Design & Study of a High Altitude Balloon with Heat-able Control Technology

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Abstract

This paper introduces the physical research approach, Modelling and design to build and control to increase the altitude apogee of a high altitude balloon using the same amount of lifting gas with several editions in the basic conditions of the balloon's platform, allowing the balloon to be used in launching scientific experiments need to be conducted at higher altitudes at a low cost, also introducing various ascent techniques and manoeuvres to increase the precession of the ascent flight phase and avoid all the turbulences and external conditions to ensure a successful mission to the near space.

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1. Nomenclature

Table 1: Nomenclature

M_{total}	Balloon total mass, kg	h	Balloon height, meter
$M_{payload}$	Payload mass, kg	F_B	*buoyancy* force, Newton
$M_{structure}$	Structure mass, kg	F_D	Drag force, Newton
V_B	Balloon volume, m^3	g	Gravity acceleration, m/s^2
ΔV_B	Change in balloon volume, m^3	h^{oo}	Second derivative of h according to time, m/s^2
ρ_{air}	Air density, kg/m^3	p_{air}	Air pressure, N/m^2
m_{He}	Helium mass, kg	p_{He}	Helium pressure, N/m^2
ρ_{He}	Helium density, kg/m^3	T_{He}	Helium temperature, k
R_{He}	Gas constant for helium, J/(kg.k)	V	Electric voltage, volt
R_{air}	Gas constant for air, J/(kg.k)	θ_{t-1}	Vector of system parameters
C_D	Coefficient of drag	X_{t-1}	Vector of system states
Area	Maximum balloon cross-section area, m^2	n	Data size, positive integer
τ	Time delay, second	a	Transfer function parameter
k	Transfer function parameter	b	Transfer function parameter
s	Laplace transform operator	T_m	Predicted temperature, k
z	Z-transform operator	dt	Sample time, second
K_p	PID controller proportional gain	k_d	PID controller derivative gain
K_i	PID controller integral gain		

2. Introduction

Delivering a scientific project or an experiment to the outer layers of the atmosphere or nearby space has always been a complex phase and a major difficulty in any project or research, especially for university's labs and students, no matter how easy/hard the project needed to fly to space is, the complexity of launching to space is difficult enough to push many innovative ideas and promising projects to die or stay as theories on the shelves.

High altitude balloons are released into near space, which is the area in the atmosphere of very little air usually between 18 and 37 km, these balloons are filled with helium or hydrogen and expand as they ascend through Earth's atmosphere with an increase in volume of the balloon, usually helium is used It's about an eighth of the density of air although Hydrogen is about a sixteenth the density of air. Helium is preferred to hydrogen as hydrogen is flammable and explosive, although hydrogen is half as heavy as helium it doesn't give you twice as much lift because the amount of lift you get is in its difference in density with respect to air. It's actually only another sixteenth of the density of air.

The capabilities of high altitude balloons are so connected to the lifting gas, it's properties and behaviour, editions and improvements from that point of view - lifting gas performance - can lead to further usage of those simple devices in more complicated applications, already in the super pressure balloons the volume of the balloon is kept relatively constant in the face of changes in the temperature of the contained lifting gas, however the idea discussed in this paper is fully focused on getting the best output from the lifting gas in order to reach higher altitudes in addition to using the lifting gas itself to control the manoeuvres and ascent/decent of the balloon. Allowing us to decrease the costs and increase the benefits from using the balloon.

As the balloon goes up through the atmosphere, the amount of air pressure reduces, as the pressure falls, the balloon expands, eventually its volume increases simply and it bursts, but this process is not that linear.

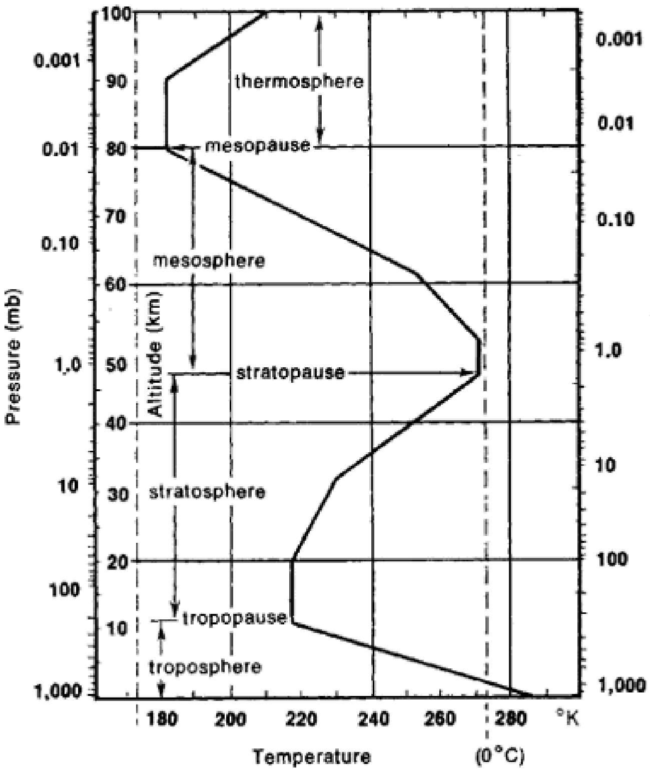

Figure 1: Variation of atmospheric temperature and pressure with altitude

As the pressure falls, the temperature falls too. So, in the troposphere (the lower atmosphere, which contains all our weather), it gets colder as you go up. However, there is ozone in the stratosphere, which is the next layer up. Ozone absorbs the Sun’s ultraviolet rays and re-emits them as heat, warming the stratosphere up. So it actually gets warmer again. Those variations are one of the challenges facing the idea to acquire a stable and precise Balloon to reach the desired altitude. in addition to tangential winds and strong turbulence using a balloon however is sounds easy to be more could ends in a catastrophically fail, however in the upcoming illustration we hope to introduce multiple ideas and implementations making it more reliable and easier to control in the same time of saving efforts, money and reaching higher altitudes.

