2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
September 24–28, 2017, Vancouver, BC, Canada

Foot-guided Agile Control of a Biped Robot through ZMP Manipulation

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Abstract— **A novel biped control is proposed. It enables a robust foot-guided maneuver and suits to the locomotion in complex environments. It treats ZMP as an indirect manipulation variable rather than the control variable, and does not need to observe the acceleration. ZMP behavior is only constrained to approach the pivot foot during a step, so that the robot can flexibly accelerate itself. The most distinctive point to the previous methods is that the motion stability is guaranteed based on the capture point only at landing, which improves agility. The optimal input, i.e., the desired position of ZMP, is analytically obtained immediately from the current state of COM, time to land, and the desired landing position, so that it can be implemented with even less computation cost. Though the limitation of the supporting region is not explicitly taken into account, it is guaranteed that the desired ZMP is confined within the region based on its convexity.**

I. INTRODUCTION

Biped robots are potentially useful mobilities that can travel in various irregular circumstances, while the biped locomotion is still technically difficult. It requires a skillful pedipulation, namely, successive stepping on limited footholds engaged with a manipulation of the ground reaction force in a limited area of the pivot sole, in order to reach the goal without falling. It should be noted that the pedipulation is paradoxical in nature; when one foot is about to take a step, the other foot undertakes a role as the pivot foot and the reaction force is concentrated on it, which often locally destabilizes the robot itself. Except for conservative walks where the ground projection of the center of mass (COM) keeps in the pivot sole, which has been conventionally called the static walk, this destabilization would be rather exploited for agile locomotions [1]. In that case, the robot has to recover the stability after landing.

If the robot is in an open space, i.e., no obstacles and bumps on the ground, the foot placement can be determined purely based on the stability [2], [3], [4], [5], [6]. Otherwise, a landing point has to be carefully chosen first in accordance with the ground profile, and then, the reaction force is to be manipulated to carry both COM and the stepping foot stably to preferred locations. Kajita et al. [7] proposed an idea to apply the preview control to this problem. Given the desired transitions of stance, a future locus of ZMP [8] is determined a priori, and then, COM is controlled in such a way that the actual ZMP follows it. The future stability is guaranteed by the regulator. The detail is reviewed in Section II-B.

This work was supported in part by by Grant-in-Aid for Scientific Research (B) (#15H02762) and Grant-in-Aid for Challenging Exploratory Research (#26540135) from Japan Society for the Promotion of Science.

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The method has three obvious drawbacks. It basically treats ZMP as the control variable. ZMP is sensitive to the contact state between the foot and the ground, so that to prescribe the desired behavior of ZMP in detail degrades the flexibility of the robot motion against perturbations. It is also a problem that it requires to measure the acceleration of COM as a part of the state variable since it significantly suffers from sensor noises. The last concern is that it is computationally expensive since it needs to solve Riccati equation in every cycle. Those issues reduce responsivity of the robot, and hence, it is not used as a realtime controller but as an online motion trajectory planner in practice.

Efforts to improve it have been made to some directions. In a biped control system designed by Nishiwaki et al. [9], it runs at a short cycle (about 30ms) in online and assigns the actual robot state to the initial value of the trajectory to be planned. Ideas to modify the desired locus of ZMP based on the deviation of the robot state [10], [11] were also proposed. Another extension by Herdt et al. [12] is to relax the constraint on the desired ZMP by inequalities that represent the supporting region, i.e., the convex hull of the contact points between the feet and the ground, and apply the model-predictive control instead of the preview control with an efficient solution [13]. However, they still lack immediacy.

This paper proposes a novel foot-guided biped control that resolves all the above issues. It treats ZMP as an indirect manipulation variable rather than the control variable, and does not need an observation of the acceleration. ZMP behavior is only constrained to approach the pivot foot during a step and the robot can flexibly accelerate itself. The most distinctive point to the previous methods is that the motion stability is guaranteed based on the capture point [5] only at landing, which improves agility. It is noteworthy that the optimal control input, i.e., the desired position of ZMP, is analytically obtained immediately from the current state of COM, time to land, and the desired landing position, so that it can be implemented with even less computation cost than the previous methods.

