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Blind Walking of a Planar Bipedal Robot on Sloped Terrain

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Abstract

Simple intuitive control strategies can be used to compel bipedal robots to walk over sloped terrain. We describe an algorithm for walking dynamically and steadily over sloped terrain with unknown slope gradients and transition locations. The algorithm is developed based on geometric considerations. The overall algorithm is very simple and does not require the biped to have an extensive sensory system for walking over moderate slopes. The ground is detected blindly using only foot contact switches. Using a few simple strategies, we have compelled a 7 link planar biped simulation to walk up and down slopes and over rolling terrain.

1 Introduction

We have successfully used Virtual Model Control to control a planar biped to walk on flat ground [4,5]. Since rough terrain locomotion is important for legged locomotion, this motivates us to apply Virtual Model Control for rough terrain locomotion of a biped.

Zheng and Shen [7] achieved control of a static biped to walk on an unknown sloped terrain using force sensors at the feet and position sensors of the joints. The implementation of the strategy was simple. However, it was only applied to static walking. Yamaguchi, et al. [6] introduced an anthropomorphic *dynamic* biped walking robot which could adapt to a humans' living floor. While performing dynamic walking, the biped used the information from a special foot system to adapt to a humans' living floor with a small unknown variations (-16 to +16 mm/step in the vertical direction, and from -3^o to +3^o for the tilt angle) in profile. Kajita and Tani [2] developed a simple control method based on massless leg model and used a scheme called "Linear Inverted Pendulum Mode" to control a biped walking on ground constituted of planes and vertical steps, such as stairs.

Dynamic bipedal walking over sloped terrain can be achieved by adding a few simple intuitive control strategies to flat ground walking algorithms. Moderate slopes can be traversed blindly, with slope detection being inferred only through foot-ground contact. In this paper we describe strategies which we used to compel a simulated 7-link planar biped to traverse slopes.

The simulations are used to study the algorithm. They used a physically realistic rigid body models based on the inertial parameters of the real robot. We made the following assumptions in all the simulations:

1. No slippage occurs during locomotion.
2. The biped has perfect actuators which provide desired torque at each joint.
3. The sloped terrain has smooth transition (such that both discrete sensors underneath the foot which has completely touched down are always turned on) and there is also no variation of terrain in the transverse direction.

2 System and Task Descriptions

The control strategies studied in this paper are designated for a physical six degree of freedom, 7-link planar biped called *Spring Flamingo*. The robot has two slim legs and a body. The legs (1 kg each) are much lighter than the body (10 kg). Each leg consists of a hip joint, a knee joint and an ankle joint. All the joints are revolute pin joints with axes perpendicular to the sagittal plane. An equivalent computer model (as shown in Figure 1) was created with approximately the same configuration and mass distribution as Spring Flamingo. The detailed parameters of this model can be found in [1].

We assume that the goal for the biped is to maintain a steady dynamic walking gait in the sagittal plane while maintaining an upright posture. We have ignored the transient problem, eg. transition from stop to walk. We also assume that the biped walking has two main phases: single support phase and double support phase.

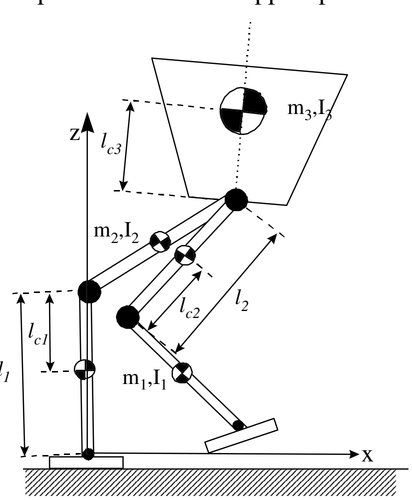


Figure 1. 7-link planar bipedal robot model.

3 Virtual Model Control approach for Biped Walking Implementation

Virtual Model Control [4,5] uses virtual mechanical components to generate real actuator torques (or forces). These joint torques create the same effect that the virtual components would have created, had they existed, thereby creating the illusion that the simulated components are connected to the real robot. Such components can include simple springs, dampers, masses, or any other imaginable component. Figure 2 shows the schematic diagram of the overall control architecture using this approach.

