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Biped Robot Locomotion in Scenes with Unknown Obstacles

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Abstract

The focus of this work is on sensor-based motion planning of a biped robot operating in an environment with obstacles. Using its sensors, the robot is able to obtain local information about its surroundings. A number of stable walking patterns are investigated. Depending on the shape and location of an obstacle on the robot's way, the decision making algorithm chooses the best relevant walking pattern; the robot then negotiates the obstacle and resumes stable motion. The proposed control strategy is based on the Zero Moment Point (ZMP). The stability of each walking pattern is ensured by adjusting the swing leg center of mass (COM) and hip position trajectories in a trial and error fashion, fast enough for real-time implementation. Simulation experiments demonstrate stability of motion when negotiating various obstacles.

1 Introduction

Biped locomotion is a popular research area in robotics due to the high adaptability of a walking robot in an unstructured environment. When attempting to automate the motion planning process for a biped walking robot, one of the main issues is assurance of dynamic stability of motion. This can be categorized into three general groups [1]: body stability, body path stability, and gait stability. A Zero Moment Point (ZMP), a point where the total forces and moments acting on the robot are zero, is usually used as a basic component for dynamically stable motion.

Stable walking using a compensative inverted pendulum was achieved e.g. by the robot [2] with eight control variables (called degrees of freedom, DOF) and an upper body acting like an inverted pendulum. Other approaches for stable locomotion, with or without ZMP use, have been considered as well (see, e.g. [5],[6],[7]). In a more recent achievement, Honda's humanoid robot P2 [8] showed the ability to walk forward, backward, right, left, up and down a staircase, and on the uneven terrain.

Now suppose the biped robot has a sensor (say, vision) that allows it to detect an object in front of it, and suppose it walks in a scene with obstacles. In principle, this should allow the robot to operate in the scene the way humans do, avoiding the obstacles while maintaining stable motion. When encountering an obstacle on its way, depending on the obstacle's size and shape, a way of recuperating from the disturbance is to step over the obstacle, or step on it, or try to pass around it. Foot placement during this operation should be planned so as to preserve dynamical stability. If feasible, such a behavior would produce dynamically stable real time motion in an unstructured environment with unknown obstacles.

Attempting such an approach is the topic of this work. The work builds and further extends the methodology presented in [3], which allows a biped robot to maintain dynamically stable motion under force disturbances. Some details are skipped due to the lack of space; for those, refer to [4].

2 The Model of Biped Locomotion

The robot consists of seven body parts [5]: one hip, two thighs, two calves, and two feet. Body parts have certain masses, which all affect the dynamics and the walking pattern. There is a total of twelve DOF – six at the hip, two at knee, and four at ankle, Figures 1, 2. Similar to the human knee, robot knee joints are able to turn only about θ_4 axis; each joint between the hip and thigh has three DOF. The ankle joint turns about θ_5 axis and θ_6 axis.

The robot is assumed to be equipped with sensors (say, a vision) capable of sensing obstacles on its way and assessing their dimensions and distances to them. Only obstacles directly in front of the robot are considered. Each obstacle is a parallelepiped: it can be

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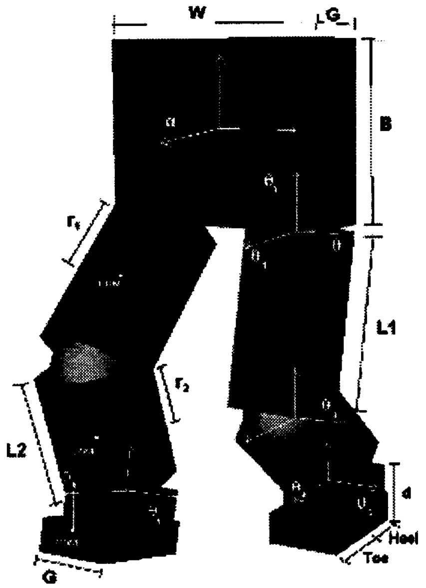

Figure 1: Model of the walking robot.

