SCIENCE ROBOTICS | FOCUS

NAVIGATION

Legged robots beyond bioinspiration

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Advances in engineering enable wheeled-legged hybrid locomotion, an achievement not feasible in biological systems.

Since its nascency, legged robot locomotion has drawn inspiration from biology. Accordingly, researchers have often learned from observations of animals to create artificial counterparts. The first-legged robots were passive walkers, one-legged hoppers, and insect-like creatures. After more than 30 years of research, we have reached a point where we see dynamic-legged robots being deployed in real-world scenarios, such as maintenance and inspection with SPOT (Boston Dynamics), mountain hikes with ANYmal (ANYbotics) (*1*), humanoids such as Digit (Agility Robotics) working in warehouses, and even robots such as Cassie (Agility Robotics) running 100 m (*2*).

However, along this 30-year journey, we have seen two branches of legged robots' development emerge. On the one hand, there have been advances made in engineering, and on the other hand, studies in biomimetics have delved deeper into aspects of locomotion and neuroscience of biological systems. In engineering, we have seen major developments coming from new materials and actuators. This branch has also exploited major advances in computer science. The advantages presented by better computing power and new discoveries in machine learning have enabled the use of artificial intelligence (AI) in truly dynamic-legged robots. In biomimetics, researchers have been influenced by nature and aim to exploit embodiment, creating more intelligent machines using fewer computational resources (*3*).

In their recent paper, Lee *et al.* (*4*) took an engineering pathway by augmenting the capabilities of the legged robot platform ANYmal with the addition of wheels. In nature, wheels are not inherently present on any animals, yet in the technological world, such a combination is possible. Adding wheels makes the robot more versatile, merging the benefits of two worlds: low-cost transport when rolling on wheels on flat surfaces and the ability to walk or even climb obstacles when the terrain becomes rough.

To achieve the wheeled-legged platform capable of navigating long distances in diverse settings, there was a need to augment the existing legged platform. The wheels were attached to the dynamic-legged robot (Fig. 1A). The control of the wheeled-legged platform relied on an AI-driven approach (Fig. 1B), which required a rich dataset for training purposes containing the robot's state information and scans of the robot's surroundings. Hence, the authors used a high-fidelity simulator of the robot to gather the data (Fig. 1C), followed by extensive parallel computation to evolve AI models. These models ensured that the robot was robust to disturbances and versatile enough to be tested on two long courses, covering more than 10 km of distance in total, in two different European cities: Zurich, Switzerland and Seville, Spain. Last, an advanced perception stack including global localization, light detection and ranging system (LIDAR), and stereo cameras was added so that the robot could navigate in the environment (Fig. 1A).

Machine learning was essential to achieving the wheeled-legged platform. The authors used model-free reinforcement techniques supported by privileged learning to obtain a controller that made smooth transitions between driving and walking. This was followed by hierarchical learning, which taught the robot to perform high-level tasks like navigation. In the privileged learning framework (*5*), the agent, here a wheeled-legged robot, has access to more sources of information about its surrounding world during the learning phase and a limited number of sensing modalities during the deployment phase. The difference between these two sets constitutes the privileged information, hence the name of the method. In the spirit of hierarchical learning, mobility-aware navigation was coupled with the locomotion controller.

Inspired by Jain *et al.* (*6*), the authors used a two-level hierarchy in which the low-level controller was supervised by goals that were learned and provided by the high-level controller. By developing low-level controllers independently, the interpretability of the robot's behaviors was enhanced, which allowed the learned controllers to be reused for different high-level applications. In this case, the application was waypoint tracking on the robot's path in a city-scale experiment.

To test the navigation controller, the robot navigated on two urban courses covering around 10 km with minimal human intervention. It successfully crossed obstacles like stairs, narrow spaces, and dynamically changing environments while also safely avoiding pedestrians.

The split between engineering and biomimetics in legged robotics research is elegantly framed in Rubenson and Sawicki (*7*). The authors see engineers adopting new technologies as they become available, whereas biological systems are stuck with the imperfectness of their embodiment, which is "good enough" from the perspective of natural selection. Evolution searches for hacks to overcome the constraints of morphology instead of engineering new structures.

