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Design of a Controllable Weather Balloon to fly on Mars

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Design of a Controllable Weather Balloon to fly on Mars

By

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Abstract:

As the National Aeronautics and Space Administration (NASA) moves closer towards placing humans on Mars, prediction of the weather on the planet becomes more vital to ensure the safety of the astronauts. Currently on Mars NASA has land based weather stations on the rovers and a few satellites orbiting the planet that help to predict the weather. They also use Earth based telescopes to look at the Martian atmosphere similar to what an orbiting satellite would [1]. These resources provide information about what the weather is like on the surface and what the weather looks like from space but there is little information from inside the atmosphere. Having a device that can fly through the atmosphere and collect data would enable scientists to generate more accurate models of the weather on Mars.

Another use for these devices could be to get aerial photographs of the planet, which could help to determine possible sites for future exploration. Also the Martian air could be collected and analyzed to determine its composition and whether there could be any airborne signs of life.

The research presented in this thesis is a first step towards designing a device to fly on Mars and take weather data. A lifting type is selected and through test flights on Earth the design is modified until a workable platform for flight testing is achieved. Once it is determined, the design is scaled to be able to fly in the Martian atmosphere.

1. Flying on Mars:

Flying on Mars is not an easy proposition. One of the big challenges is that the atmosphere is approximately one hundredth the density of Earth's atmosphere. This means that it is much harder to generate the lift required to fly on Mars as compared to Earth. Also the Martian atmospheric temperature changes by up to 100K over a day [2]. This causes the density of the atmosphere to also change greatly during the day which can make it even harder to fly.

The Martian terrain, seen in Figure 1, is also very mountainous. The highest point is 27km above the datum for the planet and the lowest point is 6km below the datum. This compared to the highest point on Earth being 8,848m above sea level and the lowest point being 10,994m below sea level [4,5]. However, a balloon cannot fly below sea level on Earth but on Mars, it can fly the whole range of the terrain on the planet. Thus the device will have to fly very high to avoid these obstacles or be able to fly around them.

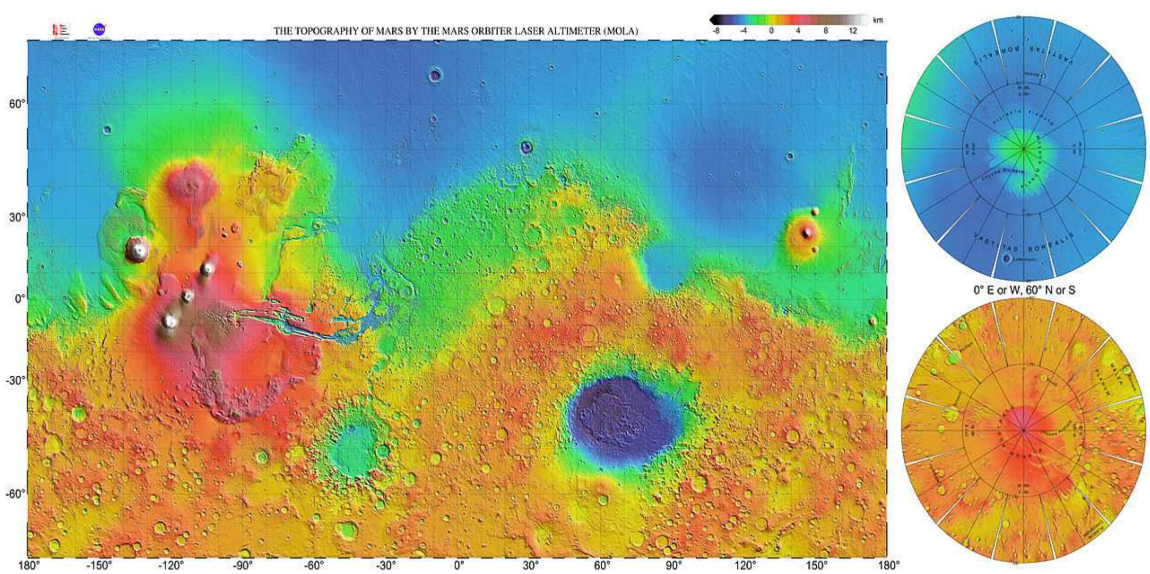

Figure 1: Terrain map of Mars [3]

The average wind speed on Mars is 5m/s and the highest recorded wind speed is 30m/s [6]. This is fast but due to the fact that the density of the atmosphere is much less than that of Earth, it does not create that much of a dynamic pressure. Relating the dynamic pressure on the Martian surface to that on the surface of Earth gives the equivalent airspeed on Earth, for reference and flight testing. The equivalent average airspeed on Earth is 1.125m/s and the maximum would be 3.375m/s at sea level.

One benefit to flying on Mars is that the acceleration due to gravity on Mars, 3.73m/s^2, is much less than Earths [7]. This means that less lift would have to be generated per unit mass to fly on Mars than on Earth.

2. Requirements:

In order to maximize the amount of scientific data gathered, it is desired to fly as long as possible. The chosen maximum height for the device to fly at is 5km above the datum for the planet. This was chosen because it would allow the flight vehicle to fly over most of the planet. This also means that the balloon must be able to steer itself to avoid hitting any mountains and other obstacles it cannot fly over. The flight vehicle must also be able to land in case there is an emergency or hazardous weather.

3. Design:

The initial design of the device was centered on eventually flying on Mars. However once an initial lifting type was decided upon, the designs were altered to allow for easier flight on Earth.

3.1. How to Achieve Lift:

Many designs were initially considered for how to fly on Mars. The more promising designs included a multirotor, an airplane, a hot air balloon and a lifting gas balloon. The multirotor was quickly determined to be impractical because in order to lift a 185 kg payload using 6 rotors they would each have to be 5.7 meters in diameter, which is too big to be practical. Also it would take a lot of energy to power the rotors to stay aloft. The airplane idea was also quickly determined to be impractical because the area of the wings would be too large and it would also require a great deal of power.

