Design of an Attitude Control System for a High-Altitude Balloon Payload

Nguyen Khoi Tran[*], David Evan Zlotnik[†], and James Richard Forbes[‡]

Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada, H3A 0C3

Physicists seek to uncover expansion history of the universe by examining polarization patterns in the cosmic microwave background (CMB). Observatories in the South Pole are used to examine these polarization patterns, but no sufficient celestial source exists to properly calibrate these observatories. A method of calibrating these observatories would be to point a tuned microwave source to the ground-based observatory from a far distance. The purpose of this paper is to outline how the McGill High-Altitude Balloon (McHAB) team intends to use a high-altitude balloon with a reaction wheel actuator to slew and point the payload at altitudes of 15km to 20km to within an accuracy of $\pm 2^\circ$. A complementary filter with an inertial measurement unit (IMU) will be used to estimate the attitude of the payload. A proportional-derivative controller will be used to control the reaction wheel, and hence point the payload to a desired angle. The main processor will be a Raspberry Pi, a single-board computer using a single-core 700MHz ARMv6 CPU. The team has previously flown a payload, McHAB-1, containing the Raspberry Pi and an IMU to test the attitude estimator and collect attitude data. The team has flown a complete prototype of the system, McHAB-2, on April 28th, 2013. Data from this flight is presented showing that the reaction wheel can better point the system as the platform reaches higher altitudes.

I. Introduction

Physicists are interested in determining the expansion rate of the universe. To do this they measure information encoded in the microwave cosmic background (CMB) using ground-based telescopes. An example of such a telescope is the South Pole Telescope (SPT). The issue with observing the CMB using ground-based telescopes is the Earth's atmosphere is a large polarizing agent that severely reduces the accuracy of the telescope's measurements. It is necessary to have a well-calibrated source outside of Earth's atmosphere but, the best measured and calibrated celestial sources are from the Wilkinson Microwave Anisotropy Probe (WAMP) satellite which still has a 1.5° systematic error.[1] Thus, it is necessary to construct a man-made calibrated microwave source elevated above Earth's atmosphere carried by a balloon to calibrate these ground-based telescopes.

The design, construction, and launch of a stratospheric balloon platform capable of pointing a microwave source spawned the McGill High Altitude Balloon (McHAB) team, a group of undergraduate and graduate students at McGill University who seek to launch high-altitude balloon platforms for research purposes. The goal is to stabilize a platform to $\pm 2^\circ$ at an altitude of 20km for 1hr, and then using post processing techniques, determine the true attitude to within $\pm 1/10^\circ$. The novelty of this paper lies in the explicit and unique approach to attitude estimation and control of a small, inexpensive, high-altitude ballooning platform. There are significant challenges in dealing with the low temperature, weight requirements, and atmospheric disturbances. To help overcome these challenges, the McHAB team contacted a local ballooning club, the Ballon Radio Amateur du Quebec (BRAQ), to help launch their first balloon system. The group successfully launched and recovered their first payload, McHAB-1, on November 18^{th}, 2012. The purpose of the McHAB-1 payload was to learn the logistics of launching stratospheric balloons as well as test the

[*]Research Assistant. To whom all correspondance should be addressed. Email: `khoi.tran@mail.mcgill.ca`

