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Similarity Evaluation of Motion based on Orbit Attractor

*Masaaki WATANABE and Masafumi OKADA

Dept. of Mechanical Sciences and Engineering, Tokyo Institute of Technology,
2-12-1 Oookayama Meguro-ku Tokyo, 152-8552 JAPAN

watanabe.m.aa@m.titech.ac.jp, okada@mep.titech.ac.jp

Abstract

Robot control system which consists of a feedback controller and reference motion pattern is widely used. However high calculation cost is required to design the control system. So far, we have developed a controller design method based on orbit attractor of nonlinear dynamics. The controller is decomposed into motion and body elements, and a new controller can be easily obtained by the combination of these elements. Though in the decomposition stage of the controllers, "same motions" for several robots have to be prepared a priori. It is not easy to define which motions are identical for more than one robot with different dynamical characteristics. In this paper, we propose a verifying method of motion similarity. This method is based on the vector field which derived from the motion element in the state-space. The effectiveness of the proposed method is evaluated by simulations using tap-dancing robots.

Key Words - dynamics-based information processing, nonlinear dynamics, attractor design, motion similarity evaluation

1. Introduction

Robot control systems consist of a stabilizing controller K and reference pattern x^{ref} as shown in figure 1. K and x^{ref} are designed based on the specified robot dynamics, motion and environments. The robot requires the same number of control systems as sets of the robot dynamics, motions and the environments in which the robot moves. Moreover, it needs a large amount of calculation to design the K and the x^{ref} for each robot in the real world, and the other x^{ref} or K also require more calculation to design them. For example, in the case of biped robot, x^{ref} have to be designed under the physical constraint of walking dynamics (e.g. ZMP constraint) which depends on the changing environments. To reduce the calculation costs, a new controller design method using the existing controllers will be effective.

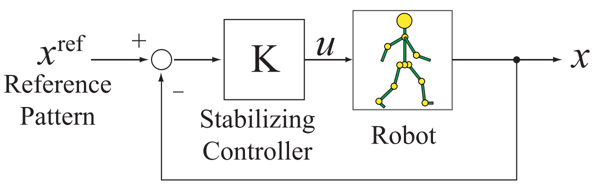

Fig.1 Basic robot control system

On the other hand, Okada[1][2] have proposed one of robot control method based on orbit attractor. In this control system, robot dynamics and controller configure a closed loop system as shown in figure 2 where controller u is a function of x. Both a K and a reference pattern are simultaneously embedded as the function in the controller. The same concept of the robot controller design is applied to cooperative task with human[3] and surgery robot[4] because of flexibility for environments. However many parameters have to be modified in the controller design method. This leads to make many efforts to design controllers. So far to overcome this issue, we have been proposed a design method of a new controller which generate a new motion[5] based on orbit attractor. This concept is similar way to obtain a symbol of body and motion[6, 7], because these methods aims to design common elements from controller which is identical for a motion. The method in [5] decomposes the controllers into motion and body elements considering the robot dynamics. By using the decomposed elements, the combination of those elements yields a new controller.

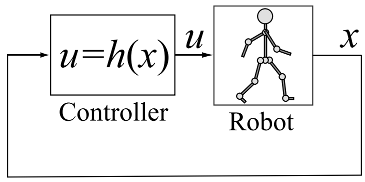

Fig.2 Robot control system based on orbit attractor

However, before the decomposition into the elements, similarity of motion and body respectively have to be preliminarily defined. Body similarity is clearly defined, however, the motion similarity between different robots is not easy. Actually, we have defined same motions for several robots with our instincts. Sometimes the appropriate elements are not obtained, and a new controller with inappropriate elements can't generate a new motion. This means that a evaluation method for the motion similarity is necessary to obtain appropriate elements. In this paper, base on the decomposed motion element, we propose the evaluation method of motion similarity. This method evaluates the difference between motion element vector and motion vector from actual motion in the state space. Finally proposed method is verified with tap-dancing robots.

2. Controller and elements design

2.1 Attractor design

In reference [2], the method of motion emergence is proposed based on orbit attractor. In this section, the design method is summarized below.

