Control Stabilization for Bi-Quadcopter Payload Delivery System

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Presentation Overview

- Motivation
- Related Work
- Dynamic Modelling
- Simulation
- Firmware Alterations
- PID Tuning
- Adaptive Controller

Drone delivery has a wide range of applications

[1]

[2]

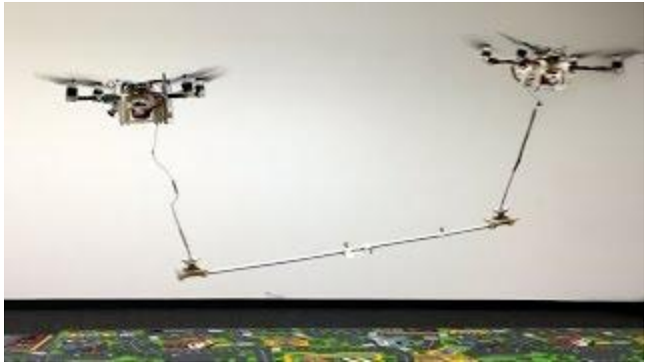
[1] Annierpalmer, "Amazon's Drone Delivery Unit hit with layoffs just as 10-year-old project finally launches," CNBC, https://www.cnbc.com/2023/01/20/amazon-drone-unit-hit-with-layoffs-as-long-awaited-program-launches.html (accessed Oct. 9, 2023).
[2] "Drone payloads to become vital in supplying medicines, test results in COVID-19 pandemic - GPS world," GPS World - The Business and Technology of Global Navigation and Positioning, https://www.gpsworld.com/drone-payloads-to-become-vital-in-supplying-medicines-test-results-in-covid-19-pandemic/ (accessed Oct. 9, 2023).

Our goal is to improve drone delivery system capacity through dual drone coordination

Features of the Dual Drone Coordination

- Dual Drone Control
- Stable Flight
- Dynamic Reconfiguration
- Payload Pickup/ Delivery

Design Inspiration:
Collaborative payload carrying



[3] H. Xie, K. Dong and P. Chirarattananon, "Cooperative Transport of a Suspended Payload via Two Aerial Robots With Inertial Sensing," in IEEE Access, vol. 10, pp. 81764-81776, 2022, doi: 10.1109/ACCESS.2022.3194932.

Collaborative transport without communication between drones

Controller	Linear Quadratic Regulator (LQR)
Hardware	Sensing - standard fisheye lens USB camera, Pixhawk PX4 IMU
	Odroid XU4 microcontroller

Design Inspiration:
Autonomous Rigidly Attached Quadcopters

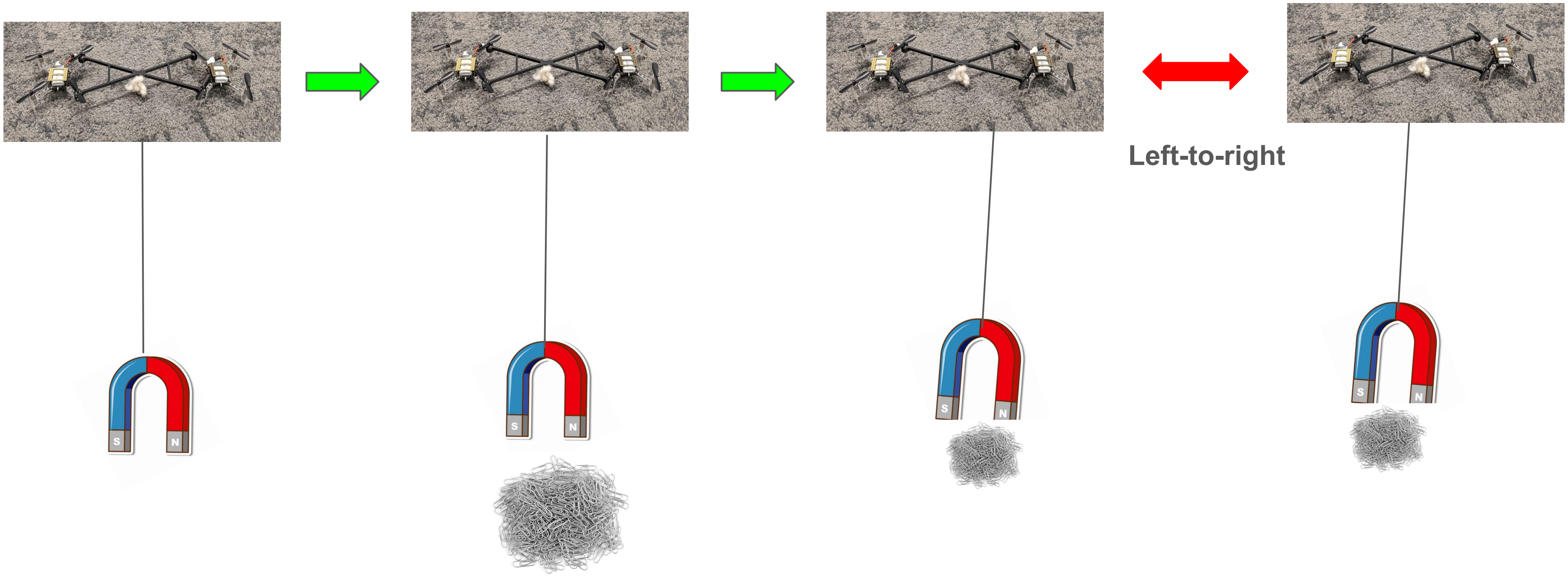
Rigidly attached quadcopters

Controller — Proportional Integral Derivative (PID)

Hardware
- Sensing - MOCAP, IMU
- Crazyflie onboard microcontroller STM32F405

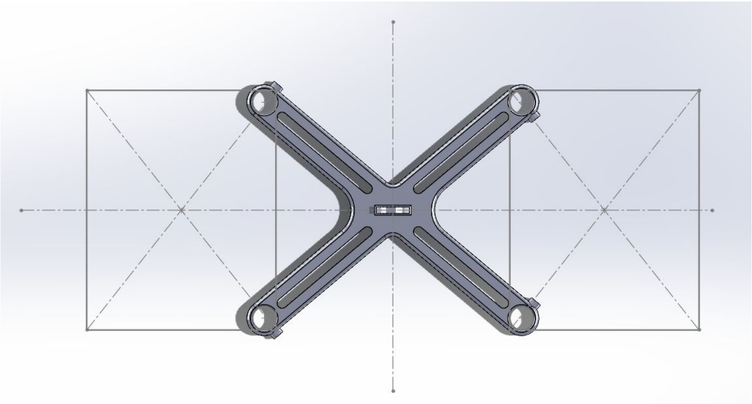
[4] D. G. Morín, J. Araujo, S. Tayamon and L. A. A. Andersson, "Autonomous Cooperative Flight of Rigidly Attached Quadcopters," 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 5309-5315, doi: 10.1109/ICRA.2019.8794266.

