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Short Communication

Wheeled-legged robots for multi-terrain locomotion in plateau environments

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ABSTRACT

Wheeled-legged robots integrate the mobility efficiency of wheeled platforms with the terrain adaptability of legged robots, making them ideal for complex, unstructured environments. However, balancing high payload capacity with agile multimodal locomotion remains a major challenge. This paper presents a field study conducted in the high-altitude region of Golmud, Qinghai, with elevations ranging from 2800 m to 4000 m. We evaluate three wheeled-legged robot platforms of different scales on diverse terrains including Gobi, desert, grassland, and wetlands. Our experiments demonstrate the robot's robust locomotion performance across multimodal tasks such as obstacle crossing, slope climbing, and terrain classification. Moreover, we validate the performance of autonomous perception systems, including real-time localization and 3D mapping, under harsh plateau conditions. The results provide valuable insights into the deployment of wheeled-legged robots in extreme natural environments and lay a solid foundation for future applications in inspection, rescue, and transport missions in high-altitude regions.

Wheeled robots possess excellent mobility and payload capabilities, but they struggle to adapt to unstructured terrains. Conversely, legged robots offer strong obstacle-crossing and climbing abilities but generally suffer from lower locomotion efficiency. As a novel mobile platform that combines the advantages of both, wheeled-legged robots exhibit superior multimodal mobility and have become an important research focus in the robotics community [1–3]. Current research on motion planning and control methods for wheeled-legged robots has made notable progress, offering valuable insights for addressing challenges such as hybrid wheel-leg locomotion, trajectory planning, navigation [4–8]. However, most existing prototypes, both domestic and international, still face challenges in balancing high load capacity and agility, demanding advancements in structural design, actuation, perception, and control systems. To address the need for agile mobility of wheeled-legged robots in complex mountainous plateau terrains, our work focuses on key technologies including multimodal locomotion system design, decision-making and planning methods, and multimode motion control, aiming to provide technical support for stable robot operation in extreme plateau environments[9].

To comprehensively evaluate the adaptability and mobility of wheeled-legged robots in complex plateau environments, we selected experimental sites in and around Golmud City, Qinghai Province, with altitudes ranging from 2800 to 4000 m. This region features diverse natural landscapes, including plateau Gobi, desert, meadow, and wetland, characterized by uneven surfaces and loose geology, with both dry and moist sections, making it highly representative and challenging. Such complex terrain not only imposes stringent requirements on the robot's stability and adaptability but also offers an ideal testbed for evaluating deployment performance under real-world plateau conditions.

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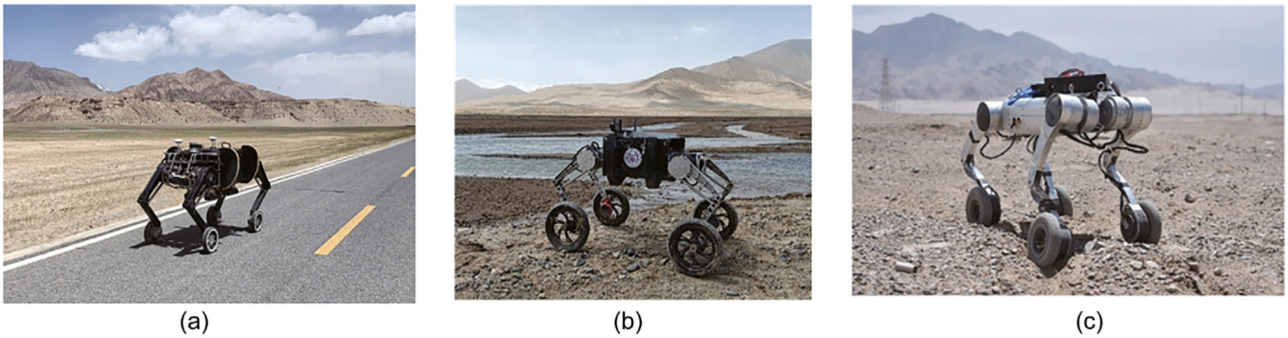

Fig. 1. Three wheeled-legged robot platforms tested in plateau environments: (a) Full-scale heavy-duty robot (> 300 kg), (b) Mid-scale prototype ($50 \sim 100$ kg), (c) Lightweight prototype (< 20 kg).

