Aero-OMEGA: Propeller-Assisted Whole-Body Control for Robust 3D Hopping Locomotion

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Abstract—Deploying monopod hopping robots in outdoor environments requires both high stability for disturbance rejection and high agility for navigating complex terrain. However, conventional monopods lack sufficient attitude authority during flight phases, resulting in degraded robustness in unstructured settings. This paper presents Aero-OMEGA, a propeller-assisted monopod that addresses this limitation through a propeller-augmented whole-body control (WBC) framework. Based on the open-source OMEGA platform with a 3-RSR parallel leg, Aero-OMEGA incorporates three lightweight propellers that provide additional controllable forces and moments while maintaining a thrust-to-weight ratio below one, thus preserving leg-driven locomotion characteristics. The proposed WBC formulation treats the robot as a single rigid body with distributed actuation from both the leg and propellers, enabling coordinated control of body motion across stance and flight. Hardware experiments and simulations demonstrate field-relevant performance, including cat-like recovery from 30° attitude disturbances, accurate velocity tracking with rapid start–stop transitions, and robust traversability over uneven terrain at 0.3 m/s. These results show that propeller-assisted whole-body control substantially enhances the stability and agility of monopod hopping robots, offering a practical path toward real-world deployment in outdoor environments.

I. INTRODUCTION

Animals can xxx; To echo the only keyword "Biologically-Inspired Robotics and Biomimetics" that we will choose when submitting

Monopod hopping robots have served as a fundamental platform for studying dynamic legged locomotion since Raibert's pioneering work [3]. As the simplest legged system capable of 3D dynamic motion, they offer an ideal testbed for developing control strategies that may later scale to more complex multi-legged platforms. Deploying monopod robots in field environments, however, demands both high stability against disturbances and high agility to traverse complex terrain.

The fundamental difficulty lies in the extended flight phase of hopping. Once the foot leaves the ground, the robot becomes fully underactuated—no ground reaction force is available to correct attitude errors or reject disturbances. Traditional monopod controllers, such as Raibert's pioneering work [3], rely entirely on the brief stance phase to regulate body orientation. This works well in controlled laboratory settings but limits robustness when facing the unpredictable disturbances common in field environments.
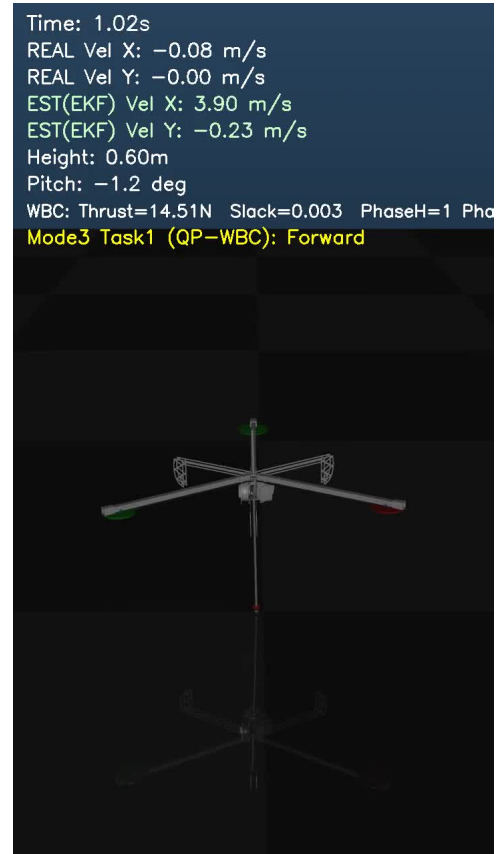

Fig. 1. Converting this idea to our robot.

Appending propellers to monopod robots offers a solution by providing continuous attitude control authority throughout the gait cycle. Our previous work on the OMEGA platform [1] established an open-source 3-RSR parallel leg mechanism for multi-mode hopping research. Building upon OMEGA, Pro-OMEGA [2] demonstrated in 2D hopping that lightweight propellers with thrust-to-weight ratio below 1 can significantly enhance robustness, enabling recovery from pitch offsets up to 20°.

In this work, we present Aero Omega, which extends propeller-assisted hopping to full 3D through a key architectural insight: *decoupling locomotion control from attitude control.* Rather than designing a single complex controller that manages both tasks, we separate them into two independent subsystems:

- The leg handles locomotion (forward motion, height regulation) via energy-based hopping control
- The propellers handle attitude stabilization via Whole Body Control with optimal thrust allocation

This decoupling provides two practical advantages. First, each subsystem can be tuned and optimized independently without affecting the other. Second, each subsystem can be pushed to its performance limits—the leg can execute aggressive hopping maneuvers while propellers maintain stable orientation, achieving the stability-agility combination required for field deployment.