The engineering approach has shown that it is possible to create versatile and robust robotic systems like wheeled-legged hybrid locomotion (*4*), but by looking at biology, we can understand how intelligence relates to the physical body. The future involves bringing these two approaches together, as evidenced by merging reinforcement learning (RL) with central pattern generators (CPGs) to develop more robust and easily learned policies (*8*) or by integrating spines with legs and wheels (*9*). However, the missing piece is in achieving versatility comparable to living creatures capable of seamlessly navigating a variety of different terrains. Such initial approaches have been observed in Baines *et al.* (*10*), where the legged robot can transition from ground locomotion to swimming. We

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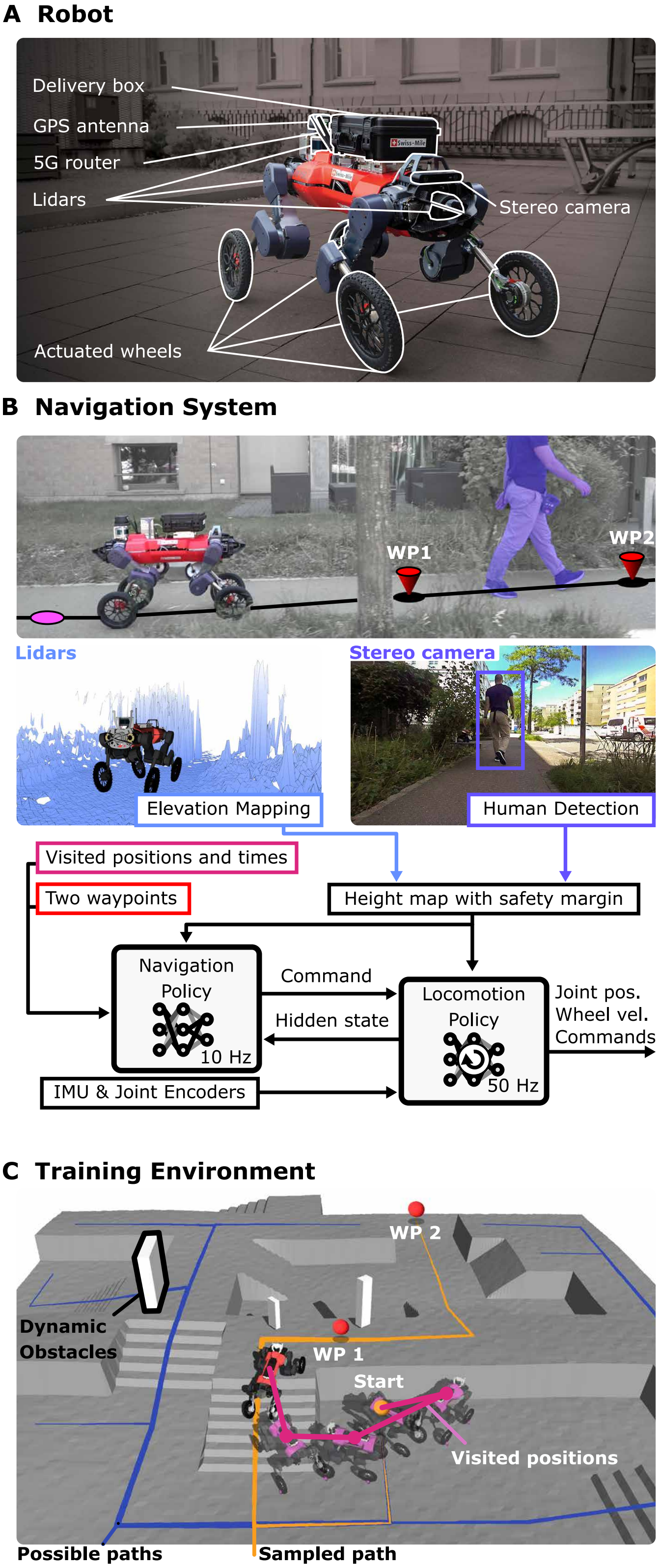

Fig. 1. System overview. (**A**) A wheeled-legged quadrupedal robot with advanced perception stack, (**B**) an overview of the navigation system, and (**C**) the virtual training environment.

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expect more research breakthroughs where emerging technology in engineering intertwines with embodied intelligence in animal locomotion. Current work on wheel-legged platforms has gone beyond bioinspiration but simultaneously opens new questions on how inspiration from animals can further improve human-made systems.

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