Flying, Hopping and Rolling: Developing a Multi-Modal Robot for Efficient All Terrain Traversal

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Background:

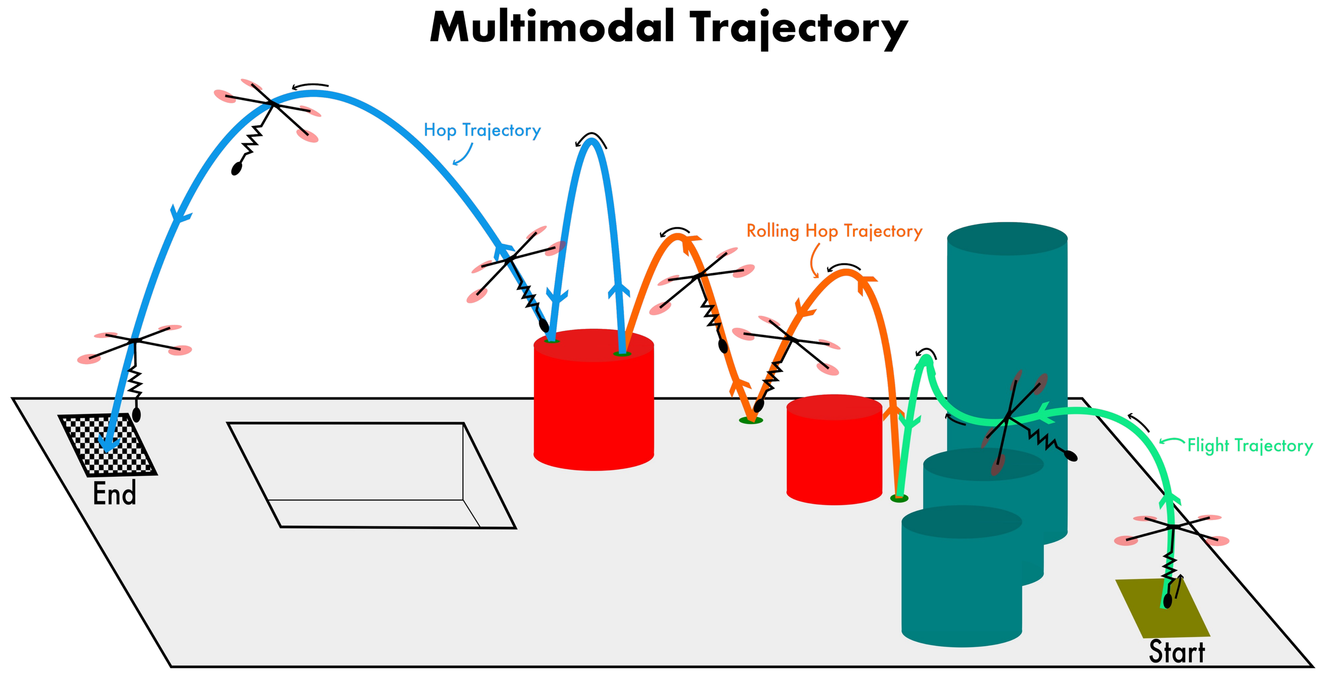
- Quadcopters are limited by their **small batteries** and **low carrying capacity**
- Hopping quadcopters improve the **Cost of Transport** and **carrying capacity** but can be made more efficient [1-3]
- Rolling is **up to 10x more efficient** on flat terrain **than flying** and consistently **outperforms walking or hopping gaits** [4-8]

Goal:

By rolling during the stance phase, we aim to maintain our momentum and decrease the **Cost of Transport** compared to standard hopping gaits and **unlock a new mode** of locomotion.

Through leveraging **multiple modes of locomotion**, we aim to navigate the environment efficiently, such as by **rolling down** ramps, **hopping over** small obstacles and **flying over** large obstructions.

