Robotica (2000) volume 18, pp. 389–402. Printed in the United Kingdom © 2000 Cambridge University Press

Local on-line planning in biped robot locomotion amongst unknown obstacles

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(Received in Final Form: December 9, 1999)

SUMMARY
The focus of this work is on sensor-based motion planning for a biped robot operating in a scene with unknown obstacles. Using on-line sensor information about its surroundings, the robot negotiates obstacles on its way. Depending on the obstacle's shape, size, and location, the decision-making system chooses an appropriate walking pattern. The robot then negotiates the obstacle and resumes stable motion. The walking pattern is chosen from a small number of precomputed patterns that together cover a reasonably wide range of possible situations. The overall control strategy is based on the concept of Zero Moment Point. Each precomputed pattern guarantees dynamically stable motion; its stability is obtained by adjusting the swing leg center of mass and hip position trajectories. The approach is fast enough for real-time implementation. Simulation experiments demonstrate stability of motion when negotiating various obstacles.

KEYWORDS: Sensor-based planning; Biped robot; Unknown obstacles; Locomotion; Zero moment point.

1. INTRODUCTION

Biped locomotion is a popular research area in robotics, due to the inherent high adaptability of a walking robot in an unstructured environment. When attempting to automate the motion planning process for a biped walking robot, the issue of dynamic stability of motion has to be tightly connected with the decision-making mechanism. The different parts of stability 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 has been achieved, e.g. by the robot[2] with eight degrees of freedom (DOF) and an upper body acting like an inverted pendulum. Based on this work, a humanoid robot with 41 DOF, called WABIAN-R, was developed.[3] Other approaches to stable locomotion, with or without the use of ZMP, have been considered as well (see, e.g. references 4–9). More recently, the humanoid robot P2 developed by a team from Honda Corp.[10] demonstrated the ability to walk forward, backward, right, left, up and down a staircase, and on the uneven terrain.

Now, suppose our biped robot has a sensor (say, vision) that allows it to detect objects in front of it, and suppose it walks in a scene with obstacles. In principle, this sensing should allow the robot to move the way humans do, avoiding obstacles on its way while maintaining stable motion. When encountering an obstacle, the robot would perceive it as a disturbance and would attempt to handle it so as to leave it behind and resume normal walk. Depending on the obstacle's size and shape, recuperating from the disturbance may include stepping over the obstacle, or stepping on it, or trying to pass around it. The problem here is to preserve stability of motion: foot placement during this kind of local operations should be planned so as to preserve dynamic stability. If feasible, such a behavior would produce dynamically stable collision-free real-time motion in an unstructured environment with unknown obstacles.

Attempting such an approach is the topic of this work. The work builds on and further extends the methodology presented in reference 6, which allows a biped robot to maintain dynamically stable motion under external force disturbances. As used here, the term "motion planning" refers only to local planning in the vicinity of the obstacle in question, and does not include the question of how the resulting motion fits into the global plan. Note, however, that the proposed algorithm can be used as part of a global sensor-based motion planning strategy (see, e.g., reference 11).

Material below is organized as follows. The model used and the connection between the concept of Zero Moment Point (ZMP) and locomotion are briefly discussed in Section 2. The strategy for maintaining stable ZMP, and thus stable motion, under external force disturbance is reviewed in Section 3, and its use in conjunction with a number of walking patterns necessary when negotiating specific types of obstacles is described in Section 4. Simulated examples are discussed in Section 5.

2. THE MODEL OF BIPED LOCOMOTION

The biped robot considered here consists of seven body parts:[7] one hip, two thighs, two calves, and two feet. There is a total of twelve DOF – six at the hip, two at the knee, and four at the ankle, see Figures 1 and 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.

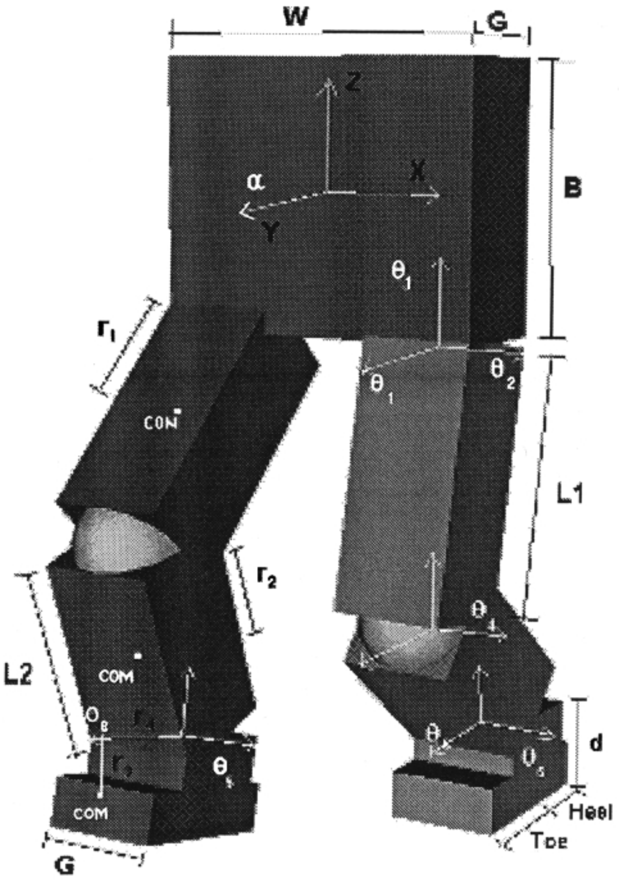

Fig. 1. Model of the walking robot.

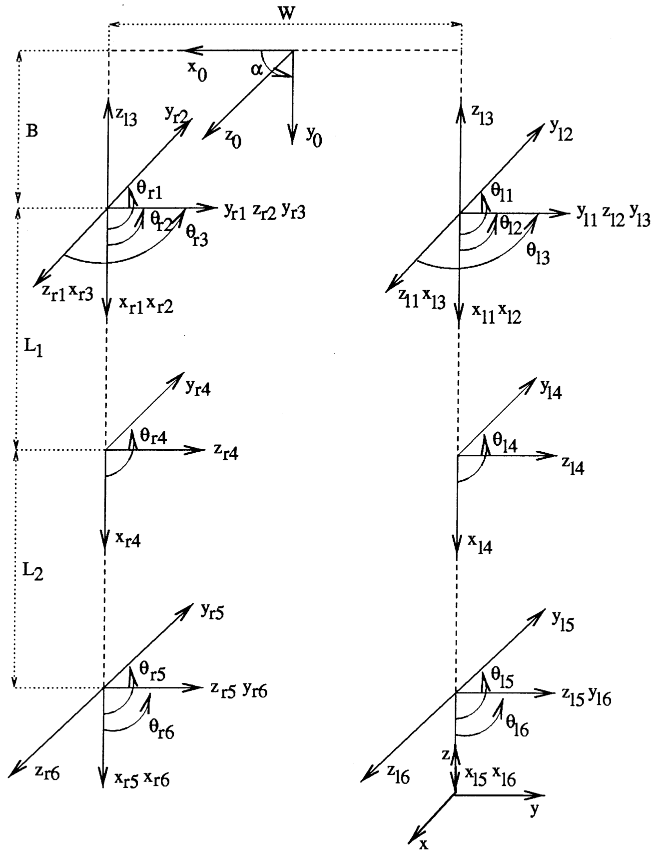

Fig. 2. The kinematic parameters.

For convenience in simulation software and following,[7] specific numeric values for linear and mass variables have been assumed in the model.

Namely, for the body parts lengths (see Figure 1):

G = 3 in (inches; about 7.6 cm),
B = 14 in,
W = 15 in,
L_1 = 14 in,
L_2 = 11 in,
d = 5 in,
Toe = 6 in,
Heel = 3 in

For the body parts masses,

mass of hip = 28.6 kg (63 pounds),
mass of thigh = 8.5 kg,
mass of calves = 5.5 kg,
mass of foot = 7.3 kg

Assume the robot is equipped with sensors (say, vision) capable of sensing surrounding obstacles and assessing their dimensions and distances to them. Among many values one can measure here, dimensions of objects and distance to them are measurements that will affect details of motion planning. For example, if the robot considers stepping over an obstacle, first it needs to position one of its feet next to the obstacle. To do that, an appropriate distance to the obstacle needs to be known. Another piece of information that will be of interest is the height of the obstacle – it will determine how high the robot's foot needs to be raised to clear the obstacle. Given its height, the obstacle may be too deep to be stepped over, in which case the robot will consider stepping on it, etc. We assume the robot's sensors allow it to obtain all such measurements.

For the sake of simplicity, assume that each obstacle is a parallelepiped: it can be small enough, thus allowing stepping over it by raising a leg; or small and deep enough so that one can step on and then off it; or tall enough, so that sidestepping is necessary to pass around it. (Realistic deviations from this assumption may make the necessary sensing measurements more complex, but should not affect the complexity of motion planning.) The maneuvers considered will not include turning. Only obstacles directly in front of the robot will be considered.

