Design and Development of a 3D-Printed Octopod Robot for Adaptive Terrain Locomotion and Autonomous Navigation

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Abstract—This paper presents the design, fabrication, and control implementation of a 3D-printed eight-legged robot (Octopod) developed as an experimental platform for terrain-adaptive locomotion. The robot was conceived as a half-meter educational-scale prototype demonstrating bio-inspired kinematics, 3D-printed modular architecture, and embedded control intelligence using low-cost microcontrollers. Each of the eight legs is driven by three servo joints, offering 24 degrees of freedom coordinated via a gait-generation algorithm implemented on an ESP32S3 microcontroller. The control strategy integrates tripod and ripple gaits for terrain adaptability while maintaining static stability. A custom power management and communication framework ensures safe, low-voltage operation suitable for undergraduate research. Experimental testing validates the feasibility of using additive manufacturing for multi-legged robots capable of traversing rough terrains. This project contributes to affordable robotics education, rapid prototyping research, and bio-inspired mobility in unstructured environments.

Index Terms—3D printing, additive manufacturing, autonomous control, bio-inspired robotics, gait generation, low-cost design, Octopod robot, terrain adaptability.

I. INTRODUCTION

Legged robotics has emerged as a vital field in mobile robotics research, enabling operation in complex terrains where wheeled or tracked systems are limited. The Octopod Robot draws inspiration from biological systems such as spiders and crabs that utilize distributed multi-leg motion to maintain stability and adaptability.

Existing legged robots such as Boston Dynamics' Spot or ETH Zurich's ANYmal demonstrate advanced terrain adaptation but are cost-prohibitive and mechanically complex. Educational and research institutions therefore require low-cost, scalable, and 3D-printable platforms for experimentation in gait dynamics and control systems.

This research introduces a half-meter footprint Octopod designed using additive manufacturing and modular construction principles. The robot emphasizes accessibility, structural optimization, and bio-inspired movement, using inexpensive components to bridge the gap between theoretical kinematics and physical implementation.

II. DESIGN OBJECTIVES

The primary objectives of the Octopod robot were as follows:

- Develop a modular 3D-printed octopod with ≤0.5 m footprint for laboratory use.
- Demonstrate stable, adaptive gaits on flat and uneven surfaces.
- Integrate low-cost electronics with safe, low-voltage operation (<12 V).
- Use bio-inspired symmetry for enhanced stability and redundancy.
- Enable open hardware and firmware design for educational use.

III. SYSTEM OVERVIEW

A. Mechanical Architecture

The Octopod consists of a central body chassis and eight identical legs, each with three servo-actuated joints: coxa (rotation), femur (lift), and tibia (extension). The overall system is symmetrical about the centerline, allowing balanced mass distribution and gait repeatability. The assembled prototype is shown in Fig. 1.

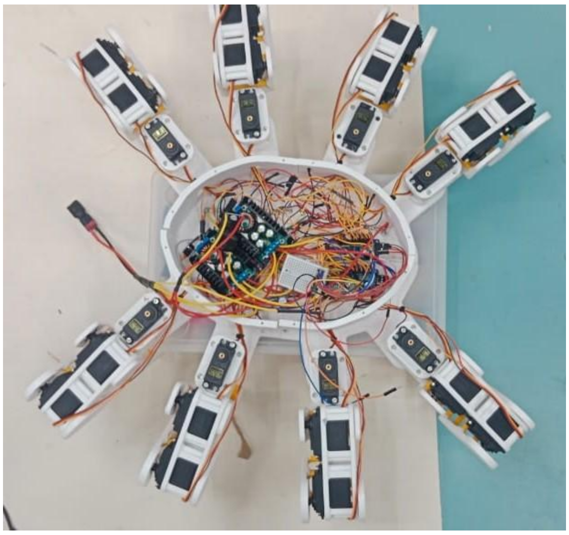

Fig. 1. Assembled Octopod Robot (top view).

TABLE I. MECHANICAL SPECIFICATIONS

Parameter	Value
Total Length	290 mm
Longest-Width	310 mm
Shortest-Width	200 mm
Height	80 mm
Ground Clearance	50 mm
Total Weight	2.8 kg
Material	PETG-HS (chassis), ABS (pillars)

The central chassis is a 3D-printed Polyethylene Terephthalate Glycol - High Speed (PETG-HS) structure reinforced with Acrylonitrile Butadiene Styrene (ABS) rods and divided into three compartments: Front (sensors and IMU), Center (control electronics), and Rear (power and communication modules).

B. Actuation and Control Electronics

Each leg comprises three metal-geared MG996R servos providing 9.8 kg·cm torque at 7.2 V. Servos are arranged to allow pitch and yaw movement at each joint. The control architecture is as follows:

- Controller: ESP32S3 (dual-core microcontroller)
- PWM Driver: PCA9685 (16-channel, I²C protocol)
- Sensors: MPU9050 (IMU), LiDaR ToF (x2 front)
- Power System: 7.4 V Li-ion battery + 6 V UBEC
- Communication: Wi-Fi & BLE

The system supports both manual control (via app) and autonomous obstacle avoidance modes.

IV. CAD DESIGN AND FABRICATION

A. CAD Modeling

The robot was designed using Autodesk Fusion 360. Each component was modeled parametrically, allowing easy scaling or reconfiguration (e.g., hexapod variant). The CAD model is illustrated in Fig. 2. Finite Element Analysis (FEA) was performed on the femur and tibia links under a 1.5 kg load, yielding:

- Max stress: 18.7 MPa
- Safety factor: 2.1 (PETG-HS yield ≈ 50 MPa)

Fig. 2. CAD model of the Octopod Robot (Autodesk Fusion 360).

