Motion Planning for Humanoid Robots in Complex Environments Based on Stance Sequence and ZMP Reference

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Abstract. It is a great challenge to plan motion for humanoid robots in complex environments especially when the terrain is cluttered and discrete. To address this problem, a novel method is proposed in this paper by planning the gait according to the stance sequence and ZMP (Zero Moment Point) reference. It consists of two components: an adaptive footstep planner and a walking pattern generator. The adaptive footstep planner can generate the stance path according to the walking rules and adjust the orientation of body relevantly. As the footstep locations are determined, Linear Inverted Pendulum Model (LIPM) is used to generate the walking pattern with a moving ZMP reference. As demonstrated in experiments on the humanoid robot HOAP-2, our method can successfully plan footstep trajectories as well as generate the stable and natural-looking gait in typical cluttered and discrete environments.

Introduction

Humanoid robotics has been an intensive research area during the last decade. The popularity of humanoid robots is largely owing to their higher flexibility of action and better mobility. In recent years, various methods of planning the motion for humanoid robot in complex environment have appeared [1, 2]. However, there is few work of humanoid robot walking on discrete and cluttered environment, where the robot has fewer choices for the next step and needs more precise planning. Fig. 1 gives a typical example of discrete and cluttered environments—"Plum Blossom Piles", which is a platform to practice Chinese Kung Fu. It is important to notice that there are many tasks which require the robot to deal with these terrains, such as rescuing the victims in the earthquake, crossing a danger area, walking over the puddles, etc. Moreover, most of these tasks are not safe for human, which is a potential field for humanoid robots.

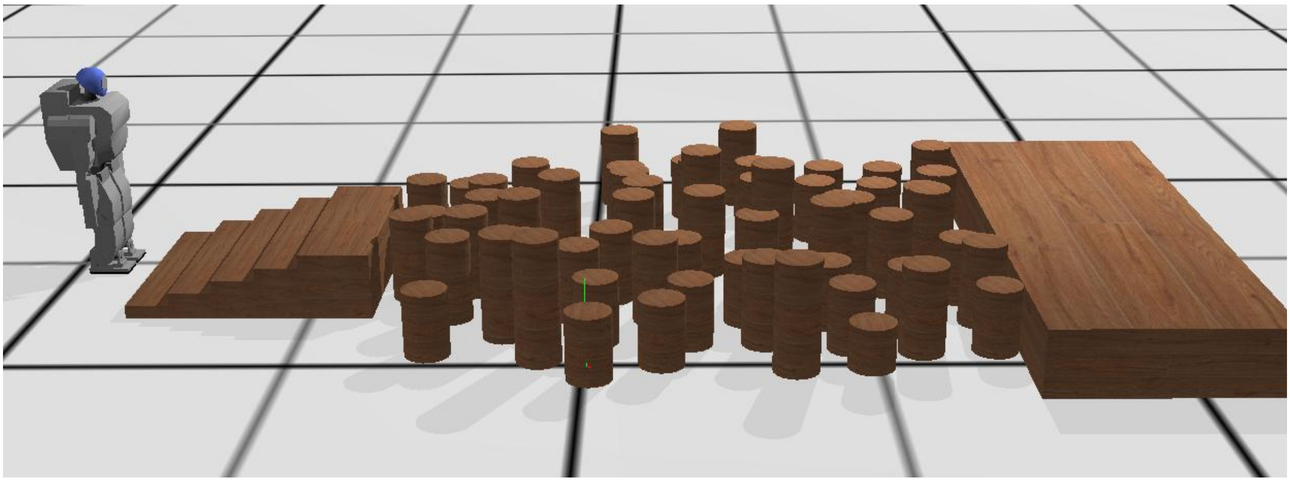


Fig.1: The plum blossom piles

Traditional footstep planning method relies on footstep transition model [3]. So the planning result is guided by the predetermined footstep model and cannot adapt to complex environments well. In this paper, an environmentally guided method is proposed to deal with this problem. Instead of using the pre-determined set of footstep location, the proposed method generates a stance path based on the terrain information and adjusts the orientation of foot accordingly. Then, according to the footstep locations, a moving ZMP reference is designed to produce a stable and natural walking gait.