The principles and architecture of the control system used here are as in reference 7, (for those interested in control issues, the work also includes a discussion on the scheme's robustness). Accordingly, two major phases in walking dynamics are hypothesized: 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 $2T_1$ the time period of support phase (here one T_1 is when the leg which is in the air is brought from the previous step, and the other T_1 – when that leg moves ahead for the next step); T_2 – the

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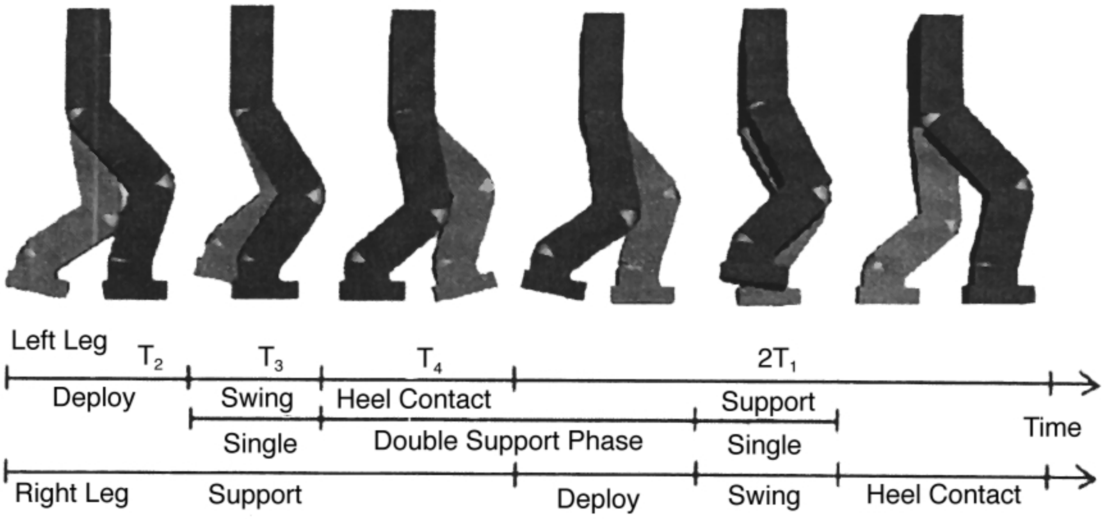

Fig. 3. Phases of a single walking cycle.

time period of deploy phase, T_3 – of swing phase, T_4 – of heel contact phase. Then, $T_2 + T_3 + T_4 = 2T_1$, and so the time period of a single walking cycle within which all body parts return to their original configuration is $4T_1$.

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 forces acting on the robot – gravity, reaction forces, and inertia forces – are balanced so that ZMP lies within the current robot footprint, then 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 between both leg footprints, the motion is dynamically stable, Figure 4.

3. ANALYSIS OF ZMP TRAJECTORY UNDER THE SIDE PUSH

Consider an external impulse force which at some moment acts on the robot, at the point shown in Figure 5 and in the direction perpendicular to the walking direction. With the robot mass fixed, the value of force can be replaced by the instantaneous velocity it generates. Assume the force always comes at the moment when the robot is in a single support phase, i.e. when one foot is in the air. Without loss of generality, assume the push occurs when the robot is in the left foot single support phase, as in Figure 5. (The control problem will be symmetrical for the right foot single support phase.) The push will move the robot center of mass off the z axis; further details will vary depending on the force value.

We will consider two situations that can take place here – when the push comes from the right, in the positive direction of y axis, and when it comes from the left, in the negative direction of y axis, Figure 4. Angular positions and velocities of the robot hip center under external forces of different values and directions are shown in Figures 6, 7, 8, and 9. If the force is large enough to move the center of mass sufficiently far from the z axis, Figure 5, the robot will start falling down in the direction of positive y, thus increasing the angle of its *angular position*. This can be seen in Figure 6: if the initial velocity exceeds 50 in/s, the robot falls down in the positive y direction.

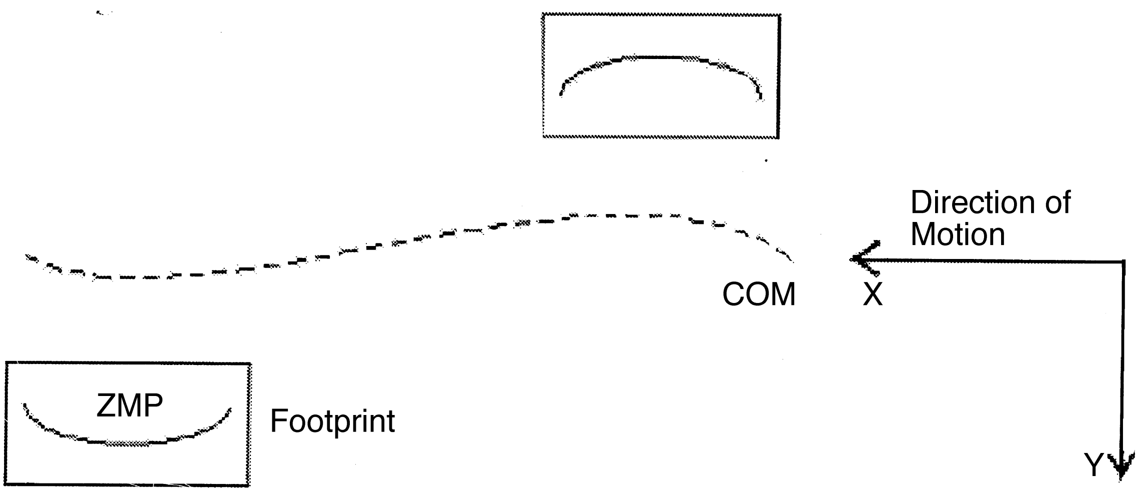

Fig. 4. Dynamically stable ZMP and COM trajectories.

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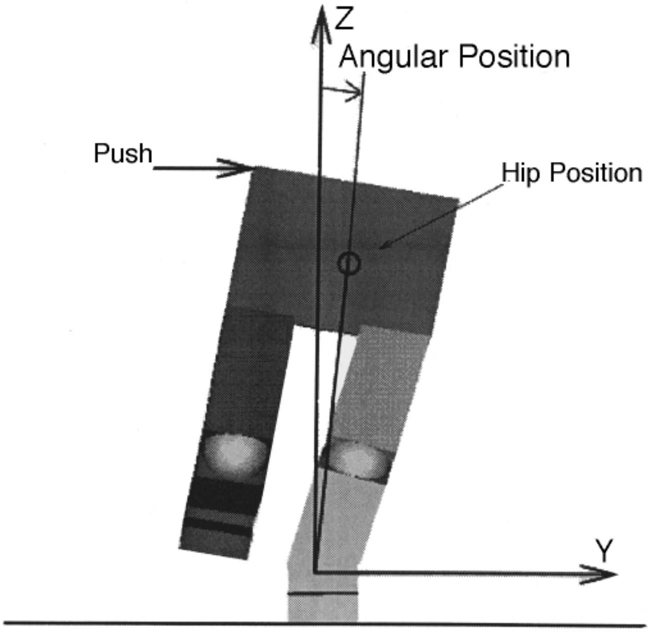

Fig. 5. Front view of the robot under a push in the positive *y* direction.

In the first situation, the push is in the positive *y* direction; the left leg is supporting and the right leg is swinging. The corresponding ZMP trajectories are shown in Figure 10. In the second situation, the push is in the negative *y* direction; again, the left leg is supporting and the right leg is swinging. The corresponding ZMP trajectories are shown in Figure 11.

Therefore, when reacting to the external force, the robot will start falling in the positive or negative *y* direction, depending on the direction of the push. If it is falling in the positive *y* direction, the ZMP trajectory shifts in the same direction; the opposite occurs for the negative *y* direction. When the push is strong, the robot may need few steps to recover its balance. In this case, even though the first step in the multiple-step recovery procedure does not preserve the

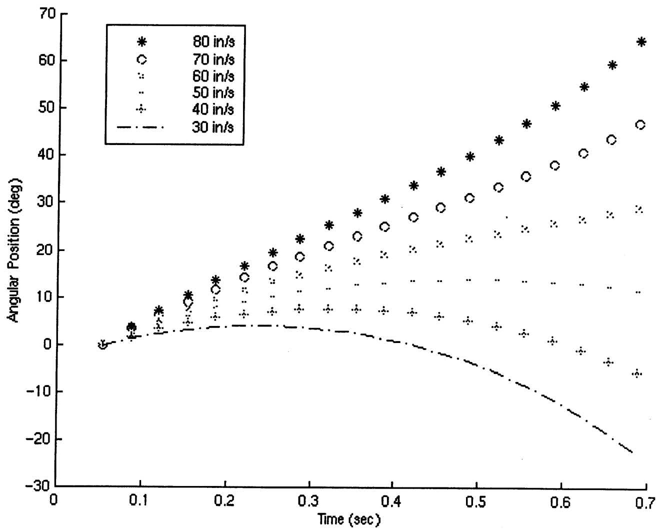

Fig. 6. Angular positions of the robot's hip when the robot is falling in the positive *y* direction (see Figure 5), under different forces; the push is from the right.