This left the balloon ideas. A hot air balloon would be good because there would not be any problems with the leakage of lifting gas and it could be landed whenever the controllers desired by turning off the burner. However, since the goal is to have the balloon be able to fly as long as possible, using a burner would not work because eventually the fuel to burn would run out and the balloon would not be able to float any more. More fuel could be added to extend the duration but this would add more weight for the balloon to lift, thus requiring more fuel to be burned to keep the balloon afloat.

Instead of a burner a resistance heater could be used to heat up the gas but because the volume of gas to lift the payload off the ground would be very large, a resistance heater would need to put out a lot of power in order to heat up all that gas. This would not work well because it would drain the onboard batteries quickly.

Thus the only design left would be using a lifting gas. A lifting gas balloon flies due to the difference in density of the lifting gas and the surrounding atmospheric gas [8]. There are many problems with this choice though. The first of which is what lifting gas should be used. The best lifting gas is hydrogen, because of its low density. However, it is very flammable, which is why it is not used for balloons on Earth. Thus for testing the design out on Earth, helium will be used. However, since there is only 0.13% oxygen in the Martian atmosphere, which is not enough to support combustion, hydrogen will be used to lift the balloon on Mars [2].

One problem with choosing hydrogen is that it can easily leak through most materials, including balloon latex. Further research should be conducted on how to solve this problem but for the current design, two extra tanks of hydrogen will be flown on the Mars balloon to increase the lifespan of the flight. Also, the balloon should be designed such that during its operational life, the material should not be stretched too thin. This is because as the balloon material gets stretched more, it gets thinner and more hydrogen can escape. This stretching can happen when the temperature rises during the day. As the atmosphere heats up, the lifting gas also heats up. This causes the hydrogen molecule's kinetic energy to increase which makes the balloon to expand. No extra lift is generated because the density relation between the inside and outside gasses stays the same as both densities drop. As the atmospheric temperature drops, later in the day, the hydrogen molecules also cool down. This reduces their kinetic energy and causes the balloon to shrink [9, 10]. Thus the balloon material should be able to withstand this daily stretching and shrinking cycle.

3.2. Controlling Direction

Having just a hydrogen filled balloon would not give the ability to control what direction it would float and there would be no way to land in case of an emergency. To solve the controlled direction problem, a fan can be placed on the instrument platform and it can vector its thrust side to side, similar to a swamp boat, and control its direction that way.

To solve the altitude control problem, many different designs were conceived and tested. The first was to re-compress the hydrogen down into extra tanks. This would reduce its buoyancy and cause it to sink. Then when it needed to go up, the hydrogen could be released and the balloon would rise. However, devices that are used to compress hydrogen, up to the pressures that they are typically stored at, are very big and heavy. Thus it would not be practical to have a compressor flying on the balloon. The hydrogen could be recompressed to a lower pressure but then more tanks would be needed to fly on the balloon.

Another design that was conceived was to use a ballonet. This is a smaller balloon inside the big balloon, that takes in atmospheric air. When it does this, the balloon sinks because of the added air weight and because as the ballonet takes up volume from the lifting gas, the lifting gas gets compressed thus increasing its density. This technique is used on blimps to control altitude on Earth. This technique was tested out on a balloon on Earth but it was not able to control the altitude of the balloon at all. The reason for this was that this technique works only on rigid air-vehicles where the outer skin does not expand as the ballonet is inflated. Thus it was decided to scrap this idea because a rigid air vehicle cannot be sent to Mars due to the volume constraints on a launch vehicle. A picture of the ballonet test flight can be seen in Figure 2. The ballonet is the small balloon inside the larger transparent balloon.

Figure 2: Ballonet test flight

The design that was ultimately determined to be the best for the altitude control would be making the balloon neutrally buoyant for a certain altitude and then using thrust vectoring for vertical control. This was chosen because the thrust would already be there, for the horizontal control, so it would not be much added weight to add in the ability to vector the thrust vertically. This thrust can be vectored down to get the balloon to rise which would allow the balloon to reach a higher altitude than with just the hydrogen alone. In case of an emergency the thrust can be vectored up, causing the balloon to go down and land quickly. This control type also allows the balloon to be smaller because it does not need to float at as high an altitude.

3.3. Balloons

Initially, for flight testing on Earth, one weather balloon that would be inflated to approximately two meters in diameter was chosen. A flight test of the weather balloon can be seen in Figure 3.

Figure 3: Weather balloon test flight

Choosing one large balloon was for simplicity of the design and to allow for a ballonet to fit inside of it. However this design presented many problems when flying on Earth. Since there was one large balloon with the motor on the bottom gondola, whenever the motor was turned on, the gondola would pitch up. If the throttle was increased too fast, the gondola would pitch up too much and would overshoot the desired angle. This is because the balloon was so large it did not want to move too quickly. The gondola would then have a damped oscillation until the balloon would start moving. This did not last long, around 5 seconds, but it did make the balloon much harder to control because the throttle could not be advanced too quickly.

Whenever the thrust was vectored to the side too fast, to try to turn the balloon, the balloon spun up slightly. Since the balloon latex was thin, because the balloon was so big, it acted like a rubber band. It would then spin down and throw the gondola around thus making the balloon uncontrollable until it settled down. Thus the thrust vectoring to the side also had to be done slowly to avoid a loss of control.

Another problem with one balloon was that the flight time was limited. The reason for this was because as the balloon latex was stretched thin, helium could escape through the latex relatively easily. Also, since the latex was so thin, the balloon was in constant danger of popping. Thus the balloon could not run into anything, even at slow speeds, and the thrust could not be increased to fast, or the thrust vectored to quickly, otherwise the balloon would pop.

A fourth problem with the balloon was that it was so large that it created a large amount of drag. This caused the balloon to float with the wind and would be very hard to control. The throttle could be increased to counter the wind but then the balloon would have problems with spinning up and the pendulum effect. Thus if there was any wind, the balloon would float away and would be very hard to control.

