Presented at the DLSU Research Congress 2017
De La Salle University, Manila, Philippines
June 20 to 22, 2017

Development of a Prototype Light-Payload Hot Air Balloon Temperature Control System

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Abstract: The reach of wireless internet, is, as with all high-frequency wireless communication, limited by many factors including absolute signal strength (i.e. transmit power, antenna radiation characteristics, receiver sensitivity) and occlusions due to line-of-sight (LOS) propagation. It stands to reason that many individuals (i.e. doctors, clinicians, teachers) in the Philippines who are currently at the outside fringes of mobile broadband coverage can gain significant benefits of reliable internet access and communications, even if such access is time-limited.

A small, automated hot air balloon is proposed to hoist so-called mobile routers to gain important LOS to a remote cellular tower. Developing an automated burner control system allows the hot air balloon to maintain its desired altitude. Temperature maintenance is accomplished using temperature sensors, a microcontroller, LPG burner, and a servo motor that controls the burner's flame-control knob. The temperature difference between the air in the balloon envelope and that of the outside (ambient) is set to 60 degrees Celsius for prototype development.

Performance tests indicate that the LPG system was able to raise the temperature of the air within the balloon envelope close to the target temperature difference, however the heat capacity of the system was under-estimated, primarily from losses due to envelope collapse. It is concluded that the heating system has to be significantly over-specified to ensure proper balloon inflation, and that the balloon envelope material's leakage and weight characteristics are of importance in small-diameter hot air balloons.

Key Words: hot air balloon; automated burner control system; temperature sensor

1. INTRODUCTION

According to Hardwood, some interference-causing factors to signals are physical objects, radio frequency interference, electrical interference, and environmental factors. Natural disasters have a high percentage of infrastructure damage, often affected are houses, hospitals, offices, and cellular towers, to name a few. Having said that, the provision of cellular communication services may be affected whenever disaster strikes. Although, there are still a lot of communities and villages in an archipelagic country like the Philippines that are barely reached by cellular communication services from major telecommunication companies. The aforementioned situations pose a great challenge for people who seek medical assistance. If cellular signals are transmitted and received at a higher altitude than most infrastructures, the interference caused by physical objects will be much lessened that it is on the ground.

A similar study was done by Vilhar et al. where it was also stated that aerial platforms are candidates in providing a temporary network service. A free-flying hot air balloon was equipped with three different network technologies: Terrestrial Trunked Radio (TETRA), Wireless Fidelity (WiFi), and WiMAX. The researchers tried to establish a connection between the transmitted aboard the hot air balloon and the receiver on their mobile car. The hot air balloon was freely flying with the direction of the wind while the mobile car is following the path of the hot air balloon on the ground.

A study was done by Apvrille et al. wherein the researchers wanted to make the drones able to fly autonomously and analyze scenarios due to the reason that the complexity of the control system may be time-consuming to the users, specifically rescue teams in times of disasters. The researchers opted for an indoor testing as drones are small in size and thus ideal for navigating through narrow pathways during disasters.

A similar study to Apvrille was done by Li et al. wherein in order to extend wireless network coverage, a drone was deployed along the line of communication and hopefully placing the drone in its ideal optimal position to maximize data rate between the cellular tower and a terminal device. The researchers concluded that when the distance between cellular tower and terminal device is small, there is no need to deploy the drone; but when there is a significant distance between the cellular tower and the terminal device, deploying the drone would mean a potential increase in data rate.

The aforementioned works demonstrate a possibility of using aerial machineries or technologies of lift to establish transient network communications that would cater to various objectives, such as during times of disaster or medical missions. Hot air balloons provide a much longer flight time compared to some technologies of lift such as helium balloons, weather balloons, or drones, as aforementioned. An improvised hot air balloon would be much portable than other aerial machineries with longer flight times like planes and blimps.

2. SYSTEM OVERVIEW

This research aims to develop a hot air balloon system with an automated burner control system. Automating the burner reduces the manpower needed to operate a hot air balloon, thus, reducing the weight the hot air balloon has to lift and also reducing the size of the hot air balloon. Reducing the size of the hot air balloon is only necessary for a small research just like this. Normal hot air balloons seen in leisure activities have huge envelopes and very high-powered burners, they are also very expensive, approximately priced at 3-4 million Philippine Peso. The system acquires inputs from two temperature sensors to signal the burner to turn off or on to control the lift of the hot air balloon.

2.1 Hot Air Balloon Module

There are three parts of the hot air balloon: the envelope, burner, and basket. The actual balloon is referred to as the envelope, which is usually made of ripstop nylon fabric; the envelope is divided into long vertical strips called gores and each gore is divided into smaller horizontal portions called panels. Located at the bottom part of the envelope is the skirt which helps with the fuel efficiency by protecting the burner from the wind. There are a lot of parameters to consider in building a hot air balloon because there is science behind it.