Balloons and Airships do have an increase in lift when their gas is warmer than the ambient temperature. This condition is known as "superheat" in LTA (lighter-than-air) terminology. Modern blimps get an extra boost in lift when they operate on a cold but sunny day; the sun warms the gas inside the envelope a few degrees higher than the temperature of the ambient air, creating extra lift. The idea to control the temperature of the lifting gas though controlling the altitude of the balloon is a concept which was discussed many years ago even if not directly, The great rigid airships of 1900-1938 often conducted take-off and landing operations in the early morning or late evening to take advantage of differences between gas temperature and ambient temperature. Using this feature could allow us to use the balloons to reach higher altitudes with more precision and maintaining simplicity and low cost in the same time.

3. Mathematical Model

Starting from the simple physics and equations of motion illustrating the balloon's behaviour and the lifting gas properties, with using Archimedes principals and motion laws we went further to detecting the variables controlling the behaviour of the balloon to reach the key to use to control the ascent and altitude the balloon can reach, we had developed the following approach;

Equation (1) describes the balloon motion in one direction h that represents the altitude.

$$\mathrm{M_{total}} * \mathrm{h^{oo}} = \mathrm{F_B} - \mathrm{F_D} - \mathrm{M_{total}} * \mathrm{g} \tag{1}$$

Where:

$$\mathrm{F_B} = \mathrm{V_B} * \rho_{\mathrm{air}} * \mathrm{g} = \frac{\mathrm{m_{He}}}{\rho_{\mathrm{He}}} * \rho_{\mathrm{air}} * \mathrm{g} \tag{2}$$

$$M_{total} = M_{structure} + M_{payload} + m_{He} \tag{3}$$

The balloon volume V_B starts from an initial value which is the first volume taken by the balloon in the atmosphere. However, it cannot exceed a certain maximum value considering the balloon material and the chemical properties of helium therefore after that certain maximum value, heating the helium is going to stress the balloon wall and will not benefit our cause, leading to a waste in energy, moreover it will act negatively on the balloon's performance.

$$\rho_{He} = \frac{p_{He}}{R_{He} * T_{\ He}}$$

so,

$$V_B = \frac{m_{He} * R_{He} * T_{He}}{p_{He}} \leq max(V_B) \tag{4}$$

As the Helium inside the balloon extends until the balloon reaches the maximum volume without any stresses from exceeding the balloon initial size. So that, equation (7) represents the buoyancy force F_B:

As,

$$p_{He} = p_{air} \tag{4}$$

Then,

$$V_B = \frac{m_{He} * R_{He} * T_{He}}{p_{air}} \tag{5}$$

$$\mathrm{F_B} = \left(\frac{\mathrm{m_{He}} * \mathrm{R_{He}} * \mathrm{T_{He}}}{\mathrm{p_{air}}}\right) * \rho_{\mathrm{air}} * \mathrm{g} \tag{7}$$

To study the Balloon dynamics, the heating mechanism that controls the helium temperature $\mathrm{T_{He}}$ and aerodynamics forces must be modelled. The aerodynamic forces are represented in a drag force directed in the opposite direction of the balloon motion.

$$F_D = \frac{1}{2}\rho_{air}(h^o)^2 * C_D * Area \tag{6}$$

From equations (1) , (7) and (8), the following equation (9) that includes all parameters affecting the balloon ascent is written below.

$$M_{total} * h^{oo} = \left(\frac{m_{He} * R_{He} * T_{He}}{p_{air}}\right) * \rho_{air} * g \ - \frac{1}{2}\rho_{air}(h^o)^2 * C_D * Area - M_{total} * g \tag{9}$$

The only controllable input to this equation is the helium temperature $\mathrm{T_{He}}$, which is adjusted to control the balloon altitude. In figures, (2) and (3) a simulation model is built for equation (9) considering the helium temperature is kept 335 k all the time to test the maximum altitude the balloon can reach on condition the balloon volume reached its maximum value on this altitude. In the control section, the time delay of $\mathrm{T_{He}}$ is considered. All air properties: temperature, pressure and density are function in the height.

