Simulation of Highly Dynamic Locomotion with a Bipedal Robot: A Fast Running Algorithm

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1 Introduction

To date, running is a high dynamic motion easily performed by humans and hardly achieved by humanoid robots. While the human can run up to $12\,m.s^{-1}$, for instance the Olympic sprinter Asafa Powell, humanoid robots reach a top speed of $2.5\,m.s^{-1}$ (Asimo [5]). Naturally there is also the planar biped of the MIT Leg Laboratory that has reached a top speed of $5.8\,m.s^{-1}$ [4]. However, the system's architecture was designed in a way that it is planar, has light legs with respect to the body, and it is not anthropomorphic.

Biomechanics studies have provided various results concerning the running gait of human being. One of the most famous results is the spring-mass model for the contact leg that explains the basis of running dynamics [2]. However, there is less information about the swing leg behavior.

Through the present paper, we aim to investigate the running gait at high speeds with a complex 3D bipedal robot. The spring-mass model is used to control the contact leg and we propose a simple coordination law to control the swing leg. Based on the control algorithm developed by J. Pratt et al. [8, 7] which proved efficiency on walking motion, we propose an extension to simulate the running motion including the latter elements. The simulation results show a stable running at $3.5\,m.s^{-1}$.

2 The Complex 3D Bipedal Robot

The complex 3D bipedal robot used to investigate the running gait control is M2.The robot model has been modified by adding three reaction masses, see Fig. 1, that substitute an upper-part.

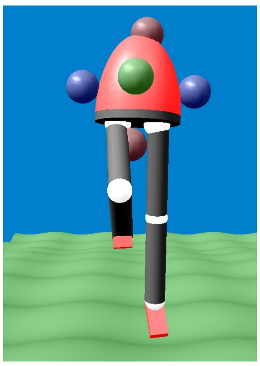

Figure 1: Simulated robot M2 plus the three reaction masses

3 Algorithm main components

The control is based on a state machine that allows to select the correct behavior of each leg according to their state, see Fig. 2. During the contact period the spring-mass model is used to control the contact leg's knee behavior. The spring stiffness is updated at each touchdown to obtain a symmetric contact behavior:

$$F^{\text{spring}} = \hat{K}\,(l_0 - l) \tag{1}$$

$$\tau^{\text{knee}} = -L^{\text{thigh}} \sin\left(\frac{q^{\text{knee}}}{2}\right) F^{\text{spring}} \tag{2}$$

$$\hat{K} = \frac{m\,g}{l_0}\left(\frac{C_1\,\dot{x}_0\,\dot{z}_0 + (C_2 + C_3\,\dot{x}_0)\,\theta_0}{(C_4\,\dot{z}_0 + (C_5 + C_6\,\dot{x}_0)\,\theta_0)\,\theta_0}\right)^2 \tag{3}$$

where the subscript "$_0$" denotes the touchdown instant and:

$C_1 = 6.058$, $C_2 = 10.05\,m^2.s^{-2}$, $C_3 = 10.75\,m.s^{-1}$
$C_4 = 12.17\,m.s^{-1}$, $C_5 = 12.17\,m^2.s^{-2}$, $C_6 = 5.272\,m.s^{-1}$

Since the contact period is mainly governed by the spring-mass model, a prediction of the contact duration is established, and then used to manage the swing leg behavior:

$$\tau^{\text{hip}}_{\text{pitch}} = K_p\left({}^{d}q^{\text{hip}}_{\text{pitch}} - q^{\text{hip}}_{\text{pitch}} -\right) + K_v\left({}^{d}\dot{q}^{\text{hip}}_{\text{pitch}} - \dot{q}^{\text{hip}}_{\text{pitch}}\right) \tag{4}$$

where ϕ_y is the body rotation in the sagittal plane and:

$${}^{d}\dot{q}^{\text{hip}}_{\text{pitch}} = \frac{q^{\text{hip}}_{\text{pitch}} - {}^{d}q^{\text{hip}}_{\text{pitch}}}{T^{\text{stance}}} \tag{5}$$

