CHEMICAL ENGINEERING TRANSACTIONS

VOL. 59, 2017

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Zhuo Yang, Junjie Ba, Jing Pan

ISBN 978-88-95608- 49-5; **ISSN** 2283-9216

DOI: 10.3303/CET1759017

Design of Joint Controller for Welding Robot and Parameter Optimization

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Joint control is the basis for welding robot to complete task space trajectory tracking, and the precision of joint control is directly related to the motion performance and precision of the robot. For the coherent and non-linear dynamic characteristics of welding robot, we use fuzzy logic to dynamically adjust the controller parameters, to improve the performance of trajectory tracking control. And then we set up the fuzzy rules to adjust the PID parameters according to the trajectory tracking error and the error change rate, and obtain the optimal initial PID parameters by optimal algorithm at the beginning of the trajectory tracking. In the trajectory tracking process, the PID parameter increment calculated by fuzzy controller is superimposed on the initial PID parameter, so that dynamically optimize joint controller parameters. The study shows that, application of dynamic fuzzy PID control can bring better single-joint step response performance and multi-joint linkage trajectory tracking performance than mere PID control.

1. Introduction

Joint control is the basis for welding robot to complete task space trajectory tracking, and the precision of joint control is directly related to the motion performance and precision of the robot. The classical robot control method is to utilize PID controller of each joint (Wen et al., 2009), and then carry out tuning and optimization of the PID controller. In order to make the PID controller parameters adapt to the changes of the robot dynamics, we may adopt the intelligent methods such as fuzzy logic, genetic algorithm and neural network to conduct dynamic adjustment on PID controller parameters, or directly use the intelligent controller to track the control of the welding robot.

Almost all the international mature robot products are taking PID controller as the basic controller, and combined with parameter dynamic optimization strategy and compensation strategy, that is because PID controller parameter adjustment is simple, and it can achieve high precision trajectory tracking under certain conditions. While intelligent control methods often need to consume a lot of computing resources, and the controller parameter adjustment process is complicated. In this paper, for the coherent and non-linear dynamic characteristics of welding robot, we use fuzzy logic to dynamically adjust the controller parameters, to improve the performance of trajectory tracking control. And then we set up the fuzzy rules to adjust the PID parameters according to the trajectory tracking error and the error change rate, and obtain the optimal initial PID parameters by optimal algorithm at the beginning of the trajectory tracking (Martin et al., 2008). In the trajectory tracking process, the PID parameter increment calculated by fuzzy controller is superimposed on the initial PID parameter, so that dynamically optimize joint controller parameters (Xiao et al., 2016).

2. Design of joint controller for welding robot

Welding robot has coherent and non-linear dynamic characteristics. In the process of exercise, the equivalent inertia moment of each joint is changing. In order to make the PID controller to adapt to a large degree of time characteristics of the robot process, we use fuzzy logic to adjust the controller parameters online, and construct the fuzzy PID controller. The fuzzy PID controller is based on PID controller, to carry out fuzzy inference with certain fuzzy rules, and get the adjustment of PID parameters, so that update PID controller parameters.

Please cite this article as: Chengxiang Li, 2017, Design of joint controller for welding robot and parameter optimization, Chemical Engineering Transactions, 59, 97-102 DOI:10.3303/CET1759017

The core of fuzzy PID controller design is to establish appropriate fuzzy rules according to technical knowledge and practical experience of engineering designer, and then with the error e and error change rate $\dot{e}$, to get the fuzzy control table adjusting the three controller parameters of k_p, k_i, k_d (Khooban et al., 2013).
The fuzzy rules of adjustment of k_p, k_i, k_d are respectively shown as Table 1~ Table 3.

