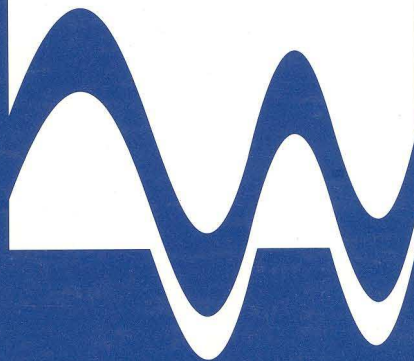


**DINA
ME97**



**7th INTERNACIONAL CONFERENCE
ON DYNAMIC PROBLEMS
IN MECHANICS**

03 - 07 MARCH 1997

HOTEL DO FRADE

ANGRA DOS REIS - RIO DE JANEIRO - BRAZIL

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Brazilian Society of Mechanical Sciences**

Kinematic Analysis of Robotic Biped Locomotion Systems

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1. Introduction

The research interest on biped walking machines have been increasing in recent years because of the many advantages over wheeled vehicles on rough terrain. Legged vehicles can traverse uneven terrain, manoeuvre in confined spaces and climb stairs with a minimum of swinging and lurching. In early work, biped walking has been studied by using simple models (e.g., inverted pendulum models) as approximations to bipeds and then analysing various methods of control [1,2]. In the spite of the prototypes that have been built, the most advanced ones can only demonstrate certain functionalities of walking [3,4]. Therefore, several researchers are in pursuit of better walking robots and continue to refine their models of locomotion [5-7].

This paper presents the kinematic study of a planar biped model with five degrees of freedom and purely rotational joints. The main purposes are threefold:

- To gain insight into the phenomenon of biped walking.
- To characterise the biped motion in terms of a set of locomotion variables.
- To establish the correlation among these locomotion variables and the system performance.

In this line of thought, the remainder of the paper is organised as follows. Section 2 describes the biped model and the method used to plan the kinematic trajectories. In section 3, a kinematic performance measure is proposed and discussed. Given this background, in section 4 we present a series of simulations to evaluate the system performance under varying conditions. Finally, in section 5, we outline the main conclusions.

2. The Robotic Biped Model

Figure 1 shows the planar model used and the leg labelling convention. In the present study, we consider a planar biped model that has seven rigid links interconnected through rotational joints. During locomotion, the stance leg (*i.e.*, the limb on the ground) has a degree of freedom formed in the contact between the foot and the ground. In the single support phase, the stance leg is in contact with the ground and carries the weight of the body, while the swing leg moves forward in preparation for the next step. The impact of the swing leg is assumed to be inelastic and the friction is sufficient to ensure that no slippage occurs. Additionally, we consider that the support shifts instantaneously from one limb to the other.

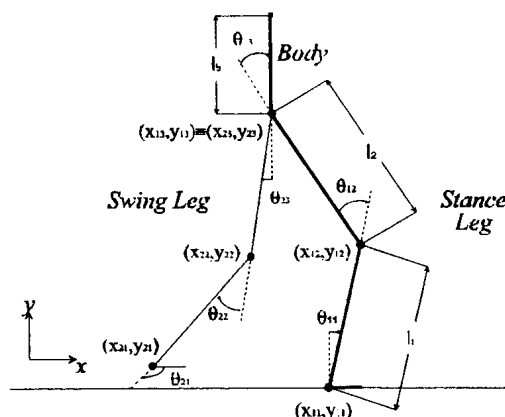


Fig. 1 - Planar biped model.

2.1. Locomotion Variables

The prescribed motion of the biped is completely characterised in terms of the following variables: length of the step L_S , hip height H_H , maximum hip ripple H_R , maximum foot clearance F_C and leg link lengths l_1 and l_2 (Fig. 2). The hip height is defined as the mean height of the hip along the cycle of walking. The hip ripple is measured as the peak-to-peak oscillation magnitude. During the experiments, we examine the role of the link lengths considering that $l_1 + l_2$ assumes a constant value equal to 1 meter.

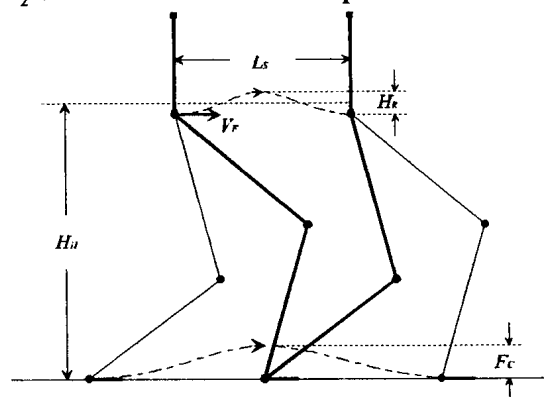


Fig. 2 - Locomotion variables.

