Accurate motion regeneration technique with robust control approach

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ABSTRACT

In this paper, the authors propose a new method of easily recognizing and regenerating robot motions used for robot motion control to perform the task of painting furniture and welding parts in small scale industries. The method is based on the process of accurate modeling, control design and experimental evaluation. In this study, the models and controllers for all joints of 3DOF robot system are obtained individually. The Robust control controller is designed to cope with uncertainties, especially the effects of the added inertia moment. In the experiment, the robust control method is compared with the existing PID control method, and the results indicate that the proposed designing method is more efficient than the traditional method.

***Keywords**: Recognition; Regeneration; Robot; Motion control; robust control; Trajectory tracking.*

1. INTRODUCTION

In recent decades, advanced robot technology has been widely applied in painting and welding processes due to its benefits such as improvement in quality of products, improvement of working environment and safety, reduction in the number of workers in hazardous environment. The work performed by the industrial robot is simple and repetitive and taught by the operator. In the automobile assembly line, for instance, the robot welds or tightens repeatedly the assigned point all the time. In order to control robot regenerate exactly target routes, many control strategies have been proposed. Some approaches such as PID control [1], sliding mode control [2] and adaptive control [3] have been used. However, these approaches require a precise model or need to identify on-line model. It is unavoidable to make heavy computation time. Moreover, the designed controllers for nonlinear MIMO system are too complicated.

In this paper, the authors propose a method for accurate regeneration of the robot motion. The identification process using the step response experiments implemented to obtain the transfer function of each joint. After that, the controllers are designed based on H_∞ control framework such that the system has stability and good control performance under influence of uncertainty and added inertia moment.

To obtain the target route, the operator moves the end effector of the robot to the desired positions and orientations. These data and inverse transfer functions of the closed loop system for each joint are used to calculate the reference signals for control systems, which makes it possible to suppress the difference between real and regenerated motion.

To evaluate the efficiency of the proposed method, experiments using the PID control and the robust control method are performed on the three degree of freedom (3DOF) robot system, and the experiment results indicate that the proposed method works well, and the robust control system can achieve stability and better control.

2. IDENTIFICATION MATHEMATICAL MODEL

To design the control system, it is necessary to have a mathematical model that reveals the dynamical behavior of a system. For robot control system design, generally a mathematical model is obtained by using either Lagrange's equations of motion or identification process. Use of Lagrange's equation of motion is not a realistic option because it is not easy to measure mass, inertia and physical properties of the robot system by dismantling it. Moreover, the friction estimation is incapable of calculating exactly from the theoretical approach. Clearly, it is a hard task to obtain the entire robot dynamics through the identification process using motion and torque data from the experiment [4-5].

In this paper, therefore, we propose a simple experimental robot identification procedure that can obtain a model for each joint of the robot system. The procedure may be described as follows: For obtaining the parameters of transfer function, a classic closed-loop identification technique is applied to a joint because it is non-self-regulated in open loop condition [6]. In our case, the proportional controller is used in identifying process.

The step responses of all joints are obtained by setting different reference values for each joint, respectively. Then one of the step responses is chosen to calculate the model which describes the representative dynamic motion of an identified joint. It is a general modeling process that strongly depends on the operating range of each joint, and the system order of closed loop transfer function $G_c(s)$ shown in figure 1 is chosen by considering the representative response selected.

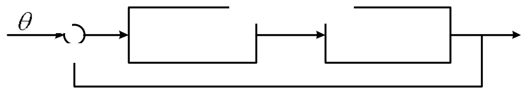


Figure 1. Closed loop system to obtain a model

In this study, all behaviors of the closed-loop system are approximated to the second order model. Therefore, the preliminary damping ratio ξ and natural frequency ω_n value that appear in the second order model are calculated according to the overshoot *POT*, steady state error e_{ss} and settling time t_{ss}. As a result, the transfer function of a joint $G(s)$ can be calculated as follows:

$$G_c(s) = \frac{PG(s)}{1+PG(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

$$\Rightarrow G(s) = \frac{\omega_n^2}{P(s^2 + 2\xi\omega_n s)}, \qquad (1)$$

Where $G_c(s)$ is a closed loop transfer function, $G(s)$ is a transfer function of each joint and P is gain of controller.