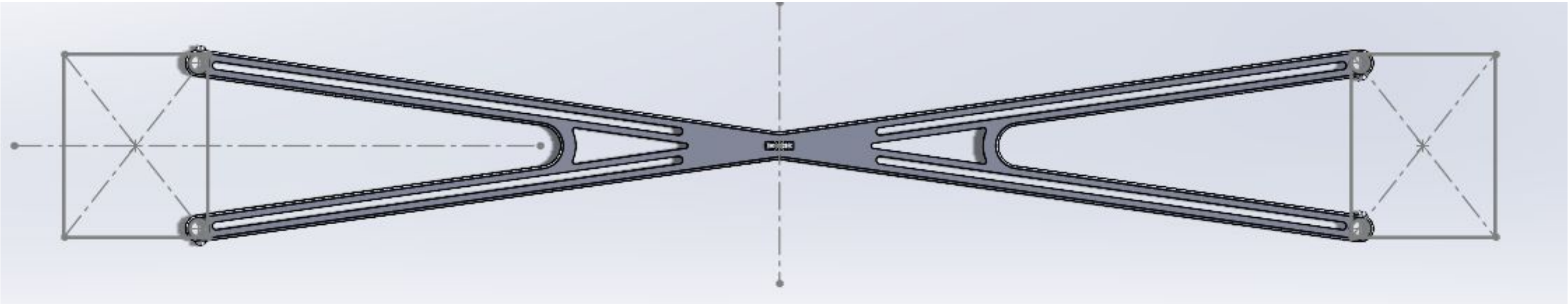
A successful demo would involve stable take-off, flight and payload pickup



3D Truss Model

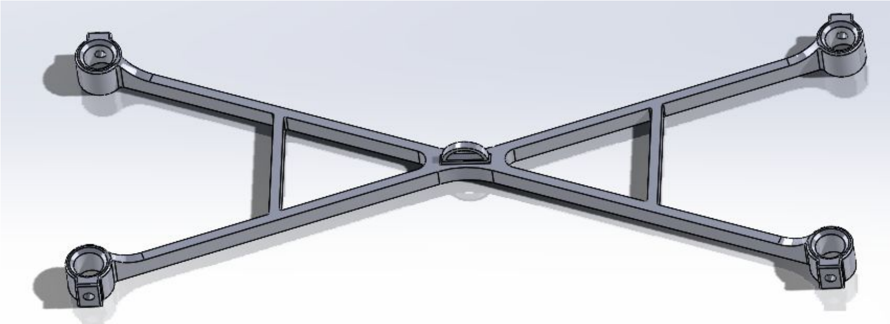
- Short model original design
    - Not a significant controls challenge
- Long Truss
    - Tradeoffs of weight and length





Changes to the Truss

- Settled on final design with similar weight to our short truss
- Sufficiently stable and lightweight enough to carry significant payload



Density = 0.001000 grams per cubic millimeter

Mass = 7.931425 grams

Volume = 7931.425432 cubic millimeters

Dynamics Recap

- Utilizing Euler angles, Lagrangian Dynamics
- Decision made to operate in the body frame, consistent with default commands
- Model easy adjusted to new wrench representations, or additional drones

$$\mathbf{R}_{\mathcal{GB}} = \mathbf{R}(\phi)\mathbf{R}(\theta)\mathbf{R}(\psi) = \begin{pmatrix} \cos(\psi)\cos(\theta) & \cos(\theta)\sin(\psi) & -\sin(\theta) & x \\ \cos(\psi)\sin(\phi)\sin(\theta) - \cos(\phi)\sin(\psi) & \cos(\phi)\cos(\psi) + \sin(\phi)\sin(\psi)\sin(\theta) & \cos(\theta)\sin(\phi) & y \\ \sin(\phi)\sin(\psi) + \cos(\phi)\cos(\psi)\sin(\theta) & \cos(\phi)\sin(\psi)\sin(\theta) - \cos(\psi)\sin(\phi) & \cos(\phi)\cos(\theta) & z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{L} = T - V \quad \frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}_i}\right) - \frac{\partial \mathcal{L}}{\partial q_i} = Q_i$$

Dynamics Model

Control Vector (Before Condensing) u= $[F_1, \; F_2, \; F_3, \; F_4, \; F_5, \; F_6, \; F_7, \; F_8, \; \tau_1, \; \tau_2, \; \tau_3, \; \tau_4, \; \tau_5, \; \tau_6, \; \tau_7, \; \tau_8]$

12x8 [Top 8 Rows are Zero]

Condensed from [12,16] to [12,8] utilizing ratios from single drone paper

B Matrix ==

$$\begin{bmatrix} 0.001838 & 0.001838 & 0.001838 & 0.001838 & 0.001838 & 0.001838 & 0.001838 & 0.001838 \\ -0.000369 & 0.000369 & -0.000369 & 0.000369 & -0.000369 & 0.000369 & -0.000369 & 0.000369 \\ 0.119682 & 0.119682 & -0.119682 & -0.119682 & 0.119682 & 0.119682 & -0.119682 & -0.119682 \\ 0.001371 & 0.001371 & 0.001371 & 0.001371 & -0.001371 & -0.001371 & -0.001371 & -0.001371 \end{bmatrix}$$

*Other SS Matrices 1s and 0s

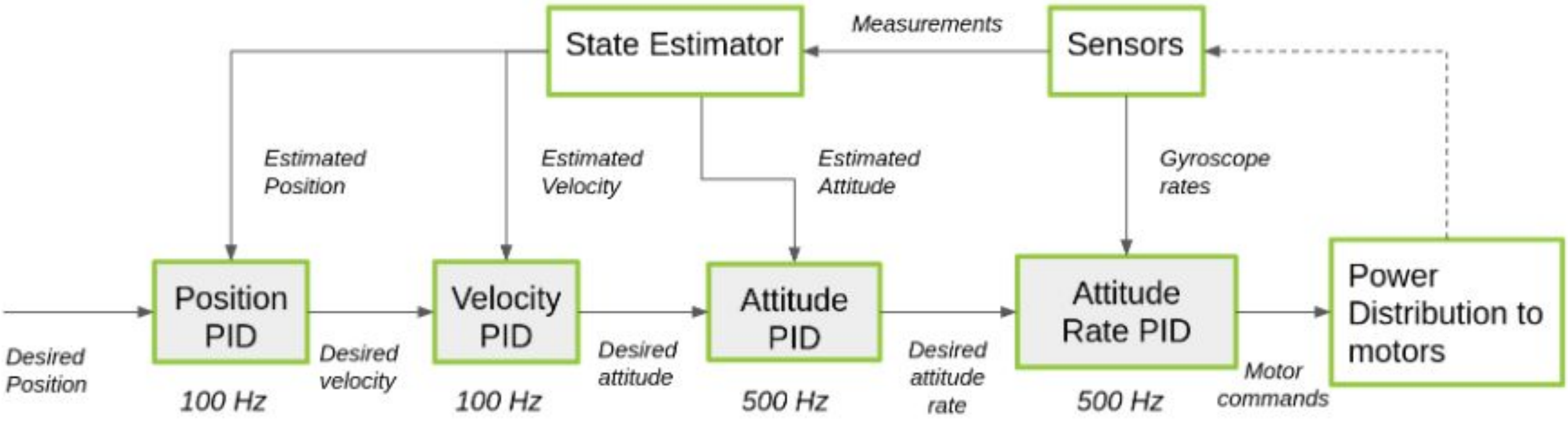
Control Vector u = $[\Omega_1, \; \Omega_2, \; \Omega_3, \; \Omega_4, \; \Omega_5, \; \Omega_6, \; \Omega_7, \; \Omega_8]$