II. ZMP MANIPULATION FOR FOOT-GUIDED LOCOMOTION

A. Biped robot model and foot-guided locomotion

The discussion goes based on the COM-ZMP model [14], [15], in which the whole-body motion is represented by the movement of COM and the torque about COM is ignored. x, y and z-axes are aligned in the longitudinal, the sideward and the vertical directions, respectively. The equation of motion

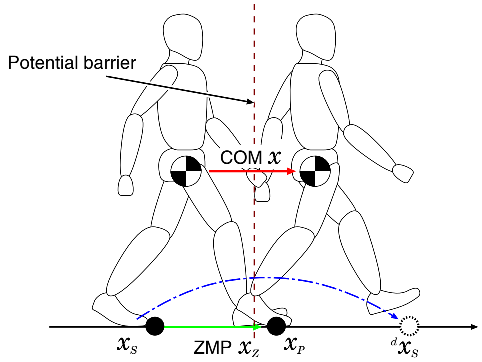


Fig. 1. Collaborative movements of COM, ZMP and the stepping foot

of COM is as follows:

$$\ddot{x} = \zeta^2(x - x_{\mathrm{Z}}) \tag{1}$$

$$\ddot{y} = \zeta^2(y - y_{\mathrm{Z}}) \tag{2}$$

$$\zeta \equiv \sqrt{\frac{g}{z - z_{\mathrm{Z}}}}, \tag{3}$$

where (x, y, z) is the position of COM, $(x_{\mathrm{Z}}, y_{\mathrm{Z}}, z_{\mathrm{Z}})$ is the position of ZMP, and $g = 9.8\mathrm{m/s}^2$ is the acceleration due to the gravity. $|\ddot{z}| \ll g$ is assumed. Note that z_{Z} is the nominal ground height and is given. Due to the symmetry of Eqs. (1) and (2), only Eq. (1) is taken into account hereafter.

Let us consider a situation where the left foot takes a step forward from x_{S} to ${}^d x_{\mathrm{S}}$ and the right foot serves as the pivot as illustrated in Fig. 1. If ZMP is initially at the middle point of the supporting region and the robot suddenly lifts up the left foot, ZMP jumps to the right sole instantaneously, COM is accelerated backward, and the robot eventually falls in the worst case. As the above thought experiment suggests, COM has to be initially accelerated forward by kicking the ground in order to take over the potential barrier. ZMP is incidentally located to the stepping sole and later travels to the pivot sole.

B. Review: ZMP control for foot-guided locomotion

Kajita et al. [7] tried to achieve the above collaborative movements of COM and ZMP by applying the preview control. Suppose the jerk of COM is the control input and ZMP the control output, Eq. (1) is rewritten as

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u \tag{4}$$

$$x_{\mathrm{Z}} = \begin{bmatrix} 1 & 0 & -\dfrac{1}{\zeta^2} \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix}, \tag{5}$$

where $u \overset{\mathrm{def}}{=} \dddot{x}$, which is determined as

$$u = \arg\min_{u} \frac{1}{2}\int_{t}^{t+T}\left\{q(x_{\mathrm{Z}} - {}^d x_{\mathrm{Z}})^2 + ru^2\right\}\mathrm{d}t, \tag{6}$$

where T is a given terminal time, and q and r are positive weighting values. ${}^d x_{\mathrm{Z}}$ is the desired locus of ZMP, which must be consistent with the transition of the pivot foot.

u is obtained by discretizing the state equation (4) with a time step T/N (N is a natural number) as

$$u = -p_1 x - p_2\dot{x} - p_3\ddot{x} + \sum_{k=1}^{N} f_k\, {}^d x_{\mathrm{Z}}[k], \tag{7}$$

where k is the time index, and ${}^d x_{\mathrm{Z}}[k] \overset{\mathrm{def}}{=} {}^d x_{\mathrm{Z}}(t + Tk/N)$. The gains p_1, p_2, p_3 and f_k ($k = 1, \cdots, N$) are computed by solving Riccati equation. Refer the original paper for details.

This method has the following three problems.

1) A highly accurate observer to estimate $\ddot{x}$ is required.
2) The desired locus of ZMP all over time has to be defined, which overconstrains the motion and reduces the flexibility against perturbations.
3) Riccati equation has to be solved in every cycle.

