Self-Orienting Payload for Weather Balloons

Thomas Miller (ME), Kyle Jeffryes (CE), Zehn Klimowicz (ME), Isai Garcia Zamora (CE)
Dr. Azer Yalin (Advisor)
Colorado State University, Fort Collins, CO, USA

WALTER SCOTT, JR. COLLEGE OF ENGINEERING
COLORADO STATE UNIVERSITY

Abstract

Background:

Traditional weather balloon payloads often experience uncontrollable rotation caused by atmospheric forces, which can compromise data collection especially for orientation-sensitive measurements like solar and atmospheric data, as well as imaging.

Research Objectives:

This project aims to develop a reaction wheel-based, PID controlled system to control the radial orientation of a weather balloon payload to improve collection of directionally dependent data. Two tests were conducted, one in the Stratosphere and one in the Troposphere to understand the control method in different environments

Theory

A reaction wheel uses principles from the law of conservation of momentum to control the satellite.

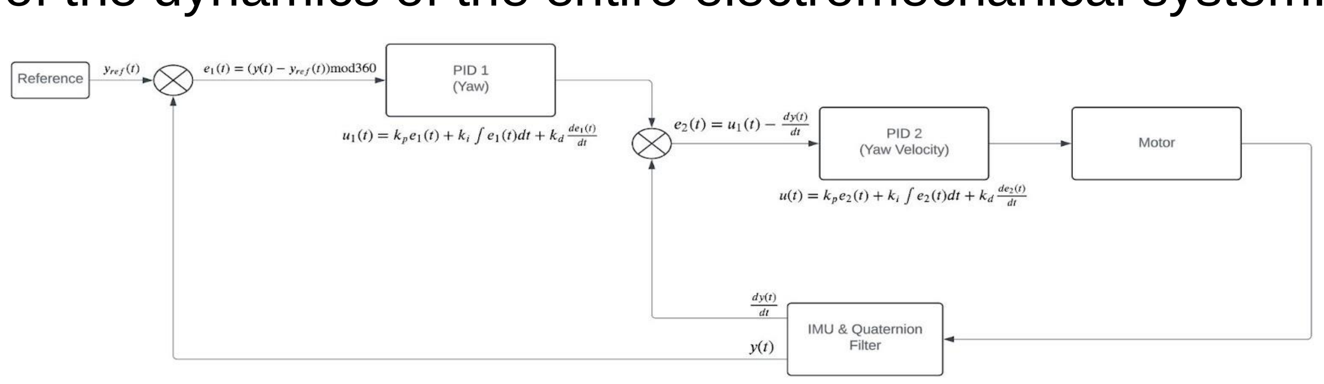
$$I_{Flywheel} \cdot \omega_{Flywheel} + I_{satellite} \cdot \omega_{satellite} = L = Constant$$

$$\Delta\omega_{satellite} = -\frac{I_{Flywheel}}{I_{satellite}} \Delta\omega_{Flywheel}$$

- A reaction wheel controls orientation by spinning in the opposite direction of the payload to adjust its rotation
- Payload orientation is managed by varying the reaction wheel's speed
- A higher mass moment of inertia (MOI) ratio between the wheel and payload provides greater control authority
- Control effectiveness is proportional to the MOI ratio and flywheel speed change

Control

Two Proportional-Integral-Derivative controllers were used on the Payload Yaw and Velocity, to stabilize around the reference point with a control action of motor PWM. This method is computationally reasonable on an embedded system and does not need exact knowledge of the dynamics of the entire electromechanical system.



