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

NIK ADAM MUQRIDZ BIN ABDUL HAKHAM 2125501

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
KULLIYYAH OF ENGINEERING
INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

JUNE 2025

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

NIK ADAM MUQRIDZ BIN ABDUL HAKHAM 2125501

Project Supervisor: Dr. Hafiz Bin Iman

A REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR A DEGREE OF BACHELOR OF ENGINEERING (AEROSPACE) (HONOURS)

ABSTRACT

This research addresses the critical challenge of dynamic instability in single-legged robotic systems, particularly during rapid transitions between ground contact and aerial phases, with the overarching goal of achieving autonomous takeoff and landing. The study proposes the design and development of a novel Single-Legged Autonomous Takeoff and Landing (SLATOL) robot, aiming to significantly advance agile robotics and enhance robot mobility in complex, unstructured environments. A comprehensive literature review revealed key research gaps, including the need for robust, surface-agnostic landing capabilities for fixed-wing Micro Aerial Vehicles (MAVs), computationally efficient control strategies for resource-limited platforms, and the effective integration of bio-inspired designs with dynamic control. To tackle these challenges, the proposed methodology employs a multi-fidelity dynamic modeling approach, commencing with the Spring-Loaded Inverted Pendulum (SLIP) model and adaptable to a Nonlinear Programming (NLP) framework for intricate dynamics. This modeling will be integrated into a layered control architecture utilizing low-level joint controllers and inverse kinematics for stable maneuvers. The mechanical design features a 2-axis leg with BLDC motors and comprehensive sensing. Initial validation will be conducted through high-fidelity Gazebo simulations to tune controllers and ensure smooth transitions, paving the way for eventual physical hardware implementation. This systematic approach is anticipated to contribute meaningfully to hybrid locomotion, bridging the benefits of flight endurance with agile ground interaction, and marking a crucial step towards versatile, multi-modal autonomous robots.

ACKNOWLEDGEMENTS

I extend my deepest gratitude to Almighty Allah for His blessings and guidance throughout this research journey, without which this endeavor would not have been possible. My sincerest appreciation goes to my esteemed supervisor, Dr. Hafiz Bin Iman, for his invaluable guidance, unwavering support, constructive criticism, and profound insights. His expertise and encouragement were instrumental in shaping this project from its inception to completion, providing direction even through the most challenging phases. I am profoundly thankful to the International Islamic University Malaysia (IIUM) and the Department of Mechanical and Aerospace Engineering for providing an exceptional academic environment, state-of-the-art facilities, and the necessary resources that facilitated this research. The knowledge imparted by all my lecturers has laid a strong foundation for this work. I also wish to express my heartfelt thanks to my beloved family, whose constant love, prayers, and emotional support have been my greatest motivation. Their patience and understanding were a continuous source of strength. Finally, I am grateful to my friends and colleagues for their camaraderie, stimulating discussions, and support that enriched my experience throughout this final year project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure 3.5: Validation by Simulation and Experiment

LIST OF ABBREVIATIONS

BLDC	Brushless Direct Current
CAD	Computer-Aided Design
CG	Center of Gravity
CoM	Center of Mass
CoP	Center of Pressure
DOF	Degrees of Freedom
FSM	Finite-State Machine
FYP	Final Year Project
IIUM	International Islamic University Malaysia
IMU	Inertial Measurement Unit
LIP	Linear Inverted Pendulum
MAV	Micro Aerial Vehicle
MPC	Model Predictive Control
NLP	Nonlinear Programming
PID	Proportional-Integral-Derivative
RL	Reinforcement Learning
ROS	Robot Operating System
SBC	Single Board Computer
SLATOL	Single-Legged Autonomous Takeoff and Landing
SLIP	Spring-Loaded Inverted Pendulum
SNAG	Stereotyped Nature-inspired Aerial Grasper
TO	Trajectory Optimization
TOL	Takeoff and Landing

UAV	Unmanned Aerial Vehicle
URDF	Unified Robot Description Format
VMC	Virtual Model Control
ZMP	Zero-Moment-Point

CHAPTER 1: INTRODUCTION

This chapter provides an overview of the research on the design and control of a single-legged robot for autonomous takeoff and landing. It includes the background (1.1), purpose (1.2), problem statement (1.3), and objectives (1.4). The significance, limitations, assumptions, scope, and definitions of terms are covered in sections (1.5) through (1.9), followed by concluding remarks (1.10).

1.1 BACKGROUND OF STUDY

Single-legged robots with autonomous takeoff and landing offer a significant advancement in robotics, potentially revolutionizing search and rescue, delivery, and planetary exploration. Inspired by hopping animals, they provide enhanced mobility in unstructured environments and reduced mechanical complexity compared to multi-legged systems. However, controlling them is challenging due to their inherent instability, especially during takeoff and landing, requiring precise control of dynamics and adaptation to varying ground conditions.

Traditional control methods often struggle with the dynamic instability of single-legged robots, prompting exploration of advanced strategies like adaptive and model predictive control for enhanced stability. Autonomous takeoff and landing necessitate sophisticated sensing and perception, enabling robots to accurately perceive their environment, estimate their state, and plan actions in real-time using sensors like IMUs, cameras, and distance sensors. This research area is driven by the need for highly mobile robots in complex environments, and addressing these challenges will advance robotic technology and its applications.

1.2 PURPOSE OF THE STUDY

This study addresses the need for agile robots in complex environments. Single-legged robots offer mobility advantages for applications like search and rescue (contributing to SDG 3: Good Health and Well-being) and environmental monitoring (supporting SDG 15: Life on Land). Developing autonomous control also advances robotics (SDG 9: Industry, Innovation and Infrastructure).

1.3 PROBLEM STATEMENT

The development of robots capable of agile locomotion in complex environments remains a significant challenge in robotics. Single-legged robots offer the potential for highly dynamic movement, but achieving stable and controlled autonomous takeoff and landing presents significant obstacles. The core problem stems from the inherent instability of single-legged systems, which, unlike multi-legged robots, must dynamically balance, especially during transitions between ground contact and aerial phases.

Addressing this challenge necessitates the development of sophisticated control algorithms. These algorithms must effectively manage the robot's dynamics for stable hopping and controlled transitions. Overcoming these hurdles is crucial for enabling single-legged robots to perform autonomous takeoff and landing, opening doors for applications in areas like search and rescue, exploration, and agile delivery. This project aims to contribute to this advancement by designing and developing a functional single-legged robot and the control framework required for autonomous takeoff and landing.

1.4 OBJECTIVES OF THE RESEARCH

The aim of this study is to design and develop a single-legged robot capable of autonomous takeoff and landing, contributing to advancements in agile robotics. This will be achieved by:

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 are the key design parameters for a single-legged robot that enable stable dynamic balance and hopping motion for autonomous takeoff and landing?
2. How can control algorithms be developed and implemented to achieve stable and controlled transitions between stance, takeoff, aerial flight, and landing for a single-legged robot?
3. How does the robot's performance (e.g., takeoff height, landing accuracy, stability) vary under different conditions and disturbances, and how can the control system be optimized for robustness?

1.6 SIGNIFICANCE OF THE STUDY

This research is important for advancing Micro Aerial Vehicle (MAV) technology in challenging environments. It explores control strategies to address stability, efficiency, and maneuverability issues specific to single-legged takeoff and landing. The findings can improve MAV performance in unconventional settings and expand their applications in areas like emergency response or targeted delivery

1.7 LIMITATIONS AND ASSUMPTIONS

This project, exploring a single-legged MAV for autonomous takeoff and landing, is a proof-of-concept study that simplifies real-world complexities. MAV dynamics will be modeled without fully accounting for wind or aerodynamics, and flight will emphasize basic takeoff/landing over advanced agility. Energy efficiency and payload capacity are not primary concerns. Initial development assumes an ideal environment, perfect actuators and sensors, and flat landing surfaces. These simplifications are necessary to establish fundamental viability

1.8 RESEARCH SCOPE

The scope of this research focuses on the design, development, and control of a single-legged robot capable of autonomous takeoff and landing. The key areas of investigation include:

1. **Robot Design and Development:** This involves the mechanical design and fabrication of the single-legged robot platform, including the selection of appropriate materials, actuators, and sensors.
2. **Control System Design and Implementation:** This includes the development of control algorithms for achieving stable takeoff, and landing on flat surfaces.
3. **Simulation and Experimental Validation:** The designed robot and control system will be evaluated through simulations and physical experiments to assess performance metrics such as takeoff height, landing accuracy, and stability with simulated aerodynamic forces disturbances from fixed wing flight MAV.

1.9 DEFINITION OF TERMS

- **Micro Aerial Vehicle (MAV):** A small, unmanned aerial vehicle designed for flight. Unlike traditional aircraft, MAVs are often used in scenarios where it is difficult or dangerous for humans to operate.
- **Single-Legged MAV:** A hypothetical configuration of a MAV that utilizes a single leg for takeoff and landing instead of the more conventional multi-rotor or fixed-wing designs. This design would prioritize agility and the ability to operate in confined spaces.
- **Autonomous Takeoff:** The process by which the single-legged MAV initiates and completes its launch sequence without external control or human intervention.
- **Autonomous Landing:** The process where the single-legged MAV returns to the ground and terminates its flight sequence without external control or human intervention.
- **Dynamic Stability:** The ability of the single-legged MAV to maintain balance and control during movement, particularly during the takeoff and landing phases, which require rapid shifts in momentum and balance.
- **Control Strategies:** Algorithms and techniques used to govern the MAV's movements, ensuring it can execute takeoff, maintain stable flight, and perform controlled landings.
- **Actuator Systems:** The mechanical components responsible for generating and controlling the MAV's movements, specifically the single leg's motion for takeoff and landing and any additional stabilization mechanisms.

