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Robot Motion Emergence by Orbit Attractor Design for Tapping Dance Robot Control

– Experimental Evaluation with Drastic Change of Dynamic Property –

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Abstract

Robots are stabilized by a controller and generate their motions based on reference motion patterns. The robot only replays the given motion pattern without considering its environments and works as an instrument e.g. industrial robots. On the other hand, the human motions are generated through the interaction between body dynamics, environments and controllers. The motion patterns are not prepared a priori, but emerge as the results of the interaction autonomously, which means the intelligence yields our motion from the "embodiment" point of view. In this paper, we design a robot motion emergence system based on an orbit attractor for the robot intelligence. A tapping dance robot is designed and the proposed methods are applied for motion emergence with large change of the dynamic property of the robot body through the motion.

keywords : *Attractor design, Dynamics-based information processing, Motion emergence, Mechanical design*

1. Introduction

In this paper, we focus on a principal of a robot motion generation and propose a control system design strategy for intelligent robots. So far, robots are stabilized by controllers, and motions are generated based on the motion pattern data as shown in Fig.1. The motion patterns determine the robot motion and the robot moves independently with its environment. This type of the motion generation strategy yields the effective results for industrial robots whose main purposes are precise task executions. On the other hand, in the human motion generation, the motion pattern does not exist a priori but emerges as the results of the interaction between the body, environments and the information processing. Because these elements are represented by dynamics, this phenomenon is interpreted that the human motion is emerged as the solution of the differential equation. Because the motion is stable, the motion pattern will be an attractor of the nonlinear dynamics. This concept corresponds to "embodiment"[1] which represents the close relationship between the intelligence and body. For the intelligent robot, it is necessary to design the control system that emerges the robot motion without the motion patterns.

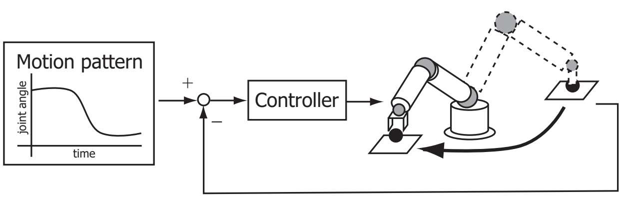

Fig.1 Conventional approach for robot motion generation

Some researches have challenged to design a robot motion emergence system based on the dynamics. Ijspeert used a central pattern generator (CPG) for the motion imitation learning [2]. This method uses the entrainment phenomenon of CPG with the learned neural network. Kotosaka realized the rhythmic motion using CPG [3]. In these methods, the dynamics works as the motion pattern generator that is decoupled with the robot's environment. Tani showed the close relationship between dynamical phenomenon, robot intelligence and symbol manipulation for robot navigation system with recurrent neural network (RNN) [4]. Tsujita realized the four-legs walk by the sensor feedback to CPG [5]. Motion generation strategy of this method is based on the mapping of the state space between CPG dynamics and the robot body dynamics, which requires heuristic parameters adjustment.

We have proposed the motion emergence system based on the entrainment phenomenon of the nonlinear dynamics for humanoid robots [6], and modified methods have been proposed based on the energy distance in the state space [7]. In this paper, we adopt the proposed method to the tapping dance robot control. Through the tapping dance motion, the dynamical property of the robot body changes drastically, and the modified method works effectively for the motion emergence.

2. Orbit attractor design method

2·1 Orbit attractor design using dynamics-based information processing

In this section, the orbit attractor design method is shown based on reference [7]. The following are assumptions for the design method.

(Assumption 1) Robot body dynamics is known.

(Assumption 2) The target closed curved line Ξ for the attractor of the robot body dynamics (state variable is $x \in R^n$) is given by

$$\Xi = \begin{bmatrix} \xi_1 & \xi_2 & \cdots & \xi_N \end{bmatrix} \in R^{n \times N} \qquad (1)$$

where N means the number of data.

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

The **Assumption 2** means that Ξ is required only for the controller design as "***Seed of Motion***".

