Development and Testing of a USM High Altitude Balloon

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Abstract. This paper discusses on tests conducted on the component and subsystem level during development of the USM High Altitude Balloon (HAB). The tests conducted by selecting initial components then tested individually based on several case studies such as reliability test, camera viewing, power consumption, thermal capability, and parachute performance. Then, the component is integrated into sub-system level for integration and functionality test. The preliminary result is utilized to tune the components and sub-systems and trial launch is conducted where the sample images are recorded and atmospheric data successfully collected.

1. Introduction

High-altitude balloon (HAB) is an unmanned balloon, typically filled with light gases such as helium. It is capable of reaching approximately 50 km above the sea level which has seized the interest of the public in recent years with more HAB projects being released into the stratosphere due to the advancement of low cost communication technology and easy accessibility to civilian global positioning system (GPS). In addition, the payload carried by HAB is also retrievable, which gives the opportunity for services and maintenance and helps in reducing space debris. A typical HAB a weather balloon used to acquire atmospheric data throughout the flight course [1].

The objective of USM HAB is to collect atmospheric data and capturing images of the earth horizon. The secondary objective is to instill the interest of spacecraft design knowledge among undergraduate’s students. The detail concept of operations and mission timeline is explained in [2].

System integration verification is vital to achieve the mission objectives. Six tests are conducted including one integration test, to ensure reliability, capability, performance, and the efficiency of the components and subsystems in various conditions. The risks associated with these
subsystems have been identified and the management plan for the risks have been developed. Each subsystem test drives the next subsystem test as seen in Figure 1.

2. System Description
The main system of HAB is regularly divided into five subsystems, which are balloon and navigation, communication, on-board data handling (OBDH) and payload, structure, and thermal subsystem. The structure uses polystyrene material in shape of a cube (30 cm x 30 cm x 30 cm) which is lightweight, waterproof, and able to float. Preliminary design suggested that the components are placed in stacking level where power system is placed at the bottom level, OBDH and payload are placed in middle level, and finally, the communications are placed on top level of the stack. The heat packs are placed at the bottom of each stack plate for thermal control. Temperature and humidity sensor as well as the antenna are positioned outside of the box in order to function better. The payload is then connected with a parachute and tied with the balloon line shown in Figure 2.

![Figure 2. HAB configuration](image)

3. Components Test
The critical subsystems are the OBDH and payload, and communication subsystem, although other subsystems are of equal importance depending on the mission’s objective. In order to avoid mission failure, it is of utmost importance that these two subsystems are thoroughly tested and verified before launching. This would ensure that the microcontroller programming is compatible with the sensors as well as the communication system. After it finishes, the communication subsystem test follows, which is done by testing the transmitter, receivers, cameras, and the GPS system. As sensors are prone to noise, which leads to error in reading, both OBDH and payload, and the communication subsystem are run through a small integration test to check its susceptibility. This to ascertain whether the communication system interferes with the sensors’ reading, and if it does, the effect shall be minimal.

Next, the structure test is carried out to check the design flaws and the ability of selected material to withstand the landing impact and the capability to float on water for a long time. Following that, a thermal test is performed to determine component functionality at optimum temperature and at low temperature condition.

In additional, the parachute is tested by integrating the final design and respective mass. During this process, the descent rate and the stability of the structure are observed. The test result become the input for redesigning parachute if necessary. Finally, an integration test is conducted on the interface and mounting between the balloon, the payload, and the parachute are done before the launching.
3.1 On-Board Data Handling (OBDH) Components & Payload

Figure 3 shows the schematic diagram of the sensor connecting to the Arduino microcontroller with power supply.

![Schematic Diagram](image)

**Figure 3.** Breadboard wiring and schematic diagram of LM35, SD Card shield, BMP180, ADXL330, camera into Arduino Mega 2560.

