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Monopod hopping on compliant terrains[☆]

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HIGHLIGHTS

- Consideration of the effects of permanent ground deformation and compaction.
- Development of a controller immune to terrain compliance.
- No knowledge requirement of ground parameters.
- Successful tackle of foot slip effects and hard impacts during touchdown.
- The methodology can be extended to other legged robots such as quadrupeds.

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ABSTRACT

One of the most intriguing research challenges in legged locomotion is robot performance on compliant terrains. The foot-terrain interaction is usually tackled by disregarding some of the effects of ground deformation, like permanent deformation and compaction; however this approach restricts their application to stiff environments. In this work, the foot-terrain interaction is studied, and used in developing a controller immune to terrain compliance. An impact dynamics model is developed, employing a viscoplastic extension of viscoelastic impact models, and used to study the performance of a monopod robot. To include the effects of compliance, a model of the robot that incorporates the description of the foot-terrain interaction is presented. A novel monopod controller immune to ground energy dissipation is developed, which does not require knowledge of ground parameters. The controller adapts to terrain changes quickly, successfully tackles the effects of slip during touchdown, and copes with the problems, which arise during hard impacts, as the terrain becomes stiffer. Simulation results demonstrate the validity of the developed analysis.

1. Introduction

A central goal in the field of legged robotics is the development of machines able to traverse rough terrain, inaccessible to wheeled vehicles. However, such machines are subject to more complex control requirements. The problem is exacerbated when running on terrain with unknown properties. Earlier approaches required a known type of terrain, to be traversed with a statically stable gait, hence simplifying control and stability issues [1]. On the contrary, quadruped robots like Minitaur [2] and IIT's HyQ have recently shown satisfying dynamic response with specific locomotion behaviors, such as bounding or trotting, by imitating animal gait patterns, on flat [3] or irregular terrains [4]. Other works focused on bipeds running over stair-like terrain [5], while early studies on the RHex platform demonstrated running on rough terrains [6]. However, this robot uses open-loop control, thus forward speed is not controlled tightly. In contrast, the Boston Dynamics' BigDog is capable of performing a variety of locomotion scenarios, such as walking, trotting or bounding, over unknown terrains; however its motion is highly inefficient [7]. On the other hand, StarlETH uses a foot placement strategy with an appropriate distribution of virtual forces among the stance legs, so as to reach and maintain a specific stable gait by rejecting perturbations, such as unexpected obstacles [8]. A similar approach with footstep planning for overcoming significantly rough terrains was used in Boston Dynamics' LittleDog [9]; however, this robot is capable of static walking only.

Despite the emergence of recent works where the ground properties are explicitly considered in the study of hopping [10,11], running [12], walking [13] or tumbling [14], many notable studies

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disregard the importance of foot-terrain interaction. For example, for the two-link monopod, the contact point between the foot and the ground was modeled as a completely stiff revolute joint [15]. A similar assumption led to a controller for a monopod hopping robot, able to control both its speed and height over rough terrain, with a single actuator [16]. In fact, most efforts in the literature consider the terrain as non-deformable. For the MIT Cheetah 2, the authors determine a target ground force profile according to the desired duty cycle and stride duration [17]. Again, the terrain is considered stiff and completely flat. On the other hand, in [18], the case of a rough terrain is considered and a control algorithm for a monopod robot on rough terrain is proposed. However, the robot was considered to possess two actuators, at its prismatic and rotational joints, while the main body apex height, which is crucial when running on rough terrain, was not controlled. Our recent work involved the preliminary development of an energy-based controller for a monopod hopping robot running over compliant terrains using only one actuator [19]. This controller could compensate for ground compliance but neglected friction and phenomena related to hard impacts.

To incorporate the foot-terrain interaction that affects leg motion and energy dissipation, a realistic representation of this interaction is needed. Usually a simplified ground model is chosen, and controllers consider ground effects as disturbances. However, this approach fails in highly deformable environments. Facing compliant terrains as a terramechanics issue [20], a number of researchers make use of Bekker or similar models [21]. Yet, these approaches do not result in an adequate representation of foot-terrain dynamic interaction in all cases. For this reason, other approaches were proposed in works such as [22], where a viscoelastic model is used, or such as [23] where the authors coined the term *"terradynamics"*. The approach in [23] is applicable to the locomotion of the robots examined, but does not include the impact effects, prominent in fast dynamic walking.