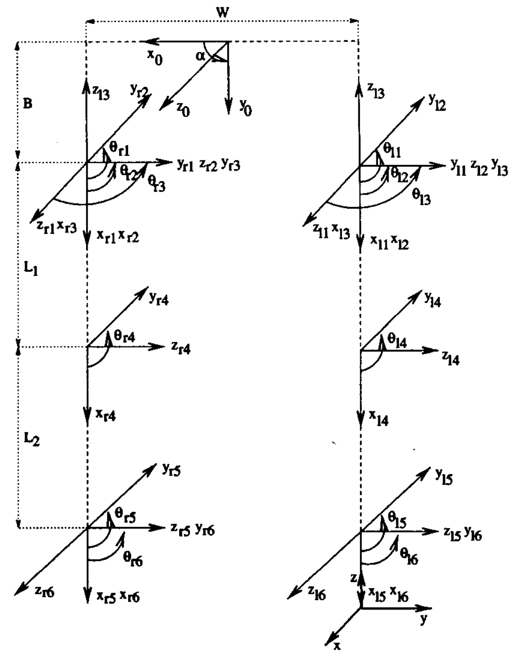

Figure 2: The kinematic parameters.

small enough to step over it by raising a leg, or small and wide enough to step on/off it, or tall enough so that side steps are necessary to pass around it.

Two major phases in walking dynamics are hypothesized [5]: single support phase and double support phase. During the single support phase, one leg is on the ground, and the other leg is in the swinging motion. As soon as the swinging leg reaches the ground, the system is in the double support phase, Figure 3. Denote T_2 the time period of deploy phase, T_3 – of swing phase, T_4 – of heel contact phase, and $2T_1$ – of support phase. The time period of a single walking cycle within which all body parts return to their original configuration is $4T_1$.

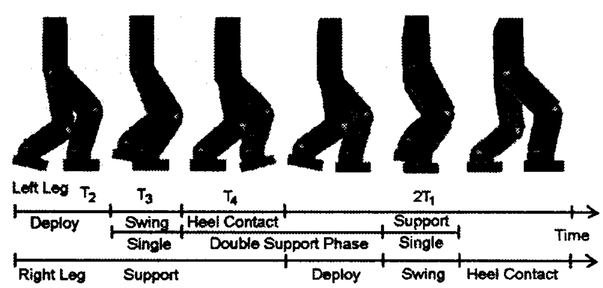

Figure 3: Phases of a single walking cycle.

3 Zero Moment Point and Locomotion

ZMP is defined as a point on the walking surface in which the total forces and moments acting on the robot are zero [1]. If at a given moment of motion all the forces acting on the robot (gravity, reaction forces, and inertia forces) are balanced so that ZMP lies within the current robot footprint, the robot's position at this moment is dynamically stable. If this is true throughout the motion, and the trajectory of the robot's center of mass (COM) is smooth and lies be-

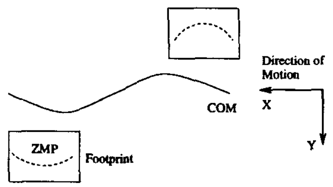

Figure 4: Phases of a single walking cycle.

tween both legs footprints, the motion is dynamically stable, Figure 4.

4 Negotiating Obstacles

We consider five basic walking patterns (including normal walk) to be used for on-line obstacle avoidance:

Variation in step length. With the robot dimensions under the model used, a normal motion step (single walking cycle) is of length 28 inches. When sensing an obstacle that is to be negotiated, the robot may decide to step on or over it, and this may require the robot first positioning itself at a specific position relative to the obstacle. This can be done by modifying the step length appropriately. Due to the effects of dynamics and related computational difficulties, it is not easy to compute the trajectory for an arbitrary step "on the fly"; instead, a small number of "typical" step lengths that together cover a large set of situations are developed and "canned". Relative to the normal step length, this includes a half step (14 inches), quarter step (7 inches), and zero step (0 inch) lengths options. By aplying an appropriate scheme for the dynamics of swing leg and hip position trajectories, a stable walk for those walking patterns is obtained.

Variation in the swing leg height. With normal walk pattern, the robot can negotiate obstacles up to 1 inch high. To step over higher obstacles, the leg needs to be raised higher than normal. This changes the whole swing leg trajectory (according to the model, the COM of a swinging leg trajectory has parabolic shape [5]). Similar to the above, five trajectories that take care of the motion dynamic stability are precomputed and stored – for the obstacle heights (height ranges) 1, 2, 3, 4, and 5 inches. (Bigger heights seem to be feasible; no attempt was made to maximize the step height for stepping on/over obstacles). After obtaining from the sensors the height and width of the obstacle that is to be negotiated, and after deciding to negotiate it by stepping on or over it, the robot chooses and executes the appropriate leg height trajectory.

Forward-side step and side step. When the obstacle is too high to step over or on it, the robot will attempt to pass around it. The (local) direction of passing around an obstacle (left or right) is decided upon beforehand; in our experiments (see below) it has been "left". If at the moment of such a decision the robot still has room for forward motion, it can be combined with side motion, producing a *forward-side step*. Otherwise, a *side step*, which has no forward component and is perpendicular to the prior direction of motion, is executed; in our scale, the side step is 6 inches long.