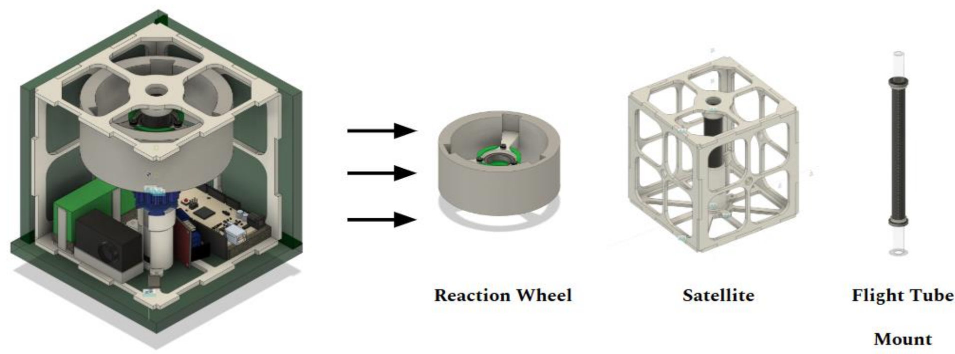
Pre-Launch Testing

Test	Purpose	Results
Freeze	Temperature variation at high altitudes	Material and Hardware Endurance
Vacuum	Near zero pressure	Device Operation
Stair	Landing vibrations	Structural Integrity
Drop	Landing impact	Structural Integrity
Whip	Violent balloon pop	Structural Integrity

Test	Purpose	Results
Functionality	Observe initial operation and extent	Endurance
Swing	Observe rope interference	Free from Interference
Ascent	Altitude control	Correct Control Operation
Worst Case	Stress test with max speed	Desaturation Function
Full Scale	Observe interaction with other payloads	Correct Operation and Control

Methods

Mechanical Design: The payload was divided into three subsystems: Reaction wheel, Satellite, and flight tube mount.



Each part was designed with the weight and mass moment of inertia in mind. The satellite contained most of the weight however needed to have a low mass moment of inertia. Meanwhile the reaction wheel's mass moment of inertia needed to be maximized. The payload also includes other critical components to the experiment such as insulating foam, a lightweight camera, and custom 3D printed parts.

Computational Design: The software design was constructed in C++ on Arduino and managed sensors (IMU and weather sensors), heating and encoded motor control calculation/actuation. The control system was a nested PID that stabilized the yaw around a reference angle.

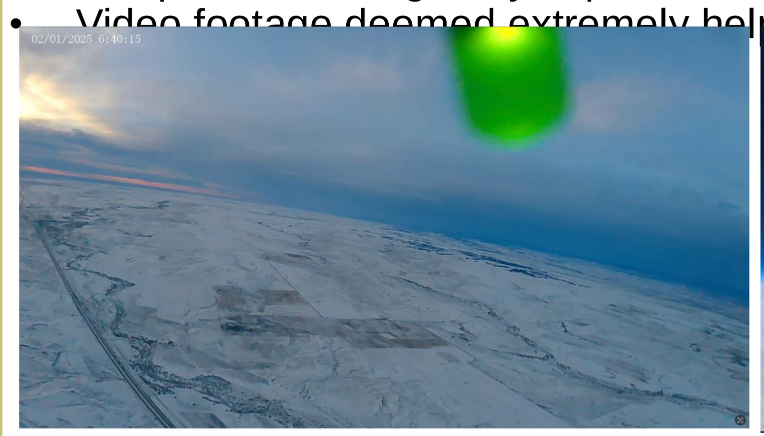
Experiment (The Launches)

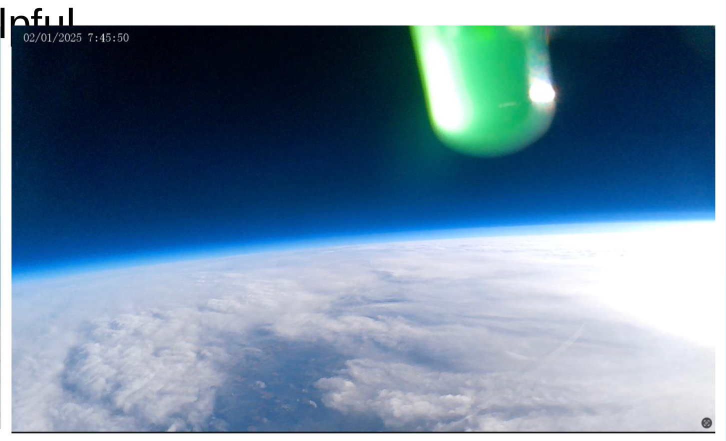
Launch 1 (Aug 3, 2024)

- Data was not collected because it corrupted on impact.
- Functioned properly and turned on at expected times, but PID was ineffective.
- Camera data was used to visually see PID performance
- Improvements were made to PID, Code, and Structure.