Multimodal Trajectory

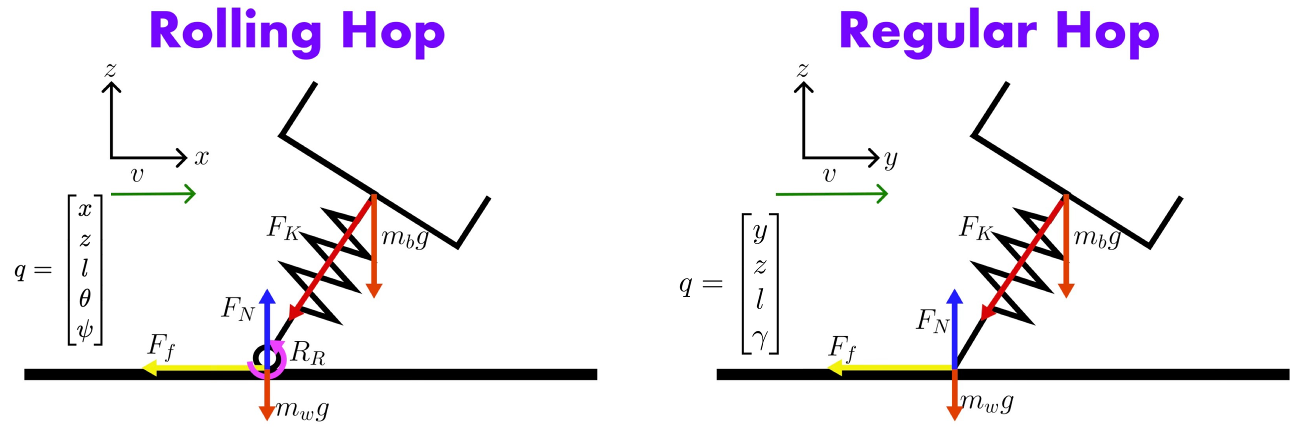


Stance Phase Dynamics:

For a state **q**, the stance phase model is written as follows, where **M** is the Mass matrix, **C** is the Coriolis Term and **G** Potential energy vector. The leg is modelled as a linear spring with a velocity-based damper. The rolling hop model additionally incorporates the **wheel spin** into the state vector and models the associated rolling resistances and inertial properties of the wheel.

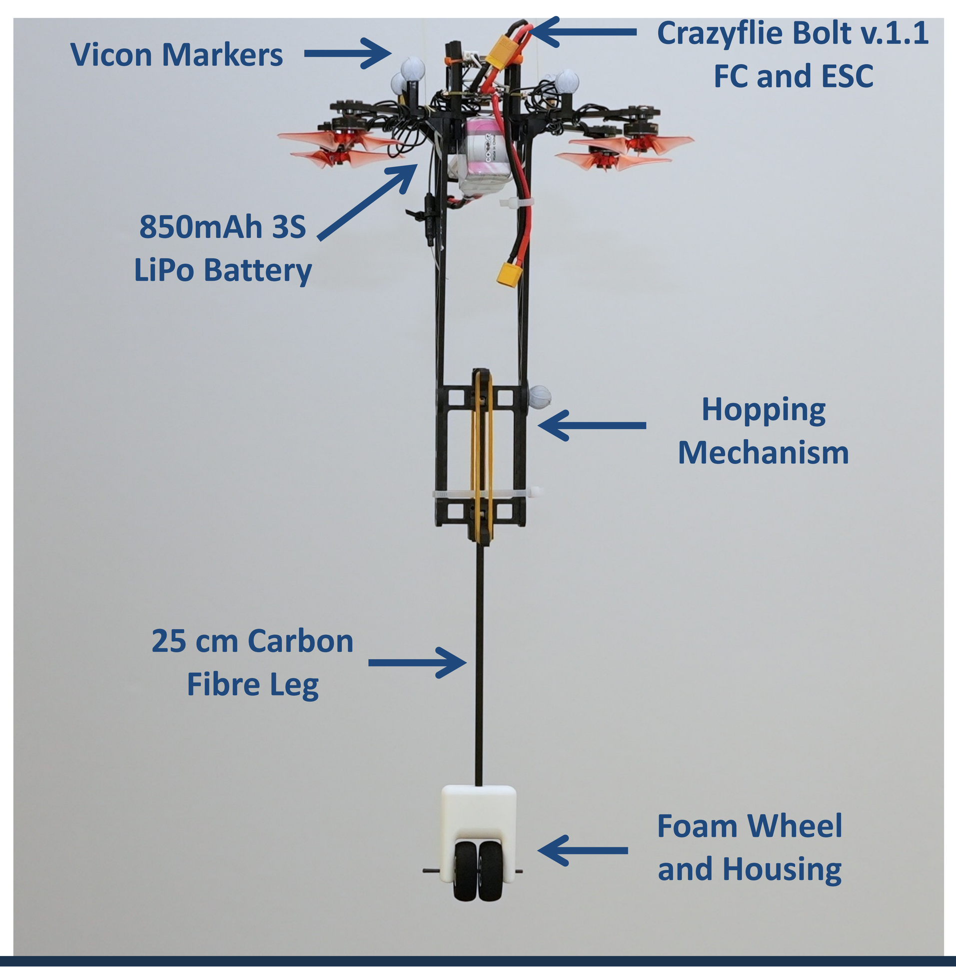
$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = Q_{\text{ext}}$$

