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Dynamics Morphing from Regulator to Oscillator on Bipedal Control

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***Abstract*— A stable non-linear oscillator for autonomous biped stepping control is designed in a top-down manner by morphing dynamics of standing regulator. It resolves three problems which have been in the conventional artificial CPG approaches, namely, 1) how to unify it with the standing control, 2) the controller parameter tuning with complicated networked unit oscillators, and 3) a design of an extra sensory feedbacks to be superimposed for stabilization. The proposed control is built upon the stabilizability-maximized COM-ZMP regulator developed by the author, and only a single parameter seamlessly connects it to a stable limit cycle without degrading the stabilization performance. By synchronizing the foot-lifting with a limit cycle of ZMP, a stable periodic alternate stepping is achieved. Since it is free from time-driven trajectory, it is expected to be a fundamental technique to build robust autonomous biped controllers.**

I. Introduction

Legged robots are expected to work by locomoting robustly and standing stably in spite of uncertainties about terrains and unpredicted disturbances in the environment. It is obvious that detailed referential motion trajectories as time-driven functions make almost no use for task operations in realistic situations. A crucial issue is to design a motor controller as an autonomous system, which is not slaved by time but by dynamical events. It is a challenging problem since the legged robots are strongly nonlinear systems with the structure-varying property[1]; they lack mechanical connection to the environment and locomote by deforming the supporting region discontinuously.

Two fundamental motions of bipeds are the standing stabilization and the periodic alternate stepping. Those motions, which we humans do without any difficulties, have different characteristics from each other in terms of dynamics. The standing stabilization means to let the center of mass (COM) converge to the equilibrium point, so that it is formulated as a regulator design problem — a linear regulator in many cases[2][3][4]. On the other hand, the autonomous periodic alternate stepping is hardly achieved in the linear control framework; it is required to make COM converge asymptotically to a stable limit cycle[5]. For this purpose, coupled van der Pol oscillator[6][7][8][9], Matsuoka oscillator[10][11][12][13][14] and Kuramoto oscillator[15][16][17], for instance, have been studied. Many of them are inspired by a biological knowledge about the motor control with the central pattern generator (CPG) [18]. Those previous controllers have the following three problems.

1) The controller structure differs largely from the standing regulator, so that it is hard (or even impossible) to unify them.
2) Tuning policy of a number of controller parameters is hardly found, since the controller is built from several mutually-connected unit oscillators in a bottom-up manner.
3) They are basically nothing more than function generators; they have adaptabilities to external perturbations, but do not have stabilization abilities themselves. Extra sensory feedbacks should be superimposed on their output signals in order to stabilize the system. It makes the controller more complicated.

This paper proposes a novel controller designed rather in a top-down manner to resolve the above shortcomings. Concerning with the standing stabilization issue, the author[19] has clarified the sufficient condition of COM regulators to maximize the stabilization performance under the constraints about reaction forces through manipulation of the zero-moment point (ZMP)[20]. It is shown that the COM regulator dynamically morphs into a nonlinear oscillator with a stable limit cycle by modulating its damping term without degrading the stabilization performance. Being different from the conventional artificial CPG approaches, an adaptive oscillation and stabilization are naturally merged on an identical controller. As the result, ZMP also converges to a limit cycle. A stable periodic alternate stepping is achieved by synchronizing foot-lifting with it. Though we take an opposite standpoint to Morimoto et al.[17] in the sense that they regard ZMP oscillation as the result of stepping, our conclusion theoretically supports their method, and moreover, clarifies the senses of each controller parameter.

