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Quick Slip-Turn of HRP-4C on its Toes

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***Abstract*— We present the realization of quick turning motion of a humanoid robot on its toes via slipping between its feet and the floor. A rotation model is described on the basis of our hypothesis that turning via slip occurs as a result of minimizing the power caused by floor friction. Using the model, the trajectory of the center of the foot can be generated to realize the desired rotational angle. Toe joints are used to realize quicker turning motion, while avoiding excessive motor load due to frictional torque. Quick slip-turn motion with toe support is successfully demonstrated using a humanoid robot HRP-4C.**

I. INTRODUCTION

In general, current humanoid robot locomotion assumes no slip contacts. As a result, robots tend to take many small steps when turning in one place; thus, a considerable amount of time is required to complete the turning motion. Taking these small steps results in inefficient energy consumption and inadequate stability. Therefore, we believe that the use of slip is important for realizing quick and smooth turning motion.

Issues regarding the proactive use of slip for humanoid motion have been addressed in some studies. The first published report on rotation using slip may be attributed to Takahashi [1], who filed a Japanese patent application in Honda during the secret development of humanoids. It was claimed that a quick turn is realized when a robot places all its legs on the floor and moves them while maintaining a uniform ground reaction force. Subsequently, Nishikawa [2] proposed a mechanical system using slip for enabling biped robots to turn. Koeda et al. [3] studied the application of slip to the turning motion of a small humanoid robot HOAP-2. A human-sized humanoid robot WABIAN-2R successfully demonstrated quick slip-turn motion through 80 degrees in 1.5 s supported by the toe and the heel [4]. Some studies [2] [4] have reported that robots can consume up to 60 percent less energy by turning using slip, as compared to turning in steps. However, the physical model of turn via slip has not been developed thus far.

The slip phenomenon has already been discussed, and our hypothesis has been demonstrated using humanoid robot platforms HRP-2 [5] and HRP-4C [6] [7]. However, the demonstrated motions were slow; therefore, we present a video showing the realization of quick and highly sophisticated slip-turn motion by humanoid robots.

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II. SLIP MODEL

First, we hypothesize that turning via slip occurs as a result of minimizing the power caused by floor friction.

$$\omega = \underset{\tilde{\omega}}{\text{argmin}} \{\mathcal{P}(\tilde{\omega})\} \tag{1}$$

where ω denotes the angular velocity of the robot, and $\mathcal{P}$ is the total power generated on both soles.

A humanoid robot can be modeled as a set of rigid bodies; we define the robot's base frame Σ_B on the pelvis, with the orientation parallel to the frontal direction of the pelvis link. The origin of the world frame Σ_W is its projection on the floor at the beginning of the robot's motion. It is assumed that the center of mass is coincident with the origin of the base frame so as to simplify the model. We constrain the left-foot motion to be symmetrical with the right-foot motion about the origin of the base frame. In addition, we do not change the foot direction.

On the basis of our hypothesis, we obtain the following expression of the angular velocity ω. Note that the detailed explanation is provided in [6].

$$\omega = \frac{12(Y_B v_x - X_B v_y)}{12(X_B^2 + Y_B^2) + l_x^2 + l_y^2} \tag{2}$$

where X_B and Y_B denote the position of the center of the sole, v_x and v_y represent the velocity components of $\boldsymbol{v}$, and l_x and l_y denote the length and width of the sole, along the x- and y-axes of the base frame, respectively, as shown in Fig. 1. This equation relates the given velocity $\boldsymbol{v}(v_x, v_y)$ to the angular velocity ω.

By calculating the time integral of (2) through the motion, the total rotation angle is obtained. However, the inverse problem cannot be solved using this model because there are several different trajectories for realizing the same rotational

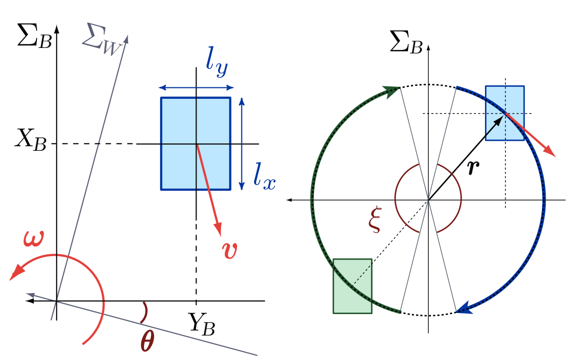

Fig. 1. Definitions of variables in the equations. Left: position of robot's foot for (2). Right: arc trajectory of both feet for (3).