Let $K = \omega_n^2 / P$ and $a = 2\xi\omega_n$. Therefore, the open loop transfer function is given as the general form

$$G(s) = \frac{K}{s(s+a)}. \qquad (2)$$

The modelling process previously mentioned can be summarized as follows:

Firstly, desirable responses for several reference values of each joint are obtained by specific PID gain in the experiment.

Secondly, the representative experiment response for each joint is chosen.

Finally, the desired model is obtained by comparing it with the representative experiment response in Matlab simulation.

3. CONTROL DESIGN AND EXPERIMENT

3.1 Control design

In this article, robust control approach is introduced to control joint motion of the robot individually. The schematic diagram of typical feedback control is shown in figure 2 where *G* is plant and *K* is controller. And *r*, *y*, *u*, *e*, *d* represent reference input, output, control, error signal and disturbance, respectively.

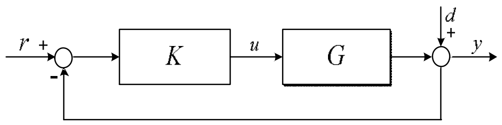


Figure 2. A closed-loop configuration with disturbance

As well known, the robust control design objective is to find a controller such that the control system has nominal performance, good tracking and disturbance attenuation with the control input constraints. If there is a controller, the generalized description is given as follows:

$$\|T_{zw}\|_\infty := \left\| \begin{matrix} W_p(I+GK)^{-1} \\ W_u K(I+GK)^{-1} \end{matrix} \right\|_\infty < \gamma \;\; (\gamma > 0). \qquad (3)$$

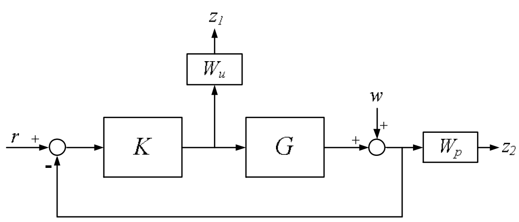


Figure 3. Control system based on H_∞ control framework.

The control scheme is illustrated in figure 3, where T_{zw} describes the transfer between w(disturbance) and z(output). It can also be interpreted to mean that the controller K is designed to minimize the transfer function between w to z as small as possible. The weighting function Wu is introduced to obtain constraint on the control signal u which does not surpass a power output, and the weighting function Wp is used to ensure robustness and disturbance rejection [7]. Then a controller satisfying the condition given in (3) can be easily calculated by using the robust control toolbox in Matlab [8-9].

3.2 Experimental setup

Figures 4 is the photo of the experimental apparatus which consists of three joints named 3DOF robot system. The controller is programmed in Labview language 9.0, the basic configuration of system hardware for digital control is the acquisition card NI-PXIe 6363 with 4-channel 16-bit 1.25MS/s A/D converter and 4-counter 32-bits installed in the PXI express-Bus of platform NI-PXIe 8115 embedded controller. Table 1 lists the specifications of the experiment apparatus.

Table 1. Specification of experimental apparatus.

Items	Joint 1	Joint 2	Joint 3
Motor Voltage [V] Rated current [A] Rated speed [RPM] Rated power [W]	Axon 24 4.64 3000 100	axon 24 3.62 7000 70	mason 24 2.3 7750 50
Reduction gear	33.75	97.5	51
Encoder [pulse/rev]	2000	2000	2000

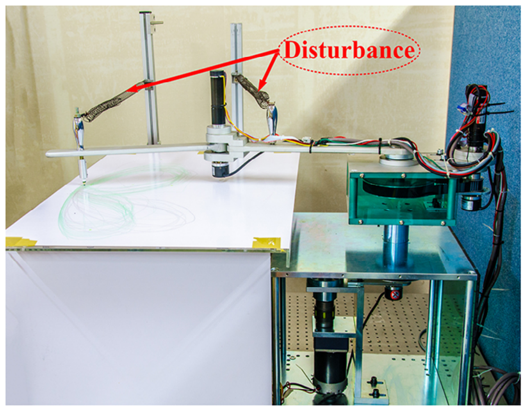


Figure 4. Photo of the experimental apparatus

To make disturbance, two springs are added in the robot system to evaluate the robust and performance of system.

