2011 IEEE/RSJ International Conference on
Intelligent Robots and Systems
September 25-30, 2011. San Francisco, CA, USA

Gait Pattern Generation and Stabilization for Humanoid Robot Based on Coupled Oscillators

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Abstract— **To achieve a balanced walking for a humanoid, it is necessary to estimate the dynamic stability of the system. However, in a small size humanoid with restricted system resource, it is hard to satisfy the performance level desired by dynamics analysis. Therefore, in this paper, we propose the feasible methods to generate gait pattern and stabilize walking based on coupled oscillators which have a clear correlation between oscillator parameters and system dynamics without a real time ZMP calculation. The proposed method was tested on the open humanoid platform DARwIn-OP for the evaluation, and the result showed that a real time gait pattern generation and stabilization were realized.**

I. Introduction

RECENTLY, small size humanoids have been developed such as DARwIn-OP [1], QRIO[2], and NAO [3]. Due to the manageability, expandability, and affordability, they are often used for education, research, and entertainment. However, because a small size humanoid has restricted system resource for its limited space and cost, there are also constraints in enlarging the application area of a humanoid. Under these circumstances, to achieve stable walking for a humanoid, it is important to consider the performance level required by a designed walking method.

Since Zero Moment Point (ZMP) [4] theory was published, various walking methods based on dynamics analysis have been suggested [5]-[11]. As these approaches require high computational cost, the approximation method of dynamics model becomes a significant issue. However, since a simplified dynamics model also tends to cause an estimation error, an appropriate approximation is required to guarantee the stability of walking. Kajita *et al.* proposed the linear inverted pendulum model for bipedal walking [5], and developed their method with the preview control of ZMP for the compensation of the model error caused by simplification [7]. Takenaka *et al.* suggested the approximate dynamics model with two point masses added to the linear inverted pendulum for reducing the estimation error [9]. Nevertheless, considering the computational performance of a small size humanoid, it is still difficult to apply the proposed methods mentioned above.

Manuscript received March 28, 2011. This work was supported in part by the Korea Ministry of Knowledge Economy under Leading R&D Support Project

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Fig. 1. Open humanoid platform DARwIn-OP

On the other side, in biologically inspired methods [13]-[18] for bipedal walking triggered by Central Pattern Generator (CPG) [12], it is significant matter to find feasible CPG parameters. However, for its large parameter space and the obscure physical relation between CPG parameters and external environmental condition, it is hard to implement on a real humanoid. Endo *et al.* proposed the reduced neural oscillator model in Cartesian coordinate system to present the explicit physical implication [17]. Morimoto *et al.* suggested the phase adaptation method based on a neural oscillator for overcoming of environmental perturbations [18].

From these studies, in this paper, we extend their neural oscillator model to the simplified coupled linear oscillator model divided into a movement oscillator and balance oscillator. The proposed oscillator model gives the continuity between oscillator parameter and dynamics estimation. Through the full body ZMP simulation, we analyze the effect of oscillator parameters on the dynamic stability of walking and show how to decide appropriate parameters for a balanced walking. We also design the feedback controller correlating with oscillator parameters and sensor data, which makes it possible to guarantee the stabilization of walking without a real time ZMP calculation.

The suggested method was tested on the open humanoid platform DARwIn-OP as in Fig. 1.

II. Gait Pattern Generation

A. Coupled Oscillator Model

The proposed coupled oscillator model is composed of two kinds of oscillator groups. Two movement oscillator groups represent the each foot trajectory, and the balance oscillator group manages the fixed Center Of Mass (COM) trajectory. All oscillator groups have six sub oscillators taking charge of

