4.
MEAM-245 Space Balloon Lab
“Balloomerang”

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Executive Summary:

We propose designing and fabricating a near-space balloon for use in future MEAM-245 labs. The balloon will have three unique capabilities. First, a software package will be created to facilitate prediction and analysis of the balloon flight. Second, the balloon will

have an active altitude control system, enabling it to stay at a desired altitude where the wind blows in the opposite direction and avoid ascending high enough that it would burst. Third, the payload will descend under a guided parachute, allowing the payload to return to the original launch site.

Many of the components of the balloon will be off the shelf, such as the communications, balloon, and parachute. We will focus on making our innovations since near-space ballooning is a relatively established field (See Background section for examples).

The software package will allow the user to examine the effects on the balloon flight of varying amounts of helium, different wind speeds and weather conditions, and different balloon shapes. CFD software will be used to acquire some of the data needed for the model, such as drag coefficients. The results from the software predictions will also be used to help program the controls for the height control and parachute.

The height control system will consist of a valve to release helium from the balloon and also a valve for ballast, most likely sand due to the low temperatures expected. The system will try to use as little material (helium/sand) in order to maintain a constant altitude within the band of reverse-direction wind.

The guided parachute will have at least two servos pulling cords connected to the parachute, allowing yaw and pitch control. There will be an onboard microcontroller, controlling the detachment of the payload from the balloon and the servos. It will be able to communicate with the onboard GPS, allowing it to steer towards the desired landing site.

We plan to have our first functional prototypes by the end of October, and to have the main subsystems tested by Christmas. We want to finish the mechanical portion as soon as possible in order to run as many tests as possible to optimize the control algorithms. To facilitate this, we have assigned each team member a subsystem. Alex is working on the software model, Joey is working on the CFD analysis, Julio is focusing on the height control, and Glauber is working on the parachute system.

There are risks involved in launching a balloon 20 miles into the atmosphere, but they can be minimized by preparedness and planning. The main concern is safety and adherence to FAA regulations. To address safety concerns, we will use proven communications gear and balloons, run our initial tests in rural areas, and test our new subsystems to the best of our abilities before running a full test. In addition, if our subsystems malfunction, the payload will still return to earth safely on an unguided parachute, like current near-space balloons. For FAA regulations, any balloon with less than a 4 lb. payload, which we plan to have, is not subject to the agency’s rules. However, we will still strive to maintain a good relationship with the agency and will follow the regulations set forth (see Appendix A).

Objectives and Requirements:

Balloon Prediction Software Package:
The purpose of our software packages is to accurately predict the path and ascent/descent rates of the balloon. A successful model will allow us to design our control systems more efficiently and to more accurately guide the balloons descent from near-space. The requirements for the software packages are enumerated in Table 1.

Table 1

Requirement	Metric: Preferable	Acceptable	Unacceptable
Must account for the following input parameters: weight, wind speed, temperature, pressure, amount of helium, balloon material properties etc.	All	All but 1	All but 2
Must follow regulations set forth by the Federal Aviation Administration set forth in Appendix A			
Must predict burst altitude within given metric	<500ft	500-1000ft	>1000ft
Must predict relationship between altitude and diameter within given error at any chosen point	1%	2%	3%
Must predict ascent rate within given metric	<3ft/s	3ft/s-5ft/s	>5ft/s
Should predict shape of the balloon as a function of height			
Should have intuitive user interface usable by second year MEAM students			
Should predict descent rate within given metric	<3ft/s	3ft/s-5ft/s	>5ft/s

Parachute:
The purpose of this subsystem is to direct the descent of the payload to a predesignated landing area. It should be light compared to the weight of the full system and also be capable of withstanding the minimum temperature in the 0-100,000ft standard atmosphere range without functionality loss. Operating temperatures must be in the 0-15,000ft standard atmosphere range.

