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How local slopes stabilize passive bipedal locomotion?

Ali Tehrani Safa [a,*], Somaye Mohammadi [a], Seyed Ehsan Hajmiri [a], Mahyar Naraghi [a], Aria Alasty [b]

[a] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran 15875, Iran
[b] Department of Mechanical Engineering, Sharif University of Technology, Tehran 14588, Iran

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ABSTRACT

By employing a few simple models of passive dynamic walking mechanism, we have shown the possibility of extending the boundaries of the maximum stable speed of these autonomous robots merely by changing their terrain. The replaced terrain consists of a series of parallel local slopes and is recognized as a general form of a ramp–stair surface. Although here, the mechanism of stabilization of the unstable locomotion patterns is not clearly known, the technique is quite simple and works effectively. The merit to the method over other strategies, could be described in two separate aspects: First, it is still completely passive; so we do not need any external energy to control the robot. Second, the existing passive trajectory is preserved; thus except for the robot's stability, other walking characteristics like speed, step length, period and efficiency, either do not change (if the machine is a point-foot walker) or ultimately minimally vary (if the model possesses other kinds of foot). This theory is validated using MSC Adams commercial software. There is hope that the presented passive strategy contributes to the development of efficient control algorithms, i.e. control methods boosting the gait stability without going against the gait efficiency.

1. Introduction

Thanks to their being humanlike, bipedal robots have been at the center of attention of robotics research community for many years. After decades, the endeavors have lead to acceptable developments in walking machines, like Asimo and Ranger [1,2]. Two favorable major classes of these machines are based on either zero moment point (ZMP) [3] or the theory of 'passive dynamic walking' (PDW) [4].

Today, most of the current humanoid robots function based on ZMP. The strategy proves fruitful in designing successful walking patterns for flat-footed bipedal machines. It uses a simple rule: calculating the required torques in which feet (foot) remain(s) on the ground. Thus, if we make sure of the statically stable behavior of the feet (foot), the dynamic stabilization of the walking is warranted. However, ZMP suffers from some important weaknesses. For example, it is not defined for point-foot walkers; so from a ZMP based point of view, adding foot is necessary to ensure the stability of the gait. Moreover, the existence of ZMP is not necessary to guarantee the balance of walking. As a well-known instance, a two-linked passive walker with fixed flat feet is continuously in a state of overturn, even in the presence of small disturbances [5,6]. In addition, robots working based

* Corresponding author at: Department of Mechanical Engineering, Amirkabir University of Technology, Tehran 15875, Iran.
E-mail address: atehranisafa@gmail.com (A. Safa).

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on ZMP are usually inefficient and unnatural-looking. These robots represent their gait with bent knees and consume a lot of energy to avoid falling; so one of the remained challenging problems in the field is designing a robot that is as efficient and natural-looking as humans.

In contrast, limit cycle walkers based on the theory of PDW present efficient and human-like gaits. For a selected machine from this class, a shallow inclined surface, or another small source of energy is sufficient to force the robot to take steps; however, with a fragile stability [2]. Therefore, if the machine starts walking with an appropriate initial condition, the convergence of the steps to a limit cycle pattern is expected; otherwise, the fall is imminent. In fact, the weakness of these uncontrolled devices is due to their narrow basin of attraction. As a result, these self-controlled robots cannot tolerate large disturbances. Furthermore, this very small domain of attraction vanishes as the slope of the ground or any energy input increases. This property indicates that since traversing a steep slope is not feasible, high speed passive dynamic walking would not be accessible either.

In order to overcome this shortage, researchers have proposed various solutions including adding auxiliary passive elements (springs or dampers) [7], employing leg retraction theory [8] or using stance knee-bend mechanism [9]. Although all of these techniques improve the performance of the biped, i.e. stability and versatility, they profoundly violate the nominal passive trajectory of the robot. In other words, these methods affect the original period, step-length and efficiency which may lead to an undesirable characteristic, i.e. an unnatural-looking gait. In this paper, we look for a solution to increase the gait stability while keeping the other walking characteristics unchanged. That means instead of altering the robot's original trajectory, a domain of attraction is produced for the robot to reach higher stable velocities. To this end, we only replace the robot's terrain with a new walking surface.

In separate researches, we have already shown that our method is applicable to the simplest passive dynamic walker [10,11]. The results indicated that it is possible to promote the stability of the walker up to the global slope of $14.90^{\circ}(0.26\text{rad})$, while by using regular ramps, the model cannot present any stable gait beyond the slope of $1.09^{\circ}(0.019\text{rad})$ [12]. This means that high speed passive dynamic walking is reachable.

In the present work, we examine and verify the technique via more realistic walking models. In this way, we consider the effects of adding feet and an upper body to the stability and the maximum speed of the gait.

The rest of the paper is organized as follows: Section 2 addresses the employed technique, i.e. the concept of the local slopes along with the dynamical modeling of the problem. Section 3 describes the basic results obtained from engaging various types of simple passive dynamic bipeds. Then, Section 4 further discusses the method and the merits to the theory deeply. Section 5 verifies the technique using MSC Adams software. Finally, the conclusion and the possible future works are presented in Section 6.

2. System overview

2.1. Walking surface

Passive dynamic walkers only need a source of potential energy to present a stable periodic behavior. This source has been traditionally provided by a shallow sloped surface, i.e. a simple ramp. When a passive walker is placed on such a surface, it can begin to take steps downward if an appropriate initial condition is induced. A question that may arise here is that what happens if other well-ordered types of terrain provide the walker with this source of energy? Here we are looking for an answer by considering the behavior of some simple, ideal passive walking robots placed on a surface described in Fig. 1.

The surface consists of a series of parallel local slopes with constant vertical distances. The angle of local slopes is shown by ψ and h denotes the vertical distance between two consecutive local slopes. Also, the overall slope angle of the surface is displayed by γ. Note that the figure is plotted based on the positive values of the parameters. Another point is that the width of the local slopes is supposed to be sufficient so that each local slope meets only one leg during the gait; consequently, each leg traverses only every other local slope. With these characteristics, the surface would be interpreted as a general form of a ramp–stair terrain. In this case, for $\psi = 0$ and $h < 0$, a series of downward stairs appears and for $h = 0$, the terrain is converted to a simple ramp.

2.2. Walking robots

We study the behavior of four well-known types of passive bipedal robots, walking on the introduced terrain. All assumptions about limit cycle walkers are respected in this study as well. Thus, double supporting, foot-scuffing, bouncing and slipping are all ignored. Moreover, walking is performed in a two dimensional space, all joints are assumed to be frictionless, and the impacts are considered as perfect plastic collisions. The bipeds are illustrated in Fig. 2 and all required parameters are defined

Fig. 1. The walking surface consists of local slopes. The ground is illustrated by the solid lines. The dashed lines are imaginary.