Related Work

Since the presence of sampling based methods, such as probabilistic roadmap method (PRM) [4], the rapidly exploring randomized tree method (RRT) [5] and their variants [6], motion planning study has been improved significantly. However, it may be difficult to apply the ordinary motion planning methods to humanoid robots directly. Because these kinds of methods only consider to circumvent obstacles and ignore the constraint of balance. Recently, techniques have been developed to generate the walking pattern for humanoid robots [7, 8]. They are committed to address problems of stable control and dynamic balance rather than searching for a collision-free path. In order to avoid collision with the obstacles, sensors are applied to perceive environment information and navigate in unknown environment [9]. However, these methods do not consider the global information and may results in local minimal.

The concept of footstep planning for biped robots is first proposed in [3], in which the algorithm uses a discrete set of predefined footstep locations that a robot can choose from for the next step. When each step points to an equal number of child nodes, a tree is generated from the initial footstep position and A* search is employed to find the best among the generated collision-free paths. This technique has been wildly applied to different robots in various kinds of environments [10,11]. There are some improvements based on this approach including the application in some dynamic environments [12] and navigation for legged robots [13]. However, the efficiency of these approaches is limited by the size of transition models. As a result, they are not feasible in some specific environments.

In this paper, a stance sequence based method is proposed to heuristically choose the feasible footstep locations and generate the whole walking patern with moving ZMP reference in typical discrete and cluttered environments.

Overview of the Approach

For the simplicity of analysis and consideration of the general cases, we currently make the following assumptions:

1) The research environment in this paper looks like a plum blossom poles scene and the surface of terrain is flat.

2) The humanoid robot owns the basic motion ability of normal walking and stepping up and down, while walking on uneven terrain is not considered.

3) The method focus on footstep planning and the manipulation of arms is not involved in our method.

The potential footstep location is defined as *stance* in this paper. Then, for a given terrain map, a discrete set $q=(h,a,x,y)$ is used to present each stance's state in the scene with four elements: h and a represent for the height and area of the stance respectively and x, y denote the center of the stance surface in the world coordinate frame. The stance serves as a sign to guide the walking. When the stance path is determined, the footstep locations are known as well.

The overall architecture of our proposed method which consists of an adaptive footstep planner and a walking pattern generator is illustrated in Fig. 2. In our methods, a stance path is first generated based on the priori information (terrain information, motion parameter and task goal). A modified A* algorithm is utilized to search the best stance path from the start point to the destination, during which basic walking rules effect the growing of searching tree. Based on the generated stance sequence, a polynomial curve is produced to determine the orientation of foot in every step. After the footstep

