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Robot Communication Principal by Motion Synchronization using Orbit Attractor

Masafumi Okada and Kenji Murakami
Dept. of Mechanical Sciences and Engineering, Tokyo Institute of Technology
2-12-1 Oookayama Meguro-ku Tokyo, 152-8552 JAPAN
okada@mep.titech.ac.jp

***Abstract*— The human communication exists in various situations of our daily life. For human – robot communication or robot – robot communication, it is useful to design a communication model based on communication principal that is an entrainment phenomenon of nonlinear dynamics. In this paper, we focus on the robot motion synchronization for robot – robot communication. The robots are controlled to be entrained to an orbit attractor that corresponds to a robot motion. By exchanging the state variables of each robot, the robots are controlled to entrain one attractor that is possible for both robots and synchronize each other. The results of this paper represent the communication principal by an entrainment phenomenon of nonlinear dynamics.**

I. Introduction

Human communication exists in our daily life with various situations. Because of wide variety, it is difficult to obtain a communication model. For example, Dance classified communications into 126 categories[1]. To substantially human–robot or robot–robot communications, it is useful to represent the communication principal with a mathematical model. In the human conversations, the protocol of the communication is language or gestures. Exchanging our ideas or intentions by the protocol, we are entrained to a consensus to understand each other and the contradictory conversation is effected as shown in Fig.1. Sometimes 'Red' is dangerous,

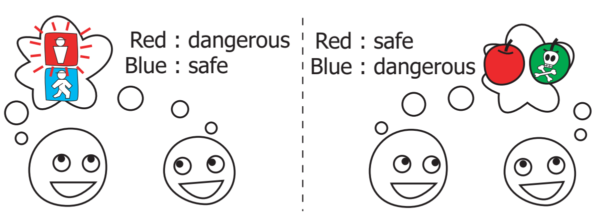

Fig. 1. Human communication by language

sometimes 'Blue' is dangerous. This is because we have consensus through the context, which is interpreted into the entrainment phenomenon of our brain dynamics. On the other hand, in the social dance for example, we dance with our partner so that we synchronize with each other after practicing our own dance by ourselves, as shown in Fig.2. In this case, not only brain dynamics but also our body dynamics are entrained to an attractor that is feasible for both of us. The entrainment phenomenon is the important element of the communication, and it is necessary to represent the communication by the entrainment phenomenon to clarify the communication principle. Miyake analyzed the importance of the entrainment phenomenon for human–human communication in the musical ensemble from 'co-creation' point of view[2].

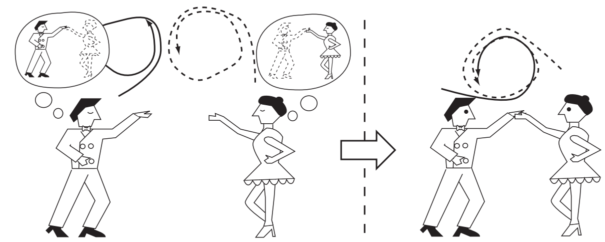

Fig. 2. Human communication in motion synchronization

Some researchers have challenged to the robot communication. They are separated into the following categories.

1) ***Human–robot communication by language or non verbal protocol*** The main subjects for the communication with language are voice recognition and utterance mechanism. Lee developed a real-time voice recognition engine[3]. Inamura[4] and Yamakata[5] realized the ambiguity reduction of the human conversation recognition using individual reference. Nishikawa et al. developed the vocalizing robot [6]. For the non verval protocol, the robot gestures and face expressions are investigated. Ogata embedded the emotional models into the robot and evaluated the effectiveness in the human–robot interaction[7]. Hashimoto[8] and Breazeal[9] developed face robots and proposed the emotion represent strategy.
2) ***Robot–robot communication*** The main subjects for the robot–robot communication are focused on the information selection or communication protocol so far. Matsuo has proposed S^3 Robot Net for network robots with position identification[10].

These methods focus on the information processing, telecommunications and the protocol for the communication. However the human-like dynamic communication that is simultaneous and real-time transmission or recognition of information is difficult to be realized by the results of an accumulation of the information processing techniques.