Table 2

Requirement	Metric: Preferable	Acceptable	Unacceptable
Must have a weight of less than 2 lbs.	< 1 lb	< 2 lbs	> 2 lbs
Must survive temperatures as low as -70 ºF and operate at temperatures as low as 5 ºF			
Must reduce the rate of descent to 30 ft/s	< 20 ft/s	< 30 ft/s	> 30 ft/s
Must be deployed by the time the payload drops to 15,000 feet	Pre-deployed	Deployed at 15,000 ft	Deployed < 15,000 ft
Must produce servo torque of			
Must land within 100 yards of target	< 10 yards	< 100 yards	> 100 yards

Must exhibit control over direction, vertical speed and horizontal speed	All	All but 1	1 or 0
Should be capable of deciding whether target is achievable, and have backup targets			

Altitude Control:

An objective the Balloomerang is to be able to effectively harness the changing of direction of the jet stream at different altitudes to steer the near space balloon. The purpose of the altitude control system is to be able to reliably control which band of air current the balloon is in: both switching between currents and to keeping it within a desired current. By controlling which current band the balloon is in and knowing the speed and direction of the current in that band, we aim to be able to control the balloon's position parallel to the ground by controlling only its altitude. The altitude control system will achieve this goal by releasing helium from the balloon (to begin a drop in altitude) or releasing ballast (to begin an increase in altitude). Another important consideration is that precision of altitude is not important, as long as it is in the desired band. That is, the main objective is to be able to maintain the balloon in an altitude band of about 30,000 feet.

Table 3

	Metric		
Requirement	Preferable	Acceptable	Unacceptable
Must cause altitude change			
Must accurately maintain balloon in 30,000 ft band	< 10,000 ft	< 30,000 ft	> 30,000 ft
Must operate temperatures as low as -70 ºF			
Must weigh less than 1 lb, excluding ballast	< 0.6 lb	< 1 lb	> 1 lb
Must be able to accurately release He and ballast at 10 g/min.*			
Should have variable He, ballast release amounts rather than binary system (one fixed release amount)			

***Note:** This requirement will change after the behavior of the wind at altitude is better known. The rate of release must be enough to maintain altitude within an band not yet fully identified.

Background:

There have been several near-space balloon launches in recent years by students as well as other enthusiasts. The majority of designs have one or several payload pods strung beneath the balloon. The payload often consists of a camera and GPS locator, enabling tracking of the balloon. These balloons are entirely passive, floating upwards until the balloon pops, then descending on a parachute. Our design concept of having the balloon return to its launch point depends on an observation made by the Taylor University High Altitude Balloon workshop team and Professor Kothmann that wind direction reverses direction at approximately 60-70,000 feet. The ceiling of operation for the balloon is 100,000 feet.

Figure 1: Wind Direction vs. Altitude

Balloon trajectory predictions have been of great interest to scientists since the discovery of the jet stream in the early 1900s. Early understanding of the jet stream came from pioneering pilots and meteorologists, two professions whose interest would remain. High-altitude ballooning is important for understanding variations in temperature and pressure across the globe, wind and weather patterns, and other environmental considerations. This data can be used to simply understand meteorology, or for subsequent balloon launches that may facilitate a flight test of some technology. Long duration balloon launches will often utilize radiosonde devices, which transmit current atmospheric data to be input into the model for more accurate trajectories. Depending on the duration of the flight, data from anticipated locations will also be taken into account for increased accuracy.

The University of Wyoming has developed a balloon trajectory forecaster that takes location, flight time, global forecast system data, and maximum altitude and gives temperature, pressure, velocity, etc. data for the flight time. This existing model will serve as a baseline model from which we can check our more preliminary model. However, it will be unusable after the integration of the altitude control system into our model.

A flow is considered axisymmetric if the pressure and cylindrical velocity components are independent of the angle of interest in the body[1]. Computational fluid dynamic studies have been done to better understand axisymmetric flow over and through given bodies, such as capillary balloon stents, flow entry in a pipe, and fully developed flow in a pipe.

In 1997, the U.S. Air Force Science Advisory board identified a need to improve the accuracy of airdrops[2] as cargo parachutes currently being used by the military and humanitarian organizations to deliver payloads such as food, ammunition and equipment are essentially 'dumb.' Once a parachute is dropped from an aircraft, there is no way to control its flight path, which is highly dependent on meteorological conditions. Thus one method for improving the accuracy of airdrops involves adding control systems to unmanned parachutes in order to improve control over their flight paths.
Current efforts to address this issue include the Affordable Guided Airdrop Systems (AGAS)[3]. The AGAS is being evaluated as a low-cost alternative for meeting the military's requirements

for precision airdrop, providing a guidance, navigation, and control system that can be placed in line with cargo parachute systems. The AGAS has a target accuracy of 328 ft in a circular domain, while early tests suggest accuracy up to 210ft. The current design concept includes implementation of a commercial global positioning system (GPS) receiver and a magnetic compass as the navigation sensors, a guidance computer to determine and activate the desired control input, and the application of pneumatic muscle actuators (PMA) as physical controllers.
While the AGAS has achieved success in preliminary prototyping, its scale is three orders of magnitude higher than what we need for our project, with a payload up to 2200lb. Therefore we need to develop a much smaller concept that because of weight restrictions may prevent us from employing some of the technologies present in the AGAS such as nitrogen tanks to actuate the PMA.