II. Stabilizability-maximized COM-ZMP Regulator[19]

It is important for the design of robust biped controllers to understand the biped robot as an open system, which dynamically interacts with the environment[21]. Let us consider a planar bipedal motion on the lateral plane as shown in Fig. 1. We assume that the inertial torque about COM is less enough to be neglected than the moment of linear inertial force about ZMP, and that the height of COM is constant as $z = \mathrm{const.}$ for simplicity. Also, let us denote the lateral COM position by x, the referential COM position by ${}^{ref}x$ and the ZMP position by x_Z, respectively. We get the following linear state

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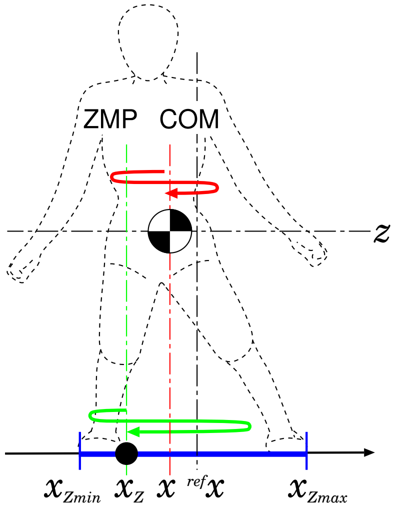


Fig. 1. An approximate mass-concentrated biped model in lateral plane. ZMP x_Z moves within the supporting region $x_{Zmin} \le x_Z \le x_{Zmax}$. The height of COM is assumed to be constant.

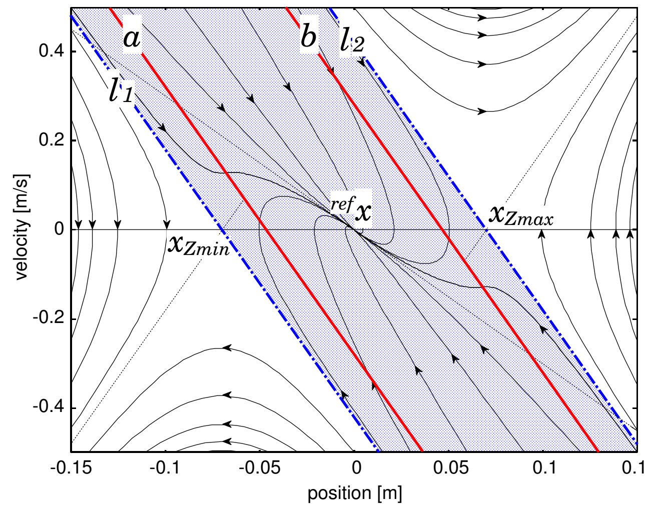


Fig. 2. Curves of the piecewise-affine autonomous system with the stabilizability-maximized COM-ZMP regulator for $\omega = \sqrt{g/0.27}$, $^{ref}x = 0$, $x_{Zmin} = -0.07$, $x_{Zmax} = 0.07$ and $q = 0.5$.

equation in which ZMP is regarded as the input[22]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\chi \\ \dot{\chi}\end{bmatrix} = \begin{bmatrix}0 & 1 \\ \omega^2 & 0\end{bmatrix}\begin{bmatrix}\chi \\ \dot{\chi}\end{bmatrix} + \begin{bmatrix}0 \\ -\omega^2\end{bmatrix}\chi_Z \tag{1}$$

where $\chi \equiv x - {}^{ref}x$, $\chi_Z \equiv x_Z - {}^{ref}x$, $\omega \equiv \sqrt{g/z}$ and $g = 9.8$[N/kg] is the acceleration due to the gravity. Even in this simplest dynamical model, χ_Z is constrained within the supporting region $[\chi_{Zmin}, \chi_{Zmax}]$ as

$$\chi_{Zmin} \le \chi_Z \le \chi_{Zmax} \tag{2}$$

where $x_{Zmin} \equiv \chi_{Zmin} + {}^{ref}x$ and $x_{Zmax} \equiv \chi_{Zmax} + {}^{ref}x$ are the right and left bounderies of the supporting region on x-axis. In this model, ZMP plays a role as a 'channel' through which the robot and the environment exchange forces.