In order to identify the parameter of each joint, the closed loop system with P controller is introduced in the experiment as shown in figure 1. And the step responses for each joint are obtained and shown in figures 5~7 where the set points are given from 5 to 50 degree with a 5-degree variation by considering operating ranges.

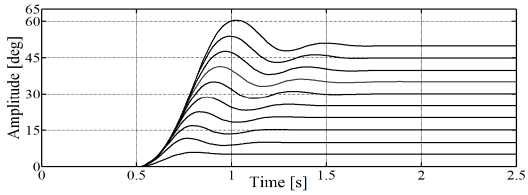


Figure 5. Step responses of joint 1 at different set points

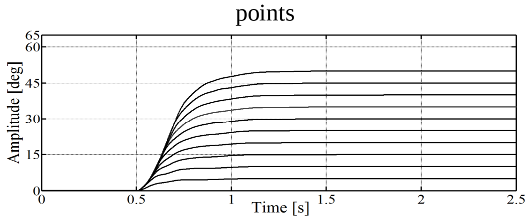


Figure 6. Step responses of joint 2 at different set points

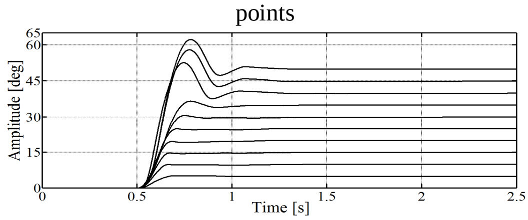


Figure 7. Step responses of joint 3 at different set points

In our robot system, the allowable operating range in all joints is ±70 degree. However, the first and second joints are operated mostly in the range ±40 degree, and the third joint is operated mostly in the range ±50 degree. Therefore, we select the step responses at 30, 30, 40 degrees as the representative responses of joint 1, 2 and 3, to obtain the mathematical model, respectively. As described in section 2, the preliminary damping ratio and natural frequency values are calculated from these representative responses, and the transfer functions of joints are calculated and simulated in Matlab. After that, it needs a few tuning times to make simulation responses most similar to the experiment responses. Figures 8~10 show the results of this process.

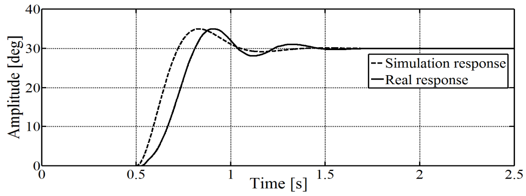


Figure 8. Simulation and real response of joint 1 at 30^0

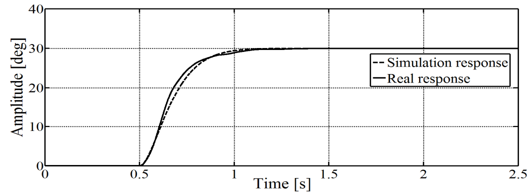


Figure 9. Simulation and real response of joint 2 at 30^0

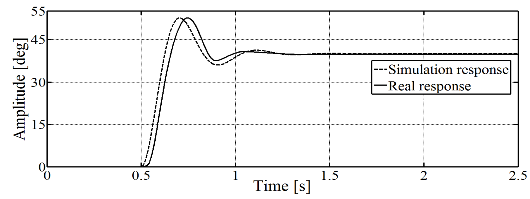


Figure 10. Simulation and real response of joint 3 at 40^0

Thus, the transfer functions for each joint are obtained as follows:

$$G_1(s)=\frac{915.8895}{s(s+9.023)},\; G_2(s)=\frac{1102.5}{s(s+19.8492)},\; G_3(s)=\frac{4358.9}{s(s+11.376)}. \tag{4}$$

In this study, two control methods (PID and robust control) are applied to evaluate the proposed robust control strategy and its performance. In the PID control scheme, the following PID controller is proposed.