As a result of these problems it was decided to switch to using a larger number of smaller balloons in the hopes that the problems with the big balloon could be alleviated. Another reason to switch to more than one balloon is that on Mars having one balloon is risky because if it pops then the mission is over. So, more balloons would give a higher redundancy in case one fails.

Initially two balloons were chosen for simplicity. However this turned out to still come to a large balloon size and thus more were needed to reduce the size of each individual balloon. Ultimately, six balloons were chosen because with that number there was a seller of balloons that fit that size, .9m diameter, and they were much cheaper than the weather balloons bought before.

Once it was decided that many balloons were needed the next question became, how to hold the balloons? The balloons could not just be held by a string to the main platform, where all the electronics and engine are, because then the same problems that happened with the big balloon would happen again. The first idea that was tested was to use a hexagonal central holder, shown in Figure 4, that could hold the tied ends of the balloons together. This worked well, for small balloons, but the balloons moved around too much when the holder was rotated. Thus the balloons were taped together to reduce the movement and it worked well. However, when this idea was tried out on the full scale balloons, the tape pulled on the balloon latex and caused the balloons to pop. Since the hexagonal holder would not be enough to hold the big balloons in place a better solution was needed.

Figure 4: Hexagonal balloon holder

The best way to hold the balloons down is to attach something to the tied off end. Thus a small hexagonal plate with a hole in it, to stick the tied off end through, was made. Just this alone was not enough to hold the balloons but it gave an attachment point for struts that would go along the side of the balloon and keep the balloon from moving to far in any direction. Three of these were made for the small scale balloons to try the concept and the balloons did not move much. A close up view of one of the balloons on the small scale model is shown in Figure 5.

Figure 5: Small scale balloon holder

With the success of the small scale holder, full scale versions were made to try on the big balloons and they worked well at keeping the balloons from moving too much when the holder was rotated. These new large balloon holders were mounted on the sides of the main platform to reduce the vertical distance from the balloons to the thrust source, seen in Figure 6. Also, since the balloon latex was not stretched as thin, and the balloons were held more tightly, the balloons did not move very much. These modifications eliminated the pendulum and the spin up problems of earlier flights. An indoor flight of the full scale flight vehicle can be seen in Figure 7.

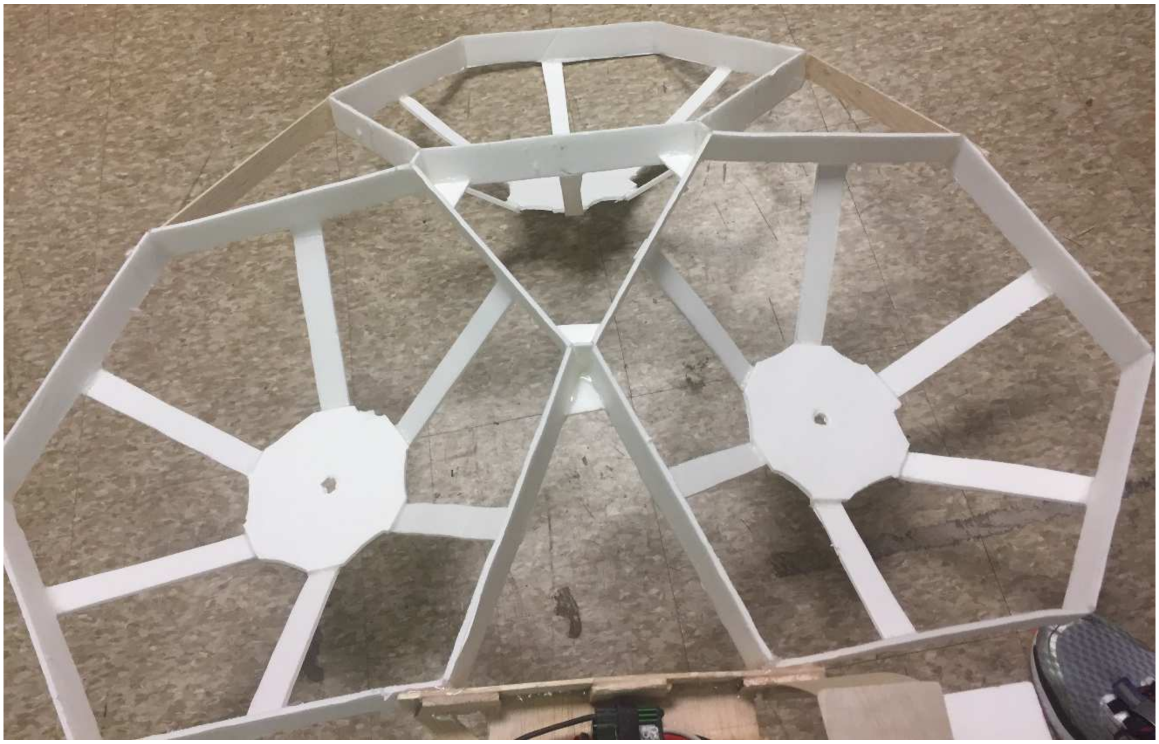

Figure 6: Big balloon holder on side of base

One downside to using many smaller balloons is that it was very hard to get all the balloons the exact same size, to provide the same lift. With the uneven lift distribution turning can be hard because the imbalance causes the base platform to bank slightly to one side, which makes it want to turn that way. This problem can be fixed by trimming the rudder to offset the turn. This also can be used to the controllers benefit because if a mass can be attached such that it can vary its position, the controller can move it to the inside of their turn, thus making it easier to turn.

Figure 7: Indoor test flight of the final vehicle design

3.4. Propulsion

The balloon size was not the only major change made over the different flights. The motor size was also changed. Initially a Cheetah A2208-17 motor was used with a 10x5 propeller, which gave a max thrust of 15.4 oz [11]. During the flights with this motor the throttle power was generally not raised about 30% because it provided a lot of thrust. When the change from one big balloon to six smaller balloons occurred, it was decided to also switch to a smaller motor to try to save weight and reduce the thrust, hopefully solving the control problems. So, a Cheetah A1504 motor with a GWS 4040 propeller was used, which gave a max thrust of 2.6 oz [12]. During the flight testing, this proved to be too feeble of thrust and a medium sized motor was purchased. This motor, a Cheetah A1510 with an 8x3.8 propeller giving a maximum thrust of 8.9 oz., gave the best performance of all the motors and became the final propulsion source for the indoors earth based test model [13].