One of the parameters that need to be taken into account in designing a hot air balloon is the size of the envelope because that is also one of the main factors that will determine its lift capability, aside from heat generated. The hot air balloon used in this research is made use of 8 gores and each gore is composed 7 panels (see Fig. 1). When all the gores are assembled, the hot air balloon has a total circumference of 8 meters and a diameter of 2.54 meters.

The amount of air that needs to be heated is dependent on the size of the envelope; the larger the envelope, the larger the amount of air that needs to be heated. Meanwhile, in calculating for the weight of the envelope, the formula below needs to be used:

$$w_e = A * w_f \qquad \text{(Eq. 1)}$$

where:
w_e = weight of the envelope (kg)
A = total surface area of the envelope (m^2)
w_f = weight of the fabric (kg/m^2)

Values obtained beforehand are the weight of the fabric and the total surface area with values of 0.087 kg/m^2 and 20.66 m^2, respectively. Using Eq. 6, the total weight of the envelope is 1.80 kg.

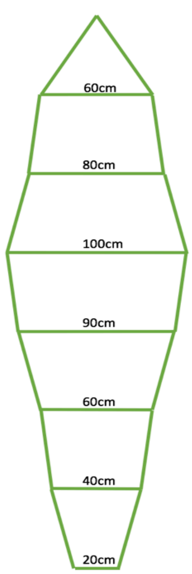

Fig. 1. Measurements of Each Gore

Aside from the weight of the envelope, the amount of air that should be heated and its mass can be calculated by:

$$m = \rho V \qquad \text{(Eq. 3)}$$

where:
m = mass of air (kg)
ρ = density of air (kg/m^3)
V = volume (m^3)

Using the density of air at 30º Celsius, which is 1.16 kg/m^3, and the total volume 8.27 m^3, the total mass of air calculated is 9.59 kg.

The values that will be used for solving the lift capability of the balloon are the volume = 8.27 m^3, weight of the balloon = 1.80 kg, and the ideal temperature difference between the ambient and inside temperature of the balloon which is 60º Celsius. To calculate the lilft capability of the balloon, it can be solved using the equation:

$$\text{Payload} = PV\left(\frac{1}{T_o + 273.15} - \frac{1}{T_i + 273.15}\right)(3.47\,x10^{-3}) - wt_b \qquad \text{(Eq. 4)}$$

where:
P = absolute pressure (Pascals)
V = volume of the balloon (m^3)
wt_b = weight of the balloon (kg)
T_o = outside temperature (Celsius)
T_i = inside temperature (Celsius)
Payload = weight that the balloon can carry (kg)

Atmospheric pressure at 0 m to 152.4 m is 101325 Pascals. Given that the outside temperature is at 30º Celsius the inside temperature must be at 90º Celsius. The weight of the envelope was the only weight considered to be the balloon weight.

Therefore, having these values, payload can be solved using Eq. 4, it was solved that the hot air balloon has a -0.22 kg payload or lift capability. The hot air balloon having a negative payload signifies that it cannot be able to lift itself. It may just inflate vertically but would not be able to fly.

2.2 Burner Control Module

The burner control module will take two inputs from two temperature sensors. One temperature sensor is placed on the envelope and the other outside. The values from each temperature sensor will then be compared that would result to a temperature difference to signal the Arduino to control the opening of the gas valve (see Fig. 2).

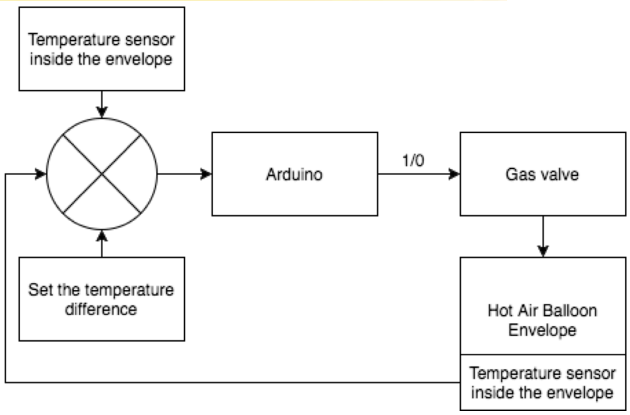

Fig. 2. Burner Control Closed Loop Feedback System

For the closed loop equation, consider the equation:

$$PWM = Kp * Set\_Temp - (Ti - To) \qquad \text{(Eq. 5)}$$

where:
PWM = pulsed width modulation
Kp = proportional gain
Set_Temp = desired temp difference
Ti = temperature inside
To = temperature outside

The PWM duty cycle sets the servo motor position. The proportional gain, Kp, was initially set for a linear response within 5 ºC, with the software hard-limiting the PWM duty cycle so that the servo motor would drive the burner throttle to positions within maximum and minimum flame limits.

