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

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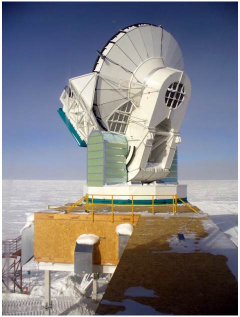
Introduction

Background

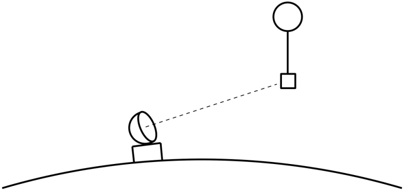
- Physicists seek to determine the expansion rate of the universe by observing polarization in the cosmic microwave background (CMB).
- Ground-based telescopes exist to observe this type of polarization.
    - No celestial source is strong enough to properly calibrate these telescopes.



Introduction

High-Altitude Ballooning

- A high-altitude balloon can be used to elevate a tuned microwave source to calibrate these telescopes.
- An actuator can be used to correctly point the source to the telescope.
- High-altitude ballooning is quickly becoming a relatively inexpensive hobby.



Goals

- Construct a high-altitude ballooning platform with attitude control for the purpose of pointing down to a ground-based telescope.
- Must be able to point to within $\pm 1^{\circ}$ at an altitude of approximately 15 km.
- Payload must be compliant with ballooning regulations.
  - Less than 6 lb per box for the Federal Aviation Administration.
  - Less than 112 ft^2 of gas in the balloon for Transport Canada.
- Inexpensive (budget of $1800).

Actuation

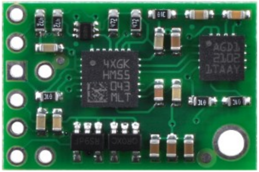
- A reaction wheel system was implemented.
- Functions by applying/creating a torque about an axis of rotation.
- A Maxon EC-60 Flat brushless motor was used as a reaction wheel.
- The flat, cylindrical shape of the inner rotor essentially serves as a flywheel.

Balloon and Interface

- 600 g Totex Balloon bought from Kaymont balloons.
  - With a 6 lb payload and 110 ft^3 of helium, this is enough to lift the payload to approximately 25 km.
- A swivel hook is used at the interface between the parachute and the balloon to decouple the box from the spinning of the balloon.

Sensors

- Inertial measurement unit (IMU) contains an accelerometer, gyroscope, and magnetometer.
  - Accelerometer measures the acceleration of the system.
  - Gyroscope measures the angular velocity.
  - Magnetometer measures the magnetic field.
- All three of these sensors can be combined using sensor fusion techniques.
- Specifically, we used a Pololu MiniImu-9 with L3G4200D gyroscope and LSM303DLM accelerometer/magnetometer which communicates on the Inter-Integrated Circuit (I^2C) bus.

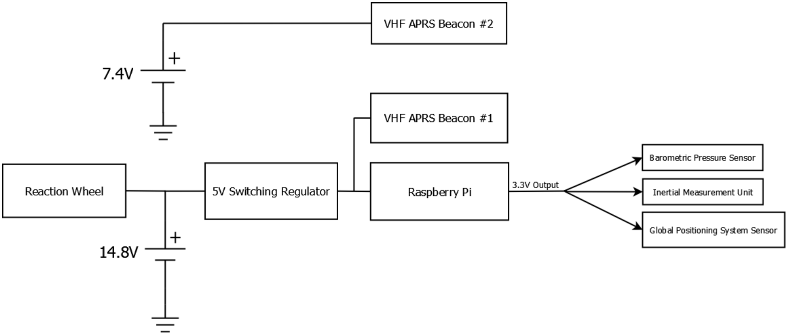


Processor

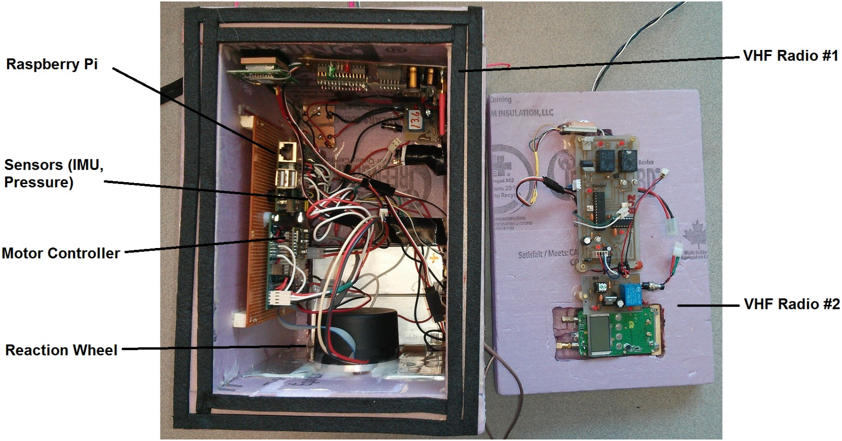
- Used a Raspberry Pi single-board computer containing a 700MHz ARMv6 processor and 512mb RAM.
- Runs on Debian Linux allowing for the entire codebase to be written in Python 2.7.
- Has breakout connections to SPI, I2C, and UART for sensor communication.