The goal mentioned in Section 2 is achieved if the biped could maintain the height, horizontal velocity and pitch of the biped's body. Note that the height and horizontal velocity are allowed to vary within a tolerable range since the *exact* trajectory of the body is not important with respect to the goal.

We use the set of virtual components (see [4,5]) as shown in Figure 3. For the height control, a virtual parallel spring-damper is attached vertically between the hip and the ground to generate a virtual vertical force F_z at the hip. For the horizontal velocty control, a virtual damper is attached horizontally between the hip and a horizontal velocity source to generate a virtual horizontal force F_x at the hip. For the body pitch control, a rotational parallel spring-damper is attached around the hip and, between the body and an imaginary non-rotational reference. This generates a virtual torque M_α about the hip. In the algorithm, the ankle of the supporting leg is limp.

The key motion parameters are the desired horizontal velocity v_{xd}, the desired vertical height of the hip z_d and the desired pitch angle of the body α_d. All these parameters define the desired motion of the body frame $O_bX_bZ_b$ with respect to the inertia frame OXZ attached to the supporting leg's ankle (during the single support phase) or hind leg (during the double support phase). We used linear virtual components which result in the following intermediate control laws:

$$F_x := b_x(\dot{x}_d - \dot{x}) \quad (1)$$

$$F_z := k_z(z_d - z) + b_z(\dot{z}_d - \dot{z}) \quad (2)$$

$$M_\alpha := k_\alpha(\alpha_d - \alpha) + b_\alpha(\dot{\alpha}_d - \dot{\alpha}) \quad (3)$$

where b_i and k_i are the damping coefficient and the spring stiffness, respectively for the virtual components in i (= x, z or α) coordinate.

Since we set the ankle of the stance leg to be limp, we can only control two of the three desired motion parameters during single support phase [4]. In this phase, we choose to maintain only the body's height and pitch angle and let the gravity dictates the horizontal velocity. The horizontal velocity of the body is controlled only during the double support phase.

The gait and virtual component parameters which affect the walking pattern and performance of the planar biped are summarized in Table 1 and Table 2 respectively. The virtual forces for both the single and the double support phases are transformed into the joint space using the equations derived in [4,5]. With this algorithm and proper selection of the variables, we have demonstrated that the biped can walk dynamically on flat ground [4,5]. The resulting controller does not need the dynamic information in order for a legged robot to perform *steady* dynamic walking. Thus, it allows a computationally less intense framework for the control since it does not require the computation of inverse dynamics for the legged robot.

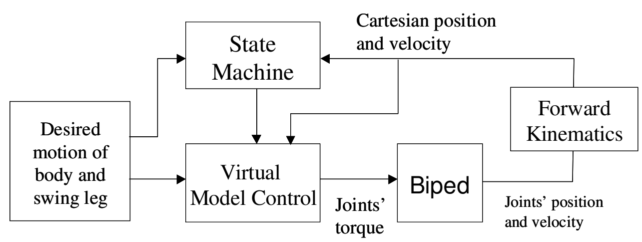


Figure 2. Control architecture

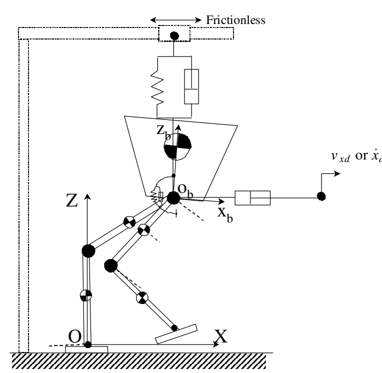


Figure 3. Virtual components used for biped walking.