The sensors and components sensitivity is tested in different environment as tabulated in Table 1. This test is to ensure that the sensor can read negative value in order to show a negative temperature. This due to the HAB will experience different temperature range during its flight [3]. The camera plays an important role in the project as the objectives of the project is to be able to capture images of the horizon. Thus, three tests are developed to evaluate the capability of the payload.

| Components            | Study Case                                      |
|-----------------------|-------------------------------------------------|
| BMP180 + LM35         | Different temperature and pressure environment  |
| SD Card Shield        | Multiple sensor logging data at the same time   |
| ADXL330               | Different direction and elevation                |

3.1.1 Camera Viewing Angle

The camera is first positioned with no angle shown in Figure 4 (a). This is to give a general idea on what is going to be in the camera frame. Due to the mission objectives, the camera angle is tilted to 35° depicted in Figure 4 (b). This is to fully capture the image of the earth surfaces as well as the horizon.
3.1.2 Camera Battery Endurance

The test is to evaluate the time taken of the battery to fully discharged during recording and how much power it required. The duration of test started from the camera has been switched on and video recording is started until it fully discharged. The total recorded footage time is assumed to be the total discharged time. The battery has a capacity of 900 mA·h and the duration of recorded footage is 143 minutes and 3 seconds. It has an operating voltage of 3.7 V. From this, the power consumption from the camera can be calculated using Equation (1).

$$Power = \frac{Capacity \times V}{3600}$$

Where, Capacity is the battery capacity in mA·h and V is the operating voltage of the camera. The power consumption of the camera calculated is 0.925 mW and power subsystem will design the power management based on the value calculated.

3.1.3 Camera Storage Capacity

In order to determine the amount of storage used for the camera, early estimation can be done by analyzing the size of each of footage saved. Since the camera in-built settings that automatically split the footage for every 30 minutes recording, it takes up 2.11 GB of memory. Thus, the memory size required per second can be calculated using Equation (2).

$$MBps = \frac{Size_{footage}}{t}$$

Here, Size_{footage} refers to the size of footage file in MB and t is the recording time in seconds. The calculated memory per unit time is 1.167 MBps, therefore, a 4-hours of a HAB flight requires approximately 16 GB of memory. However, the memory size required depends on the color intensity of footage [4]. Thus, the file size for each footage is varied. Hence, a 32 GB memory is suitable for the project.

3.2 Communication

In keeping track of HAB, there are two ways to be able to do so as shown on Figure 5.
3.2.1 Radio Frequency (RF) Transmission

Communication system is using the ham radio network coverage, in which offers an extremely wide horizontal range of coverage and helps the detection of balloon during ascent and descent. As shown in Figure 6 (b), a custom-made Arduino shield called the Trackuino is used to transmit data from HAB. It consists of a transmitter, GPS receiver, and audio beeper. The Trackuino transmits the flight data in the form of Automatic Packet Reporting System (APRS) packet data. These APRS packet data can be readily received by radios, and relayed around by digipeaters before the data are passed to the internet via an IGate. The data is sent to a website called aprs.fi, where the balloon’s live flight path can be viewed.

![Figure 6. (a) Tracking of SPOT GPS. (b) Trackuino with Radiometrix HX1 VHF Narrow Band FM 300mW Transmitter & GPS Module.](image)

3.3 Power

Power subsystem test is required to make sure the power supplied by the power source according to the estimated power requirements. The entire communications system was turned on and the actual operating voltage and current consumption was measured shown in Figure 7. The required power consumption and battery capacity are determine using Equation (3).

\[ P = IV \]  

![Figure 7. (a) Operating voltage measured. (b) Current measured during idle. (c) Current measured during transmission.](image)
Based on the results from Figure 7, the Trackuino power consumption is tabulated in Table 2. Thus, the total power consumption is listed in Table 3 is 1.89 W. Therefore, suitable power source is needed by considering every components power rating.

| Description                  | Value |
|------------------------------|-------|
| Operating Voltage, $V_o$     | 5.11 V|
| Idle Current, $I_i$          | 0.15 A|
| Transmit Current, $I_{transmit}$ | 0.29 A|
| Idle Power, $P_i$            | 0.77 W|
| Transmit Power, $P_{transmit}$ | 1.48 W|

**Table 2. Trackuino power consumption**

| Subsystem        | Power (W) |
|------------------|-----------|
| OBDH             | 0.405     |
| Payload          | 0.000     |
| Communication    | 1.480     |
| Structure        | 0.000     |
| Thermal          | 0.000     |
| Balloon & Navigation | 0.000    |
| TOTAL            | 1.885     |

**Table 3. Power consumption**

3.4 Structure

3.4.1 Drop Test
A drop test is conducted to observe the stability of the payload due to high probability of the payload landing on the sea depicted in Figure 8. If the payload toppled over during landing, the sea water may enter inside the payload bus and damaging the components. The test is performed by placing a 2 kg of weight inside the payload bus and fully attached with the parachute system. It is then drop from a height of 25 meter. The payload falls accordingly and it lands perfectly upright.