1.10 CONCLUDING REMARKS

The purpose of this chapter is to introduce the background of this research. This project seeks to develop a single-legged robot capable of autonomous takeoff and landing, addressing the challenges of achieving agile locomotion in complex environments. By exploring novel design and control strategies, the research aims to enable stable and controlled transitions between ground and aerial phases. The findings will contribute to advancements in robotic technology, particularly in enhancing mobility and adaptability. The next chapters will detail the literature review of past work both in simulation and experimental setup.

CHAPTER 2: LITERATURE REVIEW

Chapter 2 will examine the literature relevant to the problem of achieving stable and controlled autonomous takeoff and landing for single-legged robots. It will cover research that supports the project's objectives of designing a dynamically stable platform and developing the required control algorithms. It will include the introduction (2.1), single-legged robot locomotion (2.2), legged MAV locomotion (2.3), control challenges (2.4), and existing control strategies (2.5). The identified research gaps (2.6) will further motivate the problem statement and objectives of this thesis.

2.1 INTRODUCTION

The development of robots capable of agile locomotion in complex environments remains a significant challenge in robotics. Single-legged robots offer potential mobility advantages for applications such as search and rescue and environmental monitoring, and advancing their autonomous control is crucial for the broader field of robotics. This chapter will delve into the current state of research concerning the design, dynamics, control, and application of single-legged robots, particularly those with the potential for autonomous takeoff and landing. By examining the existing body of knowledge, this review will identify the key advancements, limitations, and open challenges that this thesis aims to address.

2.2 SINGLE-LEGGED ROBOT LOCOMOTION

Single-legged robot locomotion has been a fundamental area of research in legged robotics, serving as a building block for understanding more complex multi-legged systems (Huang & Zhang, 2023). This section explores the dynamics of hopping and the principles behind bio-inspired designs.

2.2.1 Hopping Dynamics

Hopping is a fundamental dynamic behavior for legged robots and a precursor to running. The dynamics of hopping are highly nonlinear and non-smooth due to interactions with the environment. Early work by Raibert (1986) demonstrated continuous hopping on physical one-legged robots. A common model used to simplify and understand the mechanics of hopping and running is the Spring-Loaded Inverted Pendulum (SLIP) model. The SLIP model represents the robot as a point mass on a massless leg with a linear spring. Huang and Zhang (2023) employed the SLIP model to control the jumping of a one-legged robot and map jumping height to foot force, mimicking animal jumping control mechanisms as visualised in Figure 2.2.1.1 and 2.2.1.2.

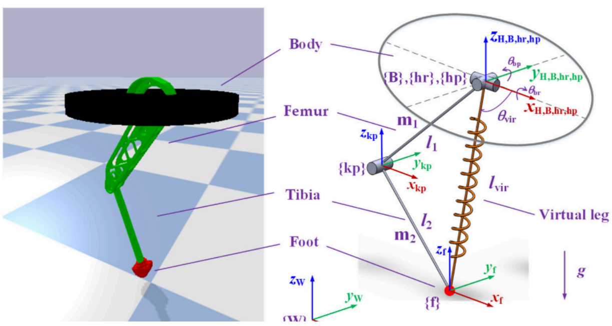


Figure 2.2.1.1: One-legged hopping kinematic model (Huang & Zhang, 2023).

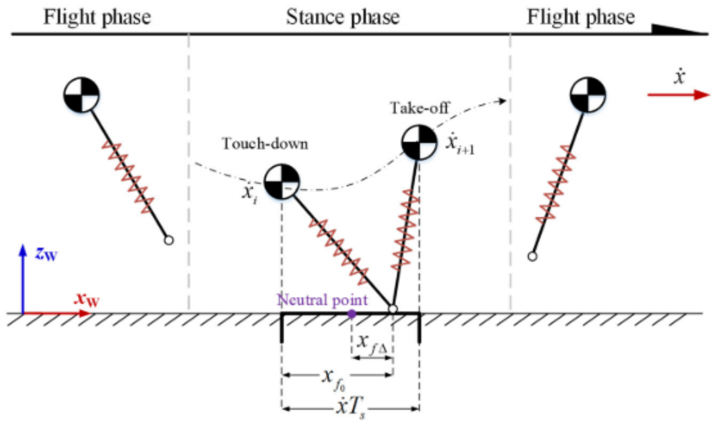


Figure 2.2.1.2: SLIP model hopping dynamics (Huang & Zhang, 2023).

The hopping process can be decomposed into distinct phases, typically stance (foot on ground) and flight (foot off ground), which are further divided into sub-phases like compression, thrust, swing, and landing. Switching between the stance and flight phases is critical for maintaining continuous locomotion. Accurately generating real-time jumping patterns that ensure overall stability through a complete jumping cycle, as shown in Figure 2.2.1.3 is essential, especially when considering factors like angular momentum. .

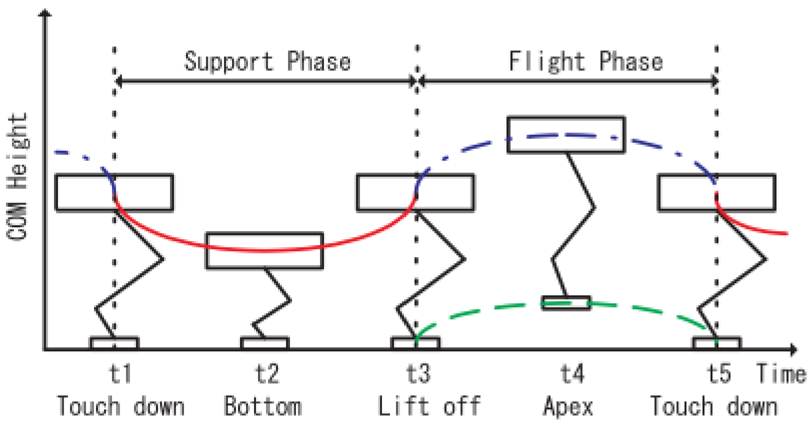


Figure 2.2.1.3: Complete Hopping Sequence (Ugurlu, 2008).

2.2.2 Bio-Inspired Robots

Drawing inspiration from biological systems has been a successful approach in designing agile and efficient legged robots. Avian locomotion, in particular, has provided valuable insights for single-legged robot design. For instance, the study by Badri-Spröwitz et al. (2022) on BirdBot as in Figure 2.2.2.1, an avian-inspired bipedal robot, uses a spring tendon network and a bistable joint reminiscent of a self-engaging and disengaging clutch observed in large birds like emus and ostriches.

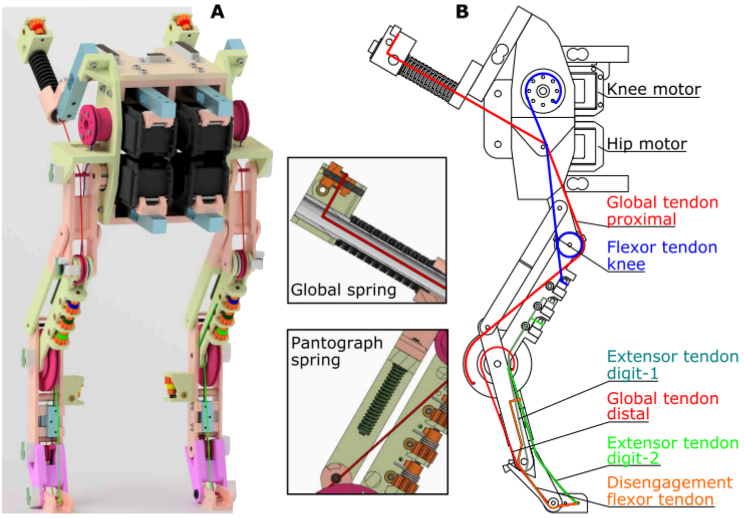


Figure 2.2.2.1: BirdBot leg design and spring tendon network (Badri-Spröwitz et al., 2022).

Another bio-inspired approach involves integrating compliance into muscle-tendon units, which is seen as a major factor for energy-efficient and robust locomotion in agile animals. This is especially relevant for distal leg segments that experience aggressive dynamics. The SELDA (Series ELastic Diaphragm for distal Actuation), as in Figure 2.2.2.2, actuator was developed for a bio-inspired robot leg to provide lightweight, low-inertia, mechanically efficient, and compliant distal actuation for agile hopping.

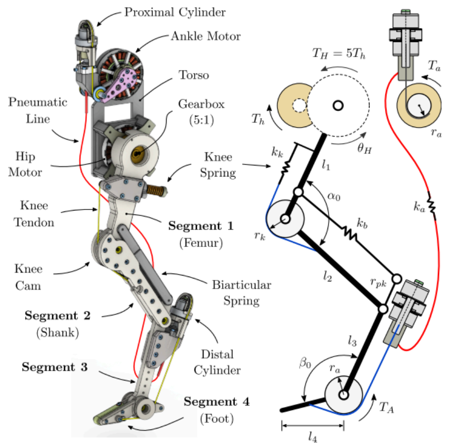


Figure 2.2.2.2: SELDA (Bolignari et. al, 2022)

Robots like Salto-1P and TTI-Hopper in Figure 2.2.2.3 are examples of monopedal bio-inspired platforms used to investigate dynamic behaviors like hopping and balancing. Salto-1P, with a body length of 0.313m, uses onboard sensors for state estimation during high-acceleration hopping. TTI-Hopper is an untethered 4-link, 3-DOF one-legged robot actuated by brushless DC motors, designed to study running dynamics with conventional actuators. These robots leverage compliant designs and control strategies, such as admittance control, to handle contact forces and achieve stable running locomotion.