Let us design the referential ZMP, which works as the input to the system to stabilize COM around the reference, with the constraint condition (2) taken into account as follows:

$$\tilde{\chi}_Z = (q+1)\left(\chi + \frac{\dot{\chi}}{\omega}\right) \tag{3}$$

$$\chi_Z = \begin{cases}\chi_{Zmax} & (\mathrm{S1}: \tilde{\chi}_Z > \chi_{Zmax}) \\ \tilde{\chi}_Z & (\mathrm{S2}: \chi_{Zmin} \le \tilde{\chi}_Z \le \chi_{Zmax}) \\ \chi_{Zmin} & (\mathrm{S3}: \tilde{\chi}_Z < \chi_{Zmin})\end{cases} \tag{4}$$

where q is a positive constant. $\tilde{\chi}_Z$ is called *the simulated ZMP*[23]. By controlling the actual ZMP to track the above referential ZMP, we get an autonomous COM dynamics, which is represented as the following piecewise-affine system:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\chi \\ \dot{\chi}\end{bmatrix} = \begin{cases}\begin{bmatrix}0 & 1 \\ \omega^2 & 0\end{bmatrix}\begin{bmatrix}\chi \\ \dot{\chi}\end{bmatrix} + \begin{bmatrix}0 \\ -\omega^2\chi_{Zmax}\end{bmatrix} & (\mathrm{S1}) \\ \begin{bmatrix}0 & 1 \\ -\omega^2 q & \omega(q+1)\end{bmatrix}\begin{bmatrix}\chi \\ \dot{\chi}\end{bmatrix} & (\mathrm{S2}) \\ \begin{bmatrix}0 & 1 \\ \omega^2 & 0\end{bmatrix}\begin{bmatrix}\chi \\ \dot{\chi}\end{bmatrix} + \begin{bmatrix}0 \\ -\omega^2\chi_{Zmin}\end{bmatrix} & (\mathrm{S3})\end{cases}. \tag{5}$$

It is known that the above controller maximizes the set of initial COM states which can be stabilized (we call it *the stable standing region*, hereafter) as long as the state (S2) includes $(\chi, \dot{\chi}) = (0, 0)$ i.e. $\chi_{Zmin} < 0 < \chi_{Zmax}$. In this sense, the controller is called *the stabilizability-maximized COM-ZMP regulator*. Refer to the paper[19] for more details. Fig. 2 shows the solution curves in the phase space of the system for $\chi_{Zmin} = -0.07$[m], $\chi_{Zmax} = 0.07$[m], $z = 0.27$[m] and $q = 0.5$. The dotted area (or, the blue area for readers with color) in the figure is the stable standing region.

III. Limit Cycle Emergence by Dynamics Morphing

For the alternate stepping, a self-excited oscillation should happen under the constraint condition (2). The stabilizability-maximized COM-ZMP regulator never yields such characteristics since it is basically a linear feedback controller. It is required to design a nonlinear feedback controller which emerges a stable limit cycle besides the property where the stabilizable region is maximized. Then, let us re-design the referential ZMP in the state (S2) instead of (3) as

$$\tilde{\chi}_Z = (q+1)\left(\chi + f(\zeta)\frac{\dot{\chi}}{\omega}\right) \tag{6}$$

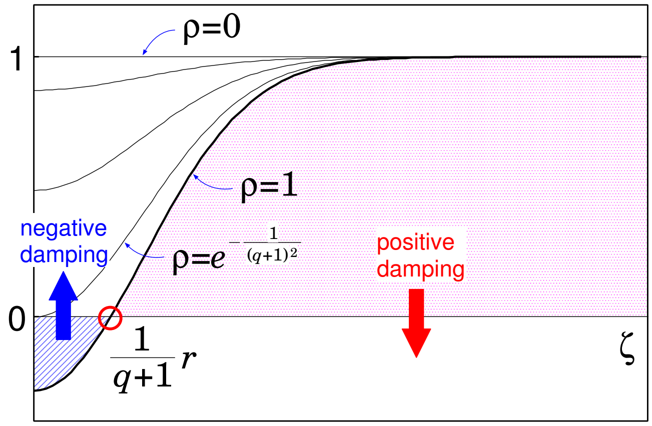


Fig. 3. Non-linear damping for a self-excited oscillation which continuously morphs from a linear damper.