Consider the robot body dynamics represented by the following difference equation;

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

where $x[k]$ is the state variable and $u[k]$ is the controller with time stamp k. The controller is designed by the nonlinear function of x as follow;

$$u[k] = h(x[k]) \tag{2}$$

The controller entrains $x[k]$ to a specified closed curve Ξ;

$$\Xi = \begin{bmatrix} \xi_1 & \xi_2 & \cdots & \xi_N \end{bmatrix} (\xi_{N+1} = \xi_1) \tag{3}$$

in the state space as an attractor. With the mathematical representation, the solution of the simultaneous difference equation (1) and (2) converges to Ξ at $k \to \infty$. In fact,the controller is designed by polynomial of ℓ-th order power of x as follow;

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

where Θ is a coefficient matrix of polynomial and $\phi(x)$ expands the state vector x to the power vector of x. For example, $x \in \mathcal{R}^2$ and $\ell = 2$ cause ϕ as;

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

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

Θ is designed by functional approximation to minimize the following cost function $J_{\Theta_i^j}$;

$$\Theta_i^j = \arg\min_{\alpha_i^j} J_{\alpha_i^j} \tag{7}$$

$$J_{\Theta_i^j} = \sum_k \left\| u_i^j[k] - \Theta_i^j \phi(x_i^j[k]) \right\|_2 \tag{8}$$

where subscript i means the motion index and superscript j means the robot body index.

In this method, the motion is emerged by the interaction between robot body dynamics in equation (1) including environment and controller in equation (2). The explicit motion pattern x^{ref} is not required, but Θ contains implicit information of motion and robot body, because the controller causes a stable motion entraining the state variable to the specified orbit.

2.2 Controller decomposition into motion and body elements

In reference[5], we have proposed a decomposition method of controller into motion and body elements by considering the robot body dynamics. This method is briefly summarized below.

In figure 3, difference vector δ_k from $x[k]$ to $x[k+1]$ in the state space is represented using dynamic equation as;

$$\begin{aligned} \delta_k &= x[k+1] - x[k] && (9) \\ &= (A - I)x[k] + Bu[k] + C && (10) \end{aligned}$$

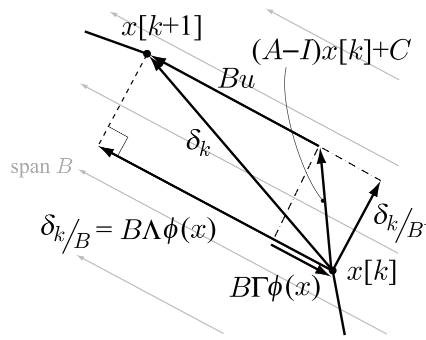

Fig.3 Decomposition of δ_k

δ_k is decomposed into $\delta_k/_B$ which is projection of δ_k onto span$B$, and $\delta_k/_{B^\perp}$ which is projection onto null space of span$B$, where $\delta_k/_B$ is represented as;

$$\delta_k/_B = BB^{\#}\delta_k \tag{11}$$

$\delta_k/_B$ means a component which can be controlled by controller, however $\delta_k/_{B^\perp}$ can be uncontrolled by controller. Then $\delta_k/_{B^\perp}$ is ignored. From the equations (9) and (10), controller is represented as;

$$\begin{aligned} Bu[k] &= Bu[k]/_B && (12) \\ &= (x[k+1] - x[k])/_B \\ &\quad - \{(A - I)x[k] + C\}/_B && (13) \end{aligned}$$

because $Bu[k]$ is parallel to span$B$. Here the first term of equation (13) indicates a motion vector, and the second one is determined by a robot dynamics. We assume that equation (13) is represented by the function of $x[k]$ using the polynomial of power of x as;

$$(x[k+1]-x[k])/_B = B\Lambda\phi(x[k]) \quad (14)$$
$$-\{(A-I)x[k]+C\}/_B = B\Gamma\phi(x[k]) \quad (15)$$

where Λ is a motion element and Γ is a body element of the controller consisting of the coefficient matrix. Then the controller is represented by sum of the right-hand side terms of the equations (14) and (15) using ϕ as;

$$B\Theta\phi(x[k]) = B\Lambda\phi(x[k]) + B\Gamma\phi(x[k]) \quad (16)$$

Then the controller Θ is decomposed into the motion element Λ and the body element Γ as;

$$\Theta = \Lambda + \Gamma \quad (17)$$

Λ is represented by the equation (14), and it is obtained by minimizing the following cost function J_{Λ_i};

$$\Lambda_i = \arg\min_{\beta} J_{\beta_i} \quad (18)$$
$$J_{\Lambda_i} = \sum_k \left\| B^{\#}(x_i[k+1]-x_i[k]) - \Lambda\phi(x) \right\| \quad (19)$$

using sets of $x[k+1]$ and $x[k]$. On the other hand, Θ_i^j and Λ_i satisfy the constraint as;

$$\Theta_i^j - \Lambda_i = \text{Common value}(=\Gamma^j) \quad (20)$$

This means that an optimized solution with constrain condition is required to obtain them. A cost function to design Θ_i^j and Λ_i is written by J with equations (8) and (19) as;

$$J = J_i^j + J_{\Lambda_i} + \sum_{j,i\neq k,\ell} \left(\Theta_i^j - \Lambda_i - \Theta_k^j + \Lambda_k\right)\lambda_\ell^T \quad (21)$$

where λ_ℓ are undetermined multipliers.