B. 3D Printing Process

TABLE II. 3D PRINTING PARAMETERS

Parameter	Value
Layer Height	0.16 mm
Infill	25% gyroid
Material	PETG-HS (body), PETG (joints)
Print Time	~30 hours
Filament Used	3 kg total
Assembly Method	M3 screw 12mm 8mm +

Printed parts were assembled into eight modular leg units that attach to the central frame via quick-release couplings.

V. KINEMATIC MODEL

A. Forward Kinematics

Each leg was modeled as a 3-DOF manipulator. Let θ_1, θ_2, θ_3 represent joint angles and L_1, L_2, L_3 denote the link lengths. The end-effector position (foot) in the local frame is:

$$x = L_1 cos\theta_1 + L_2 cos(\theta_1+\theta_2) + L_3 cos(\theta_1+\theta_2+\theta_3)$$
$$y = L_1 sin\theta_1 + L_2 sin(\theta_1+\theta_2) + L_3 sin(\theta_1+\theta_2+\theta_3) \quad ... (1)$$

Link lengths were chosen as: L_1 = 60 mm, L_2 = 80 mm, L_3 = 100 mm.

B. Inverse Kinematics

Inverse kinematics is solved geometrically using trigonometric relations to calculate joint angles for target foot positions during gait cycles. This approach enables real-time computation on the ESP32S3 without the overhead of iterative numerical solvers.

VI. GAIT CONTROL STRATEGY

A. Gait Design

Four gait types were implemented and evaluated:

- Tripod gait – Fast movement on level terrain.
- Ripple gait – Smooth, wave-like progression for uneven surfaces.
- Wave gait – High stability for slow, precise motion.
- Turn-in-place – Differential leg phase for rotation.

B. Gait Generation Algorithm

Each leg trajectory is parameterized by a sinusoidal function:

$$\theta_i(t) = A_i \sin(\omega t + \varphi_i) \quad ... (2)$$

where A_i is the amplitude, ω is the angular velocity, and φ_i is the phase shift (45° increments for 8 legs). Servo commands are generated every 20 ms and smoothed via Bézier interpolation to minimize jerk.

C. Feedback Control

The IMU provides pitch and roll data to dynamically adjust gait amplitude. PID feedback ensures body orientation correction:

$$\Delta\theta = K_p e + K^I \int e\, dt + K^D (de/dt) \quad ... (3)$$

where e is the orientation error with respect to the desired body pose.

VII. RESULTS AND PERFORMANCE

A. Static Stability

The Octopod maintained static stability when up to two adjacent legs were lifted. The stability margin averaged 25 mm on flat terrain and 18 mm on gravel, confirming the design's robustness.

B. Terrain Performance

TABLE III. TERRAIN PERFORMANCE

Terrain Type	Speed (m/s)	Notes
Smooth Floor	0.25	Stable tripod gait
Grass	0.18	Slight slip, ripple gait preferred
Gravel	0.15	Maintained traction
15° Slope	0.12	Ripple gait effective

C. Endurance

- Operating time: 50–60 minutes per charge
- Average power draw: 30 A
- Max current draw: 40 A

D. Sensing Accuracy

IMU roll-pitch accuracy: ±1.2°. LiDaR ToF range detection: up to 1.5 m with consistent obstacle detection during autonomous navigation trials.

VIII. DISCUSSION

The experiment demonstrates that 3D-printed materials can sustain dynamic robotic locomotion when designed with proper geometry and infill patterns. The octopod configuration offers redundancy, allowing continued operation even with one malfunctioning leg.

A. Mechanical Observations

- No fractures observed after 3 hours of continuous motion.
- Minimal backlash at servo joints using metal-gear servos.
- Passive heat sinks reduced thermal drift during long tests.

B. Limitations

- Servo backlash accumulates over extended operation.
- Weight distribution affects gait symmetry at steep angles.
- Limited onboard computing power restricts AI inference speed.

C. Future Work

- Integration with ROS2 framework for multi-agent exploration.

- Upgrade to brushless actuators with encoders for higher precision.
- Use of carbon-fiber PETG for structural reinforcement.
- Employ reinforcement learning for gait adaptation (TinyML).

IX. EDUCATIONAL IMPACT

This project has proven valuable as an educational platform for Design Thinking and Prototyping, Kinematics and Control Systems, Additive Manufacturing in Robotics, and AI-Integrated Mechatronics. It enables first-year and second-year students to learn the full robotics pipeline: concept → CAD → fabrication → control → testing.

The Octopod also serves as a standard lab model for future AI gait experiments and UGV applications, offering a replicable, affordable base for undergraduate research.

X. CONCLUSION

The Octopod Robot successfully demonstrates how additive manufacturing, low-cost electronics, and bio-inspired design can be combined to achieve complex legged locomotion in a small, educationally accessible system. The half-meter prototype provides a robust platform for research in terrain mobility, control algorithms, and material optimization.

The outcomes validate that even undergraduate-level engineering teams can achieve stable and intelligent robotic locomotion through interdisciplinary design thinking. This work contributes to the growing ecosystem of open-source, 3D-printed robotic platforms, encouraging hands-on exploration of legged robotics at all academic levels.

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