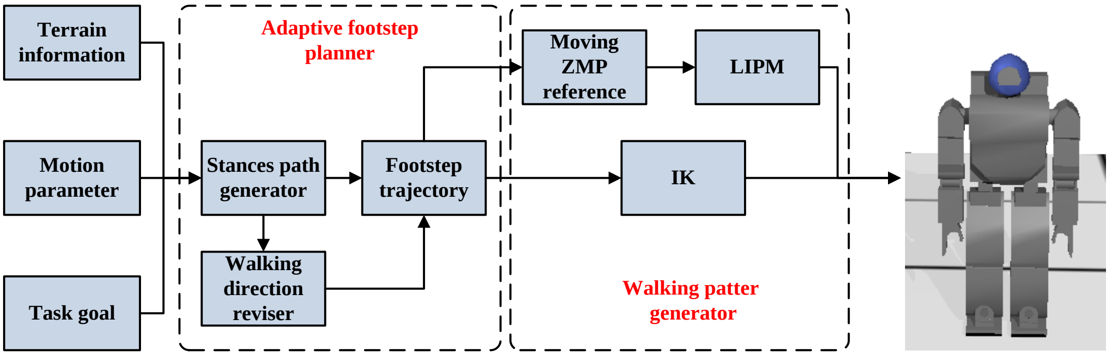


Fig. 2 Overview of the approach

location is determined, a walking pattern generator is utilized to produce the whole body motion of the robot. The position of ZMP is adjusted on foot for a stable and natural-looking walking and the analytical IK (Inverse Kinematics) formulation can quickly return a sequence of body joints from the given ZMP and CoM (Center of Mass) trajectory.

Adaptive Footstep Planner

In this section, we briefly introduce how to plan the footstep locations based on the stance sequence. Instead of using a discrete set of footstep transition model, the adaptive footstep planner generates a stance path to fix the center of sole and adjusts the orientation of foot to it. The whole planning process can be seen from Fig. 3, which will be described in further details.

A. Stance Path Searching

Based on the terrain information, a road map can be constructed by a graph $G=(V,E)$. The nodes in V are a set of stances and the edges in E correspond to links of attachable nodes. Due to the physical and mechanical constraint of robot, only two nodes q and q' meeting the following conditions can be connected as edges of the map:

$$\left\|(q_x,q_y)-(q'_x-q'_y)\right\| \le l_{\max} \cap \left\|q_h,q'_h\right\| \le h_{\max} \qquad (1)$$

Here, $l_{\max}$ and $h_{\max}$ represent the maximum stepping length and height respectively. For a given task, the start node q_{start} and goal node q_{goal} are then added to the graph G together with the adjacent nodes which meet Eq. 1. Once the graph is set up, the stance path searching process starts. Searching details is described in Algorithm.1.

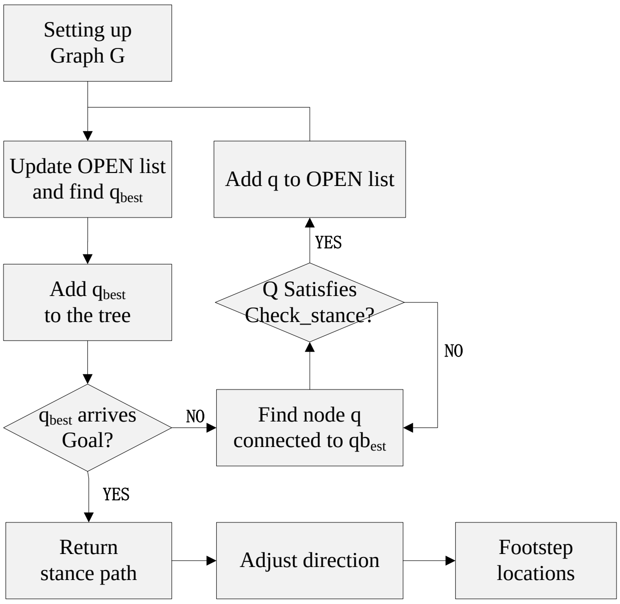


Fig. 3 The whole process of footstep planning

Algorithm 1 Search the stance path

```
T ← $q_{start}$;
OPEN← $q_{start}$;
repeat
    pick $q_{best}$ from OPEN, $f(q_{best}) \le f(q), \forall n \in$ OPEN;
    remove $q_{best}$ from OPEN and add to list CLOSE;
    if $q_{best} = q_{goal}$ then
        report SUCCESS, return path;
    end if
    for all $q$ adjacent to $q_{best}$ in $G$ do
        if $q \notin$ CLOSE and Check_Stance($q$) = true then
            if $q \notin$ OPEN then
                calculate $h(q), g(q)$ and add $q$ to OPEN;
            else if $g(q_{best} + c(q_{best}, q)) < g(q)$ then
                change $q$'s ancestor node to $q_{best}$;
            end if
        end if
    end for
until OPEN is empty
```

The tree T is started from q_{start} and the OPEN set is the priority queue with nodes in the current expanding front. Considering the walking constrains, the function *Check_Stance ( )* is used to select the appropriate stance before expanding it. The node which satisfies the function with the lowest cost is signed as q_{best} and added to the priority queue. The searching procedure is repetitively called until reaching the destination q_{goal} and the planner returns a back-pointer stance path as a result .