While 3) is relatively less severe thanks to the evolution of computers, 1) and 2) are qualitatively intractable. Herdt et al. [12] proposed to use the model-predictive control instead of the preview control in order to loosely constrain the desired ZMP by inequalities that represent the supporting region, which still has the problem 1).

C. Proposed method

In the proposed method, ZMP is treated as an indirect manipulation variable [14], [15]. Though ZMP cannot be directly manipulated, a scheme to indirectly manipulate it via the whole-body cooperation has been acknowledged [15]. The desired ZMP is not prescribed but determined in realtime, so that the problem 2) in the previous section is resolved. The problem 1) is also resolved since the state variable only includes x and $\dot{x}$.

As described in the introduction, it is rather preferred to locally destabilize COM during a step for agile locomotion [1]. Thus, the capture point [5] only at landing is taken into account. Note that the capture point is available as the stability criterion if and only if an appropriate controller works as Sugihara [16] showed. Suppose the remaining time T until landing is given. ZMP x_{Z} is determined by solving the following optimization problem:

$$x_{\mathrm{Z}} = \arg\min_{x_{\mathrm{Z}}} \frac{1}{2}\int_{t}^{t+T}(x_{\mathrm{Z}} - x_{\mathrm{P}})^2\mathrm{d}t$$

$$\text{subject to} \quad x(t+T) + \frac{\dot{x}(t+T)}{\zeta} = {}^d x_{\mathrm{S}}, \tag{8}$$

where x_{P} is the nominal position of the pivot foot, which is supposed to be invariant in $t \sim t+T$. The equality constraint means the standing stability condition at landing, where the left-hand side of the equation is the capture point at $t+T$. The optimal solution is analytically obtained as

$$x_{\mathrm{Z}} = x_{\mathrm{P}} - \frac{2(x_{\mathrm{CP}} - e^{-\zeta T}\, {}^d x_{\mathrm{SP}})}{1 - e^{-2\zeta T}}, \tag{9}$$

where

$$x_{\mathrm{CP}} \overset{\mathrm{def}}{=} x + \frac{\dot{x}}{\zeta} - x_{\mathrm{P}} \tag{10}$$

$${}^d x_{\mathrm{SP}} \overset{\mathrm{def}}{=} {}^d x_{\mathrm{S}} - x_{\mathrm{P}} \tag{11}$$

are the relative capture point to the pivot foot and the desired relative landing position of the stepping foot to the pivot foot. The proof is as follows.

Let us define the Hamiltonian for the problem (8) as

$$H \stackrel{\text{def}}{=} -\frac{1}{2}(x_{\mathrm{Z}} - x_{\mathrm{P}})^2 + \lambda_1 \dot{x} + \lambda_2 \zeta^2 (x - x_{\mathrm{Z}}) + \mu \left\{ x(t+T) + \frac{\dot{x}(t+T)}{\zeta} - {}^{d}x_{\mathrm{S}} \right\}, \tag{12}$$

where λ_1, λ_2 and μ are co-state variables associated with x, $\dot{x}$ and the transversality condition. The canonical equations of the problem are

$$\frac{\mathrm{d}\lambda_1}{\mathrm{d}t} = -\frac{\partial H}{\partial x} = -\zeta^2 \lambda_2 \tag{13}$$

$$\frac{\mathrm{d}\lambda_2}{\mathrm{d}t} = -\frac{\partial H}{\partial \dot{x}} = -\lambda_1 \tag{14}$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\partial H}{\partial \lambda_1} = \dot{x}, \tag{15}$$

$$\frac{\mathrm{d}\dot{x}}{\mathrm{d}t} = \frac{\partial H}{\partial \lambda_2} = \zeta^2 (x - x_{\mathrm{Z}}), \tag{16}$$

and the control input x_{Z} is determined from the following stationary condition:

$$\frac{\partial H}{\partial x_{\mathrm{Z}}} = 0 \quad \Leftrightarrow \quad x_{\mathrm{Z}} = x_{\mathrm{P}} - \zeta^2 \lambda_2. \tag{17}$$

