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碩士論文

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Master's Thesis

輪腳複合機器人上可變多觸地點
之全機力控制架構開發

Whole-Body Force Control Architecture on a Leg-Wheel
Transformable Robot with Varying Ground Contact Points

沈意軒

Yi-Syuan Shen

指導教授：林沛群 博士

Advisor: Pei-Chun Lin, Ph.D.

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摘要



本研究針對輪腳複合型移動平台之多觸地點特性，提出一套兼具估測、控制與實驗驗證的全機力控制架構。此類平台在具備地面接觸構型快速變化之能力下，能展現傳統足式或輪式平台難以達成之地形適應性。然而，控制上所面臨的挑戰也隨之增加，包含缺乏穩定接觸點的力資訊、機身動態的不確定性，以及多模態控制策略間的整合困難等問題。此研究以本實驗室第三代輪腳複合機器人為實作平台，分層設計並驗證一完整從底層驅動到全身協調的控制系統，實現輪腳機構於非典型接觸條件下的穩定運動。

在致動層面，本研究首先更新驅動模組 HT-04 之馬達韌體與 CAN 通訊格式，並建置模組化及易於維護之軟體架構。進一步於感測與估測層，發展一套基於虛功原理與多接觸點雅可比矩陣之觸地力估測方法，針對不同輪框區段推導接觸力分佈，並結合條件數分析，確認穩定估測構型範圍。控制層方面，設計結合阻抗與前饋解耦之高頻觸地力控制架構，突破既有輪腳系統控制頻率不足與力回饋不精準之限制。最後，於決策層整合模型預測控制方法，使系統於各種步態與地形情境下皆能實現穩定、順應與可預期之全身運動行為。

透過模擬與實驗驗證，本架構於步行、小跑與滾走等步態下，皆顯著改善了姿態穩定性與位置及速度追蹤精度，並於崎嶇地形實驗中有效避免傾覆，實現輪腳複合機器人在多變接觸構型下之穩定自主移動行為。

關鍵字：四足機器人、輪腳複合機器人、觸地力估測、阻抗控制、模型預測控制

ABSTRACT



This study presents a complete whole-body force control framework for a leg-wheel hybrid mobile platform, addressing the unique challenges posed by its multiple and changing ground contact points. The framework integrates estimation, control, and experimental validation. While this type of platform offers superior terrain adaptability compared to conventional legged or wheeled systems due to its ability to rapidly alter its contact configuration, it also introduces significant control difficulties. These include a lack of reliable force data from stable contact points, uncertainties in the robot's dynamics, and challenges in integrating multi-modal control strategies. Using our lab's third-generation leg-wheel robot as the implementation platform, this research develops and validates a complete, hierarchical control system, from low-level actuation to whole-body coordination, to achieve stable motion under unconventional contact conditions.

At the actuation level, this work begins by updating the firmware and CAN communication protocol of the HT-04 drive modules and implementing a modular, easily maintainable software architecture. At the sensing and estimation level, a ground contact force estimation method is developed based on the principle of virtual work and a multi-contact point Jacobian matrix. This method derives the contact force distribution for different seg-

ments of the wheel rim and utilizes condition number analysis to identify configurations that ensure stable estimation. At the control level, a high-frequency contact force control architecture is designed by combining impedance control with feedforward decoupling, overcoming the limitations of insufficient control frequency and imprecise force feedback in previous leg-wheel systems. Finally, at the decision-making level, Model Predictive Control (MPC) is integrated to realize stable, compliant, and predictable whole-body motion across diverse gaits and terrains.

Validated through both simulation and physical experiments, this framework demonstrates a significant improvement in postural stability and height-tracking accuracy for walking, trotting, and wheel-like-walking gaits. In rough terrain experiments, the system effectively prevents the robot from tipping over, successfully enabling stable and autonomous locomotion for the leg-wheel hybrid robot in environments with highly variable contact configurations.

Keywords: Quadruped Robot, Leg-Wheel Hybrid Robot, Contact Force Estimation, Impedance Control, Model Predictive Control