In Algorithm 1, the cost function to maintain the priority queue can be defined:

$$f(q) = g(q) + h(q) \tag{2}$$

$$g(q) = w_e E(q) + w_h H(q) \tag{3}$$

$$h(q) = w_g G(q) + w_n N(q) \tag{4}$$

The cost function $f(q)$ consists of two elements $g(q)$ and $h(q)$. Here $g(q)$ encodes the cost-to come value and $h(q)$ encodes the estimated cost to-go heuristic. $E(q)$ is computed as the sum of the edge cost of a back pointer path from q to q_{start}. $H(q)$ is a function which encodes a small penalty for path sequences that include steps bringing on height changes. This term has effect on favoring path with slight height variation of CoM. $G(q)$ estimates the distance from q to q_{goal} and $N(q)$ appraises the roughness of the region around q by calculating the obstacle density in a standard circle, with center at q. The four terms are weighted by w_e, w_h, w_g, w_n respectively.

B. Stance selection

For every node q, k denotes its depth in the searching tree. To determine whether the stance is maintained in the priority queue, the relationship between footstep location and stance sequence is set up. The walking pattern of robot can be divided into two phases: single support phase and double support phase. Two adjacent nodes q_k and q_{k-1} with an edge correspond to the double support phase and the middle point m_k between them is exploited to approximate the projection of the CoM on the *X-Y* plane. As we know, to perform a smooth body movement during walking, the orientation of body in a double support phases is determined by the former and latter footstep location together. In other words, the footstep location roughly fixes position and trajectory of the CoM. Therefore, the angle of body orientation can be obtained in the forthcoming step from the former position and orientation of CoM. Here a polynomial curve is used to approximate the body orientating trajectory in a three-steps circle. In the curve, θ_k denotes the body orientation angle before locating the foot on the stance node q_k and ϕ_k illustrates body orientation in the middle of two double support phase. The polynomial curve is generated by four known variables: $\theta_{k-1}, m_{k-2}, m_{k-1}$ and m_k. They represent former body orientation, CoM position of two prior steps and current step respectively.

To perform a safe and human-like gait in environments, three walking rules are set up for humanoid robots:

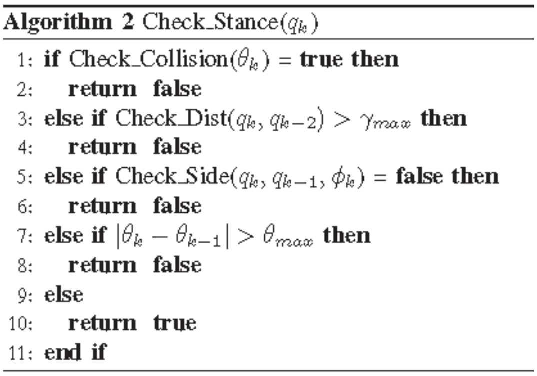
1) There are no collision between the robot and poles.
2) The length of each step and the change of body orientation must be within the limitation.
3) Left and right feet are alternate to support the robot when it is walking.

The function *Check_Stance( )* plays an important role in the footstep planning, which picks out the stance nodes meeting the walking rules. Algorithm 2 shows details of how the function works. The if-else conditions in the algorithm are judgments for walking rules respectively. $\theta_{\max}$ denotes the maximum rotation angle in one step and $\gamma_{\max}$ expresses the maximum step length. Function *Check_Collision( )* returns true when collision occurs. Function *Check_Side( )* returns true when q_k and q_{k-1} locate in the different sides of ϕ_k, which guarantees the adjacent nodes in the path corresponding to the different foot.