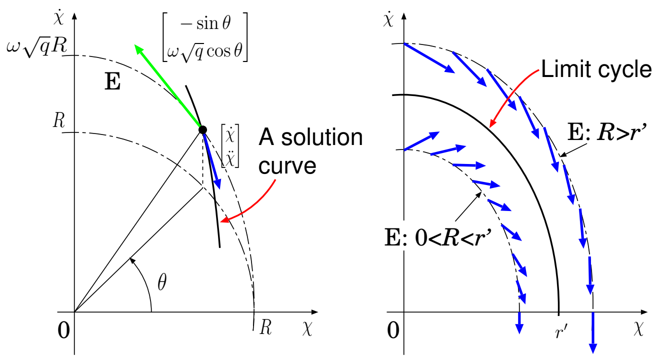


Fig. 4. The existence of a limit cycle in the system (9) is proved based on Poincaré-Bendixson's theorem.

where

$$f(\zeta) \equiv 1 - \rho \exp\left\{\frac{1}{(q+1)^2} - \frac{\zeta^2}{r^2}\right\}, \tag{7}$$

$$\zeta \equiv \sqrt{\chi^2 + \frac{\dot{\chi}^2}{\omega^2 q}}, \tag{8}$$

$r > 0$ and $\rho \geq 0$ are adjustable controller parameters, whose roles will be clarified in the following descriptions.

The system in the state (S2) is expressed by the following differential equation:

$$\ddot{\chi} + \omega(q+1)f(\zeta)\dot{\chi} + \omega^2 q \chi = 0. \tag{9}$$

The profile of $f(\zeta)$ defined by (7) with respect to ζ forms as depicted by Fig. 3. When $\rho = 0$, it becomes identical with the stabilizability-maximized COM-ZMP regulator. By increasing ρ gradually, the damping term is nonlinearly modulated. When $\rho > \exp\left\{-\frac{1}{(q+1)^2}\right\}$, the autonomous system (9) has the following stable ellipsoidal limit cycle:

$$\chi^2 + \frac{\dot{\chi}^2}{\omega^2 q} = \left\{\frac{1}{(q+1)^2} + \log\rho\right\} r^2. \tag{10}$$

This fact is proved as follows.

Proof. Here, we focus on the case where

$$\rho > \exp\left\{-\frac{1}{(q+1)^2}\right\}.$$

Let us define

$$r' \equiv \sqrt{\frac{1}{(q+1)^2} + \log\rho}\, r. \tag{11}$$

For this r',

$$\zeta \lesseqgtr r' \iff f(\zeta) \lesseqgtr 0. \tag{12}$$

Let us put the following ellipse E on the phase space as shown in the left side of Fig. 4:

$$\text{E:}\quad \chi^2 + \frac{\dot{\chi}^2}{\omega^2 q} = R^2 \quad (R > 0), \tag{13}$$

and consider a point $(\chi,\dot{\chi})$=$(R\cos\theta,\omega\sqrt{q}R\sin\theta)$ on the ellipse. Concerning with the tangential vector $[-\sin\theta, \omega\sqrt{q}\cos\theta]^{\mathrm{T}}$ of the ellipse E and the gradiant vector $[\dot{\chi}, \ddot{\chi}]^{\mathrm{T}}$ at the point, let us define

$$D(R,\theta) \equiv \begin{vmatrix} \dot{\chi} & -\sin\theta \\ \ddot{\chi} & \omega\sqrt{q}\cos\theta \end{vmatrix} = -\omega^2(q+1)\sqrt{q}f(R)\sin^2\theta. \tag{14}$$