[†]Research Assistant. Email: `david.zlotnik@mail.mcgill.ca`

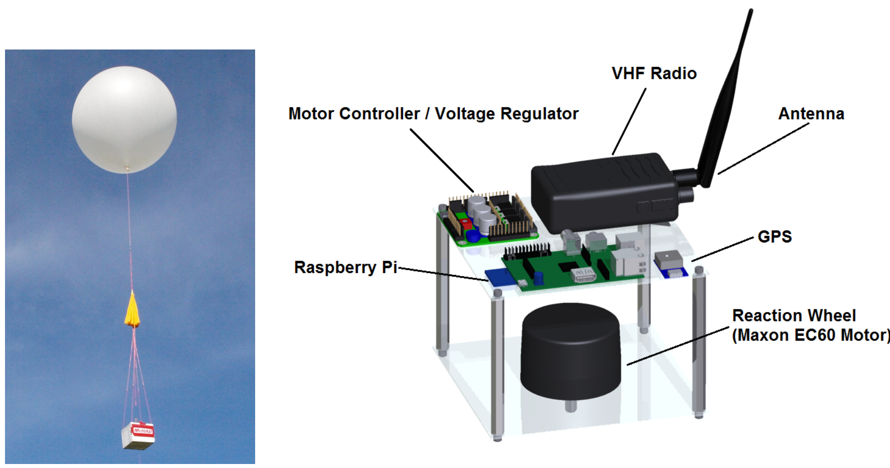
[‡]Assistant Professor. Email: `james.richard.forbes@mcgill.ca`

onboard attitude estimation system. On April 28th, 2013 the McHAB team launched their second payload, McHAB-2. The purpose of McHAB-2 was to test the on-board control system. This paper will outline the McHAB-2 payload, and discuss the flight results.

The remainder of this paper is as follows. In Section II, we illustrate a high-level overview of the entire system. In Section III and section IV we detail the mechanical and electrical systems. In Section V we present a method of attitude estimation and a simple controller. Section VI details McHAB's second flight where the attitude of the payload is estimated and controlled using the reaction wheel system with a proportional-derivative (PD) control law using the methods present in Section V.

II. System Overview

For McHAB-2, the basic balloon platform stack was kept fairly similar to McHAB-1. As shown in Fig. 1a, a meteorological weather balloon is at the top, a parachute lies between the balloon and the payload, and the payload is at the bottom. A high-density foam box encases the components shown in Fig. 1b. At the heart of the system is a Raspberry Pi single-board computer (SBC) that reads the sensors, estimates the system's attitude, and generates control commands. A large change between the preliminary design of the platform and the actual platform was the decision to put all the components on the outer walls of the box as well as remove the lithium polymer battery packaging and distribute the weight around the outer walls, as shown in Fig. 2. This reduced the weight of the platform by approximately 0.5lbs.



(a) Balloon stack (b) Preliminary Design of McHAB-2 platform

Figure 1: Platform

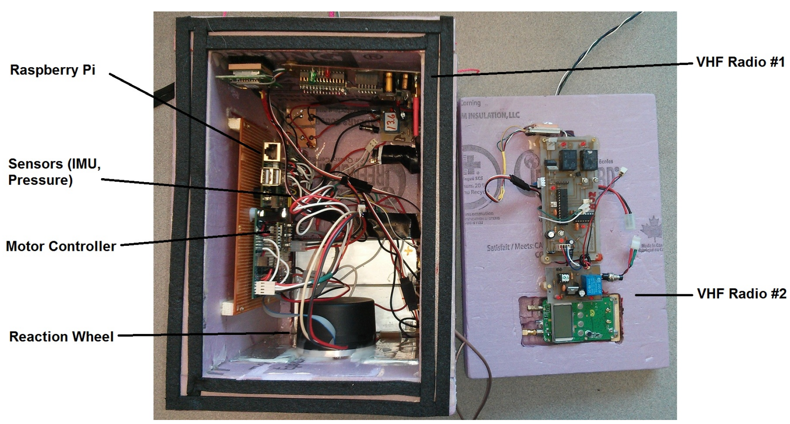


Figure 2: Actual McHAB-2 platform

III. Mechanical

A. Balloon and Interface

The balloon used in this launch is a 600g TA-type natural latex balloon from the Totex corporation. In Canada, the relevant government body that regulates unmanned balloon flights is Transport Canada (TC). Small unmanned balloon flights are largely unregulated in Canadian airspace; 'large' balloons are defined in the Canadian Aviation Regulation (CAR) 602.42 as a balloon with a gas carrying capacity of more than 115ft^3. The next lowest available size tank of Helium gas, M-size, allows us to have 108ft^3 of helium gas to satisfy this requirement. A 600g balloon with 108ft^3 of helium gas is expected to reach 25.9km, satisfactory for this mission.

