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Self-consistent Automatic Navigation of COM and Feet for Realtime Humanoid Robot Steering

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***Abstract*— A robust self-consistent humanoid navigation method is proposed. For any given targeted position and orientation, the robot robustly chases them without bankruptcies such as leg-crossing, excess stride and deadlock. The key idea is to define a canonical stance with respect to the target independently from the current configuration, and trace them by each step alternately. It locally prioritizes the foot guidance and sacrifices the COM tracking in each step. Since the feet targets are defined consistently with the targeted COM, the global COM tracking and robust navigation including pivot turns are achieved as the result.**

I. INTRODUCTION

Humanoid robots are expected to work in environments with humans. They potentially serve as our alternative bodies with appropriate intelligent assistances by operators such as situation awareness and decision making. A difficulty on that remote control operations is how to manipulate large degrees-of-freedom of the robots simultaneously. It is required to synthesize robot behaviors to achieve tasks in realtime from a few input variables by some schemes[1][2][3][4].

Let us focus on the walking transportation, which is one of the fundamental humanoid operations. For a given target position and orientation (Fig.1(a)), the motion synthesis comprises the following two steps, namely, (i) put discrete milestones of the center of mass (COM) and both feet between the current and the target configurations (Fig.1(b)), and (ii) connect the milestones smoothly (Fig.1(c)). For the step (ii), several methods[5][6][7][8][9][10] which plans dynamically consistent motion trajectories in realtime have been proposed. On the other hand, the issue around step (i) has not been sufficiently discussed. Kuffner et al.[11] and Chestnutt et al.[12] proposed footstep planning methods to avoid obstacles and to reach the target. However, it is not still an easy problem to chase the target even in an open-space environment without bankruptcy such as leg-crossing, excess stride, and deadlock in cases of the realtime navigation.

Neo et al.[13] proposed a navigation method in which COM tracks the commanded position and feet are guided so that COM is located at the midpoint of them. Nishiwaki et al.[8] pointed out that prioritizing COM causes abnormal gait depending on the initial stance, and proposed another method in which the feet placements are more prioritized. Unfortunately, it frequently fails to chase the targeted COM position as shown later in this paper. Those conflictions between COM and feet happen due to the nonholonomic constraints where only one foot can move with the other foot fixed in each step except for jumping.

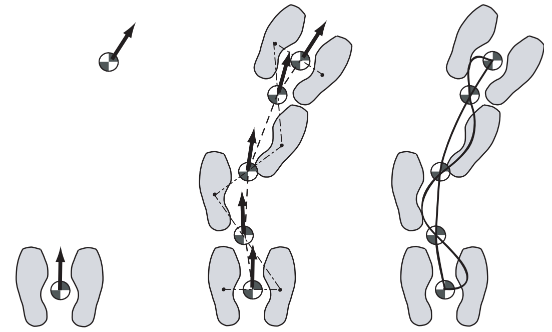

Fig. 1. Motion synthesizing process comprises (a) giving target COM position and body orientation (b) putting discrete milestones of COM and both feet and (c) connecting the milestones smoothly.

This paper proposes a self-consistent humanoid navigation method which is never bankrupted against any targets and robustly chases them. The key idea is to define a canonical stance with respect to each targeted position and orientation independently from the current configuration, and trace them by each step alternately. It locally prioritizes the foot guidance than COM in the sense that it sacrifices the COM tracking in each step. Since the feet targets are defined consistently with the targeted COM, the global COM tracking and robust navigation including pivot turns are achieved as the result.

II. SELF-CONSISTENT NAVIGATION OF COM AND FEET

A. Formulation and Conventional Methods

Let us consider the steering system which calculates the COM position, the body orientation, feet positions, and feet orientations sequentially as terminal boundary conditions of the walking motion. The input and the output of the system are as follows:

- Input : ${}^{t}\boldsymbol{p}_C[i]$, ${}^{t}\theta_B[i]$,
- Output : ${}^{d}\boldsymbol{p}_C[i]$, ${}^{d}\theta_B[i]$, ${}^{d}\boldsymbol{p}_K[i]$, ${}^{d}\theta_K[i]$,

where i ($i = 0, 1 \cdots$) is the discrete time, ${}^{t}\boldsymbol{p}_C[i]=[\,{}^{t}x_C[i]\ {}^{t}y_C[i]\,]^{\mathrm{T}}$ is the targeted COM position at i th step, ${}^{t}\theta_B[i]$ is the targeted body orientation at i th step, ${}^{d}\boldsymbol{p}_C[i] = [\,{}^{d}x_C[i]\ {}^{d}y_C[i]\,]^{\mathrm{T}}$ is the desired COM position at i th step, ${}^{d}\theta_B[i]$ is the desired body orientation at i th step, ${}^{d}\boldsymbol{p}_K[i] = [\,{}^{d}x_K[i]$

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${}^{d}y_K[i]\,]^{\mathrm{T}}$ is the desired position of the stepping foot at i th step, and ${}^{d}\theta_K[i]$ is the desired orientation of the stepping foot at i th step. The orientation is represented by an angle about z-axis. We define the configuration of a body part as a set of the position and the orientation, where the COM configuration means the COM position and the body orientation. Here, the desired configuration means the automatically inserted milestones as the terminal condition of each step.