State Vector x = $[x, \; \dot{x}, \; y, \; \dot{y}, \; z, \; \dot{z}, \; \phi, \; \dot{\phi}, \; \theta, \; \dot{\theta}, \; \psi, \; \dot{\psi}]$

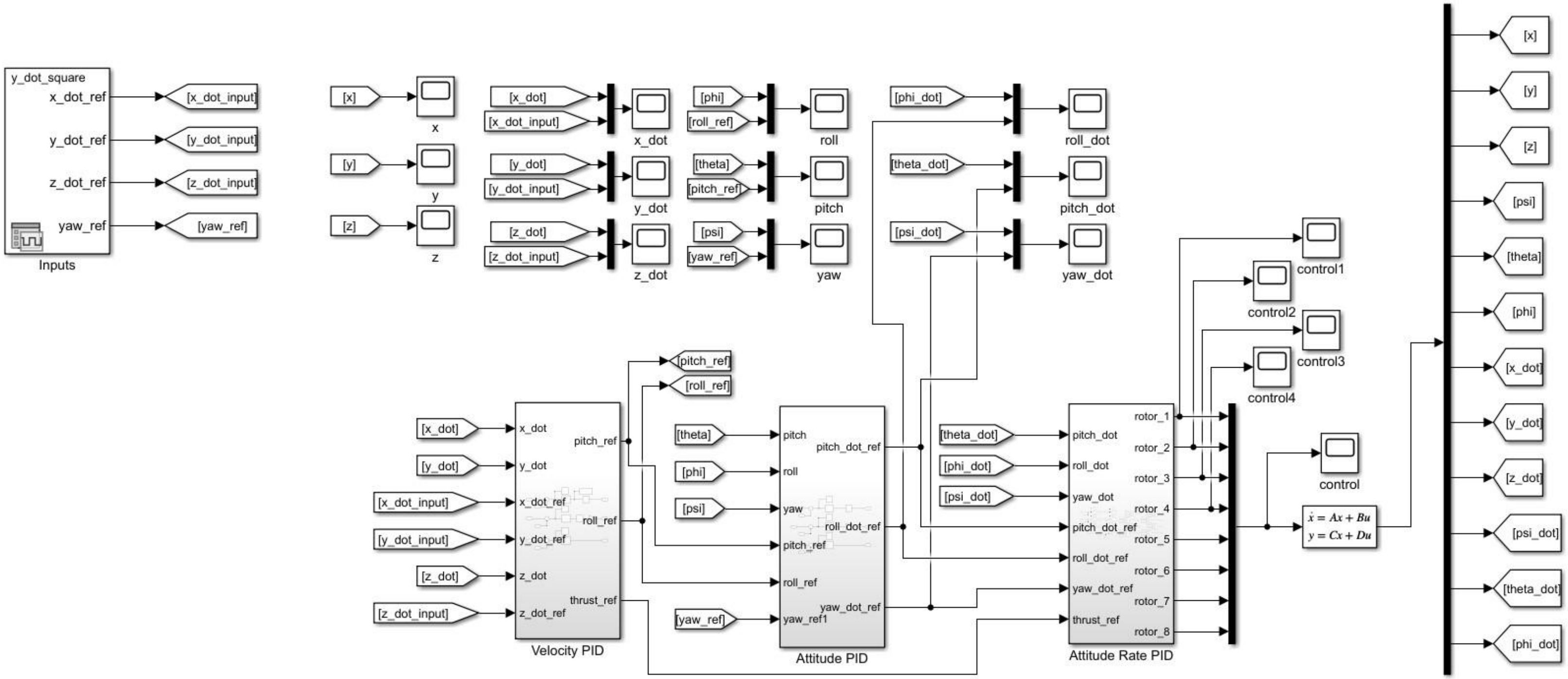
Ref Luis, C., & Le Ny, J. (August, 2016). Design of a Trajectory Tracking Controller for a Nanoquadcopter. Technical report, Mobile Robotics and Autonomous Systems Laboratory, Polytechnique Montreal.

Simulation

- The controller is 3 cascaded PID controllers.