**Figure 8.** (a) Opening of the parachute to observe payload stability during descent. (b) Landing of the payload.
3.4.2 Impact Test
Impact test is done to make sure that the main structure can resist the impact during landing when the parachute system is malfunctioned. This test is also to understand the critical part of the structure that will likely to fail first upon landing. The main structure is filled with 2 kg of weight and has been drop at height of 7 meter. The drop focuses on the edge of the structure that probably have the highest stress concentration. As the structure drops, the motion is captured with a high-speed camera. As shown in Figure 9 (a), deformation occurs at the edge of the structure and the stress propagates to the top of the structure producing cracks as shown in Figure 9 (b). The cracks produced are caused by the compression and tension of the structure under load.

![Figure 9](image)

(a) Impact testing whereby the box is drop on the edge and deformation occurs. (b) Close up view of the cracks.

3.4.3 Buoyancy Test
The retrieval period may take a long time and the payload will be exposed to the wave at the sea. Thus, the payload bus must be able to float on the sea with capable of withstanding force of the wave. The test is carried out by placing a weight of 2 kg inside the payload bus. The main structure is then wrapped with a plastic to make it water tight and attached with a long rope for retrieval process and tested to be fall on the water as in Figure 10 (a) and (b). The payload is then retrieved and has been visually inspect for any water leaking inside the structure.

![Figure 10](image)

(a) Buoyancy test preparation. (b) Impact result when it hits the water.

3.5 Thermal
Thermal tests are done on two separate case which are with -20°C freezer and -80°C freezer. BMP180 sensor along with digital thermometer and thermocouple sensor are used. The heat source for this test are heat packs. The sensors and heat packs are placed as shown in Figure 11.
Figure 11. Experimental setup of BMP 180 sensor and heat pack positioning

Figure 12 shows that the heat pack can generate heat as the temperature inside the payload is higher than the surrounding temperature.

Figure 12. Heat pack temperature test comparing with surrounding temperature.

This initial experiment lead to the next experiment with different thermal condition inside the structure as listed in Table 4. The Arduino is set up and it is calibrated shown in Figure 13 (a) based on block diagram drawn in Figure 13 (b).

Table 4. Thermal environment analysis

| Condition | Thermal Components                  | Analysis Time   |
|-----------|-------------------------------------|-----------------|
| Case 1    | No heat packs & thermal reflector   |                 |
| Case 2    | 5 heat packs                        | 1 hour 30 minutes|
| Case 3    | 5 heat packs & thermal reflector    |                 |

Figure 13. (a) Component setup and sensor calibration for -80 °C freezer experiment. (b) Thermal test block diagram.
The result for each condition are shown in Figure 14 (a). All condition started at average initial temperature of 24°C. As the time approaches minute of 20, there is an approximately 100% decrease from the initial temperature and this is due to the payload bus incapable to withstand the cold temperature. On top of that, the heat packs for case 1 and 2 are not fully released the heat. Since, heat packs are passive thermal components, it needed some time in order to release the heat. However, as time goes on to minute of 60, there is a slight increase in temperature as the heat pack started to give out its maximum heat and stabilizes the internal temperature.

It can be observed that, a heat packs along with thermal reflector are better in containing the heat inside the payload bus as it records higher temperature compare to only with heat packs. As for case 1, the internal temperature drops and it only depends on the payload bus material to withstand the cold temperature. From this test, it can be concluded that the heat packs with thermal reflector are the best in handling cold thermal environment.

The test continues using -80°C freezer with an objective to simulate the actual thermal environment in the stratosphere. This also give us the chance to test the BMP180 and Arduino UNO operating condition as both components are not able to work under -40 °C based on its product datasheet. The outer payload structure is sprayed with ethanol solution to make sure there is no contamination in the freezer. It is assumed that the ethanol solution does not have any impact to the temperature change in the payload structure.