Neo et al.[13] proposed an intuitive footstep planning method so as to reach the target COM configuration in one step at each time. The desired configurations are decided so that COM is located at the midpoint of both feet as follows:

$$
\begin{aligned}
{}^{d}\boldsymbol{p}_C[i] &= {}^{t}\boldsymbol{p}_C[i], && (1)\\
{}^{d}\theta_B[i] &= {}^{t}\theta_B[i], && (2)\\
{}^{d}\boldsymbol{p}_K[i] &= 2\,{}^{d}\boldsymbol{p}_C[i] - \boldsymbol{p}_S[i-1], && (3)\\
{}^{d}\theta_K[i] &= 2\,{}^{d}\theta_B[i] - \theta_S[i-1], && (4)
\end{aligned}
$$

where $\boldsymbol{p}_S[i] = [\,x_S[i]\ y_S[i]\,]^{\mathrm{T}}$ is the position of the supporting foot at i th step, and $\theta_S[i]$ is the orientation of the supporting foot at i th step. According to Eqs. (3)(4), i th feet configurations depend on $i-1$ th configurations, which means feet configurations are always dependent on the initial feet configurations as shown in Fig. 2(a)(b). As Nishiwaki et al.[8] pointed out, this results in unnatural walking motions such that feet positions are arranged in step along the forward direction every two steps or the sideward distance between both feet is remained while moving forward as shown in Fig. 2(a), for instance. Moreover, this method generates unnatural pivot turns where the stepping foot is not translated from the current position as shown in Fig. 2(c). These problems happen since this method gives more priority to the planning of the COM navigation than that of the feet navigation to reach the target in one step.

Nishiwaki et al.[8] proposed another footstep planning method which prioritizes feet navigation to avoid abnormal footsteps. In this method, the body displacement is transformed into the stepping foot displacement with respect to the supporting foot coordinate as follows:

$$
\begin{aligned}
{}^{d}x_K[i] &= {}^{t}x_C[i] - {}^{d}x_C[i-1] + x_S[i-1], && (5)\\
{}^{d}y_K[i] &= 2(\,{}^{t}y_C[i] - {}^{d}y_C[i-1]\,) + w + y_S[i-1], && (6)\\
w &= \begin{cases} w_c & (\text{if the left foot steps}) \\ -w_c & (\text{if the right foot steps}) \end{cases}, && (7)\\
{}^{d}\theta_K[i] &= {}^{t}\theta_B[i] - {}^{d}\theta_B[i-1] + \theta_S[i-1], && (8)
\end{aligned}
$$

where w_c is the canonical sideward distance between both feet. Given a sequence of the targeted COM configuration as Fig. 3(a), for instance, the desired COM and feet configurations are computed as shown in Fig. 3(b) on the assumption that the body position is regarded as COM and the COM configuration is located at the midpoint of both feet. In this case, COM doesn't reach the final target position. Moreover, even if the operator keeps designating the same target position until COM reaches it, COM doesn't necessarily converge to the target. While this method solves the problem on feet navigation in Neo et al.'s method[13], it lacks the reachability, which is a significant problem for the target tracking.

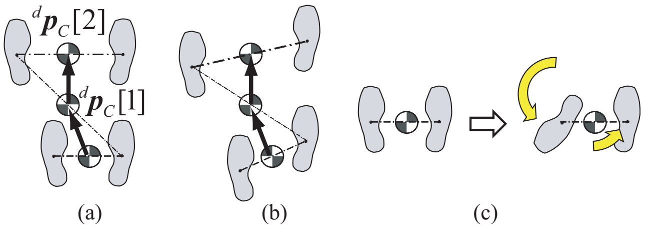


Fig. 2. A footstep planning method locating COM at the midpoint of both feet which generates (a)(b) different feet configurations dependently from initial configurations and generates (c) unnatural pivot turns in which the stepping foot is not translated from the current position.

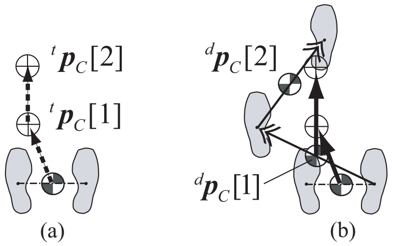


Fig. 3. A footstep planning method transforming COM displacement into foot displacement which doesn't lead COM to targets (a) as shown in (b).

