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MOBILITY OF LEGGED ROBOT LOCOMOTION WITH ELASTICALLY-SUSPENDED LOADS OVER ROUGH TERRAIN*

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Elastically-suspended loads can reduce the energetic cost of legged robot locomotion over flat ground. In this paper, we studied the effect of elastically-suspended loads on the mobility of legged robot locomotion over rough terrain. The power input and speed of a simple hexapod robot running over rough terrain with an elastically-suspended load and a rigidly-attached load was compared. On average, the robot ran 16% faster and consumed 8.9% less power while carrying an elastically-suspended load versus a rigidly-attached load over rough terrain. Therefore, the experiments suggest that elastically-suspended loads may increase the mobility of legged robot locomotion over rough terrain.

1. Introduction

Legged locomotion offers superior mobility characteristics over wheeled or tracked vehicles for locomotion in unstructured environment [1]. The RHex robot is one of the premier legged robot platforms for locomotion over rough terrain [2-4]. The tuned spring-legs of the RHex coupled with the robust alternating tripod gait inspired by the cockroach enable the RHex robot to efficiently traverse rough terrain [5-8]. Besides the use of spring-legs, the principle of elasticity is not utilized elsewhere in the robot design. The inherent mass of the batteries and electronics that power the RHex robot represent a significant proportion of the total mass and are usually rigidly-attached to the robot chassis. In prior work, the authors have shown that elastically-suspending such inherent mass from the main robot chassis with a passive compliant suspension system can significantly increase the energy efficiency of legged robot locomotion by decoupling the vertical motion of the load from that of the main robot chassis [9, 10]. However, these experiments were conducted over flat ground; actual legged robots, like the RHex, need to be able to operate in

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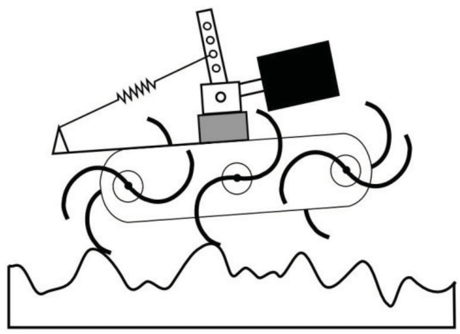
challenging environments. Therefore, the authors set out to test the effect of elastically-suspended loads on the mobility of legged robot locomotion over rough terrain. In this paper, we define mobility as the capability of the robot to traverse over rough terrain quickly and efficiently.

2. Robot Platform

A simple hexapod robot based on the RHex was modified to elastically-suspend a battery load from the main robot chassis (Figure 1). The robot used a single DC motor and an all-mechanical power transmission system to rotate two pairs of three spring-legs in an alternating tripod configuration. The suspension system used to elastically-suspended the load was inspired by the Christie suspension system [9]. It utilizes a bell crank mechanism to convert the vertical motion of the load to a largely horizontal motion of the suspension spring. The load was attached to one arm of the bell crank and a compliant linear extension spring was attached to the other arm. This compliant suspension system elastically decouples the vertical motion of the load from the vertical motion the main robot chassis. Fixing the bell crank to the main robot chassis with a bolt enables the robot to switch to a rigidly-attached load.



Robot Mass	275 g
Load Mass	125 g
Robot Dimensions	15.2 cm long 7.6 cm wide
Effective Leg Stiffness	6000 N/m
Effective Load Suspension Stiffness	37 N/m

Figure 1: The simple hexapod robot with an elastically-suspended load.

3. Experimental Methods

3.1. *Rough Terrain*

Rough terrain was simulated by randomly distributing and fixing about 150 foam pieces on a plastic track that measured 142 cm long by 47 cm wide (Figure 2). Each foam piece was about 3cm wide by 6 cm long by 1.67 cm high. Since the highest clearance of the robot was about 1.5 cm, these pieces were chosen to represent significant obstacles for the robot to surmount. The foam pieces were cut from a large foam block and each piece was quite stiff so no significant deformation occurred while the robot ran over the track.