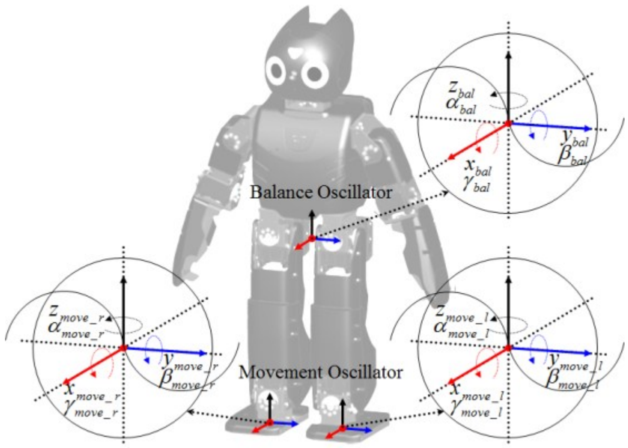

Fig. 2. Coupled oscillator model

each axis, and there are 18 oscillators in Cartesian coordinate system as shown in Fig. 2.

The total foot trajectory of a humanoid osc_{total} can be expressed by the superposition of the movement oscillator osc_{move} and balance oscillator osc_{bal} as in (1). Whereas the balance oscillator activates in the entire walking period T, the movement oscillator is restrained during Double Support Phase (DSP). We define the oscillator parameters, amplitude ρ, angular velocity ω, phase shift δ, offset μ, and DSP ratio r. From the definition above, we can express the balance oscillator as in (2) and the movement oscillator as in (3).

$$osc_{total} = osc_{move} + osc_{bal} \tag{1}$$

$$osc_{bal} = \rho_{bal}\sin(\omega_{bal}t + \delta_{bal}) + \mu_{bal} \tag{2}$$

$$osc_{move} = \begin{cases} \rho_{move} & \left[0, \frac{rT}{4}\right) \\ \rho_{move}\sin(\omega_{move}t + \delta_{move}) & \left[\frac{rT}{4}, \frac{T}{2} - \frac{rT}{4}\right) \\ -\rho_{move} & \left[\frac{T}{2} - \frac{rT}{4}, \frac{T}{2} + \frac{rT}{4}\right) \\ \rho_{move}\sin\left\{\omega_{move}\left(t - \frac{rT}{2}\right) + \delta_{move}\right\} & \left[\frac{T}{2} + \frac{rT}{4}, T - \frac{rT}{4}\right) \\ \rho_{move} & \left[T - \frac{rT}{4}, T\right) \end{cases} \tag{3}$$

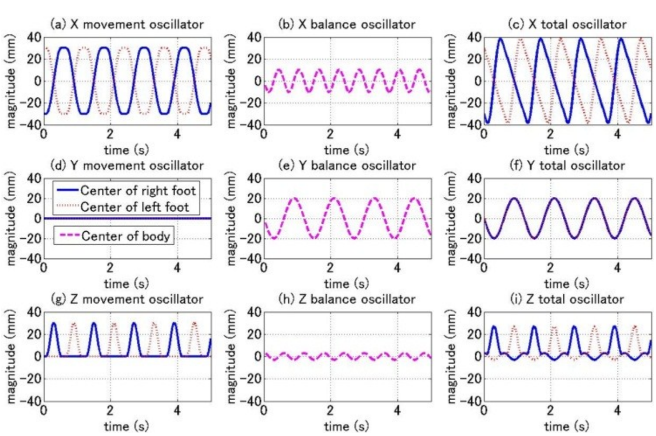

Fig. 3. Superposition of movement oscillator and balance oscillator

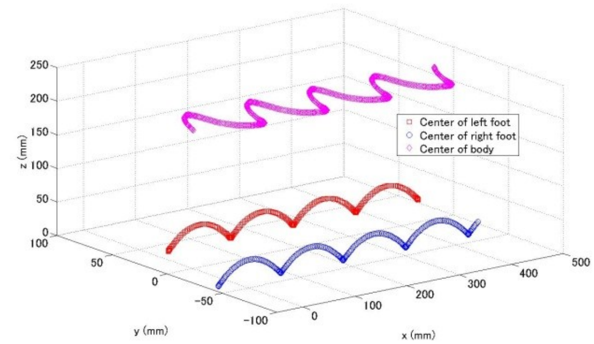

Fig. 4. Trajectories of foot and fixed COM

B. Oscillator Parameter and Gait Pattern

ω is $2n\pi/T$ where n is a positive integer and depends on the axis of sub oscillator, and δ also can be determined considering the symmetric characteristics of kinematics and a gait pattern. Therefore, for the design of a gait pattern, ρ_{move} and ρ_{bal} are the significant parameters for movement and balance.