B. Basic Navigation Scheme

The requirements on the biped navigation are as follows:

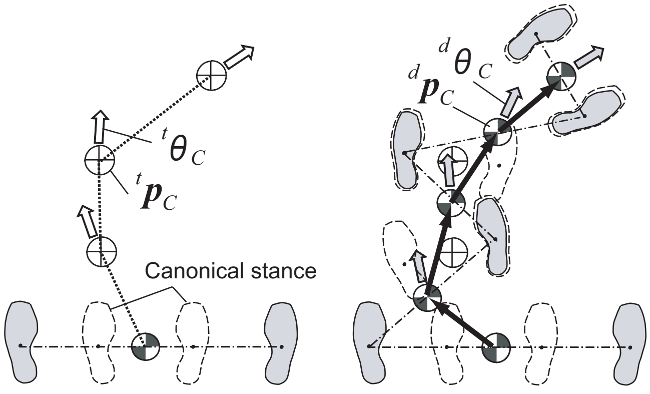
1) COM reaches the target.
2) Feet navigation is never bankrupted.

As long as the robot chases the target, we admit an error between the current COM configuration and the target configuration in condition 1). Conversely, we prioritize the foot guidance at each time to satisfy the condition 2) strictly for the prevention of the bankrupted motion such as leg-crossing, excess stride, and deadlock.

In our method, we define a canonical stance with respect to the targeted COM configuration independently from the current configuration at first. Then, the desired COM and feet configurations are planned so that feet get close to the stance. Although this method gives more priority to the planning of feet navigation, COM also approaches the target as feet navigation proceeds. Finally, COM reaches the target automatically at the time when both feet reach the canonical stance by applying the following rule.

At the canonical stance, the target feet are located on an even stance with respect to the target COM configuration. The desired configuration of the stepping foot is decided as follows:

$$
{}^{d}\boldsymbol{p}_K[i] = \begin{cases} {}^{t}\boldsymbol{p}_C[i] + \boldsymbol{R}(\,{}^{t}\theta_B[i]\,)\boldsymbol{p}_{F_C} \\ (\text{if the left foot steps}) \\ {}^{t}\boldsymbol{p}_C[i] - \boldsymbol{R}(\,{}^{t}\theta_B[i]\,)\boldsymbol{p}_{F_C} \\ (\text{if the right foot steps}) \end{cases}, \qquad (9)
$$



(a) (b)

Fig. 4. A sequence of the configurations of COM and both feet in which the feet are navigated to chase the canonical stance with respect to the target.

$$
{}^{d}\theta_K[i] = \begin{cases} {}^{t}\theta_B[i] + \theta_{F_B} & (\text{if the left foot steps}) \\ {}^{t}\theta_B[i] - \theta_{F_B} & (\text{if the right foot steps}) \end{cases}, \tag{10}
$$

$$
\boldsymbol{R}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}, \tag{11}
$$

where $\boldsymbol{p}_{F_C} = [\, x_{F_C} \; y_{F_C} \,]^{\mathrm{T}}$ is an offset vector from COM to one foot, and θ_{F_B} is an offset angle of the orientation from the body to one foot. The desired COM configuration is decided as follows:

$$
{}^{d}\boldsymbol{p}_C[i] = \frac{{}^{d}\boldsymbol{p}_K[i] + \boldsymbol{p}_S[i-1]}{2}, \tag{12}
$$

$$
{}^{d}\theta_B[i] = \frac{{}^{d}\theta_K[i] + \theta_S[i-1]}{2}. \tag{13}
$$

The foot which maximizes the COM displacement from the current configuration is chosen as the stepping foot so that the robot can reach the target efficiently. Suppose the stepping foot can ideally reach the desired configuration in one step without leg-crossing. In case that the operator doesn't change the target, COM reaches the target in two steps by the above rule. Fig. 4 shows a sequence of the desired configurations of COM and both feet planned by the proposed method in which (a) shows a sequence of the targets and (b) shows a sequence of the desired COM configurations. COM chases the target with an error from $i = 1$ to $i = 3$, and reaches the terminal target at $i = 4$ by coming up with the canonical stance with respect to the target when the operator stops updating the target.

III. AUTOMATIC LONG-DISTANCE NAVIGATION

In actual situations, the feet cannot necessarily reach the canonical stance corresponding to the targeted COM configuration in one step each. This section presents a method to place the desired foot configuration within one-step range sequentially for a long distance walk.