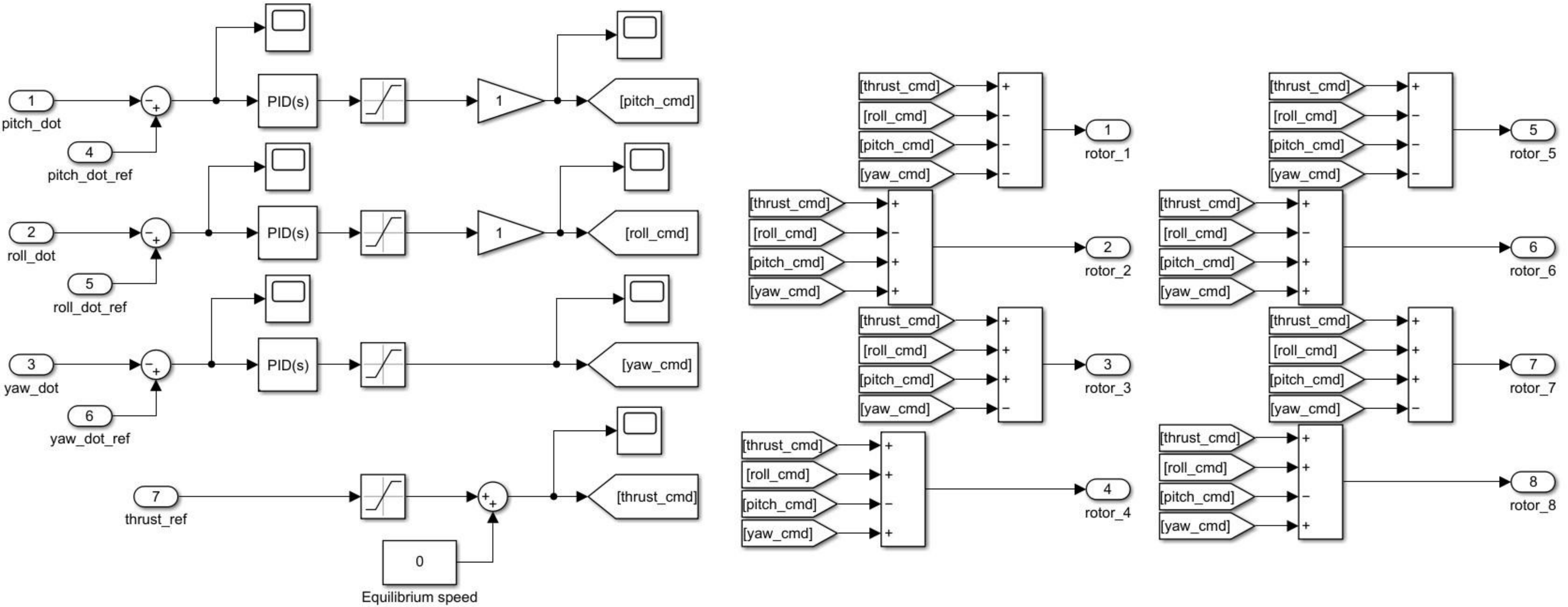


Simulation



y_dot_square
x_dot_ref
y_dot_ref
z_dot_ref
yaw_ref
Inputs
[x_dot_input]
[y_dot_input]
[z_dot_input]
[yaw_ref]
[x]
[y]
[z]
x
y
z
[x_dot]
[x_dot_input]
[y_dot]
[y_dot_input]
[z_dot]
[z_dot_input]
x_dot
y_dot
z_dot
[phi]
[roll_ref]
[theta]
[pitch_ref]
[psi]
[yaw_ref]
roll
pitch
yaw
[phi_dot]
[theta_dot]
[psi_dot]
roll_dot
pitch_dot
yaw_dot
control1
control2
control3
control4
control
[pitch_ref]
[roll_ref]
Velocity PID
Attitude PID
Attitude Rate PID
$\dot{x} = Ax + Bu$
$y = Cx + Du$
[x]
[y]
[z]
[psi]
[theta]
[phi]
[x_dot]
[y_dot]
[z_dot]
[psi_dot]
[theta_dot]
[phi_dot]

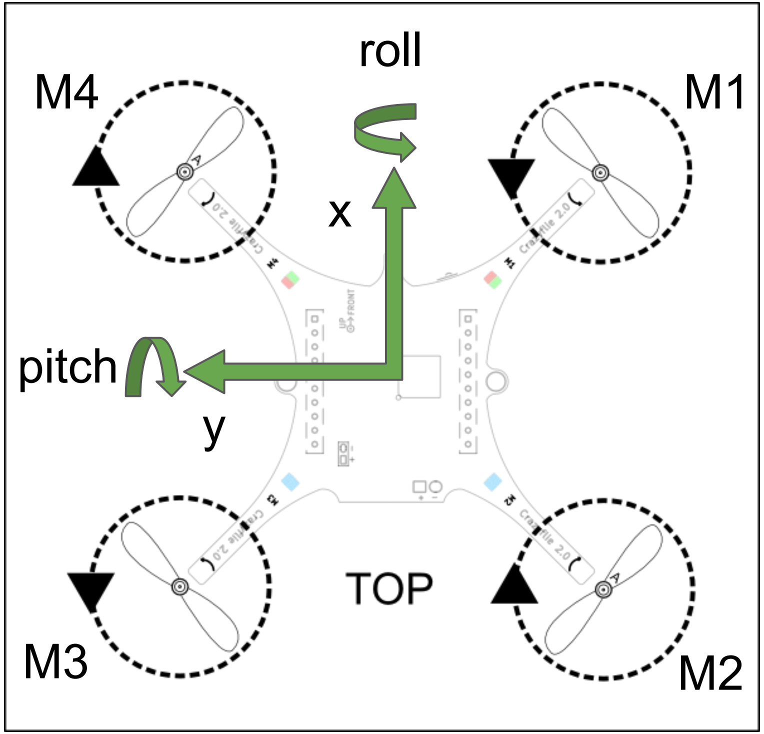
The attitude rate controller was the most impactful.



Swarm Flight - Overview

- Need to send commands to both drones simultaneously
- Control 2 drones with 1 radio using Swarm module
  - Flash **different address** on to drone
- Send commands to drones using Motion Commander (made possible by Flow Deck)
- Allows commands such as: Forwards 0.5m, turn left 90 deg, right 1 m… etc
- Sends **purely velocity setpoints**
  - Positional error accumulates

Firmware - Original Power Distribution (PWD)



M1: Thrust - Roll + Pitch + Yaw

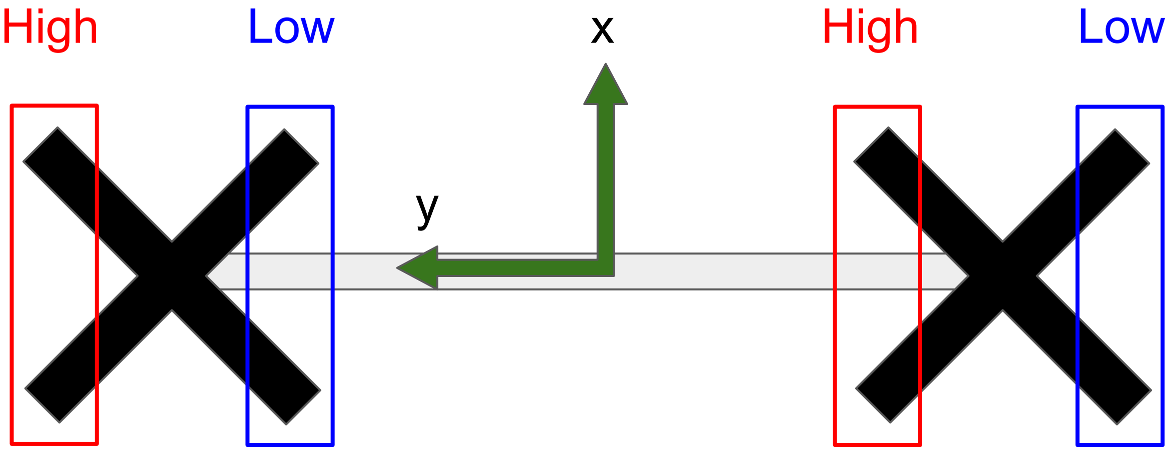
M2: Thrust - Roll - Pitch - Yaw

M3: Thrust + Roll - Pitch + Yaw

M4: Thrust + Roll + Pitch - Yaw

Firmware Modification - Existing PWD

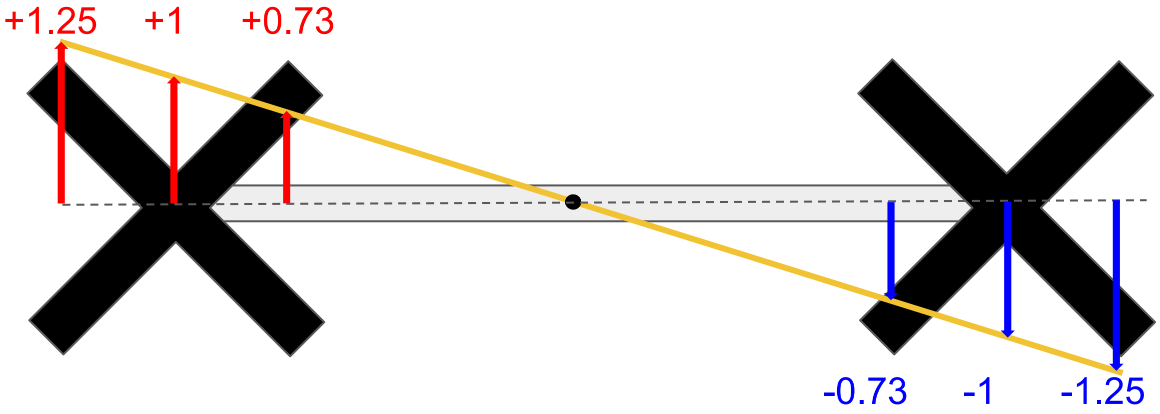
Existing (Roll):



