AERO 4200 FYP I

DESIGN AND CONTROL OF A SINGLE-LEGGED ROBOT FOR AUTONOMOUS TAKEOFF AND LANDING

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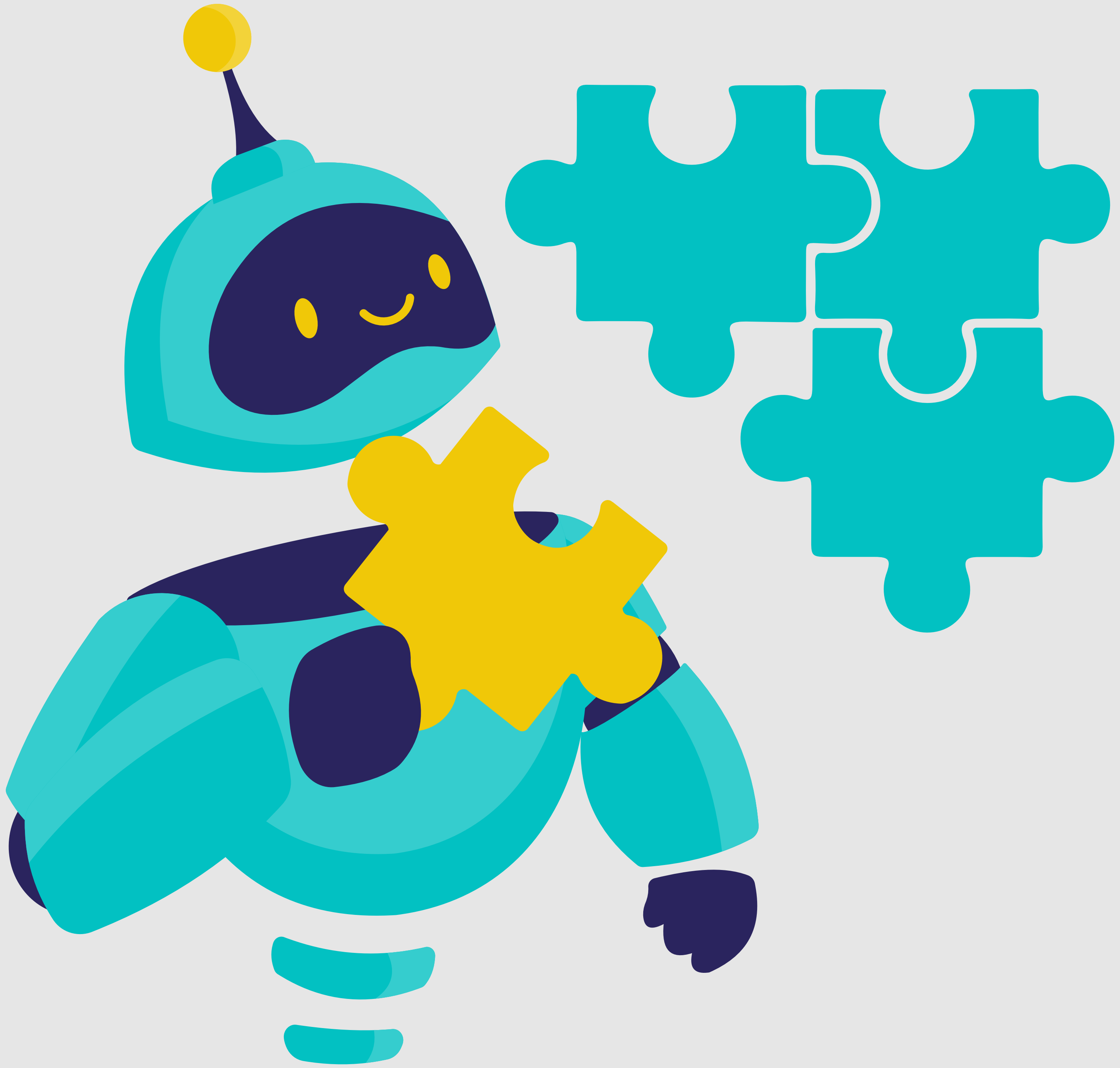
Inquiries, feedbacks and suggestions are welcomed

CONTENT



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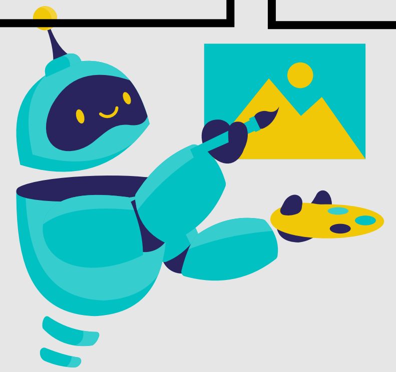
CHAPTER 1

INTRODUCTION

1	BACKGROUND OF STUDY
2	PURPOSE OF THE STUDY
3	PROBLEM STATEMENT
4	OBJECTIVES OF THE RESEARCH
5	RESEARCH QUESTIONS
6	SIGNIFICANCE OF THE STUDY
7	LIMITATIONS AND ASSUMPTIONS
8	RESEARCH SCOPE



1.1 BACKGROUND OF STUDY

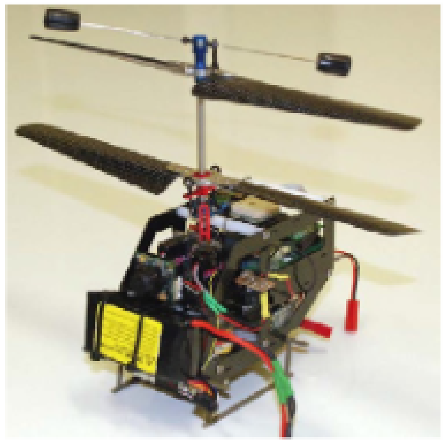
What are MAVs?

Micro Aerial Vehicles (MAVs) are a classification of smaller Unmanned Aerial Vehicles (UAVs), typically **weighing less than 1 kg** , designed for **aerial operation**.

Hybrid Locomotion:

The integration of legs onto MAVs creates **legged MAVs**, enabling **hybrid locomotion strategies**

(a) Fixed wing MAV: The BlackWidow [21]



b) Rotary wing MAV: The MAVS-TAR coaxial twin-rotor [33]

(c) Flapping wing MAV: The Nano Hummingbird [29]

1.2 MOTIVATION

SDG	Aspect
3	Search and Rescue
9	Robotics advancements
15	Environmental monitoring

1.3 PROBLEM STATEMENT

Challenge:
Achieving **stable, controlled autonomous takeoff and landing** for **single-legged** robots in complex environments.

Cause:
Inherent instability of **single-legged systems**, requiring **dynamic balancing** during ground-to-aerial transitions.

Solution :
Sophisticated **control algorithms** to manage dynamics for stable hopping and transitions.

Impact:
Crucial for enabling applications in **search and rescue, exploration, and agile delivery**.

Project Focus:
Design and develop a single-legged robot and its control framework to address this challenge.

1.4 OBJECTIVES OF THE RESEARCH

1	**Designing and modelling** a single-legged robot platform.
2	**Developing control algorithms** for autonomous takeoff and landing.
3	**Evaluating** the robot's performance in **simulations** and **experiments**.

1.5 RESEARCH QUESTIONS

1	What **key design parameters** enable stable dynamic balance and hopping for autonomous takeoff and landing?
2	How can **control algorithms achieve stable transitions** between stance, takeoff, aerial flight, and landing?
3	How does **robot performance vary**, and how can the control system be optimized for robustness under different conditions?

1.7 LIMITATIONS AND ASSUMPTIONS

1	MAV dynamics modelled **without** full **aerodynamics forces**
2	Focus on basic **take-off and landing**
3	**No** primary focus on **energy** efficiency or **payload** capacity
4	Initial development assumes **ideal environment, perfect actuators and sensors, and flat landing surfaces**

1.8 RESEARCH SCOPE

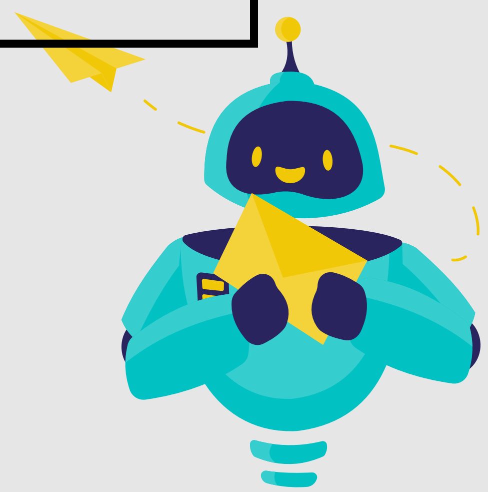
Leg Robot Design	Mechanical **design** and **fabrication**, including **material, actuator, and sensor selection**.
Control System	Development of **algorithms** for **stable** take-off and landing on flat surfaces.
Validation	**Simulation** and **experimental** evaluation of performance (**takeoff height, landing accuracy, stability**) under simulated aerodynamic disturbances.

CHAPTER 2

LITERATURE REVIEW

1	INTRODUCTION
2	SINGLE-LEGGED ROBOT LOCOMOTION
3	LEGGED MAVS LOCOMOTION

4	CONTROL CHALLENGES
5	CONTROL STRATEGIES
6	RESEARCH GAPS



2.2 SINGLE-LEGGED ROBOT LOCOMOTION

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Aspect	Key Points	Pros	Cons	Past Work
Hopping Dynamics	Fundamental, nonlinear, non-smooth Phases (Stance, Flight) Uses **SLIP** model.	**Simplifies dynamics** **Focus on key parameters.**	Simplified model (massless leg, point mass) **Omits complexities** (friction, joints).	Raibert's hoppers (Raibert, 1986) KEN-2 (Ugurlu & Kawamura, 2008) TTI-Hopper (Ugurlu et al., 2021).
Bio-Inspired Robots	**Avian-inspired** mechanics (clutching, tendons) Intrinsic compliance Distal / remote actuation.	Energy efficiency **Reduced control complexity** Robust, lightweight	Complex biological **replication** Requires **specific actuators / transmissions**.	BirdBot (Badri-Spröwitz et al., 2022) SELDA (Bolignari et al., 2022) Salto-1P (Yim et al., 2020) TTI-Hopper (Ugurlu et al., 2021).

