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Design and Control of a Lightweight Transforming Spider Quadruped with Mid-Leg Rotor Integration for Hybrid Terrestrial-Aerial Locomotion

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Abstract

This paper presents the conceptual design, theoretical framework, and control architecture for a novel hybrid locomotion robot capable of both terrestrial walking and aerial flight. The proposed system is a spider-style quadruped that transforms into a quadcopter by reconfiguring its legs into rotor arms. A key innovation is the **mid-leg rotor integration**, where motors are positioned between the ankle and foot segments. This strategy is designed to provide substantial ground clearance for large propellers during locomotion while minimizing inertial loads on the leg servos and reducing bending moments on the structure during flight. A systematic component selection process, focused on maximizing the power-to-weight ratio, targets a total system mass of **1.418 kg**. Performance simulations based on this design project a flight endurance of 6.5 minutes and a walking endurance of 26 minutes, indicating the potential viability of the design for multi-modal missions.

Keywords: Hybrid Locomotion, Transforming Robot, Quadruped, Quadcopter, Lightweight Design, Spider Robot, Mid-Leg Rotor, VTOL

1. Introduction

Traditional mobile robots are often constrained by their mode of locomotion. Terrestrial robots, such as wheeled or legged systems, offer high energy efficiency and endurance for ground-based tasks but are limited by obstacles and complex terrain. Conversely, aerial robots, particularly quadcopters, provide exceptional mobility for traversing difficult environments but suffer from high power consumption and limited flight times. This dichotomy creates a significant operational gap in applications like search and rescue, environmental monitoring, and infrastructure inspection, which require both long-duration presence and the ability to overcome significant obstacles.

To address this limitation, we propose a lightweight transforming robot that merges quadrupedal walking with quadcopter flight. The system's morphology is based on a spider-like quadruped, where each 3-DOF leg can be reconfigured into a rigid arm for a quadcopter in an X-configuration.

The principal innovation of this work is the **mid-leg rotor mounting strategy**. Unlike previous designs that place motors at the leg's extremity, our approach positions the motor and propeller assembly after the ankle joint, with a passive foot segment extending below it. This configuration is intended to yield several advantages: it provides ample ground clearance (65mm) for large, efficient 5.1-inch propellers during walking; it reduces the bending moment on the leg structure during flight; and it lowers the leg's rotational inertia, improving walking dynamics.

This paper makes the following contributions:

1. A novel mechanical design for a hybrid robot featuring a mid-leg rotor placement that enables both stable walking and efficient flight without geometric interference.
2. A comprehensive system optimization targeting an ultra-lightweight (1.418 kg) platform with a high thrust-to-weight ratio (3.1:1) using commercially available components.
3. A dual-processor control architecture that decouples real-time leg kinematics and gait generation from the primary flight control loop, enabling robust multi-modal operation.
4. A theoretical analysis of the system's projected performance and a proposed plan for future experimental validation.

2. Mechanical Design

A. System Morphology

The robot's core structure is a central body plate made from 3mm thick 3K carbon fiber, measuring 180mm x 180mm. Four 3-DOF legs are mounted at the corners on 45° diagonals, forming an 'X' shape in both walking and flight configurations. The coordinate system originates at the body's geometric center, with the +X axis defining forward motion. Each leg consists of a thigh (L1), shank (L2), and a passive foot extension (L4).

The degrees of freedom (DOF) for each leg are as follows:

- **Hip Yaw:** Rotation about the Z-axis (±90°) for leg positioning and turning.
- **Hip Pitch:** Rotation about the Y-axis (-30° to +110°) for lifting the leg and folding it into the horizontal flight plane.
- **Knee Pitch:** Rotation about the Y-axis (0° to 135°) to enable gait motion and achieve a compact folded state.
- **Ankle Pitch:** A fine-adjustment joint (-10° to +20°) for terrain adaptation.

This results in a total of 16 actuated DOF for the platform.

B. Mid-Leg Rotor Mounting Strategy

The propulsion system is integrated directly into the leg structure. A 2mm carbon fiber motor plate is mounted after the ankle servo, to which a brushless motor is affixed. A passive 85mm carbon fiber tube with a TPU foot tip extends below the motor, serving as the ground contact point.