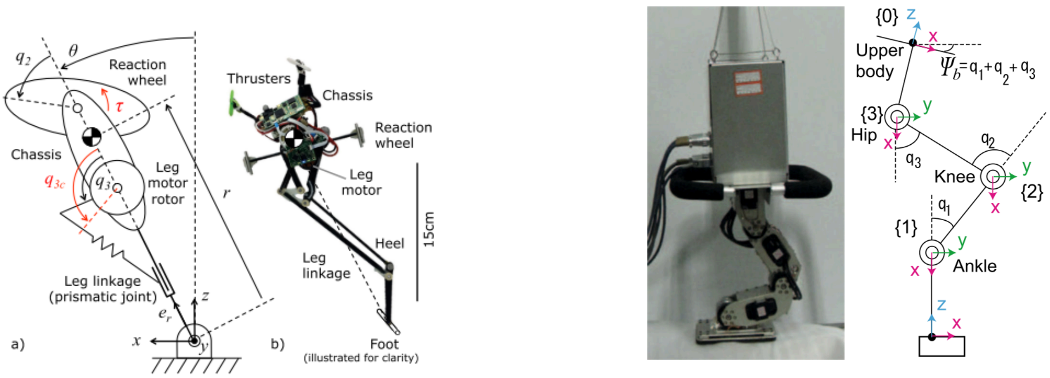


Figure 2.2.2.3: Salto-1P (Yim et al., 2020) and TTI-Hopper (Ugurlu, 2020).

Table 2.2.1: Comparison of Single-Legged Robot Locomotion

Aspect	Key Points	Pros	Cons	Past Work Discussed
Hopping Dynamics	Fundamental behavior for legged robots; Nonlinear, non-smooth; Phases: Stance (compression, thrust), Flight (swing, landing); SLIP model used for simplification.	Simplifies complex dynamics; Allows focus on key parameters.	Model is simplified (massless leg, point mass); Doesn't capture all complexities (friction, joint dynamics).	Raibert's hoppers (Raibert, 1986), KEN-2 (Ugurlu & Kawamura, 2008), TTI-Hopper (Ugurlu et al., 2021).
Bio-Inspired Robots	Avian-inspired mechanics (clutching, tendon networks); Intrinsic compliance; Distal actuation (SELDA); Remote actuation.	Energy efficiency; Reduced control complexity; Robust mechanics; Lightweight distal segments.	Complexity in replicating biological structures; May require specific actuators or transmissions	BirdBot (Badri-Spröwitz et al., 2022), SELDA actuator (Bolignari et al., 2022), Salto-1P (Yim et al., 2020), TTI-Hopper (Ugurlu et al., 2021).

SLIP models simplify hopping dynamics, but bio-inspired robots can improve energy efficiency and robustness by mimicking nature. Exploiting passive mechanics and natural dynamics reduces reliance on complex control. However, accurately translating biological systems into robust robotic designs is a major challenge, suggesting a combined approach of models and bio-inspiration. Thus, this study will use the analysis of the SLIP model for a 2 axis single legged robot due to time, budget and knowledge constraints yet still able to achieve the stated objectives.

2.3 LEGGED MAVS LOCOMOTION

While legged robots navigate terrestrial environments, Micro Aerial Vehicles (MAVs), classification of smaller Unmanned Aerial Vehicles (UAVs) typically weigh less than 1 kg, operate in the air. Combining these capabilities into a single system presents unique opportunities for locomotion in complex, arboreal, or uneven 3D environments. Currently well known types of legged MAVs are rotary wing and flapping wing.

2.3.1 Rotary-Wing Legged MAVs

The integration of legs onto MAVs allows for hybrid locomotion strategies, enabling tasks like perching, grasping, and potentially more stable landing on challenging surfaces where purely aerial approaches are difficult or impossible. Bird-inspired designs have been particularly influential in this domain, focusing on mechanisms for dynamic grasping and perching in arboreal environments.

The SNAG robot (Stereotyped Nature-inspired Aerial Grasper), shown in Figure 2.3.1.1, is a prime example, featuring bird-inspired legs and grasping mechanisms designed for perching on branches. SNAG's leg design includes analogs of avian muscle-tendon structures and utilizes a quick-release mechanism to rapidly deploy grasp force upon impact. The system uses one motor per leg for grasping and another for sagittal leg motion, which helps orient the feet and balance after perching. The underactuated toes conform to complex surfaces through a tendon differential. Perching involves rapid generation of high forces and leveraging lightweight proximal parts for agility, similar to birds (Roderick et al., 2021) .

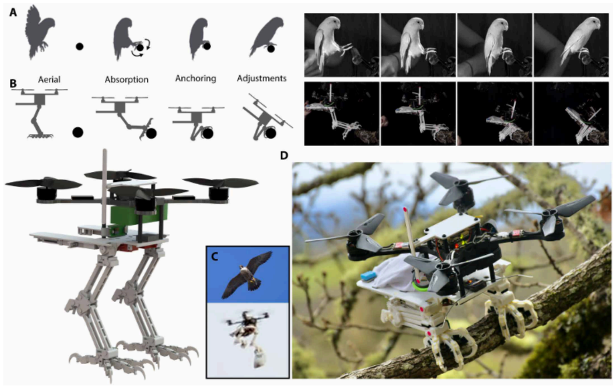


Figure 2.3.1.1: SNAG Robot (Roderick et al., 2021).

Achieving successful perching depends on various factors, including toe arrangement, quick-release trigger timing, foot ejection characteristics, leg orientation, foot placement, impact velocity, and surface conditions. Experiments with SNAG, shown in Figure 2.3.1.2, evaluated different toe arrangements (anisodactyl vs. zygodactyl) and the impact of trigger timing on perching success, illustrating the importance of mechanical design parameters. Maintaining balance after perching is also crucial and can involve controlling the robot's center of mass.

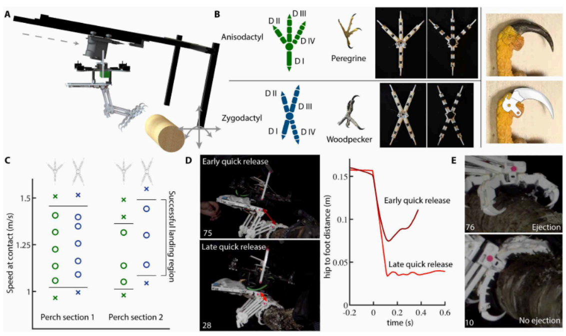


Figure 2.3.1.2: SNAG Robot with Different Toe Arrangements (Roderick et al., 2021).

2.3.2 Flapping-Wing Legged MAVs

While many legged MAVs are quadrotors or similar designs, the concept extends to fixed-wing or flapping-wing (ornithopter) platforms. The BOLT robot is an example of a system designed for both terrestrial and aerial locomotion, combining the gearbox and wings from a commercial ornithopter with custom legs. A single motor drives both the legs and wings, highlighting the challenge of achieving sufficient power density for flight while also enabling terrestrial movement. BOLT as in Figure 2.3.2.1 utilizes flapping wings and a tail to maintain passive stability when running, demonstrating a truly bipedal gait at higher speeds when the tail lifts off the ground. The sprawled leg posture also contributes to stability.

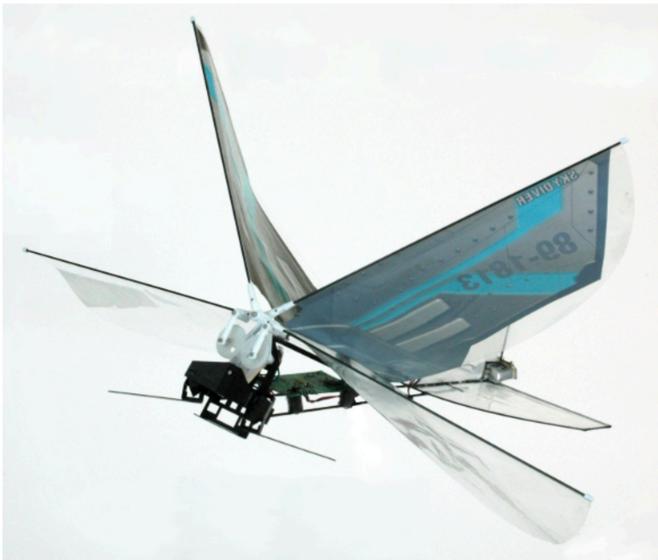


Figure 2.3.2.1: BOLT MAVs (Roderick et al., 2021).

Another flapping-wing robot, P-Flap in Figure 2.3.2.2, has been adapted for perching experiments, focusing on autonomous perching on a branch. The leg mechanism for perching is active and designed to compensate for flight inaccuracies, change the robot's pose after perching for stability, and maintain equilibrium. Key constraints include size, weight, impact resistance, and the speed/power of actuation.

The control strategy for flapping-wing perching involves controlling pitch, yaw, and height, often tuned around a specific feasible trajectory due to the highly nonlinear flight dynamics. Perching flight requires reducing forward velocity upon approaching the target. Future work includes enabling the robot to take off from the branch, requiring strategies like posture correction, utilizing friction for slow claw release, executing a forward jump, or even a controlled fall followed by flight recovery (Zufferey et al., 2022).