If a single path which leads COM to the targeted configuration is defined, a locus of the corresponding canonical stance is also defined. By tracking the locus step-by-step, the feet, and accordingly COM, approach the target in a self-consistent manner. Although any continuous path to the target COM configuration is acceptable, we define it simply by a linear interpolation as follows:

$$
{}^{I}\boldsymbol{p}_C(s) = s(\,{}^{t}\boldsymbol{p}_C[i] - {}^{d}\boldsymbol{p}_C[i-1]\,) + {}^{d}\boldsymbol{p}_C[i-1], \tag{14}
$$

$$
{}^{I}\theta_B(s) = \frac{||\,{}^{I}\boldsymbol{p}_C(s) - {}^{d}\boldsymbol{p}_C[i-1]\,||}{||\,{}^{t}\boldsymbol{p}_C[i] - {}^{d}\boldsymbol{p}_C[i-1]\,||}(\,{}^{t}\theta_B[i] - {}^{d}\theta_B[i-1]\,), \tag{15}
$$

where s $(0 \le s \le 1)$ is a parameter for the spatial interpolation, ${}^{I}\boldsymbol{p}_C(s)$ is the path of the COM position, and ${}^{I}\theta_B(s)$ is the path of the body orientation. A benefit of the above path is that it monotonously converges to the target ${}^{t}\boldsymbol{p}_C[i]$ and ${}^{t}\theta_B[i]$ with respect to s. Then, a locus of the corresponding canonical stance, which is named *the virtual rail* hereafter as Fig. 5 shows, is computed as follows:

$$
{}^{I}\boldsymbol{p}_L(s) = {}^{I}\boldsymbol{p}_C(s) - \boldsymbol{R}(\,{}^{I}\theta_B(s)\,)\,\boldsymbol{p}_{F_C}, \tag{16}
$$

$$
{}^{I}\theta_L(s) = {}^{I}\theta_B(s) - \theta_{F_B}, \tag{17}
$$

$$
{}^{I}\boldsymbol{p}_R(s) = {}^{I}\boldsymbol{p}_C(s) + \boldsymbol{R}(\,{}^{I}\theta_B(s)\,)\,\boldsymbol{p}_{F_C}, \tag{18}
$$

$$
{}^{I}\theta_R(s) = {}^{I}\theta_B(s) + \theta_{F_B}, \tag{19}
$$

where ${}^{I}\boldsymbol{p}_L(s)$ is the path of the left-foot position, ${}^{I}\theta_L(s)$ is the path of the left-foot orientation, ${}^{I}\boldsymbol{p}_R(s)$ is the path of the right-foot position, and ${}^{I}\theta_R(s)$ is the path of the right-foot orientation. Note that the nominal path of COM defined by Eqs.(14) and (15) is only used for defining the virtual rail; COM does not have to track it, but the feet discretely follow the virtual rail.

A candidate of the desired left foot configuration is computed as follows:

$$
{}^{c}\boldsymbol{p}_L[i] = {}^{I}\boldsymbol{p}_L(s_{L_i}), \tag{20}
$$

$$
{}^{c}\theta_L[i] = {}^{I}\theta_L(s_{L_i}), \tag{21}
$$

$$
\begin{aligned} s_{L_i} = \arg\max_{s}\{\,(\,{}^{I}\boldsymbol{p}_L(s), {}^{I}\theta_L(s)\,) \\ |\,(\,{}^{I}\boldsymbol{p}_L(s), {}^{I}\theta_L(s)\,) \in \mathbb{F}_L[i]\,\}, \end{aligned} \tag{22}
$$

where $\mathbb{F}_L[i]$ is a set of the geometrically feasible left-foot configurations with respect to the right foot configuration, which is defined by the operator with the workspace and collision avoidance taken into account and named *the feasible landing area*. Obviously, it has to include the left foot configuration at the canonical stance. The feasible landing area of the right foot with respect to the left foot, a candidate of the desired right foot configuration $(\,{}^{c}\boldsymbol{p}_R[i], {}^{c}\theta_R[i]\,)$ and the corresponding s_{R_i} are also computed as well. The corresponding desired COM configurations with respect to the above candidates are defined from Eqs.(12) and (13). Finally, which foot to step and where to land are decided so that COM displacement from the current configuration is maximized.

As long as the foot lands within the feasible landing area, the leg-crossing and the excess stride are avoided. However, if both s_{L_i} and s_{R_i} are zero or nil, the robot falls into a deadlock. Such situations occur if the virtual rail doesn't intersect with the feasible landing area of either the left foot or the right foot. Fig. 6(a) depicts an example case of the deadlock.

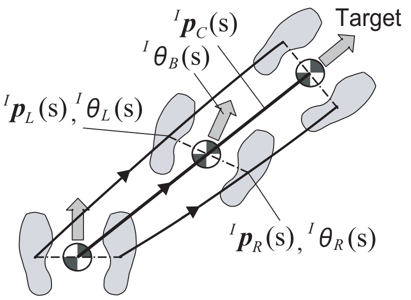


Fig. 5. Virtual rail with respect to linear-interpolated COM path.