The following discrete-time state space equation represents the robot body dynamics.

$$x[k+1] = f(x[k]) + g(x[k], u[k]) \qquad (2)$$

Where $x[k]$ means the state variable in time step k. Taylor expansion of equation (2) around ξ_i gives the following linearised dynamics.

$$x[k+1] = A_i x[k] + B_i u[k] + C_i \qquad (3)$$

Where more than second order terms are neglected. In reference [7] the controller that makes Ξ for the attractor of dynamics in equation (2), is designed by the ℓ-th order polynomial of $x[k]$ as

$$u[k] = \Theta \phi(x[k]) \qquad (4)$$

where Θ is a coefficient matrix of polynomial and $\phi(x[k])$ represents the polynomial vector of $x[k]$. For example, when $x[k] \in R^2$ and $\ell = 2$, $\phi(x[k])$ is represented as follows.

$$x[k] = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T \qquad (5)$$

$$\phi(x[k]) = \begin{bmatrix} 1 & x_1 & x_2 & x_1^2 & x_1 x_2 & x_2^2 \end{bmatrix}^T \qquad (6)$$

Because the function in equation (4) leads the entrainment phenomenon of the nonlinear dynamics, we call it as " ***entrainer*** " to distinguish from normal " ***controller*** ".

2·2 Entrainer design method

The entrainer is designed by the following algorithm. Consider $x[i]$ in equation (3) that is neighborhood of ξ_i. $x[i]$ moves $x[i+1]$, $x[i+2]$, $\cdots$, $x[i+j]$ by the input sequence $u[k]$, $(k = i, i+1, \cdots, i+j-1)$, which is represented by

$$\boldsymbol{X}_{i+1}^{i+j} = \boldsymbol{A} x[i] + \boldsymbol{B} \boldsymbol{U}_i^{i+j-1} + \boldsymbol{C} \qquad (7)$$

$$\boldsymbol{X}_{i+1}^{i+j} = \begin{bmatrix} x^T[i+1] & \cdots & x^T[i+j] \end{bmatrix}^T \qquad (8)$$

$$\boldsymbol{U}_i^{i+j-1} = \begin{bmatrix} u^T[i] & \cdots & u^T[i+j-1] \end{bmatrix}^T \qquad (9)$$

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

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

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

From these equations, the input sequence that makes $x[i]$ move along with ξ_{i+1}, ξ_{i+2}, $\cdots$, ξ_{i+j} is obtained by

$$\boldsymbol{U}_i^{i+j-1} = \boldsymbol{B}^{\#} \left(\Xi_{i+1}^{i+j} - \boldsymbol{A} x[i] - \boldsymbol{C} \right) \qquad (13)$$

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

$\boldsymbol{U}_i^{i+j-1}$ minimizes the following cost function J

$$J = \sum_{k=i+1}^{i+j} \| \xi_k - x[k] \| \qquad (15)$$

Based on $\boldsymbol{U}_i^{i+j-1}$, the trajectory of $x[i+k]$ $(k = 1, 2, \cdots, j)$ is recalculated and we obtain the sets of input and state variable (u, x). By the functional approximation, we obtain

$$\Theta = U \Phi^{\#} \qquad (16)$$

$$\Phi = \begin{bmatrix} \phi(x[1]) & \phi(x[2]) & \cdots \end{bmatrix} \qquad (17)$$

and the entrainer in equation (4) is obtained.

3. Tapping dance control via attractor design

3·1 Mechanical design of Tapping dance robot

Fig.2 shows the designed tapping dance robot. The

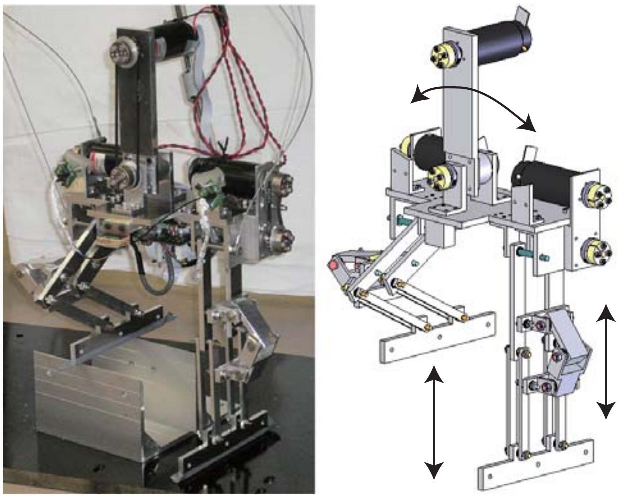

Fig.2 Tapping dance robot

height of this robot is about 450[mm], the weight is about 3.4[kg] with three geared 90[W] DC motors. This robot makes tapping dance by moving the upper body (balancing) and its legs (kicking the floor) as shown in Fig. 3

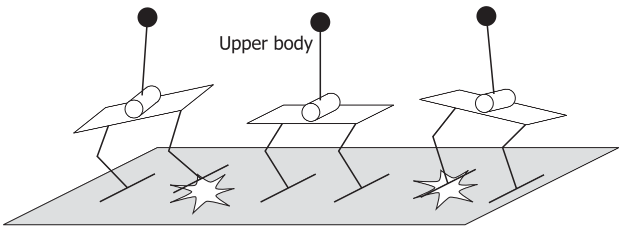

Fig.3 Motion model of tapping dance

The design specifications of the leg mechanism are as follows.

