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Design and Implementation of an Obstacle-Crossing Robot Based on Energy-Storage Mechanism

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Abstract: To address the challenges of high energy consumption and poor stability in traditional obstacle-crossing robots operating in complex terrains, this study proposes a novel two-wheel self-balancing robot integrated with a cam-spring composite energy-storage mechanism. The robot employs a torque servo motor to drive a cam for compressing springs, thereby storing elastic potential energy. Combined with a PID-based self-balancing control system, the robot achieves an efficient obstacle-crossing process characterized by "energy pre-storage, instantaneous release, and dynamic balance." The modular mechanical design features an optimized cam profile to convert rotational motion into nonlinear linear motion, while the chassis utilizes high-precision encoders and a nine-axis sensor for real-time posture adjustment. Experimental results demonstrate a 98% obstacle-crossing success rate, a 40% improvement in motion smoothness, and a 35% reduction in energy consumption compared to conventional solutions. This work provides a new pathway for designing lightweight, high-reliability obstacle-crossing robots. A functional prototype has been developed, and a utility model patent has been filed.

Keywords: Obstacle-crossing robot; Energy-storage mechanism; Cam-spring composite transmission; Self-balancing control; Anti-lock mechanism

1. Introduction

1.1 Background and Significance

Traditional obstacle-crossing robots rely on direct motor drives, which face challenges such as instantaneous high power demand (e.g., motor load reaching three times the rated torque during obstacle crossing) and friction-induced locking (success rates of 80%–85%). Existing energy-storage solutions, such as single-spring or pneumatic systems, suffer from low energy density and insufficient control precision.

This study contributes to:

Theoretical advancements: Investigating the energy-coupling mechanism of cam-spring composite transmission and refining the dynamic model for mobile robots.

Engineering Applications: Developing a high-load, low-energy-consumption obstacle-crossing mechanism for agricultural inspection and disaster rescue scenarios.

1.2 Objectives and Scope

Objectives:

Design a cam-spring energy-storage mechanism with a load capacity ≥2 kg and vertical obstacle-crossing height ≥10 mm.

Develop a PID-based self-balancing chassis to maintain body tilt angle fluctuations within ±5° during obstacle crossing. Eliminate friction-induced locking, achieving a success rate ≥95%.

Core Innovations:

High-load composite energy-storage mechanism: A cam-spring structure amplifies thrust output by 3.2× compared to traditional springs, increasing energy density by 25%.

Anti-lock follower wheel: Polytetrafluoroethylene (PTFE) wheels reduce the friction coefficient to $\mu < 0.1$, improving success rates from 85% to 98%.

Balancing-obstacle synergy control: Real-time posture adjustment via sensor fusion and synchronized energy release.

2. System Design

2.1 Mechanical Energy-Storage Mechanism

Components:

Torque servo motor (MG996R: 15 kg•cm torque, 5 rpm).

Cam (7075 aluminum alloy, Archimedes spiral profile, base radius 40 mm).

Compression spring (stiffness k = 800 N/m, max compression 50 mm, energy storage 3.6 J).

Workflow:
Driving phase: The cam rotates to lift the platform (max vertical displacement: 30 mm).
Energy storage: Platform compression stores elastic potential energy (8 s/cycle).
Energy release: At 180° cam rotation, spring energy is released (<50 ms), generating a 120 N impact force for obstacle crossing.

2.2 Self-Balancing Chassis

Hardware:

Dual brushless DC motors (3000 rpm, 1000-line encoders).
MPU6050 nine-axis sensor (attitude resolution accuracy ±0.5°).

Control Algorithm:

Incremental PID (P = 80, I = 0.5, D = 30) with Kalman filtering (response time <20 ms).
Obstacle detection triggers energy release and motor torque compensation (coefficient K = 0.3).

3. Key Technologies

3.1 Cam Profile Optimization

Solid Works Motion simulations minimized force fluctuations, achieving 92% energy transfer efficiency. Maximum pressure angle: <30°.

3.2 Anti-Lock Follower Wheel Design

PTFE wheels (φ30 mm) with deep-groove ball bearings reduced friction from μ = 0.6 to 0.08. Locking probability decreased by 15% in 30° slope tests.

3.3 Balancing Algorithm Tuning

Extended Kalman filtering eliminated sensor noise. Feed forward compensation reduced tilt fluctuations from ±10° to ±3°.

4. Experiments and Results

4.1 Performance Metrics

Metric	Traditional	Proposed	Improvement
Success rate (100 tests)	85%	98%	↑14%
Max obstacle height	150 mm	220 mm	↑47%
Energy consumption	10.2 J	6.6 J	↓35%

4.2 Prototype Specifications

Size: 200 × 250 × 200 mm, weight: 1.2 kg.
Continuous obstacle crossing: 15 cycles (200 mm step).
Balance response time: <100 ms.

5. Challenges and Future Work

5.1 Technical Challenges

Initial cam-platform misalignment was resolved via CNC machining (±0.05 mm precision). Spring stiffness increased by 10% at -10°C, necessitating low-temperature materials (e.g., titanium springs).

5.2 Future Directions

Machine learning for adaptive energy management.
Modular chassis designs for diverse terrains.

6. Conclusion

This study presents a cam-spring energy-storage robot with anti-lock mechanisms, achieving significant improvements in energy efficiency and reliability. Experimental validation confirms its applicability in complex terrains. Future work will integrate machine vision and hydraulic energy storage for broader applications.

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