Switching from hopping to running with HZD controller

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I. Summary

- Main target: Switching from hopping to running stably
- 2-layer controller:
  - Velocity-based leg adjustment (VBLA, see Sect. II) results in stable hopping and running
  - HZD control for trunk stabilization
    - ✓ Output: $z = \varphi - \varphi_d$ (φ is shown in Fig. 2)
    - ✓ Zero Dynamics Manifold: $z = \dot{z} = 0$
- Transition between hopping and running
  - Trunk leaned forward to reach the desired velocity with PI controller for tuning angle φ_d
  - Upright-trunk to run stably with target velocity

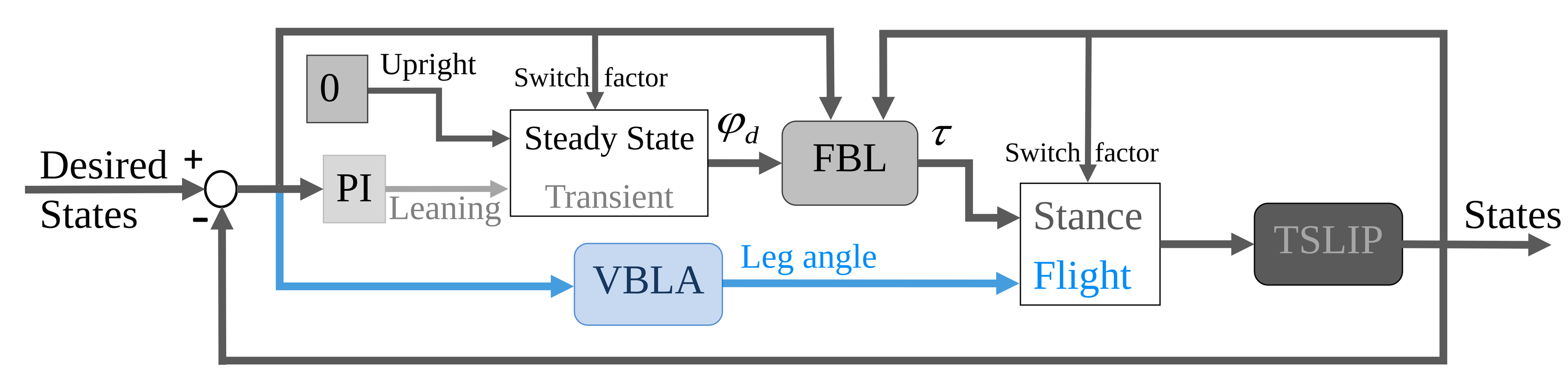

Fig. 1. The structure of HZD switching control. white blocks are switches to select output based on switch factor.

II. Velocity-based Leg Adjustment

a. Method Description

- VBLA (Velocity Based Leg Adjustment)
  - Determining the leg direction by a vector
  - Using velocity vector
  - Definitions:
    - $\vec{O}$: Leg direction vector
    - $\vec{V}$: Center of Mass (CoM) velocity
    - $\vec{G}$: Gravity vector
  - Equation: $\vec{O} = (1-\mu)\vec{V} + \mu\vec{G}$
  - Tuning parameter: $0 \le \mu \le 1$

b. Advantages:

- Fast convergence to desired velocity
- High robustness against perturbation
- Stability of ***perturbed SLIP*** model by tuning μ
  - SLIP: $p = 1$
  - Perturbed SLIP: $0<p<1$
- x: horizontal position of CoM
- y: vertical position of CoM
- l: leg length which is $\sqrt{x^2+y^2}$ during stance
- Other parameters are show in Table. 1

p: perturbation parameter

$$\begin{cases} \ddot{x} = p\dfrac{k(l_0 - l)}{M}x \\ \ddot{y} = p\dfrac{k(l_0 - l)}{M}y - g \end{cases}$$