$$G_{PID}(s)=\left(K_p+\frac{K_i}{s}+K_D s\right). \tag{5}$$

Based on the transfer functions obtained by (4), the parameters of PID controllers are calculated and simulated in Matlab. Finally, they are fine tuned in the experiment to obtain the best performance. The final PID control gains are chosen as follows:

$$\begin{aligned} &K_{p1} = 0.56,\ K_{I1} = 0.02,\ K_{D1} = 0.0001 \\ &K_{p2} = 1.1,\ K_{I2} = 0,\ K_{D2} = 0 \\ &K_{p3} = 0.366,\ K_{I3} = 0.1,\ K_{D3} = 0. \end{aligned} \tag{6}$$

The robust controller is designed to satisfy (3). In the robust control design, choosing the weighting functions depicted in figure 3 is critical, and it needs some trial and error times. Therefore, the weighting functions are chosen to calculate the controller, and then the simulations and the experiments are carried out to examine the performance. This process is repeated until good controllers are obtained. As a result, the weighting functions are chosen as follows:

$$\begin{aligned} &W_{u1} = 1; \quad W_{p1} = \frac{0.2s+6}{5s+0.015} \\ &W_{u2} = 1; \quad W_{p2} = \frac{0.01s+0.3}{s+0.003} \\ &W_{u3} = 1; \quad W_{p3} = \frac{0.01s+0.3}{s+0.003} \end{aligned} \tag{7}$$

With the chosen weighting functions above and using robust control toolbox with *hinfsys* function, the elements of the controllers for joints are calculated as follows:

$$\begin{aligned} K_1(s) &= \frac{5045s^2 + 45520s + 5.045}{s^3 + 10850s^2 + 360500s + 1081} \\ K_2(s) &= \frac{578.9s^2 + 11490s + 0.5789}{s^3 + 2897s^2 + 86040s + 258.1} \\ K_3(s) &= \frac{586.3s^2 + 6670s + 0.5863}{s^3 + 5317s^2 + 19\times 10^5 s + 570} \end{aligned} \tag{8}$$

Based on these results, we evaluated the proposed robot motion control strategy. As described earlier in the introduction part, the aim of this research is accurately to reproduce the operating pattern of the skilled person. For this purpose, we propose a new strategy which can carry out the following functions:

- Calculate the transfer functions of the closed loop system of each joint described as $G_i(s),\ (i = 1,2,3)$ in which the controller and transfer function of each joint are included.
- Calculate the inverse transfer functions $\{G_i(s)\}^{-1}$ of the closed loop system for each joint.
- Operate the robot manually and recording the angle of joints $Y_i(s)$ obtained from sensors attached in the joints.
- Input recorded data $Y_i(s)$ into the inverse transfer functions $\{G_i(s)\}^{-1}$, then the output signal $\tilde{R}_i(s)$ is obtained ($\tilde{R}_i(s)$ is regarded as the calculated reference signal).
- Input the calculated reference signal $\tilde{R}_i(s)$ to the robot control system, and then we can obtain the regenerated robot motion $\tilde{Y}_i(s)$.

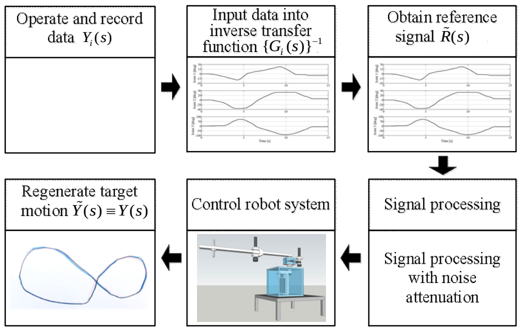
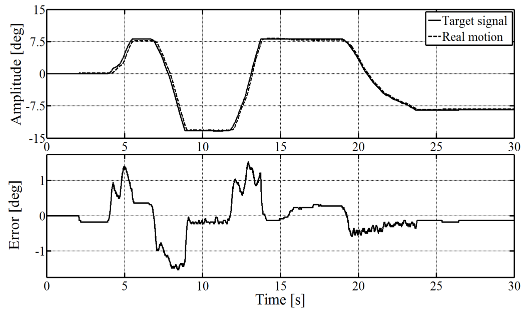


