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Dynamic Modeling and Attitude Control of High-Altitude Balloon Payload

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Dynamic Modeling & Attitude Control of a High-Altitude Balloon Payload

by

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Dedication

I would like to dedicate this Honors Capstone project report to the members of The University of Alabama in Huntsville’s Space Hardware Club for making this project possible with their funding, membership knowledge base, and constant support. In doing so, they have not only made this project possible but also have ensured its long time development and success.
Abstract

The Space Hardware Club, a student led design-build-fly organization at The University of Alabama in Huntsville, often make use of high-altitude ballooning as a resource and platform for testing, teaching, sensing, and experimentation. However, while the general dynamics of these flights have previously been empirically characterized using Inertial Measurement Unit (IMU) data, a general dynamic model has never been fully realized or studied amongst the organization’s members. Likewise, a controlling mechanism for these dynamics has also yet to be studied or implemented.

The study and control of these dynamics is important for several reasons. Aside from the intrinsic aesthetics of stabilized flight video, a stabilized and attitude controllable platform offers a foundation for better scientific experimentation and research, offering greater controllability over environmental influences, and lending to more accurate data collection. Moreover, a dynamic study and attitude control implementation of a high-altitude balloon payload serves to benefit not only the members of the Space Hardware Club but also many departments and research organizations with UAH’s umbrella.

This Honors Capstone Project report will summarize the preliminary mathematical modeling efforts of the dynamics of a HAB payload, gleaned from an extensive review of literature, and initial design and current progress of attitude stabilization control regime. Additionally, a preliminary mechanical and electrical design for a proposed HAB stabilization payload, specifically a small camera bearing payload, will also be presented.
Part 1 – Project Background

1.1 Introduction & Purpose of Project

Compared to other types of aerial and orbital testing platforms, high altitude balloons (HABs) offers a relatively cost effective solution for scientific experimentation that is easily accessible in the academic research environment. They can feature flights up to approximately 100,000 ft in mean-sea-level altitude (MSL), can have a variable flight time depending on physical characteristics of the balloon used, and can have relatively accurate altitude control depending on the style of the balloon used. Additionally, since HABs are capable of achieving such high altitudes as 100,000 ft, they are able to offer experimentation in a near space environment, not accessible by typical aviation, at a fraction of the price of putting a satellite into orbit. For small lifespan missions, this benefit is paramount with regards to mission cost.

The Space Hardware Club (SHC), a student led design-build-fly organization at the University of Alabama in Huntsville (UAH), often make use of high-altitude ballooning as a resource and platform for testing, teaching, sensing, and experimentation. Figure 1 depicts a typical high altitude balloon launch conducted by SHC. However, while the general first-order dynamics of these flights have previously been empirically characterized using Inertial Measurement Unit (IMU) data, a general dynamic model has never been fully realized or studied amongst the organization’s members. Likewise, a controlling mechanism for these dynamics has also yet to be studied or successfully implemented.
The study and control of these dynamics is important for several reasons. Aside from the intrinsic aesthetics of stabilized flight video, a stabilized and attitude controllable platform offers a foundation for better scientific experimentation and research, offering greater controllability over environmental influences, and lending to more accurate data collection. Moreover, a dynamic study and attitude control implementation of a high-altitude balloon payload serves to benefit not only the members of the Space Hardware Club but also many departments and research organizations with UAH’s umbrella.

With respect to this particular project, a stabilized and controllable HAB platform is desired in lieu of the upcoming 2017 total solar eclipse that will be passing through parts of Central and East Tennessee (Figure 2). The Alabama Space Grant Consortium (ASG) is particularly interested in captured video of this event from the perspective of a high-altitude balloon (Figure 3) as a collaborative mission effort between other Space Grant Consortium (SGC) branches in other parts of the country as a means to promote inter-SGC mission development.
Given the inherent attitude instability of a HAB payload during flight, both a method for stabilizing and pointing the suspended payload is needed in order to maintain reliable and quality footage of this eclipse. This Honors Capstone Project report summarizes the development of a first-order low-fidelity model of these dynamic flight behaviors and preliminary design of a HAB payload with a control regime to stabilize an on board camera platform for the purposes of filming this solar eclipse from high altitude.