C. Adjusting the Direction

As a stance path is generated on the first stage, the center of footstep location is determined as well. Let δ sign which foot the stance support, with δ_l for left foot and δ_r for right foot. As the δ of start node is known prior, the foot corresponding to each stance is decided as well. For example, if the walking starts from left foot, the stances with odd k also support the left foot and those with even k support the right foot. To obtain the direction of footstep location φ in each stance, the following equation can be used:

$$\varphi(q_k) = \frac{(\theta_k + \theta_{k+1})}{2} \tag{5}$$



Algorithm 2 Check_Stance(q_k)

```
if Check_Collision($\theta_k$) = true then
    return false
else if Check_Dist($q_k, q_{k-2}$) > $\gamma_{max}$ then
    return false
else if Check_Side($q_k, q_{k-1}, \phi_k$) = false then
    return false
else if $|\theta_k - \theta_{k-1}| > \theta_{max}$ then
    return false
else
    return true
end if
```

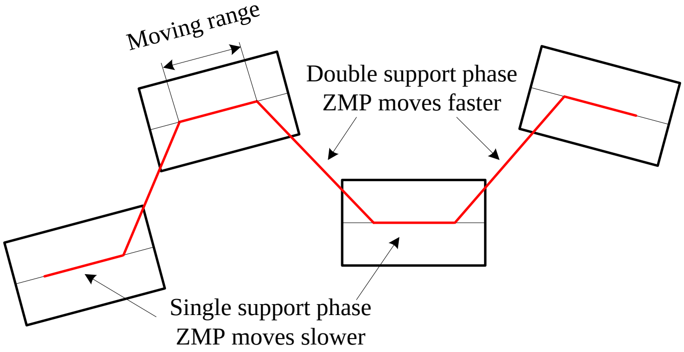


Fig. 4 Moving ZMP reference

Walking Pattern Generator

On this stage, the walking pattern of a robot can be generated from the obtained footstep locations. Here, a simple Three-Dimensional Linear Inverted Pendulum Model (3D-LIPM) is used in place of complex full dynamics models [14]. The rod corresponding to the swing leg is stretched with a stable and rotatable point on the ground and the mass point is linked to it. Let $\mathrm{c} = (c_x, c_y, c_z)$ be the position of CoM and $(\mathrm{p}_x, \mathrm{p}_y)$ represents the ZMP location on the floor, where *X*-*Y* plane coincides with the horizontal plane. Taking the property of 3D-LIPM and dynamical balance criterion into account, the relationship between the mass point and ZMP can be obtained as [6]:

$$\ddot{c}_x = \frac{g}{z_c}(c_x - p_x) \tag{6}$$

$$\ddot{c}_y = \frac{g}{z_c}(c_y - p_y) \tag{7}$$

z_c is the intercept of the plane where the simple model is constrained and g is the acceleration of gravity. For a given ZMP location, the related CoM trajectory can be obtained from Eq. 6 and Eq. 7. Once the movements of waist and feet are determined, the joint angle sequence can be obtained by inverse kinematics.

Since the goal is to achieve a dynamically stable gait, the ZMP trajectory should always lie inside the supporting polygon. The supporting polygon is defined by the supporting foot and the contact surface in the two phases. Fixed ZMP reference is designed for the pattern generation in [6]. However, researches reveal that ZMP does not stay still under the supporting foot. A moving ZMP reference will make the walking look more natural [15, 16]. According to the LIPM, the position of ZMP under sole influences the movement of mass point linking to it. When ZMP moves forward, the inverted pendulum swings ahead accordingly, which enables the robot to walk further or step higher. In short, moving ZMP reference extends the motion ability of humanoid and takes a role in generating a nature gait. However, the moving range of ZMP should not be too large. The real ZMP trajectory may have deviation from the designed reference. If the ZMP locates near to the edge of sole, the robot is likely to fall as the real ZMP slides outside the supporting polygon. Thus, the preset reference needs to move with a proper range, finding a balance point between stability and mobility. Fig. 6 demonstrates the moving ZMP reference in our method. ZMP moves along the axle wire of sole from heel to toe with an appropriate range in the single support phase and shifts from one foot to the other in the double support phase.

