Experimental Demonstration of Disturbance Suppression Control with Novel Nonlinear Disturbance Predictor based on Reconstructed Attractor

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***Abstract*— In this paper, disturbance suppression control with a novel nonlinear disturbance predictor to be used for motion control system is proposed. By design of the novel disturbance predictor, we develop Disturbance Observer to realize disturbance feedback without time delay.**

This predictor is built from the reconstructed attractor which is often used in chaos analysis. The reconstructed attractor consists of the time series of disturbance and expresses the dynamics of disturbance. Due to the characteristics of the reconstructed attractor, it is not necessary to identify or model the dynamics of disturbance. Therefore the proposed method is especially effective to compensate the interference force of multiple axes robot manipulator, friction force and so on which control tends to be complicated in the conventional methods.

In the proposed method, one-step-ahead prediction can be realized by extension of the trajectory in the state space of disturbance intuitively. But in the reconstructed attaractor, the order of the space can be selected arbitrarily as prediction is succeeded. Additionaly the state transition equation of disturbance is not necessary.

To verify the effectiveness of the prposed method, some simulation results using a double pendulum system are shown. In this simulation, though the chaotic interference force gives bad influence to the system, the proposed method can be succeeded in stabilizing the behavior of the double pendulum.

keywords - robot manipulator; reconstructed attractor; nonlinear prediction

I. INTRODUCTION

Control methods for manipulators have been studied by many researchers. The interference force between differenet axes consists of the Coriolis effect and Centrifugal force must be compensated since it exerts a bad influence to the control performance. Although many methods have been proposed to compensate this disturbance, a new controller which can reject disturbance accurately is still desired, for manipulators are required to move more precisely and fastly more than ever.

Since a long time ago, the computed torque controller and adaptive ones are familiar as methods for multiple axes manipulator. But these methods tend to be complicated so that the dinamics of a manipulator is expressed several equations and the adaptive algorithm needs more equations additionally[3].

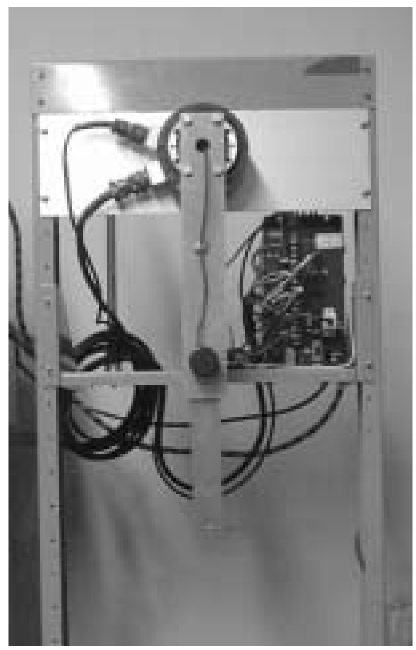


Figure 1. Overview of double pendulum

On the other hand, there is a method which controls each axes independently with Disturbance Observer[1]. In this method, it is not necesarry to model the dynamics because Disturbance Observer can compensate disturabnce automatically on each axes. But this method can't take the dynamics into account and needs short sampling time to estimate disturbance.

In this paper, A new method developing Disturbance Observer is proposed. In the proposed method, disturbance feedback without time delay is realized even if sampling time is long. Because the proposed method has a novel nonlinear predictor comprised of the reconstructed attractor which is often used in chaos analysis. The reconstructed attractor has the characteristics that it involves the dynamics of disturbance. Therefore the interference force is taken into account without identifying or modeling in the proposed method.