Table 1. Gait parameters

Parameter	*Notation*
Desired pitch angle of the body	α_d
Desired hip height from the global slope	h_d
Desired horizontal velocity of the hip	v_{xd}
Desired step length	s_l
Distance from the front ankle at which double support phase transits to single support phase	l_t
Swing leg : *a) Desired lift height* *b) Swing time*	 h_l t_s

Table 2. Parameters of virtual components

Parameter	*Notation*
1. *Spring stiffness (in* z *direction)*	k_z
2. *Damping coefficient (in* z *direction)*	b_z
3. *Damping coefficient (in* x *direction)*	b_x
4. *Rotational spring stiffness (in* α *direction)*	k_α
5. *Rotational damping coefficient (in* α *direction)*	b_α

4 Sloped Terrain Implementation

This section includes strategies for the biped to overcome sloped terrain of unknown slopes and transition locations. We assume that the terrain has no variation perpendicular to the sagittal plane. The minimum and maximum slope gradients are -20^o and +20^o, respectively. We also assume that no slippage occurs.

The simulated biped has only discrete sensors at the toe and heel to sense the foot's contact with the ground. Together with the joint position readings, the information provided by these discrete sensors is used to compute slope gradients at the start of each double support phase. The biped adjusts its gait accordingly to continue its stable locomotion on the slope.

In the double support phase, when the biped is on a slope, the front and rear supporting legs are resting on different elevations. We call the virtual slope that is formed by joining the ankle of the front and rear legs the *global slope*. The actual slope that each foot is resting on is called the *local slope*. The local and global slope gradients are computed at the beginning of the double support phase.

4.1 Upslope and Downslope Walking

There are many possible posture for the biped to adopt while walking on upslope and downslope. In this preliminary study, we choose to keep the desired horizontal velocity unchanged and the body at the same upright posture while the biped walks on the sloped terrain. We also choose to fix the desired step length of the biped. For energy efficiency, we want the biped to walk with the posture as high as possible without causing the legs to reach singular configurations. Therefore, the desired hip height of the biped is computed based on geometric considerations (considering the global slope, transition location from double to single support and the desired step length). This results in a desired body height which varies with the slope gradient.

For upslope walking, the height limit of the biped is computed based on the desired step length, the distance from the front ankle at which the double support phase transits to the single support phase, and the singularity consideration of the back supporting leg during the double support phase (see Figure 4). We denote h_{limit} to be the hip height limit measured along the direction of the gravitational field from a global slope. By geometric consideration, the hip height limit h_{limit} is computed by Equation (4):

$$h_{limit} = \sqrt{(l_1 + l_2)^2 - r^2} - r \tan\beta \qquad (4)$$

where $l_1 + l_2$ is the total length of the leg (excluding the foot); β is the slope gradient; and $r = s_l \cos\beta + l_t$.

A factor k_{height} is multiplied to the height limit h_{limit} to give the desired height of the hip from a global slope, h_d. k_{height} is typical chosen to be around *0.85*. For larger slope variations, it should be smaller.

For the downslope, depending on the swing leg's touch-down location, both the back supporting leg during the double support phase and the swing leg during the single support phase may reach singular configuration as shown in Figure 5(a) and Figure 5(b), respectively. In the algorithm, we have set the swing leg to touch down when the vertical projection of the hip is between both legs. For such strategy, the case depicted in Figure 5(b) can occur and the corresponding height limit h_{limit} is computed as in Equation (5):

$$h_{limit} = \sqrt{(l_1 + l_2)^2 - r_1^2} + r_1 \tan\beta \qquad (5)$$

where $r_1 = 0.5 s_l \cos\beta$.

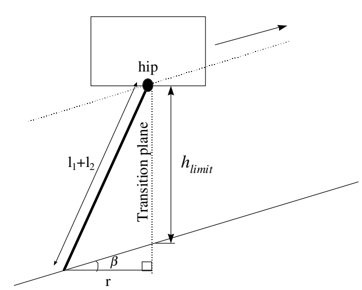
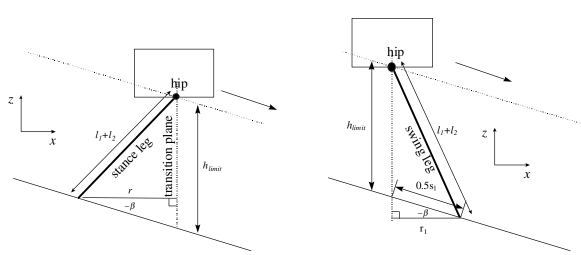


Figure 4. Geometric constraint to calculate h_{limit}: Level and upslope.



(a) (b)

Figure 5. Geometric constraint to calculate h_{limit} during downslope walking: (a) case 1; (b) case 2.