Firmware Modification - Flight Test (Existing PWD)

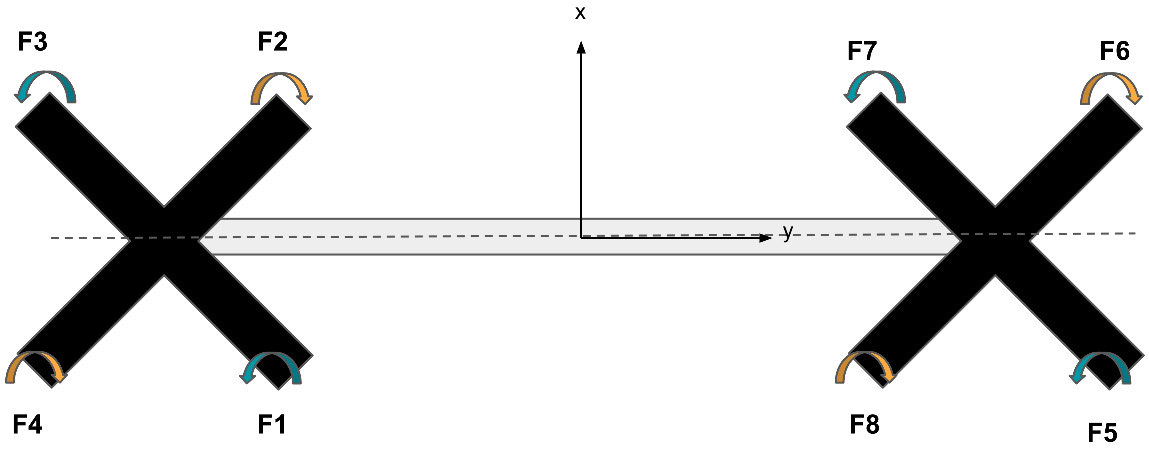
Firmware Modification - Linear PWD

Linear (Roll):



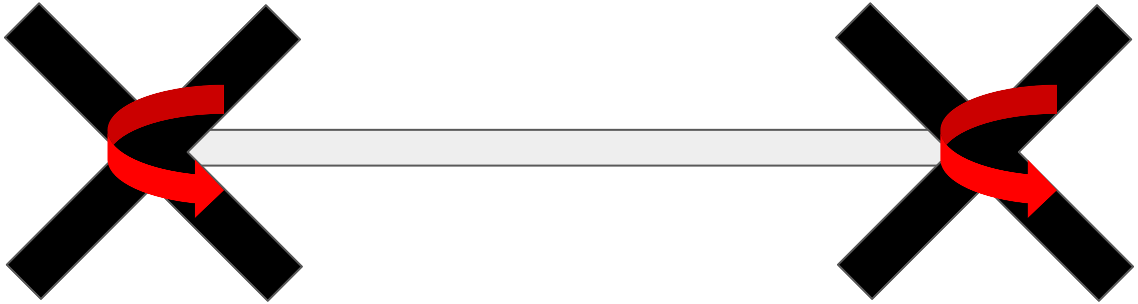
Firmware Modification - Linear PWD

Linear (Roll):

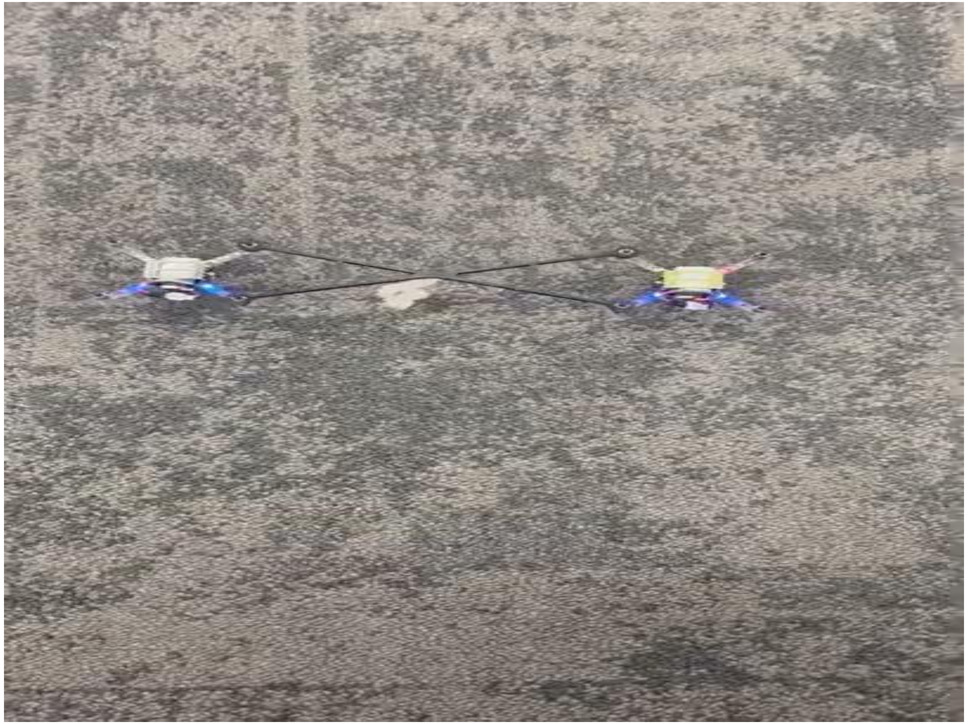


Firmware Modification - Flight Test (Linear PWD)

Firmware Modification - Yaw

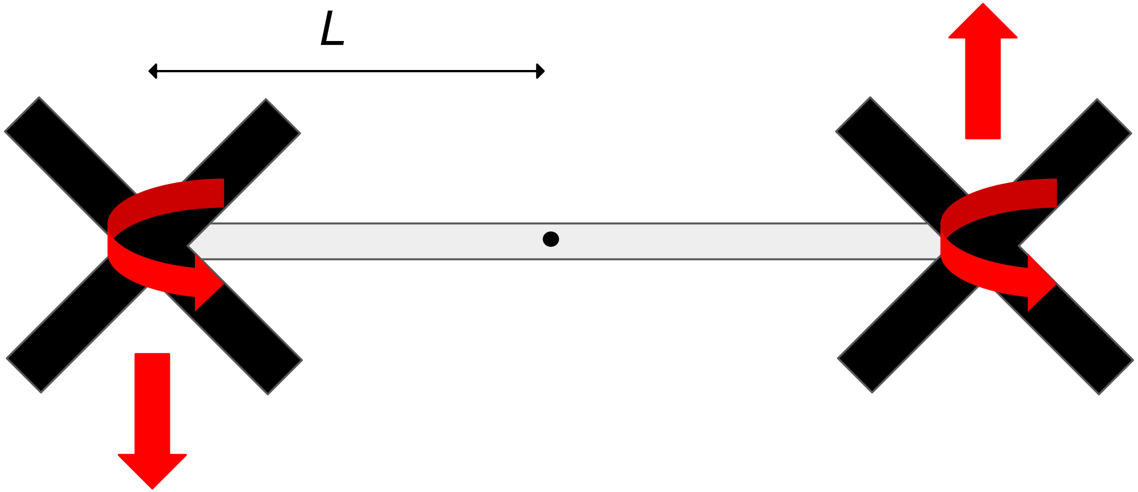


Firmware Modification - Yaw Test (Default Yaw)