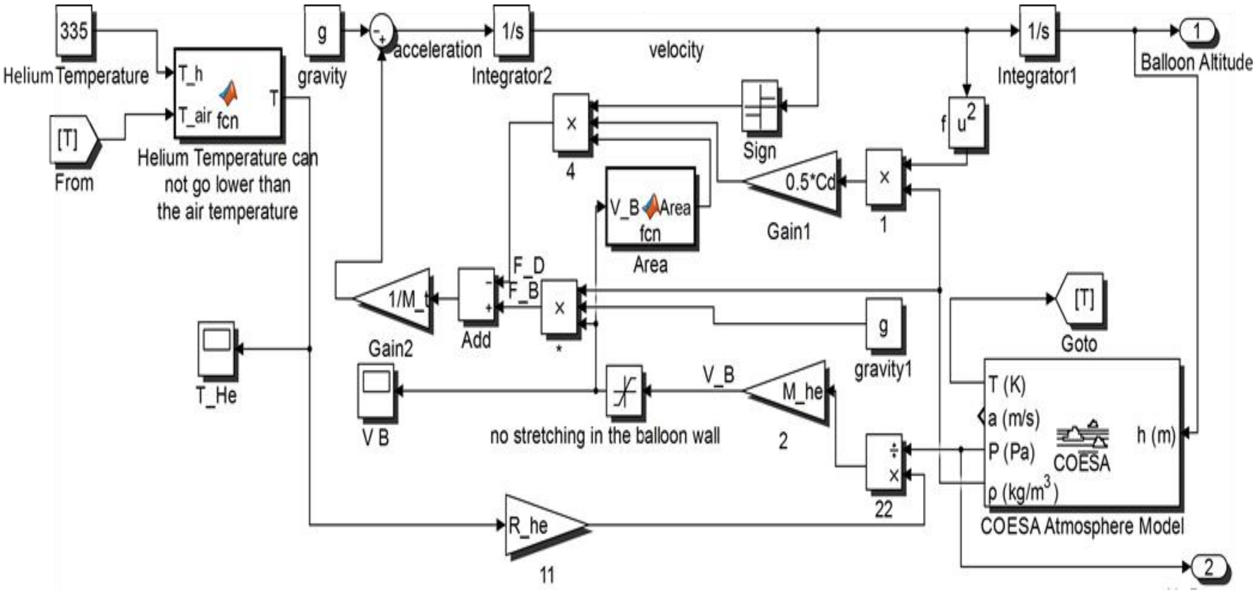

Figure 2: Simulation model for equation (9) built on a computer software (Simulink)

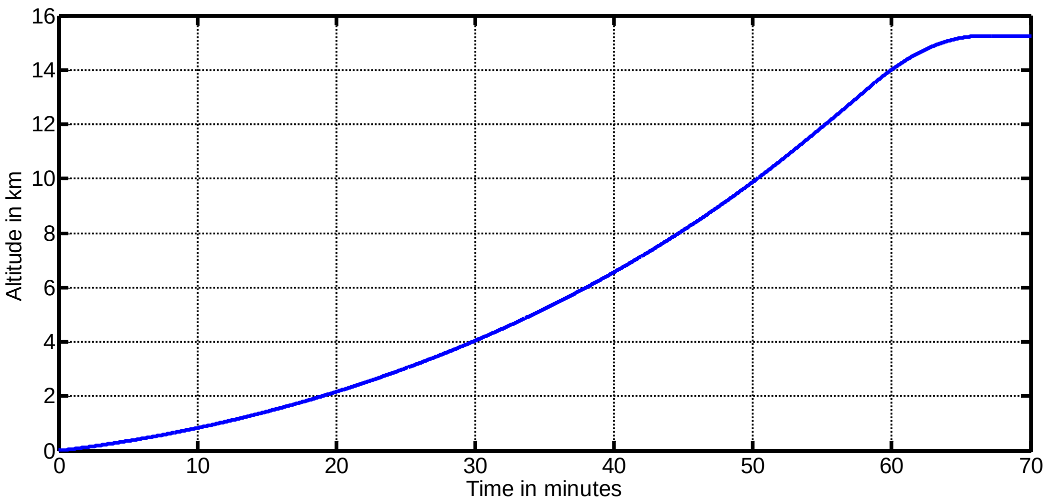

Figure 3: The balloon altitude considering the helium temperature is kept 335 k all the time in equation (9).

To avoid the turbulence in the atmosphere and reach certain altitudes at certain times, the balloon volume has to be controlled. The used actuator in that is a heater to change the helium temperature. The next three sections explain the heating system design and the altitude control algorithm.

4. Heating System

Using a heating mechanism that depends on induction heating of a metallic coil by electromagnetic induction, heat will be generated in the metal through eddy currents though the heat generated is inside the metal itself then transferred to the helium following the basics of heat transfer through convection and radiation.

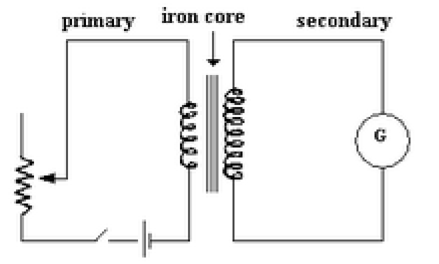

Figure 4: Electromagnetic Induction Circuit

Induction coils are recommended as Induction heating relies on the unique characteristics of radio frequency (RF) energy - that portion of the electromagnetic spectrum below infrared and microwave energy. Since heat is transferred to the product via electromagnetic waves, the part never comes into direct contact with any flame or the balloon's boundaries, the inductor itself does not get hot and there is no product contamination. When properly set up, the process becomes very repeatable and controllable which is an essential part in our design as it depends on heating the coil during different phases of flight to serve manoeuvring and control strategies.

Heat transfer through convection and radiation, an electric coil heats up warming the helium gas, though raising its temperature, Therefore as shown previously, increasing the helium's temperature results in increasing the lifting force for the balloon.

5. Heating System Modelling and Control Design

To heat the helium inside the balloon, the heater in section (4) is fixed in the lower part of the balloon and a temperature sensor in the upper part of the balloon to measure and control the balloon temperature. This thermal system includes parameters of heat transfer depend on the helium thermal conduction and convection characteristics. An experiment is performed to estimate the system parameters.