Experiments

The proposed method is implemented in Webots, which is a simulator that allows users to simulate dynamic behaviors of robots in a 3D virtual environment. The humanoid robot model used in our work is HOAP-2 designed by Fujitsu Automation. It is about 0.5*m* high and weights 7*kg*, with 25 degrees of freedom. The simulation program is running under Windows7 on an AMD 8600 processor with 2 G Byte of memory.

As discussed in the previous section, the setting of ZMP reference not only plays an important role in generating the walking pattern, but also influences the walking ability of the humanoid robot. In our experiment, the ZMP moving range is set to 0.04m. The value is determined experimentally, taking into account both the effect of balance and natural-looking. The corresponding maximum step length and the highest step that the humanoid robot can reach are 0.26*m* and 0.07*m* respectively.

In order to evaluate the proposed method, the humanoid robot is designed to walk on the plum blossom poles like environment, in which cylinders are randomly placed on the floor. There are two sets of simulation scenes and the parameters of cylinders are listed in Table. I. In each scene, our methods are tested 100 times when the positions of cylinders are randomly generated. Table II shows results of our method, including average planning time, steps and rate of successful planning. It is important to notice that the planning path change obviously with different values of w_h: when w_h is set to zero, the cost of stepping height is ignored in the planning phases; when w_h increases, the path with slight height variation of CoM is more likely to be selected by the footstep planner. Examples of the robot walking on these two sets of scenes can be seen from Fig. 5 and Fig. 6.

TABLE I PARAMETERS OF THE CYLINDERS IN ENVIRONMENTS

Cylinders	Set I						Set II		
Height (c*m*)	15	17	19	20	22.5	25	15	20	55
Number	7	15	20	35	15	8	25	50	15

