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Fast state-switching of a jamming-based foot

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1 Introduction

The design of adaptive feet that mimic the complex interaction of bones, tissue and muscles of e.g. paw-pads of dogs remains a challenge in robotics. Half-spheres of various materials are often used as feet which allows the approximation of a single point contact to the ground [1]. This enables the usage of simplified models for control which is especially important for closed-loop control in uneven/rough terrain. Nevertheless, usually advanced control strategies are required.
We try to offload such complex computational control to the mechanical design of the foot. A previous work on our quadruped robot "Oncilla" [2] investigated key-properties such as friction and damping of a foot design based on jamming of compliant granules. This design is inspired by the "Universal Gripper" [3] and is characterized by small granules enclosed by a flexible membrane subject to vacuum pressure. The gripper can adjust its stiffness depending on the applied pressure level: while it is soft when under atmospheric pressure, it gradually hardens under a higher vacuum pressure. The results in [2] revealed that the soft state is beneficial for damping the impact forces at touchdown and enables passive shape adaptation of the foot to uneven terrain whereas a harder state is required to transmit locomotion/friction forces to the ground. Therefore, we seek a rapid switch from a soft to a hardened state right after touchdown to profit from both properties which has not yet been implemented in [2]. Our aim is to help to understand how legged animals could use a change in foot stiffness depending on the situation. We thus envision the application of such a system in mobile, untethered robots which often makes the use of a usual vacuum pump unpractical. To enable mobile jamming, we propose a mechanism that uses an air storage system and a magnetic solenoid for fast state-switching.

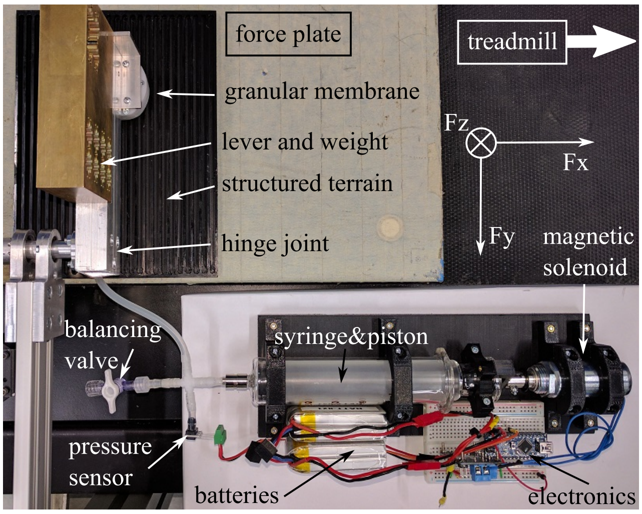

Figure 1: Complete setup (top view). A granular membrane is attached to a simplified leg (hinge joint and lever) and connected to an airtight glass syringe whose piston is fixed to the anchor of a magnetic solenoid. A treadmill moves a structured terrain, mounted on a force plate, at a constant speed. The membrane is dropped onto the ground, causing the pressure sensor to trigger the evacuation of the membrane upon ground contact. The solenoid and electronics are powered by two batteries. The manual balancing valve is used for a reset to atmospheric pressure.

2 Evacuation mechanism

For the design of the foot, the reader is referred to [2]. Here, only the setup of the performed experiments is shown in Fig. 1. The foot is formed by compliant cubic granules enclosed by a spherical latex membrane (diameter $\approx$ 2 cm). The membrane is connected to an air container (Fortuna Optima All Glass Syringe, 50 ml) whose volume can be changed, forming a closed air system with the membrane. Starting from atmospheric pressure where the granules are in their fluid state, enlarging the volume of the air container by pulling the piston lowers the vacuum pressure in the whole system, transitioning the foot into its hardened state. The piston of the glass syringe is attached to the anchor of a magnetic solenoid (ITS-LZ 2560, $\approx$ 15 W) which, when activated, pulls the piston to a fixed end position with a strong magnetic force. A microcontroller (Arduino Nano) activates the solenoid by measuring the pressure inside the membrane with a pressure sensor (Honeywell 030PAAA5). When overpressure is detected in the membrane caused by the touchdown of the foot, the solenoid immediately gets activated and the membrane evacuated. Two batteries in series (Conrad energy 7.4 V, 1200 mAh, 10 C) power the electronics. The foot - imagined on a real robot - acts in the following manner: In swing phase, the foot is in its soft state which enables damping of the impact at touchdown and passive shape adaptation to structured terrain. Upon touchdown, the foot immediately hardens, allowing the transmission of locomotive/friction forces. In swing phase, the foot then can be brought back to its soft state (not shown here).

3 Experiments

Preliminary experiments only show a proof of concept of the approach performed with one foot and aimed at addressing 2 main questions: (i) how fast is the evacuation and (ii) does state-switching alter the ground reaction forces?