Fig. 3 shows the operation of each oscillator in a front walking with parameter value $T = 1.2$, $r = 0.25$, $\rho_{move\_x} = 30$, $\rho_{move\_z} = 30$, $\rho_{bal\_x} = 10$, $\rho_{bal\_y} = 20$, and $\rho_{bal\_z} = 3$. The other ρ parameter values not mentioned above are set to zero. osc_{total_x}, osc_{total_y}, and osc_{total_z}, in Fig. 3(c)(f)(i) correspond with position values of the foot trajectory.

Fig. 4 illustrates trajectories of the fixed COM and foot in a three dimensional space. We can confirm that ρ_{move_x}, ρ_{move_z}, ρ_{bal_x}, ρ_{bal_y}, and ρ_{bal_z} exactly match with the length of stride, height of the lifting foot, magnitude of the front-rear swapping, magnitude of the lateral swapping, and magnitude of up-down swapping.

A cycloid gait pattern also can be generated by selecting the appropriate oscillator parameter values. For example, if r is given, we can find the ratio of ρ_{bal_x} with ρ_{move_x} which can make the fixed COM move at an almost uniform velocity as in Fig. 5. In the simulation above, we find that the ratio is 0.35 and is never affected by other parameters except for r.

From the generated trajectory by the proposed model, we

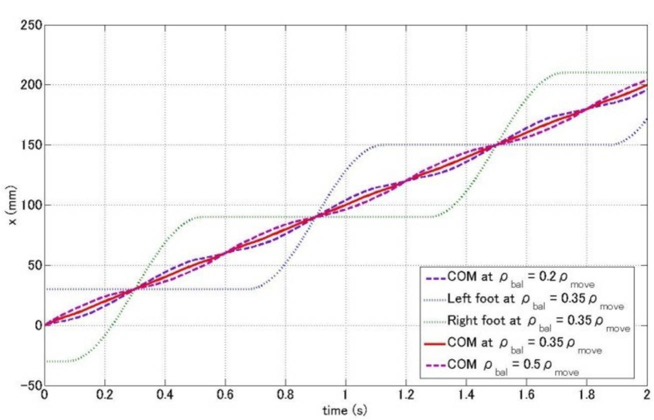

Fig. 5. Trajectories of foot and fixed COM in time with variant ratio of ρ_{bal_x} with ρ_{move_x}

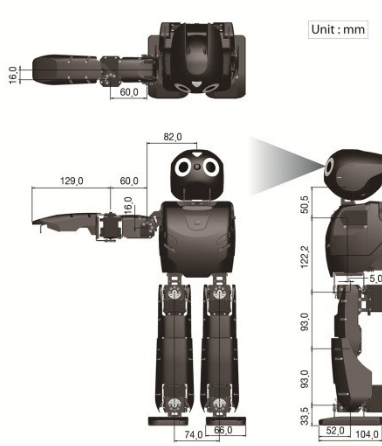

Fig. 6. Kinematic information of DARwIn-OP

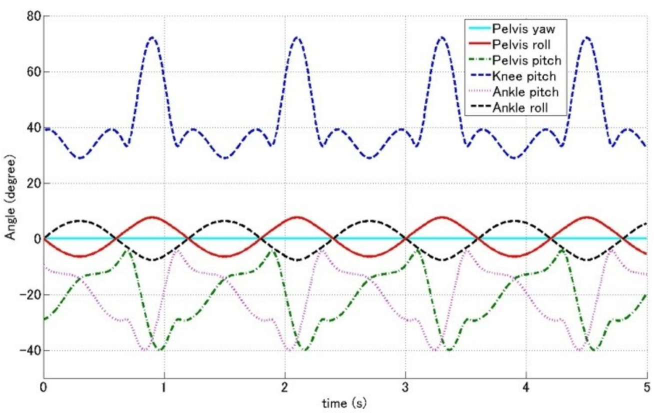

Fig. 7. Solved joint angle value by analytic inverse kinematics

calculate the joint angle by solving inverse kinematics with an analytic method. Fig. 6 gives the kinematic information of DARwIn-OP, and Fig. 7 shows the calculated joint angle of a front walking.

