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Fuzzy Footstep Planning for Humanoid Robots Using Locomotion Primitives

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Abstract

This paper presents a fuzzy footstep planner for humanoid robots in complex environments. First, we define locomotion primitives for humanoid robots. A global planner finds a global path from a navigation map that is generated based on a combination of 2.5 dimensional maps of the 3D workspace. A local planner searches for an optimal sequence of locomotion primitives along the global path by using fuzzy footstep planning. We verify our approach on a virtual humanoid robot in a simulated environment. Simulation results show a reduction in planning time and the feasibility of the proposed method.

Key Words : Fuzzy footstep planning, Motion planning, Path planning, Humanoid robot

1. Introduction

Wheeled mobile robots navigate in a 2D world and usually have 3 or less degrees of freedom(DOF). The configuration space of wheeled mobile robot can be searched efficiently by the probabilistic, sample-based motion planning methods. Legged robots like humanoid robots can walk in a 3D workspace. A typical biped robot has twelve DOF in its lower body and more in the upper body. The high degree of actuation gives the robot a wide range of motions. Humanoid robots can walk, turn, step on/down stairs [1], [2], [3], [4], [5], [6], [7], [8], [9], step over barriers [1], [10], climb over small obstacles [1], [6], [7], [9], [11], [12], climb ladder [12], and crawl through narrow passages [13], [14].

Motion planning for humanoid robots in the 3D workspace is both a computationally expensive and theoretically challenging problem. One thing that makes this problem difficult is that humanoid robot has many DOF and its configuration space is generally more than 6 dimensions. Due to many DOF of humanoid robot, it is difficult to find the robot's pose and available motions in the complex environment with various kinds of obstacles. Also, searching a path in the high dimensional configuration space needs a significant amount of memory and computation time. Because of the complexity of the configuration space and its stability requirements, it becomes difficult to find a trajectory through 3D cluttered environments and check collision with obstacles.

One strategy that simplifies a motion planning problem for humanoid robots is to use the preplanned motions which begin and end with a statically stable pose [3], [12], [15]. Much research on generation of stable and efficient gaits for humanoid robots has been conducted considering dynamic stability constraints. These patterns of motion can be reused in sequence to convert one or more preplanned steps into a walking motion. In this paper we refer to these preplanned motions as motion primitives. If these motion primitives are preplanned and optimized, the resulting motions can be more efficient, optimal and robust, and use minimal computational expense at run time.

This paper proposes a fuzzy planning strategy based on 2 maps of the 3D workspace. Using these maps, hierarchical motion plans are made, which allows the humanoid robot to navigate in complex environments using only a small set of motion primitives. The global planner finds a path by using a global navigation map that is obtained from a passage height map, an obstacle height map and a gradient height map of obstacles. The fuzzy motion planner determines a sequence of locomotion primitives. We verify our approach on a virtual humanoid robot with a simulated environment. Simulation results show a reduction in planning time and an improvement in motion stability.

2. Fuzzy Footstep Planning using Locomotion Primitives

2.1 Locomotion Primitives and Workspace

We define a pose, $q=(q_1, q_2, q_3, \cdots q_m)$, to be a set of the joint angles of the m actuators in the humanoid robot H. A configuration γ of the robot H is a point in its con-figuration space, Q where Q = SE(3) × T^m parameterized by

$$\gamma=(x_r, y_r, z_r, \phi_r, \theta_r, \psi_r, q). \tag{1}$$

The robot's global location and orientation are specified by comparing a world reference frame to a coordinate frame fixed rigidly to itself.

Because the humanoid robots has a 6+m dimensional configuration, it is difficult to find a path through 3D cluttered environments and check for collisions with the obstacles. Also, searching in the high dimensional configuration space needs a significant amount of memory and computation time and may not be able to find a solution. To simplify a motion planning problem of the robot, we define locomotion primitives for the humanoid robot.

A *locomotion primitive* of the robot is defined as

$$P_i=(\Delta x_r, \Delta y_r, \Delta z_r, \Delta\theta_r, \Delta\phi_r, \Delta\psi_r, P_i, C_{pi}, V_{pi}). \tag{2}$$

Δx_r, Δy_r and Δz_r are the net displacements of the origin of the robot's root frame in local coordinates, $\Delta\theta_r$, $\Delta\phi_r$ and $\Delta\psi_r$ are the net changes in orientation of that frame. P_i is a motion primitive, C_{pi} is the overall cost of execution time, distance of displacement, consumed energy and potential instability for the locomotion, and V_{pi} is a volume containing the swept volume of the locomotion. The task of a motion planner is to find a sequence of locomotion primitives that when applied, transform the start configuration to some goal configuration.

A humanoid robot operates in a 3D workspace, $W \subseteq R^3$. We assume the workspace can be partitioned into a floor, gates, obstacles, holes and barriers. The floor is assumed to be a horizontal and even plane. Basically, these assumptions correspond to smooth, indoor environments. In this paper, we consider motion planning of humanoid robots in the complex indoor environment as shown in Fig. 1.

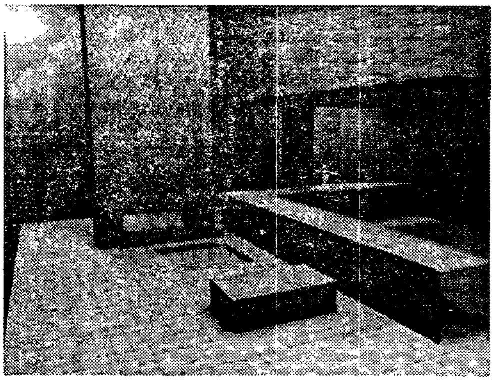

Fig 1. Virtual humanoid robot and 3D Workspace

To represent the 3D workspace, we use a combination of 2.5 dimensional maps of its environment. The obstacle height map stores the height of the floor or of an object sitting on the floor with respect to the floor plane. The robot cannot walk through the passage with a low ceiling and a low gate. The ceiling height with respect to the floor plane is stored in the ceiling height map From the obstacle height map and the ceiling height map, we can also obtained the passage height map.