This design ensures that the 5.1-inch propellers have a ground clearance of 65mm during normal walking stance, preventing ground strikes. Furthermore, by placing the motor mass closer to the body, the leg's moment of inertia is significantly reduced compared to a tip-mounted design, allowing for faster and more energy-efficient walking gaits.

C. Structural Locking Mechanism for Flight

To ensure structural rigidity during flight, a mechanical lock is required to bear the aerodynamic loads, as servo holding torque alone is insufficient and inefficient. We have designed a custom **over-center cam lock** for each leg.

The mechanism consists of a 3mm aluminum cam plate integrated with the hip pitch servo horn, a hardened M5 steel locking pin mounted on the body in a double-shear configuration, and a Hall effect sensor to confirm engagement. As the leg folds into its final flight position ($\theta = 95°$), the cam profile pushes the pin aside, which then snaps into a slot due to a spring return as the cam passes its center point. The over-center geometry ensures the lock cannot be back-driven by flight loads. Each lock is rated for a shear strength of 8 kN, providing a safety factor of 2.7x against the maximum expected flight loads.

3. System Integration and Component Selection

A. Design Objectives

The component selection was driven by a multi-objective optimization problem aimed at:

1. **Minimizing Mass:** Target total mass under 1.5 kg.
2. **Maximizing Endurance:** Target flight time > 5 minutes and walk time > 20 minutes.
3. **Ensuring Structural Integrity:** Maintain a servo torque safety factor > 1.1x and a flight thrust-to-weight ratio > 2.0.
4. **Enabling Outdoor Operation:** Require an RC control range > 500m and real-time FPV video feedback.

B. Propulsion and Actuation

Motors: T-Motor F40 PRO IV 1600KV brushless motors were selected for their high efficiency (7.2 g/W) and low weight (26.8g), providing a maximum thrust of 1100g per motor on a 4S LiPo battery.

Propellers: Gemfan 5152 tri-blade propellers were chosen for their balance of thrust and durability.

ESCs: A 4-in-1 Holybro Tekko32 35A ESC was used to save 22g compared to individual ESCs and simplify wiring.

Servos: A hybrid servo configuration was implemented. EMAX ES08MDII (13.4g, 12 kg·cm) servos are used for the hip pitch and knee joints to save weight, while higher-torque ANNIMOS 20kg servos (38g, 20 kg·cm) are used for the hip yaw joints to manage the leg's swing inertia. Ankle joints use lightweight TowerPro MG90S servos.

C. Power and Control Hardware

Battery: A Tattu R-Line 1300mAh 4S 120C LiPo battery (137g) was selected as the optimal compromise between energy density for flight and overall weight for walking efficiency.

Flight Controller (FC): A Holybro Kakute H7 V2, running ArduPilot firmware, serves as the primary flight computer. Its powerful STM32H7 processor and dual IMUs are essential for managing the complex mixing required for a hybrid vehicle and providing robust vibration rejection.

Companion Computer: A Teensy 4.0 microcontroller is proposed as a dedicated kinematics engine. It would receive high-level commands from the FC via MAVLink (UART) and perform real-time inverse kinematics calculations, generating the 12 servo PWM signals via a PCA9685 I2C servo driver. This offloads computationally intensive tasks from the FC, allowing it to focus on flight stability.

4. Kinematics and Control Architecture

A. Kinematic Modeling

The position of each foot tip is determined using forward kinematics (FK). The position of the foot tip, P_{foot}, in the body frame is calculated from the joint angles (ψ, θ, φ) and link lengths (L_1, L_2) by applying sequential rotation matrices.

Conversely, for gait generation, inverse kinematics (IK) is used to calculate the required joint angles to place the foot at a target position $P_{target} = [x, y, z]$. The solution is derived analytically. The hip yaw angle, ψ, is found first by projecting the target onto the XY plane:

$$\psi = \text{atan2}(y_{target}, x_{target})$$

The problem is then reduced to a 2D two-link planar arm in the sagittal plane, where the hip pitch (θ) and knee pitch (φ) angles are solved geometrically using the law of cosines.

B. Gait Generation and Transformation

A static **creep gait** is implemented for maximum stability, ensuring at least three legs are in contact with the ground at all times. The foot trajectory during the swing phase follows a sinusoidal arc to provide clearance, while the body moves forward smoothly during the stance phase.