Table 1: Fuzzy rules of $\triangle k_p$

$\triangle k_p$					$\dot{e}$			
		NB	NM	NS	ZO	PS	PM	PB
e	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PM	PS	ZO	NS	NS
	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NB
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	ZO	NM	NM	NM	NB	NB

Table 2: Fuzzy rules of $\triangle k_i$

$\triangle k_i$					$\dot{e}$			
		NB	NM	NS	ZO	PS	PM	PB
e	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	PM	PB	PB

Table 3: Fuzzy rules of $\triangle k_d$

$\triangle k_d$					$\dot{e}$			
		NB	NM	NS	ZO	PS	PM	PB
e	NB	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NM	NM	NS	ZO
	NS	ZO	NS	NM	NM	NS	NS	ZO
	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PB	NS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

When the velocity closed loop parameters are fixed, the position closed loop PID parameters have a certain range of adjustment. The fuzzy sets of $\triangle k_p$, $\triangle k_i$ and $\triangle k_d$ are defined as {NB, NM, NS, ZO, PB, PS, PM, PB}. The domain boundary is set as the corresponding parameter adjustment of each joint in the maximum and minimum inertia. Similarly, the fuzzy sets of the error e and error change rate $\dot{e}$ are also defined as {NB, NM, NS, ZO, PB, PS, PM, PB}, and their domains need to be determined according to actual situation, and the specific process is: firstly, take the PID parameters optimized at the start of the trajectory as fixed values, to control the trajectory tracking robot, and get the variation range of error and error change rate; then enlarge the range appropriately as the domain of enlarge the range appropriately in fuzzy position PID controller. The membership function of each fuzzy variable in the neighborhood of the domain boundary is the trapezoidal membership function, and the other segments are triangular membership functions.
This paper uses Matlab to establish the fuzzy PID control simulation model of robot joint controller, as shown in Figure 1, and then take use of the position PID parameter optimization method to get the initial PID parameters.

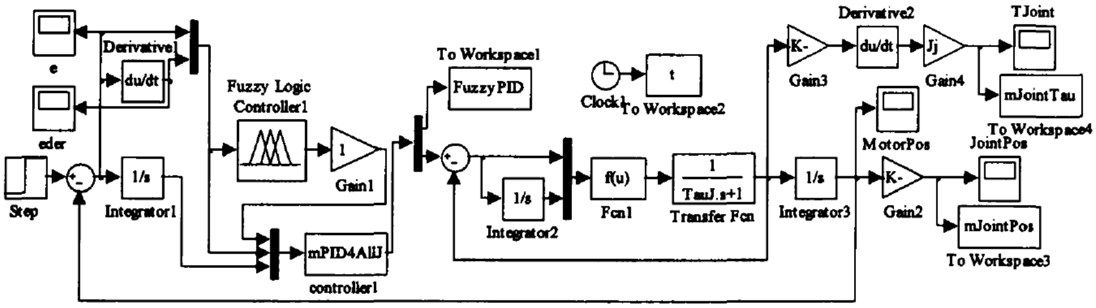


Figure 1: Fuzzy PID control simulation model of robot joint controller

In the process of joint movement, dynamically adjust PID parameters by fuzzy logic, to get the error curve of the step response of fuzzy PID control, and thus compare it with the Step response error curve of fixed PID parameter, as shown Figure 2.

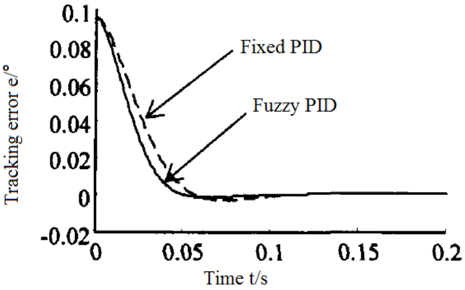
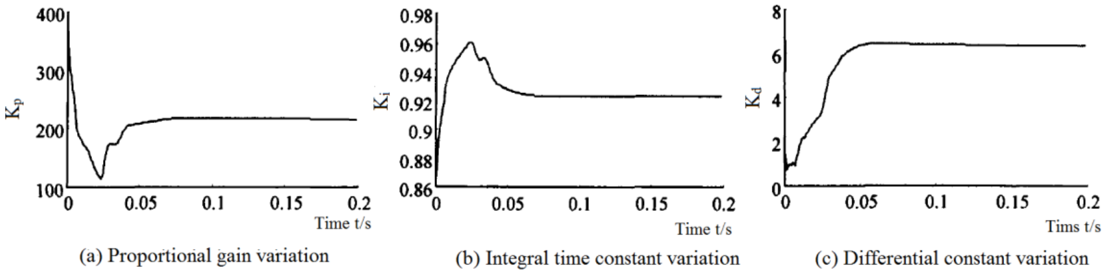


Figure 2: Step response comparison between fuzzy PID and fixed PID

We can see that, when adopting the fuzzy PID controller, both the overshoot and adjustment time of joint step response are smaller than that of fixed PID control. The adjustment time of the former is 0.045s, while the adjustment time of the latter is 0.091s. PID dynamic parameter adjustment process is shown in Figure 3.