B. Payload

1. Reaction Wheel System

The purpose of this project is to slew the payload to a desired angle. The following actuation mechanisms were considered at the start of this project: control-moment gyros (CMGs), reaction wheels, and magnetorquers. After comparing the advantages and disadvantages of each system, we decided to use a reaction wheel system. Reaction wheels are widely used in aerospace systems for attitude control.[2] A reaction wheel is driven by a electric motor that spins a rigid cylindrical mass, called a flywheel. Accelerating the flywheel in a controlled way enables slewing the payload, thereby enabling pointing of the payload.

In McHAB-2, the platform utilizes a Maxon EC-60 flat brushless motor which has a high moment of inertia. This property allowed the team to simply use the motor as a reaction wheel without manufacturing a flywheel. The reason for using a reaction wheel system as opposed to other actuation systems is that a reaction wheel system is simple to control compared to other systems. The disadvantage is that any motor has a maximum rotational speed. Since a control torque is realized by having an angular acceleration, which involves increasing or decreasing the angular velocity of the rotor, the angular velocity of the rotor eventually reaches a maximum. This is called reaction wheel saturation and the motor can no longer create a torque to stabilize the system.

Figure 3: Maxon EC-60 brushless motor

IV. Electrical

A. Processor

An emerging technology in small computing devices has been low-power ARM-based single-board computers (SBC) such as the Raspberry Pi. Since the Raspberry Pi has Universal asynchronous receiver/transmitter (UART), Inter-IC (I^2C), and Serial Peripheral Interface (SPI) pins with built-in operating system (OS) compatibility in Debian Linux, the team investigated the use of a Raspberry Pi for attitude sensing and control. The language of choice in the Raspberry Pi community is Python 2.7; the vibrant Raspberry Pi community releases open source code which assists in communicating with low-level sensors. The Raspberry Pi itself is a 700MHz ARMv6 single-core computer running Debian 'wheezy' Linux with 512MB of RAM; these specs far surpass equivalently sized embedded solutions. The OS boots off a standard SD card which can also be used for long-term storage; the team used a class-10 32GB SD card which allowed for near limitless data storage.

All of the flight software for McHAB-2 is written in Python 2.7 (ARM build) with reliance on the Python SMBus library which assists in communicating with I^2C devices since all the sensors used in this project were I^2C devices. Another useful library was the Numpy library. The attitude estimation and control code was initially written in `MATLAB` then ported to Python using the Numpy module; many `MATLAB` functions are analogous to Numpy functions.

B. Sensors

1. *Attitude Sensing*

There are a variety of ways to sense the attitude of a system. This project simply uses an inertial measurement unit (IMU) which consists of an accelerometer, gyroscope, and magnetometer. An accelerometer measures linear acceleration, a gyroscope measure angular velocity, and a magnetometer measures the magnetic field flowing through the device. The IMU used in this project is MEMS-based. Microelectromechanical systems (MEMS) are small mechanical systems at a micrometer scale that create small electrical signals that can be converted using an analog to digital converter (ADC). The IMU used in this project is a Pololu MiniIMU-9 which has all three sensors built onto a small breakout board. The MiniIMU-9 contains an 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer; the values for these sensors can all be read using the I^2C protocol.

An IMU is convenient for this project because it are very cheap, very small, and uses very little power. The measurements from these sensors provide redundant attitude information that can be used in a sensor fusion technique, such as a complementary filter, to estimate the attitude of the system.

2. *Global Positioning System*

A Global Positioning System (GPS) sensor uses the satellite system realized by the US Department of Defense (DoD) to locate the position of the sensor by measuring the time of flight of the signals sent by GPS satellites; four satellites are required to properly determine the sensor's position. This process is called trilateration and involves creating four intersecting spheres to pinpoint the location of the sensor.