The thermal systems are modelled as a first-order transfer function between the temperature and power source in our case V for voltage represents the power source. Thus, the following transfer function in equation (10) can describe this model.

$$\frac{T_{He}}{V} = \frac{k}{\tau s + 1} \tag{10}$$

To estimate these parameters using the real time collected data, the transfer function is transformed to a discrete form by Z transform as below in equation (11).

$$\frac{T_{He}}{V} = \frac{k\left(1 - e^{-\frac{dt}{\tau}}\right) z^{-1}}{1 - (e^{-\frac{dt}{\tau}})\, z^{-1}} = \frac{a\, z^{-1}}{1 - b\, z^{-1}} \tag{11}$$

Where:

$$a = k(1 - e^{-\frac{dt}{\tau}}) \quad \& \quad b = e^{-\frac{dt}{\tau}} \tag{12}$$

To estimate these two parameters a and b, the sum of square differences between the real measured values of the helium temperature T_{He} by the temperature sensor and the predicted output T_m is minimized to get the best fit to the real model. First, the open loop model equation (11) can be rewritten as following in equation (13).

$$T_m(t) = X^T{}_{t-1}\, \theta_{t-1} \tag{13}$$

Where:

$$\theta_{t-1} = [a\, , b\,]^T \quad \textit{: vector contains system parameters} \tag{14}$$
$$X_{t-1} = [V(t-1), T_{He}(t-1)] \quad \textit{: vector contains system state and input}$$

Then, the mean square error is defined as below:

$$Mean\ square\ error = \frac{1}{n}\sum_{t=1}^{n}\big(T_m(t) - T_{He}(t)\big)^2 = \frac{1}{n}\sum_{t=1}^{n}\big(X^T{}_{t-1}\, \theta_{t-1} - T_{He}(t)\big)^2 \tag{15}$$

Where: t is number of the time step in the discrete time process.

The target is to choose θ that can minimize the mean square error. So, partial differentiation of Mean Squares error w.r.t θ and setting this gradient to zero, gives the following result for n measures from the temperature sensor.

$$[a\, , b] = \theta_n = [\sum_{t=1}^{n} X_{t-1}\, X^T{}_{t-1}\,]^{-1}\ [\sum_{t=1}^{n} X_{t-1}\, T_{He}(t)\,] \tag{76}$$

Finally from equation (12), τ and k are valued and a suitable controller is designed to maintain the required helium temperature as shown in figure (5). The suitable control is PI controller as the air temperature is lower than the helium temperature. So, the integral term keeps a constant voltage that compensates that heat dissipation from the helium to the air. In addition, the helium temperature does not go lower than the air temperature. This condition is used in the whole simulation model in the next section.

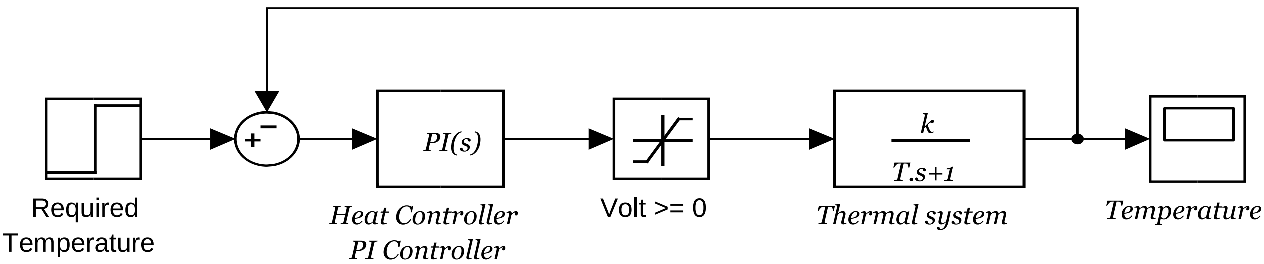

Figure 5: The block diagram of the control system to the helium temperature.

To calculate the values of the controller gains K_p & K_i , the closed loop characteristic equation is specified to have reasonable damping ratio and settling time within the heater capabilities.

6. Altitude Control Analysis and Design

The balloon is designed to ascend and descend in a certain range of altitude by heating the helium. In order to achieve that ability of controlling ascending and descending, the ratio between the helium mass and the whole balloon mass adjusts that by not making the balloon self-ascending without heating. This case makes the balloon uncontrollable and continuously ascending until it bursts at some altitude. By analysing the structure of equation (1)

$$M_{total} * h^{oo} = buoyancy\ Force - Drag\ Force - Weight \tag{17}$$

The three forces work in different ways. As the drag force is responsible for the damping and limiting the maximum ascending rate. But, the buoyancy and weight forces ascend and descend the balloon respectively. To avoid continuously ascending that leads to uncontrollable balloon until it bursts or extends to its maximum rigid volume, the following condition must be satisfied. Also, table (2) compares the simulation results among the three cases.

$$buoyancy\ Force\ at\ the\ ground < weight \tag{18}$$

$$\left(\frac{m_{He} * R_{He} * T_{He}}{p_{air}}\right) * \rho_{air} * g < M_{total} * g \tag{19}$$

However, on the start at the ground the helium temperature equals to the air temperature.

$$m_{He} * R_{He} \left(\frac{T_{air}}{p_{air}}\right) * \rho_{air} < M_{total} \tag{20}$$

$$m_{He} < M_{total} * \frac{R_{air}}{R_{He}} \tag{21}$$

Table 2: Three cases for the condition in equation (21)