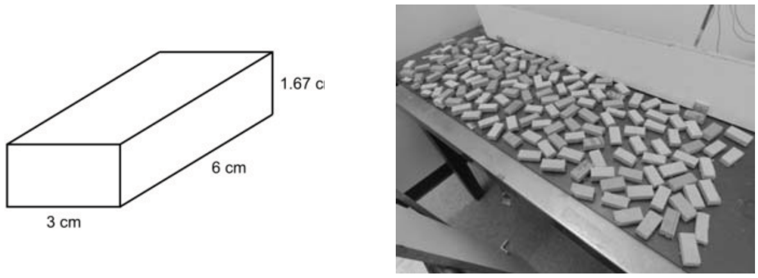


Figure 2: The rough terrain block dimensions (left) and track setup (right).

3.2. *Experimental Setup*

The power and speed of the robot with a rigidly-attached load versus an elastically-suspended load was measured to compare the relative mobility of the robot in each configuration. To determine power, the voltage across the motor terminals of the robot was measured with an ADC and the current flowing through the motor was measured with a hall-effect sensor. An analog low pass filter was used to reduce measurement noise and the robot was powered by a regulated power supply at a constant voltage during each trial. The data was sampled at 1 kHz using a USB4 DAQ. The first 0.75 seconds of data were ignored to remove the initial power spike from the comparison. The robot was started from the same point and the legs were checked for the proper alternating-tripod configuration before every trial. To measure the speed of the robot in each configuration, a laser tripwire at the end of the track was used to stop the data collection, yielding the time the robot took the traverse the known track distance. High-speed video was also taken at 240 fps to qualitatively observe the dynamics of the system in each configuration.

We also sought to determine the effect of the rough terrain height on the mobility of the robot over rough terrain. The average power and speed of the robot was measured while running it for 10 trials over a short track with flat ground and varying obstacle heights. Multiple thin books were stacked on top of each other to simulate increasing rough terrain height (Figure 3). Although the track length was shorter, the power and speed of the robot was measured using the same method discussed previously.

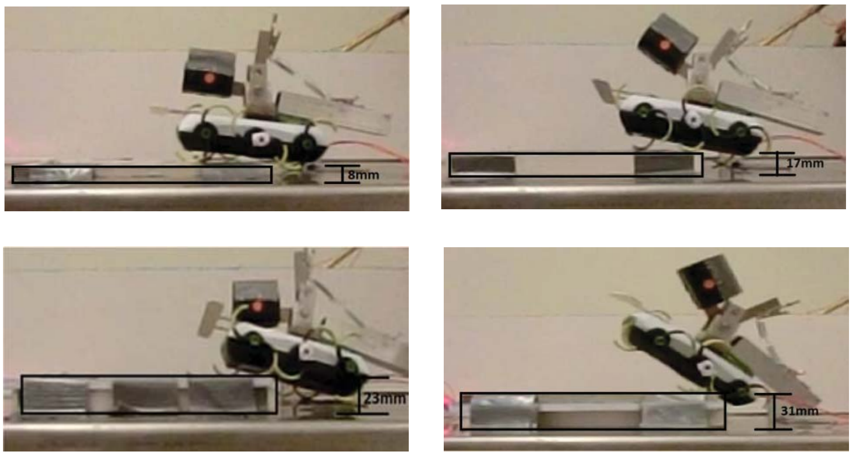


Figure 3: The speed and power of the robot was measured while running over flat ground (not shown), an 8 mm tall obstacle (top left), a 17 mm tall obstacle (top right), a 23 mm tall obstacle (bottom left), and a 31 mm tall obstacle (bottom right) to determine the effect of terrain height on the robot's mobility. The 31 mm tall obstacle proved to be too tall for the robot to reliably surmount.