Rolling Hop | **Regular Hop**

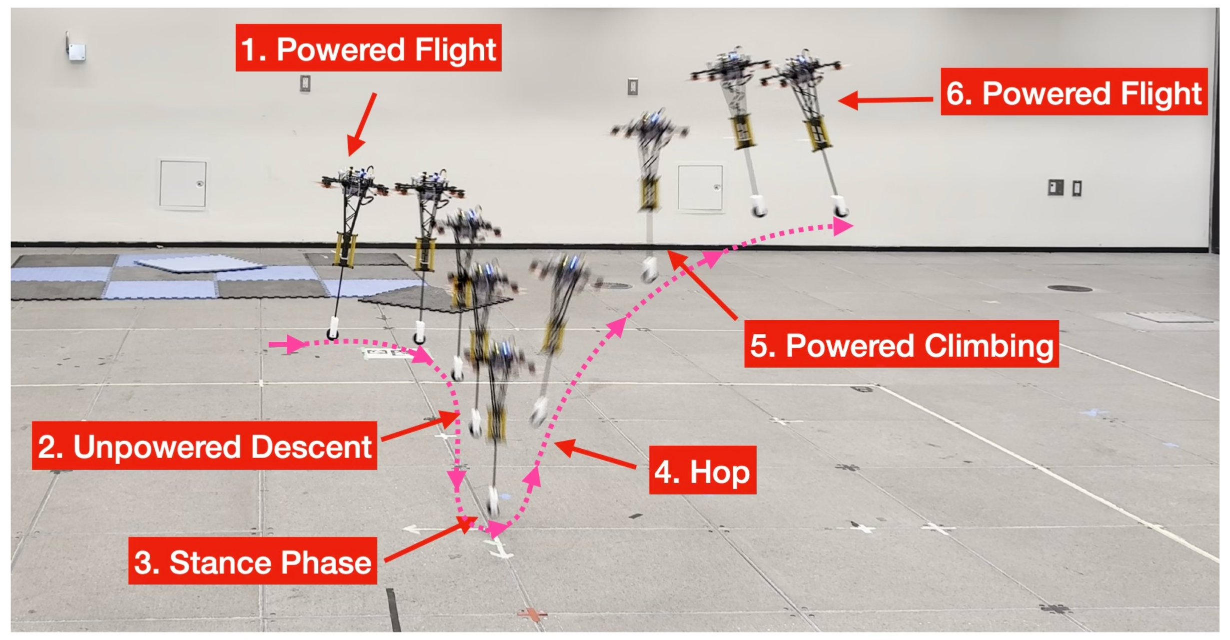


Physical Design:

The proposed robot is a quadcopter platform, **augmented with a hopping mechanism and wheeled** foot, to seamlessly transition between hops, rolling hops, flight and rolling modes of locomotion.