Firmware Modification - Yaw Setpoint Adjustment

Setpoint Adjustment:



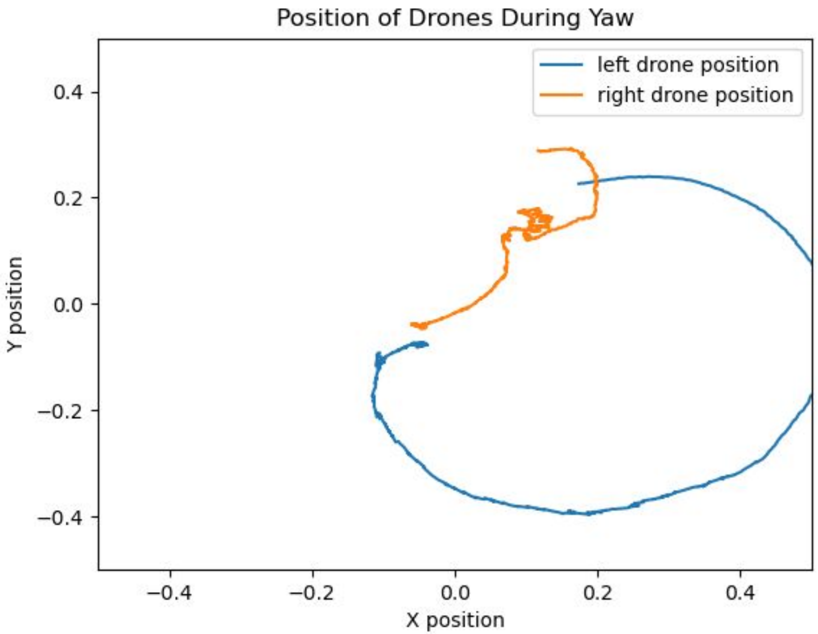
$Setpoint_{velX}$ -= $Setpoint_{YawRate} * L$

$Setpoint_{velX}$ += $Setpoint_{YawRate} * L$

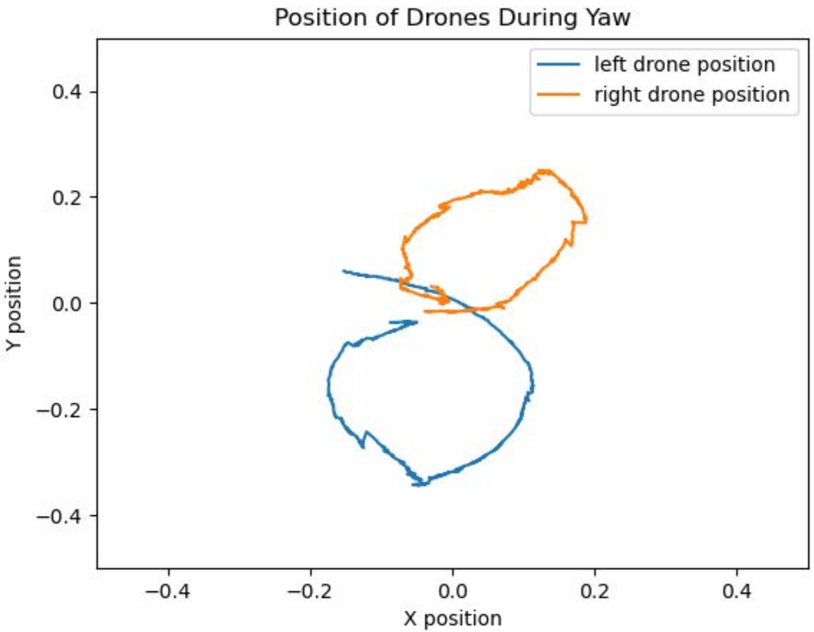
Firmware Modification - Yaw Test (Setpoint Adjusted)

Firmware Modification - Yaw Comparison

No Setpoint Change

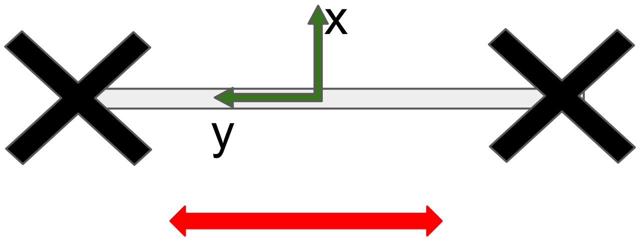


With Adjusted Setpoint



Controller Tuning

- From hardware testing, unstable maneuvers are
  - Sideways translation (roll)
- Attitude Rate PID
- Challenges
  - Abrupt changes in direction create instability
  - Swinging payload introduced general instability in flight



PID Tuning Steps

Analyze MOI Ratio	Tuning in Simulation	Tuning on Hardware	Tuning with Mass
Get intuition of PID changes based on change in Moment of Inertia (MOI)	Tune controller in Simulation	Test values from Simulation and fine tune	Tune for PID given a certain payload

New Force MOI Ratio

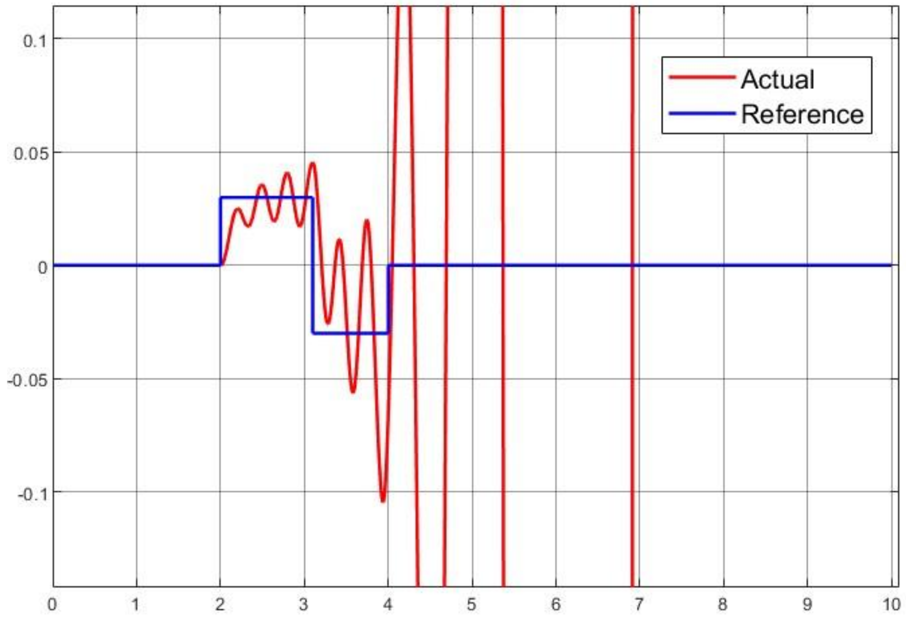
- Needed a simple, easily updated model to guide tuning
- Came up with ratio method utilizing wrench and inertia definitions
- Mixed results, but gave insight into relative PID increases on each axis