Figure 11. Teaching and motion regenerating process

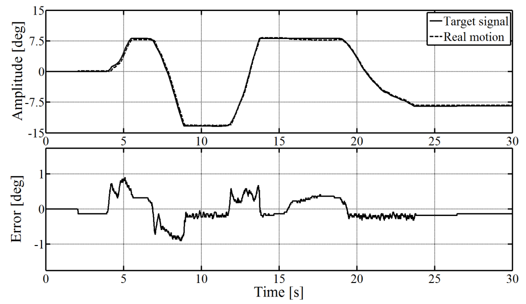
In fact, the main issue of this research is how we can suppress the difference between $Y_i(s)$ and $\tilde{Y}_i(s)$. Therefore, in this paper, a robust control system is designed on the basis of H_∞ control framework. And we experiment with and without disturbance to evaluate the robust and performance of proposed method.

3.3 Control performance without disturbance

In this experiment, the spring are not included in the robot system. Figures 12~16 show the results of the experiment obtained by using the robust and PID controllers for three joints. Figures 12~14 show the control performances for the calculated reference signals. In these figures, the solid lines show the motions made by skilled operator, and the dashed lines are the regenerated motions for three joints, respectively.

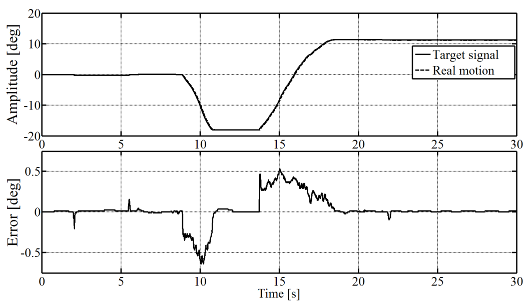


(a) PID control

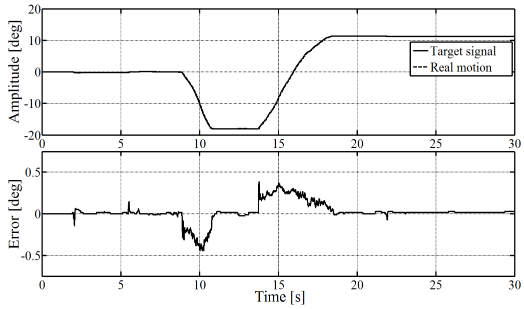


(b) Robust control

Figure 12. Regenerated motion and error of joint 1 (PID and robust control)

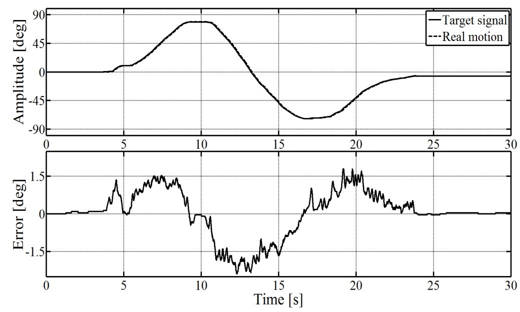


(a) PID control

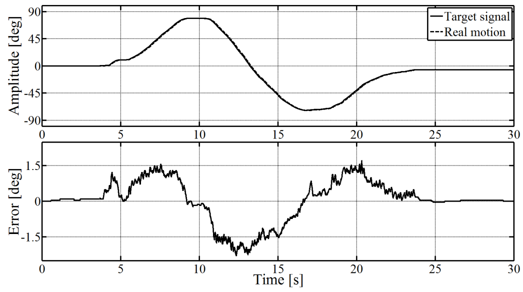


(b) Robust control

Figure 13. Regenerated motion and error of joint 2 (PID and robust control)