No.	Condition	Balloon Volume & Altitude graphs	Result
1	$m_{He} > M_{total} * \frac{R_{air}}{R_{He}}$	Figure (6)	The balloon bursts after certain altitude & no ability to control the altitude
2		Figure (7)	The balloon reaches max altitude and volume without the ability to descent & no ability to control the altitude
3	$m_{He} < M_{total} * \frac{R_{air}}{R_{He}}$	In the next section in Figures (12) and (13)	Successful altitude control & avoiding the burst or maximum volume

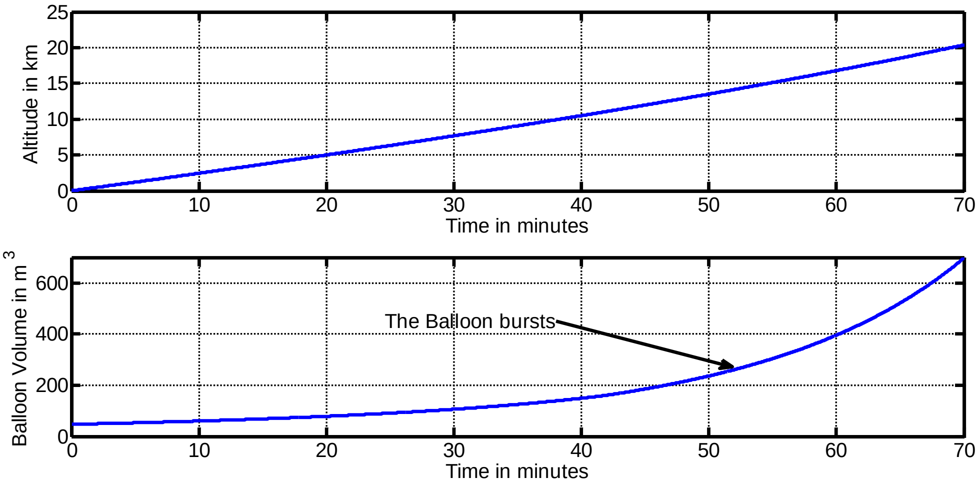

Figure 6: The time simulation of the balloon altitude and volume in case $m_{He} > M_{total} * \frac{R_{air}}{R_{He}}$ and the balloon material fails to withstand the pressure difference.

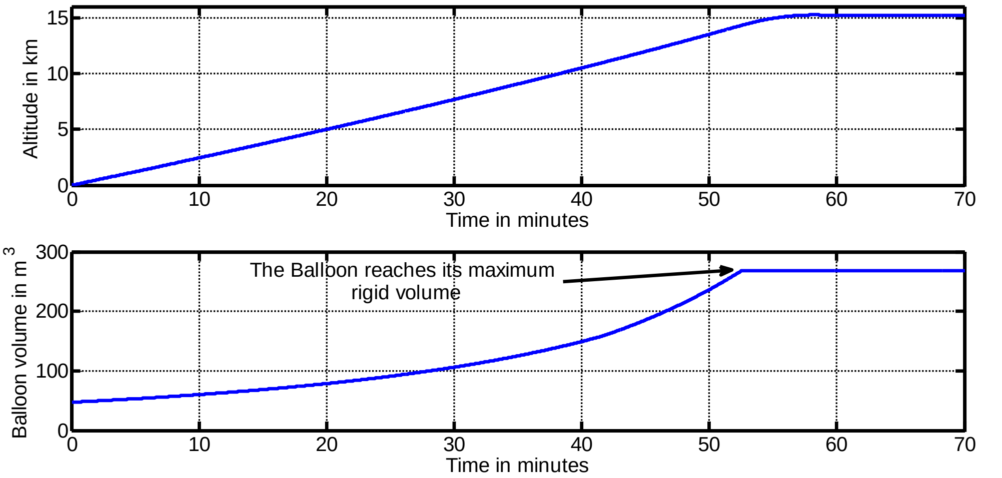

Figure 7: The time simulation of the balloon altitude and volume in case $m_{He} > M_{total} * \frac{R_{air}}{R_{He}}$ and the balloon material is extended to its maximum.

After modelling the balloon dynamics and analysing the condition, that makes the altitude control by heat achievable. In addition to model the thermal system, which is responsible for heating the helium, performing experiment to estimate its parameters and designing a suitable PI controller to achieve the required helium temperature. The next step is to design a main controller that works on the altitude to result in the balloon required volume to reach a certain altitude without oscillations. The balloon required-volume can be transformed to the required helium temperature. This next step is performed in the following discussion. Also figure (8) explains the whole process by a simulation model on a computer software.