$$\begin{pmatrix} 0 \\ 0 \\ F_1 + F_2 + F_3 + F_4 + F_5 + F_6 + F_7 + F_8 \\ -F_1\,\mathrm{Ly}_{\mathrm{ir}} - F_4\,\mathrm{Ly}_{\mathrm{ir}} - F_5\,\mathrm{Ly}_{\mathrm{ir}} - F_2\,\mathrm{Ly}_{\mathrm{or}} - F_8\,\mathrm{Ly}_{\mathrm{ir}} - F_3\,\mathrm{Ly}_{\mathrm{or}} - F_6\,\mathrm{Ly}_{\mathrm{or}} - F_7\,\mathrm{Ly}_{\mathrm{or}} \\ F_1\,\mathrm{Lx}_{\mathrm{ir}} - F_4\,\mathrm{Lx}_{\mathrm{ir}} + F_5\,\mathrm{Lx}_{\mathrm{ir}} + F_2\,\mathrm{Lx}_{\mathrm{or}} - F_8\,\mathrm{Lx}_{\mathrm{ir}} - F_3\,\mathrm{Lx}_{\mathrm{or}} + F_6\,\mathrm{Lx}_{\mathrm{or}} - F_7\,\mathrm{Lx}_{\mathrm{or}} \\ \tau_1 - \tau_2 + \tau_3 - \tau_4 + \tau_5 - \tau_6 + \tau_7 - \tau_8 \end{pmatrix}$$

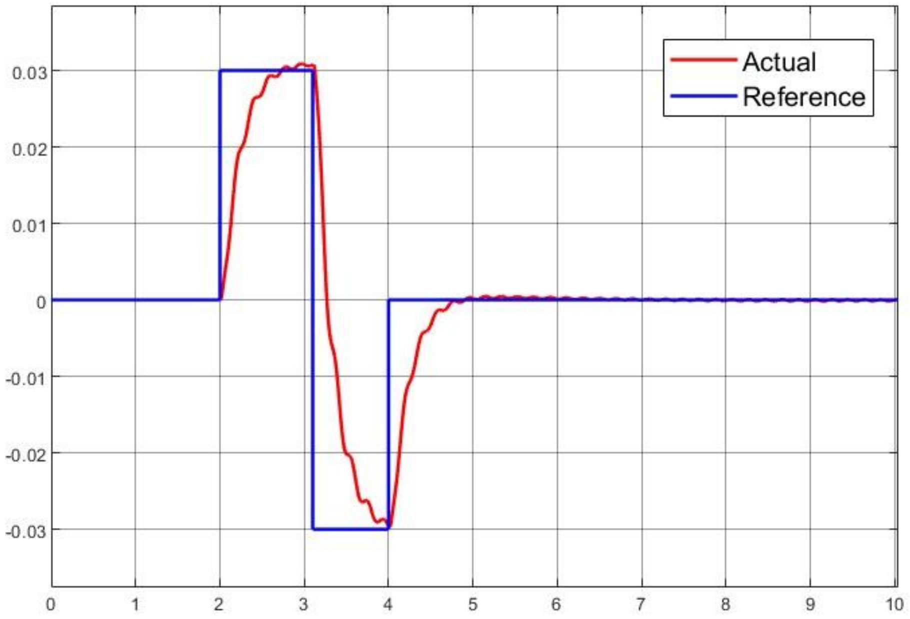
```
roll_ratio = 20.584128319459368735369963463472

pitch_ratio = 1.1469975386838440201131561479997

yaw_ratio = 33.195622855752418445263174362481
```

PID Tuning with Simulation

Y Velocity (Roll)



Default PID: Kp = 250, Ki = 500, Kd = 2.5

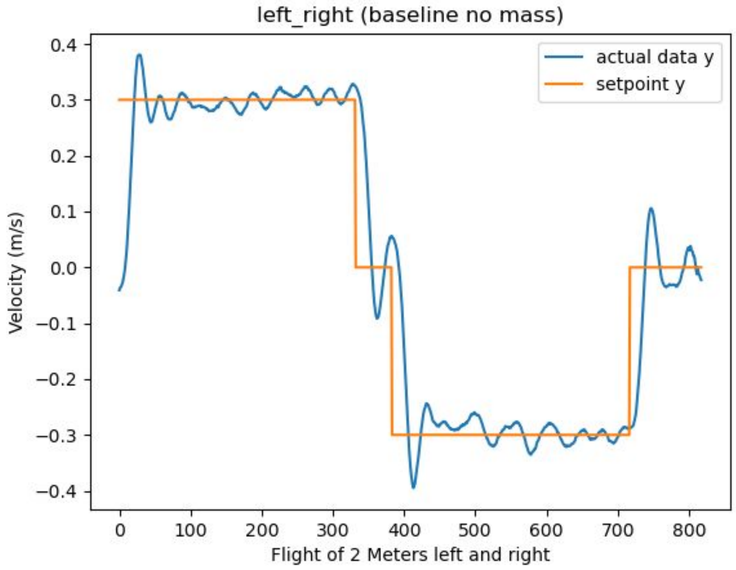


Tuned PID: Kp = 600, Ki = 500, Kd = 6

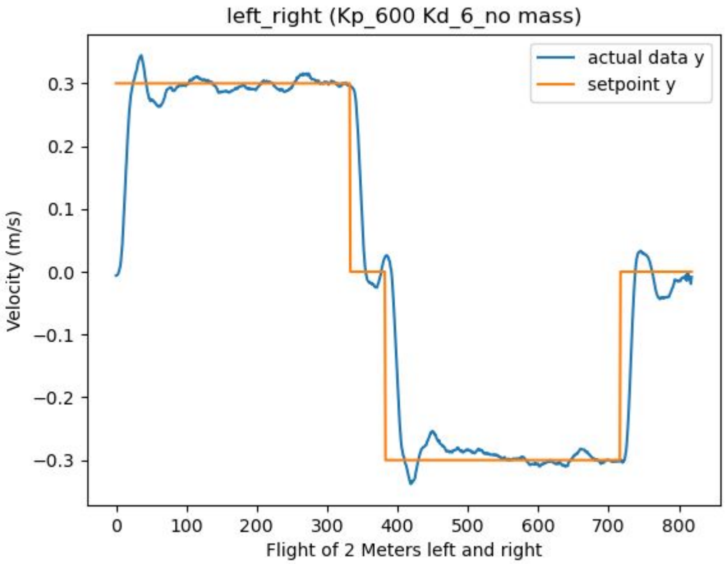
Testing PID Values through left-right flight

PID Tuning resulted in Performance Improvements

Before and after for roll (no mass)