3. Evaluation of motion similarity

Some motions for different robots have to be identified as a same motion between several robots with different dynamics in the controller decomposition of the section 2. In this section, we propose a evaluation method for motion similarity based on the motion element Λ.

From the proposed methods,the two type Θ can be designed. One is designed by equation (4) in section 2.1, and another is designed as $\widehat{\Theta}$ with Λ and Γ to minimize the equation (21) in the section 2.2. If it is an appropriate set of motions, the two Θ would generate same motions. In this paper, motion similarity is represented by the motion difference based on motion element Λ.

When the position of the state variable is x_0, the next position x_1 is represented with Θ in (4) as;

$$x_1 = Ax_0 + Bu + C \quad (22)$$
$$u = \Theta\phi(x_0) \quad (23)$$

On the other hand, another position $\widehat{x}_1$ is decided with $\widehat{\Theta}$ in (21) from the same position as;

$$\widehat{x}_1 = Ax_0 + B\widehat{u} + C \quad (24)$$
$$\widehat{u} = \widehat{\Theta}\phi(x_0) \quad (25)$$

The difference between x_1 and $\widehat{x}_1$ is motion difference. Because the two positions $x_1, \widehat{x}_1$ are calculated with same robot, the motion similarity is evaluated as V;

$$V = \|v - \widehat{v}\| \quad (26)$$
$$v = (x_1 - x_0)/_B \quad (27)$$
$$\widehat{v} = (\widehat{x}_1 - x_0)/_B = B\Lambda\phi(x_0) \quad (28)$$

Smaller value V indicates the more similar set of motions. This method corresponds to evaluate a norm of $\Delta(= v - \widehat{v})$ in figure 4.

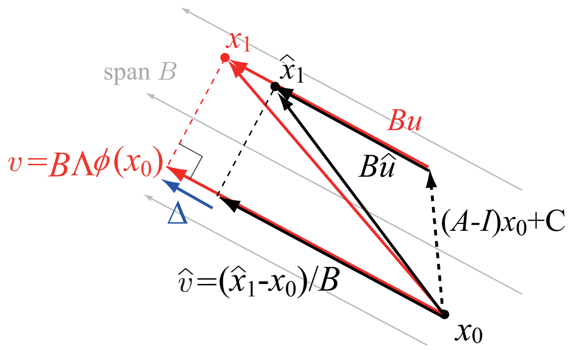

Fig.4 Motion evaluation value Δ

4. Motion evaluation with the motion element

4.1 Experimental setup of tap-dancing robots

In this section, the proposed method of motion evaluation is performed with simulation of tap-dancing robots in figure 5. There are two robots, one is robot L (the larger) and the other is robot S (the smaller). The robots make the tap-dance as shown in figure 6. The robot steps continuously by changing the grounding foot. In this paper, the tap-dancing motions are labeled by its frequency. The state variable x consists of lower body rotational angle θ_1, head rotational angle θ_2 and their velocities as;

$$x = \begin{bmatrix} \theta_1 & \dot{\theta}_1 & \theta_2 & \dot{\theta}_2 \end{bmatrix}^T \quad (29)$$