The minimum of the computed hip height limit h_{limit} between Equations (4) and (5) is used to compute the desired hip height h_d during the downslope walking. These equations can also be used for level walking where β is zero.

4.2 Transition Cases

This subsection considers transitional walking from level to slope ground and from slope to level ground, where the slope can be either ascending or descending. We first discuss the level-to-upslope and downslope-to-level transition. Both result in prematured landing of the swing leg.

For level-to-upslope transition, we employ a strategy similar to the one adopted by Zheng and Shen [7]. However, instead of using the force feedback approach, we set the ankle torque of the swing leg to zero when the swing foot touches the upslope surface. This allows the swing foot to orient itself and adapt to the slope according to the natural compliance (see [1] for details).

When both the heel and the toe of the swing foot are on the slope, they trigger the transition from the single support phase to the double support phase. The biped then computes the gradient of the global slope based on the joint angles. Note that the global slope gradient is not the same as the real slope gradient since both feet are not on the same slope yet (see Figure 6(a)). The global slope is an imaginary intermediate slope whose gradient is between the level ground gradient (equal to zero) and the actual upslope gradient. However, the biped considers the global slope to be the actual terrain slope during the double support phase. It computes the desired walking height based on the global slope.

When the biped switches to the single support phase, it continues to compute the desired walking height based on the global slope. The swing leg trajectory of the single support phase is also planned using the global slope. However, when the biped is in the double support phase again, both its legs are on the actual slope and the global slope will have the same gradient as the actual slope (see Figure 6(b)).

Note that during transition walking, the actual step length of the biped may vary significantly from the desired step length. For the level-to-upslope transition, the variation in the step length is due to the premature landing of the swing foot. The biped will reach a steady walking gait as it continues to walk on the same slope.

The usage of global slope instead of local slope to compute the desired height of the biped is analogous to the usage of a low-pass filter to get rid of high frequency noise. For example, the biped may walk on a ground with many local variation in elevation. Using global slope information will reduce unnecessarily large variation in trajectory during locomotion. The strategy for the level-to-upslope transition is also applied to the downslope-to-level transition.

We now consider the level-to-downslope and upslope-to-level transitions. During the level-to-downslope transition, the biped executes the usual walking control for single support phase until the swing time has expired. When the swing time expires, if the swing foot has not touched down, the biped will exert a preset downwards force exerted at the swing leg's ankle so that the swing foot will continue on its way down. The downward force will cause the swing leg's ankle to penetrate through a virtual surface (which is the global slope) (see Figure 7(a)). When the virtual surface is penetrated, the biped re-computes the gradient of the global slope based on the instantaneous position of the swing leg's ankle (see Figure 7(b)) and adjusts the desired hip height accordingly. This is a continuous process. After the swing leg has touched down, the state machine will switch to the double support phase and the biped will compute the intermediate global slope (see Figure 7(c)). In this phase, the biped will compute the desired hip height based on the global slope. The swing leg of the next single support state will also follow this global slope. The biped then goes through the whole sequence (Figure 7) again before both feet are on the same slope. The strategy for the level-to-downslope transition can also be applied to the upslope-to-level transition.

For both the level-to-downslope and upslope-to-level transitions, we have to control the swing leg so that it will not hit the ground prematurely. To avoid such an event, the desired lift height for the swing leg is set to a value which will enable it to clear all the edges of the level-to-downslope and upslope-to-level transitions. This is based on the assumption that we know the maximum change in the gradients for each slope transition.

Although this subsections only describe the strategies used to handle four simple slope transition cases, they are applicable to other transition cases as long as there is no vertical terrain variations.

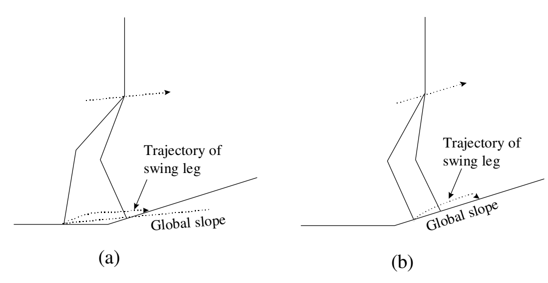


Figure 6. (a) Global slope whose gradient is different from that of the actual slope; and (b) global slope whose gradient is the same as that of the actual slope.