We get a fact

$$D(R,\theta) \lesseqgtr 0 \iff R \lesseqgtr r' \tag{15}$$

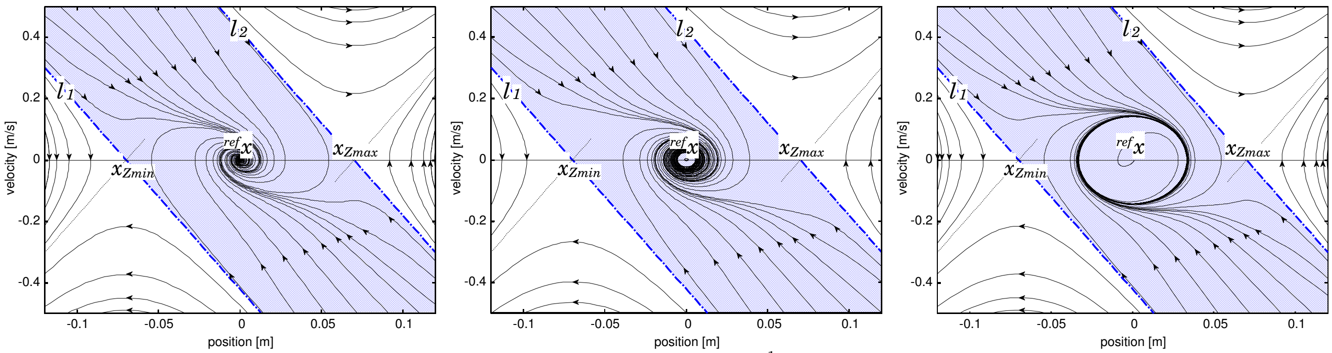
where it has equality if and only if $\theta = 0, \pi$. It means that $[\chi, \dot{\chi}]^{\mathrm{T}}$ flows into E when $R > r'$, while $[\chi, \dot{\chi}]^{\mathrm{T}}$ flows out of E when $0 < R < r'$ as illustrated by the right side of Fig. 4. Then, we can conclude that the system has an ellipsoidal stable limit cycle which coincides with E from Poincaré-Bendixson's theorem.

Q.E.D.

In particular, the solution of (10) becomes a harmonic oscillation with the amplitude $\frac{r}{q+1}$ and the period $\frac{2\pi}{\omega\sqrt{q}}$ for $\rho = 1$. Furthermore, we see

$$\lim_{\zeta\to\infty} f(\zeta) = 1 \tag{16}$$

with respect to a set of arbitrary positive q, ρ and r. The above facts tell that the proposed controller emerges a stable ellipsoidal limit cycle around the equilibrium point, but keeps a close property to the stabilizability-maximized COM-ZMP regulator at a distance from the point. Fig. 5 shows some phase portraits of the system for $\chi_{Zmin} = -0.07$[m], $\chi_{Zmax} = 0.07$[m], $z = 0.27$[m], $r = 0.05$[m] and $q = 0.5$. (a), (b) and (c) are for $\rho = 0.5$, $\rho = 0.642 \simeq e^{-\frac{1}{(q+1)^2}}$ and $\rho = 1.0$, respectively. When $\rho \simeq 0.642$, a limit cycle appears. Moreover, the stable standing region is invariant with respect to any ρ in these cases.



(a) $\rho = 0.5$ (b) $\rho = 0.642 \simeq e^{-\frac{1}{(q+1)^2}}$ (c) $\rho = 1.0$

Fig. 5. Curves of the autonomous system with non-linear ZMP feedback for $\omega = \sqrt{g/0.27}$, ${}^{ref}x = 0$, $x_{Zmin} = -0.07$, $x_{Zmax} = 0.07$, $q = 0.5$ and $r = 0.05$. ρ varies from 0.5 to 1.0. When $\rho \simeq 0.642$, a limit cycle appears. The stable standing region is invariant with respect to any ρ in these cases.

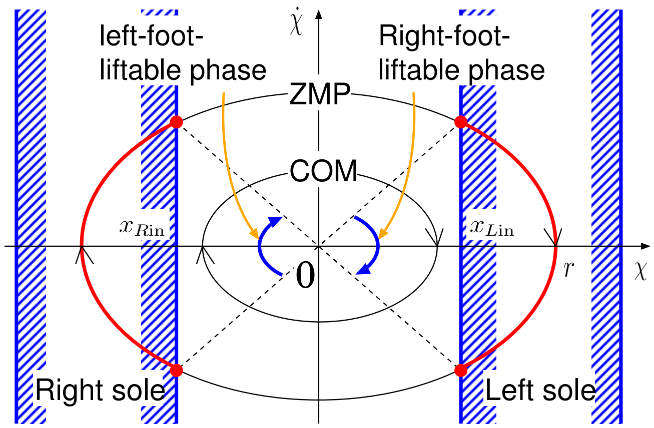


Fig. 6. Phase-synchronized step is achieved in stable oscillation. ZMP-phase and accordingly COM-phase tells permission for a foot to be lifted-up.