2.2.1 HOPPING DYNAMICS

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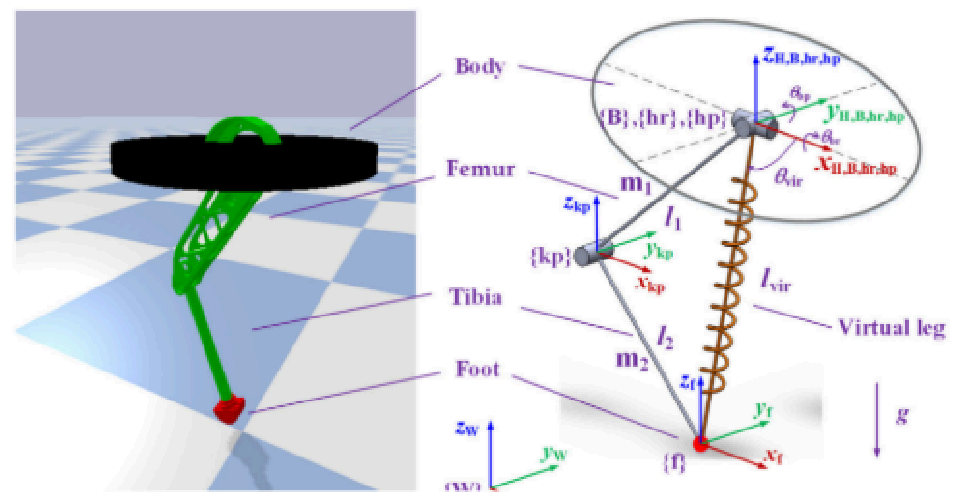

Figure 2.2.1.1: One-legged hopping kinematic model (Huang & Zhang, 2023).

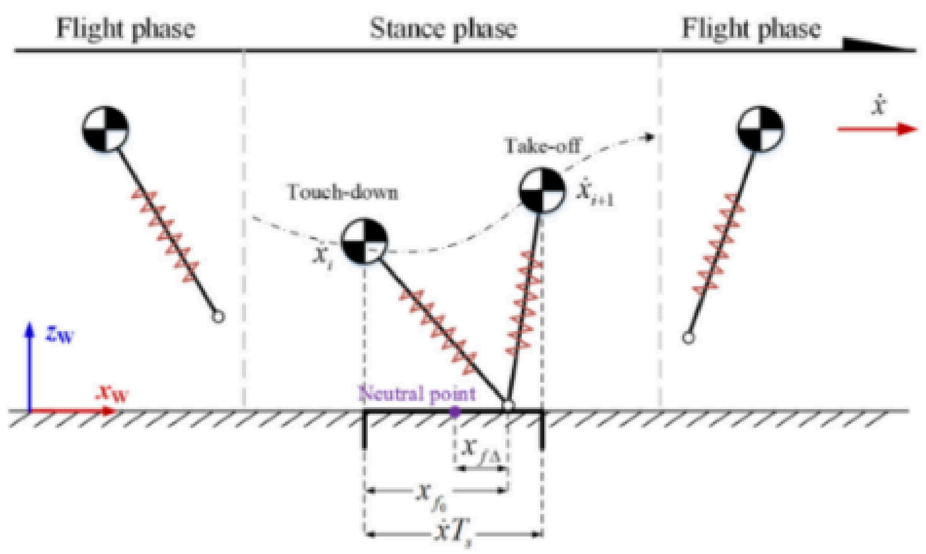

Figure 2.2.1.2: SLIP model hopping dynamics (Huang & Zhang, 2023).

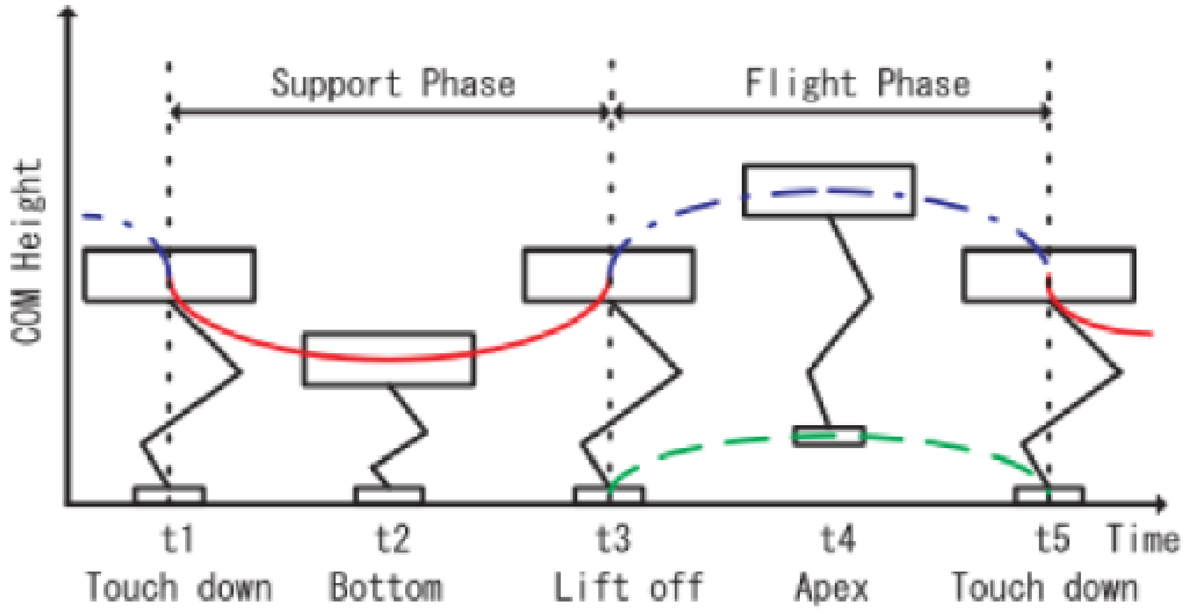

Figure 2.2.1.3: Complete Hopping Sequence (Ugurlu, 2008).

Key Points	Pros	Cons
Fundamental, nonlinear, non-smooth Phases (Stance, Flight) Uses **SLIP** model.	**Simplifies dynamics** **Focus on key parameters.**	Simplified model (massless leg, point mass) **Omits complexities** (friction, joints).

2.2.2 BIO-INSPIRED ROBOTS

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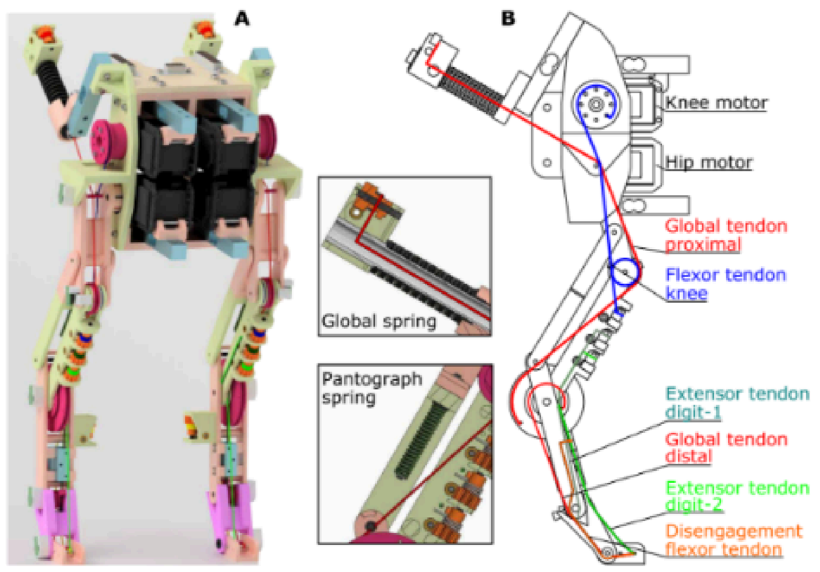

Figure 2.2.2.1: BirdBot leg design and spring tendon network (Badri-Spröwitz et al., 2022).

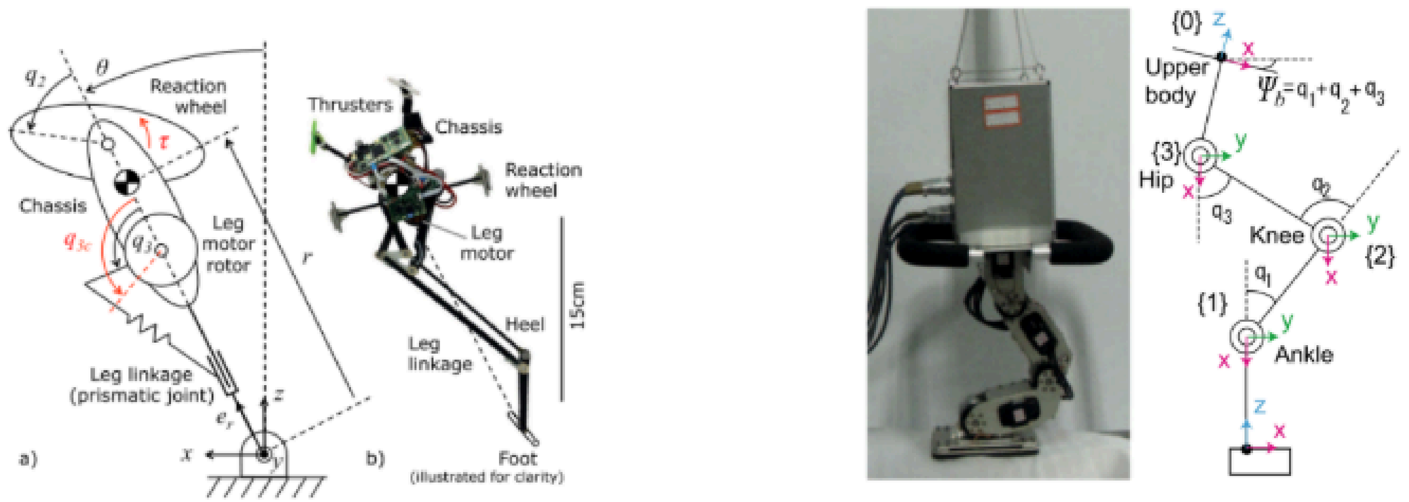

Figure 2.2.2.3: Salto-1P (Yim et al., 2020) and TTI-Hopper (Ugurlu, 2020).