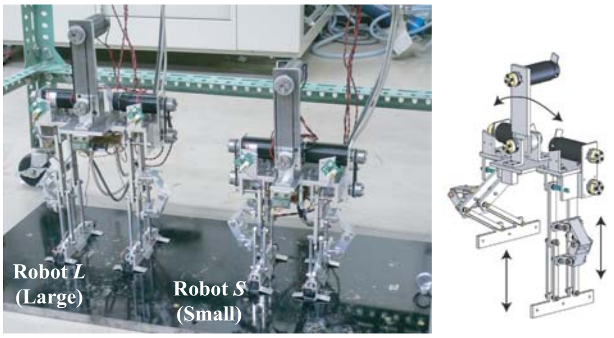

Fig.5 Tap-dancing robots

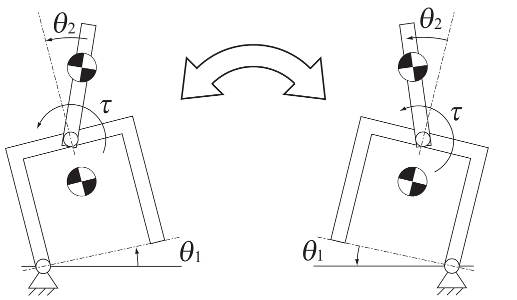

Fig.6 Motion and modeling of tap-dancing robots

4.2 Base motion for the evaluation

By using the method in the section 2.1, Θ_1^L, Θ_2^L, Θ_1^S, Θ_2^S, $\Theta_{1.5}^S$ and $\Theta_{2.5}^S$ are designed as base of motions for the evaluation. Where each subscript indicates frequency of tap-dancing motion for motion type, and Θ_i^j is a controller which generates a i-Hz tap-dancing motion for robot j. And the state variables of those motions mean x_0 for the evaluation. In this method, the number i shows average of periodic tap-dancing motions for the similarity evaluation. Actual motion frequencies are listed with labels of motion numbers in table 1. Figure 7 and 8 show

Table 1 Base motion frequency

	Robot L	Robot S
Motion 1	1.077Hz	1.034Hz
Motion 1.5	–	1.632Hz
Motion 2	2.196Hz	2.217Hz
Motion 2.5	–	2.892Hz

trajectories of state variable of the robots. Motions in figure 7 and 8 are generated by controller Θ_1^L and Θ_2^L respectively. In these figures, initial positions are indicated by circle signatures, and the state variables are entrained into a specified closed curve that means the motion. In the following, these motions are used as base motion for comparison with other motions.

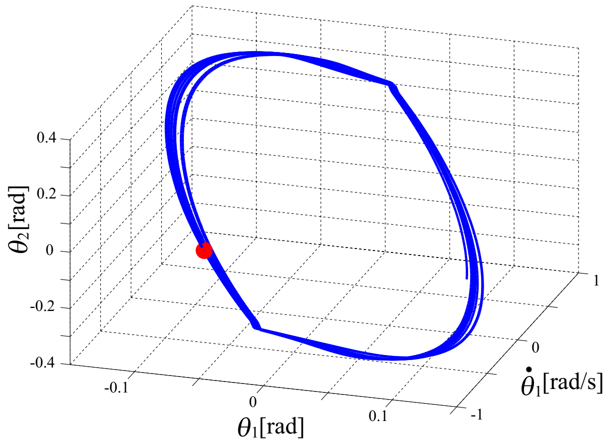

Fig.7 Locus of state variable using Θ_1^L

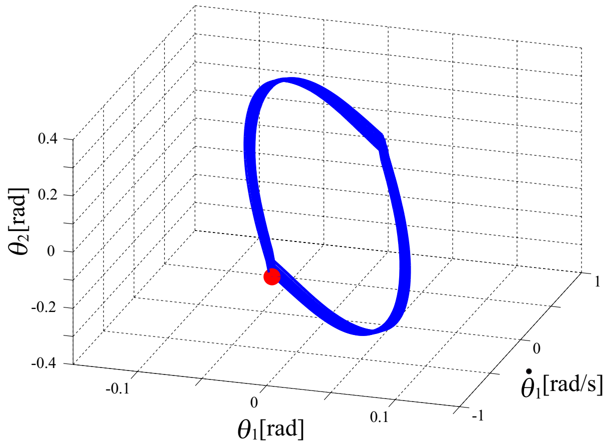

Fig.8 Locus of state variable using Θ_2^L

4.3 Motion evaluation based on the decomposed motion element

4.3.1 Controller design with two sets of the motions

Based on the method of section 2.2, a set of new controllers $\widehat{\Theta}_1^L$, $\widehat{\Theta}_2^L$, $\widehat{\Theta}_1^S$ and $\widehat{\Theta}_2^S$ is designed by equation (21) from a set of motions in table 2. This set

Table 2 Combination of new controller (Case 1)

	Robot L	Robot S	
Motion 1	$\widehat{\Theta}_1^L$	$\widehat{\Theta}_1^S$	$\rightarrow \Lambda_1$
Motion 2	$\widehat{\Theta}_2^L$	$\widehat{\Theta}_2^S$	$\rightarrow \Lambda_2$
	$\rightarrow \Gamma^L$	$\rightarrow \Gamma^S$	

of motions is defined the same motion by similar frequencies. $\widehat{\Theta}_1^L$ and $\widehat{\Theta}_2^L$ generate motions whose trajectories are drawn with red line in figure 9 and 10. For comparison, base motions are also drawn by blue line. The obtained frequencies are listed in table 3.