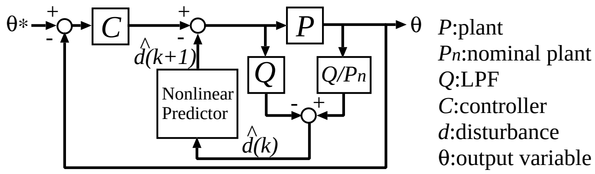


Figure 2. Configuration of system including nonlinear predictor

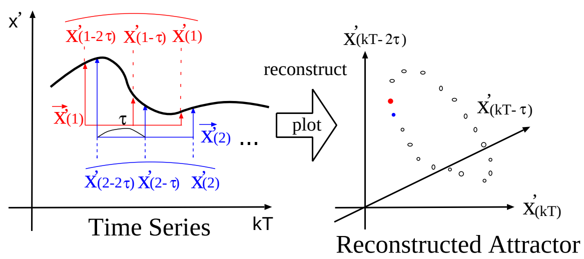


Figure 3. Concept of reconstructed attractor using time delay coordinates

Fig.1 shows the overview of a double pendulum. To verify the effectiveness of the porposed method, some simulation results using the double pendulum system are shown. In this simulation, though the chaotic interference force gives bad influence to the system, the proposed method can be secceeded in stabilizing the behavior of the double pendulum.

II. Nonlinear Prediction Using Reconstructed Attractor

The goal of this paper is to build a control system with disturbance predictor in Fig. 2. To design the disturbance predictor, the attractor which is used in chaos analysis is introduced in this section.

A. Attractor in the state space

When a dynamic system is drawn in d dimensional state space, the state vector expresses the instantaneous state of the physical value and the state vector's trajectory expresses the whole physical system behavior[2][4].

In general, a discrete time state equation is written as (1) using d dimensional state vector $\boldsymbol{x}$. In (1), $\boldsymbol{f}$ is the nonlinear dynamic equation, $\boldsymbol{g}$ is the output equation and $\boldsymbol{y}$ is the vector of observable state variables. A physically stable phenomenon is drawn as stable trajectory in a state space. In particular, a stable trajectory which attracts neighboring trajectories is called an '**attractor**'[5].

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{f}(\boldsymbol{x}(k)) \\ \boldsymbol{y}(k) &= \boldsymbol{g}(\boldsymbol{x}(k)) \end{aligned} \quad (1)$$

B. Reconstructed attractor

To draw an attractor, all of $\boldsymbol{x}$'s elements must be observable. But in most cases, all elements can't be observable. Therefore it is often helpful to use the reconstructed attractor with 'delay coordinate vector'. When the time series of a single scalar variable x_l is the only information that we can measure, 'delay coordinate vector' is reconstructed as in (2) (Fig.3).

$$\begin{aligned} \boldsymbol{x}'(k) = & [x_l(kT), x_l(kT-\tau), x_l(kT-2\tau), \ldots \\ & \ldots, x_l(kT-(q-2)\tau), x_l(kT-(q-1)\tau)] \end{aligned} \quad (2)$$

Embedding theorems guarantee that, if $q \geq 2d+1$, the vector $\boldsymbol{x}$ is generically a global one-to-one representation of the system state [6]. However such a representation may be achieved experimentally if τ is appropriately chosen even when $q < 2d+1$. Thus in this paper, we sets the order of 'delay coordinate vector' as parameters so that prediction is succeeded.

Using the 'delay coordinate vector' in this way, the reconstructed attractor is drawn in q dimensional state space.

C. Nonlinear prediction

The original dynamic system is transcribed to (3) by the 'delay coordinate vector'. It is possible to predict $\boldsymbol{x}'(k+1)$ from $\boldsymbol{x}'(k)$ by obtaining the map $\hat{\boldsymbol{f}}(\boldsymbol{x}'(k))$.

$$\begin{aligned} \boldsymbol{x}'(k+1) &= \hat{\boldsymbol{f}}(\boldsymbol{x}'(k)) \\ y(k) &= (1, 0, \cdots, 0)\boldsymbol{x}'(k) \end{aligned} \quad (3)$$

Although there are several methods to obtain the map $\hat{\boldsymbol{f}}(\boldsymbol{x}')$, Jacobian method is applied in this paper. Jacobian matrix $\boldsymbol{A}_k$ is fixed by N neighboring state vectors near $\boldsymbol{x}'(k)$ on the reconstructed attractor as in Fig.4. $\boldsymbol{x}'(k+1)$ is predicted by the approximate linear equation (4) which