In this section, we suggested the coupled oscillator model composed of balance oscillator and movement oscillator. We also defined the oscillator parameters and showed the relation of parameters with a gait pattern.

III. Dynamic Stabilization

A. Stability Analysis

To analyze the dynamic stability of a gait pattern generated based on the coupled oscillator model, we calculated ZMP by (4) and (5). We used the physical property of DARwIn-OP as in Table I for the simulation.

$$x_{ZMP} = \frac{\sum_{i=1}^{n} m_i\{(\ddot{z}+g)x_i - \ddot{x}z_i\}}{\sum_{i=1}^{n} m_i(\ddot{z}+g)} \tag{4}$$

$$y_{ZMP} = \frac{\sum_{i=1}^{n} m_i\{(\ddot{z}+g)y_i - \ddot{y}z_i\}}{\sum_{i=1}^{n} m_i(\ddot{z}+g)} \tag{5}$$

The purpose of the simulation is to verify the correlation of oscillator parameter with dynamic stability of walking.

TABLE I
PHYSICAL PROPERTY OF DARWIN-OP

Link Name	Mass (g)	Local COM x,y,z (mm)	Link Name	Mass (g)	Local COM x,y,z (mm)
head	158.0	7.6, 0.0, 18.5	pelvis yaw	27.1	-0.5, 0.0, 18.4
neck	24.3	-0.7, 1.4, 16.6	pelvis	167.1	-18.2, 8.0, -13.9
body	975.6	-19.7, -3.1,-39.4	leg upper	119.0	0.7, -0.3, -63.0
shoulder	25.9	1.4, -13.5, 10.3	leg lower	70.3	6.5, -0.6, 54.0
arm upper	168.4	0.73, 0.7, -36.2	ankle	167.1	-18.5, -0.2, 13.9
arm lower	59.3	-13.5, 6.7, -45.8	foot	79.4	-0.5, 9.5, -26.0

Generally, as T and ρ_{move} are given by a high level task such as a foot step generator or path planner, we can adjust ρ_{bal} for attaining dynamic stability. Considering the DSP ratio of human, we assumed that r was 0.25, and other parameters were set to the same value used in the previous section. The simulation results are shown in Fig. 8. The outer rectangle presents the footstep, and inner rectangle means the stable margin for ZMP analysis. The discontinuity of the ZMP trajectory comes from the lifting and landing motion of the foot, which presents a phase changing between DSP and SSP.

Fig. 8(a) shows that the ZMP trajectory almost escapes from the inner rectangle, which means the unstable state of walking is caused by low ρ_{bal_x}. Because the ZMP trajectory lies on outside of the stable margin during changing phase as in Fig. 8(c) due to low ρ_{bal_y}, the dynamic stability is not guaranteed. We can find the proper ρ_{bal_x} and ρ_{bal_y} for a stable walking in Fig. 8(b) which illustrates that the ZMP trajectory is always in the support polygon.