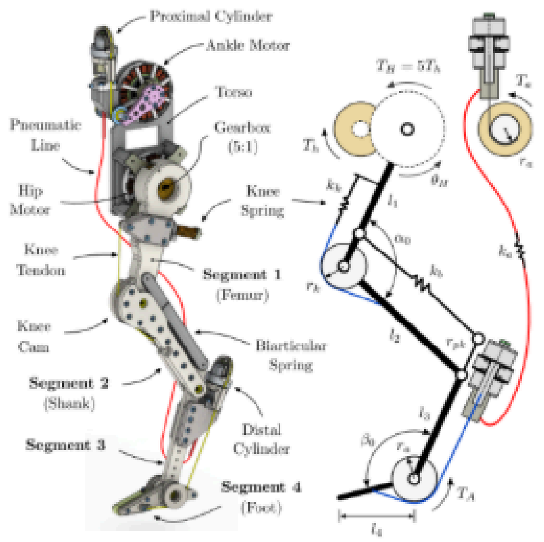

Figure 2.2.2.2: SELDA (Bolignari et. al, 2022)

Key Points	Pros	Cons
Avian-inspired mechanics (clutching, tendons) Intrinsic compliance Distal / remote actuation.	Energy efficiency **Reduced control complexity** Robust, lightweight	Complex biological **replication** Requires **specific actuators / transmissions**.

2.3 LEGGED MAVS LOCOMOTION

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Aspect	Key Points	Pros	Cons	Past Work
Rotary-Wing Legged MAVs	Integration of **legs with copters** Hybrid locomotion (air/ground) Perching/grasping (bird-inspired) Active leg mechanisms for landing/balance	Enables **complex maneuvers** like perching Access to varied terrain Potential for more stable landings	Weight and power constraints **Complexity of combined systems** Managing impacts	SNAG (Roderick, 2021)
Flapping-Wing Legged MAVs	Integration of **legs with ornithopters** / flapping-wing Single motor for wings and legs Passive stability from wings/tail Perching control	Potential for **long-duration flight** Leverages aerodynamic principles for stability.	Challenge of single motor driving both systems Highly nonlinear flight dynamics **Control complexity for transitions**	BOLT (Peterson, 2011) P-Flap (Zufferey et al., 2022)

2.3.1 ROTARY-WING LEGGED MAVS

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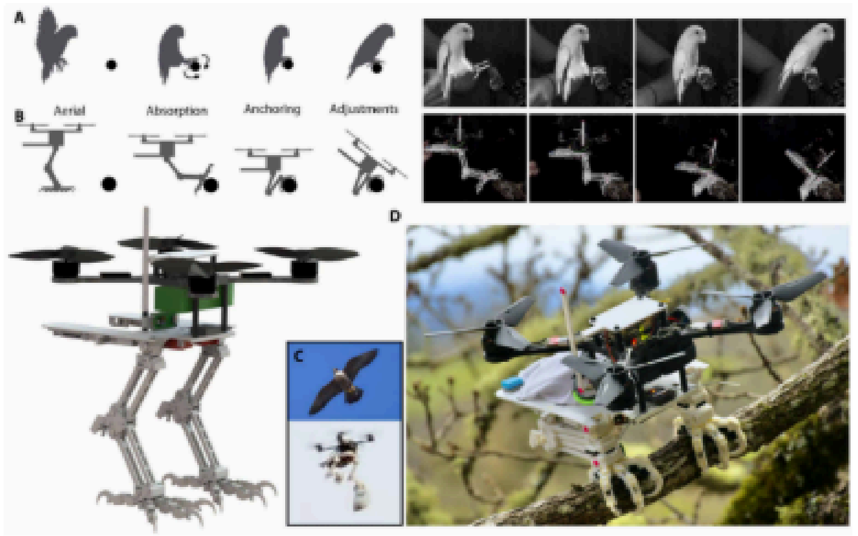

Figure 2.3.1.1: SNAG Robot (Roderick et al., 2021).

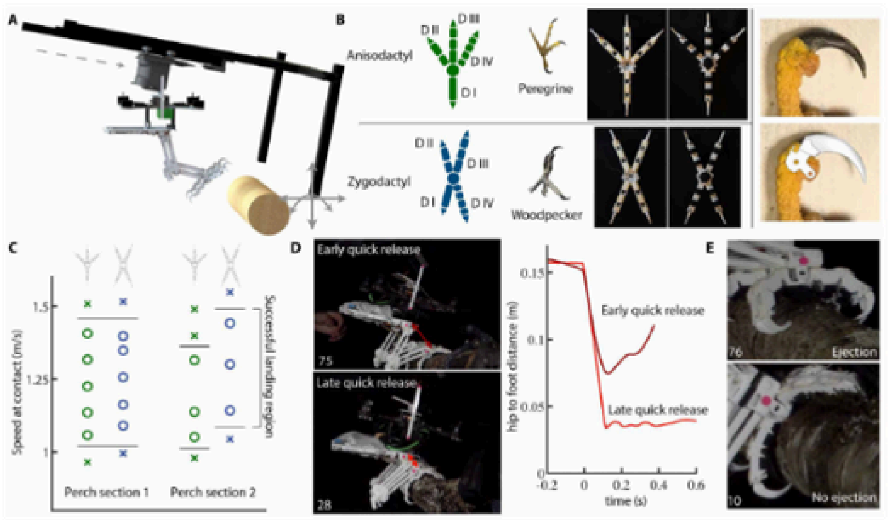

Figure 2.3.1.2: SNAG Robot with Different Toe Arrangements (Roderick et al., 2021).

Key Points	Pros	Cons
Integration of **legs with copters** Hybrid locomotion (air/ground) Perching/grasping (bird-inspired) Active leg mechanisms for landing/balance	Enables **complex maneuvers** like perching Access to varied terrain Potential for more stable landings	Weight and power constraints **Complexity of combined systems** Managing impacts

2.3.2 FLAPPING-WING LEGGED MAVS

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Figure 2.3.2.1: BOLT MAVs (Roderick et al., 2021).

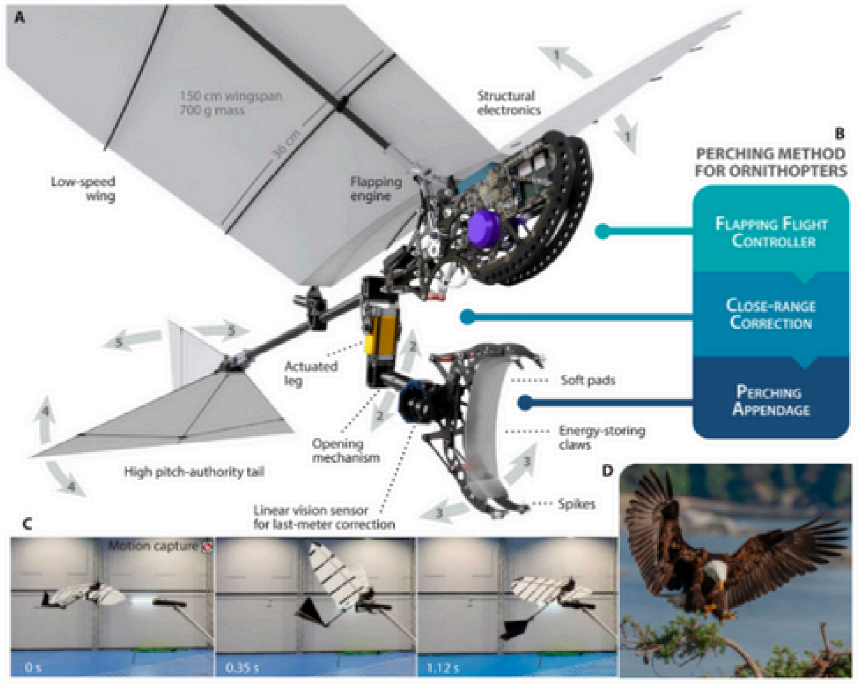

Figure 2.3.2.2: P-Flap MAVs (Zufferey et al., 2022).

Key Points	Pros	Cons
Integration of **legs with ornithopters** / flapping-wing Single motor for wings and legs Passive stability from wings/tail Perching control	Potential for **long-duration flight** Leverages aerodynamic principles for stability.	Challenge of single motor driving both systems Highly nonlinear flight dynamics **Control complexity for transitions**

2.4 CONTROL CHALLENGES

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Aspect	Key Points	Challenges	Past Work
Dynamic Instability	**Complex, non-smooth dynamics** Sensitive to terrain/noise Perturbations faster than control loops Requires robust force control.	**Balancing** during stance phases (launch/landing) **Managing CG** motion **Dependence on sensor** quality/speed.	Discussed in general legged locomotion context (BirdBot, TTI-Hopper) Passive walkers
Autonomous Take-off /Landing	Precise velocity angle control at liftoff/touchdown **Managing phase transitions** Maintaining post-landing balance	**Achieving precise landings** on targets Implementing **controlled takeoffs** (especially from elevated points) Withstanding / absorbing **impacts**;	Salto-1P's landing control (Yim et al., 2020) SNAG's perching (Roderick et al., 2021) P-Flap's perching/takeoff plan (Zufferey et al., 2022)

2.4.1 DYNAMIC INSTABILITY

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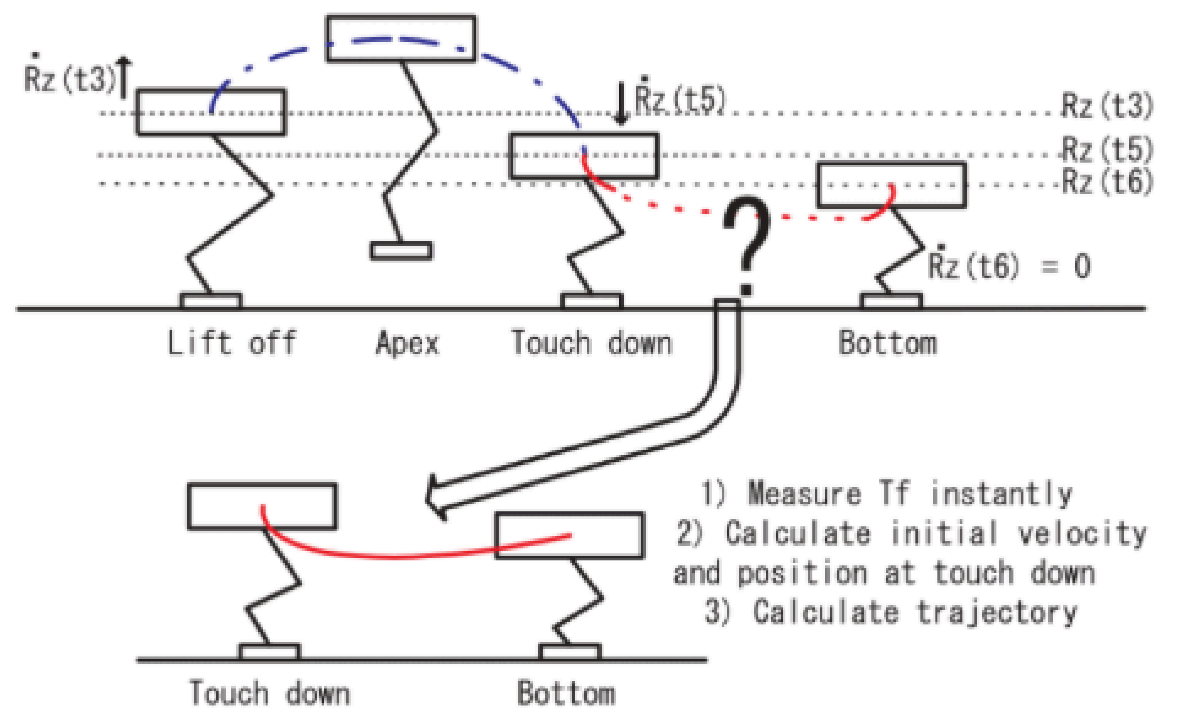

Figure 2.4.1.3: Uncertainty at a touch down state (Ugurlu, 2008).