The general solution of λ_1 and λ_2 are obtained as

$$\lambda_1 = \zeta C_1 e^{\zeta t} + \zeta C_2 e^{-\zeta t} \tag{18}$$

$$\lambda_2 = C_1 e^{\zeta t} - C_2 e^{-\zeta t} \tag{19}$$

from Eqs. (13) and (14), where C_1 and C_2 are unknown coefficients. The transversality condition yields

$$\lambda_1(t+T) = -\frac{\partial H}{\partial x(t+T)} = -\mu \tag{20}$$

$$\lambda_2(t+T) = -\frac{\partial H}{\partial \dot{x}(t+T)} = -\frac{\mu}{\zeta}, \tag{21}$$

which provides

$$\lambda_1(t+T) = \zeta \lambda_2(t+T). \tag{22}$$

By plugging Eqs. (18) and (19) into the above Eq. (22),

$$C_1 = 0, \qquad \lambda_2 = C_2 e^{-\zeta t}. \tag{23}$$

From Eqs. (1), (17) and (23), the general solution of x is

$$x = x_{\mathrm{P}} + C_3 e^{\zeta t} + C_4 e^{-\zeta t} + \frac{1}{2}\zeta^3 C_2 t e^{-\zeta t}, \tag{24}$$

where C_3 and C_4 are unknown coefficients. The differentiation of the above yields

$$\dot{x} = \zeta \left\{ C_3 e^{\zeta t} - C_4 e^{-\zeta t} + \frac{1}{2}\zeta^3 C_2 e^{-\zeta t}(1 - \zeta t) \right\}. \tag{25}$$

From Eqs. (24) and (25),

$$x_{\mathrm{CP}} = 2C_3 e^{\zeta t} + \frac{1}{2}\zeta^2 C_2 e^{-\zeta t}, \tag{26}$$

where x_{CP} is defined by Eq. (10). From Eq. (25) and the transversality condition, we get

$$x_{\mathrm{CP}} - e^{-\zeta T}\, {}^{d}x_{\mathrm{SP}} = \frac{1}{2}\zeta^2 C_2 e^{-\zeta T}(1 - e^{-2\zeta T}), \tag{27}$$

where ${}^{d}x_{\mathrm{SP}}$ is defined by Eq. (11). Finally, the solution (9) is derived by plugging the above Eq. (27) into Eq. (17).

It is noteworthy that x_{Z} is decided from the current position of capture point, which is rather easily observed [17]. If ζ is a constant, the coefficient values can be computed in advance. Even if ζ is not a constant, i.e., the height of COM varies, the coefficient values can be found with quite small computation cost. Thus, the problem 3) pointed out in the previous section is also resolved. Even the assumptions that x_{P} and ${}^{d}x_{\mathrm{S}}$ are constant can also be relaxed in practice.

Though the constraint on the desired ZMP that it has to lie within the supporting region is not explicitly taken into account, it is guaranteed that it stays within the supporting region once it enters into the region due to the monotonous convergence and the convexity of the region. The strict proof is omitted. If it is found that the desired ZMP is outside of the supporting region, it means the demanded duration T is inappropriately short so that it is extended until the corrected desired ZMP is within the region. This idea is to be reported in a future publication. If T is valid, it is reduced by the control period every after the cycle.

III. Foot control based on virtual tractor

Control of the stepping foot should also be engaged to the movement of ZMP. The following conditions are imposed:

1) the foot has to go over bumps,
2) the foot has to land at the desired point,
3) the foot can leave the ground after ZMP enters the pivot sole,
4) the foot has to land on the ground at or before $t+T$,

while the flexibility against perturbations should be preserved. In this sense, motion deviation complying with perturbations is rather accepted. Hence, it is not preferable to meet the above conditions by getting the foot to track a carefully designed time-dependent referential trajectory. Here, an idea of the virtual tractor is adopted. Though it has another mathematical background than the central issue in this paper and the detail is reported in another publication, the outline is presented as follows.