Evacuation time: To measure the evacuation time, the position of the solenoid with respect to the syringe was chosen such that the enlargement of the volume (caused by pulling the piston) resulted in a pressure difference of -180 mbar versus atmospheric pressure (same as in [2]). The time to reach this pressure difference was recorded in 5 trials.

Ground reaction force: To investigate the ground reaction forces, a series of experiments with three different feet were performed: the previously used OptoForce sensors (OF), the proposed foot in atmospheric pressure (soft state) only (GMA) and the proposed foot with state-switching (GMSS). A structured ground (4 mm grooves perpendicular to the locomotion direction) is moved with a constant speed of 0.1 km/h (0.028 m/s) on a treadmill to simulate steady-state locomotion. A simplified leg (hinge joint and lever) drops an attached foot from a height of 2 cm perpendicular to the ground plane. The forces in z- and x-direction (see Fig. 1) are measured by a force plate at 10000 Hz starting at touchdown and onward until the foot transitions into a steady-state sliding motion. Additionally, the touchdowns are recorded with a high-speed camera at 960 fps.

4 Results and Discussion

Evacuation time: The solenoid achieves the pressure difference of -180 mbar versus atmospheric pressure in 62.2 $\pm$ 3.6 ms. As a comparison, for a walking trot gait at 1 Hz with a dutyfactor of 0.5, this would correspond to 12.4 % of the stance duration which was regarded as fast enough to perform the experiments on ground reaction forces.

Impact and friction force: Fig. 2 depicts the time evolution of the normal and drag force for one trial of each foot. The force profile of the normal force as well as the high-speed recording reveal that OF is bouncing off the ground several times before it is able to transmit drag force, which in steady-state sliding motion is comparable to the drag forces of GMA and GMSS. The steady-state normal force is approximately 8 N in all cases. Both GMA and GMSS barely show any rebound, leading to improved damping properties and almost immediate drag force transmissions. However, for GMA the stretching of the membrane is mainly causing a gradually increasing drag force. In contrast, GMSS immediately hardens after touchdown and therefore can transmit a higher drag force much faster. Additionally, GMSS also profits from the passive shape adaptation and thus hardens in a terrain-adapted shape. This in combination with the damping ability enables GMSS to apply a drag force approximately one order of magnitude higher than OF and GMA right after touchdown, actively using the structure of the terrain. Fig. 3 shows images extracted from the high-speed recording. On the left, OF is shown at approximately 80 ms after the first touchdown where it lost ground contact due to rebound. In the middle, GMSS is shown at the same time instance; it already almost fully damped the impact and switched into the hardened state, starting to transmit drag force. On the right, GMA is shown in steady-state sliding motion (after $\approx$ 1.5 s); stretching of the membrane results in a reduced immediate drag force.

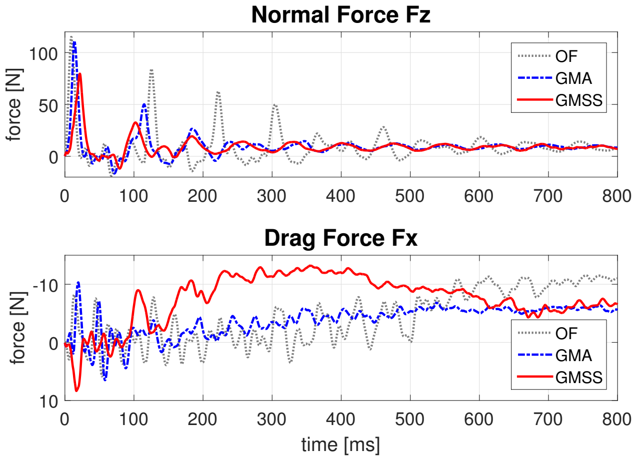

Figure 2: Normal and drag forces of the drop tests of the three tested feet. GMA and GMSS show similar damping properties while OF bounces off the ground several times, delaying the transmission of drag forces. GMSS is able to transmit higher drag forces than OF and GMA, specifically immediately after touchdown.

Figure 3: Snapshots from high-speed recordings. Left: OF at 80 ms after touchdown in rebound; Middle: GMSS at 80 ms in hardened state without rebound; Right: GMA at 1.5 s in steady-state sliding.

5 Conclusion and Future Work

In this work, we propose fast state-switching of a jamming-based foot by evacuating a membrane filled with compliant cubic granules. A pressure difference of -180 mbar for switching is achieved in just over 60 ms. Ground reaction forces, recorded for drop experiments onto a structured moving ground, indicate that this allows the foot to profit from the passive shape adaptation and damping of impact forces (soft) as well as enables an almost immediate transmission of drag forces after touchdown which additionally get augmented by the shape adaptation (hardened).

We plan to implement the system into one of our quadruped robots which requires a design revision and an investigation of the correlation between vacuum pressure and foot stiffness. Further, the unidirectional solenoid does not return the membrane to atmospheric pressure (a necessity to repeatedly use the damping and shape-adaptation properties) and state-switches the foot in a digital manner which does not allow an intermediate state between soft and hardened.

References

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