1. The sole of foot moves vertically face-to-face with the floor. This is for obtaining the vertical reaction force to dance in the same position.
2. The leg mechanism obtains an impact force from the floor in the tapping dance. The mechanical backlash of the leg breaks the robot, which means the backlash is the fatal error.

The link mechanism is better solution to satisfy the specifications, and we design a leg using the 3D closed kinematic chain as shown in Fig.4. This mechanism consists of two parallelogram links, whose coupling is occurred by part A in Fig.4. The rotation of the actuator (motor) is transformed to the prismatic motion of the sole of foot with small backlash.

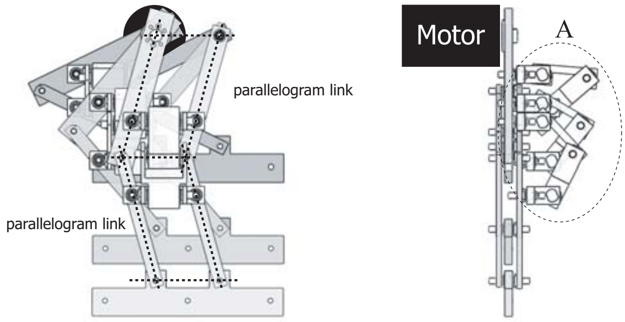

Fig.4 Leg mechanism with 3D closed loop chain

3·2 Dynamical modeling and sensing of the state variable

The dynamic property of the robot changes drastically through the tapping dance motion. The dynamical model of the robot is divided into two cases, one is the right leg grounding another is the left leg grounding as shown in Fig.5. For simplicity, the length of

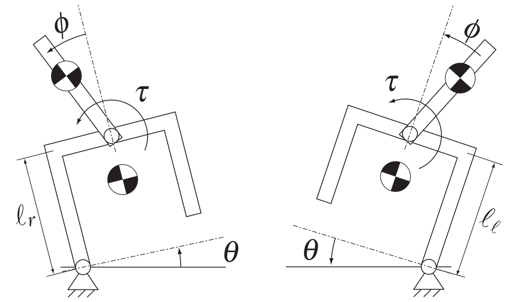

Fig.5 Dynamical model of tap dance robot

each leg ℓ_r and ℓ_ℓ is defined by a function of θ, which leads the simple dynamical model of the robot. Assuming that the grounding leg is equivalent to a fixed link and completely inelastic collision, the dynamical model is obtained in discrete time as follows.

right leg grounding

$$x[k+1] = f_r(x[k]) + g_r(x[k], u[k]) \quad (18)$$

left leg grounding

$$x[k+1] = f_\ell(x[k]) + g_\ell(x[k], u[k]) \quad (19)$$

The robot state variable $x[k]$ is common and defined by

$$x[k] = \left[\begin{array}{cccc} \theta[k] & \dot{\theta}[k] & \phi[k] & \dot{\phi}[k] \end{array} \right]^T \quad (20)$$

The input is the torque τ of the upper body.

θ and $\dot{\theta}$ are measured by the gyro sensor and accelerometer as follows. Assuming the initial value $\theta[0]$ is zero, θ is obtain by the simple integral of the gyro sensor signal ω_g.

$$\theta[k+1] = \theta[k] + \omega_g T \quad (21)$$

Where T is the sampling time. Because the drift error of the sensor or Euler approximation of the integral in (21) is not small, θ is calculated by the following equation.

$$\theta[k+1] = \theta[k] + \omega_g T + K(\theta_{acc}[k] - \theta[k]) \tag{22}$$

Where θ_{acc} is obtained from the two axes accelerometer measuring gravity and K is constant. Because the accelerometer signal contains the motion acceleration, K is selected so that only the drift term of θ becomes zero. $\dot{\theta}$ is obtained by

$$\dot{\theta}[k] = \omega_g + \frac{K(\theta_{acc}[k] - \theta[k])}{T} \tag{23}$$

$\phi[k]$ and $\dot{\phi}[k]$ are measured by the encoder on the motor.