As shown in Figure 14 (b), the internal and external temperature drops linearly. Nevertheless, the heat packs and thermal reflector can withstand the -80 °C cold temperature and able to maintain above -40 °C which is above the operating temperature for BMP180 and Arduino UNO.

3.6 Balloon & Navigation
The parachute is tested by dropping a dummy payload with a mass of 0.5 kg from height of 22.4 m. Two types of parachute are developed with two different design. The parachute is made up from plastic and nylon fabric material. Each one of the parachute has a hole at its center namely Apex Vent. The function of Apex Vent is decrease the drag by enabling the air to flow through the parachute. Without the Apex Vent, the air will accumulate at the parachute center and this increases drag [5]. The diameter of the Apex Vent is set at 0.1 m. However, selecting suitable material also gives a significant impact on the performance of the parachute. This can be seen in Table 5.
Table 5. Descent time & velocity for different types of parachutes

| Type of Parachutes                        | Descent Time (s) | Descent Velocity (ms⁻¹) |
|------------------------------------------|------------------|-------------------------|
| Plastic Parachute (without AV)           | 14.0             | 1.60                    |
| Plastic Parachute (with AV)              | 11.6             | 1.93                    |
| Nylon Fabric Parachute (without AV)      | 8.0              | 2.80                    |
| Nylon Fabric Parachute (with AV)         | 7.0              | 3.20                    |

Based on the testing result, nylon fabric parachute seen in Figure 15 (b) has a higher velocity compared to both plastic parachutes shown in Figure 15 (a). This is due to the weight of the parachute. Heavier parachute resulting a higher descent rate. The effect of Apex Vent can be seen in the table as with the same material, for instance, the nylon fabric parachute, shows a different descent time and descent rate results. Nevertheless, this is still an estimation whereas it does not take into account effect of cross-wind. During flight, the bus will experience different type of aerodynamic forces such as wind which are random. Thus, the performance of the parachute may vary at different flight conditions.

3.7 Final Design

After finishing the component tests, the final design configuration of the HAB can now be finalized. The block diagram of the system is as shown in Figure 16.
4. Flight Test
A trial launch flight test was conducted to test the system integration. The system comprises of all of the subsystems except Trackuino due to the unavailability to obtain the operating license. However, the only way to track the balloon is by using SPOT Messenger GPS. This is risky due to the capability of the SPOT Messenger that can only be used up until 6 km and the GPS might lose connection in case the balloon floats away from the launch site. Nevertheless, the flight test is done successfully as the payload are able to retrieve. The data is then compared with the International Standard Atmosphere (ISA) data and from the Malaysia Meteorological Department (MET Malaysia).

4.1 Atmospheric data
Four atmospheric data are recorded during the flight test which are altitude, temperature, pressure, and humidity. Based on Figure 17 (a), the highest altitude recorded is 24.2 km. It takes approximately 39 minutes to achieve its maximum altitude. The total flight time is 1 hour and 21 minutes, though, retrieval time took the total mission time to nearly 3 hours. Based on the same figure, the ascent rate and descent rate can be calculated which are 9.2 ms\(^{-1}\) and 10.4 ms\(^{-1}\) respectively.

\[ \text{Altitude (km)} \]
\[ \text{Time (hour)} \]

\[ \text{External Temperature (°C)} \]

\[ \text{Pressure (N/m}^2\text{)} \]

\[ \text{Humidity} \]

Figure 17. (a) Recorded altitude during trial launch. (b) Comparison of external temperature of payload bus with ISA data and MET Malaysia at different altitude.

Figure 17 (b) shows the temperature variation at different altitude. The ISA data are based on formula that are developed in 1920 by A. Toussaint [6]. The formula provides a simple and reasonable representation of the mean annual temperature results in United States yet it is not completed. The Standard Atmosphere was introduced as a reference atmosphere for the aviation industry and was never meant to be used to predict the actual barometric pressure at a particular location and was in fact developed by people who clearly recognized that there would be substantial local variations caused by latitude and seasons of the year [7]. In [8], it is clearly shown that different month and different places produces different temperatures variations. Plus, temperature change based on solar activity as there is high correlation between solar activity with the earth’s surface temperature [9].