Key Points	Challenges
Complex, non-smooth dynamics Sensitive to terrain/noise Perturbations faster than control loops Requires robust force control.	**Balancing** during stance phases (launch/landing) **Managing CG** motion **Dependence on sensor** quality/speed.

2.4.2 AUTONOMOUS TAKEOFF/LANDING

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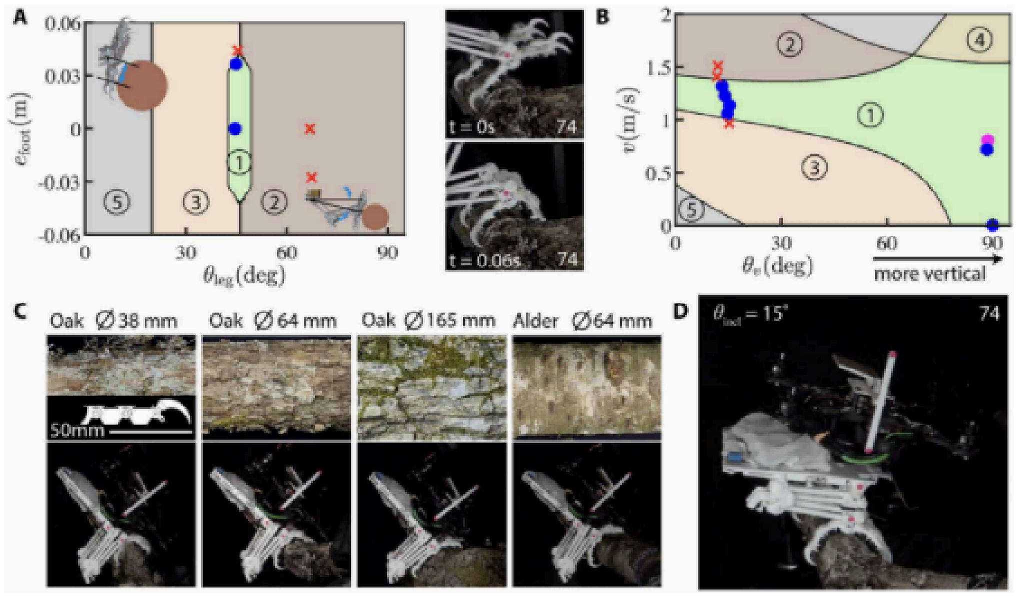

Figure 2.4.2.1: The perching sufficiency region visualizing the narrow margins for success. (Roderick et al., 2021).

Key Points	Challenges
Precise velocity angle control at liftoff/touchdown **Managing phase transitions** Maintaining post-landing balance	**Achieving precise landings** on targets Implementing **controlled takeoffs** (especially from elevated points) Withstanding / absorbing **impacts**;

2.5 CONTROL STRATEGIES

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Aspect	Key Points	Pros	Cons
Traditional and Modern Control	**Analytical dynamic models** MPC (optimization framework) **ZMP/CoP** (simplified models like LIP) VMC; FSM; **PD control**; Admittance control.	Established theory **Predictable behavior** (if model accurate) Can be **computationally efficient for simple models** Provides compliance for contact	Dependent on model accuracy Parameter estimation challenges **Can struggle with highly dynamic or complex systems** **Limited robustness to unexpected events**
Advanced Control	**Reinforcement learning** (model-free, learns policies) **Deep learning** (data-driven dynamics) Trajectory Optimization (optimizes complex plans)	Can handle **complex/nonlinear dynamics** **Learns from data**/experience Potentially more robust to modeling errors Can optimize for **high performance**	Requires **significant data**/simulation (RL); **Computational cost** (MPC, TO) Black-box nature (DL, some RL) Stability guarantees can be challenging

2.5.1 TRADITIONAL AND MODERN CONTROL

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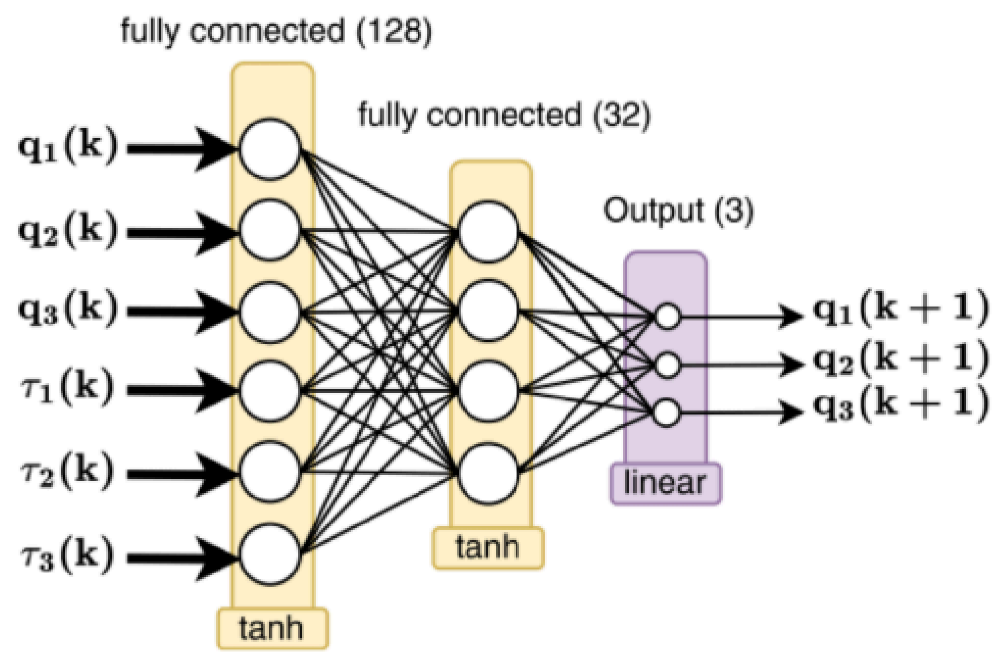


Figure 2.5.1.1: Nonlinear Model Predictive Control Architecture (El-Hussieny, 2024).

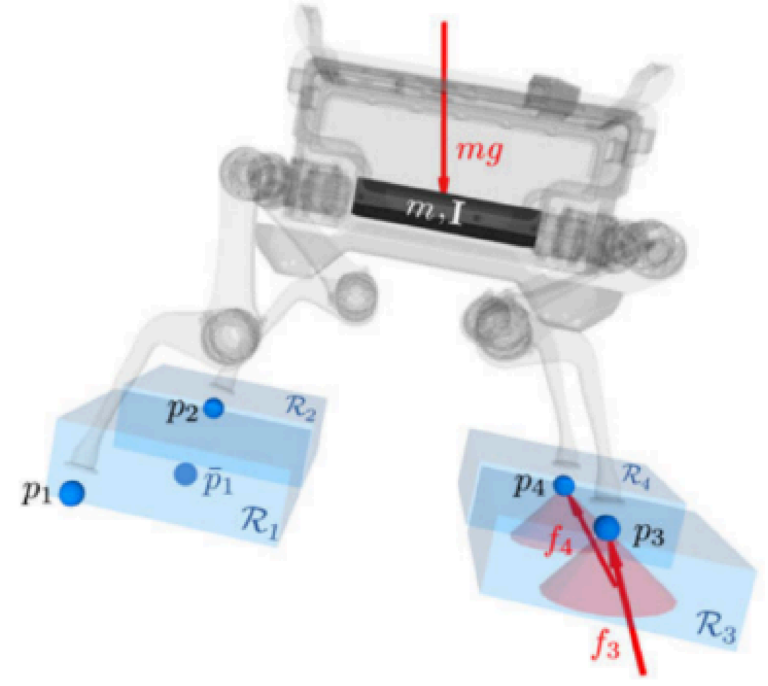
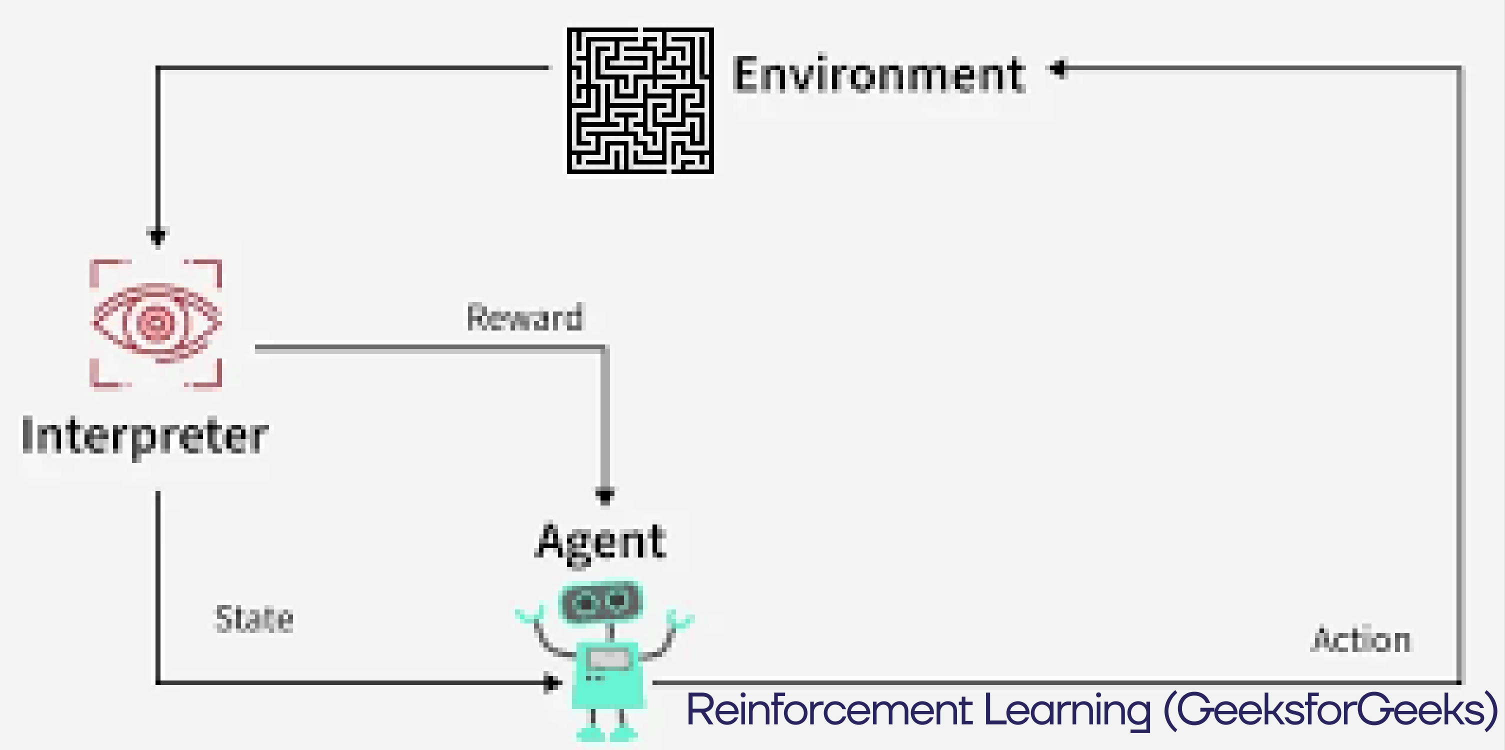