1.2 Project Planning & Logistics

With respect to the degree of work that is likely required to both analyze and model this dynamic system and develop an appropriate control scheme implementation, an incremental development schedule was conceived by the members of the SHC that would begin mission and
payload development in the Fall of 2015 and continue development into the Spring of 2017. With the exception of the first increment development which would span the first two academic semesters, each academic semester in the timeline would facilitate a single increment development. The following summarizes each increment of project development and the goals that will be accomplished:

- **Fall 2015 (Increment 1 Development)**
  - Project proposal and budget acquisition
  - Perform review of literature
  - Generate dynamic model in MATLAB/Simulink of HAB payload dynamic system
  - Fidelity comparison of dynamic model data to empirical IMU flight data
  - Development of payload yaw stabilization control law
  - Preliminary design of payload mechanics and avionics
  - Preliminary Design Review (PDR)

- **Spring 2016 (Increment 1 Development Cont.)**
  - Detailed design of payload mechanics and avionics
  - Fabrication of mechanical and avionic subsystems for yaw stabilization
  - Software implementation of state estimation and yaw stabilization control law
  - Increment 1 Critical Design Review (CDR)
  - Design revisions per design review
  - Platform dynamic testing
  - Design revisions per dynamic testing results
  - Test flights, post flight data analysis, and performance assessment

- **Fall 2016 (Increment 2 Development)**
- Reanalysis of dynamic MATLAB/Simulink model and development of roll/pitch stabilization control laws
- Redesign of mechanical gimbal system and integration with supporting roll and pitch actuators and avionics
- Increment 2 Critical Design Review (CDR)
- Design revisions per design review
- Platform dynamic testing
- Design revisions per dynamic testing results
- Test flights, post flight data analysis, and performance assessment

- **Spring 2017 (Increment 3 Development)**
  - Development of extended software functionality for payload pointing control
  - Refinement of stabilization implementation and pointing performance
  - Increment 3 Critical Design Review (CDR)
  - Design revisions per design review
  - Platform dynamic testing
  - Design revisions per dynamic testing results
  - Test flights, post flight data analysis, and performance assessment

Given the developmental increments listed above, the scope of this Honors Capstone Project will encompass the work outlined for the first increment development during the Fall 2015 academic semester. Moreover, the later increments will be carried out by the members of SHC in the subsequent academic semesters, building on the foundation of the first increment development.
Part 2 – Project Design Analysis

2.1 Introduction & Definition of HAB Dynamic System

A HAB system can usually be simplified down to four major components: the accent balloon, the balloon tether attaching the balloon to the payload mass, the decent parachute to safely carry the payload back to the ground after the balloon bursts, and the primary payload mass containing all the necessary equipment needed to carry out the desired mission objectives. A depiction of this simplified HAB system can be found in Figure 4.

The dynamics of a balloon-payload system is, like most dynamic systems, a complex system when examined in its entirety. When undergoing a dynamic analysis, several variables can be considered including physical properties of the balloon, balloon tether, and suspended payload, environmental properties such as wind forces and changes in atmospheric temperature and pressure, and coupling relationships between the different HAB components such as the inertial coupling between the balloon’s motion and the payload.

To simplify some of the complexity of this analysis and to give a starting point for the modeling process, the payload can be represented as a rigid body mass suspended from a moment arm (the tether attaching the balloon to the payload mass) in the fashion of a spherical pendulum. For this analysis, the attachment point at the balloon is assumed as a fixed inertial reference point/frame. Figure 4 depicts this modeling configuration.
Assuming the tether is perfectly rigid and does not deform or flex, the rigid body payload mass can have five degrees-of-freedom (DOFs). Two of these DOFs are pendulation about the balloon’s two axes in the horizontal plane, perpendicular to the gravitational vector. The remaining three DOFs are the attitude rotation of the payload with respect to the inertial reference frame.