The following description presents a technique to escape from the deadlock. Once it is detected that the robot is in the deadlock, the nominal COM path (14) and (15) are redefined as follows:

$$ {}^I\boldsymbol{p}_C(s) = s(\,{}^t\boldsymbol{p}_C[i] - {}^c\boldsymbol{p}_C[i-1]\,) + {}^c\boldsymbol{p}_C[i-1], \tag{23} $$

$$ {}^I\theta_B(s) = \frac{||\,{}^I\boldsymbol{p}_C(s) - {}^c\boldsymbol{p}_C[i-1]\,||}{||\,{}^t\boldsymbol{p}_C[i] - {}^c\boldsymbol{p}_C[i-1]\,||}(\,{}^t\theta_B[i]\, - \,{}^c\theta_B[i-1]\,), \tag{24} $$

where $(\,{}^c\boldsymbol{p}_C[i-1],\ {}^c\theta_B[i-1]\,)$ is *the canonical COM configuration* with respect to the pivot foot $\boldsymbol{p}_L[i-1]$ (or $\boldsymbol{p}_R[i-1]$), which is defined as follows:

$$ {}^c\boldsymbol{p}_C[i-1] = \begin{cases} \boldsymbol{p}_L[i-1] + \boldsymbol{R}(\,{}^c\theta_B[i-1]\,)\boldsymbol{p}_{F_C} \\ \quad(\text{if the left foot is the pivot foot}) \\ \boldsymbol{p}_R[i-1] - \boldsymbol{R}(\,{}^c\theta_B[i-1]\,)\boldsymbol{p}_{F_C} \\ \quad(\text{if the right foot is the pivot foot}) \end{cases}, \tag{25} $$

$$ {}^c\theta_B[i-1] = \begin{cases} \theta_L[i-1] + \theta_{F_B} \\ \quad(\text{if the left foot is the pivot foot}) \\ \theta_R[i-1] - \theta_{F_B} \\ \quad(\text{if the right foot is the pivot foot}) \end{cases}. \tag{26} $$

Namely, the canonical COM configuration has a canonical stance which includes the current configuration of at least one of the feet. Eqs.(23) and (24) means that the starting configuration of the nominal COM path is replaced with the canonical COM configuration in case of the deadlock as Fig. 6(b). Since the canonical configuration of the non-pivot foot with respect to $(\,{}^c\boldsymbol{p}_C[i-1],{}^c\theta_B[i-1]\,)$ is within the feasible landing area with respect to the pivot foot, the virtual rail necessarily intersects with the feasible landing area as Fig. 6(c) shows. Consequently, it is guaranteed that the robot can escape from the deadlock.

The algorithm of the proposed navigation method is shown in **Algorithm 1** where MaxS$(\,{}^t\boldsymbol{p}_C[i],{}^t\theta_B[i]\,)$ calculates s_{L_i}, s_{R_i} and the maximum of them. JudgeIfLeftFootStep judges if the left foot is chosen as a stepping foot.

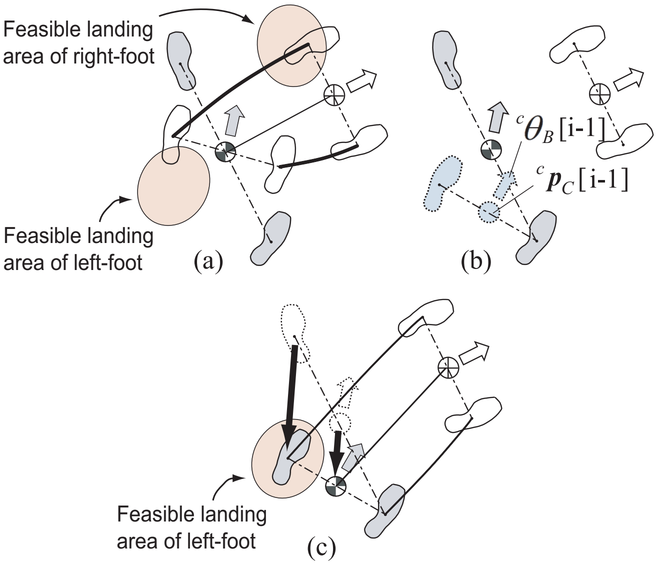


Fig. 6. (a) If the virtual rail doesn't intersect with the feasible landing area, the robot fails into a deadlock. (b) In order to escape from the deadlock, the starting configuration of the nominal COM path is replaced with the canonical COM configuration. (c) Then, the redefined virtual rail necessarily intersects with the feasible landing area.