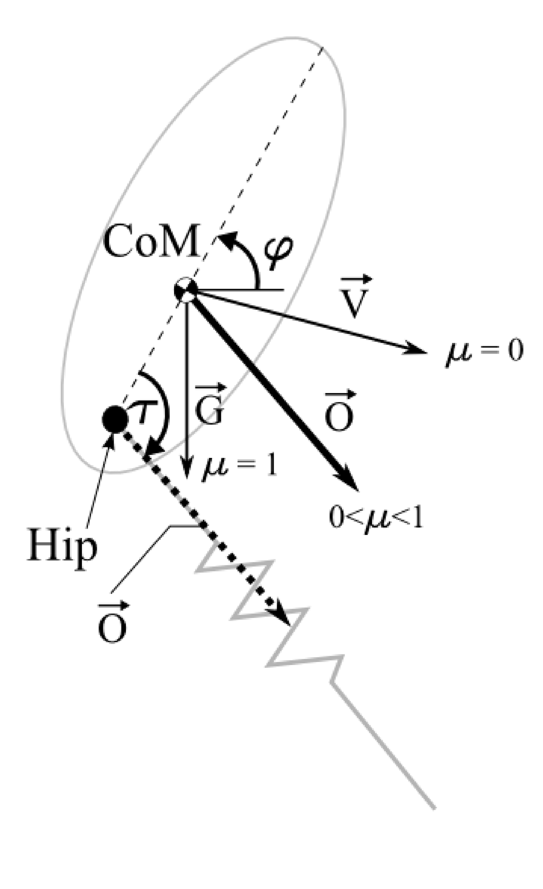

Fig. 2. TSLIP model with VBLA

III. HZD Controller for TSLIP

a. Model Description

- Assume q as the state variables vector
- System dynamical model: $\dot{q} = f(q,u)$

b. Control Design Steps:

- Virtual constraints as relation between state variables $z = h(q) = 0$
- Feedback linearization such that $z = \dot{z} = 0$
- Convert the model to the normal form
- Compute the reduced model as zero dynamics
- Find free parameters in h to stabilize zero dynamics
- Extra conditions should be satisfied in hybrid systems

c. HZD Controller for TSLIP:

- Virtual constraint: $h(q) = \varphi - \varphi_d$
- Upright trunk: $\varphi_d = 0$
  - Zero dynamics equation:

$$p = \frac{l^2}{l^2 + y r_{CoM}}$$

  - Stability of zero dynamics is guaranteed by tuning μ
- Required conditions for stability of hybrid zero dynamics are satisfied

IV. Results

- Assumptions: human-like parameters (see Table. 1)
- Leaning the trunk forward
  - Backward motion in the first step
  - Increasing the horizontal velocity
  - Reaching the desired velocity
- Switch to upright trunk
  - Stable running with upright trunk
  - Target velocity is reached
- Tuning of the velocity is achieved indirectly by adjusting the trunk angle