2.2 HAB Payload Dynamics Mathematics Model

Given the still potential complexity of the system described in the previous section, involving different coordinate frames and several coupled relationships, performing an original derivation would require an extensive amount of effort and a knowledge of advanced dynamics topics outside the current knowledge of this author. Moreover, a derivation of the equations of motion for the HAB system described in the previous section was found during an extensive
preliminary review of literature. Using the same aforementioned assumptions, this derivation, conducted by Zlotnik and Forbes [1], is as follows.

### 2.2.1 Dynamic Representation

The aforementioned HAB dynamic system can be represented in the manner depicted below in Figure 5. In Figure 5, the HAB payload is modeled as a ridged body mass, denoted by \( \mathcal{R} \). To model the pendulating motion of the payload during flight, \( \mathcal{R} \) is considered to be constrained such that it moves with the end of the pendulum, denoted by \( \mathcal{P} \). The pendulum is modeled as a rigid body which is a valid assumption since, from experience, the tether attaching the payload mass to the balloon is typically in tension during balloon ascent. While \( \mathcal{R} \) is constrained such that its pendulatatory translational motion with respect to the inertial frame is the same as the suspended end of \( \mathcal{P} \), its rotational attitude is free to rotate in three dimensions.

Moreover, for convenience, this analysis uses three reference coordinate frames. \( \mathcal{F}_i \) represents the fixed inertial reference coordinate frame with vectrix \( \mathcal{F}_i = [i_1 \ i_2 \ i_3]^T \) whose coordinate frame origin is attached at the tether attachment point of the balloon. \( \mathcal{F}_p \) represents the pendulum \( \mathcal{P} \) reference coordinate frame with vectrix \( \mathcal{F}_p = [p_1 \ p_2 \ p_3]^T \). \( \mathcal{F}_p \) shares an origin with \( \mathcal{F}_i \), and is oriented such that the vectrix component \( p_2 \) is always aligned with and pointing in the direction of the pendulum tether \( l \). Lastly, \( \mathcal{F}_b \) represents the payload body coordinate reference frame with vectrix \( \mathcal{F}_b = [b_1 \ b_2 \ b_3]^T \) whose origin is attached to the center of mass of the ridged body \( \mathcal{R} \). The pendulum \( \mathcal{P} \), has one end fixed to the origin of \( \mathcal{F}_i \) and the other attached to \( \mathcal{R} \) at point \( O \).
2.2.2 Equations of Motion:

Using the kinematic relations and constraints of the system described in Figure 5, and summarized by the derivation conducted by Zlotnik and Forbes [1], a Lagrangian approach using concepts of virtual work is used to derive the equations of motion described by Equation 1.

\[ S^T (M \ddot{v} + \Omega M \dot{v} + \alpha) = \Xi^T \lambda + \dot{S}^T (\bar{r}_b^d + \bar{r}_b^c) \]  

(1)

where

\[ \Omega = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \omega_b^{\perp} & 0 \\ 0 & 0 & \omega_b^{\perp} \end{bmatrix}, \quad \text{and} \quad \alpha = \begin{bmatrix} -m_{gb} g 1_3 \\ 0 \\ -\frac{1}{2} m_{gb} g l_b^2 c_p 1_3 \end{bmatrix} \]

For more details concerning the notational conventions and the intermediate steps required to derive Equation 1, refer to the derivation conducted by Zlotnik and Forbes [1].

