# Reactive velocity control increases energy efficiency of jumping on granular media

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## I. Background

We can improve the size and quality of data sets for research on desertification by automating data collection in remote locations [1]. One leg of the direct-drive Ghost Minitaur robot can be used to measure the shear forces required to scrape the surface of the soil, a proxy for erodibility. However, Minitaur is challenged by locomotion in the desert. Increasing the foot size significantly or adding a gearbox would reduce the robot's utility as a self-transporting sensor, so we sought other methods to improve its locomotion on sand.

Minitaur locomotes using a composition of reactive controllers [2]. To reduce the energetic cost of jumping, we developed a controller which can be composed with a vertical jumping controller [3]. In the well studied compression-extension controller [4], a virtual leg spring uses a soft gain during the first half of stance while the leg compresses. When the leg starts to extend, the virtual spring switches to a stiff gain, injecting potential energy and causing the robot to jump.

Granular media is highly dissipative: If we think of sand as a nonlinear spring with no restoring forces, the "damping" function is quadratic [5]. Observing that energy is dissipated very quickly to the ground when foot velocity is high, we add damping to the leg's virtual spring in proportion to the intrusion velocity of the foot. We call this the *active damping* controller [3], [6]. We conducted experiments with the nominal compression-extension controller by itself and composed with the active damping controller.

## II. Methods

We used a one-degree-of-freedom direct-drive hopper constrained to a linear rail representing one quarter of a Minitaur robot. In addition to linearizing the motion of the center of mass, the foot's motion was linearized by a vertical rod which passed through a linear bearing in the robot's chassis. The robot jumped in a 0.3 m x 0.3 m clear acrylic box with high walls containing 3.4mm glass beads to a depth of 0.165 m. The compaction of this media, which determines the forces it exerts, was limited to 0.61-0.63 (confirmed experimentally). The beads were stirred and smoothed between each jump.

Energy measurements were obtained by jumping the robot 25 times, recharging the battery, and recording the reported mAh. A string potentiometer measured the distance between the top of the robot's body and the top of the linear rail, and logged this data for all 25 jumps in a each experiment. Data collection is ongoing, but we report on 9 experiments with the compression-extension controller and 5 with the active damping controller.

## III. Results

The compression-extension controller used significantly more energy per jump than the active damping controller (108.93 joules vs 95.22 joules, $p < 0.02$). The active damping controller also jumped slightly higher on average (0.487 m vs 0.493 m, $p < 0.0001$).

## IV. Conclusions

Reducing the cost of locomotion on dissipative substrates such as desert sand could significantly increase the operating time of remotely operating robots. However, there are limitations to the conclusions that can be drawn from these results. Shear forces can significantly reduce the forces exerted by the ground, and it is currently unknown how the damping function of the ground changes in the presence of shear stresses.

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