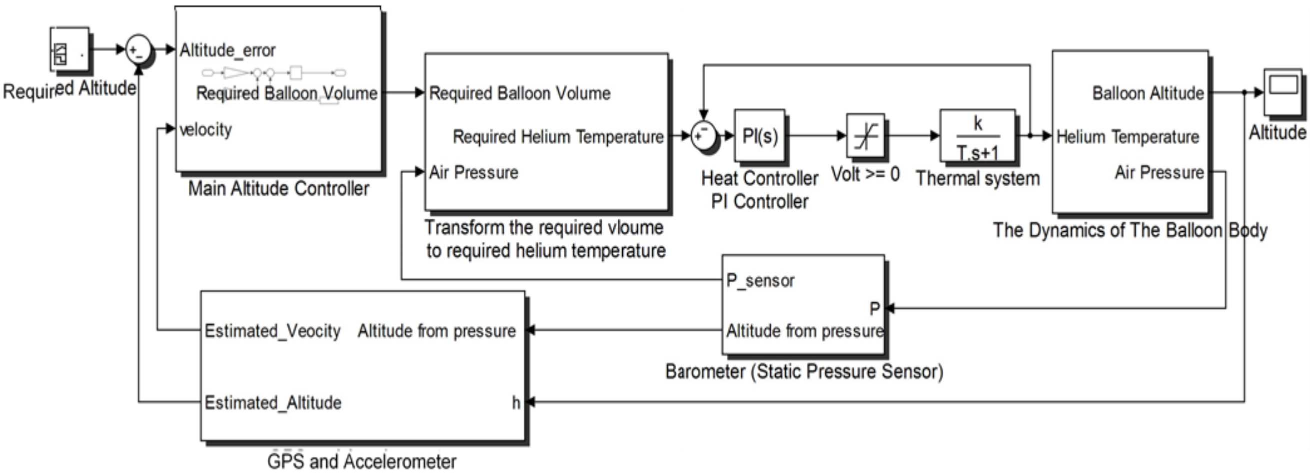

Figure 8: Simulation model built on a computer software for all systems incorporated in the balloon control system.

First, the balloon altitude is measured by GPS or pressure sensor. However, the rate of descending or ascending is estimated by fusing the data from integrating accelerometer and differentiating the altitude data. This fusion uses a complementary filter to make good use of the accelerometer high frequency bandwidth and remove its bias, due to integration, in the low frequency bandwidth using the altitude data from GPS or pressure sensor. The main altitude controller, designed as a PD controller as shown in detail below, uses these altitude and rate data to control the balloon altitude by choosing the required balloon volume. The required balloon-volume is transformed by equation (6) to the required temperature. Thus, the heat controller can achieve it.

From equation (1)

$$M_{total} * h^{oo} = V_B * \rho_{air} * g - \frac{1}{2}\rho_{air}(h^o)^2 * C_D * Area - M_{total} * g \quad (22)$$

By Linearizing this equation on the steady state at the sea level and assuming the air density is constant with h, and consider this linearization point for the balloon volume as below:

$$V_B * \rho_{air} * g = \Delta V_B * \rho_{air} * g + constant(V_B) * \rho_{air} * g = \Delta V_B * \rho_{air} * g + M_{total} * g \quad (23)$$

The following transfer function in equation (24) describes the balloon linearized-dynamics.

$$\frac{h}{\Delta V_B} = \frac{\rho_{air} * g}{(M_{total})\, s^2 + \left(\frac{1}{2} * \rho_{air} * C_D * Area\right) s} = \frac{0.24}{s(s + 0.088)} \quad (24)$$

And

$$V_B = \Delta V_B + constant(V_B) = \Delta V_B + \frac{M_{total}}{\rho_{air}@sea\ level} \quad (25)$$

The straightforward control design for this open loop transfer function is a PD controller. The root locus after the controller is shown in figure (10) and the time response in figure (11). Also, figure (9) shows the PD controller gains and structure.

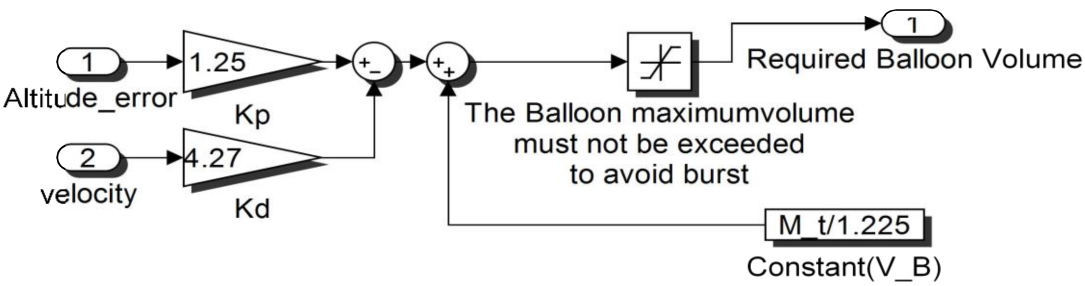

Figure 9: PD controller gains and structure for the transfer function in equation (24).

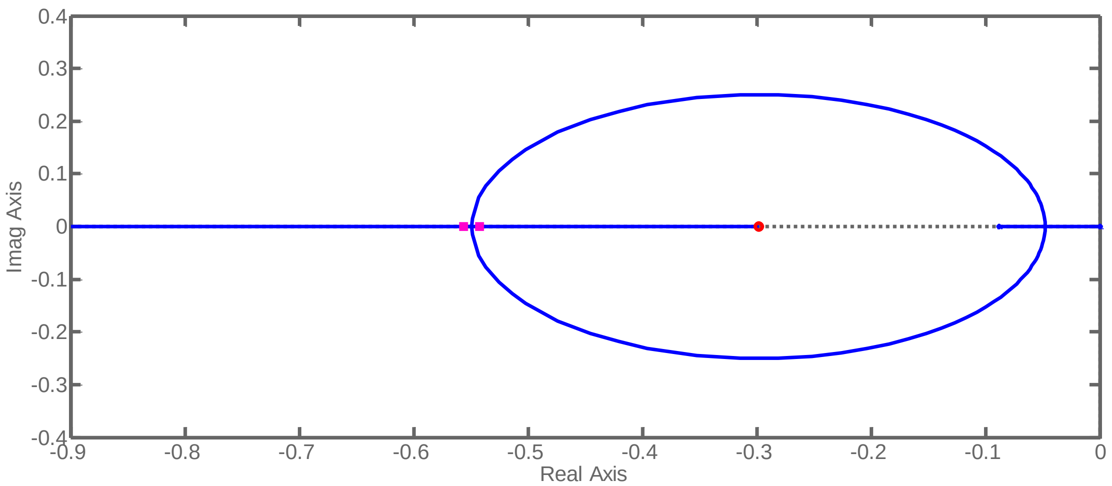

Figure 10: The root locus plot for transfer function in equation (24) after feedback and using the controller in figure (9)