angle. It is advisable for a robot to select the most *effective* motion to realize the desired rotational angle, which maximizes the angular velocity with the same magnitude as the given velocity. The velocity vector of the foot that maximizes ω has been found to be perpendicular to the position vector of the center of the foot [7]. The velocity that satisfies this condition yields to an arc trajectory, the center of which is coincident with the center of pressure assumed to be exactly the same as the midpoint of right and left feet.

The slip-turn motion for realizing the desired rotational angle θ can be generated by the equation

$$\xi = \frac{12|\boldsymbol{r}|^2 + l_x^2 + l_y^2}{12|\boldsymbol{r}|^2}\theta \tag{3}$$

where ξ denotes the angle between the initial and final position vectors of the arc trajectory, and $\boldsymbol{r}$ represents the current position vector of the center of the robot's sole, which is equal to the radius of the arc, as shown in Fig. 1.

III. MOTION ACCELERATION BY TOE SUPPORT

When a foot turns with floor slip, the frictional torque occurs as a reactive force. It is determined by integrating the product of the frictional force and the moment arm over the robot's sole. Thus, the power P required by the robot to twirl its foot on the floor is expressed as

$$P \;=\; \tau\omega \;=\; \mu N f(l_x, l_y)\omega \tag{4}$$

$$f(l_x, l_y) \;=\; g(\alpha)\; l_d \tag{5}$$

$$g(\alpha) = 1 + \frac{\alpha^2}{12\sqrt{1-\alpha^2}}\log\frac{\sqrt{1-\alpha^2}+1}{\alpha} + \frac{1-\alpha^2}{12\alpha}\log\frac{\alpha+1}{\sqrt{1-\alpha^2}} \tag{6}$$

where τ is the frictional torque, ω is the angular velocity as in (1), μ is the friction coefficient between the robot's sole and the floor, N is the normal force, $l_d = \sqrt{l_x^2 + l_y^2}$, $l_x = \alpha l_d$, and $l_y = \sqrt{1-\alpha^2}l_d$. Note that the value of P is not the same as the power $\mathcal{P}$ required to rotate the entire body in (1). The function of the length and width of the sole $f(l_x, l_y)$, given in (5) and (6), is determined by the diagonal length l_d and the ratio α; the former is the dominant factor affecting $f(l_x, l_y)$.

From (4), it can be inferred that the quicker a robot turns, the greater is the power required against $\tau\omega$. However, the motor power of a robot is limited. Therefore, the frictional torque τ has to be reduced; this can be achieved by decreasing μ, N, or l_d.

We adopt the third solution, i.e., decreasing l_d by using the toe joints of HRP-4C [8]. The motion of the toe link is generated on the basis of cubic polynomials; the initial, maximum, and final angles of the toe joints are connected during the toe support period. The maximum angle of the toe joint is set at the middle of the period.

IV. DEMONSTRATION WITH HRP-4C

Slip-turn motion with toe support was demonstrated using humanoid robot HRP-4C. In addition, we used our latest controller [9] [10] to allow motion with an extremely small stability margin. The parameters for the foot trajectory were $|\boldsymbol{r}| = 0.143$[m], $\xi = 90.0$[deg], and expected $\theta = 84.7$[deg]. Snapshots of HRP-4C taken every 0.3 s are shown in Fig. 2. The resultant rotational angle was 93.1[deg], and it was larger than the expected angle. This may attributed to a large velocity of motion, which induces non-negligible inertial force.

Fig. 2. HRP-4C turning on its toes. Total motion period: 3.0[s], toe support period: 1.2[s], turning period: 1.05[s], and maximum angle of toe joint: 30.0[deg].

V. CONCLUSIONS

We demonstrated quick turning motion of HRP-4C using slip between its feet and the ground. The foot trajectory was generated under the hypothesis that turning via slip occurs as a result of minimizing the power caused by floor friction. To realize quicker motion, the toe joints of the robot were utilized to reduce the frictional torque.

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