In this paper, we focus on the robot-robot communication which is realized as the results of entrainment phenomenon of the nonlinear dynamics. So far, we have proposed a

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robot motion emergence system using an orbit attractor[11], [12]. The reference motion pattern does not exist and the robot motion is emerged through the interaction between the controller, robot body dynamics and environments as an entrainment phenomenon of the nonlinear dynamics. By taking other party's information into the motion emergence system, a number of robots will synchronize and the robot–robot communication can be achieved as the result of the entrainment phenomenon. In this paper, we design a robot–robot communication principal applying the motion emergence method to two tapping dance robots. The results of this paper correspond to the motion communication as shown in Fig.2, which is caused by an entrainment phenomenon.

II. Motion emergence system design

A. Dynamics-based Information processing system

In this section, the orbit attractor design method is illustrated[12]. Consider the robot dynamic equation in the discrete time domain.

$$x[k+1] = f(x[k]) + g(x[k], u[k]) \tag{1}$$

where $x[k] \in R^n$ is the state variable and $u[k]$ is the input signal for the robot. The followings are assumed.

1) The target trajectory Ξ for $x[k]$ that corresponds to the robot motion

$$\Xi = \begin{bmatrix} \xi_1 & \xi_2 & \cdots & \xi_N \end{bmatrix} \in R^{n\times N} \tag{2}$$

is given. N is the number of data.

2) Ξ is cyclic, which means $\xi_{N+1} = \xi_1$.

3) Ξ is realizable, which means the input sequence $u[k]$ $(k = 1, \cdots, N)$ that achieves Ξ for the robot exists.

The assumption 1) sets the desirable motion for the robot and Ξ is the 'Seed of motion emergence'. By using Tailor expansion of equation (1) around each ξ_i, the linearized dynamics of the robot is obtained as follows.

$$x[k+1] = A_i x[k] + B_i u[k] + C_i \tag{3}$$

The controller that makes Ξ an attractor for the dynamics in equation (1) is design by the following ℓ-th order polynomial of $x[k]$,

$$u[k] = \Theta\phi(x[k]) \tag{4}$$

where $\phi(x[k])$ means the polynomial expansion of $x[k]$. When $n = 2$ and $\ell = 2$, $\phi(x[k])$ is represented as follows for example.

$$\phi(x[k]) = \begin{bmatrix} 1 & x_1 & x_2 & x_1^2 & x_1x_2 & x_2^2 \end{bmatrix}^T \tag{5}$$

$$x[k] = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T \tag{6}$$

Θ means the coefficient matrix of the polynomial.

By obtaining many pairs of $(x[k], u[k])$ defining vector field in x-space, Θ is designed by the functional approximation. The pairs of $(x[k], u[k])$ is obtained as follows.

The multi step ahead prediction of $x[i]$ is obtained as follows using the input sequence.

$$X_{i+1}^{i+j} = Ax[i] + BU_i^{i+j-1} + C \tag{7}$$

$$X_{i+1}^{i+j} = \begin{bmatrix} x^T[i+1] & \cdots & x^T[i+j] \end{bmatrix}^T \tag{8}$$

$$U_i^{i+j-1} = \begin{bmatrix} u^T[i] & \cdots & u^T[i+j-1] \end{bmatrix}^T \tag{9}$$

$$A = \begin{bmatrix} A_i^T & \cdots & \left(\prod_{k=i}^{i+j-1} A_k\right)^T \end{bmatrix}^T \tag{10}$$

$$B = \begin{bmatrix} B_i & & 0 \\ \vdots & \ddots & \\ \left(\prod_{k=i+1}^{i+j-1} A_k\right) B_i & \cdots & B_{i+j-1} \end{bmatrix} \tag{11}$$

$$C = \begin{bmatrix} C_i \\ \vdots \\ C_{i+j-1} + \sum_{k=i}^{i+j-2} \left(\left(\prod_{\ell=k+1}^{i+j-1} A_\ell \right) C_k \right) \end{bmatrix} \tag{12}$$