A problem that plagues amateur ballooning are COCOM limits placed upon GPS sensors; the GPS must turn off if it is moving faster than 1,200mph or higher than 60,000ft. The intention of this limitation is so the GPS sensors cannot be used for nefarious purposes, but amateur ballooning systems regularly climb higher than 18km. This limitation severely restricts which GPS sensors are suitable for amateur ballooning. Many GPS manufacturers interpret the COCOM limits differently and only shut off if both limitations are met. Since amateur balloons will never go faster than 1,200mph these types of sensors are sought after. McHAB was able to obtain the Inventek ISM300F2 High Altitude Build which raises the maximum altitude to 135,000ft.

C. Cutdown Mechanism

While small unmanned balloon flights are not regulated by CAR, and thus it is not stipulated that the team must create a cutdown mechanism, Montreal is very close to a natural jet stream and it is likely that the balloon could be carried very far away by this jet stream. A cutdown mechanism was also strongly suggested by BRAQ since they have experience with the balloon's remains (after burst) tangling with the parachute, preventing the parachute's deployment. A simple cutdown mechanism is to use a small resistor with an n-channel MOSFET to create a large amount of heat which will cut a nylon string that holds together the entire balloon stack. This circuit is illustrated in Fig. 4. The Raspberry Pi simply sends a cutdown command by raising a GPIO pin to 3.3V into the gate of the n-channel MOSFET.

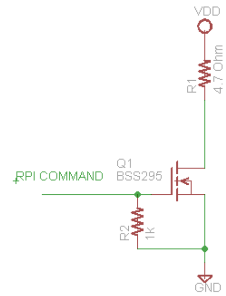


Figure 4: Schematic of cutdown mechanism

D. Communications

In McHAB-1, the team experienced poor results with the SPOT satellite locator. Once the unit reached 40,000ft, it stopped transmitting for the duration of the flight and never began retransmitting. The communication module that assisted us in finding our payload was BRAQ's Automatic Packet Reporting System (APRS) radio which operated at 144.39MHz, a VHF amateur radio frequency. The advantage to using APRS is that it is a distributed system maintained by the amateur radio community; meaning any amateur radio operator can relay coordinates they hear onto the APRS.IS server allowing the public to view these coordinates; this system avoids reliance on a single line-of-sight communicator. Since a team member recently received his amateur radio license, the team decided to use it along with BRAQ's license to fly two APRS radio beacons with call signs VA2NKT and VA2RMG.

E. Power

There are two power systems on this flight, a 14.8V system which drives the main controller, a reaction wheel, and an APRS transmitter. A separate 7.4V system only powered an APRS transmitter. On the 14.8V system, while 14.8V is required to drive the reaction wheel, the rest of the electronics operates on a 5V/3.3V logic level. The LMZ14203 switching voltage regulator is used to efficiently drop the voltage down from 14.8V to 5V and the on-board linear voltage regulator from the Raspberry Pi provides 3.3V to each sensor.

V. Attitude Estimation and Control

The dynamics and kinematics of the balloon payload system are described in detail in Ref. 3. The estimation algorithm used on McHAB-1 and the proposed controller were developed in Refs. 3 and 4. In this section, the estimation algorithm will be reviewed and updated, and the control algorithm is discretized for use with the McHAB-2 hardware.

A. Estimation

The attitude of the balloon payload must first be estimated before feedback control can be implemented. We have implemented the nonlinear complementary filter proposed in Ref. 5. This estimator evolves on $SO(3)$ and uses direct inertial measurements to update the estimated attitude.[5] It should be noted that the filter in Ref. 5 includes gyroscope bias compensation. We have not included this compensation in the estimator dynamics for this flight, however, we plan to implement this in future flights.