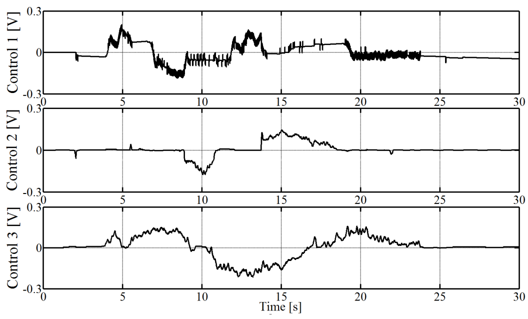


(a) PID control

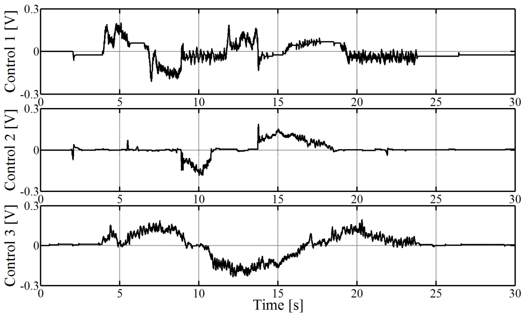


(b) Robust control

Figure 14. Regenerated motion and error of joint 3 (PID and robust control)



(a) PID control



(b) Robust control

Figure 15. Control input (PID and robust control)

Especially, figure 16 shows the target route (line drawing) made by the operator and the regenerated routes made by PID control and robust control, and where each control method is repeated 10 times to evaluate their accuracy and validity. As shown in figure 4, the target and regenerated routes are drawn by a fixed pencil at the end effector.

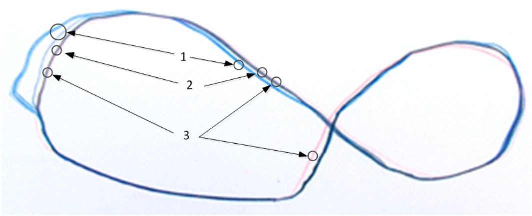


Figure 16. Regenerated line drawing motion made by PID and robust control with 10 times iteration. Where 1 is made by PID control, 2 is made by robust control and 3 is Target route

Table 2. Comparison of RMS errors [deg]

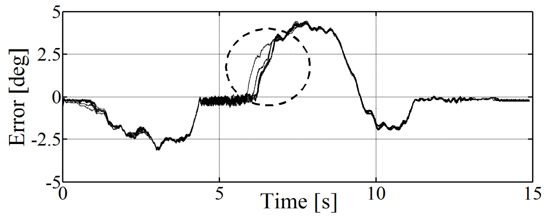
	Joint 1	Joint 2	Joint 3
PID control	0.499	0.165	0.897
Robust control	0.304	0.114	0.863

3.4 Control performance with disturbance

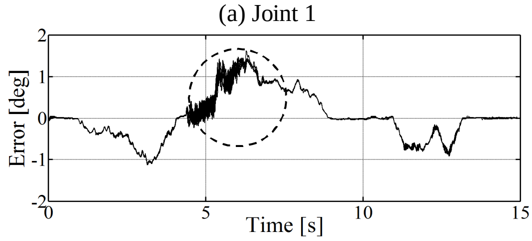
In this experiment, we consider disturbance input to evaluate robust control performance. The disturbance is produced by adding two springs to the end of joints as illustrated in figure 4. Then we can make the same experiment condition for two control strategies. By trying ten times experiments with the same target route as shown in figure 19, the error values in the each joint for two control methods are plotted in figures 17~18, and RMS errors are shown in Table 3.

Table 3. Comparison of RMS errors [deg]

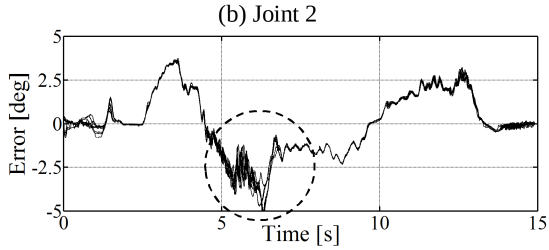
	Joint 1	Joint 2	Joint 3
PID control	1.9257	0.5612	1.8488
Robust control	1.0155	0.5612	1.1783