Transformation between walking and flight modes is managed by a finite state machine. Upon pilot command, the robot first stabilizes its stance, then executes a pre-computed 5-second trajectory to fold all four legs simultaneously into the flight configuration. The control system would continuously monitor the Hall effect sensors, and only upon confirmation that all four locks are engaged would it permit the motors to be armed for flight.

C. Flight Control

In flight mode, the system operates as a standard quadcopter under the control of the ArduPilot firmware. The FC uses a PID control loop to maintain stability, utilizing data from the dual IMUs, barometer, and LiDAR for attitude and altitude hold. The pilot would have access to standard flight modes such as Stabilize and Altitude Hold, as well as a GPS-based Return-to-Launch failsafe.

5. Theoretical Performance and Validation Plan

A. Projected Performance Metrics

Based on the selected components and design parameters, the theoretical performance of the robot is projected. The final assembled robot is expected to have a total mass of 1.418 kg. The propulsion system should generate a maximum thrust of 4.4 kg, yielding a target thrust-to-weight ratio of 3.1:1, well above the 2.0 minimum for agile flight.

TABLE I. DESIGN TARGETS

Metric	Design Target
Total Weight	< 1.5 kg
Thrust-to-Weight Ratio	> 2.0:1
Flight Endurance (Hover)	> 5 min
Walk Endurance	> 20 min
Transformation Time	< 10 sec
Ground Clearance (Prop)	> 55 mm

B. Locomotion Efficiency Analysis

An energy model was developed to determine the efficiency crossover point between walking and flying. The power consumption was estimated from component datasheets: $P_{walk} \approx 77W$ and $P_{cruise} \approx 320W$. The total energy E to travel a distance d is:

$$E_{walk}(d) = P_{walk} \times (d / v_{walk})$$

$E_{fly}(d) = E_{takeoff/land} + P_{cruise} \times (d / v_{cruise})$

By solving $E_{walk}(d) = E_{fly}(d)$ with the projected system parameters, the break-even distance was calculated to be **32.8 meters**. For distances shorter than this, walking is theoretically more energy-efficient; for longer distances, flying is superior. This provides a clear decision metric for future autonomous navigation algorithms.

C. Future Validation Strategy

Future work will involve constructing a physical prototype to validate these projections. The testing protocol will include static load tests on the lock mechanism, power draw measurements to confirm the energy model, hover endurance tests in a controlled environment, and gait stability analysis on various terrains. These experiments will be critical to verifying the practical performance of the proposed design.

6. Discussion

A. Anticipated Design Challenges

The proposed design reflects a series of critical tradeoffs. A significant challenge will be managing the servo loads. The selection of lightweight servos for the hip and knee joints, while beneficial for mass reduction, results in a low dynamic safety factor of 1.1x. This will require the gait controller to implement smooth acceleration profiles to avoid stalling. Another challenge will be wire management through the multiple rotating joints, which will require careful design to prevent fatigue and failure.

B. Limitations and Future Work

The conceptual design has several limitations. It has minimal payload capacity (<50g), lacks waterproofing, and relies on remote piloting. The transformation sequence is assumed to occur on flat ground.

Future work will focus on three main areas:

1. **Mechanical Refinement:** Upgrading key servos to increase the torque margin and incorporating conformal coating on electronics for moisture resistance.
2. **Autonomous Navigation:** Integrating a companion computer (e.g., Raspberry Pi or Jetson Nano) to implement vision-based SLAM and an autonomous decision engine based on the energy model.
3. **Payload Integration:** Designing a lightweight, gimbal-stabilized camera or a small gripper to enhance the robot's mission capabilities.

7. Conclusion

This paper has detailed the conceptual design and control architecture for a 1.418 kg hybrid quadruped-quadcopter robot. The novel mid-leg rotor configuration is proposed as a viable strategy for achieving both stable walking and efficient flight in a single, lightweight platform. Theoretical analysis and simulations suggest the system can meet its primary design goals for weight, endurance, and performance, with a projected flight time of 6.5 minutes and a walking time of 26 minutes. The analysis of the energy break-even distance provides a valuable foundation for future autonomous hybrid navigation strategies. This work lays the theoretical groundwork for a new class of multi-modal robots with a potential for applications requiring both aerial mobility and terrestrial persistence.

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