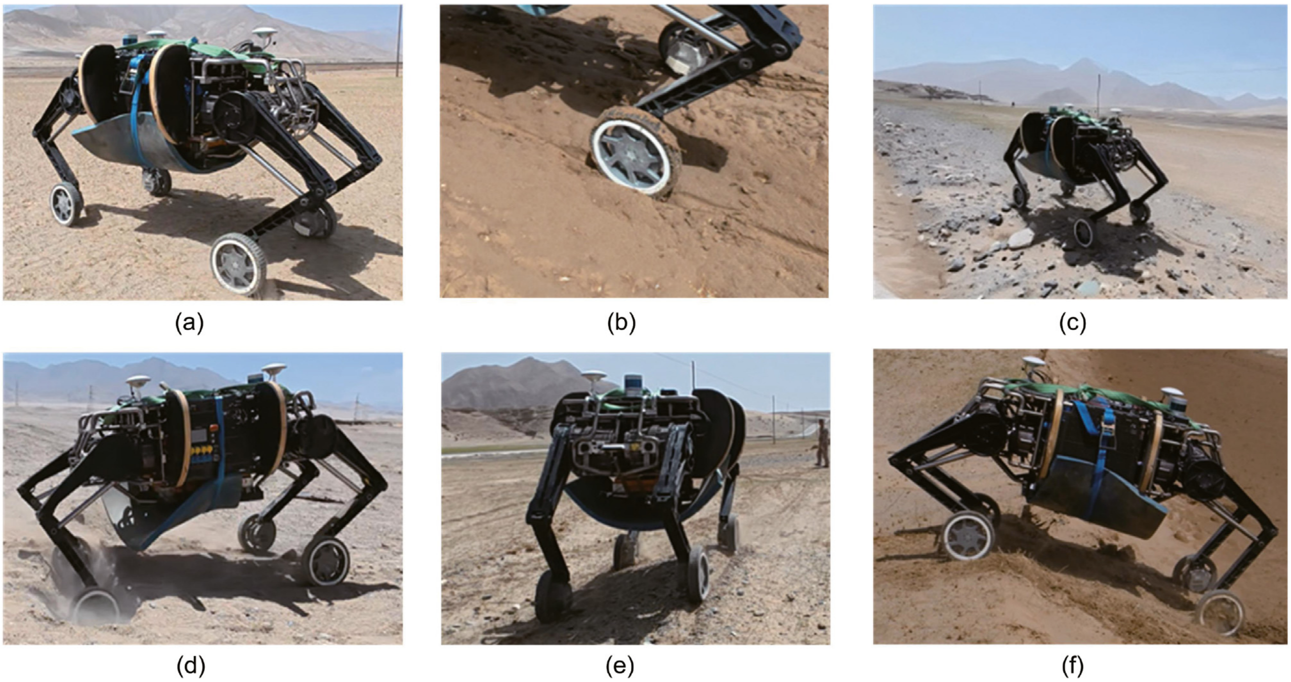

Fig. 2. Field testing of the full-scale wheeled-legged robot across various unstructured terrains in plateau environments, including (a) meadows, (b) wetlands, (c) gravel areas, (d) trenches, (e) gobi deserts, (f) ledge obstacles.

As shown in Fig. 1, we deployed three wheeled-legged robot platforms with varying weights for field testing, ranging from full-scale heavy-load systems to lightweight experimental prototypes. Fig. 1(a) shows a full-scale, high-mobility bionic wheeled-legged robot weighing over 300 kg, designed for heavy payload transport and multimodal locomotion. Fig. 1(b) presents a scaled-down prototype weighing between $50 \sim 100$ kg, which balances agility with structural testing requirements. Fig. 1(c) illustrates a lightweight experimental platform weighing less than 20 kg, primarily used for rapid evaluation of control strategies and perception algorithms.

Fig. 2 shows the performance of the full-scale robot under complex plateau terrains, including rocky slopes, sandy hills, grasslands, and loose-soil slopes. The robot performed tasks such as walking, turning, obstacle-crossing, and slope climbing. All tests were conducted via manual teleoperation using a joystick interface. The operator continuously controlled the robot's forward velocity and turning rate based on real-time terrain feedback. Each terrain segment was traversed in a single uninterrupted session without repetition or resets, simulating realistic field deployment conditions.

It is important to note that the three wheeled-legged robot platforms tested in this study differ in their actuation mechanisms and software architectures. The control framework described below applies specifically to the full-scale heavy-duty platform. This robot employed a hybrid control system combining Proximal Policy Optimization (PPO) and a low-level PD controller. The policy was trained in simulation, with observations including command inputs, joint positions and velocities, angular velocity, gravity vector, and previous actions. The actor network outputs joint position targets, which are tracked by the PD controller to produce torque commands. An overview of this control architecture is shown in Fig. 3. Using this framework, the robot achieved an unpaved-terrain locomotion speed exceeding 12 km/h, demonstrating its multimodal mobility and system robustness in challenging highland environments.