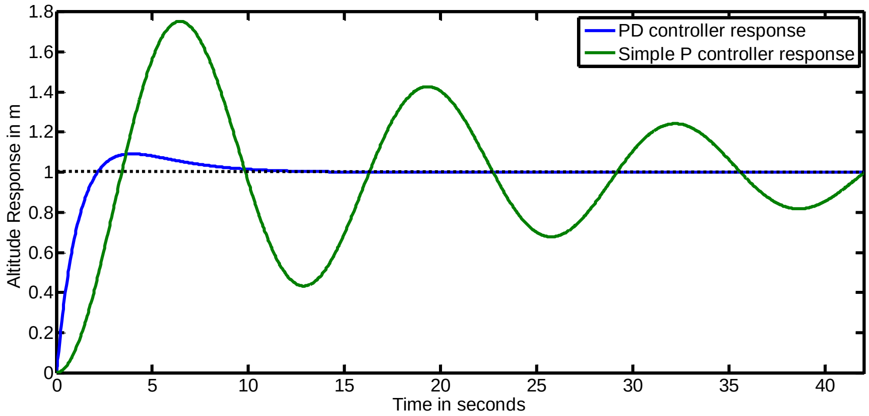

Figure 11: The controlled time response for transfer function in equation (24) after and before feedback and using the controller in figure (9)

The mission is achieved by planning the required height with time to avoid turbulences or getting a certain height on a specified time. For example, in figure (12) a mission is performed to ascend to certain altitudes then descend to the ground again.

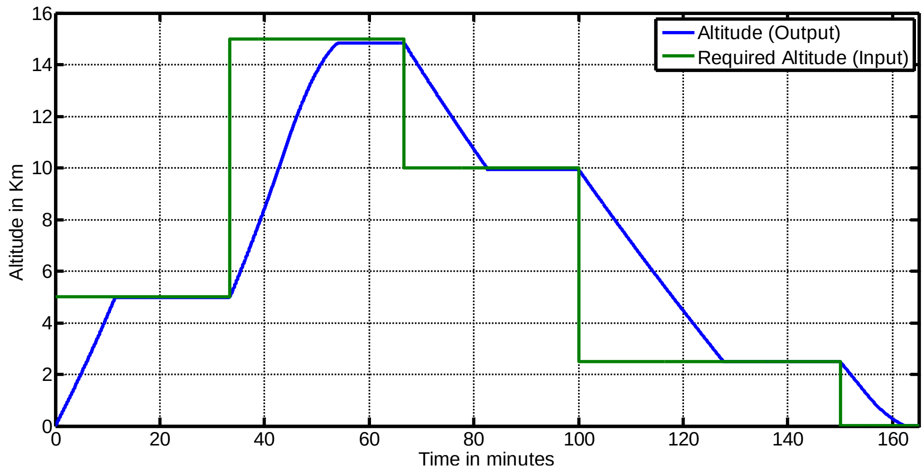

Figure 12: Mission simulation to ascend to certain altitudes then descend to the ground.

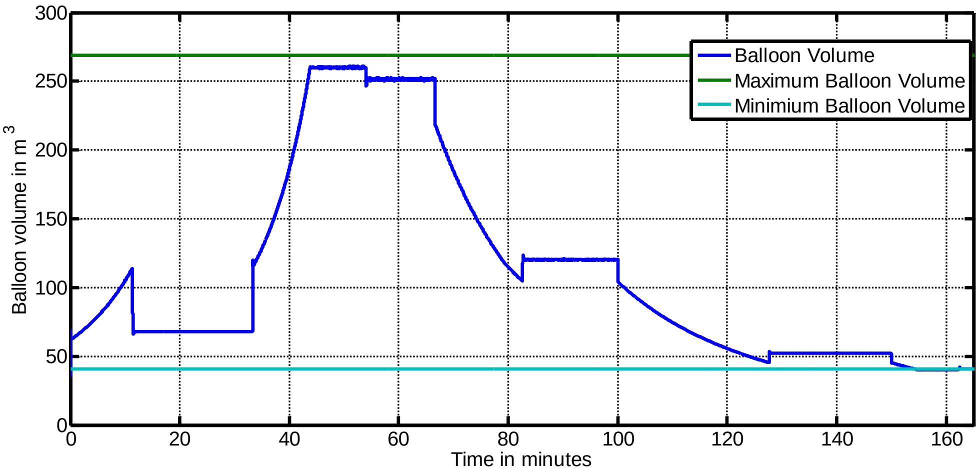

Figure 13: The balloon volume during the mission shown in figure (12).

7. Material's Technology

Choosing the material for such a design that depend on heating the lifting gas inside the balloon was so essential, adding an external effect of heat and withstanding the natural atmospheric temperature and pressure behaviour changes is something to be considered wisely and need many materials were previously and nowadays used in high altitude and weather balloons, reaching the databases of the material characteristics was important to choose the proper material to use, however keeping in mind the cost and easiness for those materials to be used and handled as those are the main aspects of our work.