Equation 1 can be further simplified if a few additional assumptions are considered. At relatively high altitude when atmospheric pressure drops substantially, pendulatory motion
becomes almost non-existent with the relative absence of external disturbance forces like wind. Likewise, roll and pitch motion of the payload body also become less relevant for similar reasons. Additionally, other terms are disregarded such as the pendulation angles and the mass of the pendulum arm. Moreover, Equation 1 reduces to the simplified relationship described by Equation 2.

\[ I_3 \dot{\omega}_3^y = \tau_d + \tau_c \]  

In Equation 2, \( I_3 \) represents the mass moment of inertia of the payload body about the yaw axis of rotation, \( \dot{\omega}_3^y \) represents angular acceleration about the same axis, and \( \tau_d \) and \( \tau_c \) represent the external disturbance torque and actuator control torque acting on the payload body respectively.

For the purposes of the preliminary design of payload yaw stabilization as part of the project’s first increment developments, Equation (2) became the primary operating equations from which much of the first-order design analysis took place.

It is important to note that due to the extensive level of assumptions made during this derivation, this model only represents a low-fidelity interpretation of the actual payload’s balloon dynamics and is only used to create a starting point from which to develop a stabilization control law for the yaw stabilization controller. For a more accurate and higher-fidelity model, Equation 1 would need to considered entirely with not further assumptions and be evaluated further including additional dynamic contributions such as viscous drag damping effects and the actual dynamics of the balloon itself during flight. It is planned for such aspects to be considered during the later increment developments of this project.
2.2 Yaw Stabilization Controller Design

Given the inherit attitude instability of the payload body under flight conditions, particularly that in the yaw rotation, it is obvious that some method of controlling the payload’s attitude is desired in order to achieve attitude stability of the stabilized camera platform in the inertial reference frame. As described in the previous section, this yaw stability is provided by a control torque $\tau_c$. In the modeling efforts described in the previous section, in order to achieve relative stability within the inertial reference frame, the control torque $\tau_c$ must attempt to negate the disturbance torque $\tau_d$ at any given time during the flight. In order to calculate the necessary value of $\tau_c$ that would best to negate $\tau_d$ a PID feedback controller is implemented following the relationship described by Equation 3.

$$\tau_c = K_P (\hat{\theta}_{3,desired} - \hat{\theta}_3) + K_I \int_{t_0}^{t_f} (\hat{\theta}_{3,desired} - \hat{\theta}_3) dt + K_D \omega^{'y}_3$$  (3)

In Equation 3, $\tau_c$ represents the calculated control torque, $K_P$ represents the PID proportional constant, $K_I$ represents the PID integral constant, $K_D$ represents the PID derivative constant, $\hat{\theta}_{3,desired}$ represents the desired yaw heading attitude referenced in the north-east-down (NED) inertial reference frame, $\hat{\theta}_3$ represents the current payload yaw heading attitude referenced in the NED inertial reference frame, and $\omega^{'y}_3$ represents the payload yaw heading attitude rate referenced in the NED inertial reference frame.

By varying the PID constants in Equation 3 an optimal yet robust control behavior can be achieved with a relatively quick response time and minimal overshoot. To determine what values should be assigned to these constants, a feedback model was created in MATLAB/Simulink [2] based on equations Equation 2 and Equation 3. A depiction of the model is depicted below in Figure 6.
Figure 6: Simplified HAB Dynamic Model & PID Controller Design Created in MATLAB/Simulink 2015a
By utilizing the internal PID tuning algorithm featured in the associated PID controller Simulink block (Figure 7) and providing the Simulink model with system mass and geometric constants, optimized values for the PID constants in Equation 3 can be determined.

![Figure 7: Simulink PID Controller Autotune Feature](image)

2.3 Flight Payload Design

The modeling efforts represented in the previous section served as an interactive tool to develop a preliminary design for the desired stabilized payload. After several proposed conceptual designs by the members of the SHC, a final design concept was selected. A depiction of this conceptual design can be found below in Figure 8.
In examining Figure 8, several unique design features immediately become apparent.