Power

- Main system powered using a single 4 cell 14.8V lithium polymer battery.
- A 5V switching regulator is used to power the Raspberry Pi along with various sensors.
- A separate 2 cell 7.4V lithium polymer battery powers one VHF transmitter.



Platform Layout

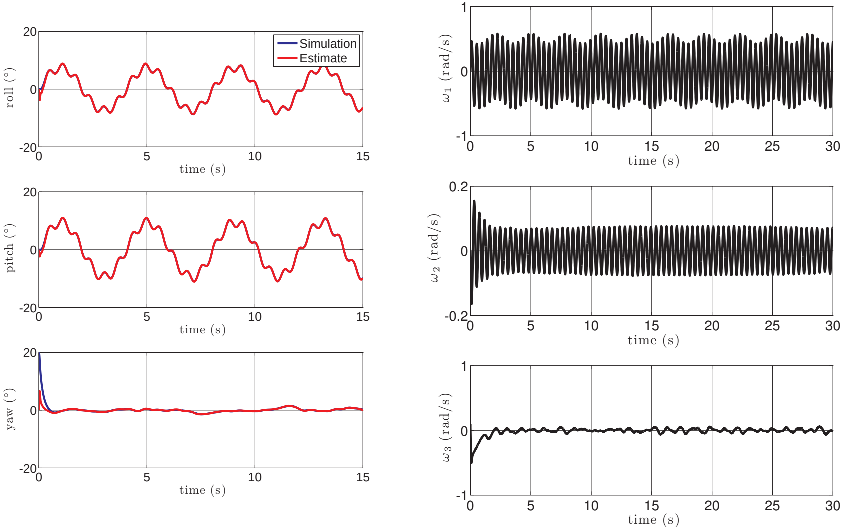


Estimation and Control

- We estimate the rotation matrix describing the attitude using the method of Mohany and Hamel.
- A more sophisticated way of estimating Euler angles (pitch, roll, yaw) of the system; similar to a complementary filter.
- The goal is to drive $\hat{\mathbf{C}}_{bi}$, the estimated attitude, to $\mathbf{C}_{bi}$, the true attitude.
- Use a PD control law based on yaw error:

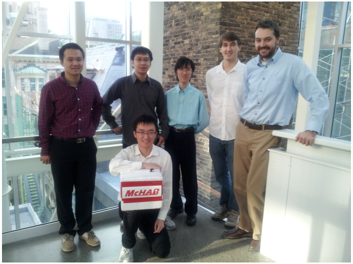
$$\tau_{c,3} = -k_p \hat{\theta}_3 - k_d \omega_3^y.$$

Simulation Results



Maiden Flight

- Created the McGill High Altitude Ballooning (McHAB) team.
- Ballon Radio Amateur du Quebec (BRAQ), a local ballooning group, helped launch the payload.
- Purpose of the first launch:
  - learn how to launch stratospheric balloons;
  - test our attitude estimator;
  - and, collect some preliminary data on atmospheric conditions.



McHAB-2

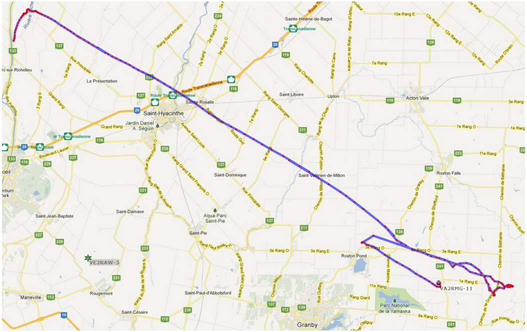
Purpose

- Collect more attitude data using the estimator.
  - Payload train now only contains one box.
- Test reaction wheel system.
- Continue to learn how to launch stratospheric balloons.