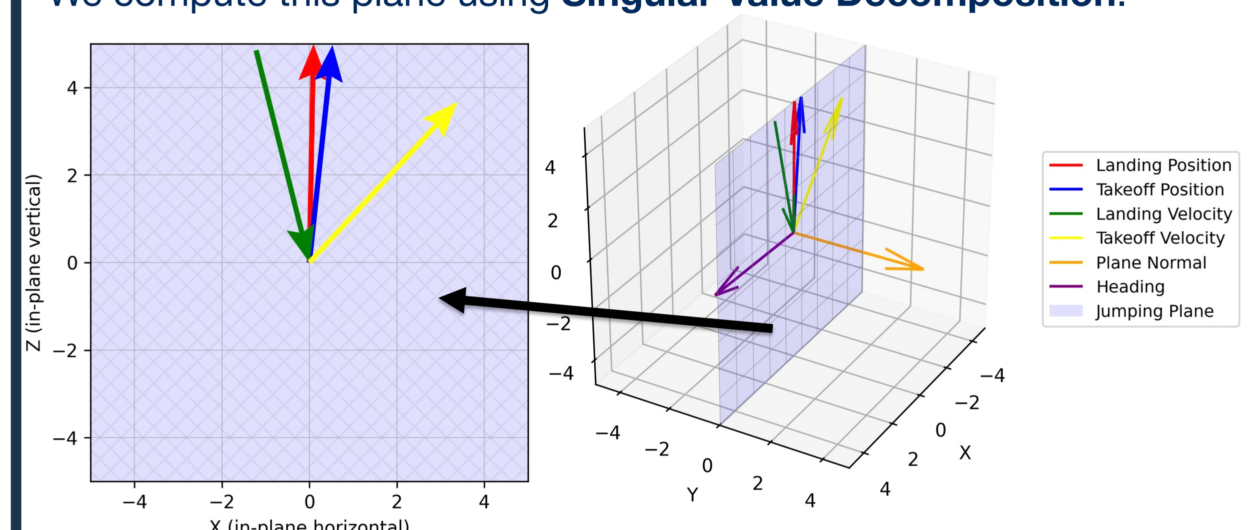


Hopping Trajectory:



Jumping Plane

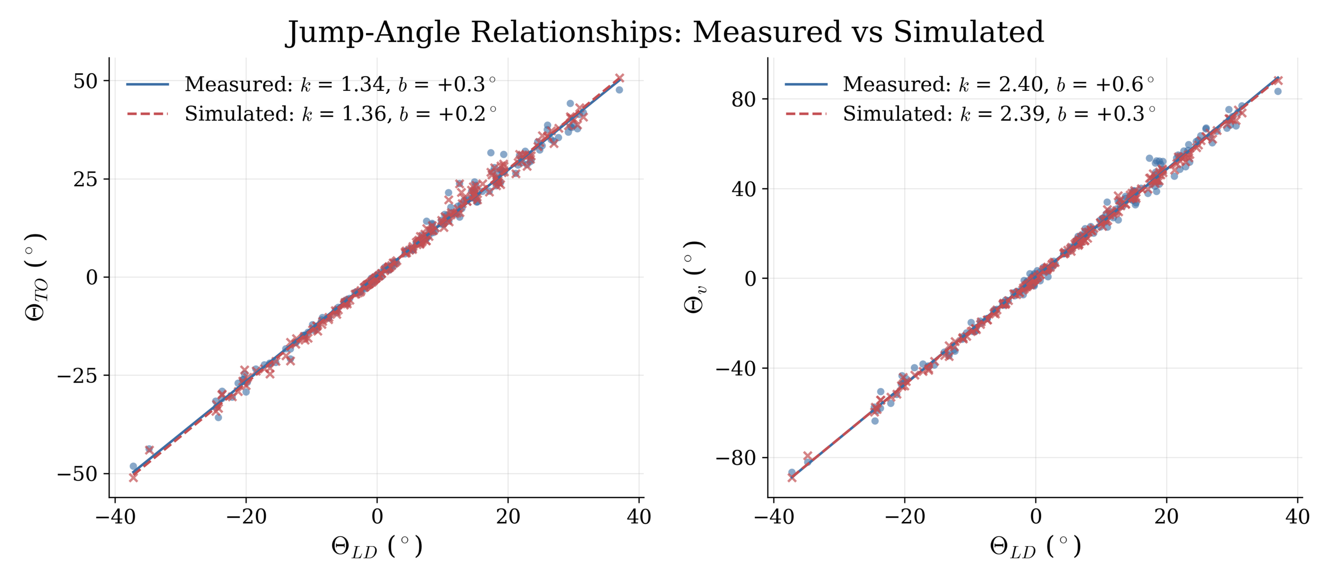
The **Jumping Plane** is defined as the plane that best fits the Landing Pose, Landing Velocity, Takeoff Pose and Takeoff Velocity. We compute this plane using **Singular Value Decomposition**.