Based on equation (7), the input sequence that makes $x[i]$ converge to ξ is obtain as follows.

$$U_i^{i+j-1} = B^{\#}\left(\Xi_{i+1}^{i+j} - Ax[i] - C\right) \tag{13}$$

$$\Xi_{i+1}^{i+j} = \begin{bmatrix} \xi_{i+1}^T & \xi_{i+2}^T & \cdots & \xi_{i+j}^T \end{bmatrix}^T \tag{14}$$

After obtaining $u[k]$ $(k = i, i+1, \cdots)$ from equation (13), $x[k]$ $(k = i+1, i+2, \cdots)$ is calculated from equation (7). By setting many initial value $x[i]$, we obtain many pairs of $(x[k], u[k])$ and the functional approximation gives the controller in (4).

B. Tapping dance emergence

1) Mechanical design of tapping dance robot: In this section, we design a tapping dance robot and design the controller. In the tapping dance motion, the dynamic property of the robot changes drastically through the motion, in which case, the conventional method in [11] is not available but the modified attractor design method in reference [12] is necessary. Fig.3 shows the designed tapping dance robot. It has actuators on each leg, one actuator on the waist.

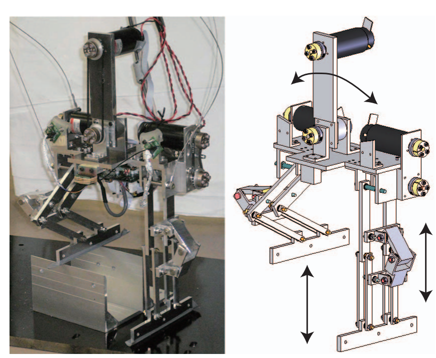

Fig. 3. Tapping dance robot

Balancing by the upper body, the robot makes step. The leg mechanism is composed by two parallelogram closed kinematic chain whose coupling is caused by A part in Fig.4. The purposes of this mechanism are as follows.

1) For the stepping at the same place, the sole of foot moves vertically keeping parallel with the ground.
2) Because the impact force works at the landing, the backlash of the leg mechanism has to be small. This is because the leg is designed by the closed kinematic chain without gears.

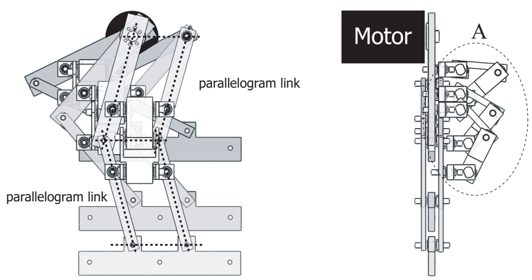

Fig. 4. Leg mechanism with 3D closed loop chain

One more robot is designed with different size. Two robots have homothetic size and shape with 350[mm] and 450[mm] height.

2) Dynamical modeling and sensors: The dynamic equation of the tapping dance robot is found by separating two situations, one is the right leg grounding, another is the left leg grounding as shown in Fig.5. For simplicity, the length

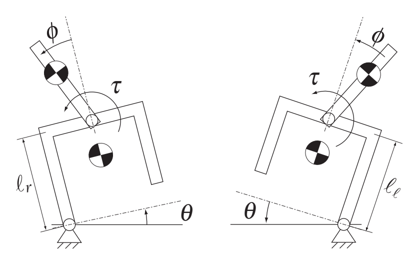

Fig. 5. Dynamical model of the tapping dance robot

of the legs are set to be the function of θ (rotation angle of the body). The state variable $x[k]$ is

$$x[k] = \begin{bmatrix} \theta[k] & \dot{\theta}[k] & \phi[k] & \dot{\phi}[k] \end{bmatrix}^T \qquad (15)$$

and the input is torque τ. θ is obtained by integrating the gyro sensor signal ω_g as

$$\theta[k+1] = \theta[k] + \omega_g T \qquad (16)$$

where T is the sampling time. However, the gyro sensor has temperature drift and equation (16) is Euler approximation of integral, it has large drift term. For drift reduction, the accelerometers are utilized. Measuring the gravity by the accelerometer, the rotation angle of the body is obtained as θ_{acc} which contains the acceleration of the motion. By using θ_{acc}, equation (16) is modified by

$$\theta[k+1] = \theta[k] + \omega_g T + K(\theta_{acc}[k] - \theta[k]) \qquad (17)$$

where K is constant. $\dot{\theta}$ is obtained by

$$\dot{\theta}[k] = \omega_g + \frac{K(\theta_{acc}[k] - \theta[k])}{T} \qquad (18)$$