Algorithm 1 LongDistanceNavigation$(\,{}^t\boldsymbol{p}_C[i],\ {}^t\theta_B[i]\,)$

```
if ${}^d\boldsymbol{p}_C[i-1] = {}^t\boldsymbol{p}_C[i]$ and ${}^d\theta_B[i-1] = {}^t\theta_B[i]$ then
    return true
end if
$s_i \leftarrow$ MaxS$(\,{}^t\boldsymbol{p}_C[i],{}^t\theta_B[i]\,)$
if JudgeIfLeftFootStep then
    $({}^d\boldsymbol{p}_K[i],\ {}^d\theta_K[i]) \leftarrow ({}^I\boldsymbol{p}_L(s_i),\ {}^I\theta_L(s_i))$
else
    $({}^d\boldsymbol{p}_K[i],\ {}^d\theta_K[i]) \leftarrow ({}^I\boldsymbol{p}_R(s_i),\ {}^I\theta_R(s_i))$
end if
$({}^d\boldsymbol{p}_C[i],\ {}^d\theta_B[i]) \leftarrow$ ( (12), (13) )
```

IV. EXPERIMENTS

A. Implementation of Navigation System

The implementation of the steering system is shown in Fig. 7 using a joystick AV8R-01(Saitek) as the input device, a humanoid robot mighty[15] as the real robot. OpenHRP[14] is also available instead of the real robot for simulation. The joystick outputs the instructions to the control PC connected via USB and they are mapped to the COM displacement and the body rotation displacement. The COM-Feet navigation program decides the sequential desired configurations of COM, body, and both feet. The trajectory planning program calculates the whole body trajectory which interpolates the segment from the current configuration to the desired configuration by the method proposed by Terada et al.[9] and the method proposed by Sugihara et al.[10]. The cycle of the motion is 0.5[s]. The inverse kinematics program calculates the whole body angles every 5[ms]. A graphical interface helps the operator to monitor the current robot state and the target configuration. Fig. 8 shows a snapshot of the program.

B. Simulation

Fig. 9 shows sequential configurations of COM and both feet of pivot turns planned by (a) (d) the method proposed by

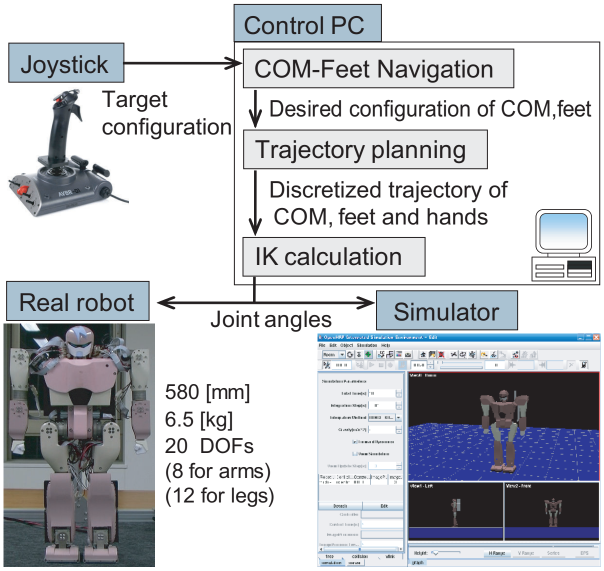


Fig. 7. Diagram of humanoid steering system.

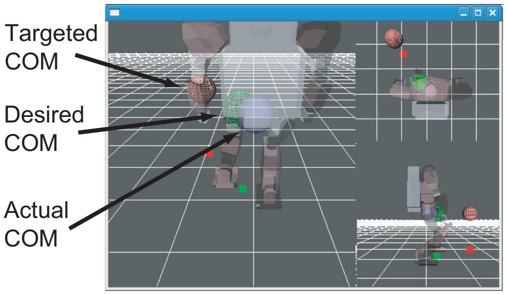
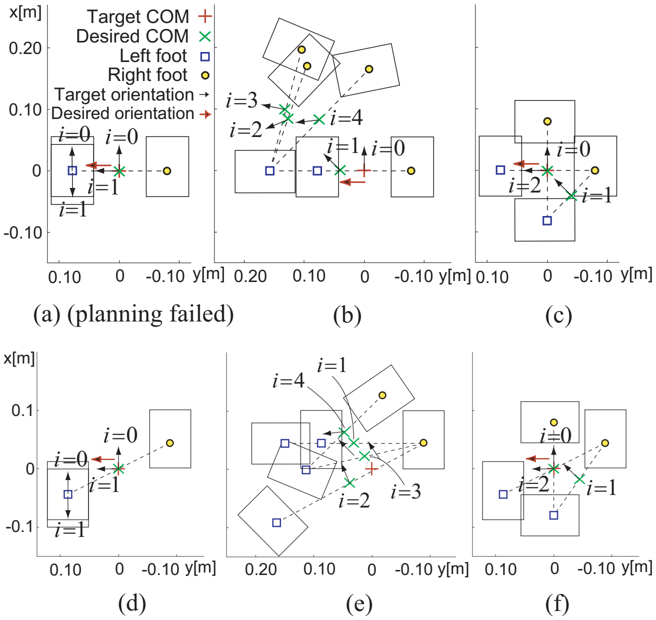


Fig. 8. Snapshot of the information presentation program.