Figs. 4 and 5 show field test results of the scaled and lightweight platforms, respectively. These robots successfully traversed complex terrains such as sand, mud, steep slopes, and rocky surfaces. Similar to the full-scale robot, the smaller platforms were remotely operated via joystick control. The speed was dynamically adjusted by the operator in response to terrain difficulty, providing a flexible evaluation of the robot's locomotion

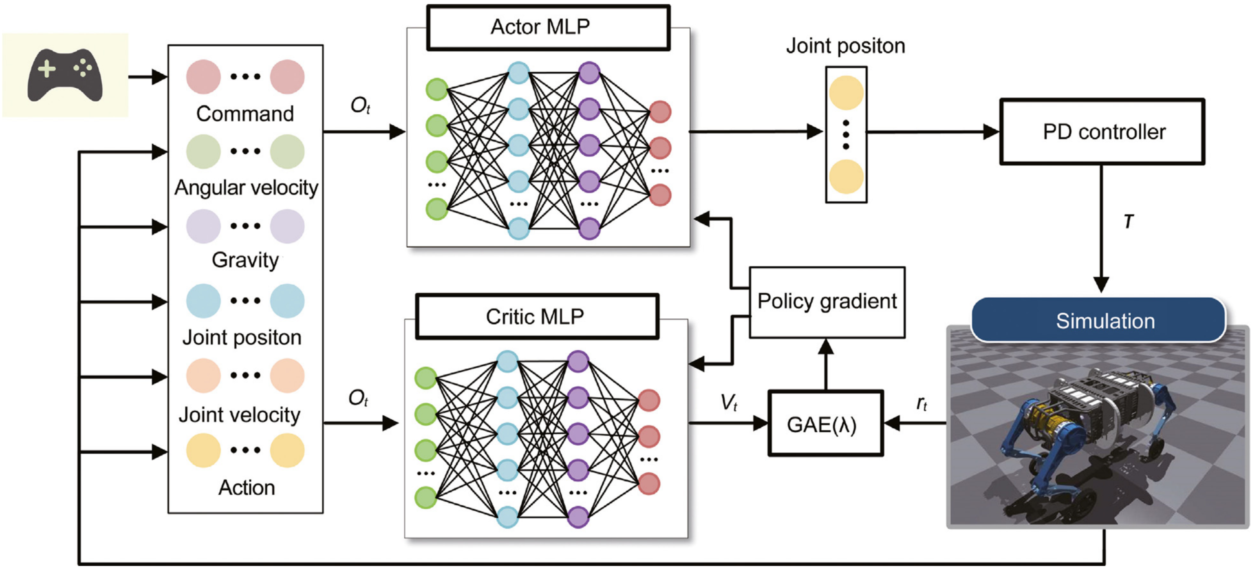

Fig. 3. Overview of the reinforcement learning-based control framework used for the full-scale heavy-duty wheeled-legged robot. The observation space includes command signals, joint states, angular velocity, gravity vector, and previous actions. The Actor MLP outputs joint position targets, which are tracked via a low-level PD controller.

Fig. 4. Field testing performance of the scaled-down prototype on unstructured plateau terrains.

Fig. 5. Field testing performance of the lightweight experimental prototype on unstructured plateau terrains.

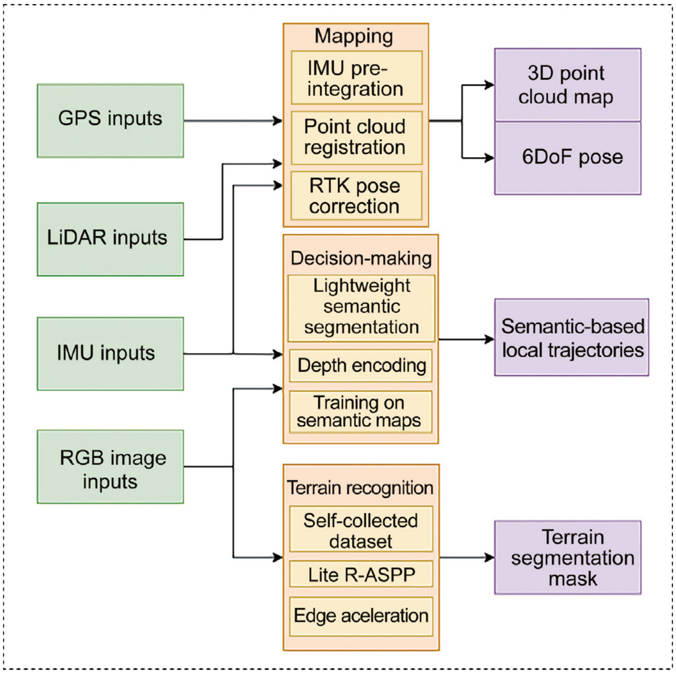

Fig. 6. Overview of our perception system.

capabilities. The scaled prototype achieved a compound locomotion speed of ≥ 27 km/h and could climb vertical obstacles over 50 cm.