IV. Phase-synchronized Biped Stepping

The transfer function $G(s)$ from x_Z to x is

$$G(s) = \frac{\omega^2}{-s^2 + \omega^2}. \tag{17}$$

Hence, we get the following frequency response:

$$G(i\Omega) = \frac{\omega^2}{\Omega^2 + \omega^2} \tag{18}$$

where i is the imaginary unit. It tells that ZMP synchronizes to COM without the phase lag with the gain $G(i\omega\sqrt{q}) = \dfrac{1}{q+1}$ when the COM state $(\chi, \dot{\chi})$ is moving asymptotically along the limit cycle. In particular, the amplitude of ZMP for $\rho = 1$ is r as long as $r < \min\{|\chi_{Zmin}|, |\chi_{Zmax}|\}$ is satisfied. Consequently, a stable alternate stepping which synchronizes with the ZMP oscillation is achieved by the following method.

First, let us define a complex number p_Z as

$$p_Z \equiv \chi_Z - \frac{(q+1)\dot{\chi}}{\omega\sqrt{q}} i. \tag{19}$$

Suppose ZMP is oscillating along x-axis with the amplitude r, and the inner edge of the left sole is at $x = x_{Lin}$. As shown in Fig. 6, ZMP lies within the left sole when p_Z satisfies

$$0 \le \phi_L \le 2\theta_L \tag{20}$$

where

$$\phi_L \equiv \angle \frac{p_Z}{p_{Lin}} \tag{21}$$

$$p_{Lin} \equiv x_{Lin} - i \sin\theta_L \tag{22}$$

$$\theta_L \equiv \cos^{-1} \frac{x_{Lin}}{r}. \tag{23}$$

Then, the right-foot lifting height z_R with respect to ϕ_L is determined by the following equation, for instance:

$$z_R = \frac{1}{2} h \left(1 - \cos\pi \frac{\tilde{\phi}_L}{\theta_L}\right) \tag{24}$$

$$\tilde{\phi}_L \equiv \mathrm{sat}\{\phi_L, 0, 2\theta_L\} \tag{25}$$

where h is the maximum foot-lifting height and $\mathrm{sat}\{x, \underline{x}, \overline{x}\}$ is the saturation function defined as

$$\mathrm{sat}\{x, \underline{x}, \overline{x}\} \equiv \begin{cases} \overline{x} & (x > \overline{x}) \\ x & (\underline{x} \le x \le \overline{x}) \\ \underline{x} & (x < \underline{x}) \end{cases}. \tag{26}$$

The left-foot lifting height z_L is also determined in a symmetric way as:

$$z_L = \frac{1}{2} h \left(1 - \cos\pi \frac{\tilde{\phi}_R}{\theta_R}\right) \tag{27}$$

$$\tilde{\phi}_R \equiv \mathrm{sat}\{\phi_R, 0, 2\theta_R\} \tag{28}$$

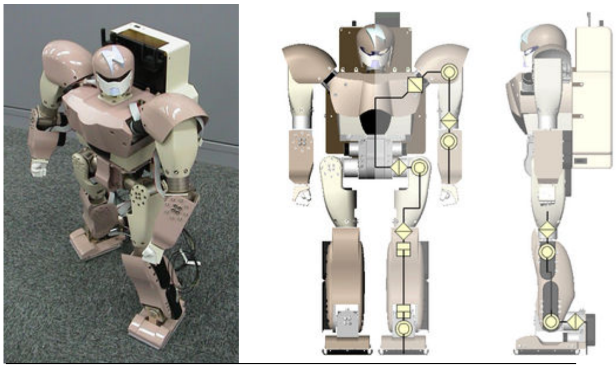
$$\phi_R \equiv \angle \frac{p_Z}{p_{Rin}} \tag{29}$$

$$p_{Rin} \equiv x_{Rin} + i \sin\theta_R \tag{30}$$

$$\theta_R \equiv \cos^{-1} \frac{-x_{Rin}}{r} \tag{31}$$

where $x_{Rin} (< 0)$ is the inner edge of the right sole.