On the other hand, another set of controllers, which are $\widehat{\Theta}_1^L$, $\widehat{\Theta}_2^L$, $\widehat{\Theta}_{1.5}^S$ and $\widehat{\Theta}_{2.5}^S$, is designed like in table 4. Two motions whose cells are painted with

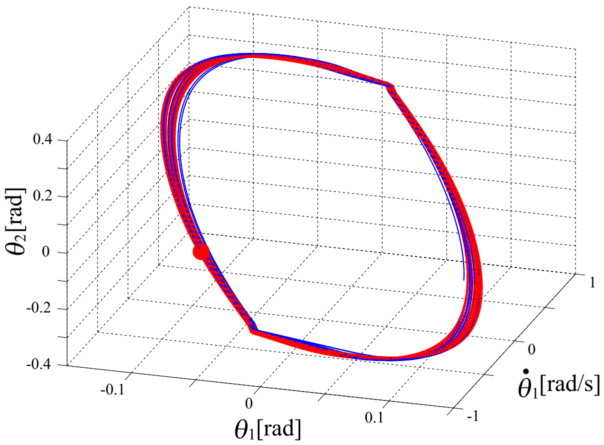

Fig.9 Locus of state variable using $\widehat{\Theta}_1^L$ (Case 1)

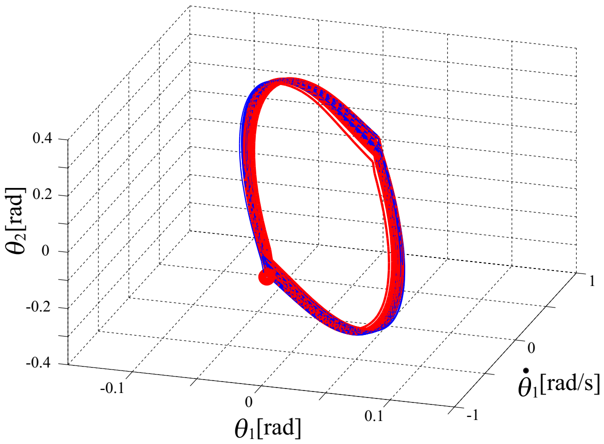

Fig.10 Locus of state variable using $\widehat{\Theta}_2^L$ (Case 1)

Table 3 Obtained motion frequency (Case 1)

	Robot L	Robot S
Motion 1	1.057Hz	1.018Hz
Motion 2	2.260Hz	2.289Hz

yellow are changed. By using the new set of con-

Table 4 Combination of new controller (Case 2)

	Robot L	Robot S	
Motion 1	$\widehat{\Theta}_1^L$	$\widehat{\Theta}_{1.5}^S$	$\to \Lambda_1$
Motion 2	$\widehat{\Theta}_2^L$	$\widehat{\Theta}_{2.5}^S$	$\to \Lambda_2$
	$\to \Gamma^L$	$\to \Gamma^S$	

trollers, the state variables draw each trajectories in the state space in figure 11 and 12. In these figures, the base motions are also drawn by blue line. Frequencies of the new motions are listed in table 5. From these trajectories and frequencies of the motions, there seems to be no difference of motion

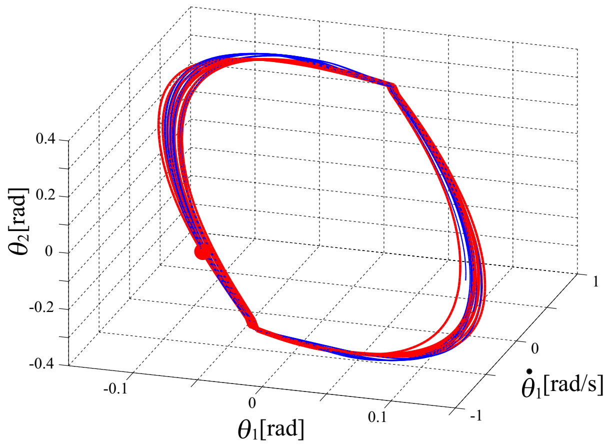

Fig.11 Locus of state variable using $\widehat{\Theta}_1^L$ (Case 2)