3.5. Leakage

One problem that did persist from the single large balloon to the many smaller balloons was the leak of the lifting gas reducing the flight time. This time however, the gas was mostly escaping from the tied off end of all the balloons. Also, since the balloons were blown up with so much helium, it was very hard to tie off the balloon ends. Thus a better technique was needed. After doing some testing of different techniques for tying off the end of the balloon, it was determined that the best and easiest method for tying off the end of the balloons is to wind up the end, zip tie off the top and bottom of the wound up end, and then tape the middle area to keep it from unwinding. This technique is shown in Figure 8. However there was still decent leakage, which reduced flight time. To solve that problem, the balloons were over inflated and ballast weight was added to offset the extra lift generated. Over time, the ballast weight was removed to keep the balloon neutrally buoyant which made the flight time much longer.

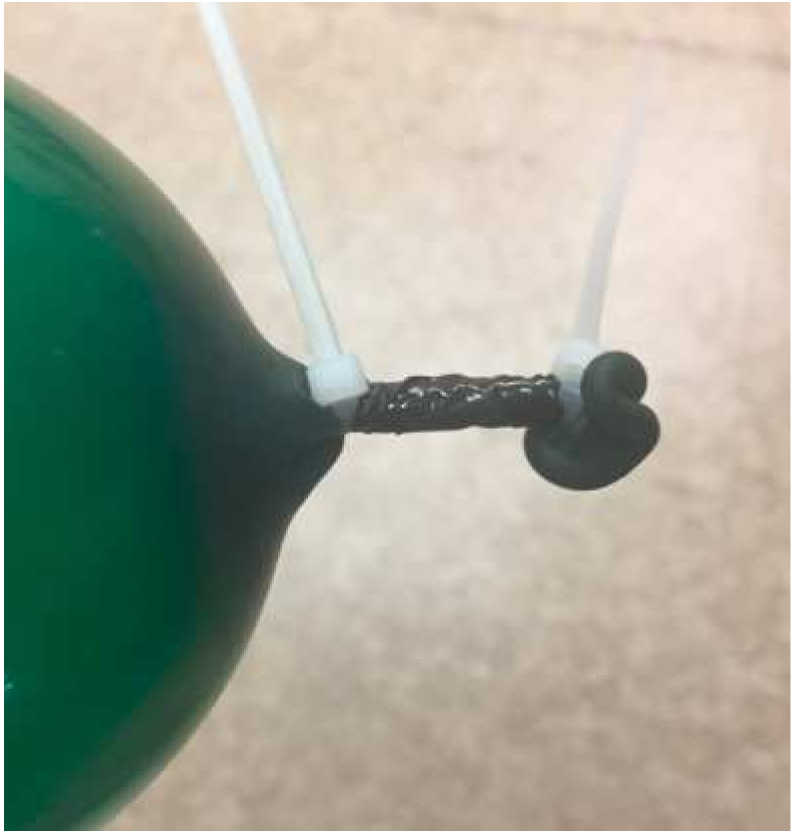

Figure 8: Balloon tying off technique

4. Scaling for Mars:

The first step to scaling the balloon rig to Mars was to find data on the Martian atmosphere. On the NASA Glenn research center website there were equations for the pressure (P), temperature (T) and density (ρ) for any altitude (h) in the Martian atmosphere [14]. Since the flight is staying below 7km, only that equation is shown and used.

for h < 7,000m

$$T = -31℃ - \left(0.00098 \frac{℃}{m}\right) * h$$

$$P = (0.699\ \text{kPa}) * \exp(\left(-0.00009 \frac{1}{\text{m}}\right) * h)$$

$$\rho = \frac{P}{\left(0.1921 \frac{kPa}{K}\right) * (T + 273.15)} \frac{\text{kg}}{\text{m}^3}$$

These equations are a curve fit of data obtained from the Mars Global Surveyor in April 1996 [14]. These equations were placed into a Matlab script, shown in Appendix A, and used to generate a data table of the temperature, pressure and density at different altitudes as well as plots of these, shown in Figure 9.