To keep the motion smooth, depending on the swinging leg at the moment of a (left) forward-side step, it may be either left or right leg that starts the maneuver. If it is the left leg, the forward-side step is simply build of the two components as above; after its execution the robot torso ends up 6 inches to the left. Because of the possible entanglement between two legs, the same cannot be done with the right leg starting the maneuver. In this case, after the step execution the right foot end up right in front of the left foot; the next step by the left leg will complete the forward-side step maneuver. Again, tied to this operation is the adjustment of the swing leg COM and hip position trajectories so as to satisfy dynamics stability.

Stepping on/off obstacles. If the obstacle is wide and flat enough to step on, sometimes it is more efficient to negotiate it by stepping on it rather than going around it. Similar to the stepping over option above, five dynamically stable trajectories, for the foot heights from 1 to 5 inches, are precomputed and stored. Once the height of such an obstacle is known, the swing leg COM and hip position trajectories are chosen from the set. The walking pattern of stepping off the obstacle is similar. Depending on the length of the obstacle, stepping on the obstacle may be followed by few normal steps, then perhaps a reduced length step, and finally stepping off step.

The flowchart of the overall decision making algorithm capable of negotiating a sequence of obstacles of the types described above is shown in Figure 5. Darkened boxes indicate the final action in the current cycle, after which a new step is initiated and the control goes to the top of the flowchart. The algorithm for selecting the walking pattern utilizes nested if-else commands.

5 Simulated Examples

Described here are the results of computer simulated experiments with two-legged locomotion in the

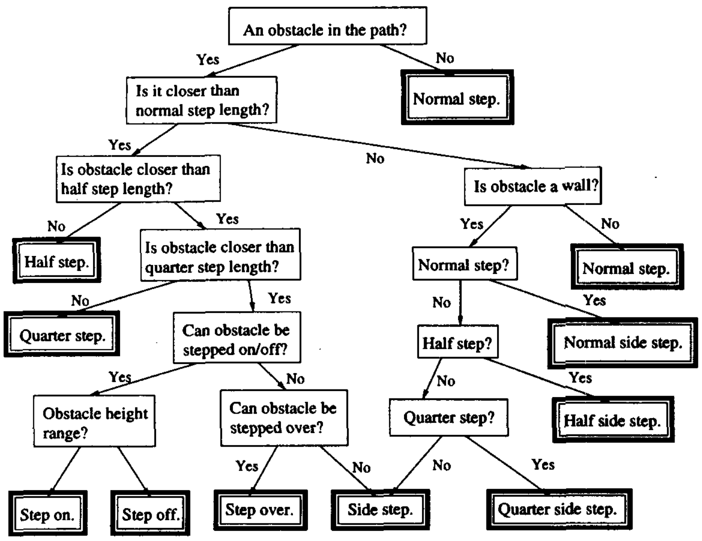

Figure 5: Flow chart of the walking pattern decision making algorithm.

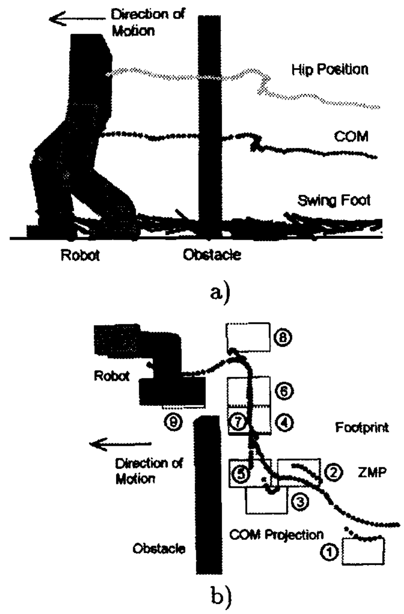

Figure 6: Stepping around a wall: a) side view; b) top view. Also shown are hip position, COM, and swing foot (broken lines) trajectories. (Positions of the robot differ in both views).

presence of obstacles.