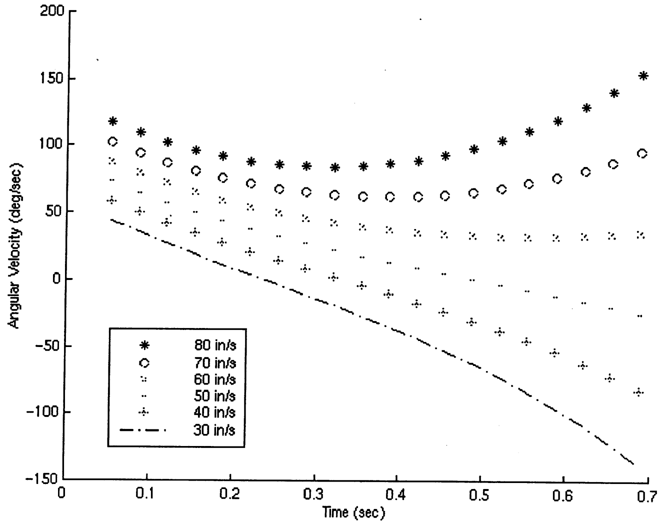

Fig. 7. Angular velocity of the hip when the robot is falling in the positive *y* direction (see Figure 5), under different forces; the push is from the right.

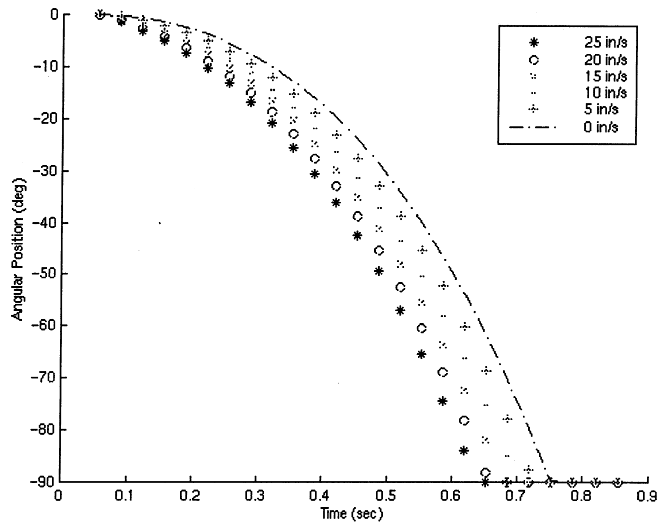

Fig. 8. Angular positions of the hip when the robot is falling in the negative *y* direction (see Figure 5), under different forces; the push is from the left.

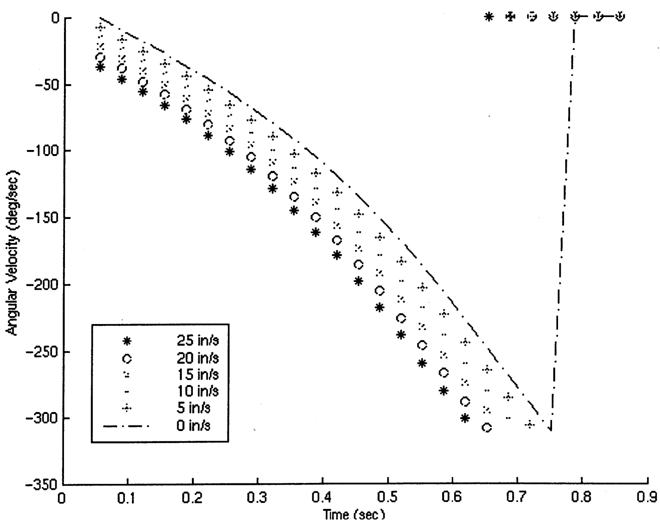

Fig. 9. Angular velocity of the hip when the robot is falling in the negative *y* direction (see Figure 5), under different forces; the push is from the left.

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ZMP and COM trajectories in the safety zone, the balance of the robot is regained by taking another recovery step.[6]

4. NEGOTIATING OBSTACLES

The mechanism above for regaining the robot balance after a side force impact will now be used in the procedure for on-line obstacle avoidance. An attempt to avoid an obstacle changes the normal pattern of dynamic balance, and so appropriate modifications of control are necessary to regain balance. For example, when attempting stepping over an obstacle, an imbalance in the ZMP trajectory occurs. This imbalance can be handled in the same way as if it were caused by an external force. We consider five basic walking patterns, – normal walk, variation in step length, variation in the step height, side stepping, and stepping on/off.

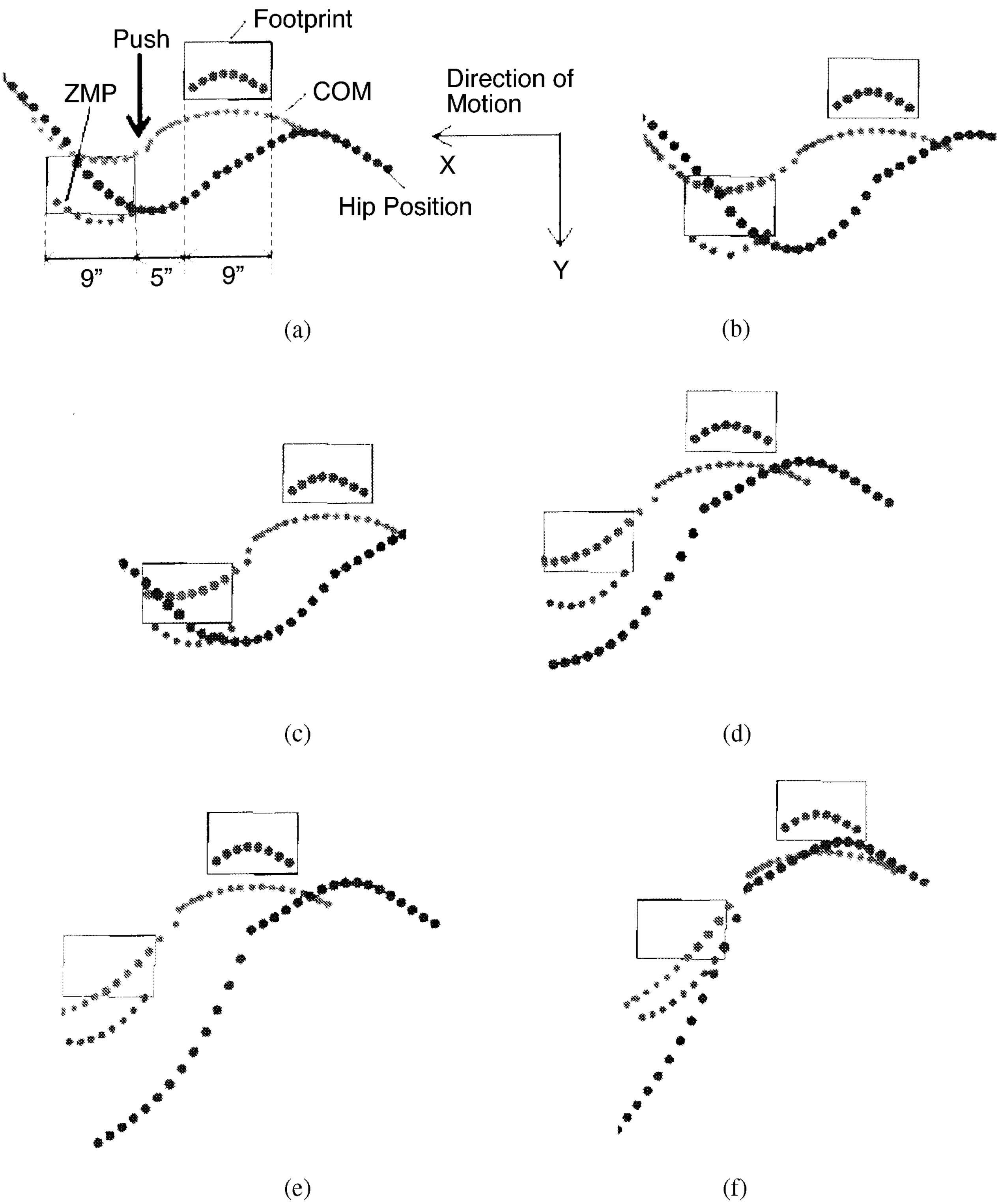

Fig. 10. ZMP trajectory under a push in the positive *y* direction, with initial velocity of (a) 0 in/sec, (b) 5 in/sec, (c) 10 in/sec, (d) 15 in/sec, (e) 20 in/sec, (f) 25 in/sec. In (a) foot/step dimensions are also shown.

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These five walking patterns are used to handle various types of on-line obstacle avoidance. For example, walking around a wall involves forward-side and side-step motion, perhaps combined with a variation in the step length. In the version of the work presented here, no combinations of side steps and on/off/over steps are considered. Similarly, as mentioned before, no attempt is made to generate purposeful motion leading the robot to some goal – this (upper) level of intelligence is outside the topic of this paper. The five walking patterns are now considered in more detail.