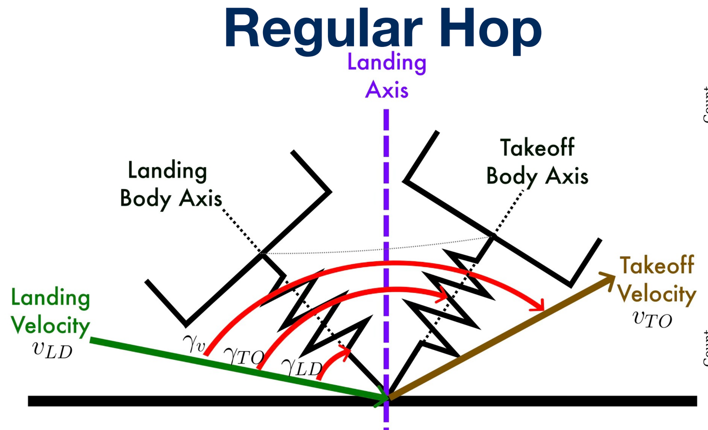
System Identification:

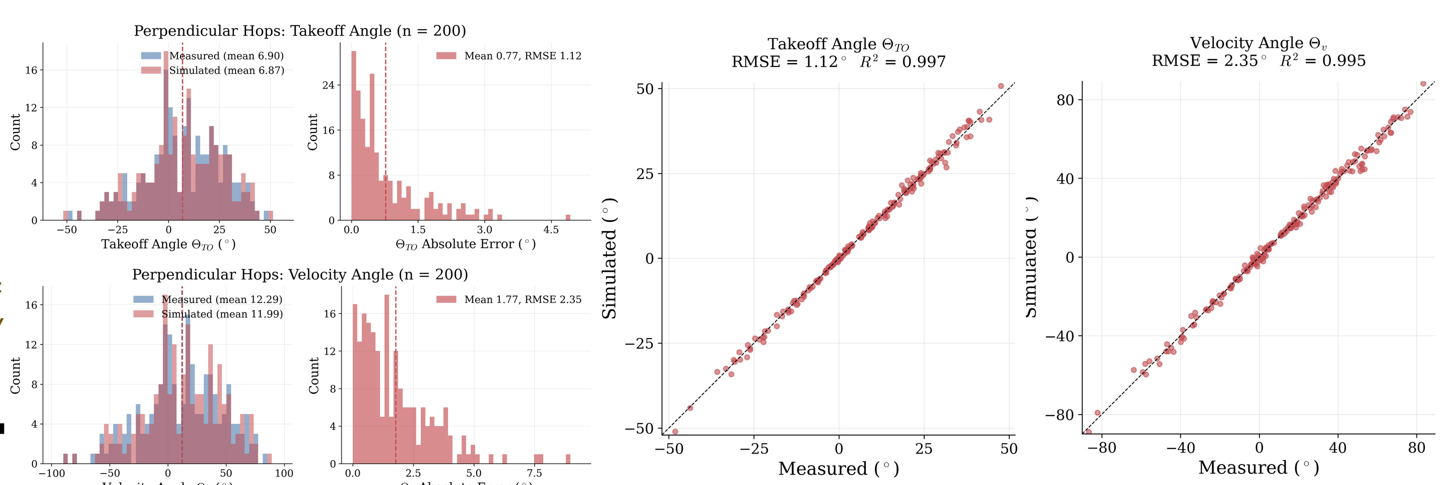
To identify the System Parameters, we must collect data on both the Rolling Hops and Regular Hops. Hops are filtered based on the **heading's direction relative to the jumping plane**, rolling hops lie in plane and regular hops are perpendicular to it. Parameters are then fit using a **Least Squares Regression.**