It can be seen that in Figure 17 (b), the experimental data recorded by the BMP180 sensor is higher compared too other two data. This is due to the placement of the BMP180 sensor that might be too close to the transmitter and the heat contained in the payload affecting the result. Yet, the data is quite promising as the pattern is the same as the MET Malaysia data.

Observing the data shown in Figure 18 (a), the pressure recorded by the sensor is fairly accurate with the ISA data as well as with MET Malaysia data. The pressure decreases exponentially with recorded pressure of \(0.158 \times 10^5\) N/m\(^2\) at the maximum altitude.

Figure 18 (b) shows the variation of humidity results compared with data from MET Malaysia. The data from MET Malaysia are scattered but generally, the pattern is the same as
experimental data where the humidity reduces as the altitude increases. This is because of the decreasing temperature resulting in colder air. The sensor works by measuring the temperature of the air as warmer air will have higher humidity content.

![Graph showing pressure and humidity data](image)

**Figure 18.** (a) Comparison of pressure from experimental data with ISA data at different altitude. (b) Variation of humidity data at different altitudes.

### 4.2 Pre-launch Trajectory

Before the launching of HAB, the balloon trajectory is done to estimate the landing position of HAB. The prediction is done using two web-based predictors that is Cambridge University Spaceflight (CUSF) Landing Prediction by the University of Cambridge [10] and the Balloon Trajectory Forecasts by University of Wyoming [11]. Unfortunately, during the pre-launch day, there is unavoidable circumstances and delayed the balloon released by 2 hours. Hence, flight path prediction is done again on new flight time and it is shown in Figure 19.

![Path tracking prediction result](image)

**Figure 19.** Path tracking prediction result. (a) Wyoming’s predictor. (b) CUSF landing predictor.

Based on Figure 19 (a), the prediction shows the launch position (blue point), burst position (red tag), and balloon position (star symbol). It is predicted that the flight time is 2 hours with a landing coordinate of 5°17'31"N, 99°28'14"E.

By using the CUSF landing predictor, the total flight time is approximately 2 hours as well compared to Balloon Trajectory Forecasts by Wyoming University observed in Figure 19 (b). The predicted landing position is at 5°17'31.3"N, 99°28'14.0"E which is identical to the Wyoming’s result. Figure 20 (a) shows the position recorded using SPOT Messenger. Notice that, between position-feed 8 and position-feed 9, there is a huge gap. There is where the commercial communication limit which
is at the altitude of 6 km. However, SPOT Messenger manage to keep alive all the time up until 24.2 km and send signal back to the ground station when it reaches 6 km during descending. The landing coordinates registered by the SPOT Messenger is 5°17’31”N, 99°28’14”E.

![Figure 20](image1.png)  
(a) Balloon trajectory recorded using SPOT Messenger during trial launch. (b) Comparison of predicted results and actual trajectory for trial launch.

According to Figure 20 (b), the flight path for all three tracking results are fairly similar. This shows that both predictors are good enough to give an early estimation for the balloon trajectory but still falls short from the actual data as there is a possibility of unknown assumptions are used during the building of the software. In addition, actual flight is affected by the actual wind behavior that is unpredictable.

4.3 Image Results
Several images are taken during the flight including the curvature of the earth and the image of Penang island during landing are shown in Figure 21.

![Figure 21](image2.png)  
(a) Sample images of the earth curvature taken by the camera.

5. Conclusion
In this paper, the development and testing of USM High Altitude Balloon is investigated. The project is aimed to be able to collect atmospheric data as well as capturing images of the earth horizon whilst instill the interest in spacecraft design knowledge among undergraduate’s students.

The project is done by undergoing component testing to test each component reliability and it is followed by integration testing. Each testing has its own case study. Next, the HAB is trial launched to get a general idea on launching a high-altitude balloon. This also gives a chance to test the components in actual condition. The result from the trial launch is promising as data recorded is fairly identical to
the actual data. However, during actual launch, the payload could not be retrieved because of misinterpreting the data from SPOT Messenger and the Trackuino and weather problem on the sea that holds off the retrieve mission.

As for future works, there will be an implementation of autonomous guidance system that will help in returning the payload back to the launch site and upgrading the communication subsystem to have better tracking of balloon.

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