distance(length(t_cruise));
for i = length(t_cruise)+2:length(t_cruise2)
    C_D_o = abs(1.28 * sin(alpha_cruise(i-1)));
    C_L_o = 2 * pi * alpha_cruise(i-1);
    F_D_cruise(i) = .5 * rho_cruise(i-1) * v_cruise(i-1)^2 * (C_D+C_D_o) * S;
    a_x_cruise(i) =  (F_g*sin(alpha_cruise(i-1)) - F_D_cruise(i))/m;
    v_cruise(i) = v_cruise(i-1) + a_x_cruise(i)*dt;
    [T(i), a(i), P_cruise(i), rho_cruise(i)] = atmoscoesa(h_cruise(i-1) / 3.2808399);
    F_L_cruise(i) = .5 * rho_cruise(i) * v_cruise(i)^2 * (C_L_MIN+C_L_o) * S;
    a_y_cruise(i) =  (F_L_cruise(i) + (F_g*cos(alpha_cruise(i-1))) )/m;
    h_cruise(i) = h_cruise(i-1) - v_cruise(i)*dt*m_ft*-sin(alpha_cruise(i-1));
    distance(i) = distance(i-1) + v_cruise(i)*dt*cos(alpha_cruise(i-1));
    if a_y_cruise(i) <= 0 && alpha_cruise(i-1) >= -(20*pi/180)
        alpha_cruise(i) = alpha_cruise(i-1)-(1*pi/180);
    elseif a_y_cruise(i) >= 0 && alpha_cruise(i-1) <= (20*pi/180)
        alpha_cruise(i) = alpha_cruise(i-1)+(1*pi/180);
    else
        alpha_cruise(i) = alpha_cruise(i-1);
    end
    %output = [a_y_cruise(i) F_L_cruise(i) (F_g*cos(alpha_cruise(i-1))) alpha_cruise(i-1)];
    %sprintf('a_y = %d\tF_L = %d\tF_g_j = %d\talpha = %d', output);
end
sprintf('d_total = %d miles', distance(end)*0.000621371192)
%-------------------------------------------------------------------------
figure
plot(alpha_cruise,h_cruise);
xlabel('alpha(rad)');
ylabel('h (ft)');
figure
plot(t_cruise2,a_y_cruise);
xlabel('time');
ylabel('a_y');
figure
plot(t_cruise2,v_cruise);
xlabel('time');
ylabel('velocity');
figure
plot(t_cruise2,alpha_cruise);
ylabel('alpha(rad)');
xlabel('time (s)');
figure
plot(t_cruise2,F_D_cruise);
ylabel('F_D');
xlabel('time (s)');
figure
plot(t_cruise2,F_L_cruise);
ylabel('F_L');
xlabel('time (s)');
figure
plot(t_cruise2,a_x_cruise);
ylabel('a_x');
xlabel('time (s)');
figure
```

```
plot(t_cruise2,h_cruise);
ylabel('h (ft)');
xlabel('time (s)');
figure
plot(distance.*0.000621371192,h_cruise);
ylabel('h (ft)');
xlabel('distance (miles)');
```

b. References

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