3·3 Acquisition of reference pattern (Seed of motion)

Because the tapping dance is unstable motion and the dynamic property of the robot changes drastically through the motion, it is not easy to calculate Seed of motion Ξ that satisfies **Assumption 3** in section 2·1. The following steps give a possible candidate of Seed of motion.

Step 1 The torque $\tau(t)$ is defined by

$$\tau(t) = K_\phi\left(\phi_{ref}(t) - \phi\right) \tag{24}$$

$$\phi_{ref}(t) = A\sin(\omega t) \tag{25}$$

where K_ϕ is feedback gain (constant), A and ω are an amplitude and frequency of the upper body vibration respectively. They are defined appropriately so that the robot makes the tapping dance. This is a feed forward control of the tapping dance motion because the robot is not stabilized but just swinging the upper body with the specific frequency independent with θ or grounding leg. The success of the tapping dance strongly depends on the initial posture of the robot. Sometimes the robot motion makes a bifurcation. We obtain a trajectory as shown in Fig.6 by trial and error parameters selection. The tapping dance cycle is not constant and the trajectory does not draw a closed curved line in the state space. The following filtering changes this trajectory to Seed of motion.

Step 2 The obtained trajectory is transformed to the following Fourier series expansion.

$$x[k] = \sum_{i=1}^{N/2} a_i \sin(\omega_i k + \phi_i), \quad \omega_i = \frac{2\pi i}{N} \tag{26}$$

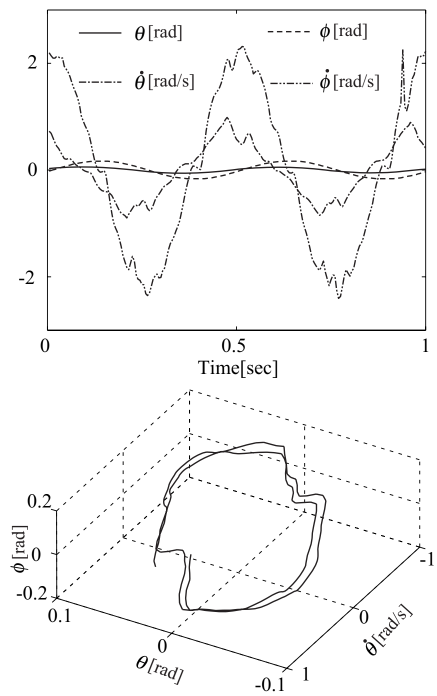

Fig.6 Experimental data with sine pattern input

Step 2 Using $\omega_i = \ell\omega$ (ℓ : positive integer), $\xi[k]$ is reconstructed by the following equation.

$$\xi[k] = \sum_{\substack{\omega_i = \ell\omega \\ \ell:\text{positive integer}}} a_i \sin(\omega_i k + \phi_i) \tag{27}$$

Step 3 Ξ is obtained by

$$\Xi = \left[\begin{array}{cccc} \xi[1] & \xi[2] & \cdots & \xi[N] \end{array}\right] \tag{28}$$

$$\xi[N+1] = \xi[1] \tag{29}$$

This filtering changes the trajectory to shown in Fig.7. The initial point equates to the end point of the trajectory, which makes a closed curved line. However, as shown in Fig.7, the amplitudes of θ and ϕ are much smaller than $\dot{\theta}$ and $\dot{\phi}$, which means the obtained closed curved line draws the slim form, and it yields difficulties for the polynomial functional approximation of the entrainer in (6). Consequently, by using the principal component analysis, we obtain a coordinate transformation T that changes the slim closed curved line to the thick form around the unit sphere in the state space as shown in Fig.8. Consider the singular value decomposition of Ξ

$$\Xi = USV^T \tag{30}$$

$$U \in R^{n\times n}, \quad S \in R^{n\times n}, \quad V \in R^{N\times n} \tag{31}$$