Symbol	Description	Value	Source
Body and geometry			
m_b	Body mass	0.2598 kg	Measured
m_w	Wheel mass	0.0134 kg	Measured
I_b	Body inertia (pitch)	1.33×10^{-3} kg m^2	Fitted
I_w	Wheel inertia	1.60×10^{-6} kg m^2	Measured
L_0	Leg rest length (CoM to axle)	0.388 m	Measured
$L_{\min}$	Leg compression stop	0.2926 m	Measured
R	Wheel radius	0.0155 m	Measured
g	Gravitational acceleration	9.81 m/s^2	Constant
Leg (elastic element)			
k	Leg spring constant	930.4 N/m	Fitted
a_0	Spring preload	0.0282 m	Fitted
c_{leg}	Leg viscous damping	≈ 0 N s/m	Fitted[a]
Wheel–ground contact			
μ	Coulomb friction coefficient	0.336	Fitted
R_R	Rolling resistance coefficient	0.0695	Fitted
k_g	Ground normal stiffness	1×10^5 N/m	Fixed
c_g	Ground normal damping	50 N s/m	Fixed
v_{ref}	Friction regularisation velocity	0.05 m/s	Fixed [b]
Calibration			
r_z	Marker centroid to CoM offset	−0.020 m	Calibrated[c]