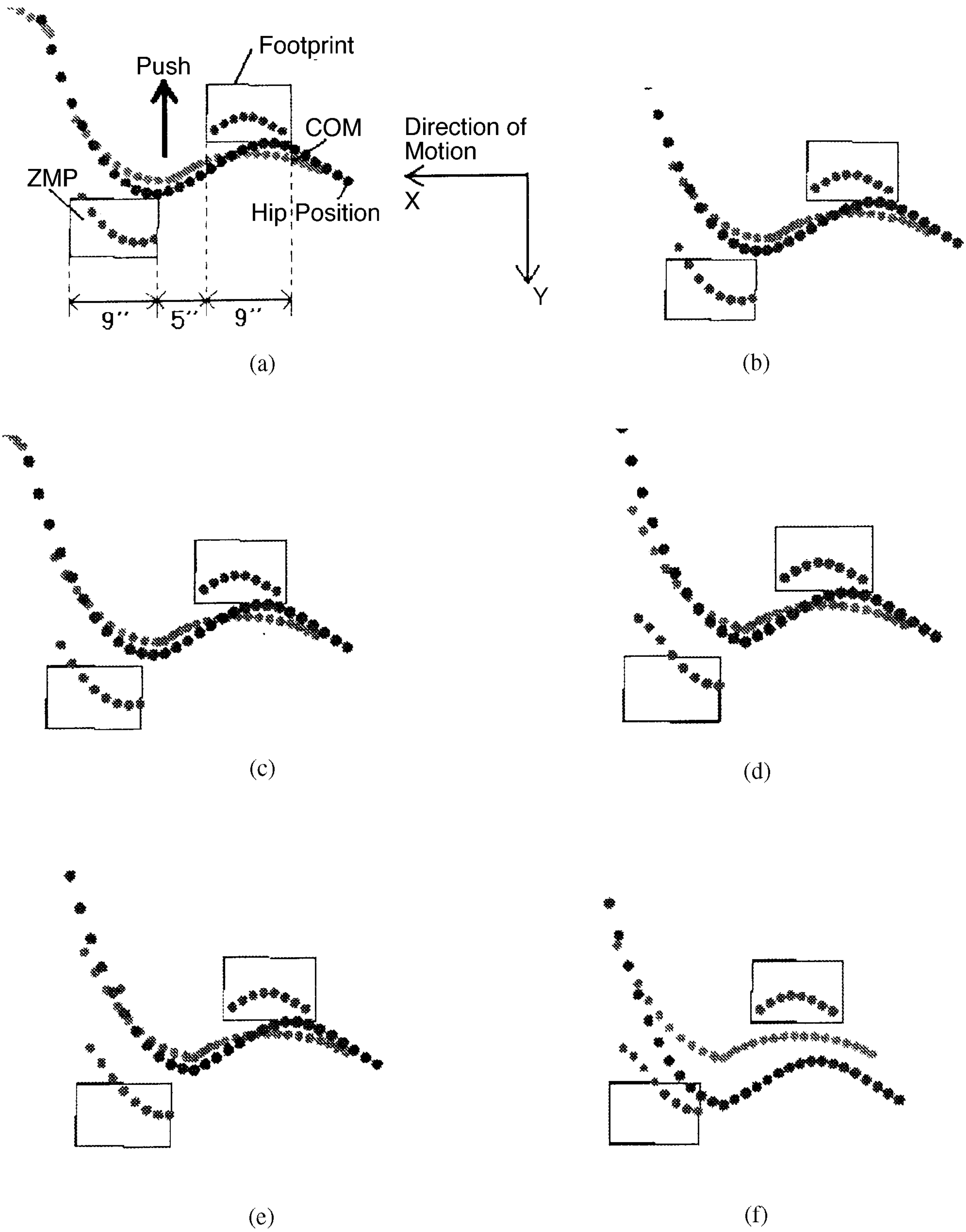

Fig. 11. ZMP trajectory under a push in the negative *y* direction, with initial velocity of (a) 30 in/sec, (b) 40 in/sec, (c) 50 in/sec, (d) 60 in/sec, (e) 70 in/sec, (f) 80 in/sec. In (a) foot/step dimensions are also shown.

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Variation in step length. With the robot dimensions assumed (see Section 2), a normal motion step – that is, a single walking cycle – is of length 28 in. When sensing on its way an obstacle that needs to be negotiated, the robot may decide to step on or over it, and this may require that the robot first positions one of its feet at a specific spot relative to the obstacle. This is done by modifying the step length. Due to the effects of dynamics and related computational difficulties, it is not easy to compute "on the fly" the trajectory for an arbitrary step length; instead, a small number of "typical" step lengths that together cover a large set of situations are developed and stored. Namely, relative to the normal step length, this includes a half step (14 in), quarter step (7 in), and zero step (0 in) length options. By applying an appropriate scheme for the dynamics of swing leg and hip position trajectories, a stable walk is obtained.

Variation in the swing leg height. While in the normal walk pattern, the robot can negotiate obstacles up to 1 in 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 a parabolic shape).[7] Unlike the fixed precomputed step length options above, here dynamically stable trajectories are computed "on the fly", with the step height as a variable. In the current version the maximum obstacle height for stepping on/over is 5 in. (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 depth 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 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 decision the robot still has room for forward motion, the latter can be combined with side motion, producing a *forward-side step*. Otherwise, a *side step* is executed, which has no forward component and is perpendicular to the prior direction of motion; in our scale, the side step is 6 in long.

To keep the motion smooth, depending on the swinging leg at the moment of, say, 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 built of the two components as above; after its execution the robot torso ends up 6 in to the left. Because of the possible entanglement between two legs, the same cannot be done with the

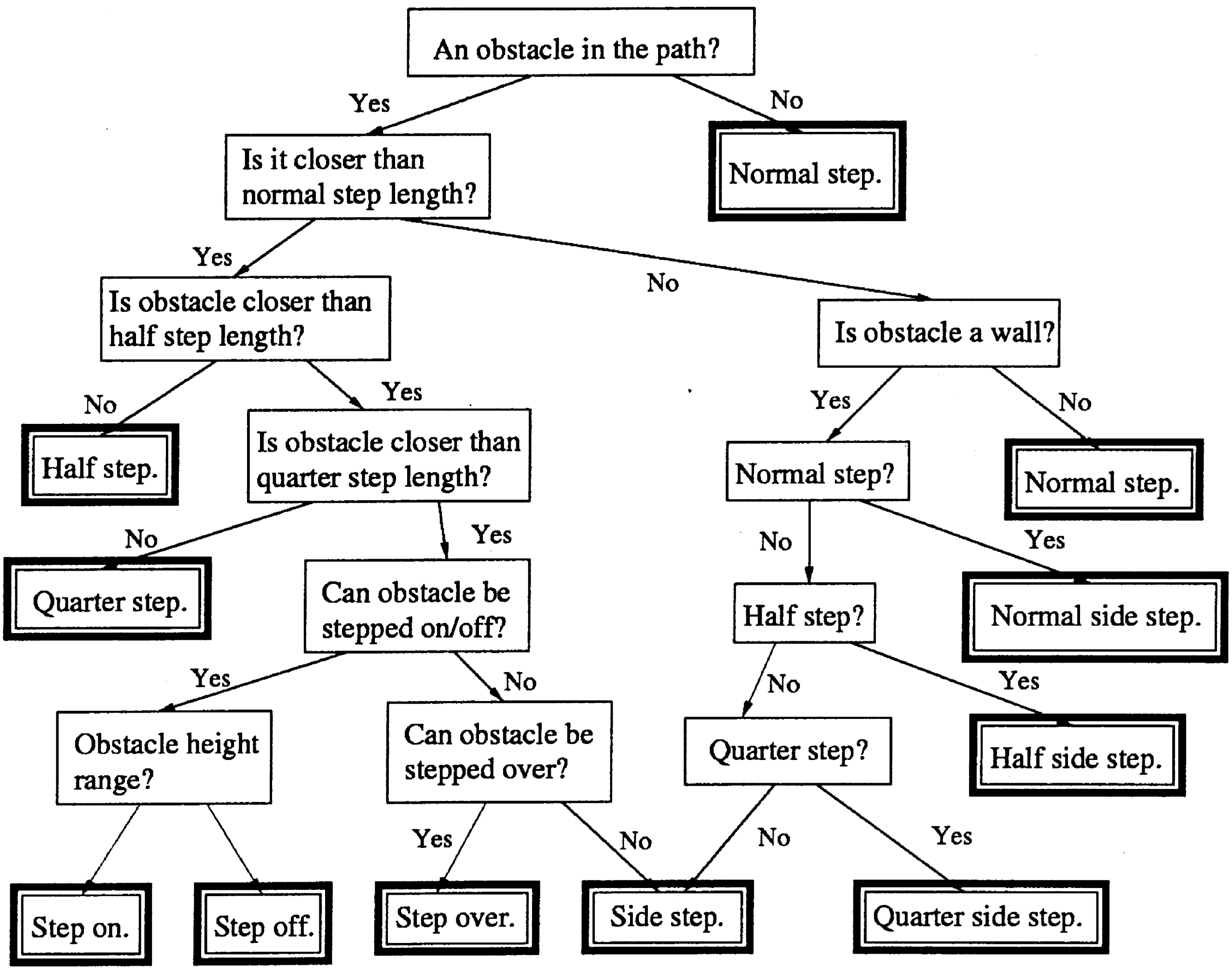

Fig. 12. Flowchart of the decision making algorithm.