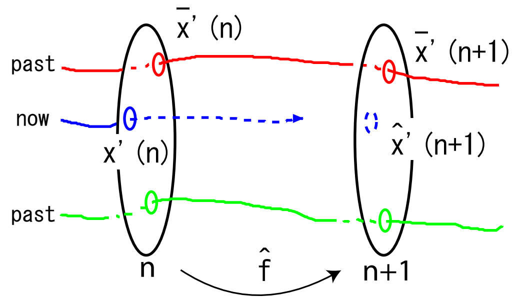
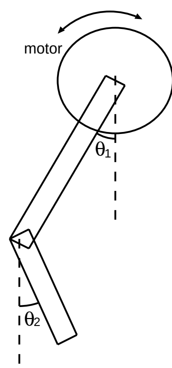
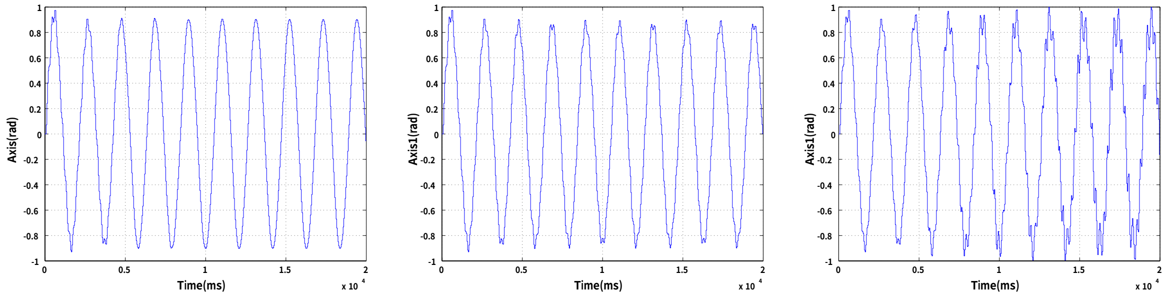


Figure 4. Prediction of next step



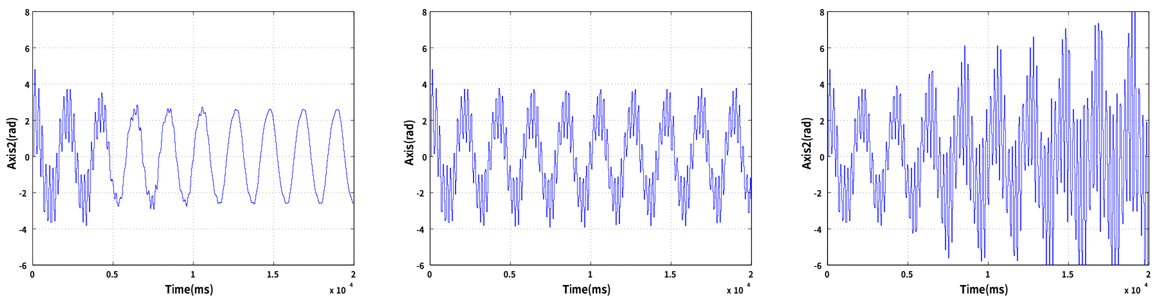
	length	weight
arm1	10[cm]	0.200[kg]
arm2	8[cm]	0.100[kg]

Figure 5. Model of double pendulum and its parameters



(a) FB of proposed prediction (b) FB of estimated disturbance (c) FB of conventional prediction

Figure 6. Time series of first axis θ_1 of double pendulum



(a) FB of proposed prediction (b) FB of estimated disurbance (c) FB of conventional prediction

Figure 7. Time series of second axis θ_2 of double pendulum

is constructed with a Jacobian matrix and the nearest state vector $\bar{\boldsymbol{x}}^{'}(k)$.

$$\hat{\boldsymbol{x}}^{'}(k+1) = \boldsymbol{A}_k(\boldsymbol{x}^{'}(k) - \bar{\boldsymbol{x}}^{'}(k)) + \bar{\boldsymbol{x}}^{'}(k+1) \quad (4)$$

III. NONLINEAR DISTURBANCE PREDICTOR FOR MANIPULATOR CONTROL

A. Dynamics of Double Pendulum

In this paper, a double pendulum shown in Fig.5 is considered. (5) is the dynamic equation of robot manipulator [7].

$$\boldsymbol{J}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{c}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{g}(\boldsymbol{\theta}) = \boldsymbol{T}_{in} \quad (5)$$