2.2. Development of the Kinematic Trajectories

The proposed algorithm accepts the hip and feet's trajectories as inputs and, by means of an inverse kinematics algorithm, generates the related joint trajectories. For purposes of smoothness the body maintains an erect posture and a constant progression velocity V_p . One trajectory that undergoes smooth motion is the flat trajectory in which the stance leg adjusts itself so that the hip maintains a constant

height. Simultaneously, it is of interest to exploit trajectories in which the hip translates with some vertical motion. To simplify the problem, we consider that such motions are based on sinusoidal functions.

In order to avoid the impact effect, at each footfall, the motion of the biped is modified so that the feet are placed on the ground with zero velocity. In accordance, the equation of the foot of the swing leg, along the x -axis, is computed by using a sinusoidal function:

$$x_{21}(t) = 2V_f \left[t - \frac{1}{2\pi f} \sin(2\pi ft) \right] \quad (1)$$

where f is the step frequency. Moreover, the vertical motion, that allows the foot to be lifted off the ground, is implemented using the function:

$$y_{21}(t) = \frac{F_c}{2} [1 - \cos(2\pi ft)] \quad (2)$$

We also assure that the swing limb arrives at the contact point when the upper body is properly centred with respect to the two lower limbs.

3. Kinematic Performance

This section covers the implementation of the performance measure used in the evaluation of the biped's kinematic performance. In mathematical terms, we shall provide a global measure of the overall dexterity of the mechanism in some average sense. Along this study, two additional performance measures were formulated to verify the correlation between different view points (not included here).

3.1. Perturbation Analysis

In this method, the joint trajectories are first computed by the inverse kinematics algorithm. Then, the angular acceleration vectors are 'corrupted' by additive noise. For simplicity reasons, it is used a uniform distribution with zero mean added to the acceleration signal. As result, the trajectories of the body suffer some distortion and can only approximate the desired one. By regarding the forward kinematics of the mechanism, we can determine a two-dimensional index based on average of the well-known mean-square-error and defined by:

$$\xi_x = \frac{1}{N_s} \sum_{i=1}^{N_s} \sqrt{\frac{1}{T} \int_0^T [\dot{x}_b^i(t) - \dot{x}_b^d(t)]^2 dt} \quad (3)$$

$$\xi_y = \frac{1}{N_s} \sum_{i=1}^{N_s} \sqrt{\frac{1}{T} \int_0^T [y_b^i(t) - y_b^d(t)]^2 dt} \quad (4)$$

where N_s is the total number of steps for averaging purposes, \dot{x}_b^i and \dot{x}_b^d are the i th sample and the desired forward velocities at the body section, respectively, and y_b^i and y_b^d are the i th sample and the desired vertical oscillations at the body. The stochastic perturbation penalises the system's performance and we shall be concerned with minimising both indices ξ_x and ξ_y .

4. Simulation Results

In this section, we perform a set of simulations to estimate how the biped robot adapts to variations in the locomotion variables. The aim is to determine the main factors that optimise the leg motion. To evaluate the system's operating features, the simulations are carried out considering a forward velocity $V_f = 1$ m/sec.

4.1. Step Length and Hip Height

To illustrate the use of the preceding results, the biped locomotion was simulated. At this phase, a major simplification is introduced by allowing the swing foot stays on the ground for all time without violating any constraint. As shown in Fig. 3, the performance function is evaluated with respect to the step length and the hip height (for equal link lengths). Considering these plots, we conclude that an important degradation occurs as the step length increases. The hip height variable also affects the measure, however, has a smaller influence.

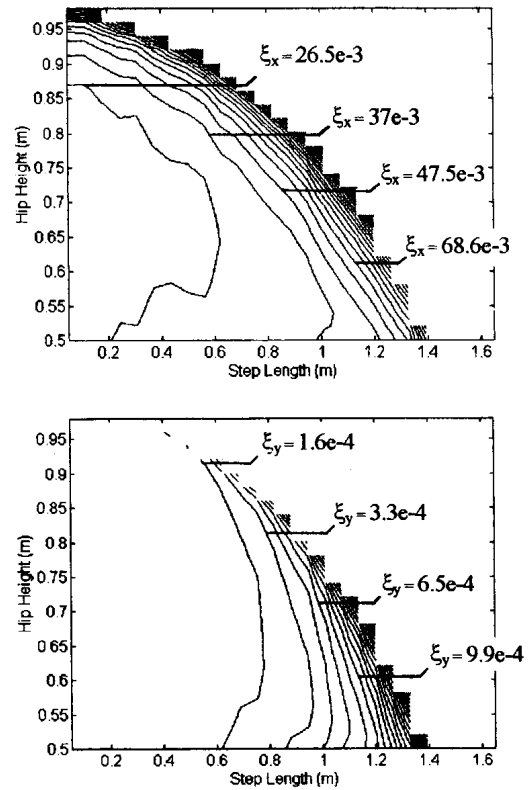


Fig. 3 - Contour plot of the performance surface along the x and y -axis.