In the case of fast dynamic walking, it is reasonable to consider the stance phase as an impact between the toe and the ground. In principle, such impacts can be modeled via three methods [24]: *the stereomechanical theory method, the Finite Element Method (FEM) and the compliant/viscoelastic approach*. The stereomechanical theory does not take into account the entire impact phase but considers it as a discontinuity, missing important impact information. On the other hand, FEM methods are computationally demanding and difficult to use online. The use of compliant (viscoelastic) models seems more appropriate, as different terrains can be described by lumped parameter models with suitable characteristics [25]. However, even in the case of viscoelastic models, permanent deformations are not modeled; for this reason, in other engineering areas, viscoplastic extensions of the viscoelastic models are proposed [26] (the reader is referred to Fig. 3 for a brief comparison between viscoelastic and viscoplastic models). Earlier work employing this approach demonstrated its potential by proving that a viscoplastic model represents more accurate the foot-terrain interaction [27]. Recent works also focus on modeling terrain compliance; however they do not cope with repetitive terrain compressions, while energy loss due to the terrain is neglected [28]. In another work, a similar approach is presented, however again the issue of repetitive loading is not modeled, although their experimental data shows the existence of this issue during stance [29].

In this paper, legged locomotion and control in the presence of foot-terrain interactions are studied. The adverse effects of terrain deformation during motion are illustrated. A viscoplastic model for impact dynamics is developed, which allows a realistic representation of the behavior of fast dynamic walking on compliant terrains. Using gait feedback, a new controller is developed, able to maintain desired apex height and speed with a single actuator. Preliminary results with an initial version of this controller were presented in [19] and extended in [30] for irregular terrains, in [31] for multi-legged robots and even for different gravities in [32]. Here a new version of this controller, capable of retaining the desired motion on terrains with permanent deformations is presented; issues concerning recompressions, friction and extremely stiff terrain are treated also. The importance of these phenomena in hybrid systems is highlighted in a more recent study [33], but no specific control action to cancel them is provided. Simulation results show that the developed controller, called x-MP-II, overcomes terrain variations under different motion scenarios, and achieves gait objectives, still using only one actuator at the robot hip.

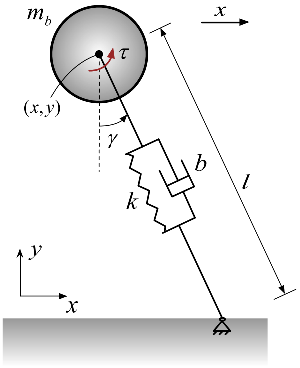

Fig. 1. Monopod simple model.

2. Background on monopod control

Simple Model (SM). A hopping monopod robot with a single actuator is considered. The robot is modeled as a body of mass m_b, with a springy leg, as shown in Fig. 1. The free length of the leg is L, the stiffness of the linear spring is k, and the torque applied by the single actuator is τ. The angle of the leg with respect to the vertical is γ and its instant length is l. The energy losses due to viscous friction in the leg prismatic degree of freedom (dof) are modeled by a damping coefficient b, while the leg mass is considered for this model to be negligible. During stance, and assuming a stiff ground with adequate friction (to avoid slip), the ground interaction can be modeled as a revolute joint. The system variables for both stance and flight phases are taken to be the coordinates of the main body x, y. The equations of motion for stance (s) are:

$$m_b\ddot{x} + k\,(L-l)\,s\gamma - b\dot{l}s\gamma = -\tau_s l^{-1} c\gamma \tag{1}$$

$$m_b\ddot{y} + m_b g - k\,(L-l)\,c\gamma + b\dot{l}c\gamma = -\tau_s l^{-1} s\gamma \tag{2}$$

where $s\gamma = \sin\gamma$, $c\gamma = \cos\gamma$, and τ_s is the stance actuator torque. During flight (f), the system is assumed to perform a ballistic trajectory, thus the equations of motion become

$$\ddot{x} = 0 \tag{3}$$

$$\ddot{y} = -g \tag{4}$$

During flight, the robot leg is servoed to a desired touchdown angle γ_{td} using a simple proportional derivative (PD) controller. As the robot reaches γ_{td}, its body must not have any residual angular velocity to reduce overshoot. To this end, the control torque applied by the actuator is set by,

$$\tau_f = k_p\,(\gamma_{td} - \gamma) + k_d\,(-\dot{\gamma}) \tag{5}$$

where k_p and k_d are controller gains.