Suppose the ground profile can be measured and the spatial referential path is defined in accordance with it. A virtual mass point moves on the path and reaches the end at $t+T$. The foot is virtually towed by the point and catches up with it before $t+T$, and the reaction force of the traction is exerted to the point. This interaction prevents abnormal responses of the foot to large deviations. The motion of the virtual tractor is ruled by the following equations:

$$\boldsymbol{p}_{\mathrm{VT}} = \boldsymbol{p}_{\mathrm{r}}(s) \tag{28}$$

$$m_{\mathrm{VT}}\ddot{s} = u_{\mathrm{A}} - \boldsymbol{f}_{\mathrm{VT}}^{\mathrm{T}} \left(\frac{\partial \boldsymbol{p}_{\mathrm{r}}}{\partial s} \right) \Big/ \left\| \frac{\partial \boldsymbol{p}_{\mathrm{r}}}{\partial s} \right\|. \tag{29}$$

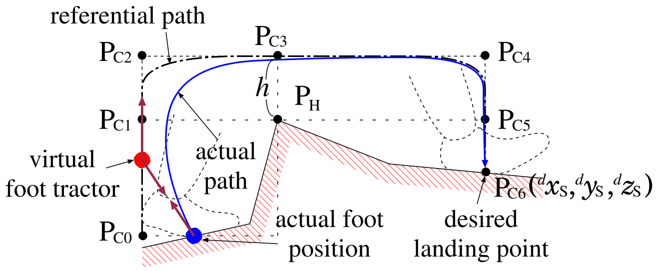


Fig. 2. Foot navigation to track a spatial path based on a virtual tractor

where $\boldsymbol{p}_{\mathrm{VT}}$ is the position of the virtual tractor, $\boldsymbol{p}_{\mathrm{r}}(s)$ is a parametric curve representing the spatial referential path, m_{VT} is the virtual mass of the virtual tractor, u_{A} is the virtual driving force, and $\boldsymbol{f}_{\mathrm{VT}}$ is the virtual traction force. $\boldsymbol{p}_{\mathrm{r}}(s)$ is designed by a NURBS curve on a vertical plane as depicted in Fig. 2, for example, where $\{\mathrm{P}_{\mathrm{C}k}\}$ $(k = 0, \cdots, 6)$ are control points, and h is a constant to secure the clearance. P_{C6} is set for the desired landing point. Although P_{C0} is chosen near the initial position of the stepping foot, it does not have to be strict. P_{H} is the highest point of the ground profile — if there is more than one highest point, the closest point to P_{C0} is chosen. P_{H} can coincide with P_{C0} or P_{C6}, in which case P_{C3} coincides with P_{C2} or P_{C4}, respectively.

Let us decide u_{A} by solving the following optimization problem:

$$\begin{aligned} u_{\mathrm{A}} =& \arg\min_{u_{\mathrm{A}}} \frac{1}{2}\int_{t}^{t+T} u_{\mathrm{A}}^2 \mathrm{d}t \\ \text{subject to} \quad & s(t+T) = 1, \quad \dot{s}(t+T) = 0, \\ & u_{\mathrm{A}} = 0 \quad \text{if } 0 \le t \le t + T_{\mathrm{L}}, \end{aligned} \tag{30}$$

where $t + T_{\mathrm{L}}$ is the time when the desired ZMP enters the pivot sole. Namely, the virtual tractor is expected to be delivered to the destination on time with the minimum effort. This is analytically solved as

$$u_{\mathrm{A}} = \begin{cases} 0 & (t \le t \le t + T_{\mathrm{L}}) \\ \dfrac{6}{T}\left(\dfrac{1-s}{T} - \dfrac{2\dot{s}}{3}\right) & (t + T_{\mathrm{L}} \le t \le t + T) \end{cases}. \tag{31}$$

The proof is omitted. Note that it is not necessary to explicitly find T_{L}; once it is checked that the desired ZMP is inside of the pivot sole, the optimization is activated until landing. Likewise, $\boldsymbol{f}_{\mathrm{VT}}$ is provided as

$$\boldsymbol{f}_{\mathrm{VT}} = \begin{cases} \boldsymbol{0} & (t \le t \le t + T_{\mathrm{L}}) \\ \dfrac{6}{\alpha T}\left(\dfrac{\boldsymbol{p}_{\mathrm{VT}} - \boldsymbol{p}_{\mathrm{S}}}{\alpha T} - \dfrac{2\dot{\boldsymbol{p}}_{\mathrm{S}}}{3}\right) & (t + T_{\mathrm{L}} \le t \le t + T), \end{cases} \tag{32}$$

where α $(0 < \alpha < 1)$ is a constant to catch up with the virtual tractor before landing, and $\boldsymbol{p}_{\mathrm{S}}$ is the position of the stepping foot. $\boldsymbol{f}_{\mathrm{VT}}$ is converted to the equivalent joint actuation torques or approximately the referential foot motion.