The envelope contains a certain volume of air according to its size. That air will be heated to obtain the desired temperature difference between the inside temperature and ambient temperature. When calculating the lift capability of the balloon, one factor that can be easily manipulated is the temperature difference ΔT. Heating the air inside would produce a higher temperature and would increase the lift capability of the balloon since it is directly proportional with it. The amount of heat needed to heat something from a certain temperature to another can be calculated using the formula:

$$Q = C_p m \Delta T \qquad \text{(Eq. 6)}$$

where:
Q = amount of heat (kJ)
C_p = specific heat (kJ/kg C)
m = mass of air (kg)
ΔT = temperature difference between hot and cold side (C)

Using this equation and the previous values obtained earlier, the resulting amount of heat is 578.27 kJ. The amount of heat obtained is essential for the lift capability of the hot air balloon since it would maintain the temperature difference required. When ΔT is constantly above the ideal temperature difference, it will help the hot air balloon to keep its upright position and keep it rising in the air.

In order for the mouth of the envelope to refrain from touching the flame and burning up, and to concentrate the heat, a makeshift chimney made from galvanized iron sheet was used (see Fig. 3). Meanwhile, the servo motor was attached to the flame control knob of the burner (see Fig. 4).

Fig. 3. Makeshift Chimney for the Burner

Fig. 4. Servo Motor Attached to the Flame Control Knob of the Burner

3. METHODOLOGY

One of the limitations of testing is performing the experiment during midday; this is due to the usual moderate to strong wind conditions during this time of the day. Usually, the wind speed during midday can be more than 5 knots which can cause the hot air balloon to tip over a little or even fall flat on the ground. Moreover, the hot air balloon cannot be deployed and testing when it is raining mainly because of the material the envelope was made – fabric.

The Arduino board was programmed so that the data from the temperature sensor for the inside temperature and the temperature sensor for the ambient temperature would be inputted well. The sensor for the inside temperature of the envelope was attached to the upper part of the envelope outside where all the gores meet. The reason for not placing the temperature sensor directly inside the envelope is because it might fall directly into the flame of the burner. Both temperature sensors for inside temperature and outside temperature of the envelope started to record the temperatures every second. While the temperature sensors continuously scanned the temperatures, the Arduino compares the temperatures and checks if the difference satisfied a temperature difference of 60° Celsius.

For the purpose of characterizing the balloon envelope thermal response, the proportional burner control loop was modified so that the measured temperature difference against the set temperature would rotate the flame throttle by 45 degrees (open) or by 5 degrees (close), i.e. bang-bang control. The captured data was then labeled as follows:

- The time the burner had to be turned on before satisfying the temperature difference during initial set up.
- The time the burner was turned off before the temperature started to drop and dissatisfy the temperature difference.

After the data gathering, this will determine the characteristics of the fabric used on how well it holds hot air inside. This will also determine the if the size of the balloon is enough to generate lift or how much lift it can actually generate given the size of the balloon. Through the data gathering, the amount of gas used for getting the hot air balloon to rise can be determined as well.

4. RESULTS AND DISCUSSION

The first test had a duration of 22 minutes and 50 seconds which captures the temperature outside the envelope and the temperature inside the envelope every second. The environment had a temperature range of 27.75°C to 28.87°C, and an average temperature of 28.25°C (see Fig. 5). The hot air balloon started to inflate vertically, from its horizontal position, around 50°C. After 20 minutes and 30 seconds, the temperature inside the envelope reached a peak of 54.13°C then the burner was turned off and the temperature started to drop continuously. After the burner was turned off, it was observed that the inside temperature dropped fairly fast compared to when the inside temperature was being risen; for example, the inside temperature took 2 minutes and 20 seconds for it to drop from 54.13°C to 32ºC while it took a long 19 minutes and 13 seconds for the inside temperature to go up from 32ºC to 54.13ºC as seen on columns 8 to 9 of Fig. 5.

The second test had a duration of 35 minutes and 59 seconds. The outside temperature range for this test was 25.75ºC to 29.25ºC, and averages at 27.74ºC (see Fig. 6). 5 minutes and 56 seconds in, the inside temperature continued to rise until 8 minutes and 16 seconds where it reached the peak value of 84.69ºC; at this point, the outside temperature is 27.94ºC which is 3.25ºC from the 60ºC theoretical ideal temperature difference needed to lift. Compared to the first test, the inside temperature peak value is much higher that it almost reached the ideal temperature difference to generate lift. From 75.50ºC and when the burner was turned off, it took 10 minutes and 10 seconds for the temperature inside the envelope to be almost equal to the temperature outside the envelope with values 26.62ºC and 26.75ºC, respectively, as seen on columns 5 to 7 of Fig. 6.