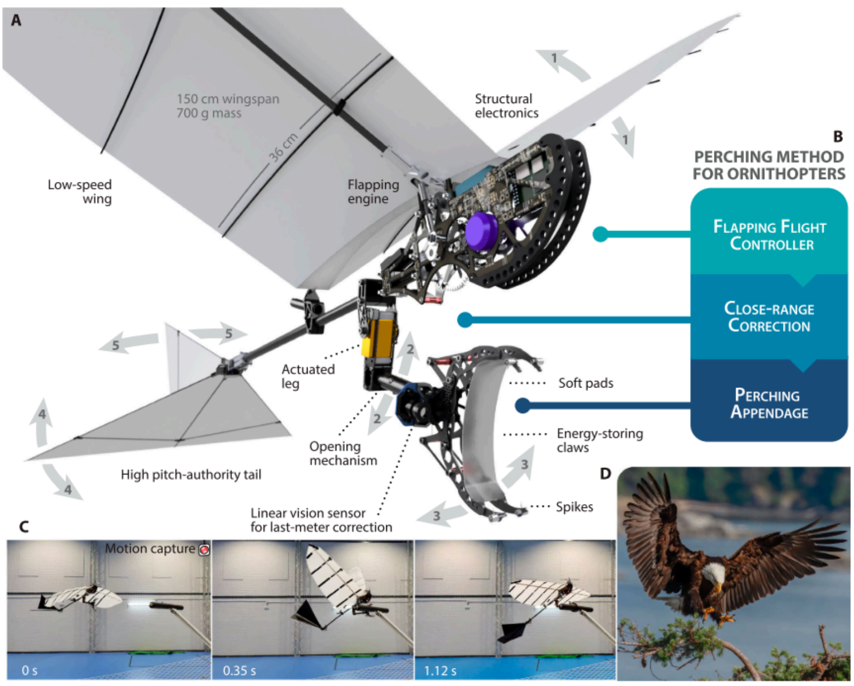


Figure 2.3.2.2: P-Flap MAVs (Zufferey et al., 2022).

Table 2.3.1: Comparison of Legged MAVs

Aspect	Key Points	Pros	Cons	Past Work Discussed
Rotary-Wing Legged MAVs	Hybrid locomotion (air/ground); Perching/grasping (bird-inspired); Active leg mechanisms for landing/balance; Dynamic grasping; Toe compliance.	Enables complex maneuvers like perching; Access to varied terrain; Potential for more stable landings.	Weight and power constraints; Complexity of combined systems; Managing impacts; Precise control for dynamic maneuvers.	SNAG (Roderick, Cutkosky, Lentink, 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)

A fixed-wing Micro Aerial Vehicle (MAV) designed for autonomous takeoff and landing using a single leg is a relatively unexplored area, identified as a research gap. Unlike traditional fixed-wing MAVs which often need runways, this concept faces the core challenge of the inherent dynamic instability of single-legged systems, requiring constant dynamic balance. This instability is particularly critical during fast transitions like takeoff and landing, involving managing momentum and absorbing impact forces. Consequently, control strategies are essential for achieving stable autonomous takeoff and landing,

2.4 CONTROL CHALLENGES

Controlling dynamic legged locomotion, especially combined with aerial phases like takeoff and landing, presents significant challenges.

2.4.1 Dynamic Instability

Legged locomotion is inherently complex and subject to dynamic instability due to discrete contact events, environmental variations, and sensorimotor noise. Maintaining stability requires robust control of leg-substrate interaction forces. External perturbations can occur faster than control loops, emphasizing the need for systems that minimize dependence on communication speed and sensor quality. Passive mechanical walkers, while energy-efficient, are particularly sensitive to initial conditions and small perturbations, with even minor issues like bouncing joint locks being destabilizing (Ugurlu, 2008) visualized in Figure 2.4.1.3.

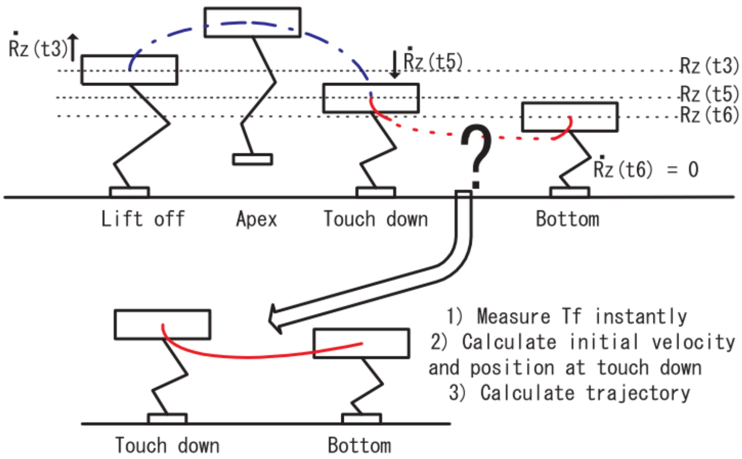


Figure 2.4.1.3: Uncertainty at a touch down state (Ugurlu, 2008).

During dynamic maneuvers like jumping, the robot must actively balance on its support during launch and landing while rapidly accelerating its body. This balancing involves managing the motion of the center of gravity as it rotates over the support and controlling radial motion away from the support. The physical ability of the robot's mechanism to recover balance is also a critical factor. Touchdown is a moment of significant uncertainty and potential instability, requiring careful control to absorb impact and maintain balance.

2.4.2 Autonomous Takeoff/Landing

Achieving autonomous takeoff and landing, particularly on challenging or non-flat surfaces (like branches), adds another layer of complexity. For jumping or leaping, accurate launch velocity is essential to reach a specific target, while accurate landing balance is needed to remain on the target without tumbling shown in Figure 2.4.2.1. This necessitates precise control over the robot's posture and velocity at liftoff and touchdown.

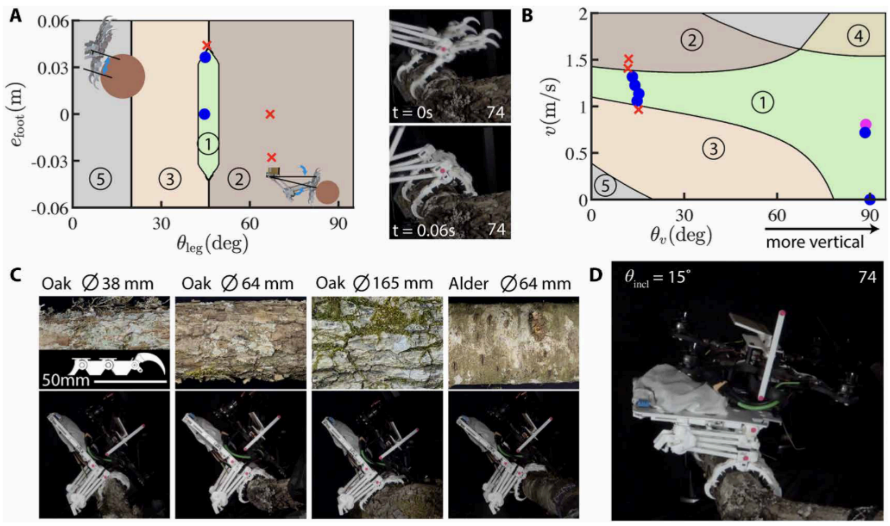


Figure 2.4.2.1: The perching sufficiency region visualizing the narrow margins for success. (Roderick et al., 2021).

Autonomous perching on elevated perches necessitates precise flight trajectory control to mitigate inaccuracies and disturbances prior to landing, exemplified by the P-Flap ornithopter. The leg mechanism must exhibit resilience to impact forces and possess the capability for post-impact postural adjustment to ensure equilibrium. Conversely, autonomous takeoff from a perch, often designated as future work, demands specific strategies. For systems like SNAG, this would involve postural correction for stability, a controlled release of the grasping mechanism (potentially utilizing friction), and the execution of a powered jump or a controlled descent. These functionalities necessitate sophisticated control strategies capable of managing phase transitions, energy storage and release, and interaction with the environment.

Table 2.4.1: Summary of Control Challenges

Aspect	Key Points	Challenges	Past Work Discussed
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 Takeoff/ 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)

2.5 CONTROL STRATEGIES

Addressing the challenges of dynamic and hybrid locomotion requires a variety of control strategies, ranging from traditional model-based methods to more advanced learning and optimization techniques.

2.5.1 Traditional Control

Historically, robotic control has heavily relied on analytical dynamic models that describe the physics of motion and environmental interaction. Model Predictive Control (MPC), as in Figure 2.5.1.1 is a favored traditional approach for gait control in bipedal robots, using an optimization framework to integrate actuation limits and performance targets. However, the efficacy of MPC depends on precise system models and accurate parameter estimation, which can be difficult in real-world settings (El-Hussieny, 2024).

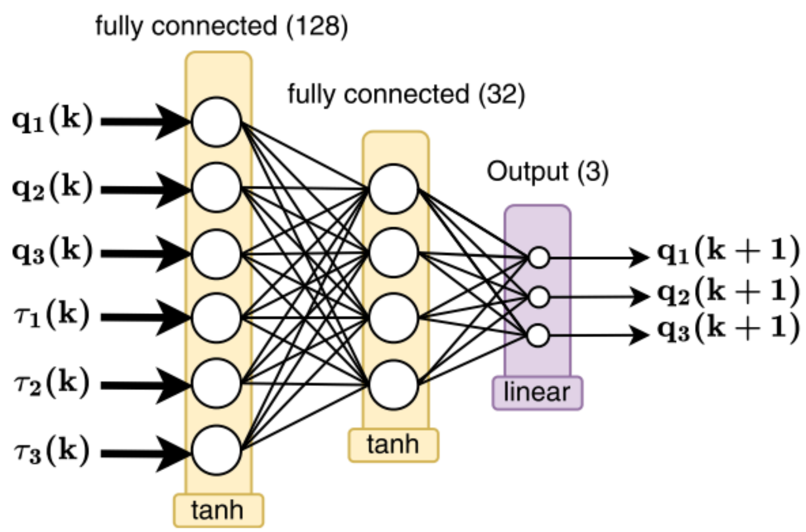


Figure 2.5.1.1: Nonlinear Model Predictive Control Architecture (El-Hussieny, 2024).