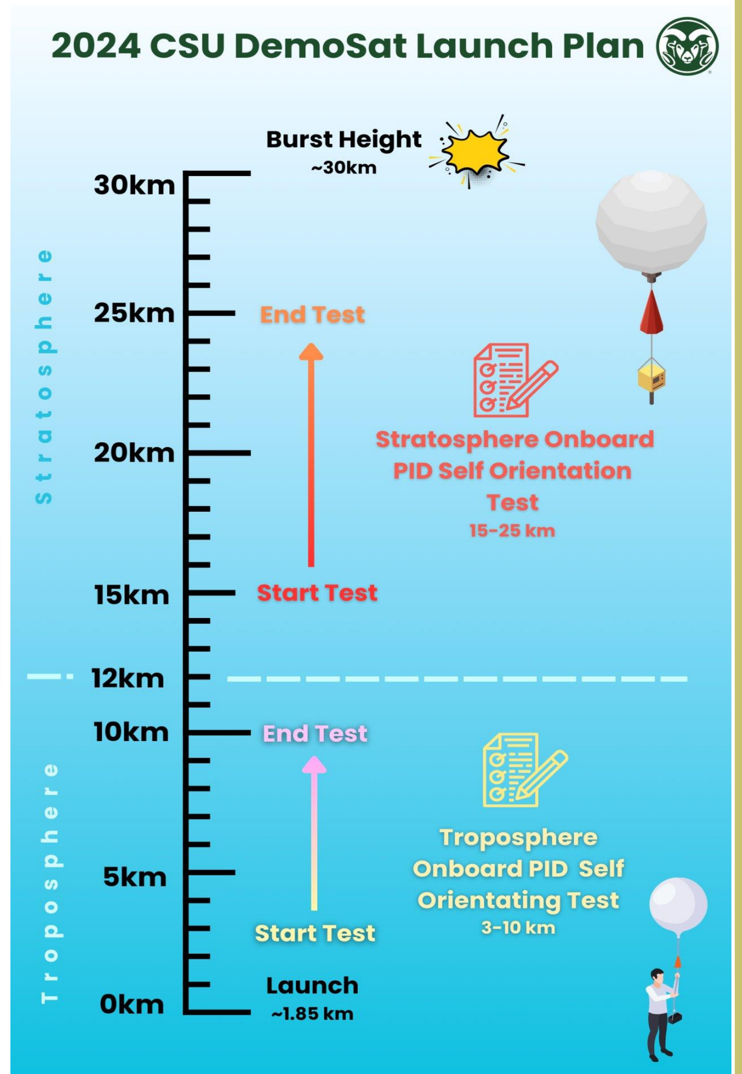
Launch 2 (Feb 1, 2025)

- The second launch followed the same testing strategy as the first launch, but with improvements.
- Data was collected
- PID performance greatly improved
- Video footage deemed extremely helpful





First picture (left) is the control period on launch two.
Second picture (right) is during the second testing window

