Paper:

Kinodynamic Planning for Humanoid Robots Walking on Uneven Terrain

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For the purpose of realizing the humanoid robot walking on uneven terrain, this paper proposes the kinodynamic gait planning method where both kinematics and dynamics of the system are considered. We can simultaneously plan both the foot-place and the whole-body motion taking the dynamical balance of the robot into consideration. As a dynamic constraint, we consider the differential equation of the robot's CoG. To solve this constraint, we use a walking pattern generator. We randomly sample the configuration space to search for the path connecting the start and the goal configurations. To show the effectiveness of the proposed methods, we show simulation and experimental results where the humanoid robot HRP-2 walks on rocky cliff with hands contacting the environment.

Keywords: humanoid robot, motion planning, random sampling, biped gait

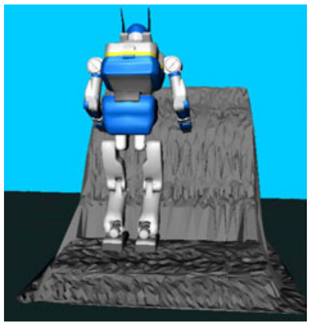

Fig. 1. Humanoid motion on rocky cliff.

1. Introduction

To realize a biped humanoid robot that can work instead of a human, the humanoid robot has to plan the motion pattern depending on its surrounding environment. Here, the motion of the robot should be planned taking several conditions into account. First, the robot has to keep balance by maintaining the contact between the foot and the environment. Second, a humanoid robot has to avoid unnecessary contact between a link and the environment. Furthermore, a humanoid robot has to select the foot placement so that the humanoid robot can finally reach the goal configuration. This research focuses on the humanoid motion planning that can take all these functions into account at the same time.

Let us focus on a typical case where the motion planning of a humanoid robot becomes necessary. **Fig. 1** shows the case where a humanoid robot walks on the rocky cliff. In this case, the humanoid robot has to select the foot placement so that the robot can keep balance easily. Also, the humanoid robot may sometimes contact the hand to its environment if it is difficult for the robot to maintain balance. Although we have a plenty of works to realize such motion, this paper first realizes a function of a humanoid robot simultaneously planning the whole body motion and the foot placement with keeping its dynamical balance.

Now, let us consider simultaneously planning the whole body motion and the foot step placement. As for the motion planning of humanoid robots, the random sampling based method such as PRM and RRT has been researched [6, 7, 10, 11, 13]. Recently, the randomized kinodynamic planning was proposed [16, 17] where it can be used for the motion planning taking the dynamics of the system into consideration. Here, the roadmap of randomly-sampled milestones are connected by using the solution of the differential equation. In this paper, we realize this simultaneous planning by including the walking pattern generator into the planner. With our proposed planner, each milestone is connected by using the solution of the differential equation expressing the relationship between the CoG and the ZMP. This paper is composed as follows; After showing the related researches in Section 2, we show the planning method in Section 3. In Section 4, we show numerical examples and experimental results.

2. Related Works

2.1. Walking Pattern Generation of Humanoid Robots

As for the walking pattern generation of humanoid robots, many researchers used the ZMP [1]. Kagami et al. [9] proposed an online walking pattern generator numerically solving the differential equation of the trunk motion. Kajita et al. [2] used the preview control. Harada et al. [3], Morisawa et al. [4] and Sugihara et al. [8] proposed the analytical solution based approaches.

2.2. Motion Planning with Collision Avoidance

As for the motion planning based on the random sampling, Kavraki et al. [19] proposed the probabilistic roadmap (PRM) planner. Kuffner et al. [15] and Sanchez et al. [18] later proposed the single-query and bi-directional method. The random sampling method was extended to the kinodynamic planner taking the velocity of the system into consideration [16, 17].

Recently, some researchers research the motion planning of a humanoid robot. Kuffner et al. [10, 11] first generate the collision free motion satisfying the statical balance and then transformed it to the dynamically stable motion. Chestnutt et al. [12] proposed a heuristic method of footstep planning. Yoshida [13] approximated the shape of the robot by a rectangular and extended the approach for a omni-directional vehicle. Harada et al. [20] proposed a random sampling based planner combining with the walking pattern generator. Recently, there are a couple of researches simultaneously planned the foot step position and the whole body motion with keeping the statical balance. Hauser et al. [6] proposed the multi-step planning method applicable to the rock-climbing humanoid robot. Sanada et al. [5] proposed a RRT based method used to avoid an obstacle.