IV. Simulations

The proposed method was verified through some preliminary simulations based on the COM-ZMP model. The following assumptions worked in the simulations:

1) The inertial effects of the body rotation and the leg movement were negligible.
2) The position and velocity of COM were accurately observed.
3) COM was accelerated such that ZMP tracked the desired position accurately, meaning that the delay of motor servo and sensor signal processing were negligible.

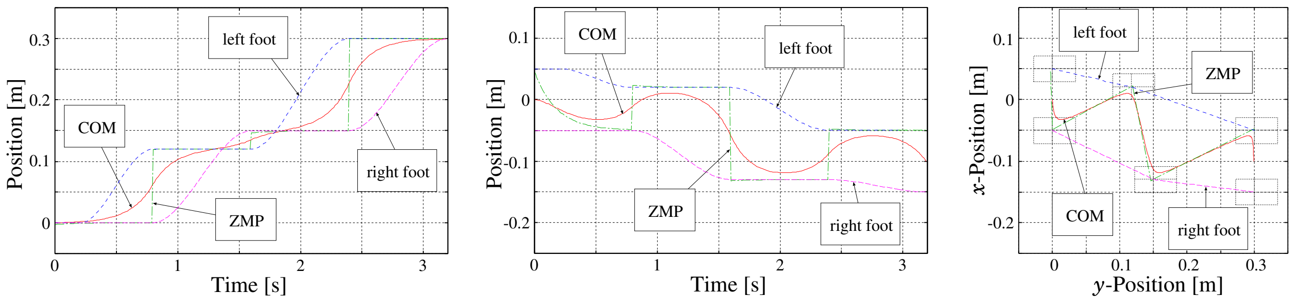
The other necessary parameters for the simulations were set as $\Delta t = 0.001$s, $z = 0.3$m. The initial position of COM, the left foot and the right foot were $(0, 0, 0.3)$, $(0, 0.05, 0)$ and $(0, -0.05, 0)$, respectively. A sequence of the desired landing points were given as $(0.12, 0.02, 0)$ (left foot), $(0.15, -0.13, 0)$ (right foot), $(0.30, -0.05, 0)$ (left foot), and $(0.30, -0.15, 0)$ (right foot) in advance. The both soles were supposed to be 0.09m×0.06m rectangular, and the nominal foot center is allocated at 0.04m forward from the heel and the middle in lateral.

Four cases were conducted under the following conditions:

Case I	$T = 0.8$s per step, no disturbances
Case II	$T = 0.5$s per step, no disturbances
Case III	$T = 0.8$s per step, intermittently constant disturbances exerted during the motion
Case IV	$T = 0.8$s per step, random disturbances exerted at every moment