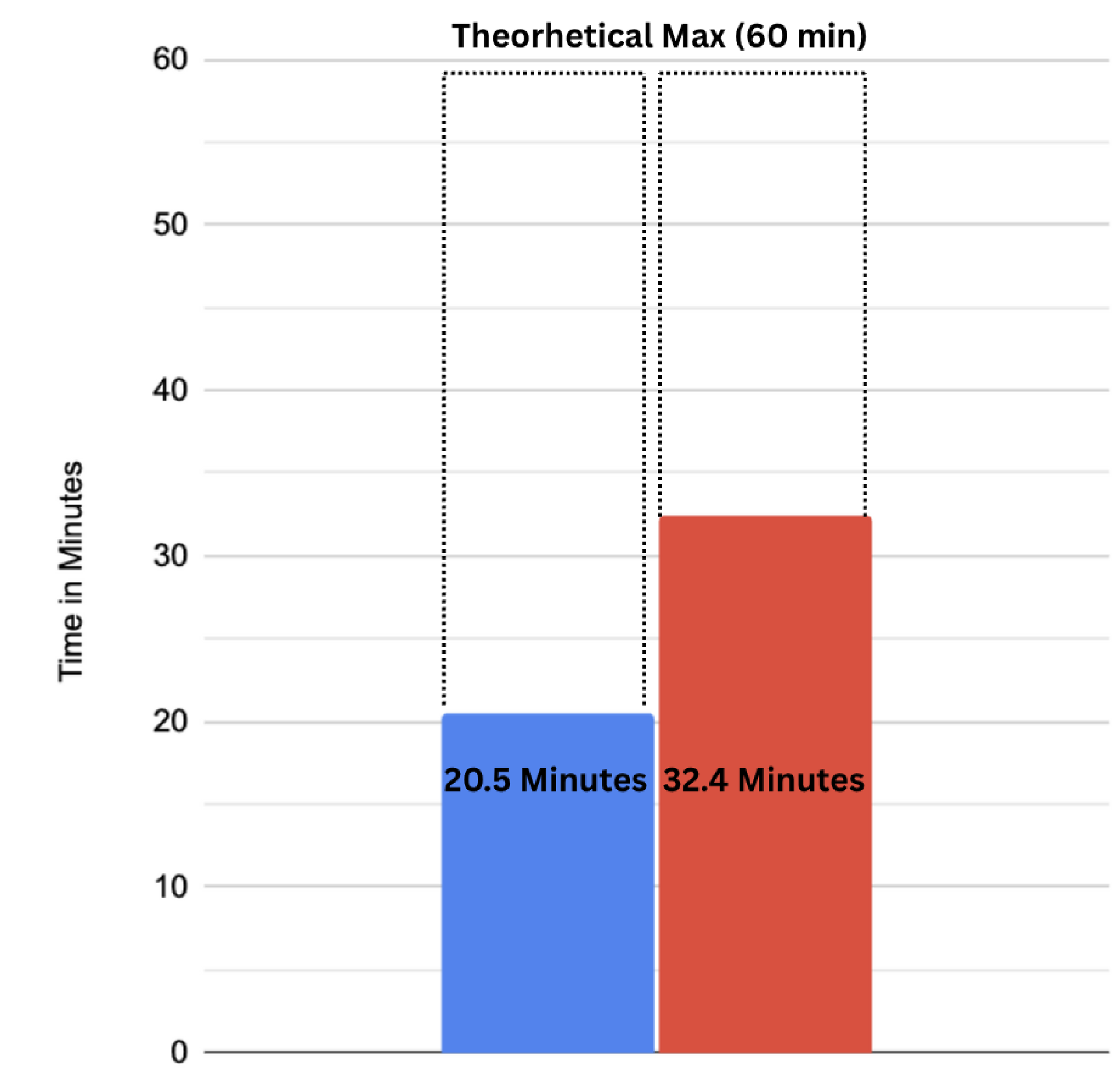


Results & Conclusions

- In the controlled state, the payload remained within ±60° of the reference point for **53.99%** of the time, with a decrease in error by approximately **20** degrees from calculating standard deviations of measurements over the flight time
- During the uncontrolled state, the payload remained for **34.72%** of the time
- Over a typical one-hour long balloon flight, an uncontrolled payload would spend roughly **20.5 minutes** in the desired FOV. With our controlled payload, we were able to increase this to **32.4 minutes** in the desired range.
- This represents a **64% increase** in the time spent within the desired range.

Further improvement that could be done would be continuing control optimization and spending further time developing a better mass moment of inertia ratio.

Time in ±60º Zone (Min) With Uncontrolled and Controlled Self Orienting Payload Normalized for One Hour



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