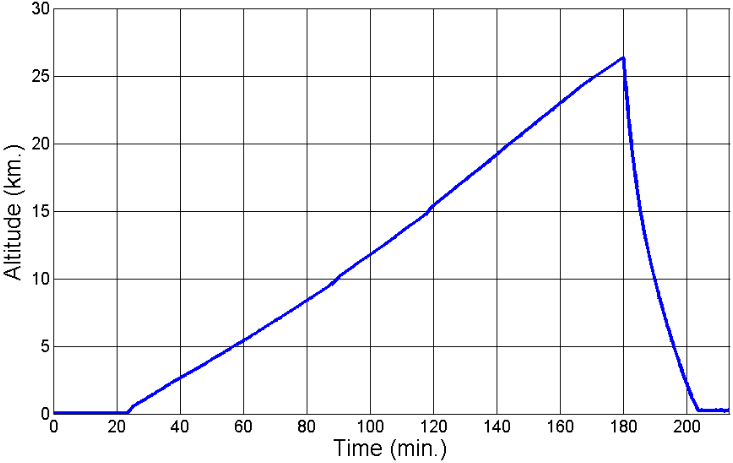
McHAB-2 Flight Results

Flight Outcome

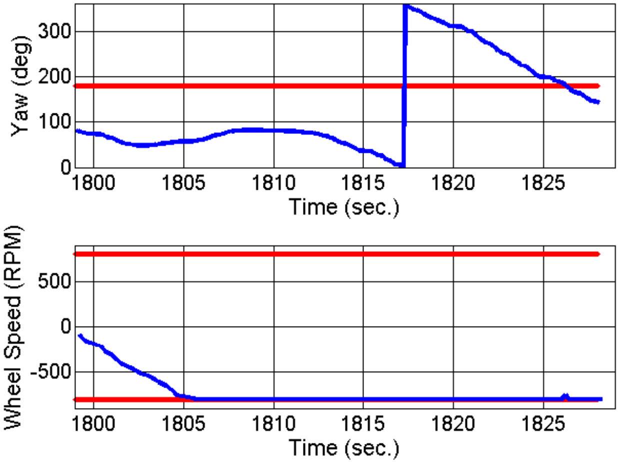
- Payload traveled 59km in 3.5hr landing close to Granby, Quebec, Canada.
- Successfully recovered payload containing data stored on the Raspberry Pi's 32GB SD card.