In addition, we also simulated the ZMP trajectory with

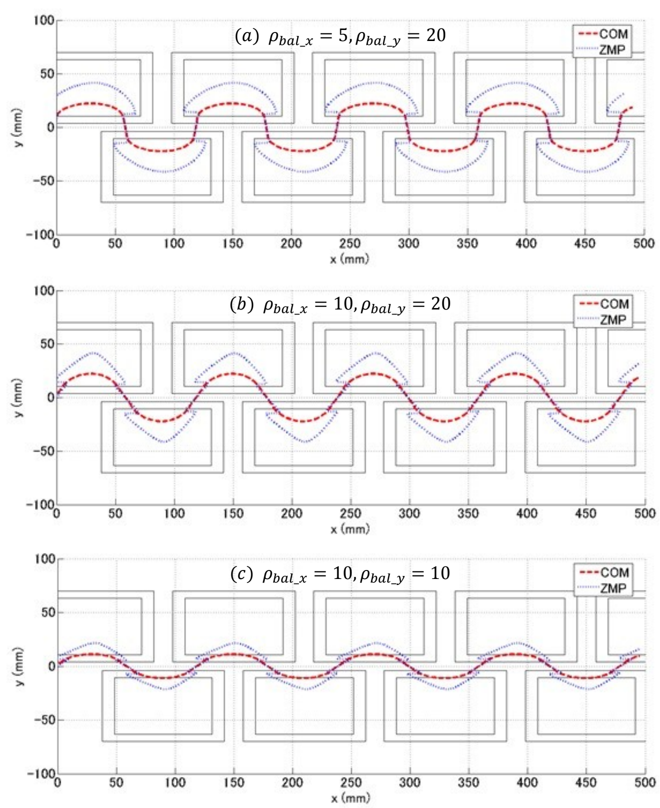

Fig. 8. Trajectories of ZMP and COM with amplitude of balance oscillator parameter ρ_{bal} adjustment

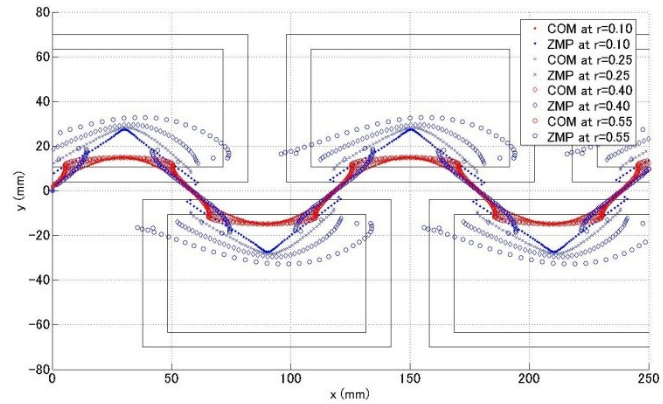

Fig. 10. Trajectories of ZMP and COM with double support phase ratio r adjustment

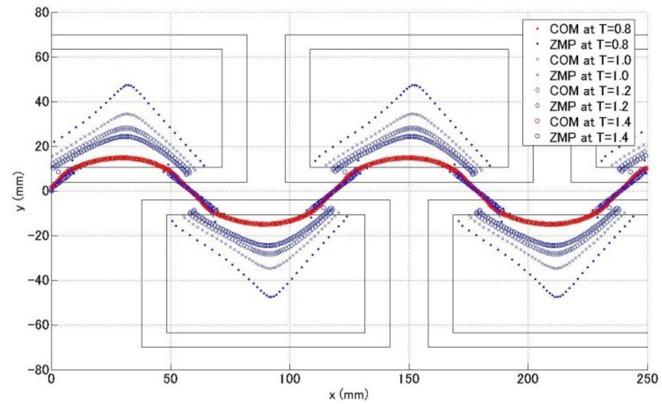

Fig. 9. Trajectories of ZMP and COM with entire walking period T adjustment

variant r from 0.1 to 0.55 in Fig. 10. As r is increased, the ZMP trajectory diverges from the COM trajectory. The adjustment of the ZMP trajectory can be also achieved by the modification of ρ_{bal}, we use r for tuning the velocity of the COM.

Finally, we tested the ZMP trajectory with variant T from 0.8 to 1.4 in Fig. 9. The result shows that the large T makes the ZMP trajectory to converge on the COM trajectory.