3) Design of "Seed of motion emergence": For design of a controller that yields an entrainment phenomenon, " Seed of motion emergence " is necessary. We obtain Ξ as follows. The robot is controlled by the following input.

$$\tau = K_\phi \left(\phi_{ref}(t) - \phi\right) \qquad (19)$$

$$\phi_{ref}(t) = a \sin(\omega t) \qquad (20)$$

where a, ω and K_ϕ are constants. From the appropriate initial value of $x[0]$, the robot makes tapping dance as shown in Fig.6. However the success of the tapping dance strictly

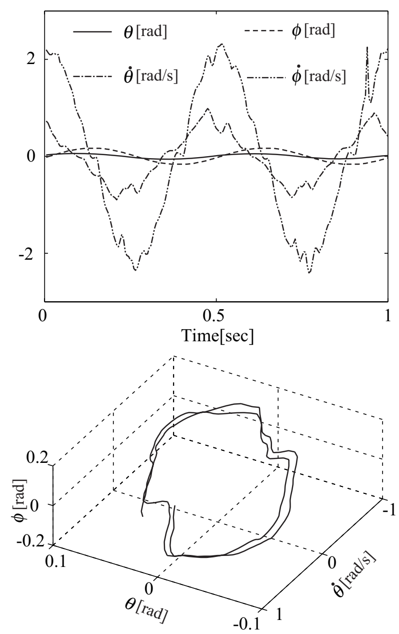

Fig. 6. Experimental data with sine pattern input

depends on the initial value and the robustness of the stability is very small. Furthermore the realized motion does not draw a cyclic pattern and does not satisfy the assumption **??** in section II-A. We obtain Ξ by the following filtering.

Step1 We obtain the Fourier series expansion of $x[k]$ as follows.

$$x[k] = \sum_{i=1}^{N/2} a_i \sin \omega_i k + b_i \cos \omega_i k, \quad \omega_i = \frac{2\pi i}{N} \qquad (21)$$

Step2 We consider only the frequency of integral multiples of ω in equation (20), and re-calculate $\widehat{x}[k]$, which is Inverse Fourier series expansion.

$$\widehat{x}[k] = \sum_{j:\text{integer}} a_j \sin j\omega k + b_j \cos j\omega k \qquad (22)$$

Step3 Ξ is obtained using $\widehat{x}[k]$. The same filtering is applied to $\tau[k]$ which is necessary to obtain C_i.

By this filtering, $x[k]$ in Fig.6 is transformed to $\xi_k = \widehat{x}[k]$ in Fig.7. $\widehat{x}[k]$ draws the smooth closed curved line in the phase plane. However, the magnitude of $\dot{\theta}$ is much larger than θ. This is fatal for designing the controller in (5) with polynomial, because $n(\gg 1)$-th order term has large influence. The normalization of the state values is necessary. The principal component analysis gives the normalizing

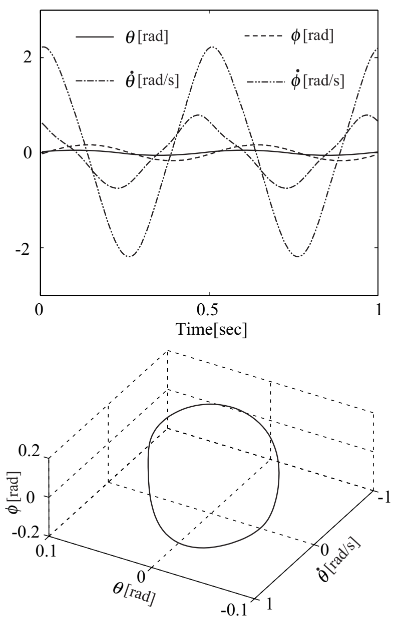

Fig. 7. FFT filtered data

coordinates transformation T. Consider the singular value decomposition of Ξ.