Other traditional methods include those based on the Zero-Moment-Point (ZMP) or Center of Pressure (CoP), often used with simplified models like the Linear Inverted Pendulum (LIP) to control the Center of Mass (CoM) motion. Winkler et al. (2018) utilize a simplified Centroidal dynamics model that relates feet position and forces to CoM motion within a trajectory optimization framework as in Figure 2.5.1.2.

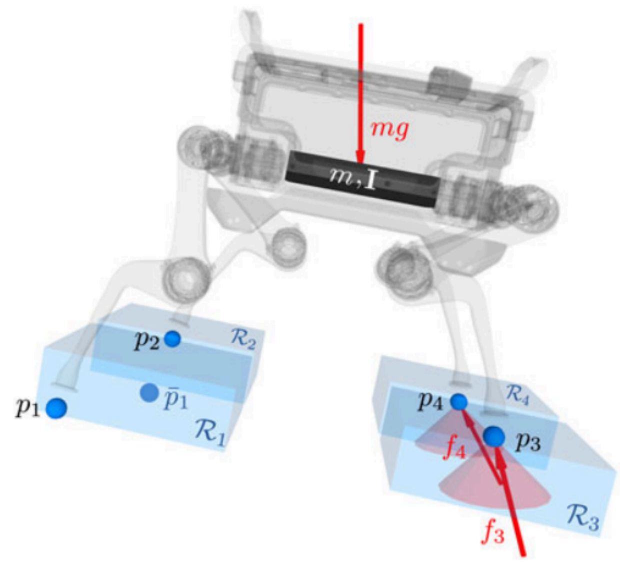


Figure 2.5.1.2: Centroidal dynamics model (Winkler et al., 2018).

Nonlinear Programming (NLP) is primarily used in trajectory optimization for legged robots, such as in the framework developed by Winkler et al. (2018). This approach transforms the complex problem of planning robot motion and forces into an NLP problem with a finite number of variables and constraints, making it solvable by standard NLP solvers. NLP is also considered as a way to achieve a more generalized dynamic representation for a single-legged robot when simpler models like the Spring-Loaded Inverted Pendulum (SLIP) are insufficient for precise maneuvers such as takeoff and landing.

Virtual Model Control (VMC) is another technique used for hopping robots, where a virtual force element is emulated between the foot and the hip joint. Finite-state machines (FSM) are commonly used to manage the different phases of locomotion, such as stance and flight, by coordinating the execution of actions in each state. Basic controllers like PD controllers are used for tasks such as hip joint trajectory tracking. To handle contact forces, especially at touchdown, techniques like Admittance Control are employed to manage the trade-off between position and force errors and provide active compliance. Figure 2.5.1.3 shows how various traditional elements are combined in a control system.

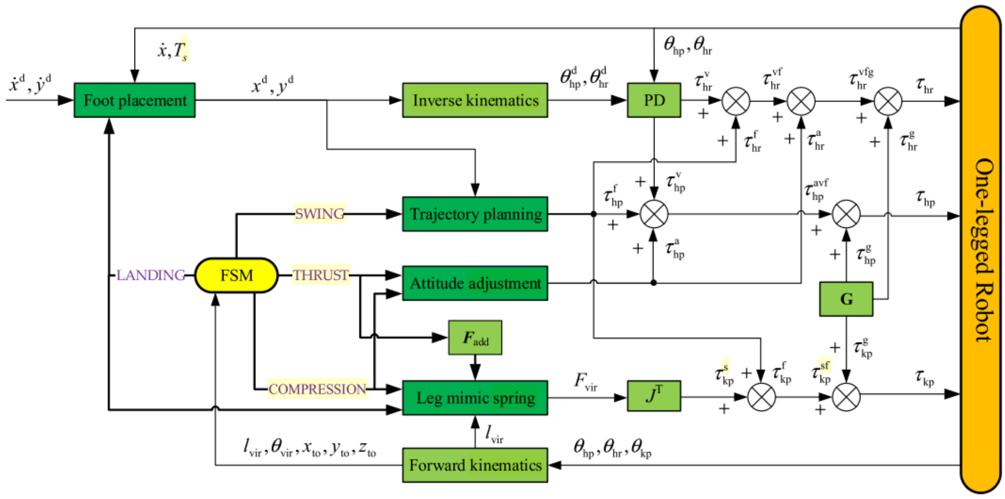


Figure 2.5.1.3: Block diagram of the one-legged robot controller (Huang & Zhang, 2023).

2.5.2 Advanced Control

Beyond traditional model-based approaches, more advanced techniques, often leveraging data or optimization, have emerged. Reinforcement learning (RL) is applied to improve the performance of dynamic locomotion, allowing robots to learn optimal control policies directly on hardware or in simulation. This model-free approach can learn parameterized motor velocity trajectories and high-level control parameters, exploiting the system's inherent dynamics for better performance, such as improved jump height and energy efficiency (Fankhauser et al., 2013).

Recent work has explored integrating deep learning models for robot dynamics within frameworks like MPC to eliminate the need for explicit analytical dynamic models. This data-driven approach can improve trajectory tracking while adhering to constraints. Trajectory Optimization (TO) is a powerful technique that can automatically determine complex motion plans, including gait sequences, step timings, footholds, swing-leg motions, and full body motion, by optimizing over continuous decision variables. This method can generate highly dynamic motions with flight phases (Winkler et al., 2018).

Hybrid approaches combining simulation-based optimization with hardware-based learning are also utilized to efficiently obtain optimal control policies. These advanced methods aim to overcome the limitations of modeling inaccuracies and enable more agile and robust performance in complex scenarios.

Table 2.5.1: Comparison of Control Strategies

Aspect	Key Points	Pros	Cons
Traditional 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.

This research will implement a novel methodology for achieving objective by integrating multi-fidelity dynamic modeling, commencing with the Spring-Loaded Inverted Pendulum (SLIP) model and adaptable to a more complex Nonlinear Programming (NLP) framework for intricate dynamics. This modeling will be incorporated into a layered control architecture, comprising low-level joint controllers, local planners for generating phase-specific trajectories, and a global planner capable of utilizing either inverse kinematics for key maneuvers like stable landing, takeoff, and stance, or advanced control techniques such as Model Predictive Control (MPC) or Reinforcement Learning (RL).

2.6 RESEARCH GAPS

Key research gaps identified in the literature review include:

- Autonomous Takeoff and Landing on Varied Surfaces:
  - There is a noted lack of robust landing and stable stance capabilities on diverse surfaces for a single-legged fixed Micro Aerial Vehicle (MAV).
- Computational Efficiency and Model Complexity:
  - Current legged robots often use complex models or intensive real-time optimization for robustness, highlighting a need for effective yet computationally light control strategies for resource-limited platforms.
- Integration of Bio-inspiration and Dynamic Control:
  - Bio-inspired designs offer efficiency and robustness, but integrating their natural mechanics with the dynamic control needed for aerial phases and contact transitions is still an ongoing research challenge.
- Takeoff from Perched or Elevated Positions:
  - Autonomous perch takeoff is often future work, unlike ground takeoff. Bird-like perching, needing grasping, has environmental limitations.
- Three-Dimensional Kinematic Models for Legged MAVs:
  - Current kinematic models for legged MAVs are mostly planar, limiting their application in 3D environments. Fully 3D kinematic models are needed for seamless aerial-terrestrial transitions in complex spaces.
- Effective Management of Dynamic Transitions:
  - Stable transitions between stance, takeoff, flight, and landing are a major challenge for single-legged robots, demanding control of dynamic shifts and precise leg movement.

The central problem this research tackles is the instability of single-legged robots, which is particularly pronounced during the critical transitions between ground contact and aerial phases. Achieving stable and controlled autonomous takeoff and landing for these dynamically challenging systems poses significant engineering obstacles.

To address these identified research gaps and the inherent difficulties, the primary aim of this study is the design and development of a single-legged robot capable of fully autonomous takeoff and landing. This research will investigate innovative design and control methodologies specifically to enable stable and controlled transitions between the robot's interaction with the ground and its aerial movements.

By focusing on this specific challenge, the intended outcome of this research is to contribute meaningfully to the broader field of robotic technology. This advancement aims to enhance the mobility and adaptability of robots, especially for agile locomotion within complex and unstructured environments. The research will be validated within a flexible simulation environment like ROS Gazebo, facilitating rapid iteration and thorough testing before any potential hardware implementation.

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.

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 .

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.

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.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter will detail the systematic approach to designing, controlling, and validating a single-legged robot for autonomous takeoff and landing, named SLATOL. It will cover the introduction (3.1), research design and overall approach (3.2), followed by specifics on robot mechanical design and modeling (3.3). The chapter will conclude with the validation by simulation (3.4) and validation by experiment (3.5).

3.1 INTRODUCTION

This chapter will systematically outline the research methodology employed for the design and control of a single-legged robot capable of autonomous takeoff and landing. It will detail the comprehensive approach taken to achieve the research objectives, from conceptualization and mechanical design to control algorithm development and validation.