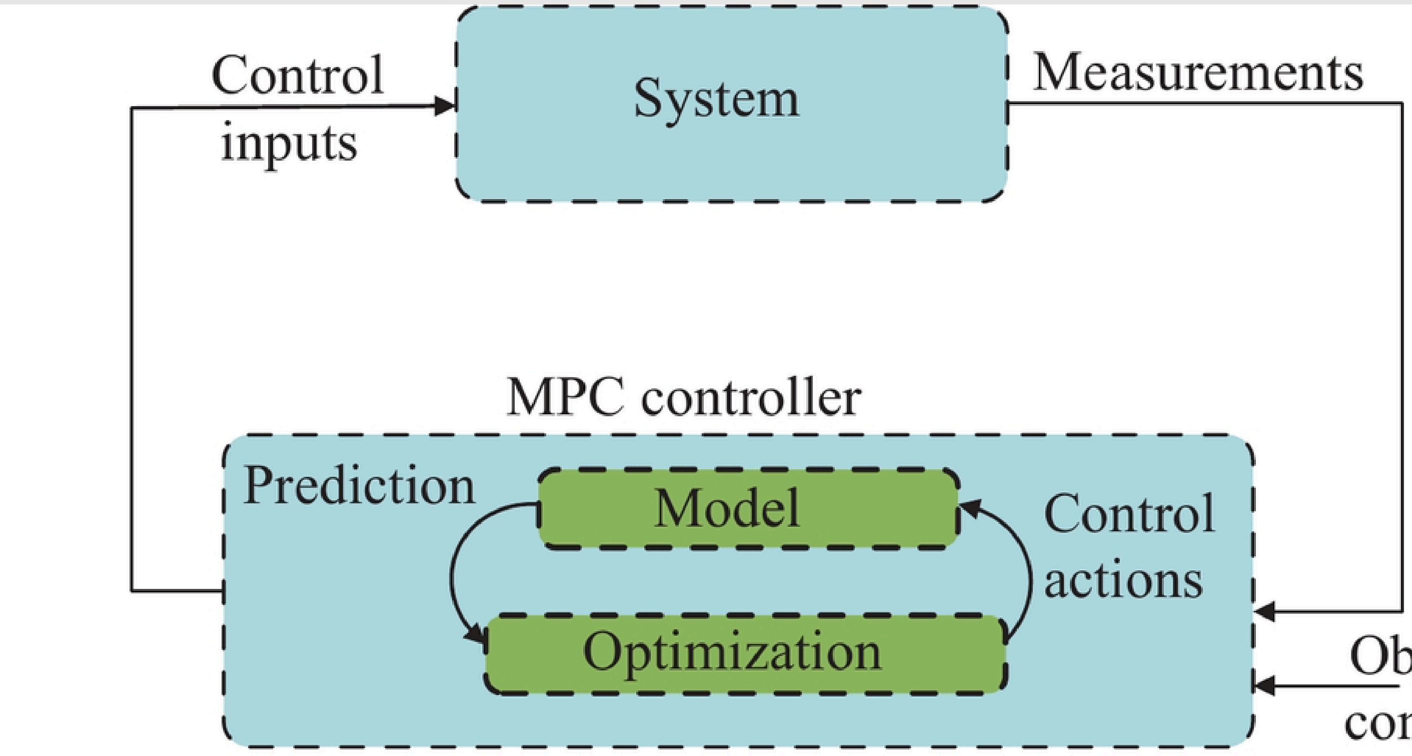
Figure 2.5.1.2: Centroidal dynamics model (Winkler et al., 2018).

Key Points	Pros	Cons
Analytical dynamic models MPC (optimization framework) **ZMP/CoP** (simplified models like LIP) VMC; FSM; **PD control**; Admittance control.	Established theory **Predictable behavior** (if model accurate) Can be **computationally efficient for simple models** Provides compliance for contact	Dependent on model accuracy Parameter estimation challenges **Can struggle with highly dynamic or complex systems** **Limited robustness to unexpected events**

2.5.2 ADVANCED CONTROL



Reinforcement Learning (GeeksforGeeks)



Model Predictive Control (IEEE)

Key Points	Pros	Cons
Reinforcement learning (model-free, learns policies) **Deep learning** (data-driven dynamics) Trajectory Optimization (optimizes complex plans)	Can handle **complex/nonlinear dynamics** **Learns from data**/experience Potentially more robust to modeling errors Can optimize for **high performance**	Requires **significant data**/simulation (RL); **Computational cost** (MPC, TO) Black-box nature (DL, some RL) Stability guarantees can be challenging

2.6 RESEARCH GAP

Table 2.6.1:Research Gap Metadata

No.	Paper Title	Author(s)	Year	Type of MAVs	Type of Leg	Leg Mathematical Model	Takeoff and Landing Capability	Control Solution	Pros	Cons
1	BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching	Badri-Spröwitz et al.	2022	Not Applicable (ground robot)	Avian-inspired with clutching	Models for energy loss in mechanical walking	Not explicitly mentioned, focuses on walking. Limited to flat terrain .	Minimal actuation, open loop, inspired by passive mechanical walkers.	Energy efficiency, minimal control.	Limited to flat, smooth terrain, sensitive stability, low ground clearance.
2	Diaphragm Ankle Actuation for Efficient Series Elastic Legged Robot Hopping	Bolignari et al.	2022	Not Applicable (ground robot)	Bio-inspired with Series Elastic Diaphragm (SELDA) at ankle	Experiment-based characterization of pneumatic transmission	Hopping robot, foot actuation timing affects hop height/velocity.	Simple, open-loop position control; active foot actuation timing	Lightweight, low-friction, high efficiency, remote actuation, compliant. Increased velocity in passive mode.	Currently under-dimensione d actuator
3	Comparison of a fixed-wing and multi-rotor UAV for environmental mapping applications A case study	Boon, Drijfhout, Tesfamichael	2017	Fixed-wing, Multi-rotor	Not Applicable	Not Applicable	Multi-rotors: easy takeoff/landing. Fixed-wing: not detailed, landing in complex areas difficult	Autonomous flights (multi-rotor), georeferencing	Multi-rotors: easy to fly/land/autonomo us. Fixed-wing: higher payload, longer flight time potentially	Multi-rotors: limited flight time/coverage. Fixed-wing: higher geometric error , problematic landmark identification
4	Real-time deep learning-based model predictive control of a 3-DOF biped robot leg	El-Hussieny	2024	Not Applicable (ground robot leg)	3-DOF biped robot leg	Deep learning-based dynamic model validated with data.	Not explicitly mentioned, focuses on leg trajectory tracking.	Deep learning-based MPC, additional constraints for safety/efficiency	Improved trajectory tracking without analytical models, enhanced safety/efficiency	Alternative controls are non-predictive or avoid online optimization.

2.6 RESEARCH GAP

5	Reinforcement learning of single legged locomotion	Fankhauser et al.	2013	Not Applicable (ground robot)	Single compliant leg (ScarlETH), series elastic actuators	Modeled body, thigh, shank; joint torque = spring deflection.	Jumping and hopping, learning jump lengths, optimizing hopping energy	Reinforcement learning (PI2) on motor velocity, learning periodic policies	Effective for locomotion performance and energy efficiency, exploits dynamics, compensates for model errors	PI2 initially for slower tasks.
6	Controlling a One-Legged Robot to Clear Obstacles by Combining the SLIP Model with Air Trajectory Planning	Huang, Zhang	2023	Not Applicable (ground robot)	One-legged, mimicking quadruped legs (3 DOF)	Combines SLIP model with Bézier curve for air trajectory.	Jumping and obstacle clearing (simulation), continuous jumping over varying heights	SLIP model + Bézier trajectory planning; foot force related to speed.	Effective obstacle clearing and stable jumping (simulation), mimics animal jumping	Primarily simulation-based, few prior studies on one-legged obstacle clearing.
7	Experimental dynamics of wing-assisted running for a bipedal ornithopter	Peterson et al.	2011	Bipedal ornithopter	Bipedal, assists running	Focus on experimental dynamics, model not detailed in excerpt.	Focus on wing-assisted running, takeoff/landing not primary focus in excerpt	Not detailed in excerpt, focus on experimental dynamics.	Investigates dynamics of a novel MAV design	Takeoff and landing not a primary focus in the excerpt.
8	Bird-inspired dynamic grasping and perching in arboreal environments	Roderick, Cutkosky, Lentink	2021	Quadcopter (SNAG)	Two legs with bird-inspired grasping (claws)	Model of perching sufficiency region based on contact, momentum	Dynamic grasping and perching on branches, also object catching. Takeoff from branch is future work	Stereotyped passive/active control, open/closed-loop balance	Reliable perching on diverse surfaces, bird-inspired, also catches objects	Takeoff from branch is a challenge .
9	Series elastic behavior of biarticular muscle-tendon structure in a robotic leg	Ruppert, Badri-Spröwitz	2019	Not Applicable (ground robot leg)	Two-segmented with distal biarticular elastic element	Mathematical model characterizing leg behavior under forces/torques.	Tested in monoped hopping and vertical drop.	Control not primary focus initially; future work on controllers utilizing reflection effect	Novel perspective on elastic element placement, potential energy recuperation, additional DOF	Functional morphology of multiple compliances not fully understood .