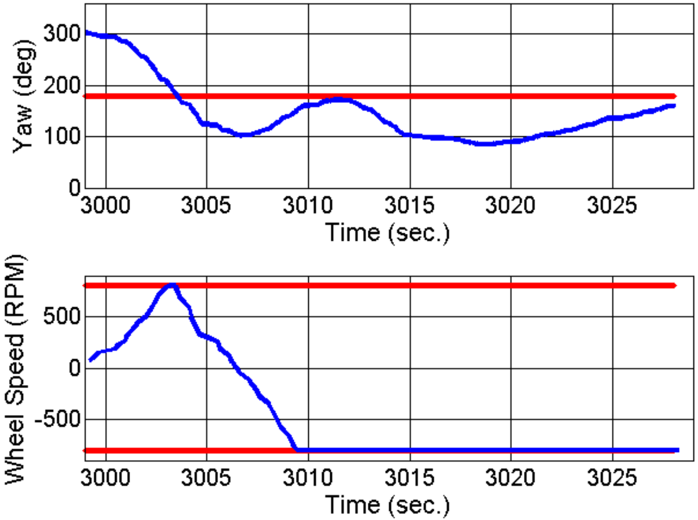
McHAB-2 Altitude



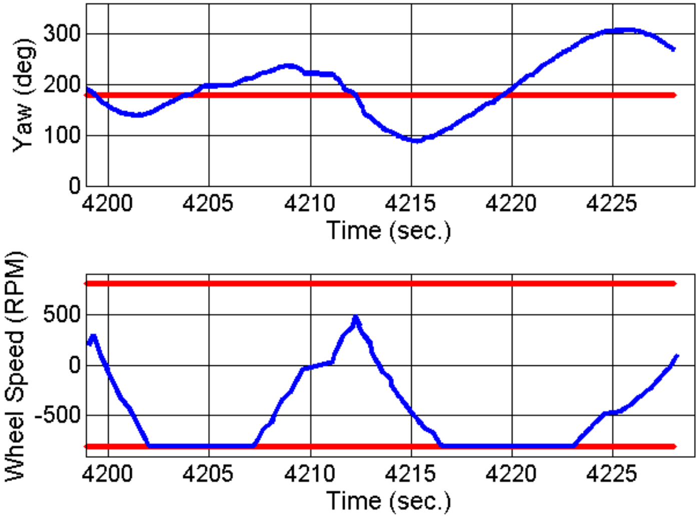
McHAB-2 Control of Yaw Axis at 1.2km



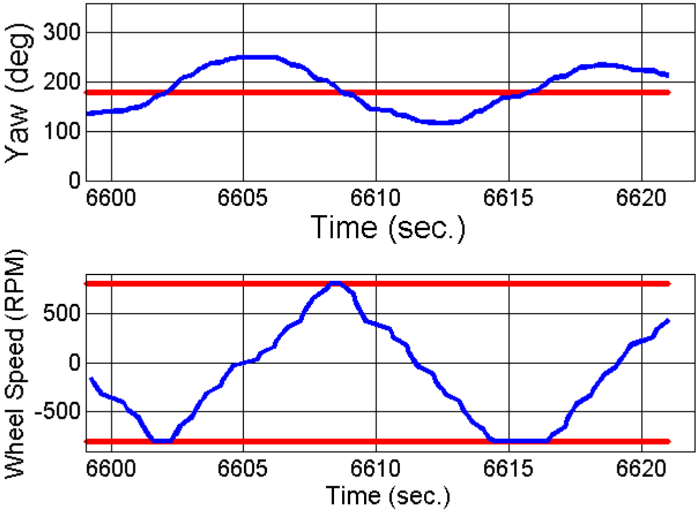
McHAB-2 Control of Yaw Axis at 4km



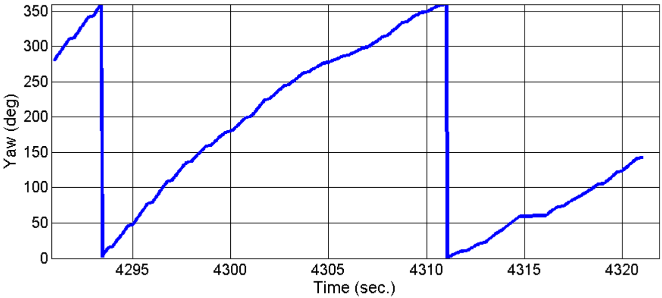
McHAB-2 Control of Yaw Axis at 6.8km



McHAB-2 Control of Yaw Axis at 13.5km



McHAB-2 Yaw Axis at 7km with no control



Conclusions and Future Work

Conclusions

- Reaction wheel inertia does not provide enough control torque.
- Reaction wheel does not saturate as fast at higher altitudes.
- No adequate means to desaturate the reaction wheel.

Future Work - McHAB-3/SPT HAB

- Equip with reaction wheel with a flywheel to increase the control authority.
- Determine how to effectively desaturate the reaction wheel.
- Redevelop software using a microcontroller.

Questions

Thank you for your attention, and attending.

Questions?

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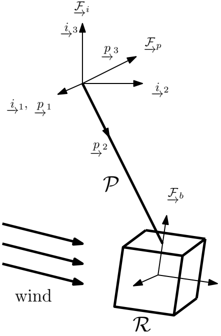
Presentation created using LaTeX and Beamer.

Modelling the System

- Model the system as two rigid bodies, a pendulum representing the tether, and the platform.
- Use Lagrange's equation to derive the motion equations:

$$\hat{\mathbf{M}}(\boldsymbol{\theta}^{bi}, \boldsymbol{\theta}^{pi})\dot{\hat{\boldsymbol{\nu}}} + \hat{\mathbf{f}}_{non} = \hat{\mathbf{f}} + \hat{\boldsymbol{\tau}}_c,$$

where $\hat{\boldsymbol{\nu}} = [\boldsymbol{\omega}_b^{bi^{\mathsf{T}}} \;\; \boldsymbol{\omega}_p^{pi^{\mathsf{T}}}]^{\mathsf{T}}$, $\hat{\mathbf{f}}_{non}$ are the nonlinear inertial forces, $\hat{\mathbf{f}}$ are disturbances, and $\hat{\boldsymbol{\tau}}_c$ is the control torque.



Estimation and Control

- We estimate the rotation matrix describing the attitude using the method of Mohany and Hamel.
- The goal is to drive $\hat{\mathbf{C}}_{bi}$, the estimated attitude, to $\mathbf{C}_{bi}$, the true attitude. Specifically,

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

  where $\hat{\boldsymbol{\omega}} = \boldsymbol{\omega}_b^{bi^y} + \boldsymbol{\sigma}$, and $\boldsymbol{\sigma}$ is the innovation,

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

  where

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

  are the estimates of $\mathbf{g}_i$ and $\mathbf{m}_i$ expressed in the body frame.
- Use a PD control law based on yaw error:

  $$\tau_{c,3} = -k_p\hat{\theta}_3 - k_d\omega_3^y.$$