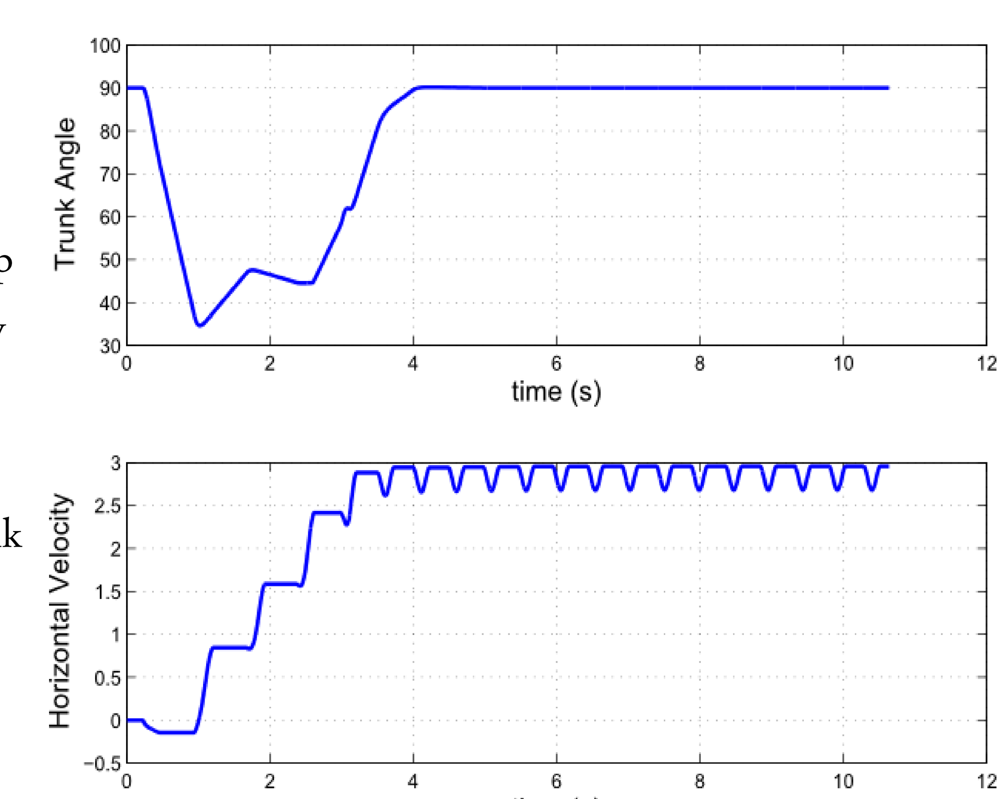

Fig. 3. Switching from hopping to running with 3 m/s

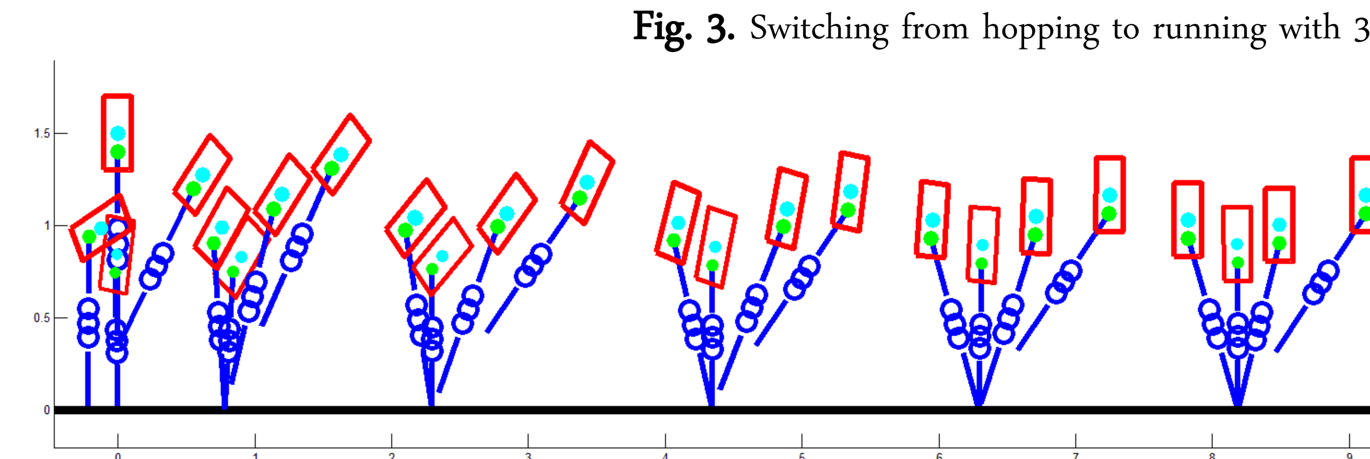

Fig. 4. Simulated hop to run for 6 first steps

V. Discussions

- Switch from running to hopping is achievable only with changing μ
- A new method based on HZD control is presented to switch from hopping to running
- Comparison with other HZD approaches for running (e. g. Poulakakis et al.):
  - Different leg adjustment method
  - Lower active DoF in this approach
    - ✓ Removing the prismatic joint in leg
    - ✓ Ability of VBLA in control of perturbed SLIP makes this improvement
- Stability
  - Guaranteed with upright trunk
  - Not guaranteed in transient phase

Table. 1. Human parameters for TSLIP model based on Maus et al. 2010

Parameters	Symbol	Value (unit)
Trunk mass	M	80 (kg)
Leg stiffness	k	15696 (N/m)
Trunk moment of inertia	J	4.58 (kgm²)
Distance hip-CoM	r_{CoM}	0.1 (m)
Leg rest length	l_0	1 (m)

H. M. Maus, S. Lipfert, M. Gross, J. Rummel, and A. Seyfarth, "Upright human gait did not provide a major mechanical challenge for our ancestors," Nature Communications, vol. 1, no. 6, pp. 1–6, 2010.

I. Poulakakis and J. W. Grizzle, "The spring loaded inverted pendulum as the hybrid zero dynamics of an asymmetric hopper," IEEE Transaction on Automatic Control, vol. 54, no. 8, pp. 1779–1793, 2009.