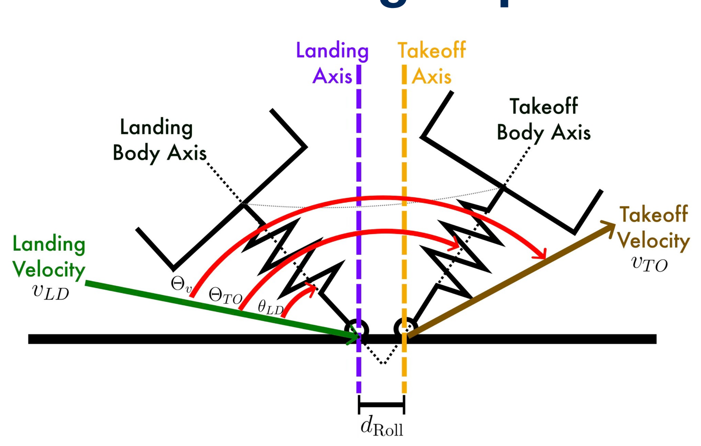


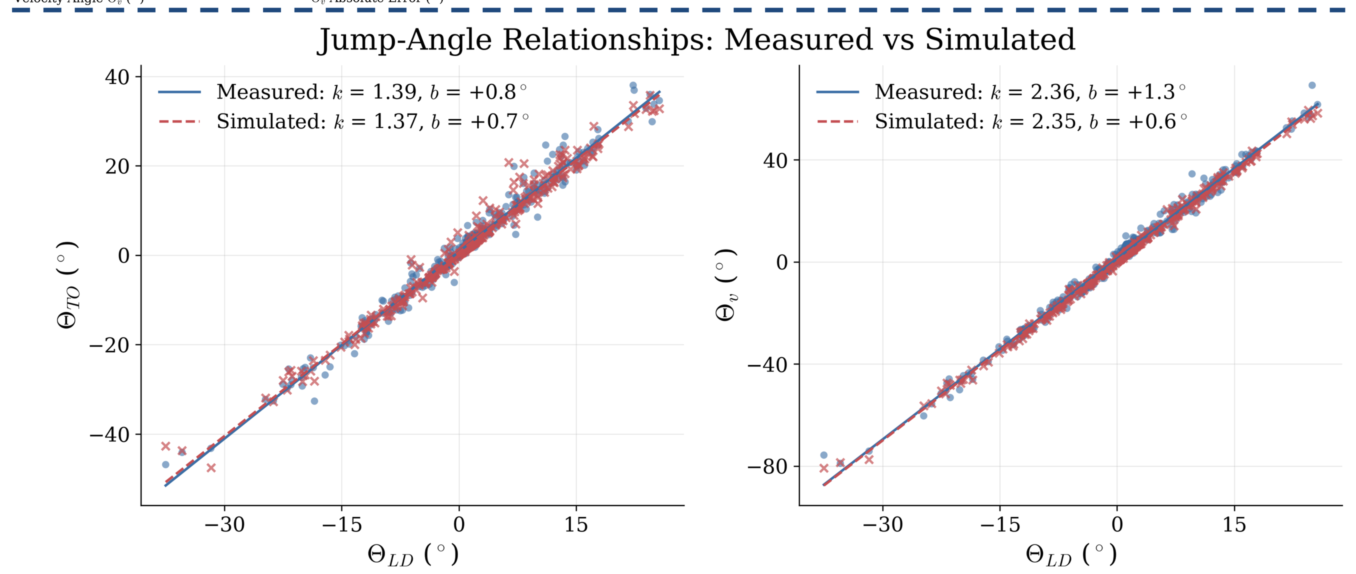
Regular Hop

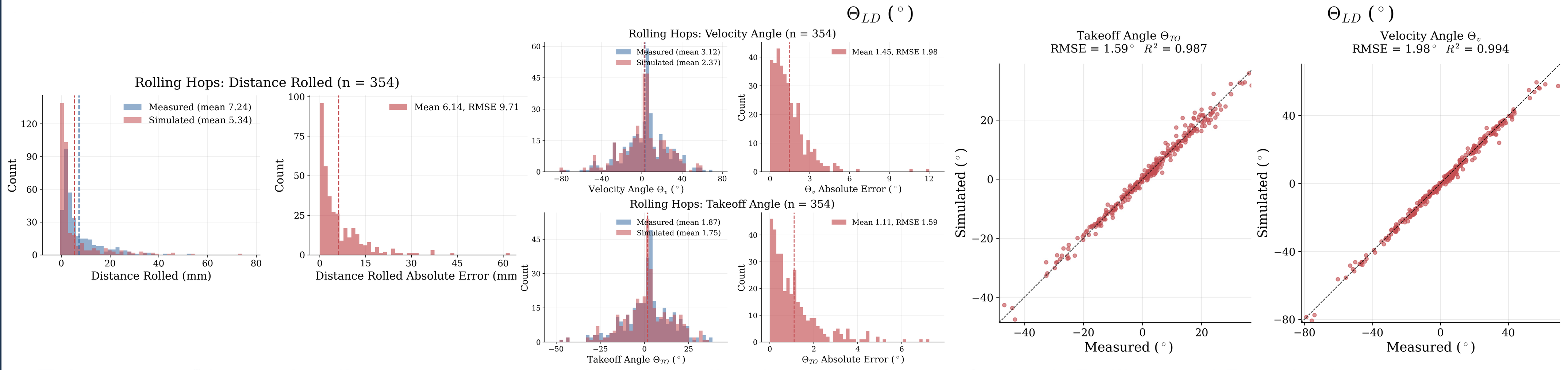




Rolling Hop







Takeaway: Given a landing state we can reliably predict the takeoff state for both Rolling and Regular hops.

Next Steps:

- Construct a **State Lattice** using the identified models
- Quantify the **Cost of Transport** of each mode to estimate the energy cost of a given trajectory
- Use a path planner to find the most energy efficient trajectory
- Add **onboard LiDAR** for **autonomous traversal**

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