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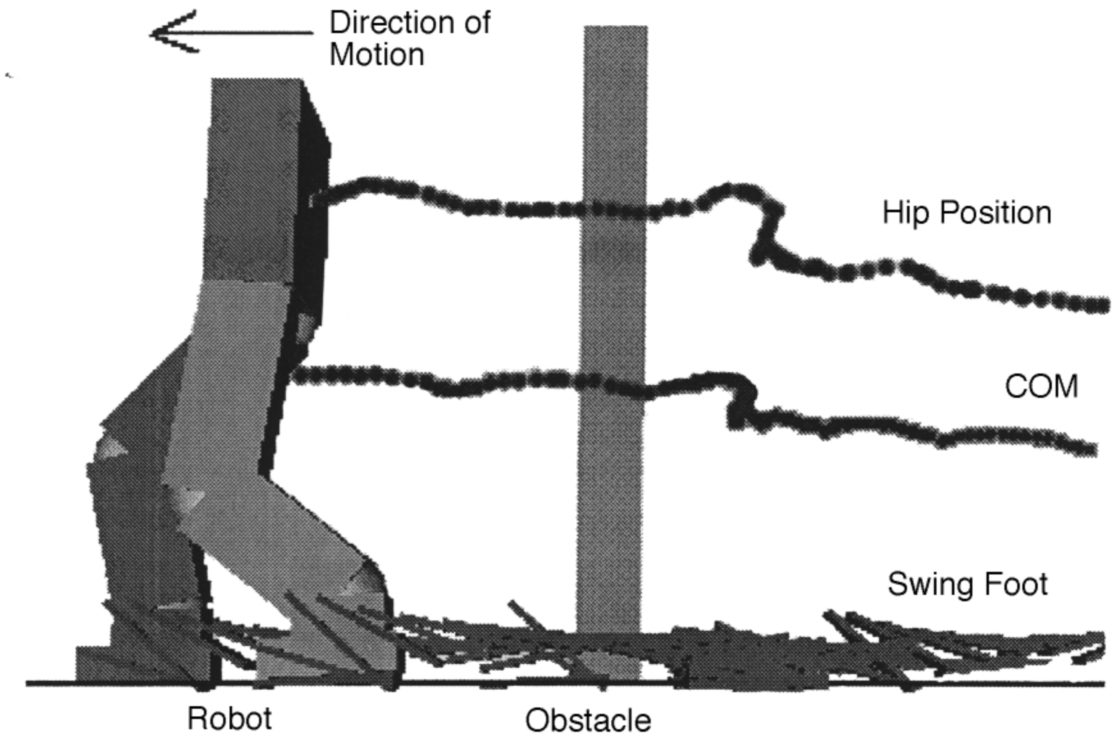

Fig. 13a. Stepping around a tall obstacle: (a) side view; (b) top view. Also shown are hip position, COM, and swing foot (broken lines) trajectories. (Positions of the robot differ in both views.)

right leg starting the maneuver. In this case, after the step execution is complete, the right foot ends up precisely 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 dynamic 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, a set of five dynamically stable trajectories, for the foot heights varying from 1 to 5 inches, are precomputed and stored. Once the obstacle height 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 obstacle depth, stepping on the obstacle may be followed by one or more normal steps, then perhaps a reduced length step, and finally by a stepping off step.

The algorithm for selecting the walking pattern utilizes nested if-else commands. The flowchart of the overall decision making algorithm capable of negotiating a sequence of obstacles of the types described is shown in Figure 12. Darker boxes indicate the final action in the current step cycle, after which a new step is initiated and the control goes to the top of the flowchart.

To see how the logic depicted in the flowchart works, consider, for example, the case when at the distance of 1.7 normal steps in front of it the robot senses a block (obstacle), whose dimensions are such that the robot can step over it. Follow Figure 12. As the answer to the first question, "An obstacle in the path?" is "Yes", the robot checks if the block is closer than one normal step length. This being "No", the robot checks if the block is a wall (or it can be stepped over). As the answer is "No", the robot executes a normal step. At this point the decision-making process switches back to the top of the flowchart. Since now the robot is one step closer to the block, the answer to "Is it closer than one step length?" is "Yes", and to the next question, "Is it closer than half step length?" it is "No". Hence the robot makes a half step, and the logic switches again to the flowchart's top. Now the robot is very close to the block, and a process similar to the above brings the sequence, "Is it closer than quarter step length?" – "Yes"; "Can the obstacle be stepped on/off?" – "No", and "Can the obstacle be stepped over?" – "Yes". Now the robot executes the step-over pattern.

5. SIMULATED EXAMPLES

Described here are computer simulated experiments with two-legged locomotion in the presence of obstacles. The experiments made use of a three-dimensional simulation/animation software for biped locomotion developed in the University of Wisconsin Robotics Lab. The package is based on the OpenGL and Forms Library graphics interface, and also on our internal motion planning simulation package.[12] The simulation interface includes various features, such as

- "on-the-fly" start/stop of the walking,
- generating sidewise horizontal hip push disturbances of specified direction/magnitude,

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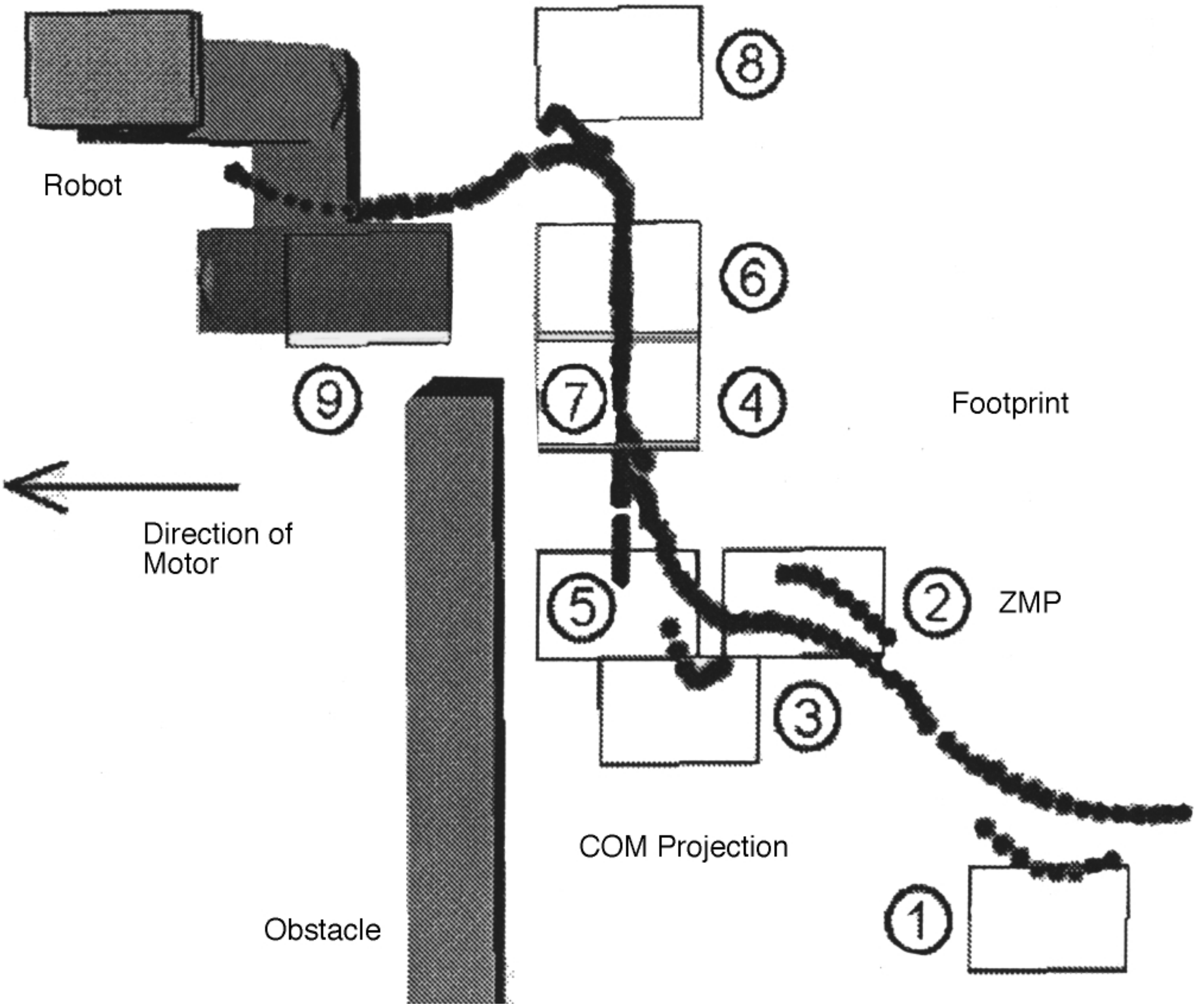

Fig. 13b.