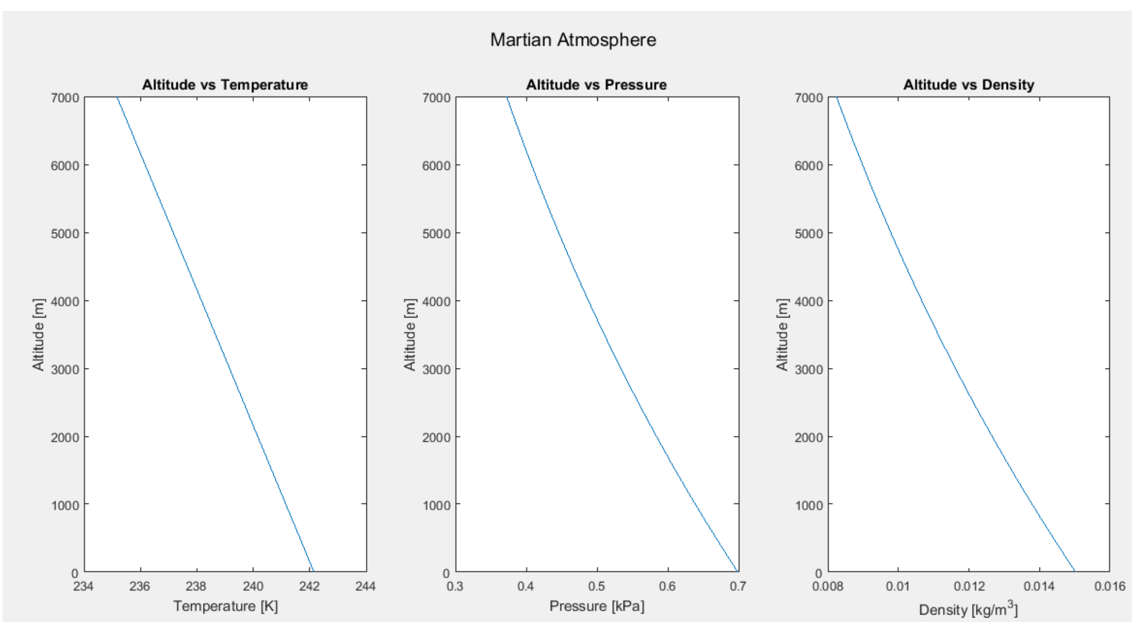

Figure 9: Graph of P, T, ρ at different Mars altitudes

4.1. Balloon Size

The next step to scaling the balloon rig was to find out the volume of hydrogen needed to make the balloon buoyant and what size of balloons that requires. Initially the amount of mass the balloon has to carry had to be defined. Data used for the tanks in the matlab program can be found in Appendix B. It was assumed that 2 tanks of extra hydrogen [15, 16], 68kg each, would be carried with the balloon, and the 185kg payload of electronics, batteries, sensors, and motors. The 185kg payload was determined from the mass of the Mars Exploration Rovers, assuming that the total mass would remain the same from that rover to this balloon [17].

After the mass to be carried was determined, the density of the hydrogen at all altitudes was determined by using the ideal gas law. The lifting capacity of the balloon hydrogen was obtained by taking the difference between the density of the hydrogen and the density of the atmospheric gas for each altitude. Dividing the mass flying on the balloon by the difference in densities gives the required volume of hydrogen to fly at each altitude. The volume at the buoyancy altitude is then selected, and given the volume of hydrogen each tank can hold, 2140 m^3, [15, 16] the number of tanks required to make the balloon buoyant at that altitude is determined. Using this volume and the number of balloons flying, the radius of each balloon can be determined assuming each balloon is a sphere. This code can be seen in Appendix C.

Setting the buoyancy altitude to 10m, enough to get over rocks and other small obstacles, the volume of hydrogen required to lift the 321kg payload is 22,425 m^3. This would require 13 tanks of hydrogen and would make each balloon 9.63m in radius for 6 balloons.

4.2. Propeller Blade Size

The final step in scaling the balloon rig for Mars is to determine the size of the fan blades required to fly at a 5km altitude. The first step to doing this was to write the equations of motion for the vertical and horizontal directions. These equations could then be used to solve for the diameter of the propellers, what angle to deflect the thrust for all the altitudes and the maximum forward velocity achievable at these altitudes. The assumptions that went into creating these equations are that there is no wind, that the balloon volume does not change with altitude and that the coefficient of drag would be similar to that of a diamond due to the shape of the balloons viewed from above.

The forces in the vertical direction are:

$$\sum F_{vertical} = N\, T_{one} \sin(\theta) + L_{balloons} - W = 0 \qquad (1)$$

$$T_{one} = N * \sqrt[3]{\frac{\pi}{2} D_{prop}^2\, \rho_{atm}\, P_{one}^2} \qquad (2)$$

$$L_{balloons} = g_{mars}\, V_{balloon}\, (\rho_{atm} - \rho_{H2}) \qquad (3)$$

$$P_{one} = VIe \qquad (4)$$

Where N is the number of engines, T_{one} is the thrust from one engine, θ is the angle that the thrust is vectored down, $L_{balloons}$ is the lift from the balloons, W is the weight of the device, D_{prop} is the diameter of the propeller, ρ_{atm} is the density of the atmosphere, P_{one} is the power generated from one engine, g_{mars} is the acceleration due to gravity on Mars, $V_{balloon}$ is the volume of the balloons, ρ_{H2} is the density of the hydrogen, V is the voltage of one motor, I is the current of one motor and e is the efficiency of one motor.

The forces in the horizontal direction are:

$$\sum F_{horizontal} = N\, T_{one} \cos(\theta) - F_D = 0 \tag{5}$$

$$T_{one} = \frac{\pi}{2} D_{prop}^2\, \rho_{atm} \left(\frac{P_{one}}{T_{one}}\right)^2 - \frac{\pi}{2} D_{prop}^2\, V_{Forward} \left(\frac{P_{one}}{T_{one}}\right) \quad [18] \tag{6}$$

$$F_D = \frac{1}{2} \rho_{atm}\, V_{Forward}^2\, C_D\, A_D \tag{7}$$

Where F_D is the drag force, $V_{Forward}$ is the velocity in the forward direction, C_D is the coefficient of drag and A_D is the drag area.

Using equations 1 through 4, the diameter of a propeller can be solved for.

$$D_{prop} = \sqrt[2]{\left(\frac{2}{\pi\, \rho_{atm}\, P_{tot}^2}\right) * \left[\left(\frac{g_{mars}}{\sin(\theta) N}\right) * \left(m_{balloon} - V_{balloon} * (\rho_{atm} - \rho_{h2})\right)\right]^3} \tag{8}$$

This equation needs the maximum downward deflection angle for the thrust, assumed to be 45 degrees. The motor that was chosen, data in Appendix B, gave the largest power for one engine, 4617.6W. These numbers as well as the payload mass, balloon volume and the densities for the max altitude can be plugged into this equation to find the diameter of the propeller required to fly at 5km. The resulting diameter, for N=6 motors, is 1.83m.