B. Balance Controller

Through the ZMP simulation, we can find appropriate parameters for stable walking. However, because there is the model error of a humanoid, it is hard to apply the parameters on a real robot without any compensation method. In addition, in a small size humanoid, the low accuracy of actuators can be a problem which makes it difficult for a robot to keep up with the desired trajectory. Therefore, based on the analyzed relation between oscillator parameters and dynamic stability in previous section, we propose the balance controller correlating with oscillator parameters and sensor data.

We assume the dynamic model of a humanoid to be an inverted pendulum model. From its dynamic formula in (6), we designed the feedback controller generating the cancelation torque required to sustain dynamic stability as in (7).

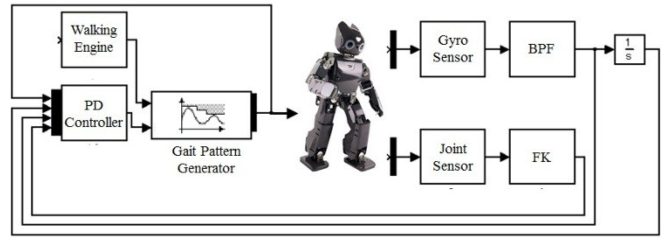

Fig. 11. Walking balance controller block diagram

$$\ddot{\theta_r} = \frac{g}{z_{com}}\sin\theta_r + \frac{1}{m_{z_{com}}}\tau \qquad (6)$$

$$\tau = k_p\theta_r + k_d\dot{\theta_r} \qquad (7)$$

θ_r means an angle error of a robot between the sensed trajectory and desired trajectory. z_{com} is the height of COM, and $m_{z_{com}}$ is the mass of the COM. The computed compensation torque is provided to the balance oscillator parameter μ_{bal}. Although the physical meaning of μ_{bal} is not torque but angular position and because the actuators of DARwIn-OP support only position control and speed control, we assume that μ_{bal} operates as a torque generator. Then, osc_{bal} can be written as (8).

$$osc_{bal} = \rho_{bal}\sin(\omega_{bal}t + \delta_{bal}) + k_p\theta_r + k_d\dot{\theta_r} \qquad (8)$$

Fig. 11 shows the feedback controller for stable walking. We use gyro sensor data for $\dot{\theta_r}$ and joint angle sensor data for θ_r because $\dot{\theta_r}$ from joint angle sensor has a noise and θ_r from gyro sensor tends to diverge by drift. k_p and k_d are found by the experimental method.

In this section, we proved the correlation between oscillator parameters and dynamic stability based on the ZMP simulation and showed how to decide the appropriate parameters. We also proposed the balance controller compensating not only model error but also the low accuracy

Fig. 12. Device description of DARwIn-OP

TABLE II
OVERALL SPECIFICATION OF DARWIN-OP

Category	Description	Data
Dimension	Height	0.455 m
	Weight	2.8 kg
DOF	Head	2 DOF
	Arm	2 x 3 DOF
	Leg	2 x 6 DOF
Main Controller	CPU	Intel Atom Z530 @ 1.6GHz
	RAM	DDR2 1 GB
	Disk	Flash Disk 4 GB
	Network	Ethernet/WiFi
	USB Port	2 x USB2.0
Sub Controller	CPU	ARM 32-bit Cortex-M3
	Frequency	72 MHz
	Flash Memory	512 KB
	SRAM	64 KB
Actuator RX-28M	Holding Torque	24 kgf·cm @ 12 V
	Speed	45 RPM @ No Load
	Position Sensor	Magnetic Potentiometer
	Resolution	0.072°
	Command Interface	Serial 3 MBPS
Sensor	Gyroscope	3-Axis
	Accelerometer	3-Axis
	Pressure-meter	2 x 4 FSR
	Camera	2 MP HD USB
Software	O/S	Linux Ubuntu
	Framework	open-DARwIn SDK
	Language	C++ / Java
	Compiler	GCC

of the actuator in a small size humanoid for stable walking.