The estimator dynamics obey

$$\dot{\hat{\mathbf{C}}}_{bi} = -(\boldsymbol{\omega}^y + \boldsymbol{\sigma})^\times \hat{\mathbf{C}}_{bi},$$

where $\hat{\mathbf{C}}_{bi}$ is the rotation matrix describing the current estimate of the true attitude, described by $\mathbf{C}_{bi}$, $\boldsymbol{\omega}^y$ is the measured angular velocity of the payload, and $\boldsymbol{\sigma}$ is the innovation term.[5] The innovation must be chosen such that $\hat{\mathbf{C}}_{bi}$ is driven to $\mathbf{C}_{bi}$. To this end, we consider the accelerometer and magnetometer measurements, denoted $\mathbf{g}_b^y$ and $\mathbf{m}_b^y$ respectively. Here, the subscript b denotes that the measurements are expressed in the body frame of the payload. The real gravitational acceleration and magnetic field vectors can be expressed in a North, East, Down (NED) inertial frame as $\mathbf{g}_i$ and $\mathbf{m}_i$. We assume that $\mathbf{g}_i = [0\ 0\ 1]^\mathsf{T}$ and we calculate $\mathbf{m}_i$ on board from the IGRF-11 magnetic field model.[6] Then, our estimate of the inertial measurements expressed in the body frame can be found by

$$\hat{\mathbf{g}}_b = \hat{\mathbf{C}}_{bi}\mathbf{g}_i \quad \text{and} \quad \hat{\mathbf{m}}_b = \hat{\mathbf{C}}_{bi}\mathbf{m}_i.$$

Now, the innovation term can be constructed by comparing the estimated and measured inertial measurements,

$$\boldsymbol{\sigma} = -k(k_g\hat{\mathbf{g}}_b^\times\mathbf{g}_b^y + k_m\hat{\mathbf{m}}_b^\times\mathbf{m}_b^y),$$

where $0 < k < \infty$, $0 < k_g < \infty$, and $0 < k_m < \infty$ are constants.[5]

B. Control

The control algorithm of the balloon platform was considered in Refs. 3 and 4. The simple proportional and derivative controller takes the form,

$$\tau_c = -k_p\hat{\theta}_3 - k_d\omega_3^y,$$

where τ_c is the control torque imposed on the payload from the reaction wheel, $\hat{\theta}_3$ is the estimated yaw angle of the payload extracted from $\hat{\mathbf{C}}_{bi}$ and ω_3^y is the third component of the measured angular velocity. Since we are only equipped with a speed controller for the Maxon motor, we cannot command the motor torque directly. Instead, when the control command is updated the speed of the motor is set such that the change in angular momentum of the motor will create the desired torque. The rate of angular momentum of the wheel is $\dot{h} = I_s\dot{\omega}_s$, where I_s is the moment of inertia of the motor and ω_s is its angular velocity. Then, discretizing we find

$$\begin{aligned} \tau_c &= -\dot{h} \\ \tau_c &= -I_s\frac{\Delta\omega_s}{T}, \end{aligned}$$

where T is the sample time and $\Delta\omega_s$ is the required change in angular velocity of the motor. Rearranging,

$$\Delta\omega_s = -\tau_c\frac{T}{I_s}.$$

The speed command to the motor can then be found by summing the past angular velocity changes,[7]

$$\omega_s^k = \sum_{i=0}^{k}\Delta\omega_s^i.$$

VI. McHAB-2

A. Purpose

McHAB-2 was launched on April 28, 2013. Again, BRAQ assisted the team in launching their second balloon. The purpose for this flight was to fly an updated attitude estimator which dynamically updated the Earth's magnetic field based on its current location and height as well as to fly the reaction wheel system. This system will give the team a baseline on which to design future systems.

B. Flight

The team once again launched from the same location as McHAB-1, along the Richelieu river North-East of Montreal, Quebec, Canada. The payload travelled 59km and landed near Granby, Quebec, Canada. To test the control, the control system was activated for 30 seconds every 10 minutes.

