On the utility of active damping leg for safe landing from a free fall

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1 Introduction

Humans have a remarkable ability of surviving free-falls from large heights with minor or no injuries at all [1]. This capability can be enhanced through practice as demonstrated by practitioners of Parkour. We aim to develop a robot that has an equivalent, if not higher, levels of athleticism than humans. There have been many novel hardware designs that have successfully demonstrated a bipedal robot landing from heights under one meter. However, to the best of our knowledge, very few have tackled the problem of surviving high impact free-falls [2].

The impact from a free-fall can cause a legged robot to fail structurally (i.e. break a structural component) or mechanically (i.e. actuator overload). A comprehensive list of passive and active hardware and software approaches to deal with high impact landing is presented by Dallali et al [2]. In this study, we investigate the use of a variable damping shin to dissipate the kinetic energy accrued from the free fall, and control the leg after impact, to protect the hardware from damage. We aim to build a high-impact resistant 2D monoped robot (Fig. 1), model and control its landing maneuver.

2 Mechanical Hardware Design

The robot is a 2 degree-of-freedom monoped (Fig. 1) designed as a precursor to a highly dynamical biped capable of robustly surviving the impact of landing feet first from free-falls, and controlling the system energy to efficiently transition from landing to walking/running gaits. The leg is 1 meter long, with a mass of 8 kilograms, and is composed of a thigh and shin of equal length.

The monoped's design takes into consideration the designs principles used by agile bipeds and quadrupeds, like the MIT Cheetah[3]. Actuators is placed closer to the center-of-mass, thus decreasing the leg inertia. Actuators $A1$ and $A2$ are placed co-axially at the hip joint. $A1$ controls the hip joint with $\theta_h \in [90^\circ, 260^\circ]$ and $A2$ controls the knee joint through a four-bar linkage mechanism with $\theta_k \in [0^\circ, 90^\circ]$.

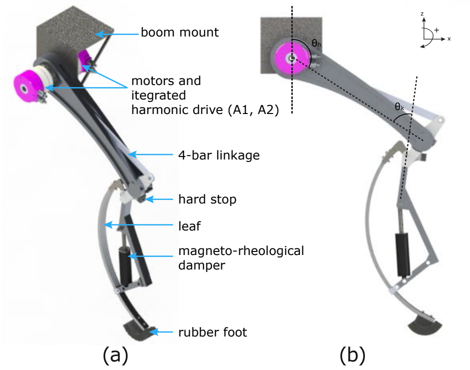

Figure 1: (a) Isometric view and (b) Side view of the leg design

The novelty of our monoped design is in the shin. Though other bipedal robots use a J-shaped carbon-fiber springs in their shin and feet [4], an active damping element was not used. The shin's design is highly based on the elastic stilts known as "power stilts" used for the act of powerbocking. The design has been modified to contain a long stroke Magneto-Rheological(MR) Damper(RD-8040-1 : developed by Lord Corporation) in parallel to the leaf spring. The damper has a stroke length of 7.5 cm and is capable of dissipating forces up to 2400 N.

In the next section, we simulate free fall on a simplified leg model to analyze and validate the impact of active damping in safe landing.

3 Analysis of Landing from Free Fall

This study aims to assess the impact of variable leg damping on the landing efficiency of a robot. Specifically, we highlight the advantages of active damping in the context of jump landing. To this end, a simplified leg model is chosen. The leg is approximated as a simple mass-spring-damper system, as depicted in Fig.2.

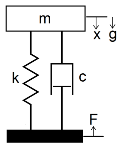

Figure 2: Schematic of the simplified leg model

The post-impact dynamics of the leg evolve according to (1). Here x denotes the displacement of the center-of-mass, while k and c denote spring and damping coefficients, respectively. F is the ground reaction force(GRF) and g is the acceleration due to gravity.

$$m\ddot{x} + c\dot{x} + kx = F - mg \tag{1}$$

For this analysis, two sets of simulations were carried out, with passive and active damping. Each set consists of four free fall simulations, where the robot is dropped from heights ranging between $2-8$ meters. For the passive case, we set stiffness and damping coefficients to 941 N/m and 173 Ns/m, respectively. They are chosen such that the damping ratio,ξ, is equal to 1. On the other hand, for the active damping case, the damping coefficient c was increased proportional to the drop height. The peak ground reaction forces and the maximum leg displacements post-impact for each free fall simulation are depicted in Fig.3

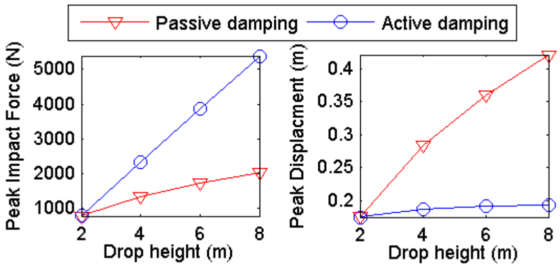

Figure 3: Comparison of active and passive damping scenarios post impact: Plots of peak impact forces and post-impact peak leg displacements for four free fall simulations.

Note that, with passive damping the peak leg displacement increases more steeply with increase in free fall height. For the 8m drop, it was 42 cm. However, in practice, springs and dampers typically have shorter stroke limits. This will cause the spring-damper system to saturate at some intermediate position, causing the robot to bounce.

However, with active damping, the peak leg displacement curve is much flatter, there is just a 1.8 cm variation across the simulate height range. For the 8m drop, the peak displacement was significantly lower only 19.4 cm. The only drawback of active damping is the increase in peak impact forces.

Motivated by these preliminary results, an augmented leg model with a passive spring and an active damper is conceived.

4 Augmented Leg with Active Damping Model

Active damping is achieved using Magneto-Rheological(MR) Dampers. They have received a lot of attention in the recent past. The damping behavior of the MR damper is highly nonlinear in nature. Several phenomenological models have been proposed to model their behavior. The Bouc-Wen model is relatively more popular and capable of exhibiting a wide variety of hysteretic behavior. In this model, the damper force F is given by,

$$F = c_0\dot{x} + k_0(x - x_0) + \alpha z \tag{2}$$

were, c_0 and k_0 are passive damping and stiffness coefficients of the MR Damper, respectively. Here, z, called the evolutionary variable, is obtained from,

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x} \tag{3}$$

The parameters α,β,γ and A are called shape parameters that are governed by the input current. By controlling z and the shape parameters, we achieve higher damping ratios.

For the purposes of this work, the model will be linearized and an equivalent damping coefficient c_{eff} would be determined such that $||F - F_l||_2^2$ is minimized. Here, F_l is defined as shown in (4)

$$F_l = c_{eff}\dot{x} \tag{4}$$

5 DISCUSSION

In this draft we propose a novel leg design with an actively damping shin. Preliminary results with a simplified leg model has shown promising improvement in post-impact leg compression due to active damping.

Our immediate focus is towards building the robotic leg proposed in section 2 and conducting drop tests. Moving forward, we intend to experimentally determine c_{eff} and build a suitable controller to experimentally realize landing maneuvers similar to those achieved in the simulation.

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