IV. EXPERIMENT AND RESULT

A. Experimental Environment

We tested the proposed coupled oscillator model and balance controller on the open humanoid platform DARwIn-OP. The overall specification of DARwIn-OP is shown in Table II. As DARwIn-OP has the structure based on a standard PC, all simulation codes can be ported with the minimal modification. Joint angle sensors and 3-axis gyro sensor as in Fig. 12 are used for experiments. We programmed the suggested method by C++ on Linux, and all devices such as actuators and sensors can be accessed by open-DARwIn SDK via internal USB port. We set the main control period to 8 ms considering the system performance.

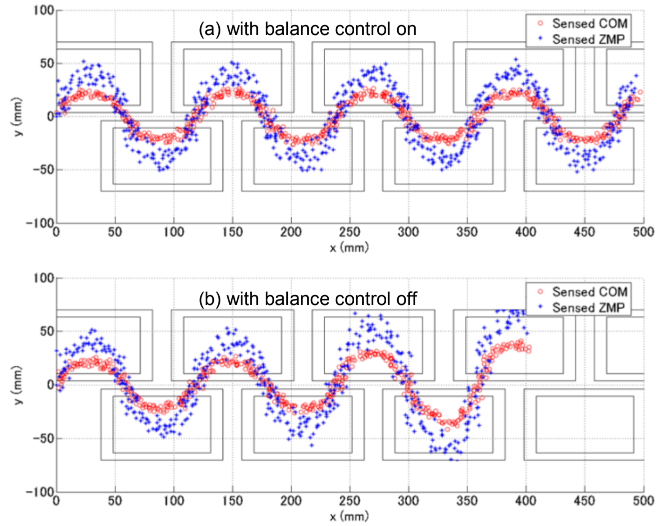

Fig. 13. Trajectories of sensed ZMP and COM with balance control on/off

B. Effect of balance controller

Firstly, we carried out the experiment on stable walking with the decided oscillator parameters in the previous section. During the test, the joint angle data was stored, and then transferred to a simulator for the analysis. The ZMP and COM calculated from the sensed joint angle data are shown in Fig. 13. With the balance control on, DARwIn-OP maintained its dynamic stability of walking, and the sensed ZMP trajectory is also on the stable region as in Fig. 13(a). However, when the balance control is off, the sensed ZMP diverged as in Fig. 13(b), and DARwIn-OP fell down immediately. From this experiment, we can find that the proposed balance controller deal with the model error and the low performance of the actuator as in Fig. 14.

Secondly, we provided DARwIn-OP with various movement oscillator parameters such as ρ_{move_x}, ρ_{move_y}, and ρ_{move_a} which had a fixed or zero value in the previous section. To generate the proper parameter, we prepared the vision processing routine for the ball tracking using the built in camera on DARwIn-OP. The distance and direction from the robot to the ball were calculated every 60 ms and were supplied to the implemented coupled oscillator. Fig. 15 shows

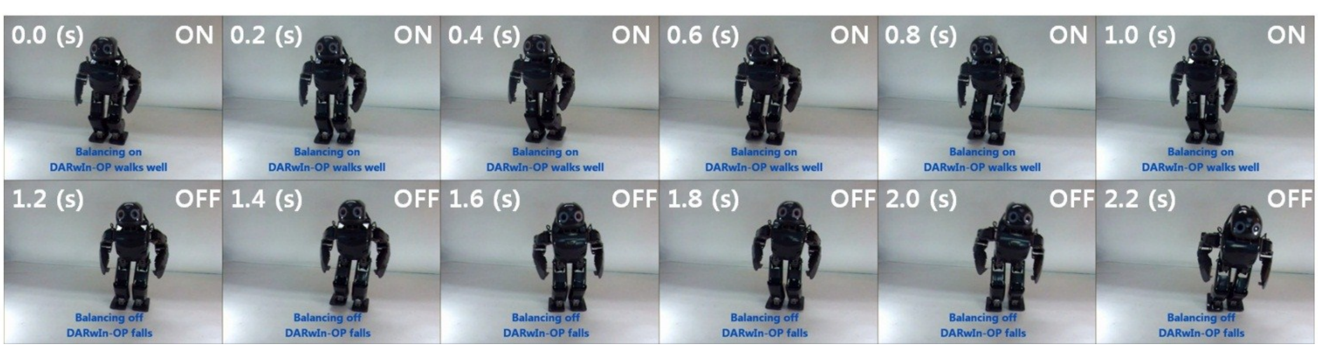

Fig. 14. Gait pattern generation and stabilization of DARwIn-OP with balance control on/off