Here, $\boldsymbol{J}(\boldsymbol{\theta})$ is the inertia matrix, $\boldsymbol{g}(\boldsymbol{\theta})$ is the gravitational force and $\boldsymbol{T}_{in}$ is the input torque. $\boldsymbol{c}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$ represents the Coriolis effect and Centrifugal force to take the form of (6).

$$\boldsymbol{c}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) = \dot{\boldsymbol{J}}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} - \frac{1}{2}\frac{\partial}{\partial \boldsymbol{\theta}}(\dot{\boldsymbol{\theta}}^T \boldsymbol{J}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}) \quad (6)$$

The interference force $\boldsymbol{T}_d$ is estimated by Disturbance Observer. By using Disturbance Observer each axes can be treated as an independent single pendulum. The interference force between different axes and the gravitational force can be treated as disturbance as given by the form of (8).

$$diag\boldsymbol{J}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} = \boldsymbol{T}_{in} - \boldsymbol{T}_d \quad (7)$$

$$\boldsymbol{T}_d = (\boldsymbol{J}(\boldsymbol{\theta}) - diag\boldsymbol{J}(\boldsymbol{\theta}))\ddot{\boldsymbol{\theta}} + \boldsymbol{c}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{g}(\boldsymbol{\theta}) \quad (8)$$

(8) is converted to the state equation (9) in the discrete time domain. From (9), disturbance to the first axis has some dynamics given by $\hat{\boldsymbol{f}}_{d,1}$.

$$T_{d,1}(k+1) = \hat{\boldsymbol{f}}_{d,1}(T_{d,1}(k)) \quad (9)$$

If the prediction of $T_{d,1}(k+1)$ from $T_{d,1}(k)$ is realized, it is achieved to feedback disturbance without any time delay. But the map $\hat{\boldsymbol{f}}_{d,1}$ is usually too complicated to be formulated.

In practice, the 'delay coordinate vector' is constructed from the time series of the estimated disturbance as in (2). The reconstructed attractor is expected to be drawn even if the discrete state equation (9) might not be obtained.

B. Simulation

The sinusoidal curve reference angle is given to the first axis and its angle is controlled by the tuned PD controller. The second axis is fluctuated by the interference force even if no torque is applied. In other words the first axis is interfered by the action-reaction effect from the second axis. This is not a problem if the interference force varies slowly enough to be suppressed by the position controller.

In the proposed method the reconstructed attractor is obtained with a dimension of 3, and a delay time of $80[\mathbf{ms}]$. The time series of the first axis θ_1 and the second axis θ_2 with the proposed disturbance prediction feedback are shown in Figs.6 (a) and 7 (a). In addition, likewise the disturbance estimation feedback by Disturbance Observer are shown in Figs.6 (b) and 7 (b) and the conventional disturbance feedback by first order approximation (10) are shown in Figs.6 (c) and 7 (c).