Now that the diameter of the blades was determined, the same equation can be re-configured to solve for the deflection angle required to fly at a specific altitude.

$$\theta = \sin^{-1}\left(\frac{g_{mars}}{N \sqrt[3]{\frac{\pi}{2} D_{prop}^2\, \rho_{atm}\, P_{tot}^2}} * \left[m_{balloon} - V_{balloon} (\rho_{atm} - \rho_{h2})\right]\right) \tag{9}$$

Using these angles, the maximum forward velocity at all of the altitudes, assuming no wind, can be found using equations 5, 6 and 7. A graph of the obtained velocities is shown in Figure 10.

$$\left(\frac{\rho\, C_D A_D}{2\, N \cos(\theta)}\right) V_1^6 + \left(\frac{4\, A_{prop}\, P_{tot}\, N \cos(\theta)}{C_D\, A_D}\right) V_1^3 - \left(\frac{8\, A_{prop}\, P_{tot}\, N^2 \cos^2(\theta)}{\rho\, C_D^2\, A_D^2}\right) = 0$$

The velocity at the float level, 10m, is 7.53 m/s, at the maximum altitude, the velocity is 7.33 m/s, and the largest velocity, 7.81 m/s, occurs at an altitude of 2490m. The matlab code used to generate these numbers can be found in Appendix D.

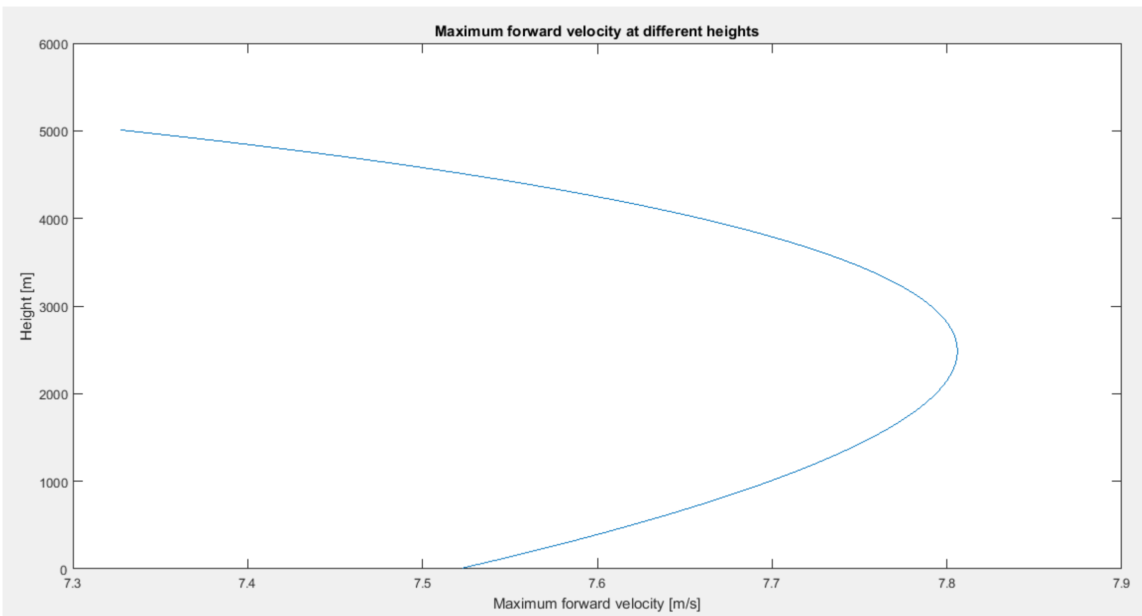

Figure 10: Graph of Maximum velocity at different altitudes on Mars

5. Future work:

There are many areas that can be expanded upon from the current work. One area would be to work on making the Earth based test model use an inertial measurement (IMU) system for navigation instead of GPS. The current design uses GPS for navigation however there is no such navigation system on Mars. Thus until one would be set up, an IMU would have to be used to control the flight direction on Mars.

The Mars simulations also could use refining. They do not take into account the change of temperature on the Martian atmosphere. Also, a more accurate drag coefficient for the Mars balloon design could also be obtained.

A final place for future work is to make the helium, used for the Earth flight testing, more reusable. Currently after each test flight all the remaining helium is vented to the atmosphere. This is a large waste in that for each flight, approximately $200 worth of helium is needed to generate enough lift for flight. If this helium could be reused, it would save a lot of money.

6. References

[1] Howell, Elizabeth. "Mars Colony Weather Forecast: Dusty." Seeker, 12 Oct. 2016. Web. <http://www.seeker.com/mars-weather-forecast-colony-astronauts-weather-extreme-events-dust-st-2042454438.html>.

[2] "Mars' Atmosphere: Composition, Climate & Weather." *Space.com*. Ed. Tim Sharp. N.p., 3 Aug. 2012. Web. 04 Apr. 2017. <http://www.space.com/16903-mars-atmosphere-climate-weather.html>.

[3] "Geography of Mars." *Wikipedia*. Wikimedia Foundation, 19 May 2014. Web. <https://en.wikipedia.org/wiki/Geography_of_Mars#/media/File:Mars_topography_(MOLA_dataset)_with_poles_HiRes.jpg>.

[4] Cessna, Abby. "Tallest Mountains." *Universe Today*. N.p., 24 Dec. 2015. Web. <http://www.universetoday.com/46969/tallest-mountains/>.

[5] "Deepest Part of the Ocean." *Geology.com*. N.p., n.d. Web. <http://geology.com/records/deepest-part-of-the-ocean.shtml>.

[6] Boumis, Robert. "The Average Wind Speed on Mars." *Sciencing*. N.p., n.d. Web. <http://sciencing.com/average-wind-speed-mars-3805.html>.

[7] Rossi, JahShiRah. "Acceleration Due to Gravity on Mars." *Hypertextbook*. The Physics Factbook, 2004. Web. <http://hypertextbook.com/facts/2004/JahshirahRossi.shtml>.

[8] Brain, Marshall. "How Helium Balloons Work." *HowStuffWorks Science*. HowStuffWorks, 01 Apr. 2000. Web. <http://science.howstuffworks.com/helium2.htm>.

[9] Leiden, Kathi. "Why Do Helium Balloons Deflate Faster in Cold Air?" Ask Zephyr, 7 Jan. 2016. Web. <http://askzephyr.com/why-do-helium-balloons-deflate-faster-in-cold-air/>.

