Exploring the structure of bipedal asymmetrical gaits using a template model

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I. Introduction

It has been shown that switching among different gaits as speed changes can help animals reduce their energy expenditure [1]. Many bipeds, including humans, usually *walk* at low speeds and *run* at high speeds. These two gaits are *symmetrical gaits* in which the two legs are half a period out of phase, but otherwise go through the same motion over the course of a stride. Locomotion in nature, however, is not exclusively limited to such symmetrical gaits. Crows or kangaroos, for example, prefer to *hop* over a large range of speeds. In hopping, they use both legs in a fully synchronized fashion. When this exact synchronization in the leg motions is lost, yet the phase delay is still below half of a stride, a full range of *asymmetrical* gaits arises. Commonly these gaits are classified as *bipedal galloping*. However, it is difficult to understand the underlying dynamics of these asymmetrical locomotion patterns due to the large number of degrees of freedom expressed by the animals. To this end, we developed a unified Spring Loaded Inverted Pendulum model with passive swing leg motions. By changing the resting angles of the swings legs, this model has great potential to explain the natural gait patterns from bipedal animals such as the Egyptian jerboa (*Jaculus jaculus*) [2].

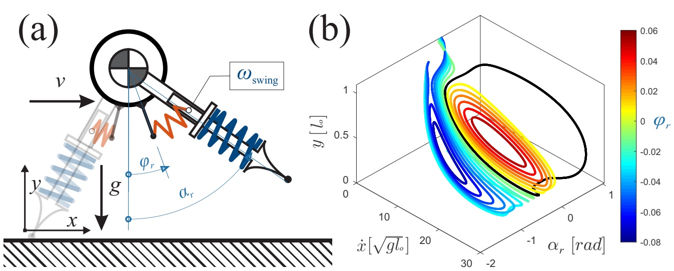

Fig. 1. (a) The bipedal model with different resting swing leg angles φ_r. (b) The numerical continuation results with resting swing leg angles $\varphi_r \in [-0.08, +0.06]$ rad. The branch with zero resting angle is shown in black.

II. Methods

Based on our previous work [3], with a single set of parameter values, the proposed model Fig. 1(a) is capable of reproducing a large number of gait patterns at various speeds including asymmetrical running, hopping, and galloping. Also, we found these footfall patterns can be identified as bifurcations from a simple jumping in-place motion. Therefore, this template model is suitable for modeling the gait transitions and revealing relationships among different gait patterns in bipeds.

In order to find periodic solutions of this model, we formulated the gait creation as a *boundary value problem* (BVP). We defined a gait as a periodic motion in which all states except for the horizontal position x return to their original values after one full *stride*. Without loss of generality, the apex transition ($\dot{y} = 0$) was selected as the Poincaré section for this limit cycle analysis. Finding a gait in this model was thus equivalent to solving for solutions of the following problem:

$$\mathrm{T}(\boldsymbol{Z}) := \begin{bmatrix} \ddot{\boldsymbol{q}} - \mathrm{f}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{p}, \boldsymbol{T}) \\ \dot{\boldsymbol{q}}\left(T_k^+\right) - h\left(\boldsymbol{q}\left(T_k^-\right), \dot{\boldsymbol{q}}\left(T_k^-\right)\right) \\ \mathrm{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{p}, \boldsymbol{T}) \end{bmatrix} = \boldsymbol{0}. \quad (1)$$

The solution vector of this equation, $\boldsymbol{Z}$, combines the generalized positions and velocities of the model ($\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$), system parameters $\boldsymbol{p}$, and the vector of footfall timings $\boldsymbol{T}$. The boundary and interior-point conditions in C were used to enforce that all states are periodic and the legs are fully extended at touchdown and liftoff. Then we ran numerical continuations for a given set of parameters $\boldsymbol{p_k}$ to explored the structure of the galloping gait patterns from the proposed model (Fig. 1(b)). We also compared the simulated kinematic results from our model with the recorded jerboa locomotion data and verified to what degree this simplified model can be used to explain the locomotion patterns of animals in nature.

III. Best Possible Outcome

We will systematically explore the structure of the solution manifold from the continuation results. Our expectation is that, as we gradually vary the parameters, it will be clear how one asymmetrical gait evolves into many other bipedal gait patterns. Based on the identified results, we will gain new knowledge of how and when bipedal animals switch gait patterns. Furthermore, this study can inform controller design of legged robots to achieve more agile motion.

References

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