Concept Selection:

We have adopted almost all of the basic concepts we came up with for the Balloomerang project: modeling the ascent and form of the balloon, controlling the height of the balloon, and developing a guided parachute return system. We considered developing our own communications system with the balloon, but abandoned the idea due to lack of expertise in the field and availability of a commercial product. There are, however, several concepts to choose from in some of the subsystems.

There are two main basic areas to consider in the parachute subsystem: the parachute itself and the actuator/steering system.

Table 4

Parachute type	*Advantages*	*Disadvantages*
Round	Simple, currently used for cargo applications, steerable if an air escape is added to the canope	Moderate oscillations, low forward speed (~5mph)
Cruciform	Low oscillations, low rate of descent	Availability, currently under research on the army
Ram-air	Creates lift, high forward speed (15-25mph)	Complex, more expensive

At this point the most feasible options are the ram-air and round types. The advantages of the ram-air make it easier to steer and thus probably easier to integrate with the remote/autonomous guidance system. Also, its higher forward speed allows for a better handling of cross winds, contributing to the final accuracy of the device. On the other hand, the round type is the current industry choice for cargo drops. Further investigation and decision will be made in the near future once the first prototype is built.

Table 5

Actuator type	*Advantages*	*Disadvantages*
Electric servo	Easy to implement; almost plug&play	Power-to-weight ratio; more powerful servos require considerable battery size

Solenoid/pneumatic actuator	Strong, fast output	Need of compressed gas; more complex implementation

The two main restrictions for the actuator are its weight, as it will be the heaviest steering component, and the operating temperature. As temperatures considered in this project are extremely low, features taken for granted on the use of servos must be re-evaluated as to ensure proper operation during the balloon descent. For example, it is known that most common batteries last much less at lower temperatures. Other concerns include the functionality of hinges/joints under thermal contraction.

In the altitude control subsystem, it was quickly determined that bleeding helium from the balloon was the most logical way to trigger a descent. The question was how to most effectively trigger an ascent. Two main options were considered: releasing compressed helium back into the balloon and dumping ballast. The first option was discarded because of the vast amounts of helium that would be required to make an impact on the balloon. A balloon about 2 meters in diameter at sea level contains about 4200 liters of helium. If one assumes that one could carry one liter of helium compressed at 200 times the atmospheric pressure, carrying compressed helium could at most add 3.8% to the volume of the balloon. On the other hand, carrying ballast would have a bigger impact. The total expected weight of the balloon will likely not exceed 10 lbs, or 4.53 kg. One might reasonably expect to carry one kilogram of ballast, meaning that the balloon system's total weight could be modified by over 20%. Dropping ballast is a more logical and effective way to raise the balloon's altitude.

The next question is what to use as ballast. While water would seem like an obvious choice for many reasons, the extremely low temperatures involved at such high altitudes eliminate it and nearly all liquids, absent some form of external heating. Even automobile anti-freeze fluid typically has a freezing point of about -30 degrees Fahrenheit; a point much higher than the anticipated -70 degrees Fahrenheit at high altitude. In order to minimize the total weight of the apparatus, a heating system is less desirable than dumping solid ballast. Sand or something like it is a good alternative, as it is easy to work with, can pour easily, and will have only a minimal environmental impact. Of course, an important consequence of this discussion about freezing liquids is that any sand used as ballast must be absolutely dry, or it might freeze, clump, and not dispense properly.

Design Concept:

Parachute:

Canopy diameter – Parachute design rule: 44 in^2 per ounce of payload. This yields an S=20 ft^2 drag area for a W=4lb weight, equivalent to a 5ft canopy diameter round parachute. For this configuration, the terminal velocity is

= 16 ft/s

Considering ρ = 0.002sl/ft^3 @ 5,000ft and C_D = 0.75, which is a reasonable first approximation for a round parachute. The resulting V is more conservative than the current speed for some human parachutes, that lie around 21ft/s.

Band width – A narrower band width will make the parachute less stable, although it will increase it's drag coefficient. A sweet spot is to be found to determine a good balance between stability and rate of descent. Another way to increase a round parachute stability is to cut holes/slits in the fabric of the canopy, to allow for an air exit. This alternative also has to be measured as it reduces the drag coefficient of the object.