4.2. Hip Ripple

Upon this point, we consider a hip trajectory with a sinusoidal oscillation. In this case, we applied a flat hip trajectory, while the foot of the swing leg remains at the ground. The contour plot in Fig. 4 displays the performance values using the perturbation analysis method. From this simulation, we can observe that the optimum hip ripple tends to a zero value and, further, it remains almost unchanged to hip height variations.

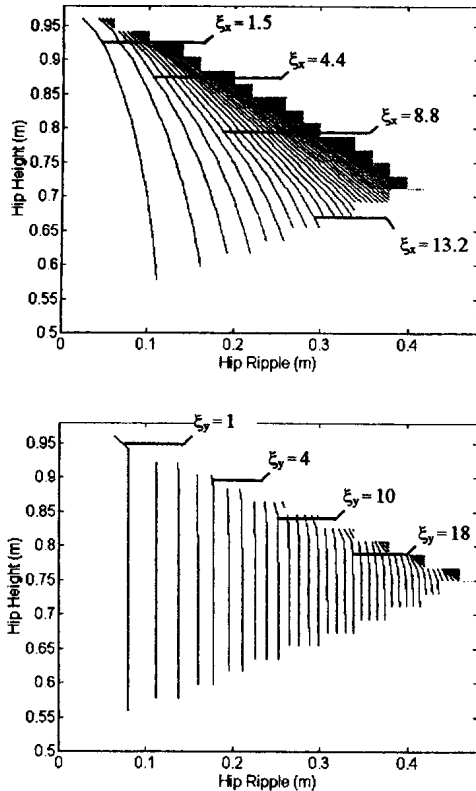


Fig. 4 - Contour plot: H_H versus H_R ($L_S = 40$ cm).

4.3. Foot Clearance

Another variable that should be tested is the effect of foot clearance. Until now, all the experiences considered that the foot stays on the ground. Next, the goal is to analyse the situation in which the foot can be lifted off the ground. In Fig. 5 we study the influence of F_C for different hip height conditions. The results can be expressed as contours of constant performance measure values in terms of H_H .

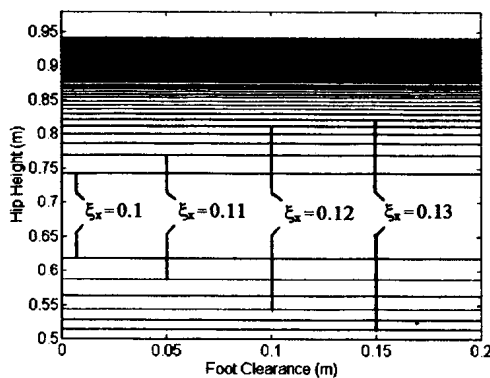


Fig. 5 - Contour plot: H_H versus F_C ($L_S = 40$ cm).

4.4. Relative Link Lengths

We now investigate the role of the link lengths, l_1 and l_2 , in the system's performance. Figure 6 depicts the curve of ξ_x given the link length. As can be observed,

the optimum solution occurs when the knee-ankle length is higher ($l_1 = 0.74$ cm) than the hip-knee length ($l_2 = 0.26$ cm). The simulation also indicates that for l_1 in the range from 40 to 90 cm the performance index remains almost constant.

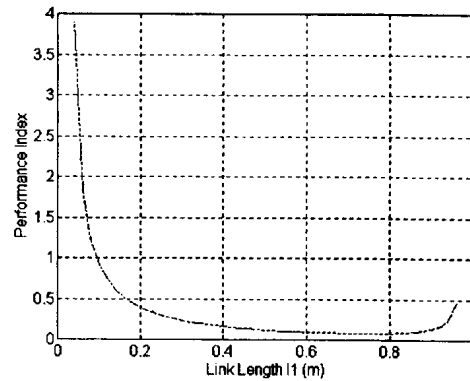


Fig. 6 - Performance curve versus link length l_1 .

5. Conclusions

In this paper, we have studied a quantitative measure for analysing the kinematic performance of biped systems. The graphical results provide a more concrete illustration of the system's properties. The perturbation analysis method seems to be elegant although computationally exigent. Although our focus has been on kinematic dexterity, certain aspects of locomotion are not necessarily captured by the measures proposed. Thus, future work in this area will address the refinement of our models to incorporate dynamics, as well as exploring human-like walking principles.

6. References

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