- modification, initializing, and storing system parameters,
- modification of robot dimensions, masses, rendering features (e.g. color and texture),
- opening additional windows and manipulating frames of reference,
- similation of the floor the robot walks on,
- choice of projections, such as the orthogonal and perspective views,
- manipulating the field of view, zoom in/out, and the viewer position,
- displaying COM and ZMP three-dimensional trajectories and their projections,
- step-by-step display of positions of the body parts,
- handling file libraries.

The following is the description of five simulation experiments.

Avoiding a tall obstacle. If the obstacle's height prevents the robot from stepping on or over it, it is designated as a "tall obstacle". A tall obstacle 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 obstacle at the step execution time. Smoothness of COM and hip position trajectories indicates stability of the walking dynamics, Figure 13. While at 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 a few side steps and then a 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 obstacle were wider, more side steps would be executed.

Stepping over a block. With our model, the robot can step over a block of up to 5 in high and up to 4 in deep. Note the smoothness of the COM and hip trajectories, Figure 14 – 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 14) is a normal step, to get close enough to the obstacle to prepare for stepping over it. As this is still not close enough, a quarter

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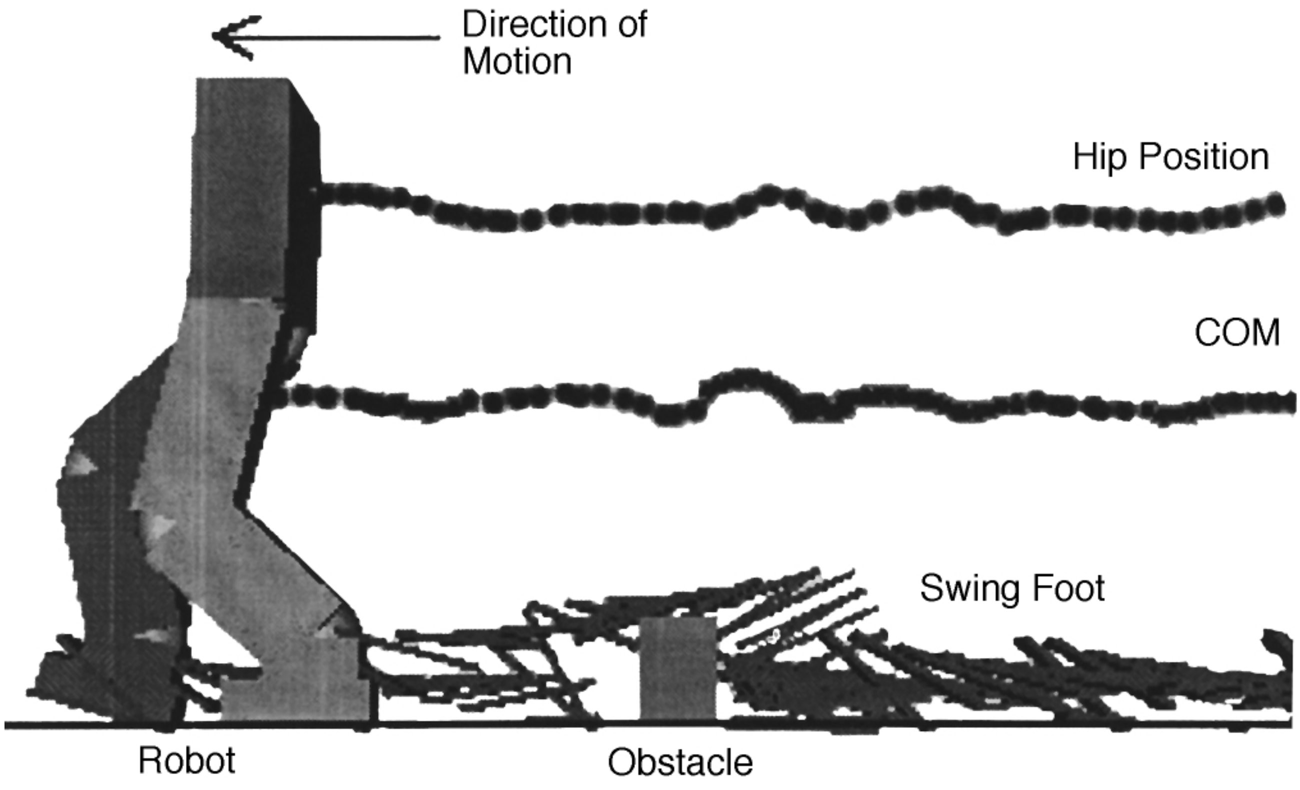

Fig. 14a. Stepping over a block: (a) side view; (b) top view. Also shown are hip position, COM, and swing foot trajectories. (Positions of the robot differ in both views.)

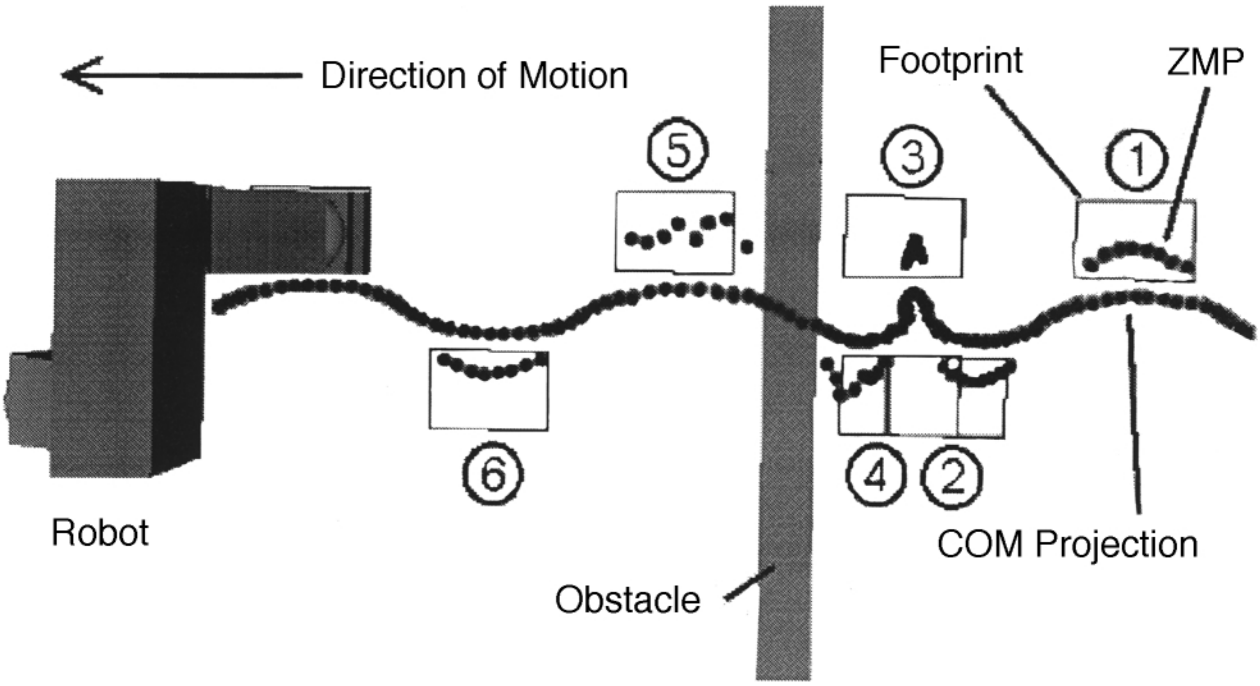

Fig. 14b.

size step is executed (footprint 3). Then a zero step is executed (footprint 4). 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 14, it is in balance again.

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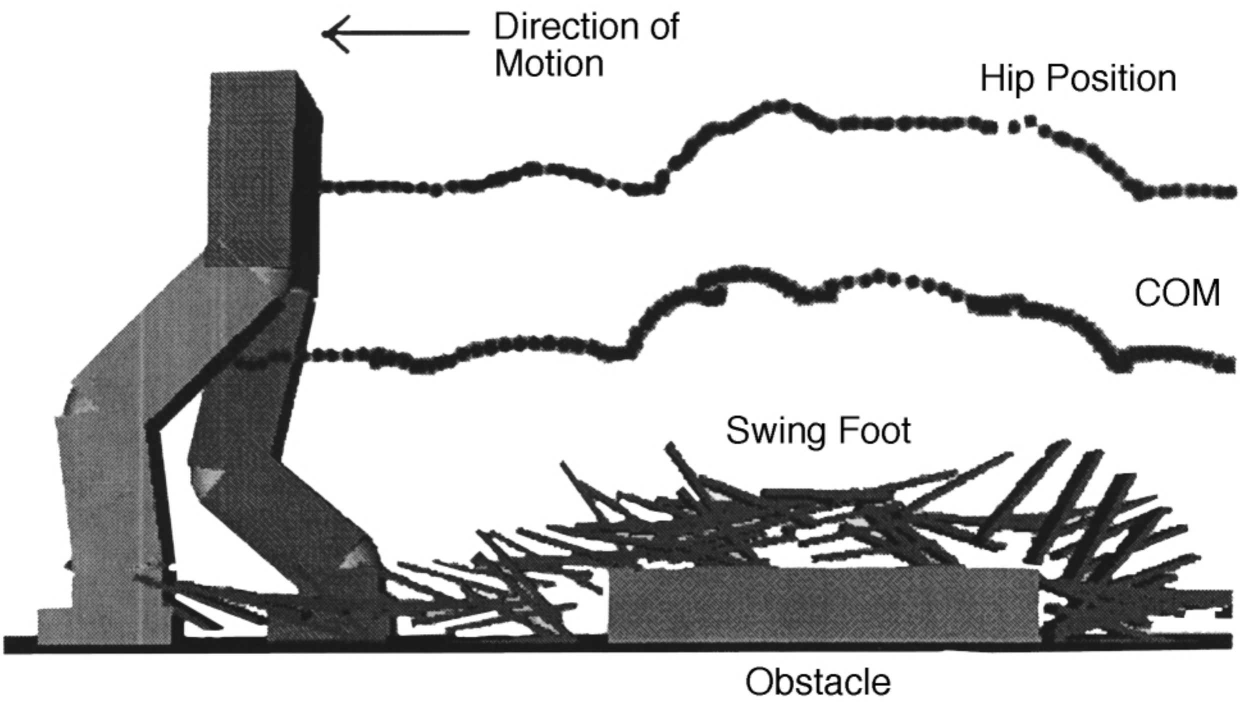