3.2 RESEARCH DESIGN AND OVERALL APPROACH

The research will primarily employ a simulation-based approach for developing and testing the robot's design and control algorithms in a high-fidelity environment. This iterative process allows for rapid prototyping and performance evaluation. Contingent on promising simulation results, a physical prototype will be considered for experimental validation to confirm real-world applicability.

3.2.1 System Architecture Overview

The single-legged robot system will integrate a mechanical platform featuring a 2-axis rotation leg driven by two motors, a comprehensive sensing suite, and a multi-layered control system. This hierarchical control system will manage low-level actuator commands and high-level maneuver planning for autonomous takeoff, landing, and stable hopping.

3.2.2 Phases of Research

Table 3.2.2 outlines the sequential stages of the research project, detailing the key activities to be performed and the expected outcomes at each phase, from conceptualization to final analysis.

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

This section will detail the robot's mechanical architecture, its core components, and the mathematical frameworks vital for understanding its motion. Figure 3.3 visualizes the flowchart for this project. Table 3.3 lists overall hardware needed for SLATOL.

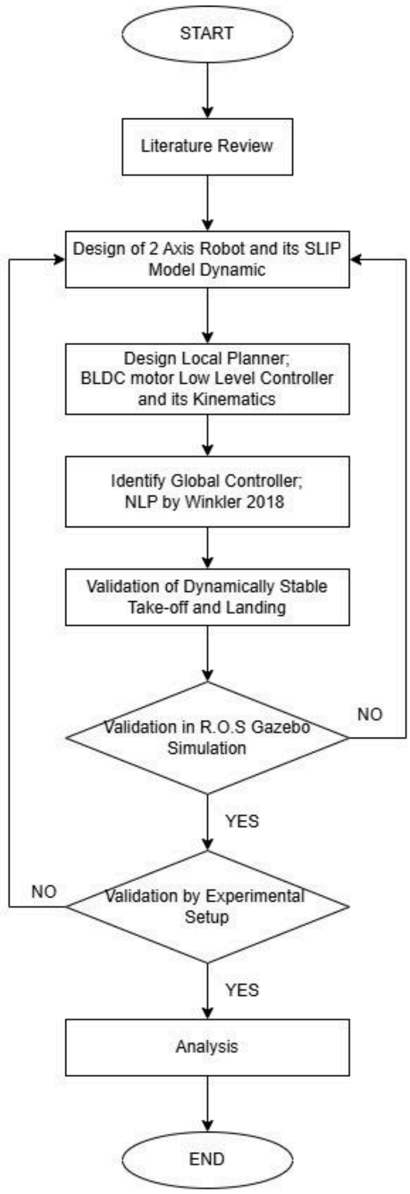
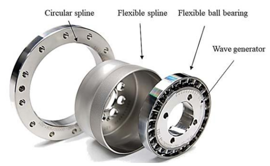
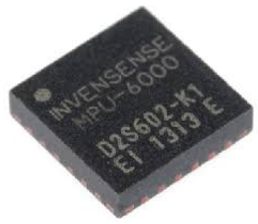
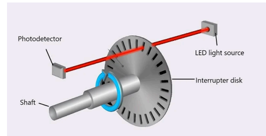
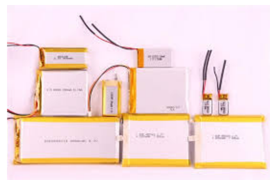


Figure 3.3: SLATOL Research Methodology Flowchart

Table 3.3: SLATOL *Robot Component*

No	Component Category	Specific Component/ Material	Key Properties	Figures
1	**Structural Frame Link**	Hollow Carbon Fiber Tubes	Superior strength-to-weight ratio, high tensile strength, structural stiffness, excellent damping.	
2	**Leg Mechanism (Joints)**	Harmonic Drive	Reduction angular speed to increase torque	
3	**Actuators (Joints)**	Brushless DC motor (BLDC)	High power density, efficiency, reliability, longevity; Reduced gear ratios, improved back-drivability	

4	**Sensors**	IMUs	High-frequency egomotion, precise state estimation, reliable foot contact/slip detection, reduced position drift.	
		Encoders	Join feedback	
5	**Processing unit**	Single Board Computer (SBC)	Central processing unit, to execute complex control algorithms and handle high-speed data acquisition from all sensors.	
6	**Power source**	Li-Po battery	Small size power source	

3.3.1 BLDC Motor Kinematics Model

This section elucidates the kinematic principles of the BLDC motors actuating the single-legged robot. Essential for accurate leg movement modeling, the translation from electrical input to joint mechanical motion is presented, illustrated by Figure 3.3.1: Schematics of BLDC motor. Quantitative relationships include Eq. (1) for the position model and Eq. (2) for the velocity model, alongside other motor characteristics (Nise, 2016).

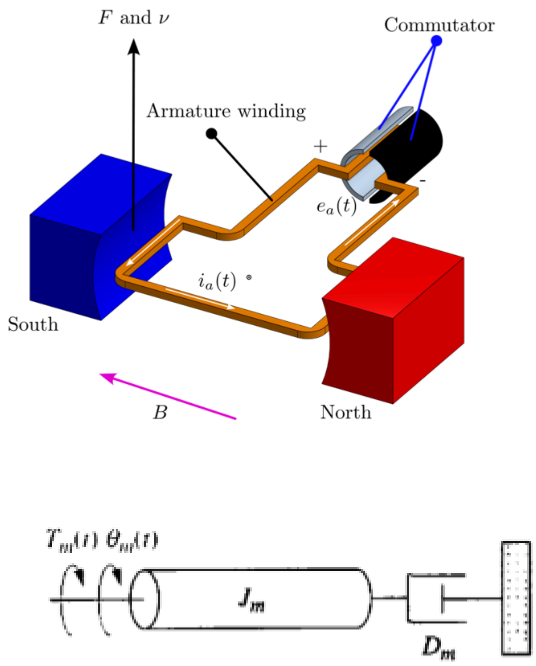


Figure 3.3.1: Schematics of BLDC motor (Nise, 2016)

$$\frac{\theta_m(s)}{Ea\,(s)} = \frac{K}{s\,(s+\alpha)} \qquad (1)$$

$$\frac{s\,\theta_m(s)}{Ea\,(s)} = \frac{K}{(s+\alpha)} \qquad (2)$$

3.3.2 Kinematic Modeling for 2-Axis Leg

Kinematic modeling describes the robot's motion without considering the forces and torques causing it. For a 2-axis single leg as in Figure 3.3.2, both forward and inverse kinematics are essential. This is achieved by assuming no external aerodynamic force, F = 0 and restricted Y movement, set by Planar Move Plugin in R.O.S Gazebo, $\theta 3 = 0$.

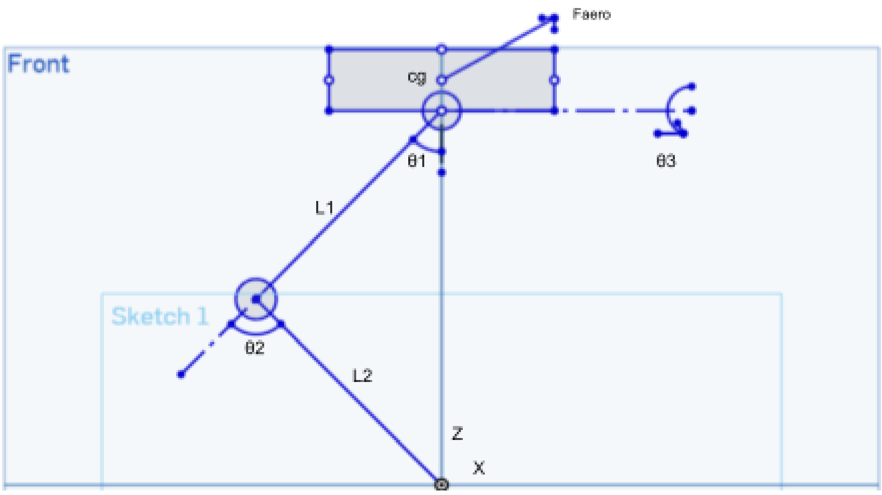


Figure 3.3.2: 2-axis model of SLATOL

3.3.2.1 Forward Kinematics

Forward kinematics calculates the end-effector (foot) position and orientation given the joint angles and link lengths. For a planar 2-DOF leg with revolute joints, the position (x, y) of the foot can be described as in Eq. (3).

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

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

3.3.2.2 Inverse Kinematics

Inverse kinematics calculates joint angles for a desired end-effector position, typically using trigonometry for 2-DOF planar legs with multiple solutions as in Eq. (4). It's crucial for trajectory generation, guiding precise foot placements in control during landing, takeoff, or balance.

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

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

3.3.2.3 Jacobian System

The Jacobian matrix is fundamental in robotics, relating the velocities of 2-joint robot joints to the linear and angular velocities of its end-effector shown in Eq. (5).

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

3.3.3 Spring-Loaded Inverted Pendulum (SLIP) Kinematic Modeling for 3-Axis Leg

A Spring-Loaded Inverted Pendulum (SLIP) model, shown in Figure 3.3.3.1 is utilized to control the jumping of the one-legged robot. This model centralizes the robot's mass at the body's center, with the legs acting as a massless spring. The jumping height is mapped to the foot force, mimicking animal jumping control mechanisms. The mathematical model can be utilized from Huang and Zhang (2023).