First, a single axis gimbal system is used such that the desired camera stabilization platform is isolated from the main body of the payload. Moreover, the actual “payload” under stabilization is not the entire payload mass, but rather only the camera stabilization platform. This is done due to
the lower mass and mass moments of inertia of the camera stabilization platform relative to the main payload body. In doing so, the required control torque described in Equation 2 and Equation 3 will be substantially less than if the entire payload mass was attempted to be stabilized. In doing so, a smaller actuator motor can be selected, requiring a relatively smaller power supply, and overall reducing the mass and complexity of the proposed payload.

A second characteristic identifiable in Figure 8 is the inverted orientation of the payload with respect the manner in which the camera is attached and the vertical extension of the rigid body geometry of the payload. The inverted design was proposed such that minimal obstruction of the camera field-of-view (FOV) by the payload geometry would be achieved. Additionally, this inverted design promotes better foresight for future project increment integration for eventual roll and pitch stability when a three-axis gimbal system is implemented.

The purpose of the vertical extension of the rigid body geometry of payload was to promote improved damping in the roll and pitch axes. By varying the length and mass distribution of this extensional geometry, much of the disturbing effect in the roll and pitch axes of the payload body can be minimized, lending to better passive stabilization, and promoting less effort required by a roll and pitch stabilization controller in future project increment developments. In the future increments, an optimization of the length and mass characteristics of this extensional body will be analyzed.

2.3.2 Selected Embedded Controller Electronics

Like the preliminary mechanical design described in the previous selection, preliminary selections of the required electrical components needed to facilitate the desired control regime have also been investigated. From a subsystem perspective, three major components were researched and selected: an embedded microcontroller system, a 9-DOF IMU with an embedded
digital-motion-processing algorithm for attitude state estimation, and the rotational control actuator and subsequent actuator control circuit.

Given the obvious active dynamic control applications in this project, an embedded microcontroller capable of relatively high processing and update rates (~100 Hz) was needed in order to achieve reasonable control loop stability and mitigating system lag. As a cost effective solution to this design goal, the Arduino Due embedded microcontroller system (Figure 9) was selected.

![Figure 9: Arduino Due Microcontroller Platform](image)

The Arduino Due is one of the more advanced microcontroller in the Arduino family featuring Atmel’s AT91SAM3X8E 32-bit microcontroller with an ARM Cortex-M3 processor, capable of achieving clock speed of 84 MHz. Additionally, the Due features several interfacing pins, consisting of 54 digital pins (12 of which can provide a PWM output), 12 analog inputs, and the capability of utilizing USART for TTL serial communication and I2C and SPI digital communications protocols. Given these baseline microcontroller features, the Arduino Due represents a diverse developmental platform more than capable of achieving the aforementioned mission objectives and control regime as well as capable of adapting its future to future increment project development expansions.
Given the desired feedback control loop needed for yaw axis stabilization, a reliable and relatively precise yet cost effective 9-DOF IMU was needed for payload attitude state estimation. Given the proposed control law and governing equations of motion a 9-DOF IMU consisting of a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer was required in order to obtain a known yaw heading attitude based on an absolute reference frame (earth’s gravitational and magnetic fields). Additionally, to help alleviate some of the initial labor overhead required by the first increment of development of this project, it was also desired to select and IMU with an onboard digital-motion-processor to produce the best possible attitude estimate using a sensor fusion algorithm.

Given these aforementioned IMU constrains, several units were researched and analyzed and the Bosch Sensortec BNO055 Absolute Orientation 9-DOF IMU attached to a development circuit board created by Adafruit industries (Figure 10) was selected given its extensive features, exhaustive documentation and software libraries, and history of reliability within the hobbyist community.

![Figure 10: Bosch Sensortec BNO055 9-DOF Abs. Orientation IMU](image)

The BNO055 is a diverse all-in-one 9-DOF IMU chip capable that utilizes ARM Cortex-M0 processor and extended Kalman filter state estimation sensor fusion algorithm to estimate
attitude and dynamic behavior. Given this onboard sensor fusion algorithm, the embedded firmware of the BNO0555 is capable of outputting a diverse range of dynamic data, including: attitude Euler angles, attitude quaternions, angular velocities, axial accelerations, axial magnetic field strengths, gravitational data, and temperature. Much of this data output at a 100 Hz rate over an I2C digital communication protocol. Moreover, this sensor fits well within both the control operational constraints and system interface requirements of the proposed payload design.