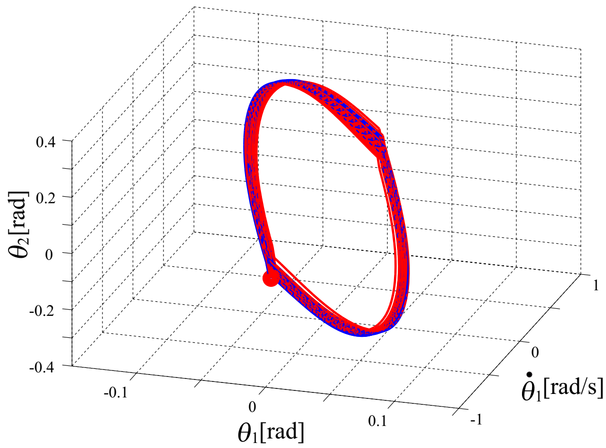

Fig.12 Locus of state variable using $\widehat{\Theta}_2^L$ (Case 2)

Table 5 Obtained motion frequency (Case 2)

	Robot L	Robot S
Motion 1	1.039Hz	1.660Hz
Motion 2	2.226Hz	2.920Hz

between new and based motions.

4.3.2 Motion evaluation

The evaluation results from these two simulation with the equation (26) are shown in figure 13 and 14. Where each $*$ and $\circ$ is result of Case 1 and Case 2 respectively. From these results, the motion set of Case 2 is higher motion similarity than the set of Case 1, because the evaluation value V of Case 1 is lower than Case 2. This means that the motion element of Case 2 is more ideal than the element of Case 1, and appropriate new controllers (e.g. $\widehat{\Theta}_{1.5}^L$) is designed by combination of ideal Λ and Γ from the motion set of Case 2. This indicates that robot motion can't be directly evaluated by its motion frequency. The same motion for smaller robot should have faster frequency than the motion for the larger robot. This

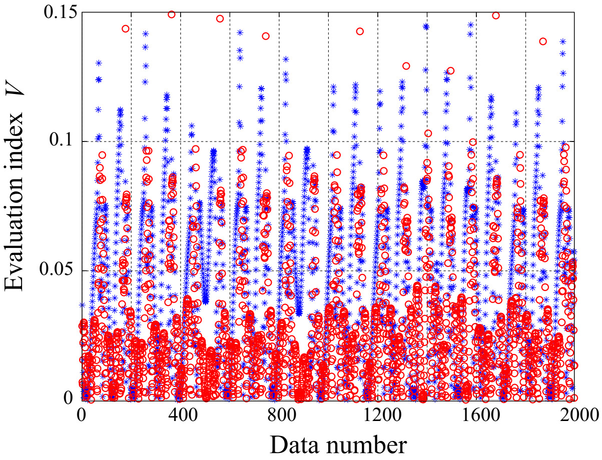

Fig.13 Motion evaluation index of Motion 1 for robot L

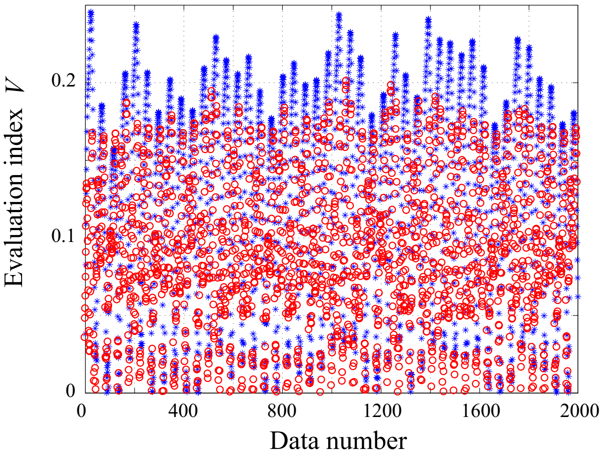

Fig.14 Motion evaluation index of Motion 2 for robot L

attributes difference of characteristic frequency from the robot's mechanical characteristics.

5. Conclusion

In this paper, based on the motion element, the evaluation method of motion similarity is verified. The results of this paper are as follows;

1. The evaluation method of motion similarity is expressed based on vector field of motion in state space which is generated by motion element.
2. With the simulation of tap-dancing robots, the proposed method provides an appropriate result for the evaluation of motion similarity.
3. Especially, this result matches our feeling of the motion similarity.

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