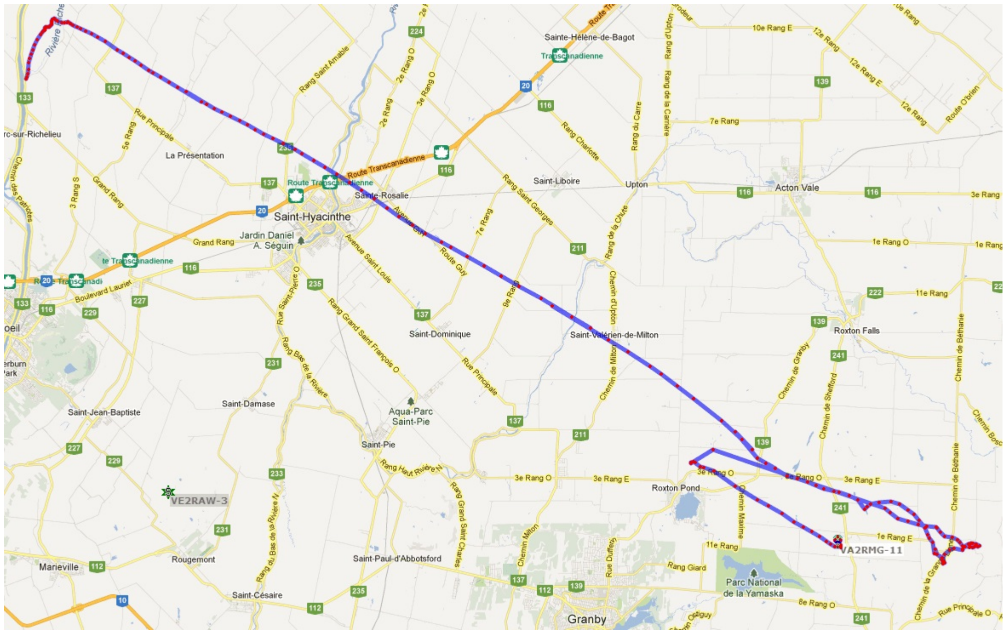


Figure 5: Flight path of McHAB-2

C. Results

The team was able to recover the payload which contained all the data written onto the Raspberry Pi's 32GB SD card. In Fig 6, the altitude vs. time graph is shown. From Fig. 6, the flight time was 3hr and the payload reached a peak altitude of 26.34km.