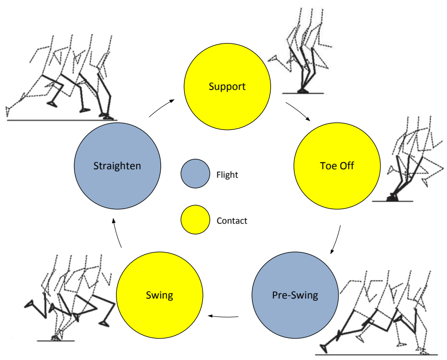

Figure 2: Bioinspired state machine based on [6]

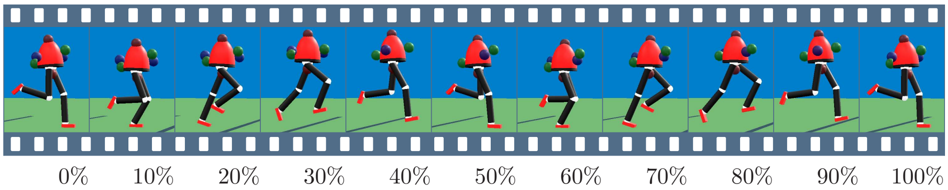

Figure 3: Snapshots of the bipedal running simulation at $3.5 m.s^{-1}$

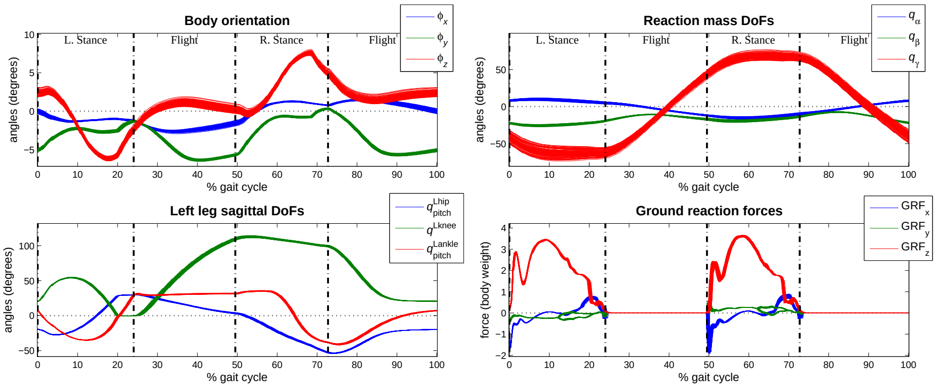

Figure 4: Simulation results. The graphs show data of 100 successive gait cycles of one simulation. Each cycle begins and ends at left foot touchdown.

Table 1: Running simulation main characteristics (average) at a forward speed of $3.5 m.s^{-1}$. They are, respectively: stride rate and length, duration of the cycle, stance and flight, leg stiffness, and both vertical ground reaction force peaks in unit per body weight (BW).

Stride		Duration (*sec.*)			Leg Stiffness	Vertical GRF (*BW*)	
Rate (*Hz*)	L (*m*)	Cycle	Stance	Flight	($kN.m^{-1}$)	1^{st} Peak	2^{nd} Peak
1.07	3.24	0.93	0.21	0.25	16	2.85	3.36

4 Results

We simulated the running robot with the Yobotics! Simulation Construction Set [1]. A stable running simulation at $3.5 m.s^{-1}$ was obtained with human like gait, see Fig. 3. The general results are shown in Fig. 4 and Table 1.

5 Open questions

The main question we are now trying to answer is the following: is it possible to implement a spring-like behavior for walking as suggested in [3] and to obtain accordingly a unified control method for walking and running?
In parallel, we have raised the following point. The human being is able to perform countless kind of motions. The dynamic walking community mainly focuses on understanding and generating the locomotion one. However, could we learn more about controlling such complex systems that are humanoid robots by trying to perform highly dynamic motions (for instance, acrobatic ones)? And could it be used for understanding/generating locomotion?

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