Morimoto et al.[17] empirically showed a possibility to achieve a stable stepping by modulating the leg motion phase so as to be entrained with the ZMP oscillation. Our method theoretically supports the reasons i) why the natural



Name:	mighty
Height:	580 [mm]
Weight:	6.5 [kg]
Number of joints:	20 (8 for arms,12 for legs)

Fig. 7. External view and specifications of the simulated robot

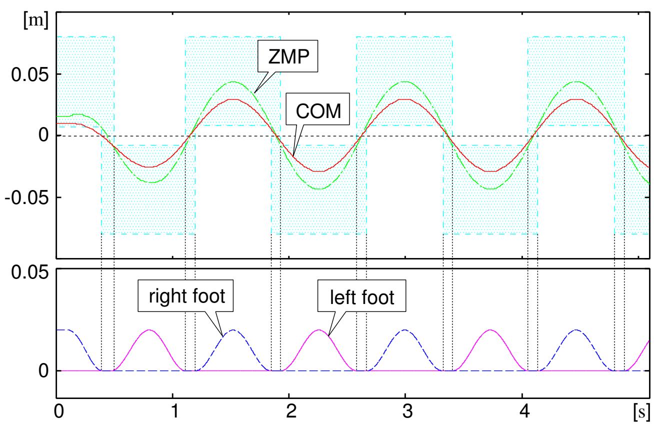


Fig. 8. Loci of COM, ZMP and height of both feet of a phase-synchronized stepping for $q = 0.5$, $\rho = 1.0$ and $r = 0.044$[m]. The dotted area is the supporting region.

system frequency is a good choice for the natural frequency of the phase oscillator, ii) why it is valid to define the system phase by the argument of ZMP and its rate, and iii) why such a synchronization of the stepping to ZMP movement makes the system robust against perturbations. An advantage of the proposed method to their work is that more purposely-designed controller enables an explicit adjustment of the oscillation period and amplitude. Also, note that we define the system phase by a combination of ZMP and COM velocity, which is different from Morimoto et al.'s. We think it better since our definition is available even in cases where ZMP is stuck at the edge of the supporting region.

V. Simulation

Some simulations of stepping motions were conducted on a dynamics model of a miniature anthropomorphic robot mighty[24] (Fig. 7). The total robot mass is assumed to be concentrated at COM in the model, for simplicity. The width of each sole is 0.078[m]. In the simulations, $\chi_{Zmin} = -0.08$[m], $\chi_{Zmax} = 0.08$[m] and $z = 0.27$[m].

In the first simulation, q, ρ and r were set for 0.5, 1.0 and 0.044[m], respectively. The loci of COM, ZMP and foot-height of the result motion for the initial condition $(\chi, \dot{\chi})$=(0.01, 0.0) are shown in Fig. 8. The dotted area (or the cyan area for readers with color) is the supporting region. It is seen that a self-excited oscillation at a period about 1.5[s] is generated with consistent phase-synchronized supporting-foot alternations. The amplitude of COM and ZMP were about 0.029[m] and 0.044[m], respectively. They are the same with the theoretical values. Fig. 9 shows snapshots of the motion animation.

In the next simulation, q, ρ and r were set for 2.0, 1.0 and 0.044[m], respectively. The loci of COM, ZMP and foot-height of the result motion for the initial condition $(\chi, \dot{\chi})$=(0.01, 0.0) are shown in Fig. 10. The oscillation period was about 0.74[s] (half of the previous simulation). The amplitude of COM and ZMP were about 0.017[m] and 0.044[m], respectively. They also coincided with the expected values. It is an advantage of the proposed method over the former limit-cycle approaches that it is easy to adjust the oscillation period and amplitude independently as these results show.

In the last simulation, q, ρ and r were set for 0.5, 1.0 and 0.088[m], respectively. The loci of COM, ZMP and foot-heightfor the initial condition $(\chi, \dot{\chi})$=(0.01, 0.0) are shown in Fig. 11. Since r exceeds the edge of the supporting region, ZMP is frequently saturated during the motion, in which the system becomes uncontrollable. It also made the oscillation period longer than the theoretical value 1.5[s]. In spite of that, a stable oscillation with consistent stepping was still achieved due to the controller's property with maximized stable standing region.

