Development and Control of a Quadruped Robot With Capstan Drives and Reinforcement Learning

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Hundreds of U.S. workers are killed annually performing inspections in confined spaces, industrial facilities, and critical infrastructure, with thousands more suffering severe injuries (Bureau of Labor Statistics, 2020). Legged robots can traverse these environments in place of humans, yet current quadrupeds cost tens of thousands of dollars, limiting deployment to well-funded organizations. We present a 12-degree-of-freedom, 15 kg quadruped powered by capstan actuators fabricated through 3D printing or plastic molding at roughly $50 per actuator, motor included. Capstan drives provide efficient, low-backlash transmission but introduce mechanical imprecisions that make conventional model-based control unreliable. To address this challenge, we trained a locomotion policy via proximal policy optimization in NVIDIA Isaac Sim, applying extensive domain randomization to ensure robustness to hardware variability. Training completed in 14 hours on a single consumer GPU. The learned policy transfers successfully to both MuJoCo and Gazebo simulators as well as to the physical robot, reaching a peak velocity of 2.0 m/s and maintaining stable control up to 1.6 m/s with a velocity tracking error of 5.6% in MuJoCo. With off-the-shelf motors and drivers, the complete robot can be mass-produced for under $2,000, compared to approximately $75,000 for Boston Dynamics' Spot. This work constitutes the first demonstration of sim-to-real reinforcement learning on a capstan-driven quadruped, establishing that learning-based control can overcome low-cost actuator imprecisions and enable wider deployment of capable legged robots for hazardous environment inspection.

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