Fig. 15a. Stepping on/off a block: (a) side view; (b) top view.

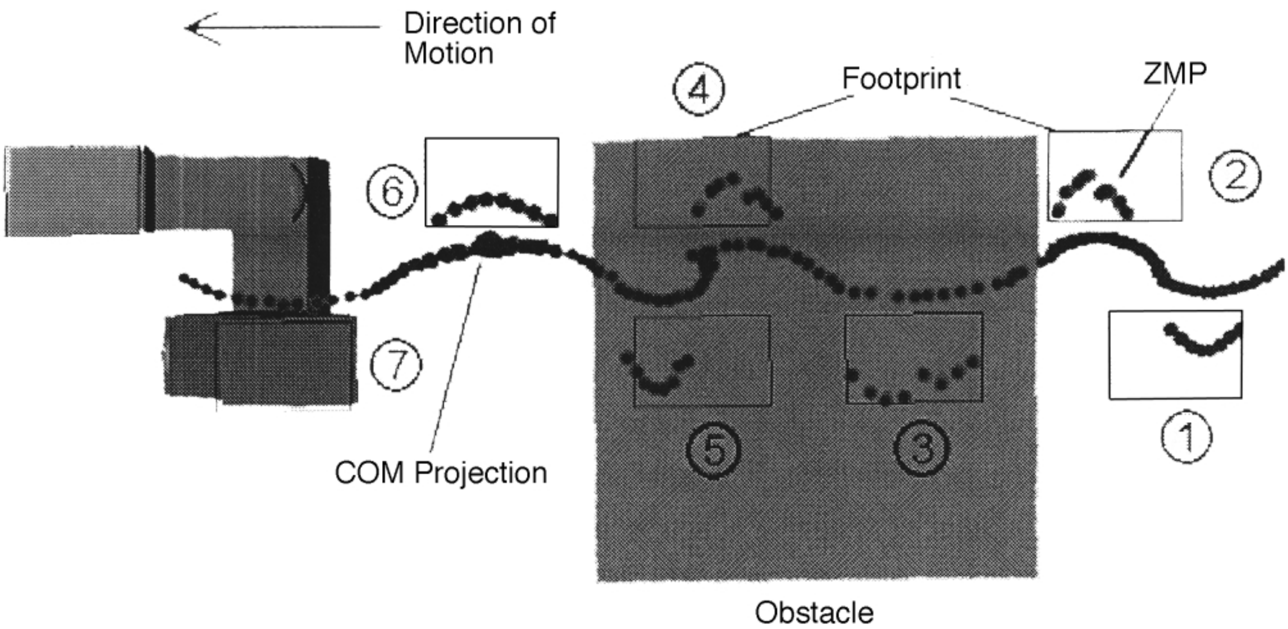

Fig. 15b.

Stepping on/off a block. If the obstacle's height is up to 5 in and its depth (the dimension in the direction of motion) is more than the length of the robot foot (9 in), 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 15 are: height = 5 in, depth = 30 in, width = 30 in. Given this obstacle width and given the width of the robot (W = 18 in, Figure 1), the robot will step on the obstacle, make one full step while on it, and step off on the ground. The very 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 indicate that the step is stable. While on the obstacle, the robot decides to take a normal step before preparing for stepping off. Then, with both its feet aligned, the robot sets to step off the obstacle (footprints 4 and 5). The stepping-off

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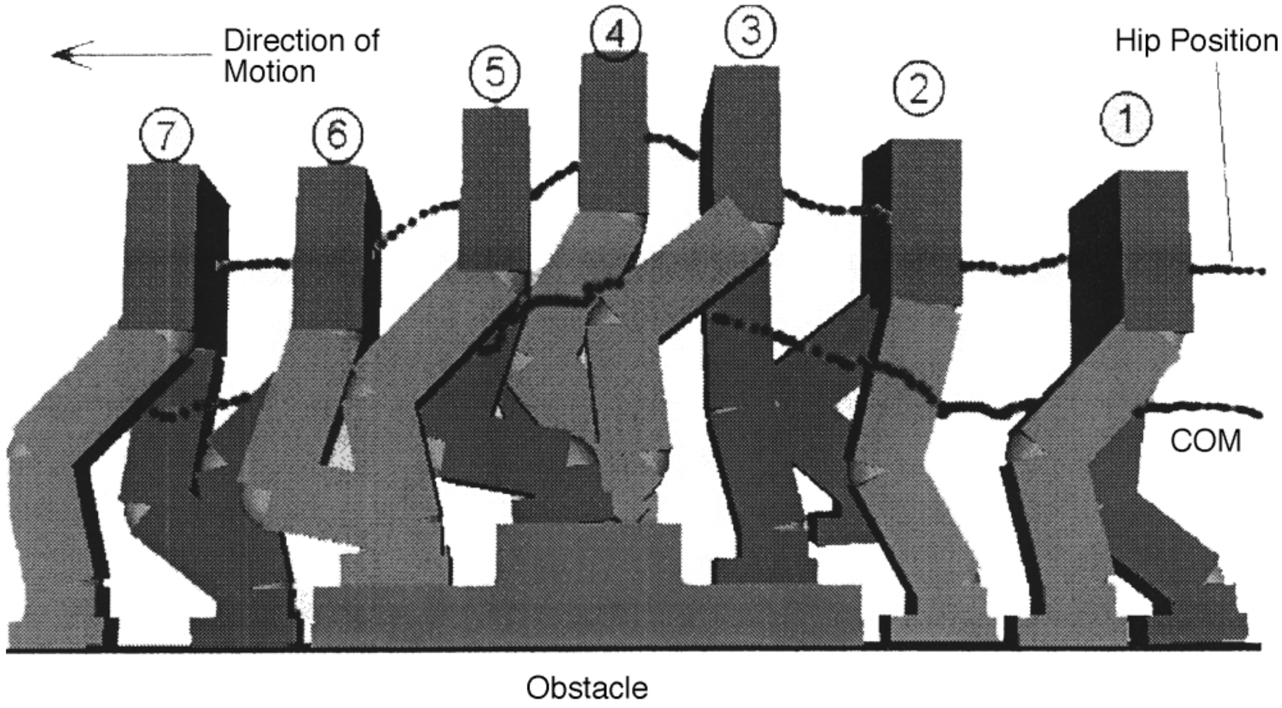

Fig. 16a. Walking a staircase: (a) side view (a number of robot positions along the path are shown); (b) top view.