Neo et al.[13], (b) (e) the method proposed by Nishiwaki et al.[8], and (c) (f) our method, where ${}^{d}\boldsymbol{p}_C[0]=[0\ 0]^{\mathrm{T}}$, ${}^{d}\theta_B[0]=0$ ${}^{t}\boldsymbol{p}_C[i]=[0\ 0]^{\mathrm{T}}$, ${}^{t}\theta_B[i]=\frac{\pi}{2}$, $\boldsymbol{p}_{F_C}=[0\ 0.08]^{\mathrm{T}}$, and $\theta_{F_B}=0$ in common, and Fig. 10 shows snapshots of the terminal posture of Fig. 9 (a)(b)(c). The unit of length is $[m]$, while that of angle is $[rad]$. The upper figure is the result started from ${}^{d}\boldsymbol{p}_L[0]=[0\ 0.08]^{\mathrm{T}}$, ${}^{d}\theta_L[0]=0$, ${}^{d}\boldsymbol{p}_R[0]=[0\ \ -0.08]^{\mathrm{T}}$, and ${}^{d}\theta_R[0]=0$ and the lower figure is the result started from ${}^{d}\boldsymbol{p}_L[0]=[-0.05\ 0.08]^{\mathrm{T}}$, ${}^{d}\theta_L[0]=0$, ${}^{d}\boldsymbol{p}_R[0]=[0.05\ -0.08]^{\mathrm{T}}$, and ${}^{d}\theta_R[0]=0$. Fig. 9(a) resulted in the failure because of exceeding the feasible landing area. The planned posture which could not be realized is shown in Fig. 10(a) where we removed joint angle limitation to solve inverse kinematics. In Fig. 9(d), the unnatural terminal posture maintaining the initial feet positions is generated though COM reached the target. In Fig. 9(b)(e), COM didn't reach the target within 4 steps while the operator kept designating. The posture at $i=4$ in Fig. 9(b) is shown in Fig. 10 (b). In Fig. 9(c)(f), COM reached the target at $i=2$ when a canonical stance is realized. The robot took the constant terminal configuration of COM and feet in both cases as shown in Fig. 10(c), which did not cause the unnatural posture.

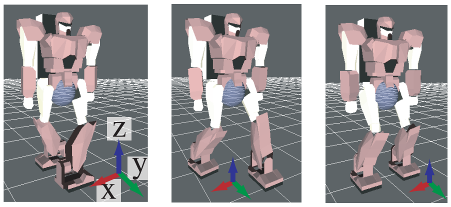
Fig. 11 shows sequential configurations of COM and both feet of a walking motion planned by (a) the method proposed by Neo et al.[13], (b) the method proposed by Nishiwaki et al.[8], and (c) our method, where ${}^{d}\boldsymbol{p}_C[0]=[0\ 0]^{\mathrm{T}}$, ${}^{d}\theta_B[0]=0$, ${}^{t}\boldsymbol{p}_C[1]=[0.07\ -0.03]^{\mathrm{T}}$, ${}^{t}\boldsymbol{p}_C[2]=[0.14\ -0.03]^{\mathrm{T}}$, ${}^{t}\boldsymbol{p}_C[3]=[0.21\ -0.07]^{\mathrm{T}}$, ${}^{t}\theta_B[i]=0$, $\boldsymbol{p}_{F_C}=[0\ 0.05]^{\mathrm{T}}$, and $\theta_{F_B}=0$ in common. In Fig. 11(a), the planning caused the excess stride as shown in Fig. 12(a) while COM reached all targets. In Fig. 11(b), an error from the target was reamained while the operator kept designating. Fig. 11(b) shows the planned configurations from $i=1$ to $i=4$ and Fig.12(b) shows the posture at $i=4$. In Fig. 11(c), while COM configuration had an error from the targets to chase the canonical stance at $i=1,2,3$, COM reached the final target when both feet reached the stance at $i=4$. The terminal posture is shown in Fig. 12(c).