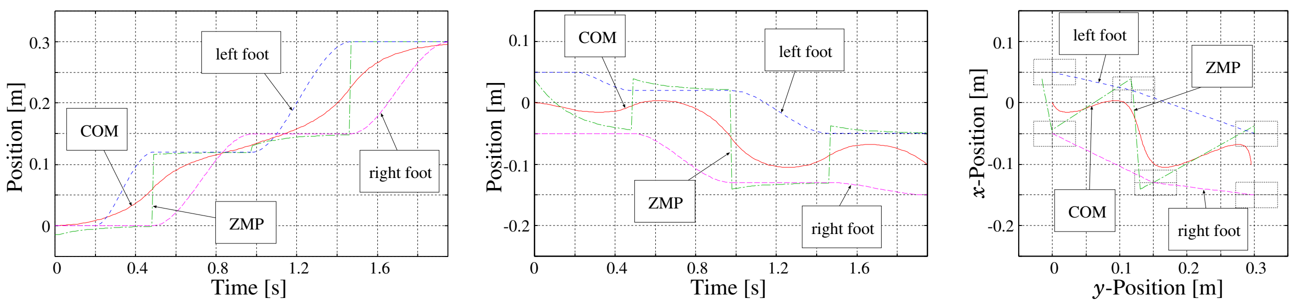
Figs. 3∼6 show the loci of COM, ZMP and the feet in the above four cases, respectively. The feet tracked the desired sequence of landing positions and reached the final goal without falling in all the cases. Although the double support phases are almost invisible in the graphs, the transition of ZMP from the stepping foot to the pivot foot during ground-kicking were managed and the stepping motion certainly conformed to it. It is observed in Figs. 3 and 4 that the magnitude of the side-swaying of COM in Case I is larger than that in Case II, while that of ZMP in the former is smaller than that of the latter. It is because COM had to be confined in the lateral stance in shorter term in the latter case. Those results show that the proposed controller can automatically adjust the desired ZMP in accordance with the given terminal condition. In Case III, the disturbance forces were exerted during the term hatched in Fig. 5, due to which ZMP was initially displaced 0.01m backward and 0.01m leftward from the desired position. Though it caused unexpected acceleration of COM and the locus of COM was deviated from that in Fig. 3, the terminal boundary conditions were robustly satisfied. In Case IV, ZMP was displaced ±0.01m both forward and sideward as shown in Fig. 6, which possibly models fluctuation of ZMP due to the unevenness of the ground. The effect of this deviation at high-frequency can be hardly observed in the locus of COM, so that it is concluded the proposed controller is less sensitive to the deviation of ZMP.

A full-body dynamics simulation was also conducted with a scenario in which a humanoid robot [18] with about 0.6m height walked over stairs with 0.03m steps and 0.1m spans. The forward dynamics including contact force computation,



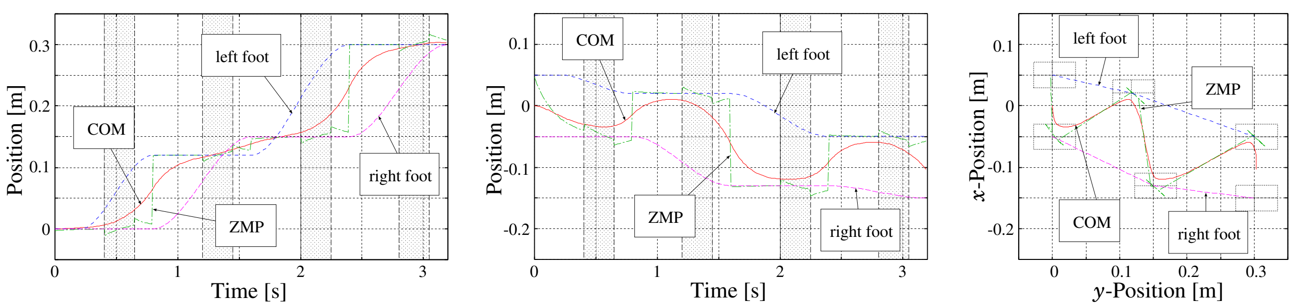
(a) t-x (b) t-y (c) x-y

Fig. 3. Loci of COM, ZMP, feet ($T = 0.8$s, $z = 0.3$m, no perturbation)



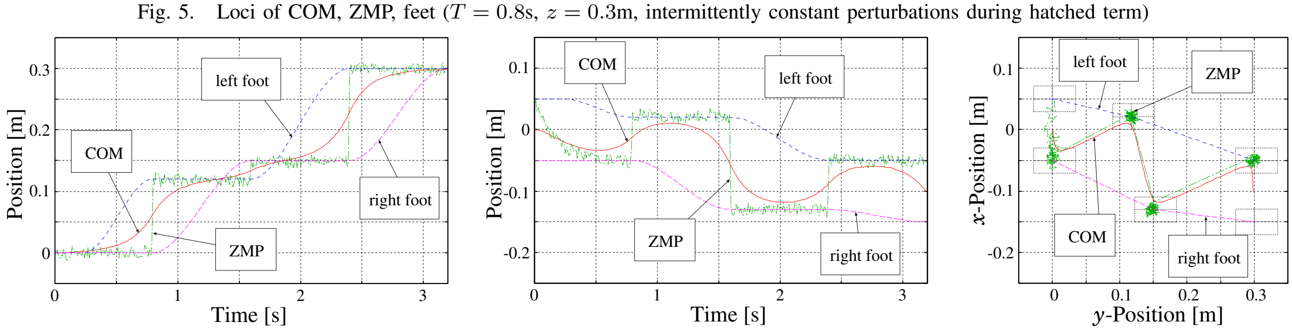
(a) t-x (b) t-y (c) x-y

Fig. 4. Loci of COM, ZMP, feet ($T = 0.5$s, $z = 0.3$m, no perturbation)