This paper presents the decoupled control architecture for propeller-assisted 3D monopod hopping, and validates its field-relevant capabilities through experiments and simulations—including cat-like recovery from $30°$ attitude offsets, velocity tracking with rapid start-stop, and robust locomotion over uneven terrain. Results demonstrate that this approach enables significantly enhanced stability and agility compared to leg-only control, suggesting a practical path toward field deployment of monopod robots.

II. SYSTEM AND MODELING

This section summarizes the hardware and the models used for whole-body control in both simulation and hardware deployment.

A. Mechanical System

The platform is based on the open-source OMEGA monopod with a 3-RSR parallel leg and three lightweight propellers mounted on the trunk in a Y-configuration.

B. Electronic System

The control system runs onboard on a Raspberry Pi 4B at 500Hz, communicating with leg motors via CAN bus and propeller motors via VESC drivers. State estimation is provided by an onboard IMU.

C. Serial Leg Equivalent Model

The 3-RSR parallel leg mechanism provides 3-DOF translational motion for the foot. For simulation, an equivalent serial leg with roll (θ_1), pitch (θ_2), and prismatic (d) joints is adopted to preserve the same workspace. The leg Jacobian $\boldsymbol{J}_{leg} \in \mathbb{R}^{3\times3}$ maps foot forces to joint torques:

$$\boldsymbol{\tau}_{leg} = \boldsymbol{J}_{leg}^T \boldsymbol{f}_{foot} \qquad (1)$$

D. Propeller Configuration

Each propeller produces a unidirectional thrust $t_i \geq 0$ along the body z-axis. Let $\boldsymbol{R}_{wb} \in SO(3)$ be the rotation from body to world frame and $\boldsymbol{e}_3 = [0,0,1]^T$. The thrust direction in world frame is $\boldsymbol{z}_w = \boldsymbol{R}_{wb}\boldsymbol{e}_3$, and the thrust force is $\boldsymbol{f}_{p,i} = \boldsymbol{z}_w t_i$.

E. Single Rigid Body (SRB) Model

To describe whole-body wrench generation, an SRB wrench balance is used with a stance contact force $\boldsymbol{f}_c$ and propeller thrusts t_i. During stance:

$$\boldsymbol{f}_c + \sum_{i=1}^{3} \boldsymbol{z}_w t_i = m(\boldsymbol{a} - \boldsymbol{g}), \qquad (2)$$

$$\boldsymbol{r}_c \times \boldsymbol{f}_c + \sum_{i=1}^{3} \boldsymbol{r}_i \times (\boldsymbol{z}_w t_i) = \boldsymbol{\tau}, \qquad (3)$$

where $\boldsymbol{r}_c$ and $\boldsymbol{r}_i$ are the lever arms (world frame). During flight, $\boldsymbol{f}_c = \boldsymbol{0}$.

F. Hybrid Full-body Dynamics

Full-body dynamics with contact constraints are used. The equations of motion are

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{S}^T\boldsymbol{\tau} + \boldsymbol{J}_c^T\boldsymbol{f}_c + \sum_{i=1}^{3}\boldsymbol{J}_{p,i}^T(\boldsymbol{z}_w t_i), \quad (4)$$

where $\boldsymbol{q}$ includes the floating base and leg joints, $\boldsymbol{\tau}$ are commanded leg joint torques, and $\boldsymbol{J}_c$ is the stance foot Jacobian. In stance, the non-slipping contact acceleration constraint is imposed:

$$\boldsymbol{J}_c\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}_c\dot{\boldsymbol{q}} = \boldsymbol{0}. \qquad (5)$$

G. Torque Mapping for Hardware Deployment

For deployment on the physical 3-RSR parallel mechanism, serial joint torques are mapped to parallel joint torques via Jacobian transformation [1]:

$$\boldsymbol{\tau}^{\mathcal{P}} = (\boldsymbol{J}^{\mathcal{P}})^T(\boldsymbol{J}^{\mathcal{S}})^{-T}\boldsymbol{\tau}^{\mathcal{S}} \qquad (6)$$

where $\boldsymbol{J}^{\mathcal{P}}$ and $\boldsymbol{J}^{\mathcal{S}}$ are the parallel and serial leg Jacobians respectively. This enables the same controller developed in simulation to be deployed on the physical robot.

III. CONTROL SYNTHESIS

A QP-based whole-body controller (WBC) with propeller assistance is used. A Raibert-style swing-leg rule provides a flight-phase foot placement target [3], while a full-body QP computes feasible leg torques and propeller thrusts under unified dynamics and contact constraints.