[10] Delgado, Justin S. "Flying High: How Ambient Temperature Affects the Bouyancy of Helium Filled Latex Balloons." (2015): n. pag. California State Science Fair. Web. <http://cssf.usc.edu//History/2015/Projects/35429.pdf>.

[11] “Cheetah A2208-17 Brushless Outrunner Motor." BP Hobbies, n.d. Web. <https://www.bphobbies.com/view.asp?id=V450327&pid=B1898551>.

[12] "Cheetah A1504 Brushless Outrunner Motor." BP Hobbies, n.d. Web. <http://www.bphobbies.com/view.asp?id=J0655750&pid=i0740230>.

[13] "Cheetah A1510 Brushless Outrunner Motor." BP Hobbies, n.d. Web. <https://www.bphobbies.com/View.asp?id=V450327&pid=I0740231>.

[14] "Mars Atmosphere Model Metric Units." Ed. Nancy Hall. NASA, 05 May 2015. Web. <https://www.grc.nasa.gov/www/k-12/airplane/atmosmrm.html>.

[15] "Cylinder & Valve Data." Tech Air, n.d. Web. <http://www.techair.com/Literature+MSDS/cylinder+valve_data.html>.

[16] "SPECIALTY GAS CYLINDER SPECIFICATIONS." (n.d.): n. pag. Linde. Web. <http://www.lindecanada.com/internet.lg.lg.can/en/images/specialty-gas-cylinder-sizes-canada135_102689.pdf?v=.>.

[17] "Spacecraft." *Mars Exploration Rovers*. NASA, n.d. Web. <https://mars.nasa.gov/mer/mission/spacecraft_surface_rover.html>.

[18] "Froudes' Momentum Theory: (Actuator Disk Theory)." (n.d.): n. pag. Iowa State University. Web. <http://www.public.iastate.edu/~aero442/unit2.pdf>.

[19] "Drag Coefficient." *The Engineering ToolBox*. N.p., n.d. Web. <http://www.engineeringtoolbox.com/drag-coefficient-d_627.html>.

[20] "Power 360 Brushless Outrunner Motor, 180Kv." *E-flite*. N.p., n.d. Web. <http://www.e-fliterc.com/Products/Default.aspx?ProdID=EFLM4360A>.

[21] Nozawa, Tetsuo. "[JSAP] Tokai University Unveils 100W DC Motor with 96% Efficiency." *Nikkei Technology Online*. N.p., 3 Apr. 2009. Web. <http://techon.nikkeibp.co.jp/english/NEWS_EN/20090403/168295/>.

7. **Appendix A:** Matlab Code For Mars Atmosphere

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%Ben Ivie
%Masters thesis research
%4/6/2017

clc;
clear all;
close all;

%These create matricies to store the data
h=zeros(701,1); %height [m]
P=zeros(701,1); %Pressure [kPa]
T=zeros(701,1); %Temperature [K]
d=zeros(701,1); %Density [kg/m^3]
n=1;

%This steps through the altitude, in increments of 10m, up to 7km
for count=0:10:7000
    h(n,1)=count;
    %These are the equations found on the NASA Glenn website
    T(n,1)=(-31-0.000998*count)+273.15;
    P(n,1)=0.699*exp(-0.00009*count);
    d(n,1)=P(n,1)/(.1921*T(n,1));
    n=n+1;
end

%These create plots of the Altitude vs temperature, pressure and
density
subplot(1,3,1);
plot(T,h);
title('Altitude vs Temperature');
ylabel('Altitude [m]');
xlabel('Temperature [K]');

subplot(1,3,2);
plot(P,h);
title('Altitude vs Pressure');
ylabel('Altitude [m]');
xlabel('Pressure [kPa]');

subplot(1,3,3);
plot(d,h);
title('Altitude vs Density');
ylabel('Altitude [m]');
xlabel('Density [kg/m^3]');
suptitle('Martian Atmosphere');
```

8. **Appendix B:** Data Obtained and used for matlab codes

The following numbers were used in the matlab codes but were not discussed in the body of the thesis.

The tank that was selected was: HC 500 tank [15, 16]
Tank storable volume: 2140 m^3
Tank mass: 68kg

The drag coefficient assumed for the balloon would be: $C_D = .8$ [19]

The engine that was selected was: Power 360 Brushless Outrunner Motor [20]
Engine voltage: 44.4 V
Engine current: 130 Amps
Efficiency of a DC motor: .8

9. **Appendix C:** Matlab Code For Balloon Volume

```
%Ben Ivie
%Masters thesis research
%4/6/2017

%%%%%%%Run Mars_Atmosphere first%%%%%%%%
clc;
float_alt=10; %set the float altitude you want the balloon to fly
to here [m] do only for every 10 meters
num1=(float_alt/10)+1;
tankn=2; %number of tanks flying with the balloon
tankm=68; %mass of 1 tank [kg]
mp=185; %mass of the payload assumed from the Mars Exploration
rovers [kg]
mballoon=mp+tankn*tankm %Total mass flying on the balloon [kg]

%This creates matricies to store the data below
dh2=zeros(701,1);
diff=zeros(701,1);
rad=zeros(701,1);
V=zeros(701,1);
n=1;
R=4124; %This is the gas constant for different gasses
    %Hydrogen:4124 Helium:2077 Nitrogen:296.8 Oxygen: 259.8

%This steps through the altitude, in increments of 10m, up to 7km
for count1=0:10:7000 %This last number is the max height for
which the equations work
    dh2(n,1)=(P(n,1)*1000)/(R*T(n,1)); %density of the lifting
gas
    diff(n,1)=d(n,1)-dh2(n,1); %This is the lifting capacity for
different altitudes
    V(n,1)=mballoon/diff(n,1); %Balloon volume [m^3] required to
fly at different altitudes
    n=n+1;
end
Vmax=V(num1,1) %[m^3] Volume required to fly at the float level
tv=43; %tank gas volume on earth [L]
ans1=(T(num1,1)/P(num1,1))*(41368.54/288.15)*tv*.001; %This gives
the volume of hydrogen
        %that would be in a HC500 tank at Mars temp and pressure
at the
        %float level
tanks=ceil(Vmax/ans1)+tankn %number of tanks to get the desired
balloon volume
N=6; %number of balloons
R_1balloon=((3/(4*pi()))*(Vmax/N))^(1/3) %Radius of 1 ballon [m]
```

10. Appendix D: Matlab Code For Propeller Blade Size