4. Results and Discussion

Twenty trials were conducted for the robot traveling over the rough terrain with a rigidly-attached load and with an elastically-suspended load. On average, the robot with an elastically-suspended load traversed the rough terrain 16% faster while consuming 8.9% less power than with a rigidly-attached load (Figure 4). Furthermore, the robot with a rigidly-attached load failed to travel

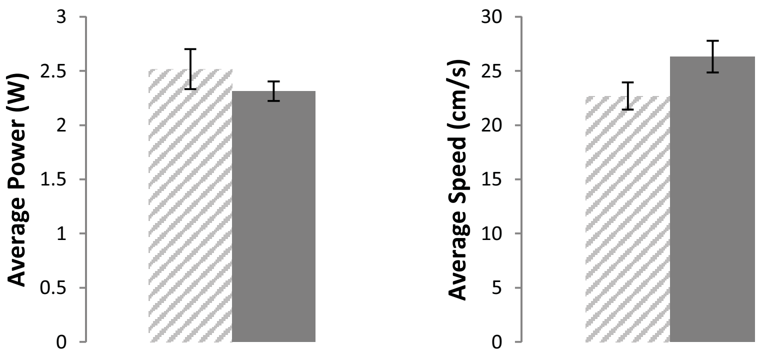


Figure 4: The average power and average speed for the robot with a rigidly-attached load (hatched) and an elastically-suspended load (shaded). The error bars show the standard deviation over 20 trails (not including the failed trails where the robot got stuck or hit the wall).

the entire track length four times because it got stuck twice and hit the right wall twice. The robot with an elastically-suspended load only failed once by getting stuck. The randomness of the rough terrain resulted in a relatively high standard deviation, but the overall trend is clear. The data shows that the robot was able to traverse the rough terrain noticeably faster with slightly less power consumption while carrying an elastically-suspended load versus a rigidly-attached load. Therefore, these experiments indicate that elastically-suspended loads could improve the mobility of legged robots traversing rough terrain.

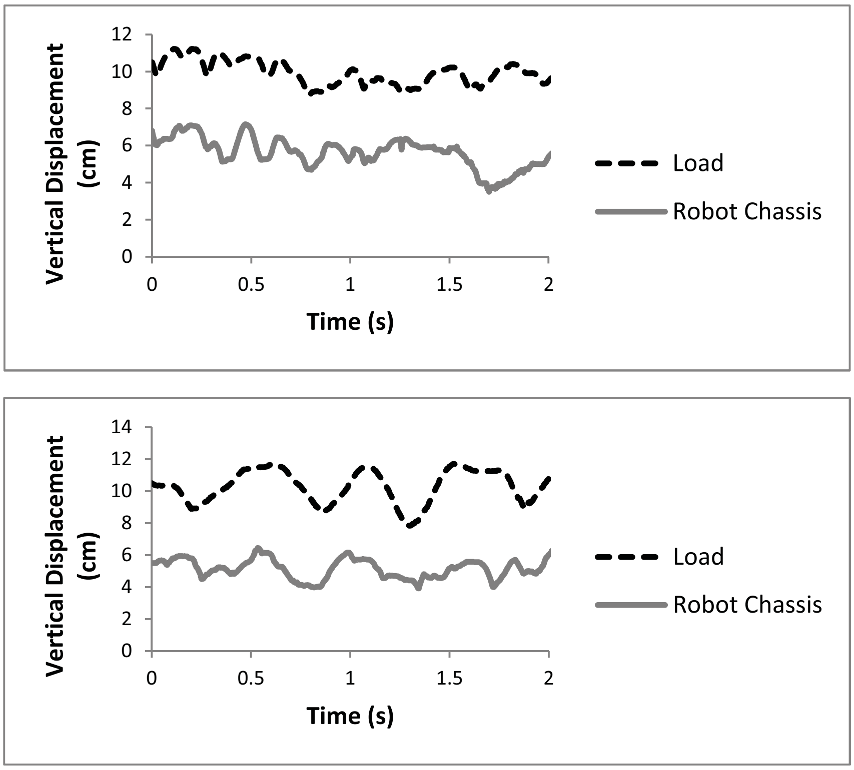


Figure 5: Data from high-speed video recorded at 240 fps showing the behavior of the robot running over rough terrain with a rigidly-attached load (top) and an elastically-suspended load (bottom). The point tracking was performed using the open source software Tracker Video.