VI. Conclusion

A novel nonlinear feedback controller for biped robots was proposed. It morphs the COM dynamics of an optimally tuned standing-stabilization regulator into a stable self-excited oscillator with a suitable property to the supporting region constraint. A top-down controller design enabled explicit adjustments of the oscillation period and amplitude.

This framework seamlessly connects the standing stabilizer and the periodic alternate stepping controller, which have been separately studied, by a single parameter ρ. It is expected that transitional motions such as stepping-out motion will also be possible by modulating ρ dynamically. The definition of the phase, however, is not trivial in transitional states. Some sensor-fusion techniques to estimate the phase[9] might be required. It is the future work.

The COM-ZMP model on which the discussion went is the simplest model to represent biped dynamics, so that it can conceal differences of body constitutions. Such a macroscopic idea is thought to be widely applicable. The author thinks resolved COM rate control[25] is available to enhance it to the full-body biped robot dynamics.

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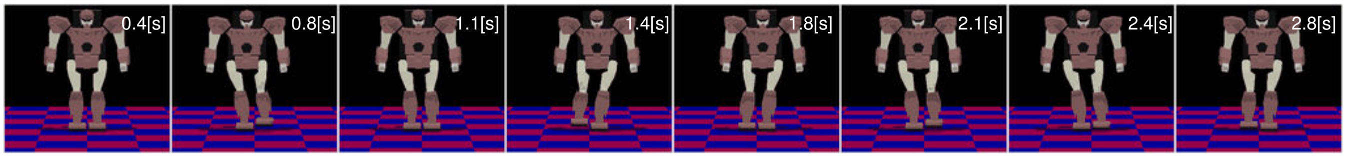

Fig. 9. Snapshots of a phase-synchronized stepping motion, the loci of whose COM, ZMP and foot-height were plotted in Fig. 8.

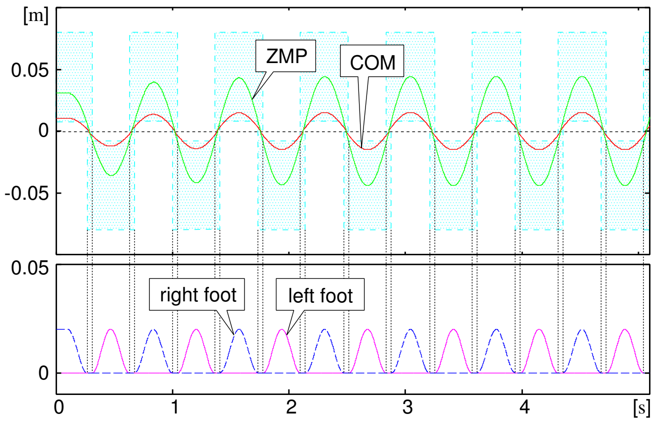

Fig. 10. Loci of COM, ZMP and height of both feet of a phase-synchronized stepping for $q = 2.0$, $\rho = 1.0$ and $r = 0.044$[m]. The dotted area is the supporting region.

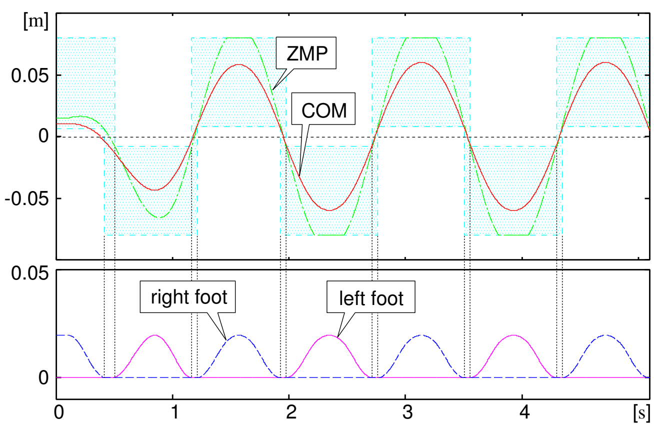

Fig. 11. Loci of COM, ZMP and height of both feet of a phase-synchronized stepping for $q = 0.5$, $\rho = 1.0$ and $r = 0.088$[m]. The dotted area is the supporting region.

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