```
%Ben Ivie
%Masters thesis research
%4/6/2017

clc;
clear all;
close all;

%This first part generates the temperature, pressure and density
in the
%Mars atmosphere
h=zeros(701,1); %height [m]
P=zeros(701,1); %Pressure [kPa]
T=zeros(701,1); %Temperature [K]
d=zeros(701,1); %Density [kg/m^3]
m=1;

for count01=0:10:7000
    h(m,1)=count01;
    T(m,1)=(-31-0.000998*count01)+273.15;
    P(m,1)=0.699*exp(-0.00009*count01);
    d(m,1)=P(m,1)/(.1921*T(m,1));
    m=m+1;
end

Vmax= 2.2425e+04; %Volume of the balloon [m^3] taken from
Balloon_Tank_Volume
theta_max=pi()/4; %Maximum angle the elevator can be deflected
down [radians]
N=6; %Number of fans

%This is to get the balloon mass
maxalt=5000; %set the max altitude in m you want the balloon to
fly to here [m] do only for every 10 meters
num1=(maxalt/10)+1;

%This calculates the mass in kg flying on the balloon
tankn=2; %number of tanks flying with the balloon
tankm=68; %mass of 1 tank [kg]
mp=185; %mass of the payload assumed from the Mars Exploration
rovers [kg]
mballoon=mp+tankn*tankm %Total mass flying on the balloon [kg]

%This is to get the engine power
V=44.4; %Voltage for one engine [volts]
I=130; %Current for one engine [amps]
e=.80; %efficency of one engine
Power=V*I*e; %Power from one engine [Watts]

R=4124; %These are the gas constants for different gasses
    %Hydrogen:4124 Helium:2077 Nitrogen:296.8 Oxygen: 259.8
```

```
alt=10; %set the float altitude you want the balloon to fly to
here [m] do only for every 10 meters
num2=(alt/10)+1;
dh2=(P(num2,1)*1000)/(R*T(num2,1)); %density of the lifting gas
at float level

gmars=3.73; %Acceleration due to gravity on Mars
weight=gmars*mballoon; %Weight of the craft

dens_max=d(num1,1);
diff1=dens_max-dh2; %lifting capcity at the float level

%Diameter in meters to get to maximum altitude with maximum
deflection
diam=sqrt((2/(pi()*dens_max*(Power^2)))*((gmars/(sin(theta_max)*N
))*(mballoon-Vmax*diff1))^3)

Cd=.8; %Drag coefficient for the rig (assuming it looks like an
angled cube
R_1balloon=9.6271; %radius of 1 ballon [m] Found from
Balloon_Tank_Volume
Ad=(R_1balloon*2)*(4*2*R_1balloon)+(2*diam)*(3*diam); %Drag area
[m^2]
    %assuming 4 ballons showing to the wind and the center drag
is
    %the size of 2 fan blades wide and 3 tall

%This generates matricies to store the data in
thetad=zeros(num1,1); %Theta in degrees
thetar=zeros(num1,1); %Theta in radians
V1=zeros(num1,1); %Maximum forward velocity [m/s]
hf=zeros(num1,1); %Flying height [m]
n=1;

%This steps through the altitude, in increments of 10m, to the
maximum
%flying altitude
for count1=0:10:maxalt
    %This first part calculates the deflection angle of the
elevator to fly
    %at a certain altitude
    dens=d(n,1);
    cons=gmars/(N*((pi()/2)*(diam^2)*dens*(Power^2))^(1/3));
    diff=dens-dh2;
    thetad(n,1)=asind(cons*(mballoon-Vmax*(diff)));
    thetar(n,1)=asin(cons*(mballoon-Vmax*(diff)));
    %%%%%

    %This second part solves for the maximum forward velocity at
each
    %altitude, assuming no wind
    cons1=(dens*Cd*Ad)/(2*N*cos(thetar(n,1)));

cons2=(8*(pi()/4)*(diam^2)*(Power^2)*(N^2)*(cos(thetar(n,1)))^2)/
(dens*(Cd^2)*(Ad^2));
```

```
    cons3=(4*(pi()/4)*(diam^2)*Power*N*cos(thetar(n,1)))/(Cd*Ad);
    p=[cons1 0 0 cons3 0 0 cons2];
    ans1=roots(p);
    ans2=real(ans1);
    ans3=max(ans2);
    V1(n,1)=ans3; %Maximum forward velocity [m/s]

    hf(n,1)=n*10;
    n=n+1;
end

%This generates a plot of the maximum forward velocity at
different
%altitudes
plot(V1,hf);
xlabel('Maximum forward velocity [m/s]');
ylabel('Height [m]');
title('Maximum forward velocity at different heights');

%This prints out forward velocity at certain altitudes to the
command
%window
ans1=max(V1);
[J,I]=find(V1==ans1);
Vmax=V1(J,I) %maximum forward velocity [m/s]
h_Vmax=hf(J,I) %altitude for maximum forward velocity [m]
V_float=V1(2,1) %forward velocity at float altitde [m/s]
V_5000m=V1(n-1,1) %forward velocity at maximum altitude [m/s]
```

Benjamin Richard Ivie was born in Rochester, New York on September 12th, 1994 to Susan Richmond and Richard Ivie. He graduated from Wheatland Chili High School in 2012 as salutatorian. He then went on to Lehigh University where he graduated, in 2016, with a Bachelor's of Science Degree in Mechanical Engineering with highest honors. He stayed at Lehigh to pursue a Master's of Science degree in Mechanical Engineering.