(a) t-x (b) t-y (c) x-y

Fig. 5. Loci of COM, ZMP, feet ($T = 0.8$s, $z = 0.3$m, intermittently constant perturbations during hatched term)



(a) t-x (b) t-y (c) x-y

Fig. 6. Loci of COM, ZMP, feet ($T = 0.8$s, $z = 0.3$m, random perturbations during during all term)

motor dynamics in servo control and friction in gears was based on Wakisaka et al.'s method [19]. The desired ZMP is converted to the equivalent desired acceleration of COM and finally to the desired whole joint angles through the inverse kinematics [15]. Each joint was controlled by PID compensation to track the desired value. The parameters were set for $T = 1.4$s, $m_{\mathrm{VT}} = 1.0$kg and $\alpha = 2/3$. The desired landing points and the COM height were automatically allocated in online in accordance with the given destinations and the ground profile. The feet were controlled based on the method in Section III. The robot succeeded to go over the stairs. The loci of COM, ZMP and the feet in x-y and x-z planes are plotted in Fig. 7. Though the time series of them are omitted due to the limited space, it was confirmed that they satisfied the conditions 1)$\sim$4) in Section III.

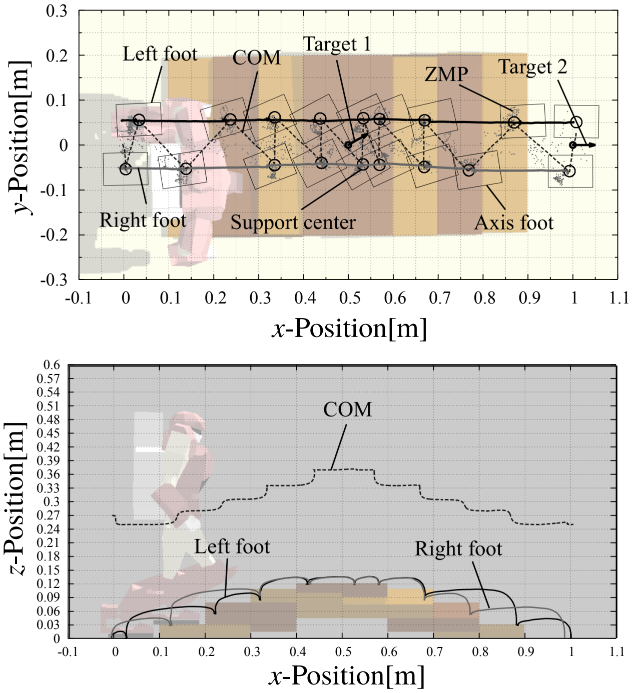


Fig. 7. Result of a walking simulation on stairs

V. CONCLUSIONS

A novel foot-guided biped control was proposed. It is favorable in terms of flexibility against perturbations and computation cost as confirmed through computer simulations. Another benefit is that it does not require an observation of the acceleration of COM, which makes it available in realtime control. This point will be verified in a future work.

An idea to treat ZMP as an indirect manipulation variable is not widely adopted and might seem eccentric since ZMP depends on the equilibrium of external torques, which are resulted from the robot motion. The authors, however, think it effective in order to improve the robot agility.

They also think it is important to relax constraints on motion for higher flexibility. To focus on the capture point only at landing is based on that thought, and showed a promising orientation toward trajectory-free locomotion control.

The issue of computation cost might not be serious, given the latest advancement of computers. However, it should be emphasized that a heavy optimization is not the sole solution for sophisticated biped robots.

The method cannot cope with too large perturbation; in such cases, the desired landing position should be modified. Though it is out of the scope of this paper, the proposed controller can work together with that scheme.

ACKNOWLEDGMENT

The authors would thank Mr. Naoki Wakisaka and Mr. Hiroshi Atsuta for their discussing the analytical solution of the optimization problem.

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