$$\Xi = USV^T, \quad U \in R^{n\times n}, \quad S \in R^{n\times n}, \quad V \in R^{N\times n} \tag{23}$$

Because the following equations are satisfied,

$$U^T U = I, \quad V^T V = I \tag{24}$$

the following coordinate transformation matrix T

$$T = \frac{1}{N} S^{-1} U^T \tag{25}$$

normalizes ξ_k by

$$\widetilde{\xi}_k = T\xi_k \tag{26}$$

4) Tapping dance emergence: By using Ξ obtained in section II-B.3, we design the controller that causes an orbit attractor, and realize the tapping dance motion emergence. Fig.8 shows the experimental data of the tapping dance and the sequential photograph is shown in Fig.9. "$*$" means the initial value $x[0] = 0$. The orbit attractor is designed and the tapping dance is emerged.

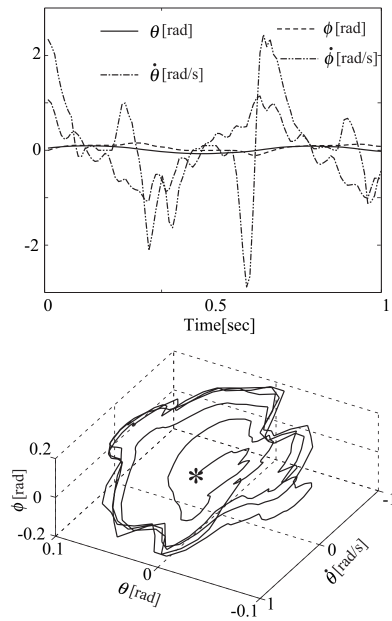

Fig. 8. Experimental data of tapping dance via attractor design

III. Robot motion synchronization and communication

A. Control algorithm for motion synchronization

The experimental results in the previous section show that the tapping dance motion is emerged through the interaction between the controller, robot body and environments. By using the other robot's motion information, a number of robots synchronize thought the entrainment phenomenon. The realized motion is feasible for both robots, which means the robot–robot communication principal is realized as the entrainment phenomenon.

Consider two robots entrained to orbit attractors,

$$x^1[k+1] = A_i^1 x^1[k] + B_i^1 u^1[k] + C_i^1 \tag{27}$$

$$u^1[k] = \Theta^1 \phi(x^1[k]) \tag{28}$$

$$x^2[k+1] = A_j^2 x^2[k] + B_j^2 u^2[k] + C_j^2 \tag{29}$$

$$u^2[k] = \Theta^2 \phi(x^2[k]) \tag{30}$$

where the suffix means the number of the robot and the subscript means the nearest ξ_i to $x[k]$. Consider the control input $\delta u^\ell[k]$ that makes $x^\ell[k]$ (i=1,2) come near each other

$$u^\ell[k] = \Theta^\ell \phi(x^\ell[k]) + \delta u^\ell[k] \tag{31}$$

By this input, the dynamics in (27) is changed as

$$x^1[k+1] + \delta = A_i^1 x^1[k] + B_i^1(\Theta\phi(x[k]) + \delta u^1[k]) + C_i \tag{32}$$

From equation (32), the following equation is satisfied,

$$\delta = B_i^1 \delta u^1[k] \tag{33}$$

and the control algorithm that makes the state variable in (27) go near to that of (29) is obtained by

$$\delta u^1[k] = B_i^{1\#}\delta = B_i^{1\#}\Lambda\left(x^2[k] - x^1[k]\right) \tag{34}$$