High-speed video from the experiments showed that elastically suspending a load decouples the vertical motion of the load mass from the motion of the main robot chassis (Figure 5). The decoupling of these motions may enable the robot to resist the high-frequency perturbations that result from running over the rough terrain, enabling it to traverse the rough terrain more quickly and efficiently. The authors hypothesize that the complaint suspension essentially acts as a low-pass filter. High-frequency perturbations do not affect the legged robot system with a compliant load suspension as much as when the robot is carrying a rigidly-attached load. The robot is essentially lifting less effective mass while it traverses over the rough terrain due to the compliant load suspension. The motion of the elastically-suspended load mass also seems influence the motion of the main robot chassis, possibly enabling the robot to surmount rough terrain perturbations more effectively.

During the experimental trials, the robot traversed rough terrain with many perturbations due to the randomly dispersed blocks that were approximately 1.67 cm high on average. To better understand the effect of such rough terrain on the mobility of the robot, we tested the effect of a single perturbation of varying heights on the average power and speed of the robot.

The data shows that regardless of whether the robot was traveling over flat ground or a 2.3 cm high perturbation, the robot ran on average approximately 5.7% faster while consuming approximately 3.3% less power with an elastically-suspended load versus a rigidly-attached load (Figure). The robot was also tested while running over a 3.1 cm perturbation, but it was unable to get over this obstacle consistently because of the orientation of the suspended load mechanism (Figure 3).

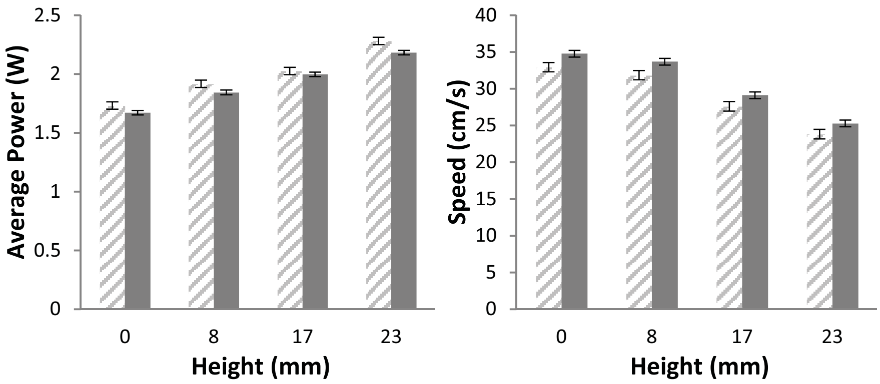


Figure 6: The regardless of the rough terrain height, the robot ran over the short track approximately 5.7% faster while consuming approximately 3.3% less power on average with an elastically-suspended load versus a rigidly-attached load. The error bars show the standard deviation over 10 trials.

The robot was able to travel over rough terrain with numerous randomly distributed perturbations 16% faster with 8.9% less power consumption while carrying an elastically-suspended load versus a rigidly-attached load, but was only able to travel 5.7% faster with 3.3% less power consumption while running over a single perturbation of the same height as the average height of the rough terrain. Since the robot was only run over a single perturbation in the latter experiments, the differences between the mobility of the robot with an elastically-suspended load versus a rigidly-attached load were not as pronounced. The data shows that the numerous perturbations of the rough terrain increase the difference between the mobility of the robot with a rigidly-attached load and an elastically-suspended load. Over a longer stretch of rough terrain, these differences may be further magnified. It is still unclear what effect height has on the mobility of legged robot locomotion over a long stretch of rough terrain. We plan to investigate the effect of terrain height and frequency on mobility in the future.

5. Conclusion

The mobility of legged robot locomotion over rough terrain could be increased by elastically-suspending part of the inherent mass of a legged robot with a compliant suspension system and decoupling the vertical motion of the load from the vertical motion of the robot chassis. This has numerous potential applications for legged robots because batteries, electronics, fuel, vision systems, or sensitive components could be elastically-suspended from the robot body to increase the mobility of legged robot locomotion over rough terrain.

Acknowledgments

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