2.6 RESEARCH GAP

10	Fast ground-to-air transition with avian-inspired multifunctional legs	Shin et al.	2024	Fixed wing bipedal MAVs	Bird-inspired with passively compliant toe joints	Jumping take-off simulation model (6 DOF).	Jumping forward demonstrated experimentally with different feet . Take-off simulated/validated.	Same control command for different foot designs	Compliant toes influence jump performance, simulation matches experiments	Increased mechanical complexity with compliant joints.
11	Real-time jumping trajectory generation for a one-legged robot based on discretized ZMP equation in polar co-ordinates	Ugurlu	2008	Not Applicable (ground robot, KEN-2)	One-legged	Discretized ZMP equation in polar coordinates (includes angular momentum).	Jumping robot, online pattern generation for stability. Simulation/experimental results.	Online jumping pattern generation based on discretized ZMP	Ensures stability during jumping by including angular momentum smoothly	May have limitations of ZMP in highly dynamic maneuvers.
12	Compliant locomotion control for an untethered one-legged robot with trajectory generation characterizing varying inertia and angular momentum	Ugurlu	2021	Not Applicable (ground robot, one-legged)	One-legged with conventional actuators	Trajectory generator (EZR) for inertia/angular momentum. Admittance controller with stability proof.	Agile balancing and locomotion, running on incline, continuous jumps. Handles contact forces.	Compliant control, EZR trajectory generation, admittance control	Computationally inexpensive compliant control, proven stability, dynamically consistent trajectories, stable running on uneven terrain	"Stiff-by-nature" system might limit extreme compliance without active control.
13	Selection of The Most Proper Unmanned Aerial Vehicle for Transportation in Emergency Operations by Using Analytic Hierarchy Process	Ulukavak, Miman	2021	Fixed-wing, Multi-rotor (Class I)	Not Applicable	Not Applicable	Landing field and ease of use key criteria for emergency selection. Difficulties in complex environments.	Analytic Hierarchy Process (AHP) based on expert opinion and criteria	Structured method for UAV selection based on multiple criteria and expert input, useful for emergency planning	Relies on subjective expert opinions, brand knowledge not considered.

2.6 RESEARCH GAP

14	Gait and Trajectory Optimization for Legged Systems Through Phase-Based End-Effector Parameterization	Winkler et al.	2018	Applicable to various legged systems	Not specified generally	Focus on trajectory optimization using simplified models, predefined/optimized footholds.	Foothold placement crucial for stability, indirectly related to takeoff/landing for legged aerial vehicles.	Trajectory optimization via phase-based end-effector parameterization, often with ZMP constraints	Fast solver usable online, allows determining optimal footholds/timings	Model simplifications can restrict base motions if footholds are predefined.
15	Precision robotic leaping and landing using stance-phase balance	Yim et al.	2020	Not Applicable (ground robot, Salto-1P)	Single leg with series-elastic power modulation	Model with rigid bodies and prismatic leg joint. Derivation of landing leg angle strategy.	Precision leaping to targets and balanced landing achieved. Approximate landing limits derived.	Combines high-performance balance control with high-power jumping; lean angle control	Achieves precise leaping and balanced landing on small base, landing strategy to arrest motion	Focus on single-legged robot, may not directly apply to more complex systems.
16	How ornithopters can perch autonomously on a branch	Zufferey et al.	2022	Flapping-wing ornithopter	Legs with perching mechanism (claws)	Experimental validation emphasized, model not primary focus in excerpt.	Autonomous perching on branches by grasping with claws. Takeoff from branch is future work.	Triple control (attitude, position, frequency), local branch detection with line-scan sensor	Autonomous perching, bird-inspired mechanism	Takeoff from branch is a challenge , current sensor limited outdoors.

2.6 RESEARCH GAP

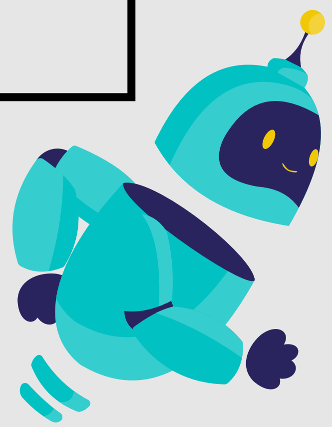
Unexplored Area	**Autonomous takeoff and landing** for **fixed-wing** Micro Aerial Vehicles (**MAVs**) using a **single leg** on **flat surface** without grasping
Significance	Fixed wing : **Longer flight endurance** than copters Single leg : **Eliminate launching mechanism** or runaway for lighter TOL mobility
Key Challenge	Inherent dynamic instability of single-legged systems, especially during fast transitions (takeoff/landing), requiring constant balance.
Key Solution	Development of specialized control strategies for stable autonomous takeoff and landing

CHAPTER 3

METHODOLOGY

1	INTRODUCTION
2	RESEARCH DESIGN AND OVERALL APPROACH
3	ROBOT MECHANICAL DESIGN AND MODELING

4	VALIDATION
5	PRELIMINARY SETUP



3.2 RESEARCH DESIGN AND OVERALL APPROACH

Table 3.2.2: Phases of Research

Phase	Proposed Activities	Deliverables
Phase 1: Conceptualization & Literature Review	Literature review, gap identification, objective formulation, preliminary design	Objectives, preliminary design concepts, literature review report.
Phase 2: Mechanical Design & Dynamic Modeling	Detailed mechanical design, component selection, kinematic & dynamic modeling.	CAD models, component specs, mathematical models.
Phase 3: Control System Development & Simulation	Design low and high-level controllers, extensive Gazebo simulation.	Control algorithms, simulation models/data, refined parameters.
Phase 4: Prototype Fabrication & Experimental Validation	Fabricate prototype, conduct experiments, compare simulation vs. real-world.	Robot prototype, experiment documentation & data, comparative analysis.
Phase 5: Data Analysis & Discussion	Analyze simulation and experimental data, evaluate performance, discuss findings.	Data analysis, performance report, conclusions

3.3 ROBOT MECHANICAL DESIGN AND MODELING

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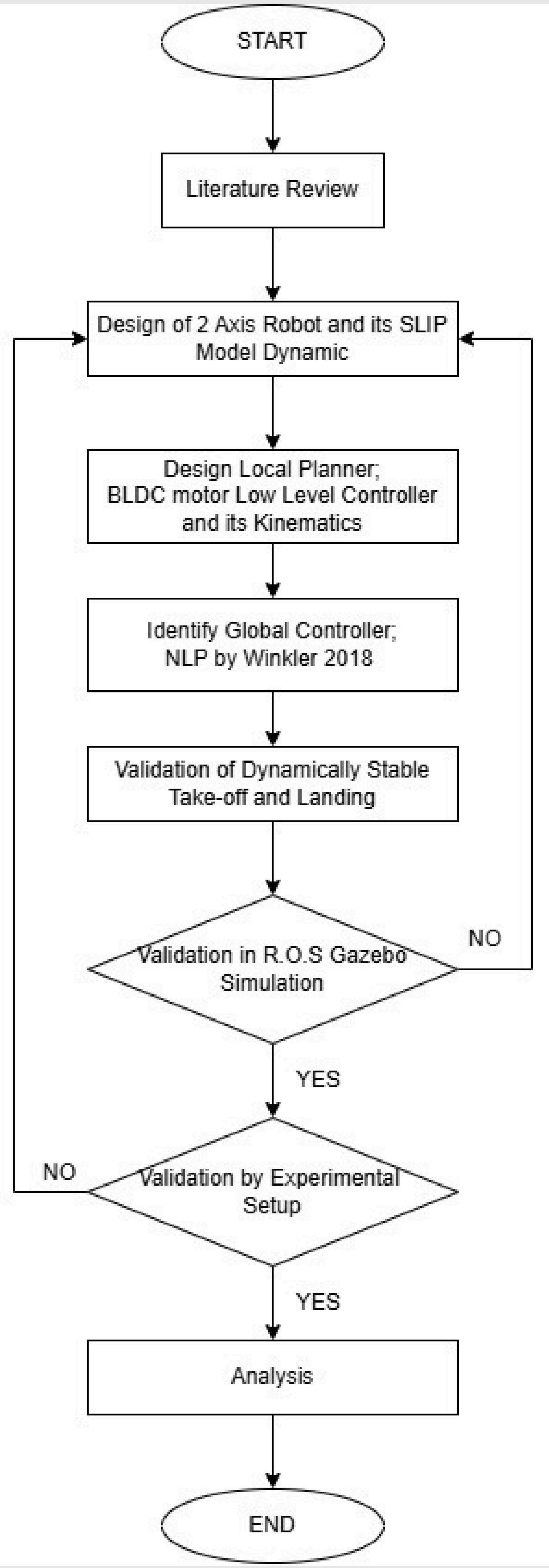
1	**Designing and modelling** a single-legged robot platform.
2	**Developing control algorithms** for autonomous takeoff and landing.
3	**Evaluating** the robot's performance in **simulations** and **experiments**.



