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Mechanical and virtual compliance for robot locomotion in a compliant world

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Abstract

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Mechanical and virtual compliance for robot locomotion in a compliant world

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I. INTRODUCTION

With improvements in additive manufacturing, programmable materials, and meta-materials that exhibit complex behaviors, the choice of where to place the line between control implemented in the robot's morphology and in its programming is becoming more and more available to the designer. We suggest that a useful way to place this line is by considering the aspects of control for which the designer needs more *plasticity* of behavior in terms of sensory capability or responsiveness to changing environments, or more *robustness* of behavior in terms of sensitivity to perturbations, sensor noise, and energy efficiency. The example of compliance in robot locomotion over complex, yielding terrain highlights the trade-off between robustness and plasticity.

A. Locomotion in a compliant world

We take our robots to natural deserts, complex environments with compliant substrates that exhibit unpredictable behavior. Dry, relatively homogeneous granular media with known parameters like grain density and friction exerts forces in response to intrusion that are well characterized by bulk-behavior models [1], [2]. Of course, a natural desert environment will contain significant variation in packing density, grain size, and moisture content, even within the length of a single robot (or human) stride [3], [4]. Bulk-behavior models cannot therefore be relied upon to provide accurate predictions of the behavior of natural desert sand in response to intrusion.

It is intuitive to increase the forces applied to the ground in order to either offset the energy lost to this highly dissipative substrate, or to achieve a stronger reaction force from the ground. However, competent interaction with ground of this type, whether "competence" means control over height, use of minimal effort, or some other metric, cannot be accomplished this way. Exerting more force simply further excites the granular media, losing more energy without necessarily resulting in a higher jump [2], [5], [6].

B. Locomotion using compliance

Fig. 1. RHex [7] (left) and Minitaur [8] at Oceano Dunes and White Sands.

One method of programming locomotion is to use the Spring-Loaded Inverted Pendulum (SLIP) model [9]. RHex [7] and Minitaur [8] (Fig. 1) both run using SLIP-like dynamics, but the compliance in RHex is implemented mechanically in its springy C-shaped legs, and the compliance in Minitaur is implemented in software using proportional-derivative (PD) control on the two opposing motors in each leg.

1) Mechanical compliance: RHex exhibits SLIP-like dynamics when it runs by loading potential energy into its legs during the first half of stance, and releasing this potential energy to propel itself forward during the second half of stance [10]. The mechanical springs in the C-legs implement a PD controller on the leg extension by virtue of the spring force exerted by the legs in response to displacement. This controller takes trivial time and power to compute the restoring force and does not rely on any sensors other than the motors' encoders. Furthermore, until the legs reach mechanical failure, they store and release energy at no cost from the robot's power supply.

2) Virtual compliance: Each of Minitaur's four legs emulates a linear spring using PD control on two opposing direct-drive (no gearbox) motors through a four-bar linkage [8]. Exerting this emulated spring force costs energy from the robot's power supply. However, perturbations of the leg's position and velocity are "visible" to the robot, meaning that it can respond to this information as a sensory input.

C. Robustness and plasticity

We contrast the locomotion capability (*robustness* of behavior) to the sensory capability and adaptability (*plasticity*) conferred by mechanical and virtual compliance in our robots.

1) Sensing capability: A single direct-drive Minitaur leg has recently been developed as mechanical shear stress sensor that can be used to study erosion processes [11]. Because the compliance in the Minitaur robot's legs comes entirely from software, it is able to sense perturbations at its toe –

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information that is not available to the RHex robot, which has mechanical compliance that hides information about its interactions with its environment from its motors.

2) Locomotion capability: In general, predictable morphological adaptations like wider feet that reduce the foot pressure of the locomotor [12] provide advantage in natural desert environments. A RHex with legs twice as wide as the standard 2.6 cm walked faster than a RHex with standard-issue legs while following the same path over 430 meters in the Tengger desert, and had a lower specific resistance [4]. The robot with wider legs also turned further in a single maneuver [4]. Both of these improvements to performance may be explained by the reduction in foot pressure causing an increase in "effective" leg length, that is, the length of the leg that does not intrude into the sand and over which the leg is able to pivot [13]. The mechanical implementation of RHex's compliance enabled us to further improve RHex's locomotion in desert environments by increasing the gear ratio nearly three times, from 28:1 to 79:1, without altering the compliance of its legs [11].

When tested in White Sands, Minitaur overheated quickly and was not able to transport itself for more than a few minutes without needing to cool down. The interventions used for RHex would severely limit Minitaur's utility for desert research: Increasing the foot mass by too much or gearing down the robot both reduce the sensing capability of the robot.

3) Adaptability: The natural environment is inherently unpredictable. While in general wider legs improved RHex's performance in natural deserts, there are specific situations in which this seeming adaptation is not advantageous. On a 30-degree dune that had recently experienced rainfall at the Tengger, we were unable to climb a dune with the wide-legged robot, which could not find purchase on the dry sand near the surface of the dune. The robot using standard-issue legs penetrated past the soft, dry sand and was able to ascend the dune by walking on the damp, cohesive sand underneath the surface [4]. The mechanical compliance in RHex's legs produces *robust* behavior that is consistent in execution and requires no sensory input or extra power, but the robot is unable to adapt to unpredictable situations: it is not *plastic*.

In contrast, a Minitaur leg, which has programmable compliance, can reactively change its compliance properties. By considering the compliant robot leg interacting with a compliant, highly dissipative ground as a two-spring system in which the ground's "spring" has no restoring motion, we are able to mitigate the transfer of energy from the robot's leg to the sand, and thus the transfer of energy from the robot's battery to the ground. Since the compliance of the leg is created in software it can be changed to adapt to the changing environment. By adding a virtual damper and "dissipating" energy into the robot's leg "spring" in proportion to the intrusion velocity of the robot's foot into the sand, we were able to reduce the mechanical energy required to jump to a fixed height by 50% and the losses to Joule heating in the motors by 20% in simulation [6] and emulation [5] with a single, vertically hopping direct-drive leg.

II. CONCLUSION

Where do we put the line between mechanical and virtual implementations of compliance? Compliance created through PD control comes at a cost from the robot's power supply, but it confers the advantages of sensory capability and adaptability. The robot is able to sense features of its environment through its motors that may be useful both for the human experimenters and for its own locomotion. It is also able to change aspects of its compliance in response to its environment. If it is not necessary to change behavior in response to a changing situation, a designer can implement many aspects of control in the morphology of the robot and benefit from the robustness to perturbations and noise and the energy efficiency that such morphological implementations provide for "free". In a compliant world with unpredictable bulk-behavior forces, the ability to sense perturbations and plastically change behavior in response may be more important.

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