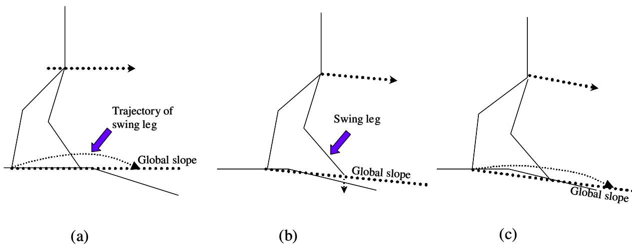


Figure 7. Sequence for level-to-downslope transition.

5 Simulations Results

The simulated biped was tested over several terrain profiles, two of which we discuss below. Sloped terrain *Profile One* (shown in the top graph of Figure 9) was used in the simulation to observe and compare the key output variables for the upslope, downslope and transition terrain walking of the biped. Sloped terrain *Profile Two* (shown in the top graph of Figure 10) which is rougher than *Profile One* was used to illustrate the robustness of our approach for the biped to walk over a sloped terrain which consisted of a series of unknown slopes.

The desired values of the key gaits' variables and the virtual components' parameter were set as in Table 3. The desired hip height of the biped was computed as discussed in the previous section.

5.1 Walking Over the Terrain Profile One

Figure 8 shows a stick diagram of the biped walking over the sloped terrain *Profile One* from left to right. Figure 9 show the profiles of the key variables. In Figure 9, the vertical "dash-dot" and "dotted" lines represent the start of the single support and the double support phases, respectively.

The third graph from the top of Figure 9 shows the actual hip height profile (solid line) of the biped measured from the global slope. This graph shows that the biped was able to track the desired hip height (dashed line) within a tolerable range. The ripple found in the actual hip height profile was mainly due to the swing leg dynamics and the variation in the effective mass of the biped as perceived at the hip.

We observe that when the global slope gradient was negative, the desired hip height (dashed line in the top third graph of Figure 9) of the biped was higher than when the global slope gradient was positive. This was the result of the geometric considerations (Subsection 4.1) when we computed the desired hip height of the biped.

From the horizontal velocity ($\dot{x}$) profile of the hip in Figure 9, we observe that the velocity fluctuation is higher for upslope walking than for downslope walking. This is mainly due to two causes. First, the dynamic frequency of the biped during the single support phase is higher for upslope walking than for downslope walking because the hip height of the biped (measured from the slope) is lower.

Table 3. Desired values of some of the gait variables and the parameters of the virtual components set in the simulation

Variable/parameter	*Value*
α_d	0 rad
v_{xd}	0.4 m/s
s_l	0.28 m
l_t	-0.03m
h_l	0.07 m
k_z	500 N/m
b_z	200 Ns/m
b_x	200 Ns/m
k_α	50 Nm
b_α	20 Nms

The swing leg trajectory is the second cause for the difference in the velocity profile. We observe from the stick diagram that the swing leg has different trajectories for upslope, downslope and level walking. Hence, the dynamic disturbance of the swing leg for each of the cases is also different. This results in different velocity profiles for the three cases. For example, in the upslope walking, the swing leg starts from a configuration which is closer to the singular configuration (ie., fully straightened), thus causing higher disturbance to the horizontal velocity.

The horizontal velocity also deviates significantly from the desired value at the upslope-to-level transition and the level-to-downslope transition. This is mainly due to the fact that the biped takes additional time to *feel* the ground at these locations during the single support phase. This delay in step time results in slightly higher horizontal velocity when the biped reaches the next double support phase. We also observe that the horizontal hip velocity, just after the touch down of the swing leg, is a fraction of the velocity just before the touch down. This is due to the impact effect of the swing leg when it touches down [3].

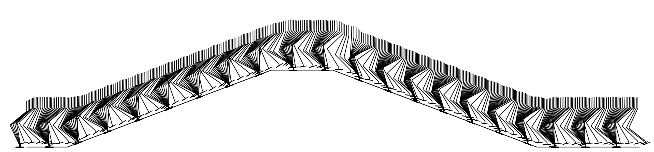


Figure 8. Stick diagram of the biped walking over the sloped terrain Profile One from left to right (spaced approximately 0.08 s apart and showing only the left leg).