For the selection of the rotation control actuator, a signal axis brushless gimbal motor was selected. A brushless motor, rather than a servo or some other DC rotational motor/actuator, was selected due to its popularity and extensive developmental support within the UAV community, mainly in its use with airborne camera gimbal platforms with very successful history of providing inertial stabilization of a camera platform. Moreover, RCTimer’s GBM5208-SR DSLR Gimbal Motor with Slip Ring (Figure 11) was selected as the control actuator for the proposed platform.

![GBM5208-SR Brushless Gimbal Motor with Slip Ring](image)

**Figure 11: GBM5208-SR Brushless Gimbal Motor with Slip Ring**

The GBM5208-SR is a hobbyist grade brushless motor designed specifically for large airborne DLSR gimbal systems, specified to reliably carry and stabilize a mass of approximately
2 kg. Given the relatively lightweight platform and payload projected to be carried by the proposed payload, this should be well within the required torque specifications. Additionally, the GBM5208-SR also features a central hollow shaft and slip ring mechanic. With this unique mechanical makeup and feature, an unimpeded continuous yaw rotation can be achieved using this motor, eliminating the need to “unwind” the electronics mounted on the stabilized platform due to routed communication cable twisting.

In order for the Arduino Due Microcontroller to obtain precise and reliable control over the brushless gimbal motor, an additional motor controller circuit was needed such that a relatively high voltage and high current power supply could be modulated by the microcontroller to generate the three AC voltage signals needed to drive the motor. Given its popularity amongst both the hobbyist and professional community, STMicroelectronics’ L6234PD Brushless DC Motor Driver was selected as the driver used to provide control over the brushless gimbal motor. Additionally, an open-source development circuit board was also found for the L6234PD (Figure 12), produced by Seeedstudio which aided in easier integration within the proposed payload system.

Figure 12: L6234PD Brushless DC Motor Driver on Open-Source Development Circuit Board
The L6234PD motor controller features a triple h-bridge circuit allowing for three bi-directional independent voltage controls. Moreover, this allows for a diverse control almost any three-phase brushless motor. Additionally, L6234PD along with the aforementioned development circuit board with intermediate supplemental electronics, additional features such as back-electromagnetic-force sensing capabilities are also made available. Moreover, given the features and electrical characteristics of both the L6234PD, the supporting intermediate electrical components, and development circuit board, this motor controller subsystem assembly is more than capable of meeting the project design constraints with a relatively large factor of safety.
Part 3 – Concluding Remarks & Future Plans

In this Honors Capstone Report, a preliminary design for a yaw-stabilized high altitude balloon platform as the first increment development step in creating a three-axis stabilized platform was explored. The motivation for developing such a platform is the desire to obtain quality footage of the 2017 total solar eclipse from an altitude of 100,000 ft. This preliminary design consisted of a dynamic analysis of a high altitude balloon and payload and was conducted using resources gleaned from an extensive review of literature. Additionally, a PID control law was also developed given the analyzed dynamics and a preliminary payload platform design was also suggested utilizing and Arduino Due for the controlling microcontroller embedded system, a 9-DOF IMU with an extended Kalman Filter sensor fusion state estimation algorithm, and a signal axis brushless gimbal motor with a slip ring for the continuous yaw rotation actuation.

As of the conclusion of the Fall 2015 academic semester, much of the preliminary design for the desired payload platform has been completed and incremental testing of the payload subsystems is underway. With the continued efforts of the members of UAH’s SHC, final fabrication of the first increment payload development is set to conclude sometime during the Spring 2016 academic semester with a subsequent demonstrational test flight directly following. Based on the data collected during this test flight and the relative evaluated performance of the completed system, the developments of the second increment of this project will then begin.
Reference List