However, there has been no research on humanoid motion planning where the foot-step position and the whole-body motion are simultaneously planned with keeping the dynamical balance of the robot. With this paper, we define that the robot maintains its dynamical balance if the contact wrench sum applied to the robot from the environment is included strictly inside the wrench cone [21]. Here, the contact wrench sum and the wrench cone can be replaced by the ZMP and the support polygon if we use the ZMP.

3. Definitions

3.1. Configuration Space

Figure 2 shows the model of a humanoid robot. Let $\boldsymbol{\xi}_*$ be the six dimensional vector composed of the position $\boldsymbol{p}_*$ and the orientation $\boldsymbol{\phi}_*$ of the coordinate frame fixed to a link of the robot. The subscripts Fj, Hj ($j = r, l$), B and G denote the feet, the hands, the waist and the CoG, respectively.

We assume that the 3D models of the robot and the environment are known. These models are used for collision checking. A configuration of a humanoid robot is composed of the position/orientation of the waist ($\boldsymbol{\xi}_B$) and all joint angles ($\boldsymbol{\theta}$). Let us consider the following coordinate transformation:

$$(\boldsymbol{p}_G, \boldsymbol{\phi}_B, \boldsymbol{\xi}_{Fr}, \boldsymbol{\xi}_{Fl}, \boldsymbol{\xi}_{Hr}, \boldsymbol{\xi}_{Hl}, \boldsymbol{\theta}_r) = \boldsymbol{f}(\boldsymbol{\xi}_B, \boldsymbol{\theta}) \quad \cdots \quad (1)$$

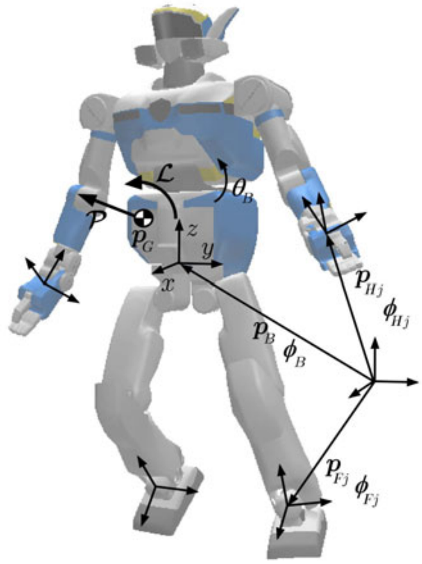

Fig. 2. Model of HRP2 humanoid robot.

where $\boldsymbol{\theta}_r$ denotes the joint angles of the chest, the neck and the finger. Among the coordinate variables defined in Eq. (1), we specify the desired trajectory for the position/orientation of the hands. The hand trajectory is expressed w.r.t. either the inertial coordinate or the chest coordinate systems. Hence, we consider the following configuration space when planning the motion of a humanoid robot:

$$\boldsymbol{q} = (\boldsymbol{p}_G, \boldsymbol{\phi}_B, \boldsymbol{\xi}_{Fr}, \boldsymbol{\xi}_{Fl}, \boldsymbol{\theta}_r) \in \mathcal{C} \quad \cdots \quad (2)$$

where $\mathcal{C}$ denotes the configuration space of the robot and $\mathcal{C}_{free} \subset \mathcal{C}$ its free space. We plan the motion of the robot based on Eq. (2). Our proposed planner can be applied to general humanoid robots where its configuration has the form of Eq. (2) and where each arm/leg has at least 6DOF.

3.2. Walking Pattern Generation

Among the variables defined in Eq. (2), the horizontal position of the CoG has to be determined so as to satisfy the dynamical balance of the robot. Let $\boldsymbol{p}_G = (x_G, y_G, z_G)$ and $\boldsymbol{p}_Z = (x_Z, y_Z, z_Z)$ be the position of the CoG and ZMP, respectively. Also, let $x - y$ plane coincide with the horizontal plane. The following differential constraints are imposed on the system:

$$\ddot{x}_G = \frac{g}{z_G - z_Z}(x_G - x_Z) \quad \cdots \quad (3)$$

$$\ddot{y}_G = \frac{g}{z_G - z_Z}(y_G - y_Z). \quad \cdots \quad (4)$$

Let us assume that the start and the goal configurations are given. The trajectories of x_G and y_G from the start to the goal can be calculated by using Eqs. (3) and (4) corresponding to the sampled foot position. Also, $\hat{\boldsymbol{q}}$ and $\boldsymbol{p}_Z$ are sampled to search for the collision-free upper body motion.

In this research, we use the conventional ZMP based walking pattern generator. Here, we considered neither