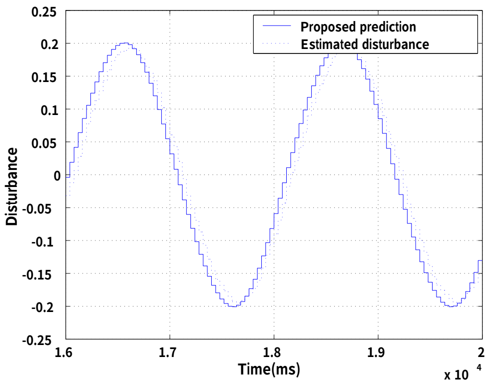


Figure 8. Predicted disturbance in proposed method

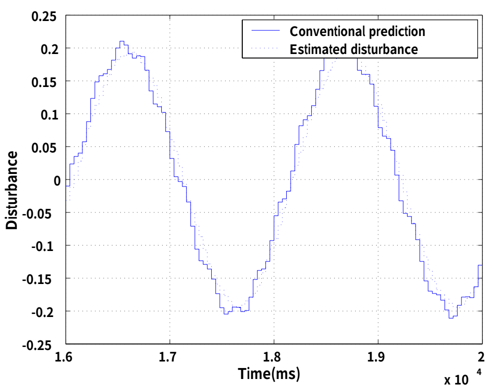


Figure 9. Predicted disturbance in conventional method

$$\hat{x}'(k+1) = \frac{d\hat{f}}{dt}(x'(k) - x'(k-1)) + x'(k) \quad (10)$$

In these figures, the proposed method can stabilize the double pendulum with only single input to the first axis. On the contrary, the conventional method can't stabilize the double pendulum. Because the conventional method can't predict the one-step-ahead disturbance precisely and the error between truth and prediction of the disturbance makes the double pendulum transpire so called 'Butterfly Effect'. Through these simulation results, it is proved that the proposed method is effective for more accurate prediction.

Additionally the predicted disturbance in the proposed method and the conventional method are shown in Figs. 8, 9. In Fig. 8, the proposed predictor can predict the one-step-ahead disturbance as compared with the estimated disturbance. On the other hand, the conventional predictor can't predict accurately and the predicted disturbance becomes vibrated for the incorrect predicted disturbance make the system unstable.

C. Experimental setup

To verify the effectiveness of the proposed method actually, experiments with a double pendulum will be executed. The configuration of the experimental equipment is shown in Fig. 10. In experiments, we use ART-linux to

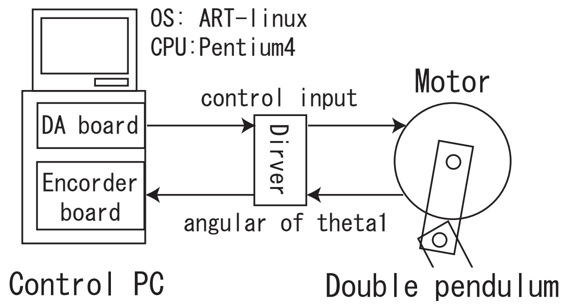


Figure 10. Configuration of experimental equipment

execute with strict timing requirement of control sampling time.

IV. CONCLUSION

In this paper, the nonlinear disturbance suppression control with a novel nonlinear disturbance predictor is proposed. In the simulation of a double pendulum, we succeed in predicting the one-step-ahead disturbance. Although only periodic disturbance is treated in this paper's simulation, this predictor is effective even if there are unknown dynamics such as friction force or even chaotic behavior which is difficult to be modeled. By feeding back the predicted disturbance, it is possible to change control performance more precisely.

REFERENCES

[1] Takaji Umeno, Tomoaki Kaneko, Yoichi Hori: "Robust Servosystem Design with Two Degrees of, Freedom and its Application to Novel Motion Control of Robust Manipulators", *IEEE Trans. on IE*, Vol. 40, No. 5, pp. 473-485, 1993.

[2] Michiaki Inomoto, Yoichi Hori, Kazuyuki Aihara: "Accuracy Improvement and Synchronization of Nonlinear Prediction with Reconstruction of Attractor and Its Application to a Walking Robot", *IEICE Tran. A*, Vol. J80-A, No. 1, pp. 126-134, 1997. (in Japanese)

[3] Louis L. Whitcomb, Alfred A. Rizzi, Daniel E. Koditschek: "Comparative Experiments with a New Adaptive controller for Robot Arms", *IEEE Tran. on robotics and automation*, Vol. 9, No. 1, Feb, 1993.

[4] Hiroshi Shikano, Yoichi Hori: "Stabilization Control of Double Pendulum Using Reconstructed Attractor", *Trans. IEE of Japan*, Vol. 120-D, No. 1, Jan, 2000. (in Japanese)

[5] Troy Shinbrot, Celso Grebogi, Edward Ott, James A. Yorke: "Using small perturbations to control chaos", *NATURE*, vol. 363, 3 June, 1993.

[6] Tim Sauer, James A. Yorke, Martin Casdagli: "Embedology", *Journal of Statistical Physics*, Vol. 65, No. 3/4, pp. 579-616, 1991.

[7] Toshiyuki Murakami, Kouhei Ohnishi: "A Study of Stability and Workspace Decoupling Control Based on Robot Control in Multi-Degrees-of-Freedom Robot" , *Trans. IEE of Japan*, Vol. 113-D, No. 5, 1993. (in Japanese)