Avoiding a wall. If the obstacle's height prevents the robot from stepping on or over it, it is designated as "wall". It can be negotiated by passing around it, by using forward-side or side stepping. The choice depends on the distance between the robot and the wall at the step execution time. Smoothness of COM and hip trajectories indicates stability of the walking dynamics, Figure 6. While at the position 1 (footprint 1 in the figure), the robot sees the obstacle, decides to pass around it, and executes a forward-side step followed by few normal steps. Note that after the forward-side step for a short while the ZMP trajectory is out of the safety zone; but, since in the second step (footprint 2) the robot regains its stability by bringing the ZMP trajectory to the safety zone, the robot maintains its balance. If the wall were wider, more than one forward-side steps would be executed.

Stepping over a block. With our model, the robot can step over a block of up to 5 inches high and up to 4 inches wide. When stepping over a 5 inch high block, the robot has 14 inches of thigh height, 11 inches of calve height, and 5 inches of foot height. The ratio between the height of the block and the total height of the model leg is thus one-to-six. Note the smoothness of the COM and hip position trajectories, Figure 7 – this indicates dynamic stability. Notice also that the swing foot trajectory does not touch the obstacle; this means there is no collision between the swing foot and the obstacle.

The robot's first step (footprint 2, Figure 7) is a normal step, to get close enough to the obstacle to prepare for stepping over it. This turns out to be insufficient – on the second step (footprint 3) a quarter size step is executed. Then (footprint 4), a zero step is executed; now both feet are aligned and the robot is ready for stepping over the obstacle. While the ZMP and COM trajectories have been in the safety zone so far, during the stepping-over step (transition between footprints 4 and 5) they temporarily move out of the safety zone. Similar to the forward-side maneuver above, in the next step stability is regained by bringing the ZMP trajectory back to the safety zone. By the time the robot reaches footprint 6, Figure 7, it is in balance again.

Stepping on/off a block. If the obstacle's height is up to 5 inches and its width is more than the length of the robot foot (9 inches), the robot will attempt to step on the obstacle instead of stepping over or going around it. The dimensions of the obstacle shown in Figure 8 are: height = 5 inches, width = 30 inches, and depth = 15 inches. The first step, of the quarter step length, positions the robot closer to the obstacle (footprint 2). On the next step it steps onto the obstacle; the ZMP and COM trajectories here indicates step stability. When on the obstacle, the robot decides to

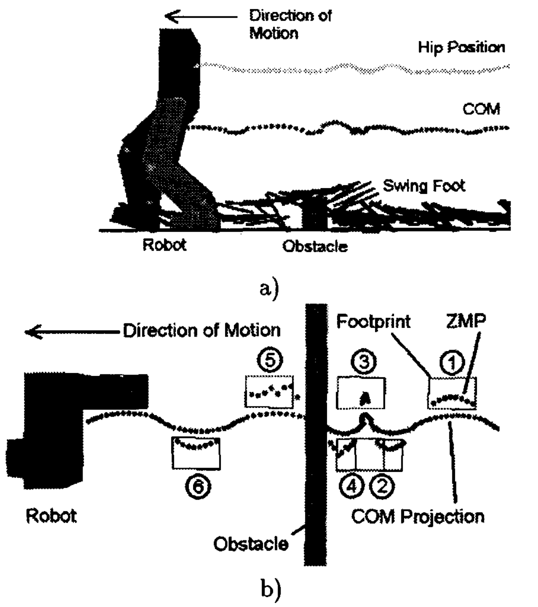

Figure 7: Stepping over a block: a) side view; b) top view. Also shown are hip position, COM, and swing foot trajectories. (Positions of the robot differ in both views).

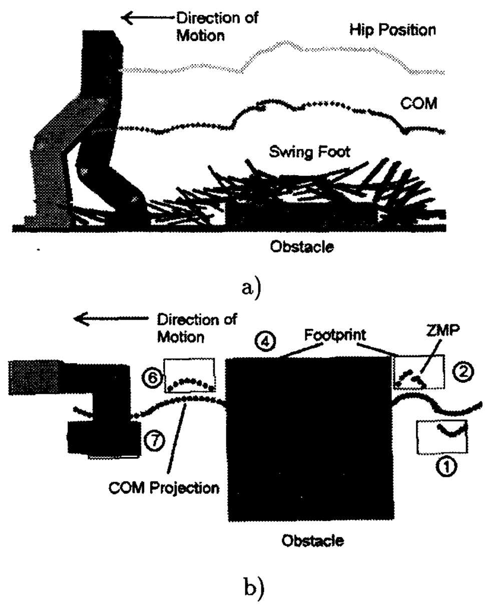

Figure 8: Stepping on/off a block: a) side view; b) top view.

take a normal step before preparing for the stepping-off scheme. When its both feet are aligned, the robot sets to step off the obstacle, (footprints 4 and 5). The stepping-off stage is stable as well, as indicated by the ZMP and COM trajectories, footprint 5. The swing foot trajectory indicates that there is no collision between the swing foot and the obstacle, Figure 8.