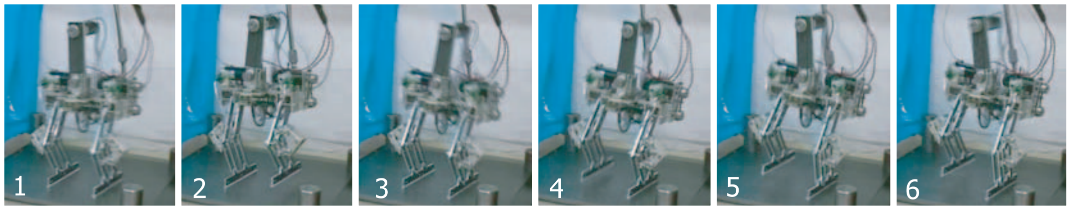

Fig. 9. Realization of tapping dance

where Λ is a constant. Equation (34) means that by adding $\widehat{V}^1$,

$$\widehat{V}^1 = (A_i^1 - I)x^1[k] + B_i^1 u^1[k] + C_i + B_i^1 B_i^{1\#}\Lambda\left(x^2[k] - x^1[k]\right) \tag{35}$$

$x^1[k]$ is moved to $x^1[k+1]+\delta$ as sown in Fig.10. From

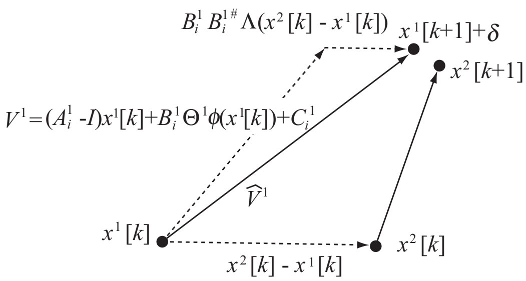

Fig. 10. Movement of the dynamics with motion synchronization

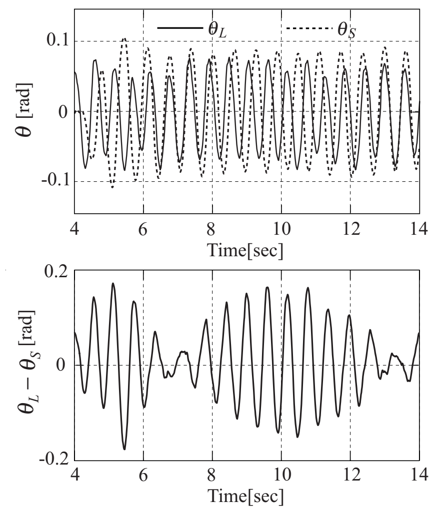

Fig. 11. Tap dance motions without communication

these considerations, the control input for synchronization is obtained as

$$u^1[k] = \Theta^1\phi(x^1[k]) + B_i^{1\#}\Lambda^1\left(x^2[k] - x^1[k]\right) \tag{36}$$

$$u^2[k] = \Theta^2\phi(x^2[k]) + B_i^{2\#}\Lambda^2\left(x^1[k] - x^2[k]\right) \tag{37}$$

where Λ defines the rate of synchronization. When $\Lambda = 0$, each robot performs the original motion without synchronization, when $\Lambda = 1$, the robot just follows another. Beause the change of B_i^ℓ according to ξ_i is small on the tapping dance robot, we use

$$B_i^{\ell\#} = \left[\frac{1}{N}\sum_{i=1}^{N} B_i^\ell\right]^\#, \quad \ell = 1,2 \tag{38}$$

B. Communication of the tapping dance robots

For two tapping dance robots L(Large) and S(Small), we design the entrainer (the controller that causes entrainment) and realize the tapping dance motion. The experimental results are shown in Fig.11 with $\Lambda^L = \Lambda^S = 0$, which means two robots do not communicate with. The upper figure shows the θ of L and S, the lower figure shows $\theta_L - \theta_S$. The robot L moves in about 1.8[Hz] and the robot S moves in about 1.6[Hz]. Because these motions are decided by the interaction between the robot body and environments, the frequencies of the motions are not constant. Because of the difference of the frequencies, the beat period is appeared.