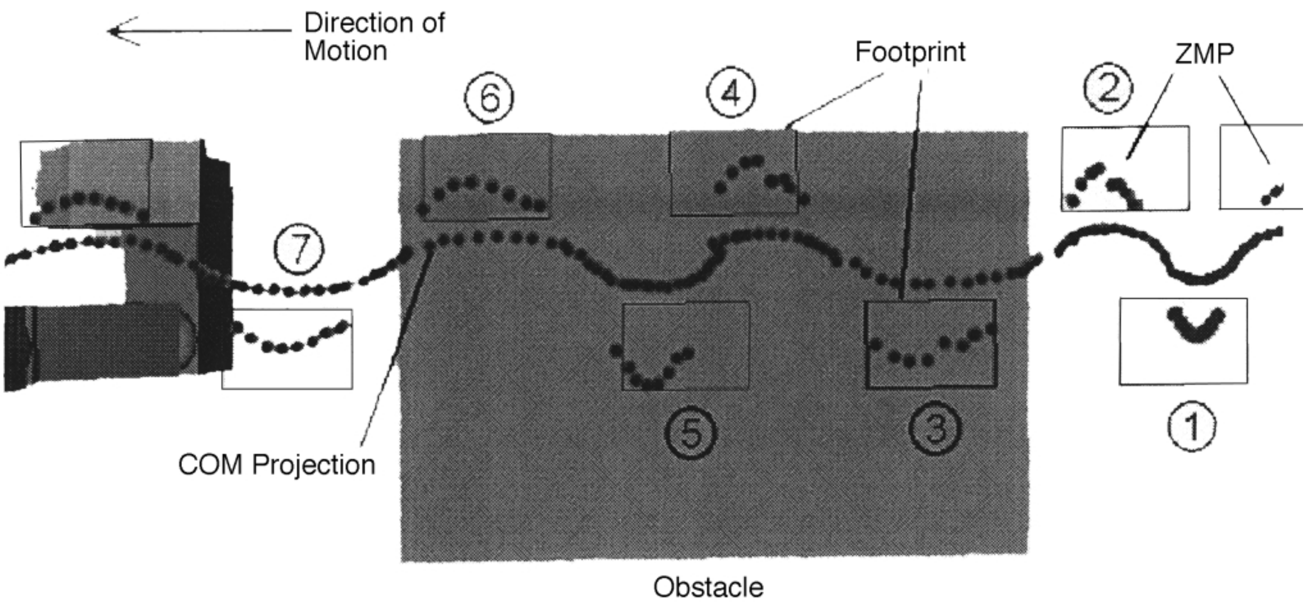

Fig. 16b.

stage is stable as well, as indicated by the ZMP and COM trajectories, footprint 6. The swing foot trajectory indicates that there is no collision between the swing foot and the obstacle, Figure 15.

Walking a staircase. This operation is done via a combination of the stepping-on/off patterns. The dimensions of each stair in the staircase shown in Figure 16 are: height = 5 in, depth = 15 in, and width = 30 in. The first step brings the robot closer to the staircase. Then it steps on the first stair; the ZMP trajectory indicates that this motion is stable, see footprint 2 in Figure 16. 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 stair so as to align both feet, this would be inefficient and is not necessary. Instead, under its step planning decision making procedure the robot makes one step over the first stair and then immediately another step onto the second stair, footprints 2, 3, 4. While on the second stair, the robot adjusts the distance by making a small step, and then steps off the staircase. The ZMP and COM trajectories during the whole process are in the safety zone; note the smoothness of the hip and COM trajectories, Figure 16; this indicates stability of the transition between walk patterns. Note also

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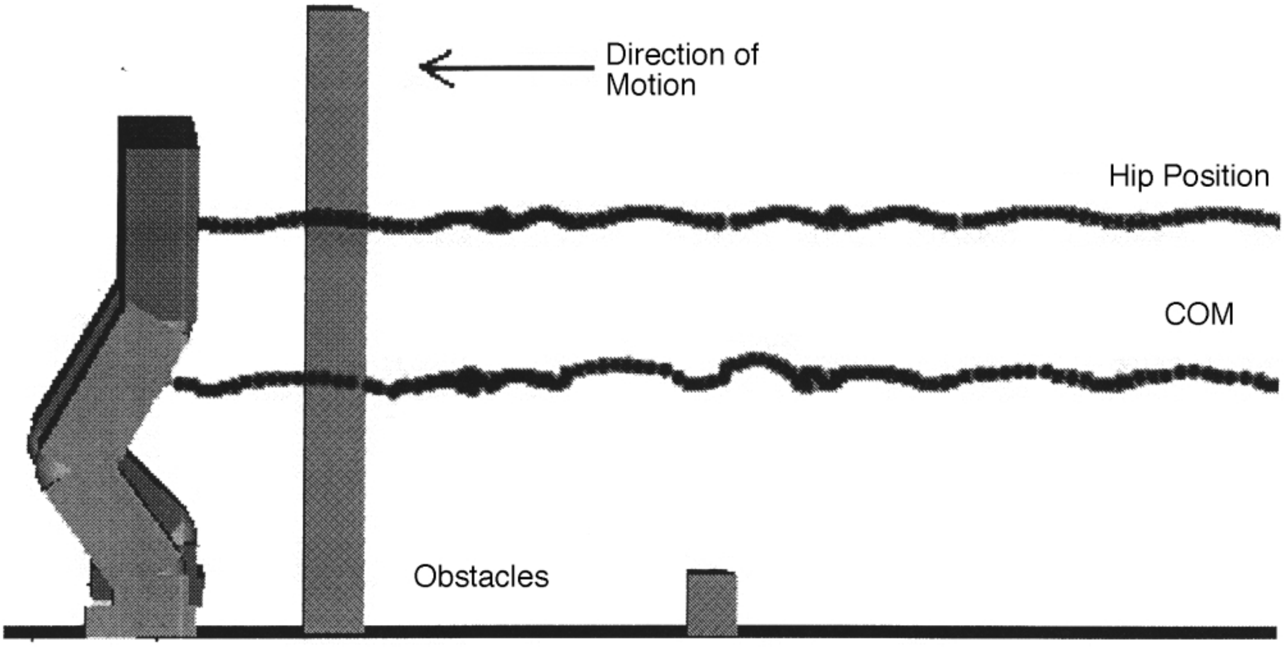

Fig. 17a. A combination of obstacles – stepping over a block and around a tall obstacle: (a) side view; (b) top view. (Positions of the robot differ in both views.)

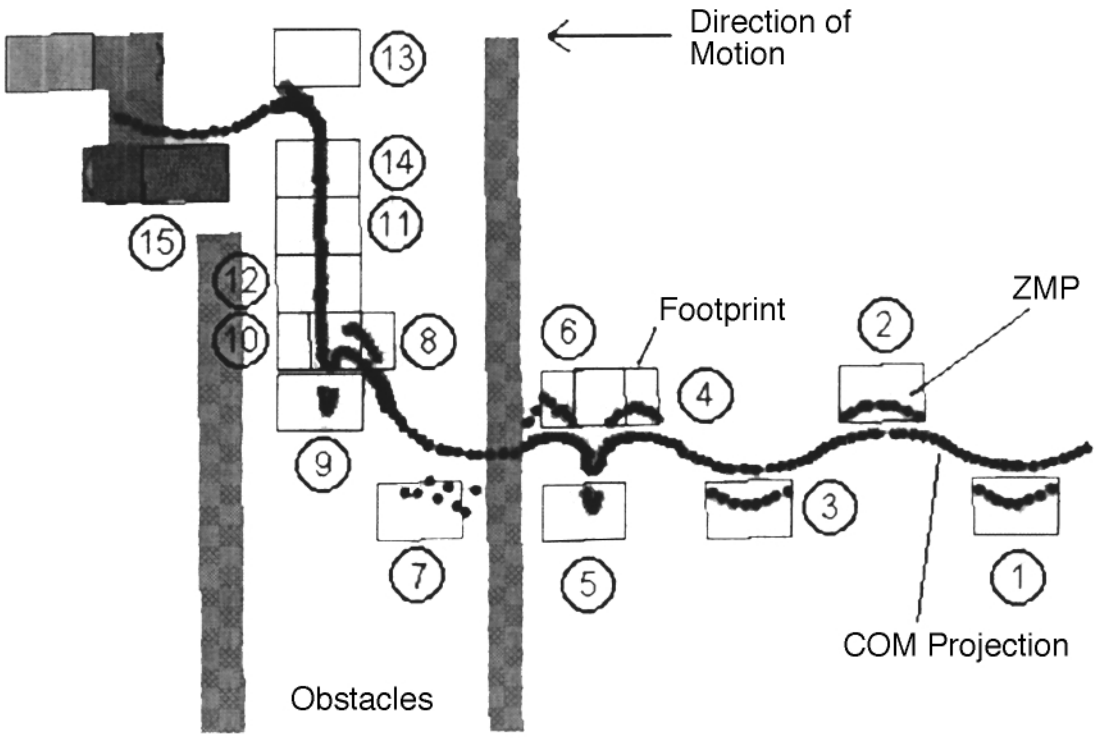

Fig. 17b.

that the swing foot trajectory does not interfere with the stairs.

A combination of obstacles. Attempted here is the process of stepping over a block obstacle followed by passing around a tall obstacle. Unlike in Figure 13, the robot senses the tall obstacle a bit late, 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 tall obstacle and takes a quarter length side step toward it (footprint 8, Figure 17). Then, since the tall obstacle extends further to the side, the robot executes a quarter side step, sees that the obstacle is no longer obstructing its path, takes a normal step and continues walking past the obstacle. The ZMP and COM trajectories (Figure 17) are all in the safety zone, indicating

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that the combination of the stepping over pattern and the stepping around pattern is a stable pattern.

6. CONCLUSIONS

In this work we investigate techniques for sensor-based motion planning for a biped mobile robot moving among unknown still obstacles. When negotiating obstacles, stable motion is achieved by combining schemes from a set of stable walking patterns designed so as to cover a variety of obstacle types. The results indicate feasibility of stable motion: using local sensory data in simulated scenes, the robot avoids obstacles and resumes dynamically stable motion. One of the main issues addressed is stability of transitions between the walking patterns used. Even if motion stability is achieved for one instantiation of a certain walking pattern, the steps before and after it are likely to strongly influence the trajectories of the Zero Moment Point, the robot's center of mass, and the swing leg center of mass.

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