A. Leg Control for Locomotion

1) Stance Phase: Energy Regulation: During stance, a virtual spring model regulates hopping height through energy injection/dissipation:

$$f_{leg} = k(l_0 - l_{leg}) \pm k_e(E_{des} - E) \qquad (7)$$

where the sign depends on leg compression/extension phase. The desired energy E_{des} is determined by target hopping height and velocity.

2) Flight Phase: Foot Placement: During flight, the Raibert foot placement law [3] computes the landing position:

$$\boldsymbol{p}_{foot}^{des} = K_v \boldsymbol{v} + K_r(\boldsymbol{v} - \boldsymbol{v}_{des}) \qquad (8)$$

where K_v and K_r are feedforward and feedback gains. The foot position is transformed to body frame to ensure gravity-aligned placement.

B. Whole-body QP-WBC

A QP is solved at each control step with decision variables $\boldsymbol{x} = [\ddot{\boldsymbol{q}}^T, \boldsymbol{\tau}^T, \boldsymbol{f}_c^T, \boldsymbol{t}^T]^T$, where $\boldsymbol{t} = [t_1, t_2, t_3]^T$. The formulation uses a weighted least-squares objective:

$$\min_{\boldsymbol{x}} \quad \|\boldsymbol{J}_{b,p}\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}_{b,p}\dot{\boldsymbol{q}} - \boldsymbol{a}^{des}\|_{\boldsymbol{W}_p}^2 \; + \; \|\boldsymbol{J}_{b,r}\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}_{b,r}\dot{\boldsymbol{q}} - \boldsymbol{\alpha}^{des}\|_{\boldsymbol{W}_r}^2$$
$$+ \; \|\boldsymbol{J}_s\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}_s\dot{\boldsymbol{q}} - \boldsymbol{a}_s^{des}\|_{\boldsymbol{W}_s}^2 \quad \text{(flight only)}$$
$$+ \; \|\boldsymbol{x}\|_{\boldsymbol{W}_{reg}}^2$$
$$\text{s.t.} \quad \text{full-body dynamics (4)},$$
$$\text{contact constraint (5)} \quad \text{(stance only)},$$
$$f_{c,z} \geq 0, \quad |f_{c,x}| \leq \mu f_{c,z}, \quad |f_{c,y}| \leq \mu f_{c,z},$$
$$\boldsymbol{\tau}_{min} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{max}, \quad \boldsymbol{0} \leq \boldsymbol{t} \leq \boldsymbol{t}_{max}, \qquad (9)$$

where $\boldsymbol{J}_{b,p}$ and $\boldsymbol{J}_{b,r}$ are the base linear and angular Jacobians. $\boldsymbol{a}^{des}$ and $\boldsymbol{\alpha}^{des}$ are computed from height/velocity tracking and attitude regulation. $\boldsymbol{J}_s$ is the swing-foot Jacobian and $\boldsymbol{a}_s^{des}$ is a swing-foot desired Cartesian acceleration (e.g., PD tracking of $\boldsymbol{p}_{foot}^{des}$). In flight, $\boldsymbol{f}_c$ is clamped to $\boldsymbol{0}$ and the swing-foot task is activated.

a) Reference generation: The desired base linear acceleration is generated by a vertical hopping reference and horizontal velocity tracking. A smooth periodic height reference is used:

$$z_{ref}(t) = z_0 + \frac{A}{2}\left(1 - \cos(2\pi f t)\right), \qquad (10)$$

with feedforward $\ddot{z}_{ff}(t)$, and set

$$a_z^{des} = \ddot{z}_{ff} + k_p(z_{ref} - z) + k_d(\dot{z}_{ref} - \dot{z}), \qquad (11)$$

In flight, a_z^{des} is saturated to prevent excessive ascent and to return toward the baseline height. For the horizontal directions,

$$a_x^{des} = k_v(v_{x,ref} - v_x), \quad a_y^{des} = k_v(v_{y,ref} - v_y), \qquad (12)$$

where k_v is down-weighted during hopping to prioritize vertical motion. A desired roll/pitch is computed from $\boldsymbol{a}^{des}$ (small-angle approximation), and a PD law yields the desired angular acceleration for roll/pitch while yaw is ignored:

$$\alpha_x^{des} = -k_R(\phi - \phi_{des}) - k_\omega \omega_x, \quad \alpha_y^{des} = -k_R(\theta - \theta_{des}) - k_\omega \omega_y, \quad \alpha_z^{des} = 0. \qquad (13)$$

IV. RESULTS

A. Simulation

B. Hardware Experiments

V. CONCLUSION AND FUTURE WORK

ACKNOWLEDGMENT

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