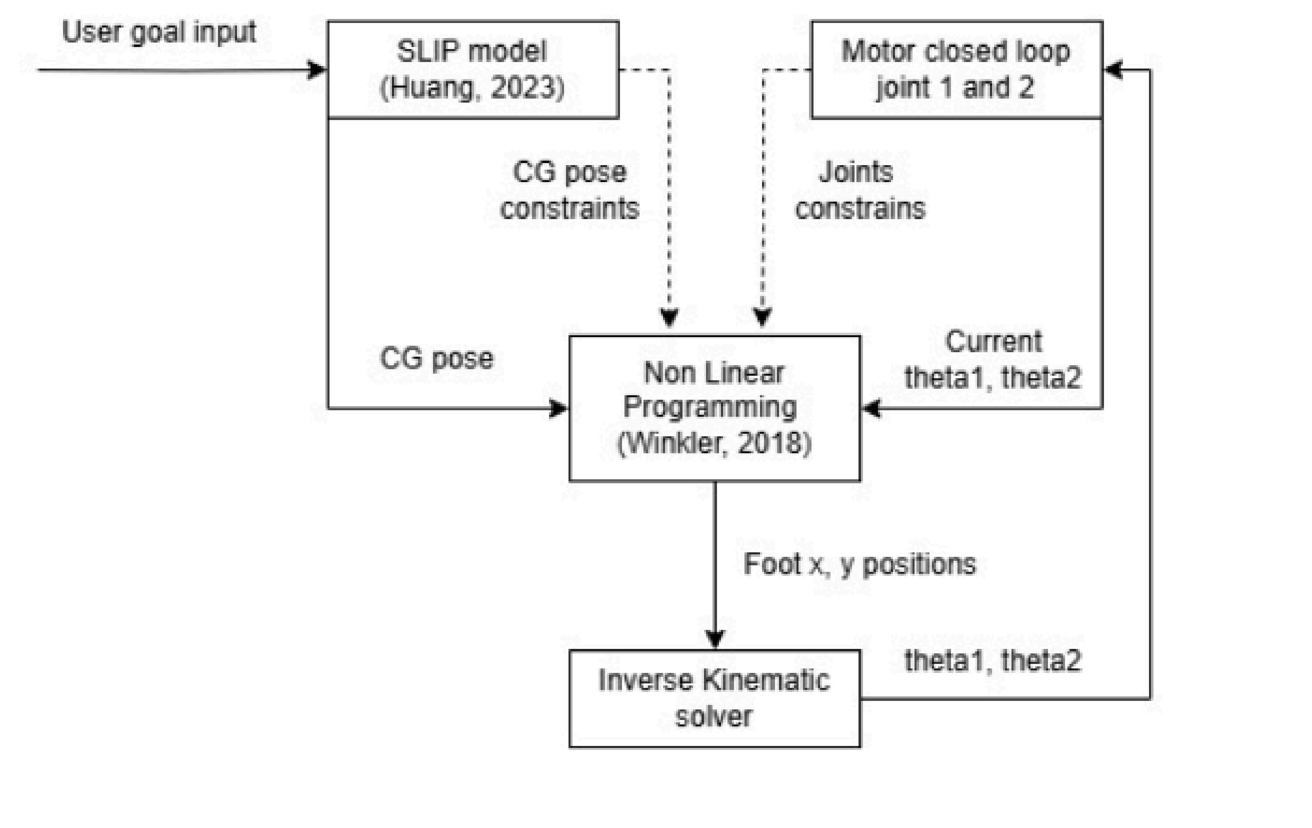


Figure 3.3.5: Generalized model of SLATOL

3.3 ROBOT MECHANICAL DESIGN AND MODELING

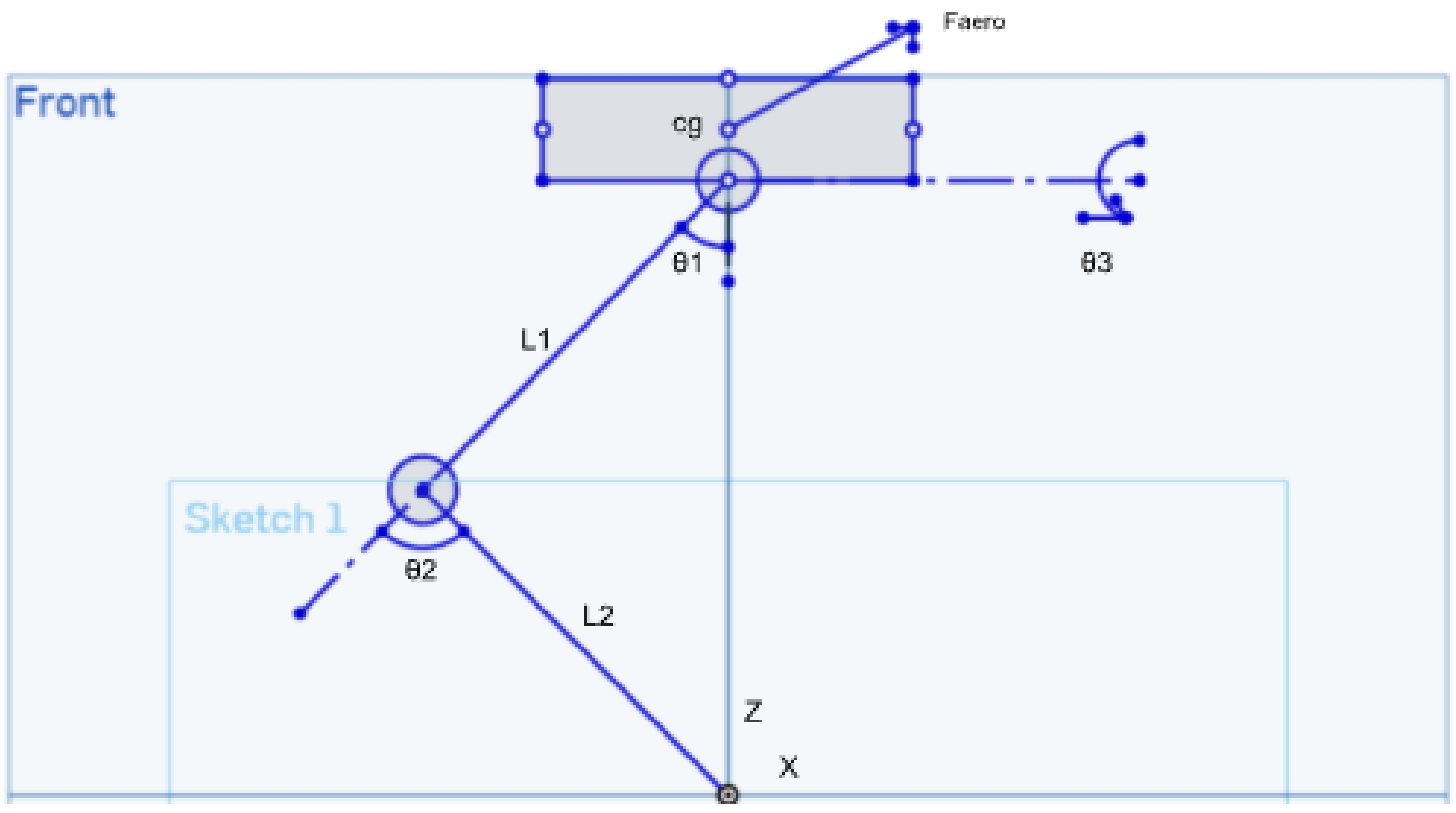


Figure 3.3.2: 2-axis model of SLATOL

$$x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2)$$

$$y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) \qquad (3)$$

Forward Kinematics

$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{L_2 \sin\theta_2}{L_1 + L_2 \cos\theta_2}\right)$$

$$\theta_2 = \cos^{-1}\left(\frac{x^2 + y^2 - L_1^2 - L_2^2}{2 L_1 L_2}\right) \qquad (4)$$

Inverse Kinematics

$$J = \begin{bmatrix} -L_2 \sin(\theta_1+\theta_2) - L_1 \sin(\theta_1) & -L_2 \sin(\theta_1+\theta_2) \\ L_2 \cos(\theta_1+\theta_2) + L_1 \cos(\theta_1) & L_2 \cos(\theta_1+\theta_2) \end{bmatrix} \qquad (5)$$

Jacobian Sytem

3.4 VALIDATION

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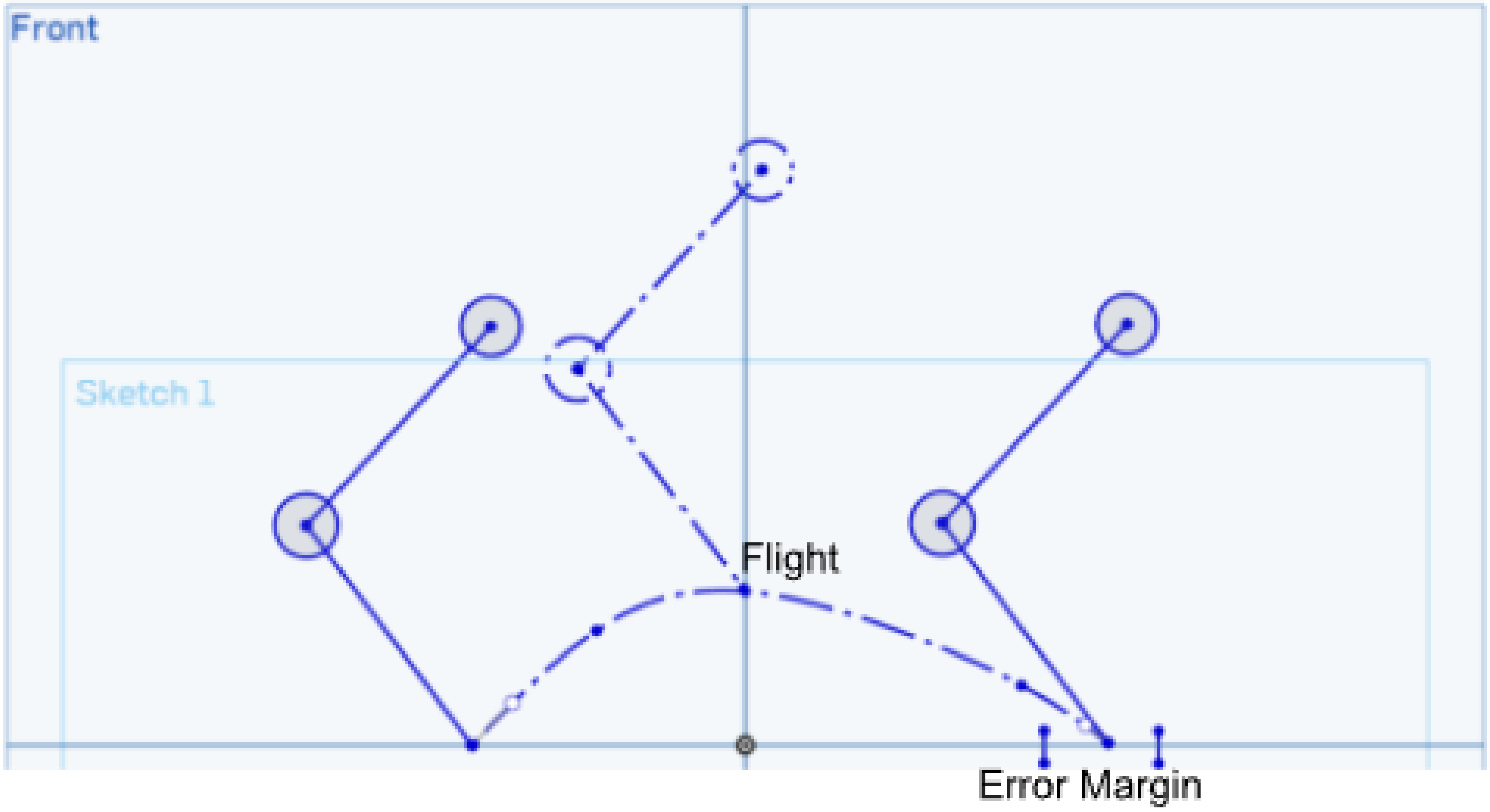