Material properties/thickness – The canopy fabric material properties and dimensions will affect how resistant the parachute will be to the drag force. If it is too weak, the chute may tear apart during descent. However, an overestimate on thickness/amount of material needed may result in unnecessary storage volume when the parachute is packed.

Another aspect of the parachute design concept is the deployment device. This will be considered later on as its design depends on the layout of the actuators and ballast system.

Parachute actuators/steering system:

At this point, a 4lb output is being required from each actuator. This is an overestimate for the 4lb payload currently considered. Commercially available pneumatic actuators can easily meet this requirement while keeping reasonable weights (<0.5lb each), although a compressed gas tank is not included. On a pneumatic system, the size of the tank will ultimately determine how many instruction cycles can be sent to the steerable parachute during descent, i.e. how many times it can be told to steer left or right.

On the other hand, electric servos that meet the desired output have a considerable weight disadvantage for the same rating pneumatic actuator, without batteries included. Furthermore, pneumatic actuators respond much quicker (instantaneously for our purposes) if compared to an average servo.

Altitude Control:

The altitude control's design concept involves the releasing of Helium from the balloon, and ballast, most likely sand (or similar) from a reservoir.

At the base of the balloon (above the parachute and payload), would be placed a valve system controlled by a servo. A short hose would lead from inside balloon to this device. The system would consist of a short, round length of pipe fitted with a butterfly valve. The valve would be controlled by a rotating servo, mounted on the outside of the pipe. This servo would open and close the valve, allowing helium to escape. The servo would receive its commands via a wire that extends from the main payload around the parachute.

The ballast would be released in an analogous fashion to the helium bleeding system. Attached to the payload will be a vessel designed to contain sand. At the base of this vessel will be a hole, covered by a sliding plate. The plate will be controlled by a small servo that provided translational motion. By moving this plate off of the hole it covers, sand will be released, lowering the overall mass of the balloon and triggering an ascent.

Balloon Prediction Software:

We plan to make two predictive software packages. The first will provide an estimated flight path and height for the balloon based on several input parameters. The second will predict the shape of the balloon as a function of height and speed. The two programs are linked, because the output from the second will be used in the main program to determine drag, probable burst point, and ascent rate. Both programs will be coded in MATLAB, due to our familiarity with the language.

The shape-prediction program will use mainly tabular input and output. It will take in atmospheric data as a function of height (pressure, wind speed, temperature) as well as information about the balloon (elasticity, pressure, initial diameter, etc). With these parameters, the program will calculate how the balloon will deform, taking into account the properties of the balloon skin as they change due to temperature, pressure and deformation, the aerodynamic forces on the balloon, and the external conditions. The program will allow the user to set conditions such as the altitude, vertical velocity, and volume of helium of the balloon. The program will output the diameter of the balloon, or, if it has deformed into an ellipsoid, the major and minor diameters. We may use CFD software such as FLUENT to examine how the aerodynamic properties of the balloon change with shape.

The main prediction program will take many inputs and iterate between two user-specified heights using an ODE solver such as ODE45. We will find the equations by solving the equations of motion and finding all forces acting on the balloon. The two main forces are the buoyancy force from the helium in the balloon and the drag force from the wind and ascent rate. Both will depend on the shape of the balloon, since the volume of air displaced will increase as the balloon grows. The drag will also increase due to the increase in surface area, although the decrease in density of the air could offset some or all of the increase. Meteorological data will be obtained from ? (National weather service?). The program will have several variables available as a function of height: the drag coefficient, diameter of the balloon (ideally, this program would be able to call the shape-prediction program at each step in the iteration), and atmospheric data. The program would output a history of the three-dimensional position coordinates measured from the starting position as well as the velocity vector.

These programs will be used to provide a starting point for calibrating the other systems of the balloon, such as the height control and guided parachute. They will also be used by future MEAM 245 students in their lab. While there are several balloon prediction software packages on the Internet, they do not allow for the detailed input that our program will accept. In addition, most programs are written for the Midwest, and do not have the meteorological data for Pennsylvania. Two such programs are the University of Wyoming's Balloon Trajectory Forecasts (http://weather.uwyo.edu/polar/balloon_traj.html) and Near Space Ventures' On-Line Near Space Flight Track Prediction Utility (http://nearspaceventures.com/w3Baltrak/readyget.pl). The features of these programs are compared in Table 1.