As follows a simple comparison between the 4 most commonly used materials in manufacturing of the high altitude balloons;

Table 3: Comparison between previously selected materials for high altitude balloons

Material	Density	Ultimate tensile stress	Melting point
Latex	60 - 95 Kg/m3	27.5 MPa	105-110 °C
Nylon	1150 Kg/m3	30 -68.9 MPa	190–350 °C
Metalized Sheets (Mylar)	1390 Kg/m3	196 MPa	254 °C
Polyethylene (PE)	910 - 960 Kg/m3	60.2 MPa.	115 -135 °C

*All data are in the ideal cases, numbers are subjected to be changed depending on production and design processes.

8. Balloon Design

The balloon design depends on introducing a platform that will be able to use the previous theories to allow the balloon to maintain its function and reach its goal with the new techniques, certain aspects were monitored for the balloon design in order to serve that purpose;

Table 4: Balloon design example inputs

Payload Weight	50 kg
Target Apogee Altitude prior to heating	10 km
Target Apogee Altitude after heating	40 km
Balloon's max. Height	8 m
Balloon's max width	3.5 m
Balloon's material	Mylar
Lifting gas	Helium

- **Reliability**

Reaching the desired altitude with precision and with the least risks to the flying payload avoiding all the possibilities for shifting and accidents is one of the main focus points of the design.

For the conventional balloons, several precautions to be provided to make sure the balloon don't intercept a plane or even flying birds which could harm the birds or cause problems for the flight. Rather than the conventional uncontrolled high altitude balloons, Using a guidance system through the heating mechanism offers a better control on the ascent and decent of the balloon.

- **Handy size**

Introducing the heating concept from the very beginning aims to offer the maximum usage of the lifting gas filling a certain volume at the start of the flight, the balloon's size on starting the ascent phase should fit into a football/baseball field.
This condition is because every University or High school has its own or even a free access to such type of fields, though the process of setting the test field and getting the experiment done will cost nothing as it's already a reachable facility.

- **Cost**

The balloon's total price should not reach a 20% of the price of the cheapest platform that can conduct the same sort of testing experiment (reaching the same altitude with the same capabilities), though 20% is considered a high percentage, further plans and modifications are to be added to guarantee introducing the cheapest design preserving all the quality & performance.

To launch an experiment to the low earth orbit LEO,

- **Reusability**

As reusability is one of the main aspects of this design for keeping the cost as low as possible compared to the qualities and performance introduced, using the same hardware multiple times is so essential as losing the heating mechanism and balloon structure would cost, therefore getting the balloon back safe to the ground is an important phase to be considered.

9. Mission Design

To ensure a successful flight, a complete mission design study was precisely made to introduce the steps needed to be performed for the balloon to reach the desired altitude and finish the required mission with the best performance.

First of all, filling the balloon with the lifting gas - helium – slowly it will be released to start the ascent phase.

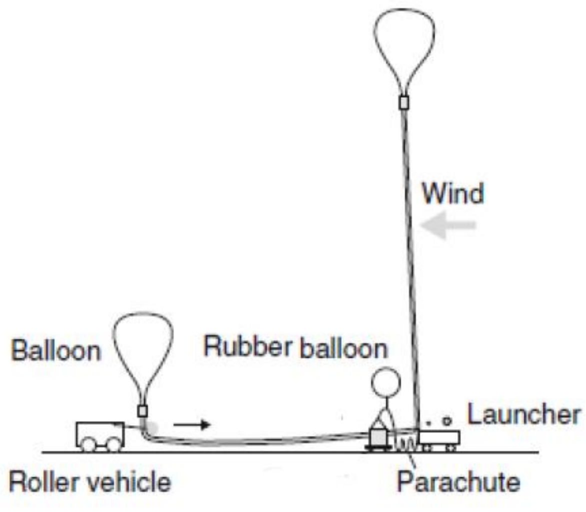

Figure 14: illustration of static launch method.

The balloon must be in a downwind position, so when the balloon is released it is moored to the ground until all slack is removed from the system.

In order to having accurate detailed information about the forecast, wind turbulence and conditions of flights, a weather rubber balloon will be sent prior to the main balloon launch.

After reaching the altitude of 20 Km - which is the same altitude where the helium only with no additional heating can put the balloon up in the atmosphere - the heating mechanism will start working heating the helium up to …….. °C gradually, raising the balloon to reach up to an altitude of 40 km depending on the required mission or experiment.

Depending on the feedback reading from the system of sensors & weather forecast, heating of the helium will start and stop in order to control the acceleration of the balloon to avoid the turbulences and side winds that may affect the balloon's stability.

After reaching the desired altitude, the heating mechanism completely stops working allowing the helium to cool down again, though losing altitude and therefore starting the decent phase to the altitude of 20 km, the same manoeuvring strategies and techniques will be performed to insure precise decent of the balloon.

Venting the helium will starts as soon as the balloon reaches the altitude of 20 Km, venting the lifting gas will force the balloon to fall down slowly back to earth with the effect of the gravitational force, venting can be precisely controlled through valves and regulators. After venting nearly all the helium inside the balloon, a simple recover system using parachutes will open to land the platform with the balloon back safe to earth.
Detecting where the balloon landed can be configured using the ground positioning system GPS mounted on board of the balloon navigation system, though recovering the balloon back to the ground station, checking it then filling it back again with helium then equipping it with the experiment hardware will make it ready for another flight in no time.

10. Conclusion

Implementing these ideas and additions discussed should increase the reliability, performance and control of the high altitude balloons, encountering most of the disadvantages of using balloons this will offer a variety of new applications. With keeping an eye on maintaining the cost, reaching the near space will be also much easier rather than using sophisticated launch platforms.

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