2.2 Fuzzy Motion Planning

In complex environments as shown in Fig. 1, the motion planner should have various kinds of locomotion primitives such as walking, turning, stepping on/down and stepping over, to cope with the various obstacles, maintain the stability of the robot, and find a feasible sequence of primitives.

We assume that the humanoid robot is a mobile robot with a bounding volume, which is obtained from the set of locomotion primitives. The proposed planner generates a 2D global navigation map and finds a global path based on the global navigation map. At first, we consider the vertical obstructions that prevent the robot from moving. The vertical hard obstacles are decided based on a minimum height of the pathway that the robot can move through. The 2D global passage map is obtained from the passage height map.

Also, the hard obstacles are decided by using both a steepness and a height difference of the object, which can be obtained from the gradient height map of obstacle and the obstacle height map. We can find that the global obstacle map shows the edges or borders of the hard obstacles. From the global passage map and the global obstacle map, we can obtain a 2D global navigation map for the global path planner, which is similar to the navigation maps for wheeled mobile robots. Fig. 2 shows a global obstacle map of the workspace.

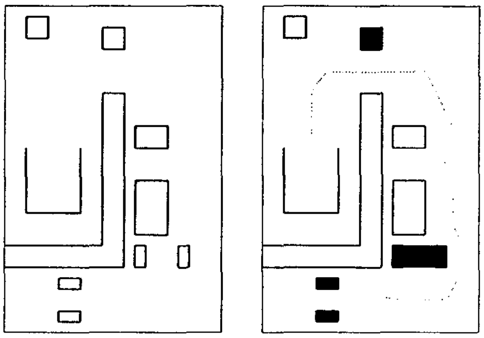

Fig. 2. Global navigation map and path

Given an initial configuration $\gamma_{initial}$, a goal configuration γ_{goal}, the task of the global path planner is to find a 2D global path that is selected amongst a set of feasible paths. Since the motion plans that find shortest Euclidean path bring the robot too close to obstacles, we use a maximum clearance planning method, Wavefront/NF2 algorithm, to find a global path that has a maximum clearance with obstacles as shown in Fig. 2. The task of fuzzy motion planner is the footstep planning that searches for a sequence of locomotion primitives along a global path.

We employ the fuzzy footstep planner to find an feasible sequence of locomotion primitives. Fig. 3 and Fig. 4 show the fuzzy variables and control rules of the fuzzy footstep planner.

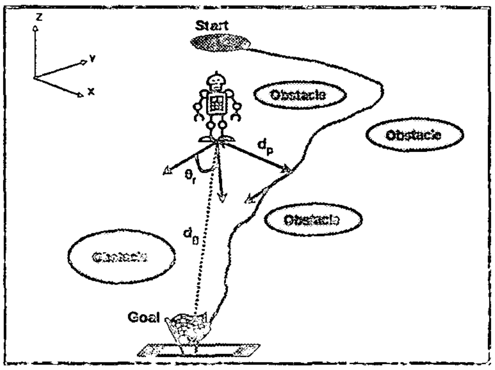

Fig. 3. Definition of fuzzy variables

$h_s = FSP(d_p,\theta_r)$		d_p				
		NB	NS	ZO	PS	PB
θ_r	PB	RS	RT	RT	RD	LS
	PS	RS	RD	RT	NW	LS
	ZO	RS	NW	NW	NW	LS
	NS	RS	NW	LT	LD	LS
	NB	RS	LD	LT	LT	LS

Fig. 4. Fuzzy planning rules

3. Simulation Results

To verify our approach, we use a simulated 28-DOF virtual humanoid robot. The fuzzy footstep planner has access to 12 primitives including walking, walking with a turning motion, a shuffle step, and so on. All primitives are assumed statically stable and the transitions are at statically stable poses. Fig. 3 shows some results we have attained in our simulation environment.

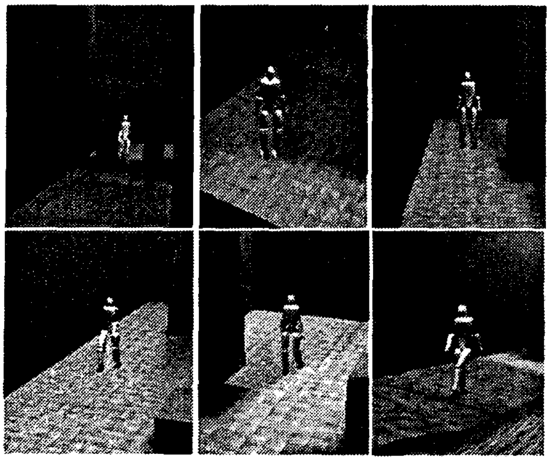

Fig. 5. Snapshots of simulation results

4. Conclusions

We present a fuzzy footstep planning method that finds a global path and an feasible sequence of locomotion primitives for a humanoid robot. To solve the motion planning problem, we design a planner based on locomotion primitives and use a fuzzy planning to reduce the search space of the planner. Using the global path, the proposed planner decreases the number of required locomotion primitives and efficiently copes with an environment. We verify our approach on a virtual humanoid robot with simulated environment. Simulation results show a fast planning time.

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