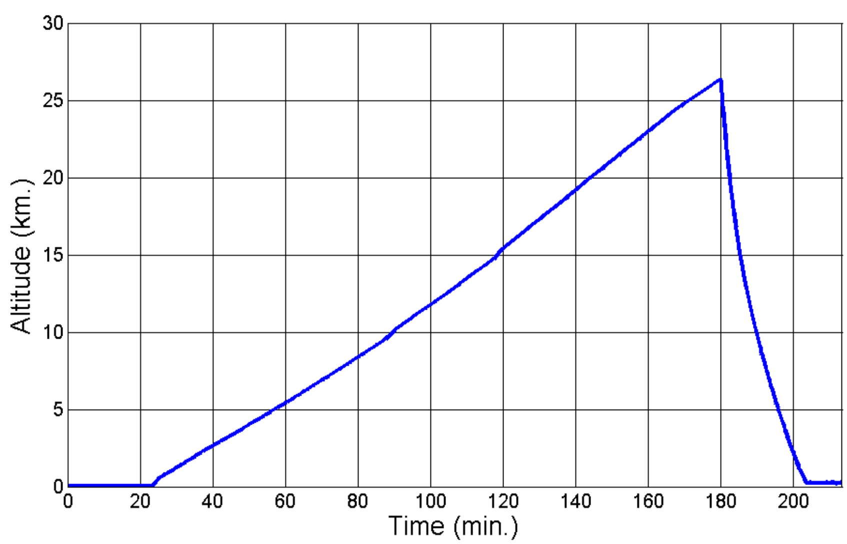
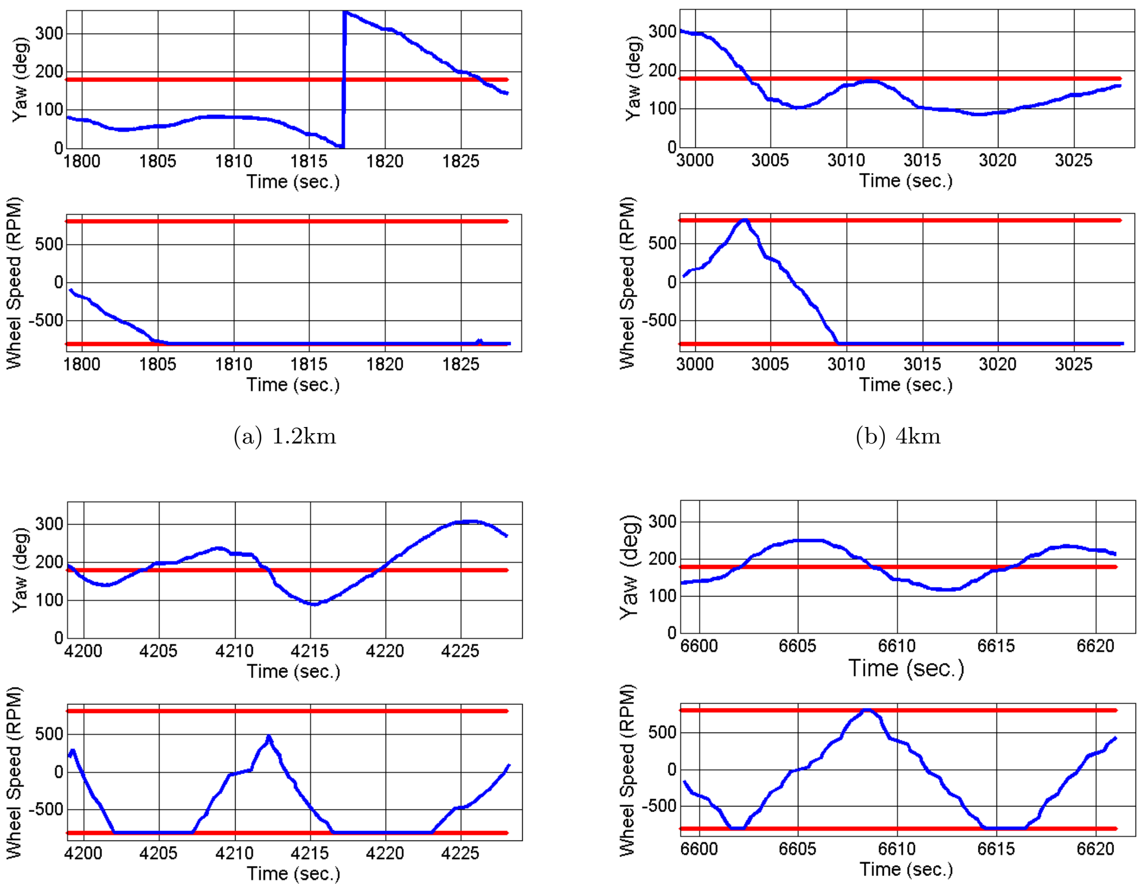


Figure 6: Altitude vs. Time of McHAB-2

The important data from this flight was the data relating to the yaw axis of the system when the reaction wheel control system was activated. As noted earlier, the control system was only activated every 10 minutes for 30 seconds. The control system was designed to point the payload South, which is 180° from North. Fig. 7 shows the yaw axis of the system along with the motor RPM during these instances. Fig. 7a shows the first time the control system was activated, at 1.2km, and indicates that the motor saturates very quickly. As the payload floated higher, the motor saturated less often and was able to better control the system. The last time the control was turned on was at 13.5km and points at roughly $\pm 60°$. This illustrates the fact that the pointing becomes better as the platform ascends higher. While the pointing error is very high, it shows that this system is capable of stabilizing the platform. Fig. 8 illustrates the yaw of the platform under no control at 7km in a 30 second interval to show the difference between the controlled system and uncontrolled system. These results serve as a baseline for the McHAB team. Future work will be to resize the reaction wheel in order to reach the pointing accuracy required.



(a) 1.2km (b) 4km

(c) 6.8km (d) 13.5km

Figure 7: Platform yaw angle and motor RPM at various altitudes. Red line for yaw angle indicates the target pointing angle. Red lines for the motor RPM indicate saturation speeds.