(a) Joint 1

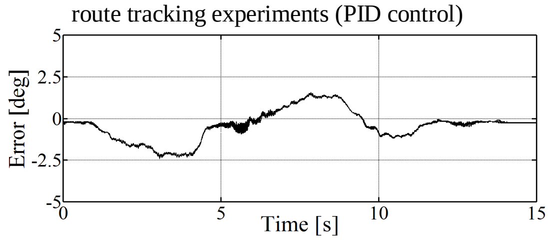


(b) Joint 2

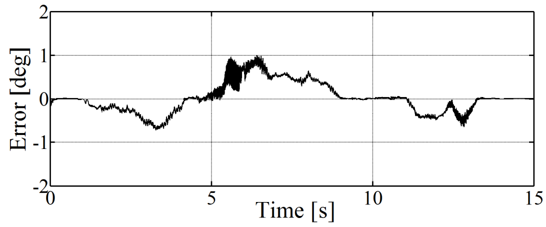


(c) Joint 3

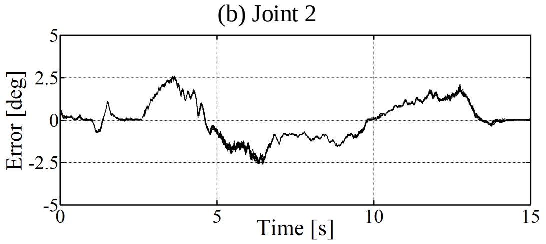
Figure 17. Errors obtained from 10 times target route tracking experiments (PID control)



(a) Joint 1



(b) Joint 2



(c) Joint 3

Figigure 18. Errors obtained from 10 times target route tracking experiments (Robust control)

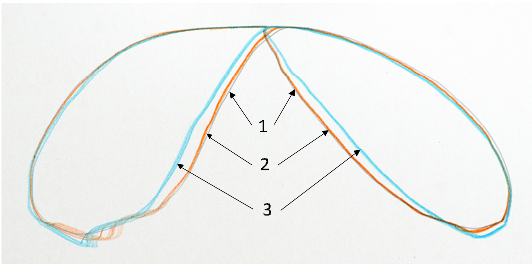


Figure 19. Regenerated line drawing motion made by PID and robust control with 10 times iteration. Where 1 is Target route, 2 is Robust control and 3 is PID control

According to the figures 12~19 and Table 2 and 3, it is clear that both controllers can keep the system stability and robust performance. However RMS errors in Robust control are smaller than in PID control in both two experiments. In addition, the robust control is more stable than PID control when external disturbance are inserted in system shown in figures 17~18 in which errors made by PID control variation more than robust control. It means that motion control using robust control strategy shows better results than PID control method.

4. CONCLUSION

This paper proposed method for accurate motion regeneration of robot. This method includes identification, calculating reference signal from output motion and design robust controller processes. The proposed method is evaluated by experiment and compared with PID control. The results of the experiment clearly indicate that the proposed strategy is simple and capable of achieving robust stability and good control with accurate target tracking. This means that we do not need to use the entire dynamic motion of robot system which is very difficult to obtain, and nor do we need to design the complicated controller for MIMO system.

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Ứng dụng điều khiển bền vững để tái tạo chính xác chuyển động của robot

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TÓM TẮT

Trong bài báo này, tác giả đưa ra một phương pháp mới để dễ dàng nhận biết và tái tạo lại chuyển động của robot thường được dùng trong ngành sơn và hàn cho những chi tiết có kích thước nhỏ trong công nghiệp. Phương pháp này được thực hiện dựa vào quá trình nhận dạng mô hình, thiết kế bộ điều khiển và làm thí nghiệm để đánh giá. Trong nghiên cứu này, các mô hình và bộ điều khiển của robot 3 bậc tự do được nhận dạng và thiết kế cho từng khớp. Bộ điều khiển bền vững được thiết kế để khắc phục sự không chắc chắn của mô hình cũng như sự tương tác chuyển động giữa các khớp. Trong phần thí nghiệm, phương pháp điều khiển bền vững được so sánh với phương pháp điều khiển PID và các kết quả cho thấy rằng phương pháp trình bày trong bài báo hiệu quả hơn so với phương pháp PID truyền thống.

Keywords: *Nhận dạng, Tái tạo, Robot, Điều khiển chuyển động, Điều khiển bền vững, Trajectory tracking.*

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