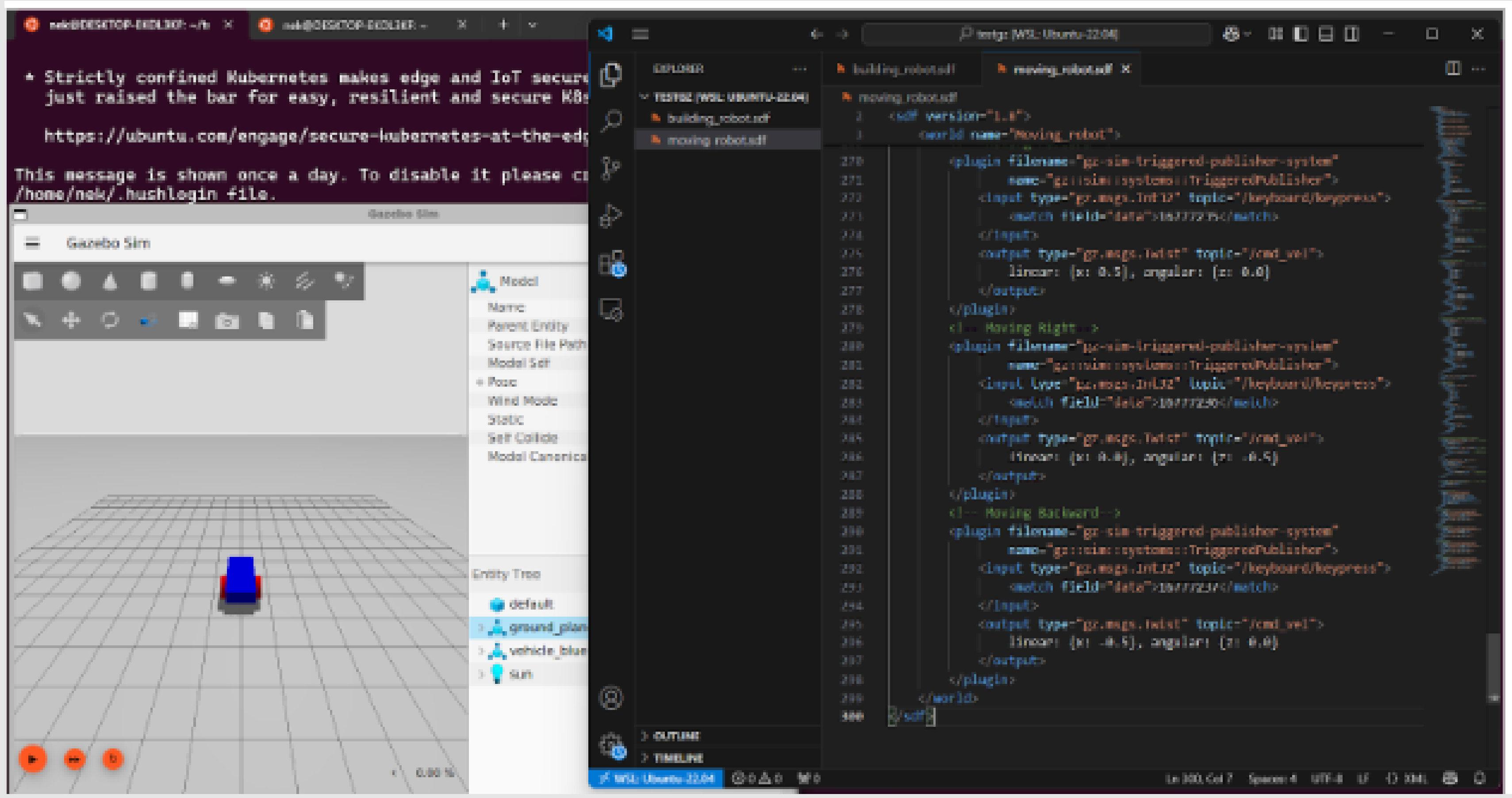
Figure 3.5: Validation by Simulation and Experiment

Simulation and **experimental** evaluation of performance

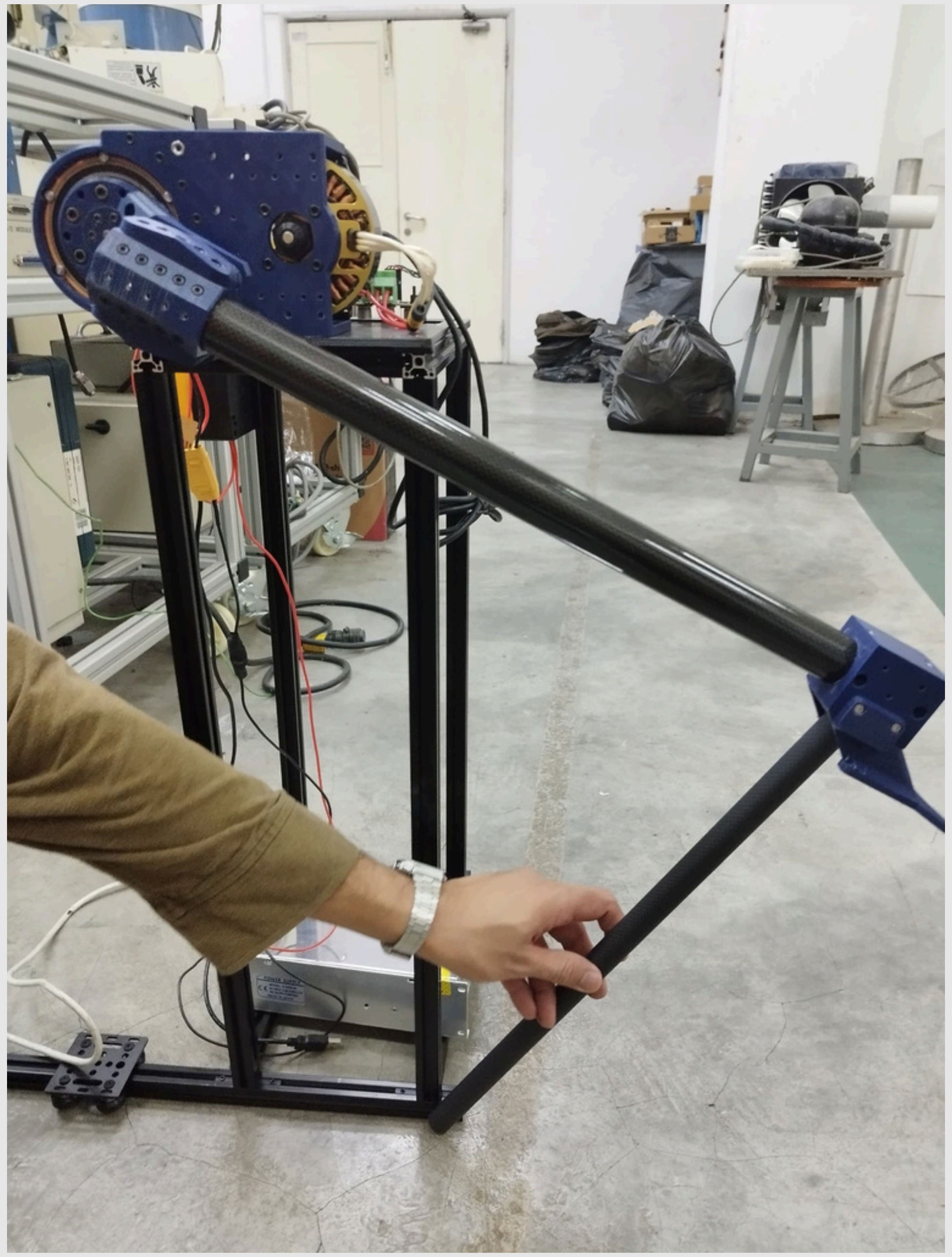
1. **Takeoff height**
2. **Landing accuracy**
3. **Stability**

under simulated aerodynamic disturbances.

3.5 PRELIMINARY SETUP



ROS Gazebo Simulation Preliminary Setup



Test Bed Experimental Preliminary Setup

4. CONCLUSION

Goal	Achieve **Autonomous Takeoff and Landing** (ATOL) by addressing **dynamic instability** in **single-legged** robotic systems during rapid **ground-aerial transitions** for a **fixed wing MAV**.
Objective 1	**Designing and modelling** a single-legged robot platform.
Objective 2	**Developing control algorithms** for autonomous takeoff and landing.
Objective 3	**Evaluating** the robot's performance in **simulations** and **experiments**.
Methodolo gy	Multi-fidelity dynamic modelling (**SLIP** to **NLP**) with a layered control architecture (**IK**/advanced control) on a **2-axis leg design** with validation in **ROS Gazebo simulation** and **experimental setup**.

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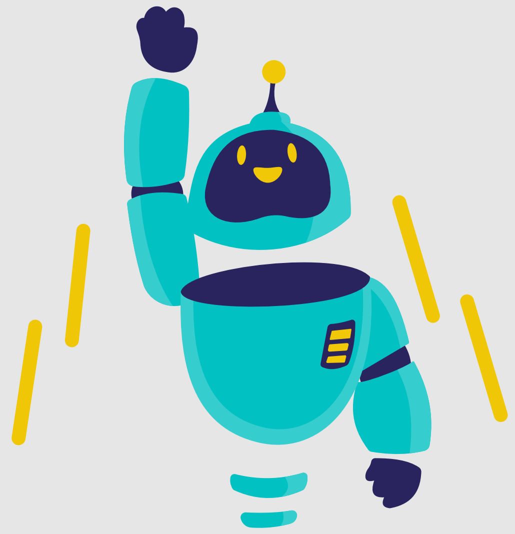

THANK YOU

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Inquiries, feedbacks and suggestions are welcomed