Error: 8.5%



Error: 6.4%

Improved payload capacity from dual drone system

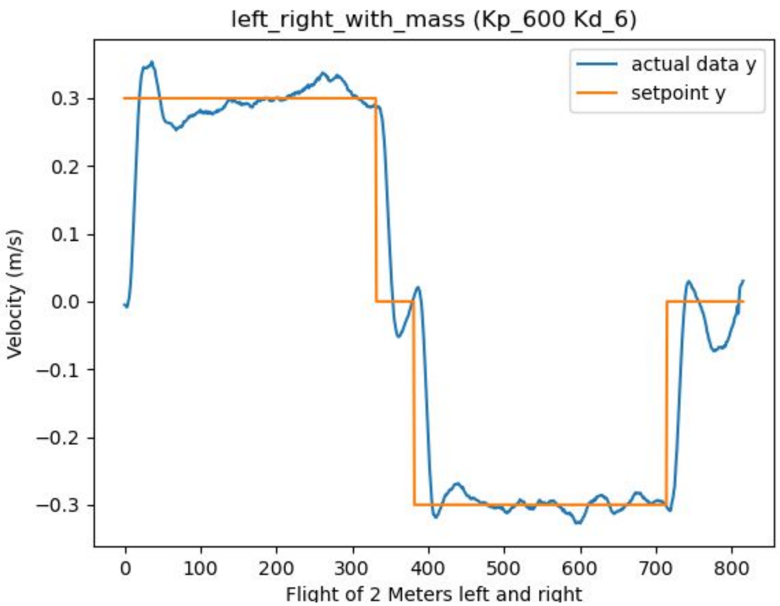
- Tested payload capacity with magnets (3g each)

Single Drone Payload	Dual Drone Payload*
2 magnets + 2 paper clips = 7 g	**3 magnets + 2 paper clips = 10 g**

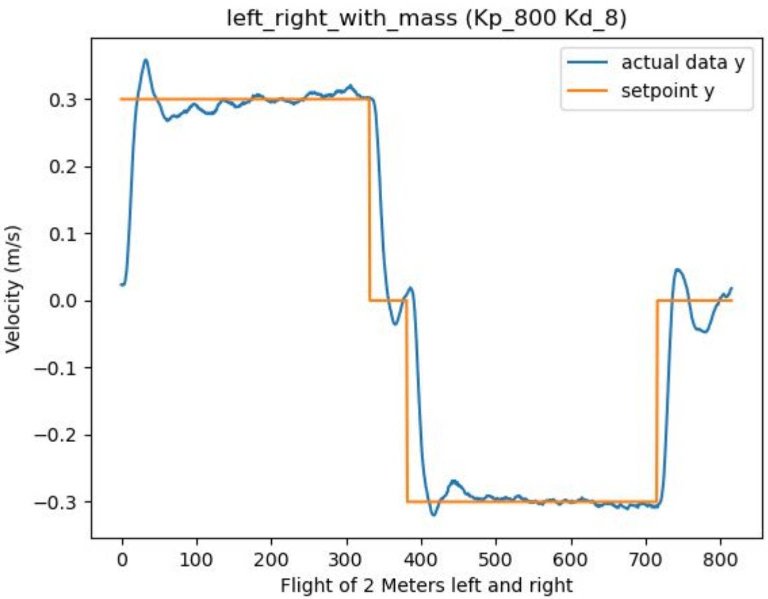
*on top of 8 g truss

PID Tuning resulted in Performance Improvements

Before and after for roll (with mass ~8g):

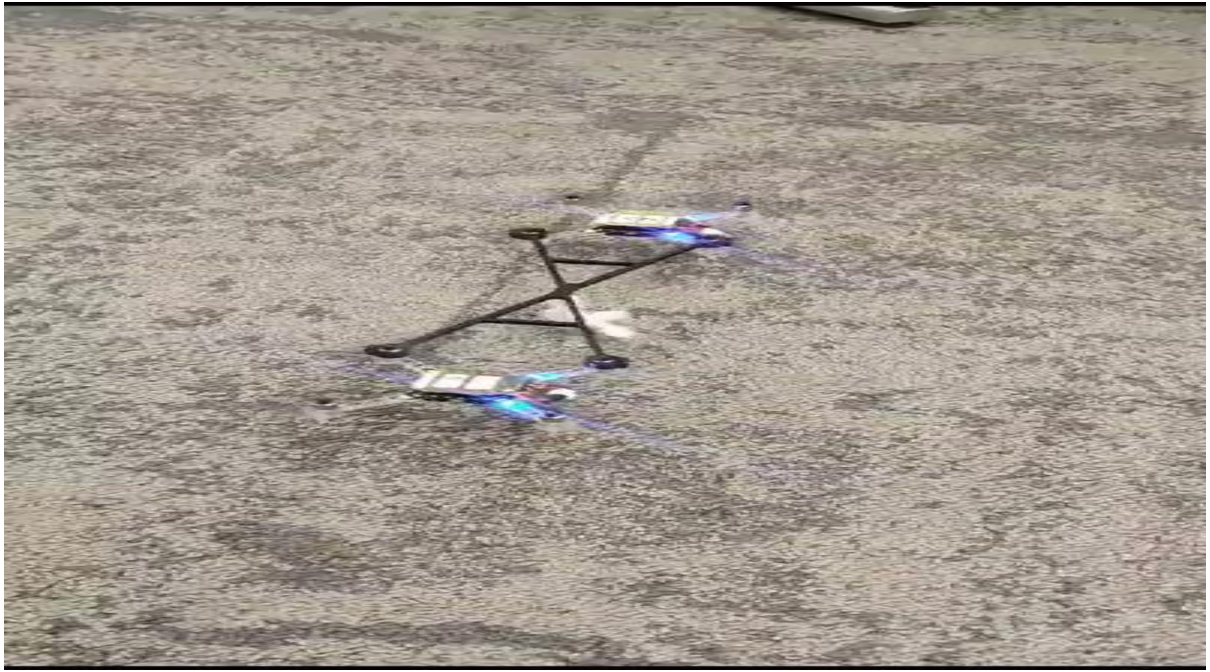


Error: 7.4%



Error: 5.8%

Final Flight Performance



Take off and land at payload pickup site

Final Flight Performance

After payload pickup, moving left and right

Final Flight Performance

Payload stability

Adaptive Controller based on mass of payload

- Linearly Interpolate between PWM & PID Values from dual drone with and without 8g payload

	Without Payload	**With 8 g Payload**
PWM	49500	52000
PID Values	**Kp = 600**, Ki = 500, **Kd = 6**	**Kp = 800**, Ki = 500, **Kd = 8**

Adaptive Controller based on mass of payload

Fly to Pick Up Destination	Pick Up Load	Measure Hover PWM	Scale PID Values	Continue to Drop Off
Fly to location of paper clips	The magnet will attract a random number of paperclips as payload	After taking off with payload, measure the hover PWM	Scale PID values based on measured PWM	Continue flight

Full load pickup demonstration

Single Drone vs Dual Drone Review

- The dual-drone system has an increased payload capacity and a decreased trajectory error.

	Single	**Dual**	**Change**
Payload	7 g	**10 g**	~43% Increase
Left-Right Test Error %	7.8%	**5.8%**	~26% Decrease

Future Work

- Perform further testing to see the stability limits of the dual-drone system

- Investigate whether framework can be extended to even more drones

Questions