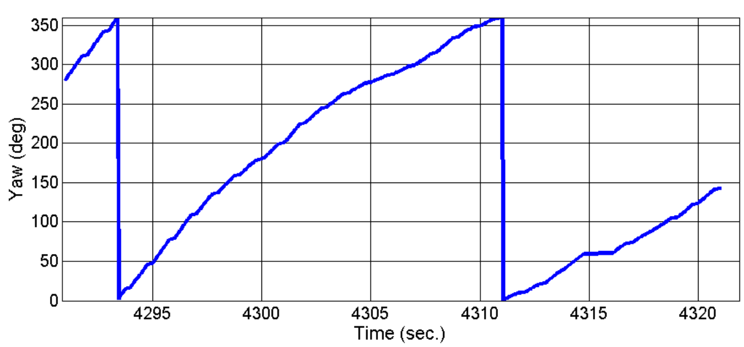


Figure 8: Uncontrolled system at 7km

VII. Closing Remarks

This paper presents the design, construction, and test of a stratospheric balloon platform capable of attitude stabilization. The high-level system is first presented, then the mechanical design and actuation method is reviewed. Next, the electrical systems were considered; the on-board processor, sensors, cutdown mechanism, communication systems, and power systems were discussed. The estimation method and control of the platform is explained. Finally, the launch of this system is detailed. The launch of McHAB-2 led to successful results in evaluating the reaction wheel system. While the pointing accuracy is still low, it gave the team a baseline on which to build upon when undertaking the design the next reaction wheel system. It also gave the team more data to better understand the turbulent nature of the upper atmosphere. Notably it was found that in the upper atmosphere the conditions are relatively calm and the external disturbances are relatively low compared to conditions in the lower atmosphere.

VIII. Acknowledgments

The McHAB team is very grateful for the assistance provided by the Ballon Radio Amateur du Quebec (BRAQ). In particular, the team would like to thank BRAQ member Michel Graveline. The McHAB team would like to also thank Profs. Matt Dobbs and Victoria Kaspi from the Department of Physics and McGill University for funding the McHAB team.

References

[1]Weiland, J. L., Odegard, N., Hill, R. S., Wollack, E., Hinshaw, G., Greason, M. R., Jarosik, N., Page, L., Bennett, C. L., Dunkley, J., Gold, B., Halpern, M., Kogut, A., Komatsu, E., Larson, D., Limon, M., Meyer, S. S., Nolta, M. R., Smith, K. M., Spergel, D. N., Tucker, G. S., and Wright, E. L., "Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Planets and Celestial Calibration Sources," *The Astrophysical Journal Supplement Series*, Vol. 192, Feb. 2011, pp. 19–40.

[2]Leverence, R., Rovera, M., and Staunch, R., "Attitude Control Systems," Tech. rep., Worcester Polytechnic Institute, April 2008.

[3]Zlotnik, D. E. and Forbes, J. R., "Dynamic Modelling, Estimation, and Control for Precision Pointing of an Atmospheric Balloon Platform," *2013 CCToMM M3 Symposium, Montreal, Quebec, Canada, May 30-31, 2013*.

[4]Tran, N. K., He, X., Zlotnik, D. E., and Forbes, J. R., "Attitude Sensing and Control of a Stratospheric Ballon Platform," *AIAA Balloon Systems Conference, Daytona Beach, Florida, USA, March 25-28, 2013*.

[5]Hamel, T. and Mahony, R., "Attitude Estimation on SO(3) Based on Direct Inertial Measurements," *IEEE International Conference on Robotics and Automation, Orlando, Florida, USA, May 15-19, 2006*, pp. 2170 –2175.

[6]Finlay, C., Maus, S., Beggan, C., Bondar, T., Chambodut, A., Chernova, T., Chulliat, A., Golovkov, V., Hamilton, B., Hamoudi, M., et al., "International Geomagnetic Reference Field: The Eleventh Generation," *Geophysical Journal International*, Vol. 183, No. 3, 2010, pp. 1216–1230.

[7]Kerns, A., "DSR, Spring 2012," Tech. rep., Cornell University, May 2012.