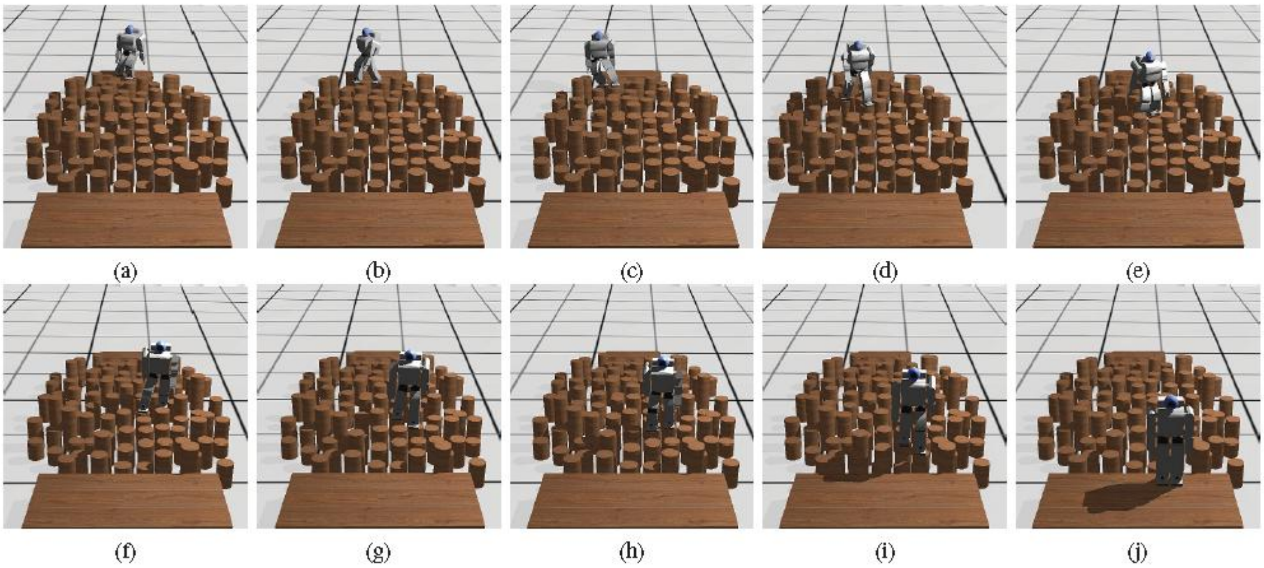


Fig. 5 Snapshots of the simulated walking on Set I

TABLE II RESULTS OF OUR METHOD

	w_h	Time	Steps	Rate		w_h	Time	Steps	Rate
Set I	0	1.69	31.8	78.4%	Set II	0	1.38	28.6	71.6%
	0.4	1.83	33.6	76.2%		0.4	1.29	27.8	70.3%
	0.8	2.01	36.5	77.9%		0.8	1.58	31.2	73.4%

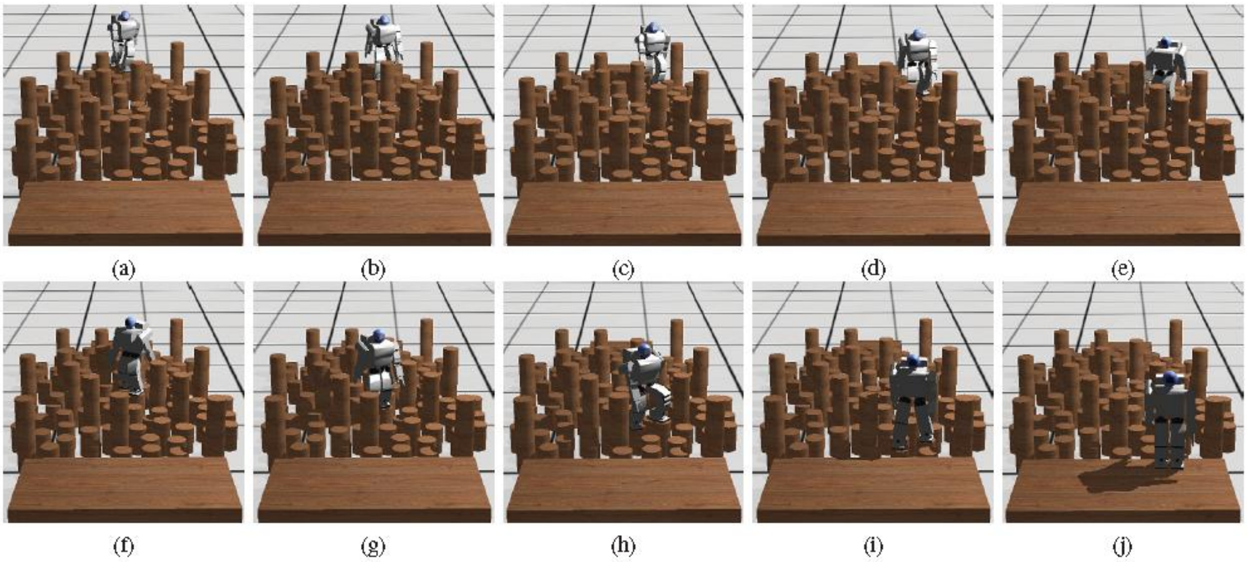


Fig. 6 Snapshots of the simulated walking on Set II

Conclusion

In this paper, a method is proposed to plan the motion for humanoid robots walking in environments where the terrain is discrete and cluttered. The method is composed of an adaptive footstep planner and a walking pattern generator based on the idea of stance sequence and ZMP reference respectively. The approach takes different aspects such as nature-looking, efficiency and collision-free into consideration in one frame. The experiments show that the proposed method has promising results and we plan to extend it to uneven terrains in the future.

Acknowledgement

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