real time gait pattern generation and stabilization with various movement oscillator parameters. Through the test, we can confirm that the proposed method overcomes the dynamic error caused by the change of parameters.

V. CONCLUSION

In this paper, we proposed the coupled oscillator model divided into movement oscillator and balance oscillator which has the clear correlation between oscillator parameters and system dynamics for the gait pattern generation. We also designed the feedback controller correlating with oscillator parameters and sensor data to guarantee the stabilization of walking without a real time ZMP calculation.

The proposed method was tested on the open humanoid platform DARwIn-OP, and the result showed that real time gait pattern generation and stabilization were achieved.

We will extend the suggested coupled oscillator model to support the phase modification for retaining of dynamic stability under an unpredictable perturbation.

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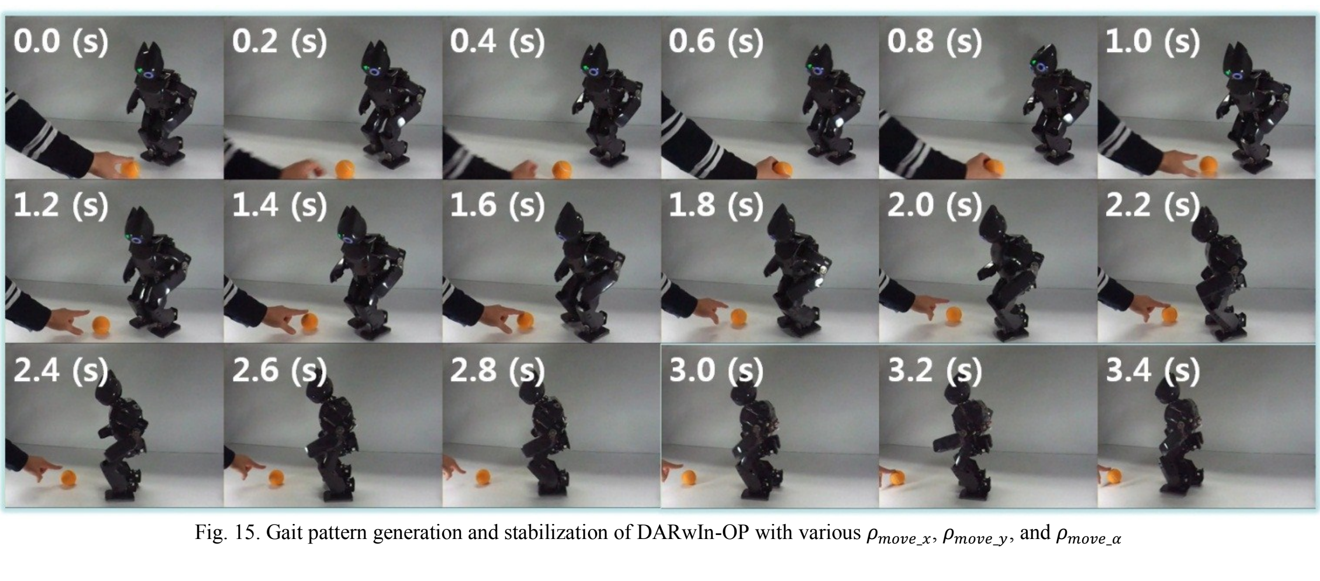

Fig. 15. Gait pattern generation and stabilization of DARwIn-OP with various ρ_{move_x}, ρ_{move_y}, and ρ_{move_α}