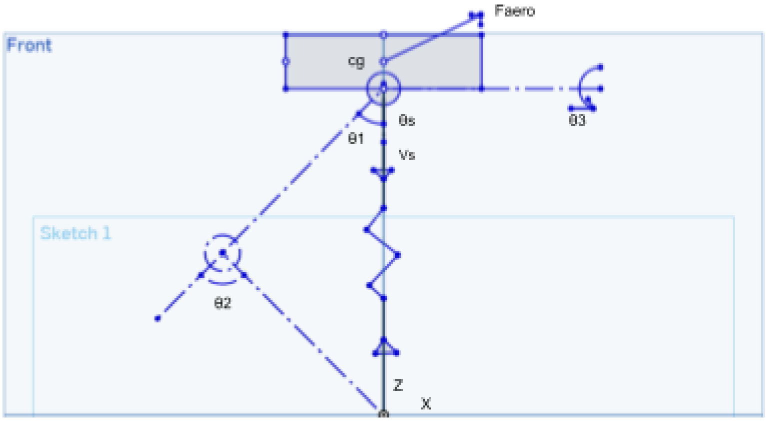


Figure 3.3.3.1: SLIP model of SLATOL

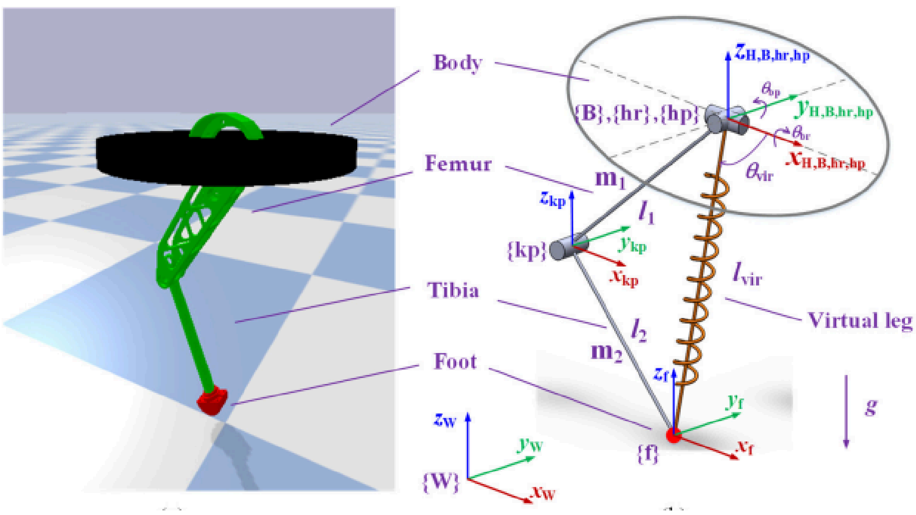


Figure 3.3.3.2: SLIP model of One-legged Robot (Huang & Zhang, 2023)

3.3.5 Integration of Models into Control System

This section details the integrated control architecture for the Single-Legged Autonomous Takeoff and Landing (SLATOL) robot, as depicted in Figure 3.3.5. The system commences with the SLIP model from Huang 2023 but simplified for kinematics control, providing the Takeoff and Landing (TOL) trajectory of the center of gravity's pose, which interacts with a Motor Closed Loop handling angular positions and angular velocities. These elements feed into a Non-Linear Programming module (Winkler, 2018), generating desired x,y positions. Subsequently, an Inverse Kinematic Solver translates these positions into joint angles (θ1,θ2), which in turn inform the motor control system, thus closing the loop. This comprehensive integration ensures coordinated motion and robust control crucial for autonomous takeoff and landing maneuvers.

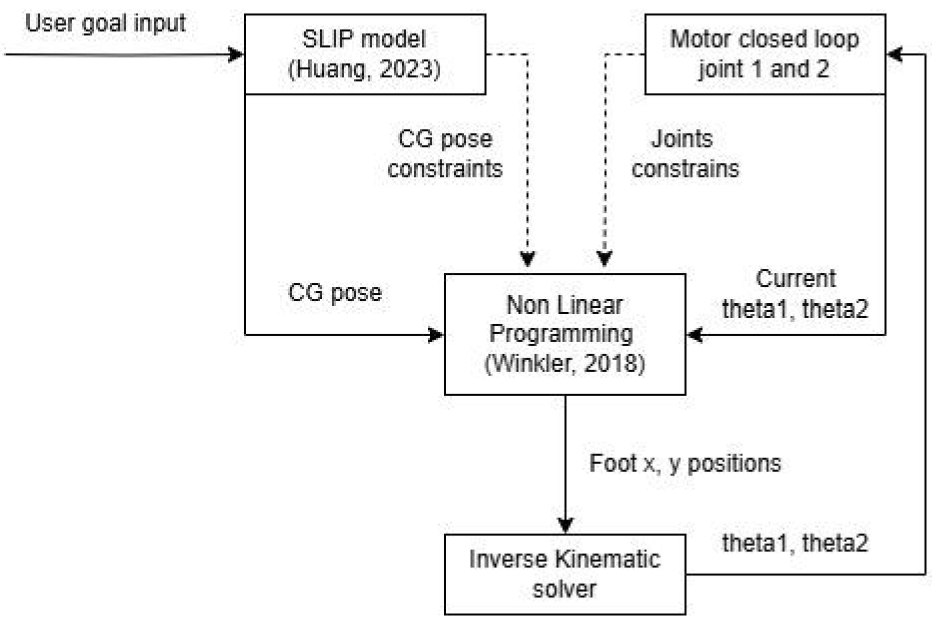


Figure 3.3.5: Generalized model of SLATOL

3.4 VALIDATION BY SIMULATION

3.4.1 Accurate Representation of Physical Properties

High-fidelity simulation in Gazebo relies on accurately representing the robot's physical properties.

- **URDF/SDF Models:** The Unified Robot Description Format (URDF) or Simulation Description Format (SDF), often augmented with XACRO for modularity, are used to define the robot's links (rigid bodies) and joints.
- **Mass and Inertia:** Precise mass and inertia tensors for each link must be specified in the URDF/SDF. These properties are critical for realistic dynamic behavior, especially during highly dynamic maneuvers.
- **Joint Limits:** Correctly defining joint position, velocity, and effort limits ensures that the simulated robot operates within its physical constraints, preventing unrealistic movements.
- **Motor Characteristics:** Simulating realistic motor dynamics (e.g., torque curves, velocity limits, friction, and reflected inertia through gearboxes) is crucial. Using Gazebo's ros-control plugins or custom controllers that account for these characteristics will yield more accurate predictions of real-world performance.

3.4.2 Environmental Interactions

Accurate representation of the environment is equally important for realistic simulation.

- **Terrain and Obstacles:** Gazebo allows for importing or creating diverse terrains (e.g., flat ground, uneven surfaces, inclines) and populating the environment with obstacles (static or dynamic) to test the robot's robustness and adaptability.
- **Contact Physics:** Modeling realistic contact forces and collisions between the robot's foot and the ground is one of the most challenging aspects of legged robot simulation. Proper tuning of contact parameters (e.g., friction coefficients, restitution coefficients, damping) within Gazebo's physics engine (e.g., ODE, Bullet) is essential to avoid instabilities and achieve believable ground interaction.
- **Sensor Noise:** Incorporating sensor noise models (e.g., Gaussian noise, bias, drift) for IMUs, cameras, and distance sensors will help in developing control algorithms that are robust to real-world sensor imperfections.
- **Gravity and World Properties:** The simulation environment must accurately represent gravity and other global physics properties to ensure the robot's dynamics are consistent with the real world.

By meticulously modeling these aspects, the Gazebo simulation as shown in Figure 3.4 will provide a high-fidelity virtual testbed, allowing for comprehensive validation of the mechanical design and control strategies before transitioning to physical prototyping.

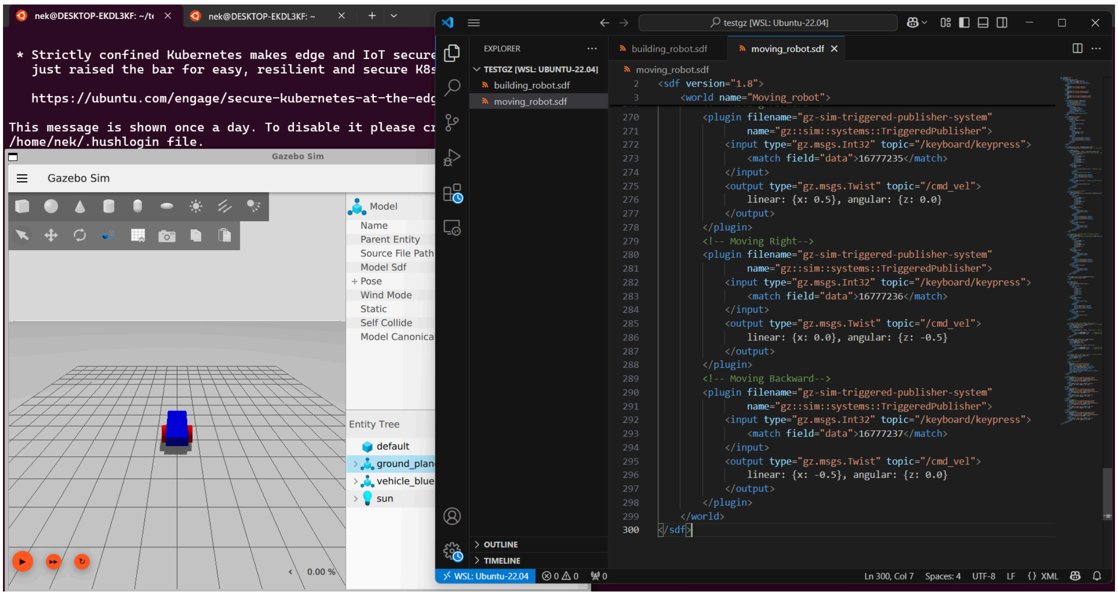


Figure 3.4: ROS Gazebo Simulation Preliminary Setup

Validation of the SLATOL system will occur in a simulated environment, necessitated by the current exclusion of aerodynamic forces. This phase aims to meticulously tune the SLATOL's controller, ensuring its ability to achieve stable takeoff and landing. Specifically, SLATOL must smoothly transition from an initial position to a user-defined or higher-level planned goal input within the simulation, visualised in Figure 3.5.