The outside temperature range for the third test was from 22ºC to 26.25ºC and averaged at 24.49ºC (see Fig. 7). After 19 minutes and 25 seconds, there was exactly a 60ºC temperature difference between the outside temperature and inside temperature with 24.50ºC and 84.50ºC, respectively. However, there was still no lift being generated and thus the researchers tried to let the temperature rise by not turning off the burner. At 24 minutes and 9 seconds, the inside temperature reached a peak of 87.94ºC with 24.87ºC, a temperature difference of 63.07ºC. It was decided to turn off the burner because there was still no lift being generated.

For the gas consumption, the LPG tank had a total weight of 22.3 kilograms – 12.5 kilograms for the tank itself and 9.8 kilograms for the LPG content – before any tests were done. After the first two tests, the LPG content went down to 9 kilograms and after the third test, the LPG content went down to 8.4 kilograms.

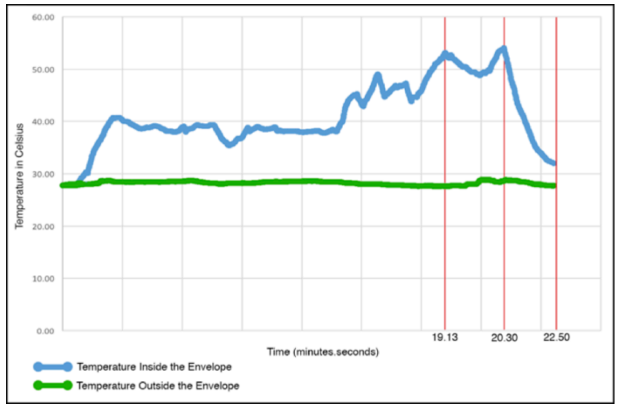

Fig. 5. Outside Temperature and Inside Temperature Values from Test 1

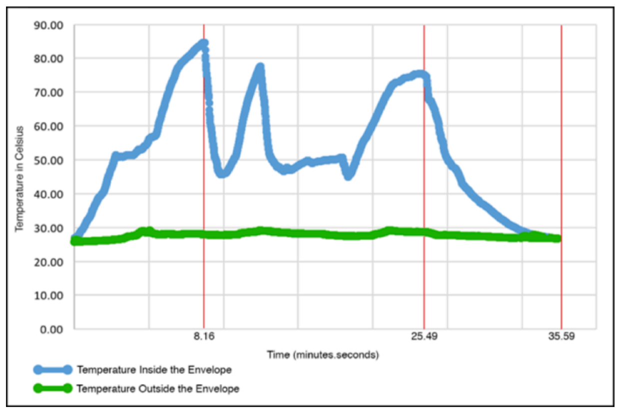

Fig. 6. Outside and Inside Temperature Values from Test 2

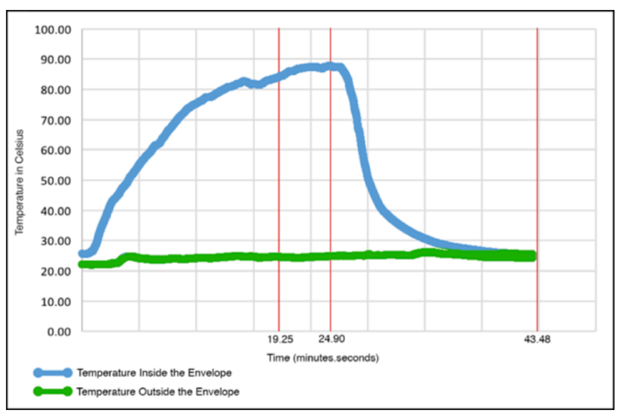

Fig. 7. Outside Temperature and Inside Temperature Values from Test 3

5. CONCLUSION

Other than the size of the envelope, the material that it is made out of is highly important because this dictates how well it can hold the hot air inside. During the first two tests, the servo motor was not able to lower down the flame because the peak temperatures for both tests did not reach the ideal temperature difference of 60ºC, as per the if condition of the servo motor to turn to 5 degrees. For the third test, the servo turned to 5 degrees after satisfying the ideal temperature difference. However, there were no lift being generated and thus the researchers decided to let the burner turn on again at its maximum flame control.

During all the tests performed, the envelope needed to be lightly supported regardless if it is rising vertically (see Fig. 8). Not supporting the envelope would cause it to droop. Although based from the calculations that it would not lift, still the envelope should be able to rise vertically on its own without any support. Thus, it can be concluded that the factors that may have affected the results are the type of fabric used for the envelope – the fabric does not hold the air inside the envelope well enough for it to generate lift.

Fig. 8. People Lightly Supporting the Envelope

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