Benefits of an Actuated Spine in Agile Quadruped Locomotion

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***Abstract*— The spine plays a crucial role in the dynamic locomotion of quadrupedal animals, improving the stability, speed, and efficiency of their gait, especially for fast-paced and highly agile movements [1], [2]. Therefore, the spine is also a promising and natural way to extend the capabilities of quadruped robots [3], [4], [5], [6]. This paper investigates the benefits of an actuated spine for learning agile quadruped locomotion in high-speed running and climbing scenarios with the Silver Badger robot from MAB Robotics with a 1-DOF spine in the sagittal plane.**

The evaluation of agile locomotion needs effective metrics for locomotion speed and energy efficiency allowing for a fair comparison between robots of different types and sizes. The Froude number [7] measures the size-independent locomotion speed, and the cost of transport [8] quantifies the energy efficiency of the locomotion. The two dimensionless metrics are defined as follows:

$$\mathrm{Fr} = \frac{v^2}{gh}, \quad \mathrm{COT} = \frac{P}{mgv}$$

where v is the forward velocity, g is the gravitational acceleration, h is the height of the hips, P is the used power and m is the mass.

To empirically test the advantages of the actuated spine, we conducted a set of experiments in the MuJoCo simulator [9] with PPO [10], a Reinforcement Learning (RL) algorithm. All experiments use domain randomization and observation noise to ensure transferability to the real robot.

To investigate the robot's energy efficiency and maximum running velocity, we designed an automatic learning curriculum that gradually increases the target velocity. Fig. 2 shows that, with a locked spine, the robot achieves a maximum of 5.0 m/s forward velocity at the end of training. Enabling the spine during learning improves the maximum velocity to 5.9 m/s. This increase in velocity is also reflected in the Froude number and an improvement in stability can be seen in the average episode length. The active spine achieves a $\mathrm{Fr} \approx 9.7$ while the locked spine only reaches a $\mathrm{Fr} \approx 6.7$ with a 3% shorter episode length. Visual inspection shows that the RL policy learns to contract the body with the spine to pull the legs forward and prepare the next step, which leads to a more natural-looking, faster, and stable gait. When utilizing the motor of the spine joint, the energy consumption increases by 6.2% (81 Wh) at the maximum running velocity, but through the higher increase in top speed, this leads to a more energy-efficient gait at the end with a $\mathrm{COT} \approx 2.1$ compared to the locked spine with a $\mathrm{COT} \approx 2.3$.

Besides fast running, another task that requires a high level of agility is climbing. To identify the climbing capabilities of the Silver Badger, we created an inverted pyramid environment with evenly-spaced stairs (Fig. 1). Again, an automatic curriculum guides the learning process by increasing the height of the stairs every time the robot successfully climbs seven consecutive stairs. At the end of training, the maximum stair height the robot can climb is 0.7 m, which is 2.2x its standing height. On average, the version with the active spine can climb 4 cm higher while consuming the same amount of energy as the robot with the locked spine.

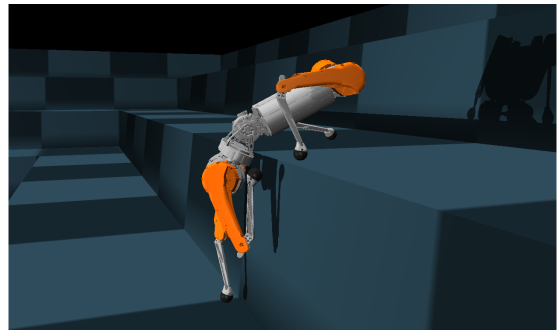

Fig. 1. Inverted pyramid stairs for the climbing experiments in simulation. The robot actively uses its spine to bend the front part of the trunk over the stairs and get leverage for the rest of its body.

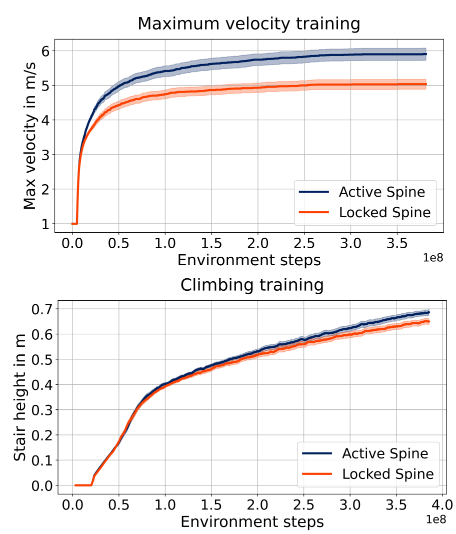

Fig. 2. Achieved maximum forward velocity (top) and maximum stair height (bottom) during the two learning curricula. The thick line and shaded area show the mean and the standard error respectively over 20 seeds.

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