Leveraging Winter 2020's algorithm, the validation process will focus on defining constraints derived from the Spring-Loaded Inverted Pendulum (SLIP) model and the motor's operational characteristics. These constraints will encompass limitations on joints, angular position, and velocity..

3.5 VALIDATION BY EXPERIMENT

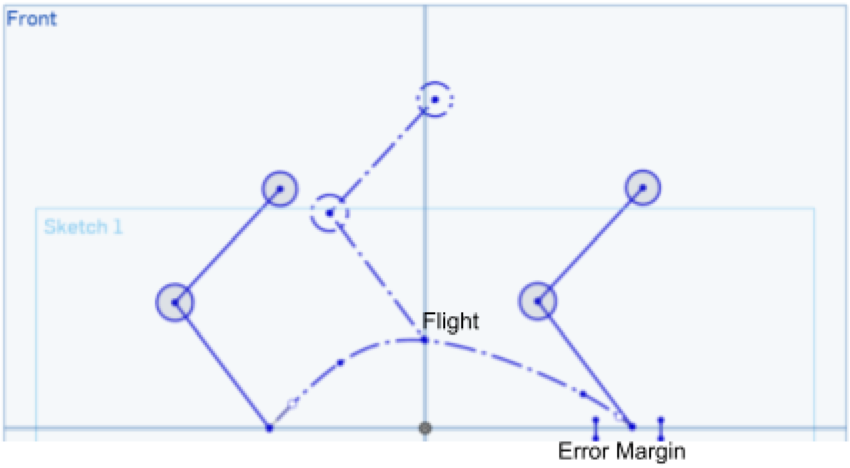


Figure 3.5: Validation by Simulation and Experiment

Hardware validation will commence only after simulation results demonstrate the robot leg's capability to sustain stable hopping, consistent with the experimental design established in Section 3.4.

Subsequently, a crucial comparison will be made between the error margin observed in the simulated environment and that obtained during physical hardware validation. The simulation will depict the robot leg's flight from an initial position to a specified goal input, provided by a user or a higher-level planning algorithm, with an associated error margin. Progression to hardware validation will occur only if this simulated error margin is deemed sufficiently small.

The same experimental activity, specifically hopping from an initial position to the designated goal input, will then be replicated on the physical hardware. An error margin will similarly be measured during this physical trial. Finally, a direct comparison will be conducted between the error margin derived from the simulation and the error margin obtained from the hardware validation.

CHAPTER 4: CONCLUSION

This report presents a research proposal detailing the foundational elements for the Design and Control of a Single-Legged Robot for Autonomous Takeoff and Landing (SLATOL). This research will address the critical challenge of dynamic instability in single-legged robotic systems during rapid ground-aerial transitions

The proposed study aims to design this robot, develop robust control algorithms for autonomous takeoff/landing, and evaluate its performance via simulations and eventual physical experiments. A comprehensive literature review has highlighted hopping dynamics and bio-inspiration, identifying key research gaps to be addressed: robust surface-agnostic landing for fixed-wing MAVs, efficient control, and advanced 3D kinematic models.

The proposed methodology employs multi-fidelity dynamic modeling (from SLIP to NLP) and a layered control architecture utilizing inverse kinematics for stable maneuvers. The robot's mechanical design will incorporate a 2-axis leg with BLDC motors and sensors. Validation will commence with high-fidelity Gazebo simulations for controller tuning and smooth transitions, preceding hardware implementation.

In conclusion, this research is anticipated to significantly contribute to agile robotics by bridging flight endurance with agile ground interaction through a novel SLATOL platform and control framework. The systematic approach directly addresses dynamic instability during critical phase transitions. Expected outcomes will advance hybrid locomotion, enabling versatile autonomous robots for complex, unstructured environments, marking a crucial step towards seamless multi-modal operation.

REFERENCES

Badri-Spröwitz, A., Herbort, O., Rienesl, R., Spröwitz, T., & Blickhan, R. (2022). BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. Science Robotics, 7(64), eabg4055. https://www.science.org/doi/10.1126/scirobotics.abg4055

Bolignari, L., Slijkhuis, R., Cestari, M., Ajallooeian, M., Lefeber, D., & Vanderborght, B. (2022). Diaphragm Ankle Actuation for Efficient Series Elastic Legged Robot Hopping. Frontiers in Neurorobotics, 16, 853542. https://doi.org/10.48550/arXiv.2203.01595

Boon, M. A., Drijfhout, A. P., and Tesfamichael, S.: COMPARISON OF A FIXED-WING AND MULTI-ROTOR UAV FOR ENVIRONMENTAL MAPPING APPLICATIONS: A CASE STUDY, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W6, 47–54, https://doi.org/10.5194/isprs-archives-XLII-2-W6-47-2017 , 2017

El-Hussieny, H. (2024). Real-time deep learning-based model predictive control of a 3-DOF biped robot leg. Scientific Reports, 14(1), 15191. https://doi.org/10.1038/s41598-024-66104-y

Fankhauser, P., захватав, M., вертикали, E., & Hü, M. (2013). Reinforcement learning of single legged locomotion. In 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 5552-5557). IEEE. 10.1109/IROS.2013.6696352.

Huang, S., & Zhang, X. (2023). Controlling a One-Legged Robot to Clear Obstacles by Combining the SLIP Model with Air Trajectory Planning. Biomimetics, 8(1), 66. https://doi.org/10.3390/biomimetics8010066

Peterson, B. W., Spagna, J. L., &ющая, P. C. (2011). Experimental dynamics of wing-assisted running for a bipedal ornithopter. In 2011 IEEE International Conference on Robotics and Automation (pp. 3933-3938). IEEE. 10.1109/IROS.2011.6095041

Roderick, W. R. T., Cutkosky, M. R., & Lentink, D. (2021). Bird-inspired dynamic grasping and perching in arboreal environments. Science Robotics, 6(61), eabj7562. https://doi.org/10.1126/scirobotics.abj7562

Ruppert, F., & Badri-Spröwitz, A. (2019). Series Elastic Behavior of Biarticular Muscle-Tendon Structure in a Robotic Leg. Frontiers in Neurorobotics, 13, 64. https://doi.org/10.3389/fnbot.2019.00064

Shin, W. D., Phan, H.-V., Daley, M. A., Ijspeert, A. J., & Floreano, D. (2024). Fast ground-to-air transition with avian-inspired multifunctional legs. Nature. https://doi.org/10.1038/s41586-024-08228-9

Ugurlu, B. (2008). Real-time jumping trajectory generation for a one-legged robot based on discretized ZMP equation in polar co-ordinates. In 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 3745-3750). IEEE. 10.1109/IECON.2008.4758204.

Ugurlu, B. (2021). Compliant locomotion control for an untethered one-legged robot with trajectory generation characterizing varying inertia and angular momentum. Autonomous Robots, 45(5-6), 805-819. 10.1007/s10514-021-10010-z

Ulukavak, M., & Miman, M. (2021). Selection of The Most Proper Unmanned Aerial Vehicle for Transportation in Emergency Operations by Using Analytic Hierarchy Process. International Journal of Environment and Geoinformatics (IJEGEO), 8(1), 078-091. https://doi.org/10.30897/ijegeo.760758

Winkler, A. W., Bellicoso, C. D., Hutter, M., & Buchli, J. (2018). Gait and Trajectory Optimization for Legged Systems Through Phase-Based End-Effector Parameterization. IEEE Robotics and Automation Letters, 3(2), 1560-1567. https://doi.org/10.1109/LRA.2018.2794473

Yim, J. K., & Fearing, R. S. (2020). Precision robotic leaping and landing using stance-phase balance. IEEE Robotics and Automation Letters, 5(2), 3484-3491. https://doi.org/10.1109/LRA.2020.2976597

Zufferey, R., Bello, F., Siddall, R., Armanini, S. F., & Kovac, M. (2022). How ornithopters can perch autonomously on a branch. Nature Communications, 13(1), 7493. https://doi.org/10.1038/s41467-022-35356-5

APPENDIX A - GANTT CHART FYP 1

TASK FYP 1	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Briefing FYP1															
Tittle Selection															
Chapter 1: Introduction															
Chapter 2: Literature Review															
Chapter 3: Methodology															
Report Writing															
Final Report Submission															
Preparation and Presentation															

APPENDIX A - GANTT CHART FYP 2

TASK FYP 2	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Phase 1: Conceptualization & Literature Review	■														
Phase 2: Mechanical Design & Dynamic Modeling		■	■	■											
Phase 3: Control System Development & Simulation					■	■	■	■							
Phase 4: Prototype Fabrication & Experimental Validation									■	■	■	■	■		
Phase 5: Data Analysis & Discussion					■	■	■	■	■	■	■	■	■		
Report Writing			■	■	■	■	■	■	■	■	■	■	■		
Final Report Submission													■		
Preparation and Presentation														■	■