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.

1 INTRODUCTION

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

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Monopod hopping robots have served as a fundamental platform for studying dynamic legged locomotion since Raibert's pioneering work [**?**]. 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 [**?**], 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.

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Figure 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 [**?**] established an open-source 3-RSR parallel leg mechanism for multi-mode hopping research. Building upon OMEGA, Pro-OMEGA [**?**] 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.

2 SYSTEM AND MODELING

This section introduces the Aero Omega robot, which consists of a mechanical system, an electronic system, and a dynamics model.

2.1 Mechanical System

2.2 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.

2.3 Serial Leg Equivalent Model

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

$$\boldsymbol{\tau}_{leg} = \boldsymbol{J}_{leg}^T \boldsymbol{f}_{foot} \tag{1}$$

2.4 Propeller Configuration

Three propellers are mounted in a Y-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 $\boldsymbol{f}_{p,i} = \boldsymbol{z}_w t_i$. The tri-rotor configuration provides strong roll/pitch authority; yaw is treated as passive in this work.

2.5 Single Rigid Body (SRB) Model

For control design in mode3, we model the robot as a single rigid body (SRB) subject to a stance contact force at the foot and propeller thrust forces applied at fixed attachment points on the base. Let $\boldsymbol{p} \in \mathbb{R}^3$ be the base position, $\boldsymbol{v}$ the base linear velocity, and $\boldsymbol{\omega}$ the base angular velocity. In world frame, the SRB wrench balance is

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

Table 1: Physical Parameters of Aero Omega

Parameter	Symbol	Value
Total mass	m	3.23 kg
Natural leg length	l_0	0.464 m
Leg offset	Δl	0.1313 m
Inertia (Roll/Pitch)	I_{xx}, I_{yy}	0.5 kg·m^2
Inertia (Yaw)	I_{zz}	0.3 kg·m^2
Propeller arm length	l_p	0.57 m
Thrust coefficient	C_T	0.015
Max thrust per propeller	f_{max}	12 N

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

where $\boldsymbol{f}_c$ is the stance contact force, $\boldsymbol{r}_c$ is the vector from base to contact point, and $\boldsymbol{r}_i$ is the vector from base to the i-th propeller attachment point (all expressed in world frame). $\boldsymbol{a}$ and $\boldsymbol{\tau}$ denote the desired base linear acceleration and desired net moment, respectively. During flight, we set $\boldsymbol{f}_c = \boldsymbol{0}$.

2.6 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 [**?**]:

$$\boldsymbol{\tau}^{\mathcal{P}} = (\boldsymbol{J}^{\mathcal{P}})^T (\boldsymbol{J}^{\mathcal{S}})^{-T} \boldsymbol{\tau}^{\mathcal{S}} \tag{4}$$

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.

Table **??** summarizes the robot's physical parameters.

3 CONTROL SYNTHESIS

The control of Aero Omega is organized in a task-decoupled manner: the leg provides locomotion (hopping energy regulation and swing-foot placement), while the propellers provide additional attitude authority. In mode3, these actuators are coordinated through an SRB-based QP-WBC that allocates stance contact force and individual propeller thrusts under a unified dynamics constraint.

3.1 Leg Control for Locomotion

3.1.1 Stance Phase: Energy Regulation

During stance, a virtual spring model regulates hopping height through energy injection/dissipation:

$$f_{leg} = k(l_0 - l_{leg}) \pm k_e(E_{des} - E) \tag{5}$$

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

3.1.2 Flight Phase: Foot Placement

During flight, the Raibert foot placement law [**?**] computes the landing position:

$$\boldsymbol{p}_{foot}^{des} = K_v \boldsymbol{v} + K_r(\boldsymbol{v} - \boldsymbol{v}_{des}) \tag{6}$$

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

3.2 Mode3: SRB QP-WBC with Tri-rotor Assistance

In mode3, we solve a quadratic program each control step to compute the stance contact force $\boldsymbol{f}_c$ and individual propeller thrusts $\boldsymbol{t} = [t_1, t_2, t_3]^T$. The SRB dynamics (Eqs. **??**–**??**) are enforced as equality constraints (with slack variables to guarantee feasibility), and the following inequality constraints are applied:

- **Unilateral contact and friction**: $f_{c,z} \geq 0$, and a friction pyramid $|f_{c,x}| \leq \mu f_{c,z}$, $|f_{c,y}| \leq \mu f_{c,z}$ in stance.
- **Thrust bounds**: $0 \leq t_i \leq t_{\max}$.
- **Flight phase constraint**: in flight, we clamp $\boldsymbol{f}_c = \boldsymbol{0}$, leaving propellers to satisfy the softened SRB dynamics.

The QP objective tracks the desired base wrench ($m(\boldsymbol{a}_{des} - \boldsymbol{g})$, $\boldsymbol{\tau}_{des}$) while regularizing contact force, thrust magnitude, and slack variables. $\boldsymbol{a}_{des}$ is generated from height/velocity tracking (with hopping height reference in mode3), and $\boldsymbol{\tau}_{des}$ is generated from roll/pitch regulation to a desired tilt computed from the desired horizontal acceleration (small-angle approximation), while yaw is ignored.

3.2.1 Hopping Height Reference (Mode3)

To realize rhythmic hopping in mode3, we track a periodic reference on the base height:

$$z_{ref}(t) = z_0 + A\frac{1 - \cos(2\pi f t)}{2}, \tag{7}$$

where z_0 is the baseline height, A is the hop amplitude, and f is the hop frequency. A PD+feedforward law generates the desired vertical acceleration from $z_{ref}(t)$, which is then used to form $\boldsymbol{a}_{des}$ for the SRB QP-WBC.

3.3 Task-decoupled Architecture

Although mode3 uses a unified SRB dynamics constraint to coordinate leg contact and propeller thrusts, the overall architecture remains task-decoupled: the leg primarily regulates hopping and swing-foot placement, while the propellers mainly provide additional attitude authority and assist the net wrench tracking during both stance and flight.

4 RESULTS

4.1 Simulation

4.2 Hardware Experiments

5 CONCLUSION AND FUTURE WORK

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