Walking a staircase. This operation is done via a combination of the stepping-on/off patterns. The dimensions of the staircase shown in Figure 9 are: height = 5 inches for each step, width = 15 inches, and depth = 15 inches. The first step brings the robot closer to the obstacle. It then decides to step on the first stair. The ZMP trajectory here, footprint 2 in Figure 9, indicates that this motion is stable. Like in a normal human walk, the robot then strides its swing leg to the second stair, footprint 4. Though it would be safer to step on the staircase so that both feet are aligned on one step each time, this would be inefficient, and is not necessary. Therefore, the decision making algorithm makes one leg step over the first staircase and then immediately the other leg step on the second staircase, footprints 2, 3, 4. On top of the second stair, the robot adjusts the distance by making a small step, and then step off the staircase. The ZMP and COM trajectories during the whole process are in the safety zone; note the smoothness of the hip position and COM trajectories, Figure 9; this indicates stability of the transition between walk patterns. Note also that the swing foot trajectory does not interfere with the staircases.

A combination of obstacles. Shown here is the process of stepping over a block obstacle followed by passing around a wall. Unlike in Figure 6, the robot senses the wall, after it steps over the first (block) obstacle. The block is negotiated much the same as above: adjust the distance and step over. After stepping over the block obstacle, the robot sees the wall and takes a quarter length side step (footprint 6, Figure 10). After that, since the wall extends further to the side, the robot executes a quarter side step, sees that the wall is no longer obstructs its path, takes a normal step and continues walking past the wall. the ZMP and COM trajectories (Figure 10) are all in the safety zone, indicating that the combination of the stepping over pattern and the stepping around pattern is a stable pattern.

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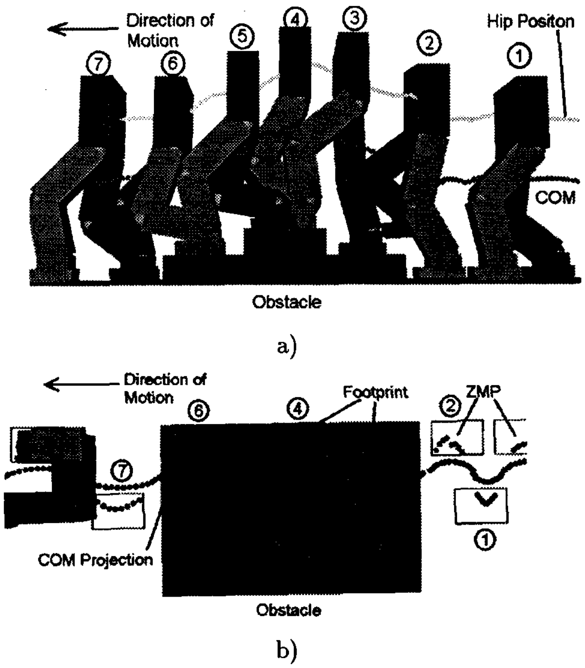

Figure 9: Walking staircases: a) side view (a number of robot positions along the path are shown); b) top view.

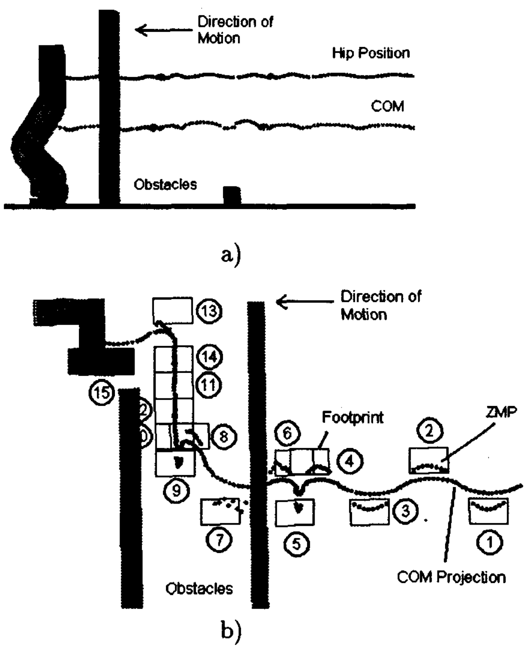

Figure 10: A combination of obstacles – stepping over a block and around a wall: a) side view; b) top view. (Positions of the robot differ in both views).

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