Throughout testing, the robots faced challenges such as frequent terrain changes and significant slopes. The most difficult terrain involved loose-soil slopes, where wheels often slipped due to insufficient traction and partial sinking. The robots overcame this by leveraging leg-lifting capabilities and coordinated wheeled-legged locomotion strategies, achieving effective slope climbing.

In addition to locomotion testing, we have equipped the robot with a perception system for localization, mapping, decision-making navigation, and terrain recognition (see Fig. 6).

We evaluated the autonomous perception system for localization and mapping accuracy. In typical plateau terrains, we performed 3D mapping of surrounding obstacles (see Fig. 7), achieving a mapping error below 1.5% of actual distances and a localization frequency exceeding 50 Hz.

As shown in Fig. 8, we collected and annotated over 900 images of typical plateau terrains, covering eight categories: puddles, mud, vertical obstacles, gravel, steps, grassland, sand, and ditches. On this dataset, our terrain classification algorithm achieved an average accuracy of 87.5%, with results shown in Fig. 9.

This field test in Golmud Plateau verified the locomotion capabilities and system stability of multiple wheeled-legged robot platforms in natural environments at altitudes between 2800 and 4000 m. The results demonstrate that both heavy-duty and lightweight platforms can stably traverse various terrain types such as Gobi, desert, meadow, and wetland, exhibiting excellent environmental adaptability and autonomous mobility. Key technologies like localization, mapping, and terrain classification

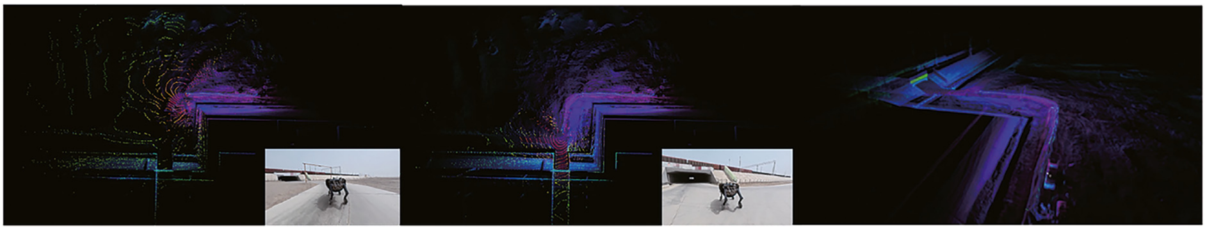

Fig. 7. 3D map of a plateau scene generated by the robot's autonomous perception system.

Fig. 8. Collected dataset of typical plateau terrains.

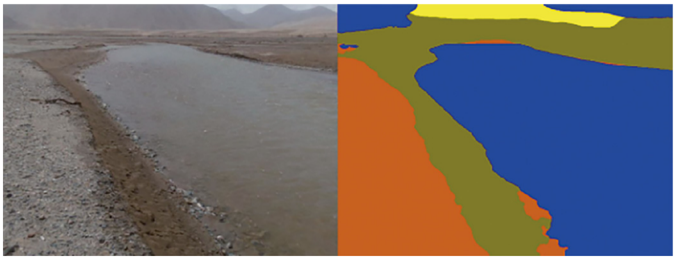

Fig. 9. Terrain classification results based on the plateau dataset.

were also successfully validated under plateau conditions, enhancing the robot's decision-making capability in sensor-limited, communication-deprived scenarios.

This real-world plateau validation lays a solid foundation for long-term field deployment of wheeled-legged robots. Looking ahead to applications in regions like the Qinghai-Tibet Plateau, these robots show great potential for unmanned inspection, disaster rescue, logistics transport in extreme environments, and ecological monitoring. Future research will focus on energy efficiency in high-altitude conditions, multi-robot coordination, intelligent planning, and robust perception, advancing the reliable deployment of wheeled-legged robots in more extreme natural scenarios.

CRediT authorship contribution statement

Kang Wang: Conceptualization. **Jinmian Hou:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology. **Shichao Zhou:** Writing – original draft, Methodology. **Dachuang Wei:** Writing – original draft. **Wei Xu:** Project administration. **Yulin Wang:** Project administration. **Hui Chai:** Project administration. **Lingkun Chen:** Project administration. **Qiuguo Zhu:** Project administration. **Liang Gao:** Project administration. **Min Guo:** Conceptualization. **Guoteng Zhang:** Conceptualization. **Zhongqu Xie:** Conceptualization. **Tuo Liu:** Conceptualization. **Mingyue Zhu:** Writing – original draft. **Yueming Wang:** Conceptualization. **Tong Yan:** Conceptualization. **Jingsong Gao:** Writing – original draft. **Meng Hong:** Writing – original draft. **Weikai Ding:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.birob.2025.100256.

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