Because the following equation is satisfied,

$$V^T V = I \tag{32}$$

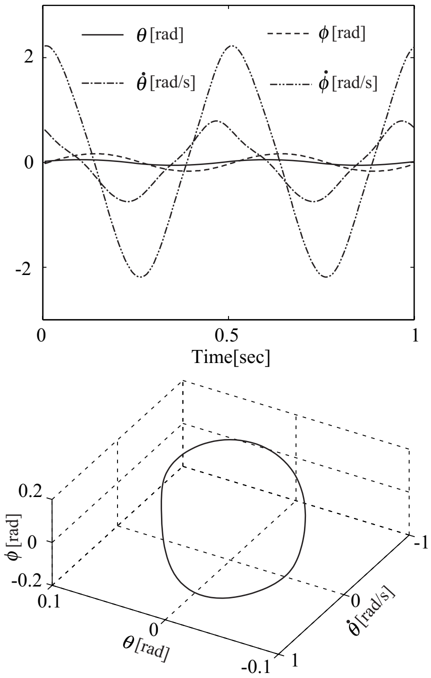

Fig.7 FFT filtered data

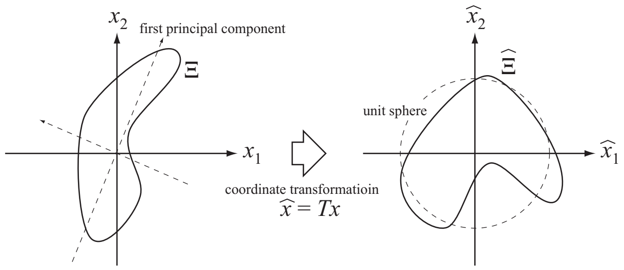

Fig.8 Coordinate transformation

the coordinate transformation is obtained by

$$T = \frac{1}{N} S^{-1} U^T \tag{33}$$

and Seed of motion $\widehat{\Xi}$ is obtained by

$$\widehat{\Xi}[k] = T\Xi \tag{34}$$

The obtained closed curved line Ξ or $\widehat{\Xi}$ does not confirm the satisfaction of **Assumption 3**, which means the reference motion pattern Ξ is the seed of the motion emergence and only used for the design of the entrainer.

3·4 Tapping dance motion emergence

By using $\widehat{\Xi}$, we obtain the entrainer and realize the tapping dance motion emergence. Fig.9 shows the experimental results. $*$ represents the inital value of the state valiable. Fig.10 shows the emerged tapping dance (one cycle). These figures show that we design the entrainer for the robot motion with drastic change of the dynamic property, and the motion is emerged.

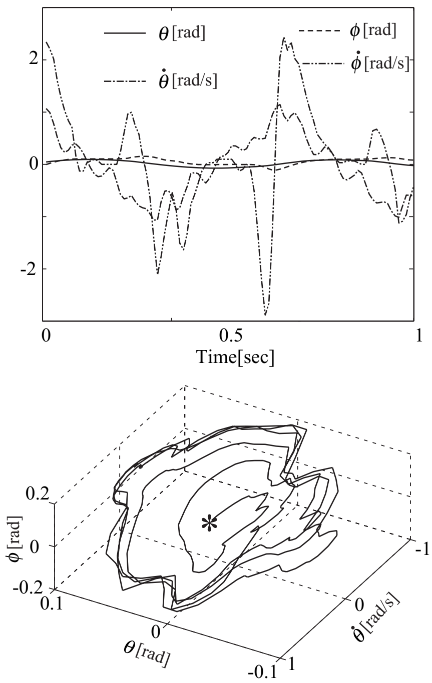

Fig.9 Experimental data of tap dance via attractor design

4. Conclusions

In this paper, we focus on the robot motion generation system and design a motion emergence of the robot based on the entrainment phenomenon of the nonlinear dynamics. The results of this paper are as follows.

- The tapping dance robot is designed using closed kinematic chain with small backlash.
- We propose the coordinate transformation method based on the principal component analysis, which makes the polynomial functional approximation for the entrainer design easy.
- The tapping dance motion is emerged by the attractor design. The dynamic property of the robot changes drastically through the tapping dance.

Acknowledgement

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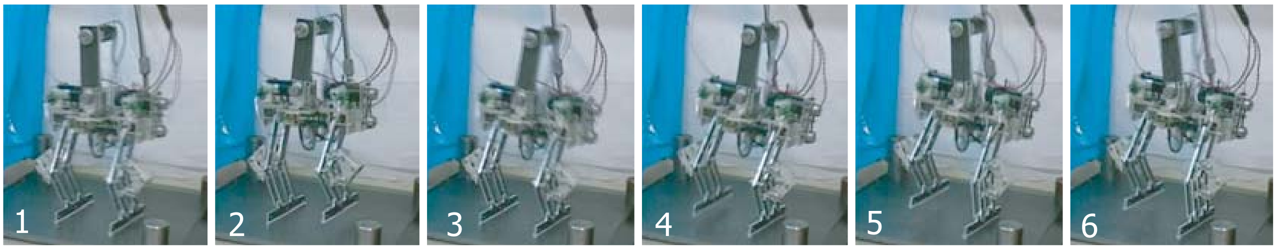

Fig.10 Realization of tapping dance

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