In the next experiment, we set Λ^L and Λ^S as

$$\Lambda^L = 0.2I, \quad \Lambda^S = 0.4I \tag{39}$$

and the experimental result is shown in Fig.12. Same as Fig.11, θ_L, θ_S and $\theta_L - \theta_S$ are shown. Around in the passage of six seconds, two robots are syncronized, which is shown by the small value of $\theta_L - \theta_S$. The frequency of the synchronized motion is about 1.7[Hz] and two robots are entrained one motion that is feasible for both robots, which means two robots communicate with each other and synchronization as the result of the entrainment phenomenon of the nonlinear dynamics. Fig.13 shows the experimental results of the synchronization. The upper figure shows the motion without communication and the lower figure shows with communication, which is one cycle motion.

C. Considerations

This paper focuses on the cyclic motion because the convergence of the synchronization is slow. By setting the appropriate Λ, the leader follower control for cooperative object carrying will be available with non-cyclic (infinite cycle) attractor. Moreover, we use all of state variables for the information of communication because the attractor design method is based on the nonlinear state feedback, which makes impossible to stabilize the robots with large different kinematic and/or dynamic property. Some estimators, for example, extended Kalman filter, will enable the reduction

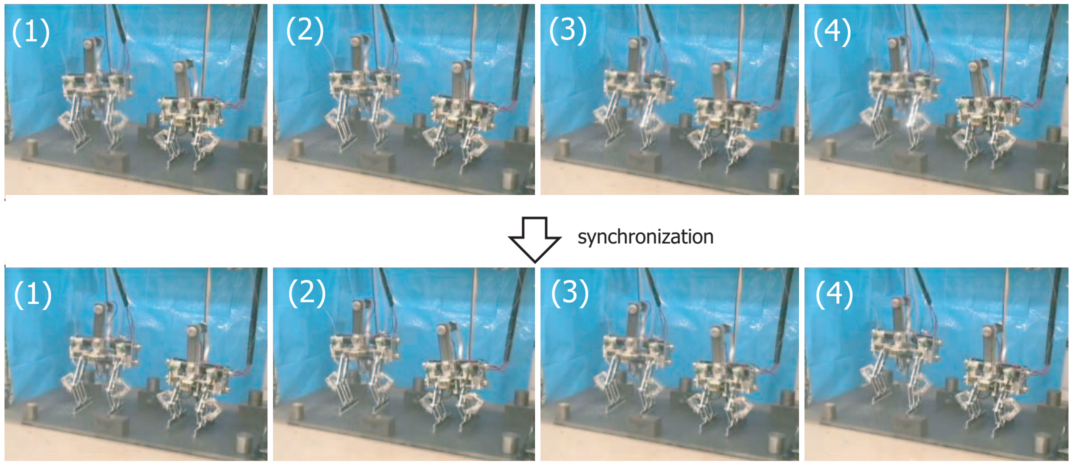

Fig. 13. Motion synchronization of tapping dance robots

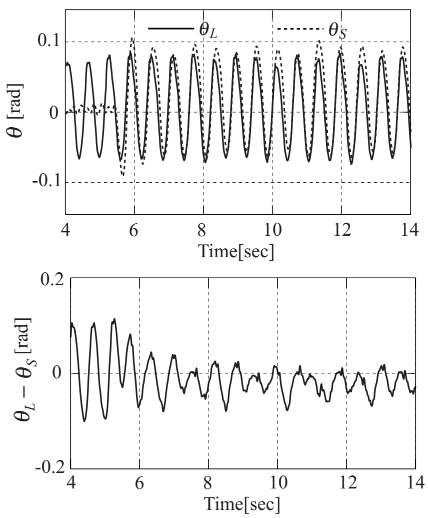

Fig. 12. Tap dance motions with communication

of information (output feedback) or stabilization of different robots. We confirmed that the other value of Λ^L and Λ^S change the convergence speed of the synchronization by experiments.

IV. Conclusions

In this paper, we design a robot communication principal by an entrainment phenomenon of the nonlinear dynamics and realize the robot communication.

- We realize the tapping dance motion in which the dynamic property of the robots changes drastically through the motion, by the orbit attractor design method.
- We propose the motion synchronization control method using the entrainer.
- The results of this paper show that two robots are entrained to a feasible motion for both robots, which realizes the robot communication by an entrainment phenomenon of the nonlinear dynamics.

Acknowledgment

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