(a) (planning failed) (b) (c)

(d) (e) (f)

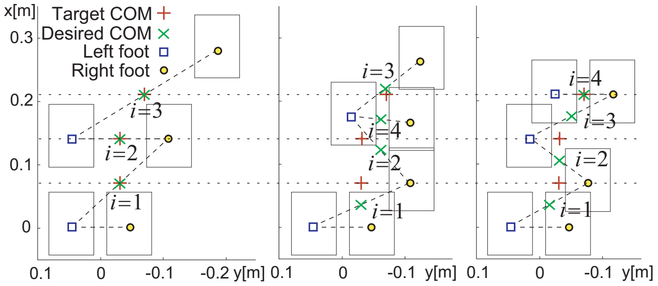
Fig. 9. Footsteps of pivot turns planned by (a) (d) the method proposed by Neo et al.[13], (b) (e) the method proposed by Nishiwaki et al.[8] and (c) (f) our method where the lower figures started from different initial states and ${}^{t}\boldsymbol{p}_C[i]=[0\ 0]^{\mathrm{T}}$, and ${}^{t}\theta_B[i]=\frac{\pi}{2}$ in common.



(a) $i=1$ (b) $i=4$ (c) $i=2$

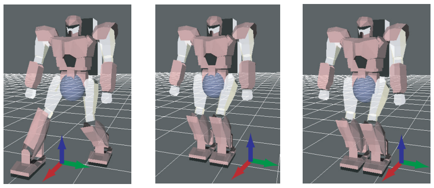
Fig. 10. Snapshots of the terminal posture in which (a) ((b), (c)) corresponds to that in Fig.9.

Fig. 13 shows sequential footsteps of a target tracking motion planned by our method on the assumption that the ground is even and obstacles don't exist near the tracking route, and Fig. 14 shows COM sequences of the motion and the actual COM trajectory. Starting from the same configuration as is used in Fig. 11, the operator updated instructions every some times, where ${}^{t}\boldsymbol{p}_C[1]=[0.13\ 0.27]^{\mathrm{T}}$,



(a) (b) (c)

Fig. 11. Footsteps of rightward and forward walking planned by (a) the method proposed by Neo et al.[13], (b) the method proposed by Nishiwaki et al.[8] and (c) our method aiming at the same target configuration at each time.



(a) $i=3$ (b) $i=4$ (c) $i=4$

Fig. 12. Snapshots of the terminal posture in which (a) ((b), (c)) corresponds to that in Fig.11.

${}^{t}\theta_B[1]=1.57$, ${}^{t}\boldsymbol{p}_C[5]=[0.42\ 0.07]^{\mathrm{T}}$, ${}^{t}\theta_B[5]=-1.00$, ${}^{t}\boldsymbol{p}_C[9]=[0.65\ 0.29]^{\mathrm{T}}$, and ${}^{t}\theta_B[9]=0.89$. Both feet moved aiming at the target stance varied by the target as shown in Fig. 13 without bankruptcy of the feet navigation, and COM chased the updated target robustly as shown in Fig. 14. After the operator stopped updating the target at $i=10$, both feet got close to the target stance and reached finally at $i=13$, when the target COM configuration was realized simultaneously. We consider that the proposed method is effective for the realtime steering of biped robots in case obstacles don't exist near the robot.

V. CONCLUSION

We proposed a self-consistent humanoid navigation method which robustly chases the target without bankruptcy. The key idea is to define a canonical stance with respect to the target configuration independently from the current configuration. The advantages of our method are that pivot turns are planned, planned motions don't result in unnatural postures at the end of the movement, and COM chases sequential targets robustly.

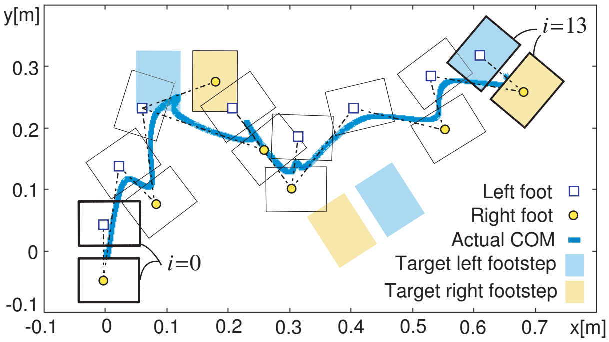


Fig. 13. Transportation sequence of footsteps planned by proposed method advancing toward the target stance without bankruptcy of feet navigation.

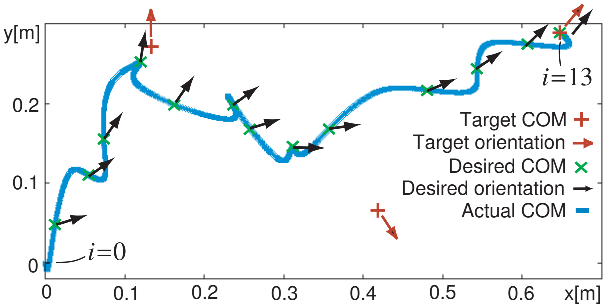


Fig. 14. Transportation sequence of COM planned by proposed method to chase the target which was updated 3 times.

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