Table 6

	University of Wyoming	Near Space Ventures	MEAM
Starting Location	Yes	Yes	Yes
Weather for starting location	Yes	Yes	Yes
Ascent Rate	No	Constant	Calculated (Varying)
Amount of helium in balloon	No	No	Yes
Change in shape of balloon	No	No	Yes

Project plan and Budget:

Table 7

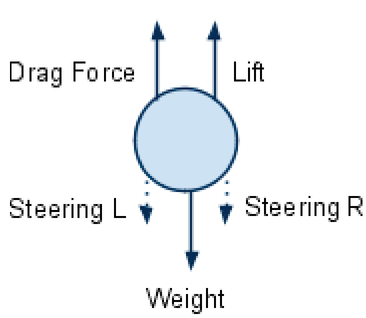
Part	*Estimated price (US$)*
Parachute	400
Large Weather Balloon (2)	400
Smaller Weather Balloons	200
Valves	100
Servos and electric components	100
Miscellaneous	100

Risks:

(1) Incomplete or failed deployment of the parachute could lead to loss of the payload, which is unacceptable. Special care will be taken to make a reliable deployment system or to have the parachute pre-deployed.
(2) Malfunction of the parachute servos could lead to loss of control of the parachute and possible loss of payload. If the servos fail to function as planned, they should be shut off and the payload allowed to land wherever the wind blows for recovery.
(3) If the air current direction in the jet stream is not predictable or consistent, the ability of the balloon/parachute combination to return to its launching point could be compromised. Early tests should be held in a rural area to minimize problems arising from wayward flights.
(4) Failure of altitude control mechanisms. This failure would not lead to payload loss, but would defeat the objective of controlling horizontal balloon movement through altitude control.

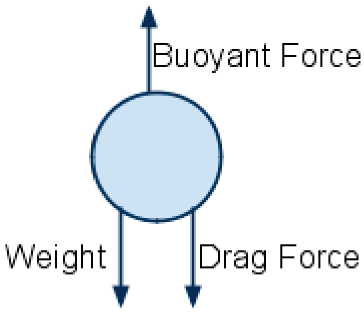
Validation and Analyses:

Free body diagram (FBD) of the parachute:



Assuming the steering force for a human-controlled ram-air chute is 10lbs for each side, for a 150lbs weight, and scaling it down linearly for a 4lbs cargo, the force required from the servos is approximately 0.27lbs.

FBD of balloon:



This diagram can be used to create a force balance on the balloon (note that the circle in the diagram represents the both the helium-filled balloon and the total mass of the payload). The force balance is shown below (the positive direction is defined as up in the diagram above):

Fnet = Fbuoynat - Mtot*g - Fdrag

Fnet = $\frac{4}{3}\pi r^3\rho_{air}g - M_{tot}g - \frac{1}{2}\rho_{air}v^2AC_D$

Where rho is the density of air, r is the radius of the balloon, g is the gravitational constant, Mtot is the total mass, v is the velocity of the balloon, A is the cross sectional area of the balloon, and Cd is the drag coefficient (a function of the Reynolds number of the fluid).

It is clear how the altitude system would affect this equation. Releasing ballast would diminish the total mass of the system, increasing the net force. Bleeding helium would diminish the radius of the balloon, diminishing the buoyant force and the net force. If the balloon is near equilibrium to begin with, a small change in the net force can change the direction of the balloon. One of the challenges of the modeling component of this project will be to determine the effect of the drag force on the movement of the balloon.

References:

[1]Neustupa, Jiří, Pokorný, Milan, 2001: Axisymmetric Flow of Navier-Stokes Fluid in the Whole Space with Non-Zero Agular Velocity Component, *Mathematica Bohemica*, 126, No.2, p 469-481

The University of Wyoming Balloon Trajectory Forecaster http://weather.uwyo.edu/polar/balloon_traj.html

Collander, Randall, M.I.R Girz, Cecilia, 2001: Evaluation of Balloon Trajectory Forecast Routines for GAINS, NOAA Research – Forecast Systems Laboratory

[2] “Summary Report: New World Vistas, Air and Space Power for the 21st Century,” USAF Science Advisory Board, 1997.

[3] Dellicker, S., Benney, R., and Brown, G., “Guidance and Control for Flat-Circular Parachutes,” *Journal of Aircraft*, Vol. 38, No. 5, 2001, pp. 809-817.

Appendices: