Switching from hopping to running with HZD controller

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1 Introduction

Between different modelling of animal hopping, walking and running, the most popular one is Spring Loaded Inverted Pendulum (SLIP) model [1],[2]. Through the representation of the body in SLIP by a point mass, trunk stabilization is not addressed. With addition of trunk, it is extended to TSLIP (Trunk SLIP) in which hip torque is applicable for control. Mostly, the control is performed in two layers; one for leg adjustment and another for trunk stabilization. Various methods are presented by researchers to make a stable running [1],[2], but changing the speed with stability background was not the main focus in the literature.
In this research, hopping is defined as jumping vertically without any movement in horizontal direction (running with zero velocity). Unlike running, an asymptotically stable hopping is not achievable with a fixed angle of attack[1]. Most of the control approaches for running/hopping robots, are variations of Raiberts controller, [3]. The main target of this paper is presenting a controller that has the ability to change the speed based on Hybrid Zero Dynamics (HZD) stability analysis. To reach this goal, two layer controller is designed to produce asymptotically stable hopping and running with upright trunk. Then, a PI controller is employed to switch from hopping to running via leaning the trunk forward. After obtaining the desired speed, returning the trunk to upright position guarantees the stability of running analytically.

2 HZD switching Control

In the first layer of the controller, a Velocity (vector) Based Leg Adjustment (VBLA) technique is presented for SLIP model to set the horizontal speed to its desired value as fast as possible (see Fig. 1). Using the vector instead of only horizontal term of the velocity makes some benefits for this method compared with common approaches [3], [1]. Faster convergence and more robustness are some of these advantages. In this method, the leg direction is given by the vector ($\vec{O}$), computed as the weighted average of the Center of Mass (CoM) velocity ($\vec{V}$) and the gravity vector ($\vec{G}$) as shown in Eq. 1. It is proved that for hopping, there exists a specific weight (μ) that vanishes the initial horizontal speed (as perturbation), in only one step. Such weights are computed for running respected to desired velocity too.

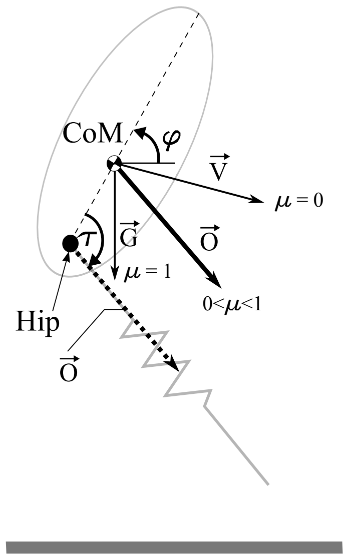

Figure 1: Velocity Based Leg Adjustment

$$\vec{O} = (1-\mu)\vec{V} + \mu\vec{G}, \quad 0 < \mu < 1 \tag{1}$$

In the second layer, Feedback linearization (FBL) is utilized to set the trunk angle to a desired value (ϕ_d) via hip torque (τ), shown in Fig. 1. Hybrid zero dynamics analysis is employed to investigate the stability. For hopping, upright trunk is desirable and by defining it as zero dynamics manifold, its asymptotic stability is proved. In addition, upright trunk is applicable for running as observed in human locomotion too [4]. Therefore, the controller makes stable running and hopping with tuning μ. It is important that this is able to convert running to hopping only with changing μ, but it is not possible in the other direction (from hopping to running). Because, in hopping, the horizontal velocity is zero and changing the weight does not affect the leg angle. This goal is achieved by inserting one transient phase to the controller that works stably for both kinds of motions. As-

[1] The angle of attack is the angle of leg with the horizontal line when the leg hits the ground (Touch Down moment)

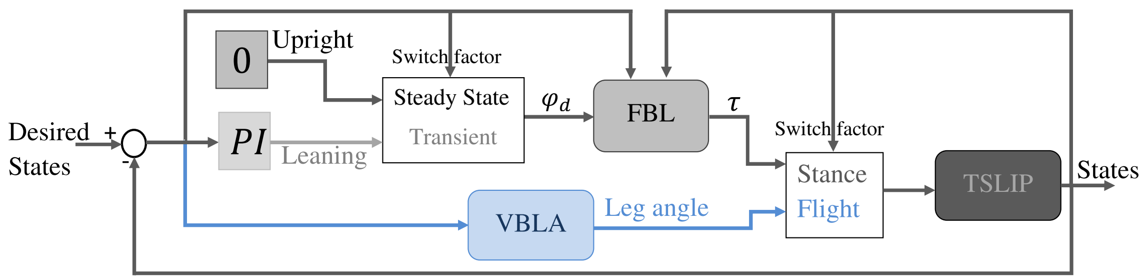

Figure 2: The structure of HZD switching control. white blocks are switches select output based on switch factor.

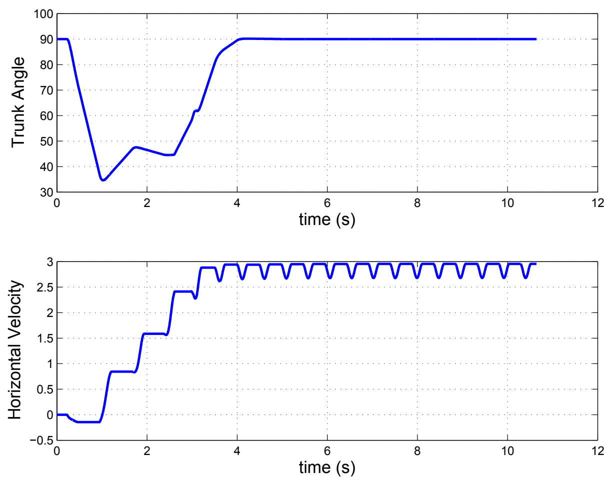

Figure 3: Switching from hopping to running with horizontal speed (3 m/s)

sume that the trunk angle and the horizontal speed are the input and output of the system in transient phase, respectively. Then, in order to reach the desired speed, a PI controller is utilized to determine ϕ_d as an input of FBL that means turning the trunk in forward direction. After reaching the desired velocity, ϕ_d is set to zero and the trunk returns to the upright position (see fig. 2).

3 Results & Discussion

Different versions of HZD are used for stable running of Asymmetric SLIP (ASLIP)[2] by Poulakakis [1]. The main significant points in our approach which make it completely different from the previous ones are as follows. The first one is presenting a new leg adjustment technique for SLIP with stability proof that is needed to show the stability of the zero dynamics in the complete model. In this approach to guaranty the stability, an appropriate weight is computed based on system parameters. After extension to TSLIP, only one degree of actuation is needed to bring the states on the zero dynamics manifold. In contrast with Poulakakis approach, in which a prismatic actuator is needed to convert the model to SLIP, precisely, here a reduced order system which is close (not exactly the same) to SLIP model with some extra terms is sufficient for designing stabilizing VBLA controller. It means that the control targets are achieved with lower degrees of actuation beside satisfying the stability conditions.

[2] ASLIP is another representation of TSLIP

Table 1: Human parameters for TSLIP model

fixed parameters	symbol	value
trunk mass	m	80 [kg]
leg stiffness	k	15696[N/m]
trunk moment of inertia	J	4.58 [kg m^2]
distance hip-CoM	r_{CoM}	0.1 [m]
leg initial length	l_0	1 [m]
leg adjustment parameter	μ	[0, 1]

The TSLIP model with human parameters, stated in Table. 1, is simulated for hoping on one leg and then switching to running. The main target of this paper is using HZD controller to change the velocity considerably that is shown in fig. 3 (from 0 to 3 m/s). Although the transient phase which employs PI to tune the desired angle in feedback linearization, does not have stability guaranty, it is limited between two stable phases. It provides the condition for making a smooth alteration between hopping and running. In fig. 3, the trunk angle reduces that is equivalent to lean forward and after reaching the desired speed in apex, it returns to upright position.

The Stick animation of the motion for 6 first steps that is required to reach the desired velocity, is shown in Fig. 4. The motion starts from horizontal position 0, next at first step the robots moves shortly backward that is because of leaning the trunk forward. It can be observed as a small undershoot of horizontal velocity in Fig. 3 (below), too. Then, it moves forward because of the force produced by the leg adjustment and trunk orientation. Note that the hip torque only tries to bring the trunk angle to its desired value and without any attempts to move forward, it is resulted from the dynamics of the system. Therefore, in each step's stance phase the trunk rotates to increase the horizontal velocity. The smaller velocity error, the smaller angle of leaning forward. Finally, after 6 steps, with horizontal velocity equal to 3 (m/s), the

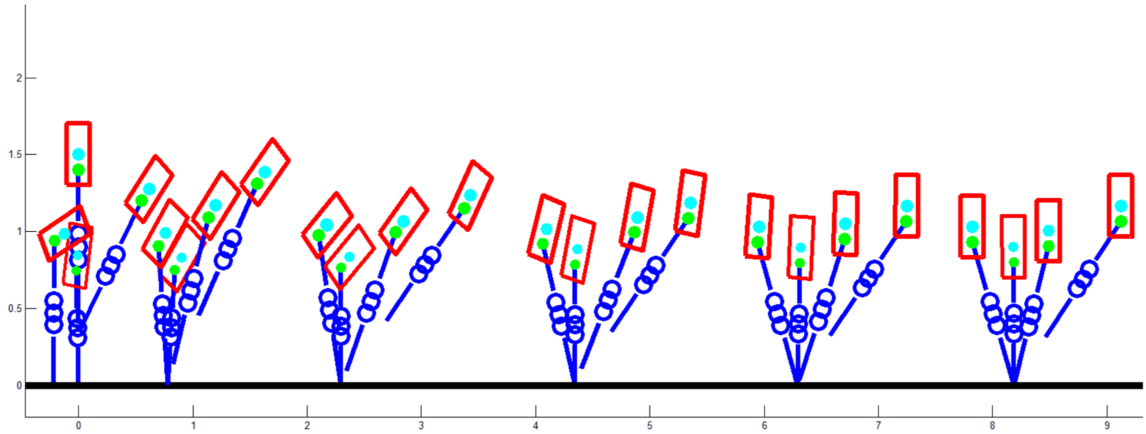

Figure 4: Stick Animation of hop to run motion

trunk will be completely upright (Fig. 3 and Fig. 4). We are interested in this posture, for its stability proof.

4 Open questions

As stated before, with hybrid zero dynamics analysis, the stability of the system is shown except in transition between two moving phases. It is the main challenge for this method. Addition of mass to leg and considering the model in presence of damping are the next steps in this research which are under construction.

5 Acknowledgment

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