5.2 Walking Over the Terrain *Profile Two*

The results from the terrain *Profile Two* demonstrate the robustness of the algorithm developed for the sloped terrain walking. Figure 10 shows the profiles of the key variables. Note that the profile of the terrain was not known to the biped in advance. The biped was required to *feel* its way through the terrain. From Figure 10, we observe that the biped can cope with this rougher terrain without much difficulty. The actual hip height, hip horizontal velocity and pitch angle of the body were well-behaved in the simulation.

6 Conclusions

This paper has demonstrated the successful application of the Virtual Model Control to a simulated seven-link planar biped for it to walk *dynamically* and *steadily* over sloped terrain with unknown slope gradients and transition locations. It was assumed that the slope gradients were between -20^o and +20^o; and the sloped terrain had maximum transitional gradient change of less than 20^o. In the implementation, the *global slope* was used to compute the desired hip height based on geometric considerations and this resulted in a straight line trajectory parallel to the global slope. It was very simple to implement and did not require an extensive sensory system to achieve blind walking. The algorithms can be extended to more abrupt terrain changes, such as stair climbing, if properties such as the general location and layout of the terrain is known or detected visually [1].

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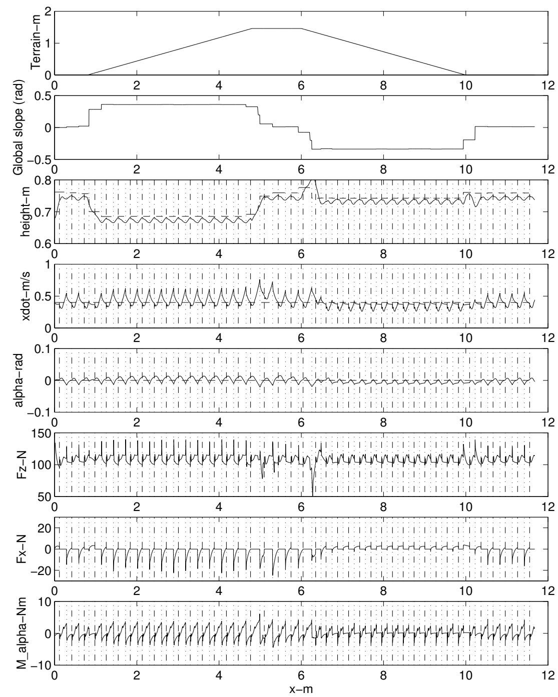

Figure 9. Profiles of the key variables when the biped walked over the sloped terrain Profile One.

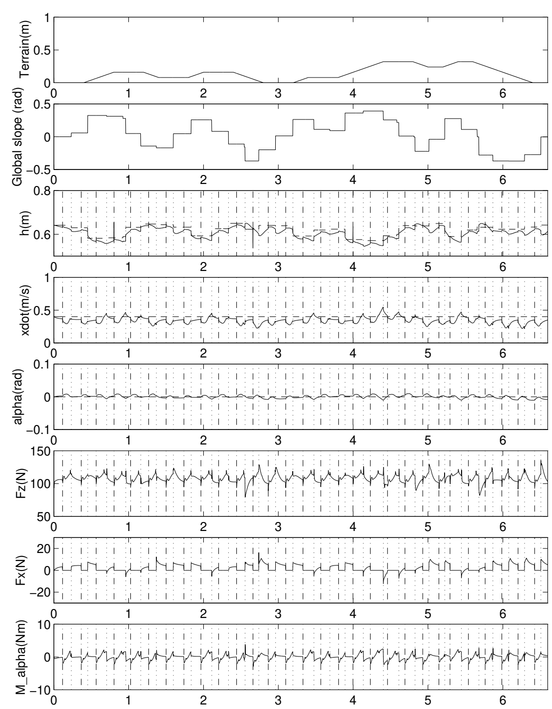

Figure 10. Profiles of the key variables when the biped walked over the sloped terrain Profile Two.