(a) Proportional gain variation (b) Integral time constant variation (c) Differential constant variation

Figure 3: PID dynamic parameter adjustment process

3. Parameter optimization of joint controller for welding robot

Single joint control of robot is the basis of six joint control and trajectory tracking control (Reham et al., 2016). When using PID controller as robot joint controller, the initial control parameters of each joint should be adjusted, to make the robot's motion performance and trajectory tracking achieve the desired state and the effects of gravity and inertia coupling are neglected (Liu, 2014). First of all, we adjust the parameter of speed closed loop PI controller, and then adjust the parameter of position closed loop PID controller (Meza et al., 2012).

Using PI controller can make the speed closed loop remains stable. The speed closed loop transfer function is as below:

$$\mathrm{G}_{mv}(\mathrm{S}) = \frac{\Omega(S)}{V(S)} = \frac{K_{vp}K_I(T_{vi}S+1)}{T_J T_{vi}S^2+(K_{vp}K_I T_{vi})S+K_{vp}K_I} \tag{1}$$

The coefficients of the closed loop transfer function are positive real numbers, according to Routh criterion, we can know that the speed closed-loop is stable. Slow response of the closed-loop speed will cause the delay of the closed loop, in the absence of vibration of the robot joint, the setting value of K_{vp} is larger, the faster speed closed-loop response will be.

In order to make the speed closed-loop controller work in an ideal state, the control parameters K_{vp} and T_{vi} need to be optimized. The step response can effectively test the transient and steady state performance of the controller, therefore, the step response is used to analyze the controller performance under various PI control parameters. We adopted the sequential quadratic programming algorithm to establish the PI controller parameter optimization model, whose optimization target is as below:

$$\min(\mathrm{t}_s)$$

$$s.t. M_p \leq 1\%, e_{ss} \leq 0.1\%, \tau_{max} \leq \tau_{UP} \tag{2}$$

In the formula, t_s is adjustment time; M_p is maximum overshoot; e_{ss} is steady - state error; τ_{max} is maximum control torque.

In order to make the speed closed loop has a faster response performance, the maximum permissible overshoot is 1%; maximum permissible steady state error is 0.1%. Under the two circumstances of maximum inertia and minimum inertia pose, we optimized the parameters of the speed closed-loop controller, to find out the optimal PI parameters for each joint to reach a certain speed in the shortest time.

Taking the joints of the welding robot as the control object, and establish a single joint speed controller parameter optimization model with Matlab, as shown in Figure 4.

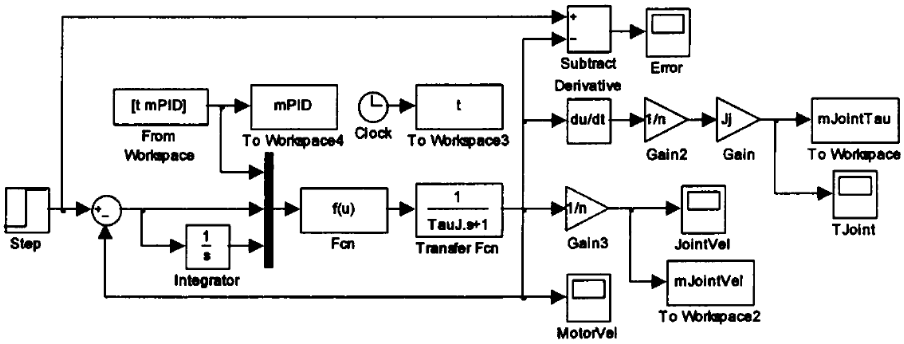


Figure 4: Parameter optimization model of single - joint speed controller

We use the sequential quadratic programming algorithm to optimize the parameters of the speed controller, and obtain the optimized PI controller parameters and step response performance of each joint of welding robot, as show in Table 4.

The PID controller can be used to make the single joint position closed loop with good robustness and control precision. For the position closed loop, speed closed loop is a second order system, so reasonable configuration of position PID parameters will help achieve arbitrary configuration of the position closed-loop system pole (Sood, 2011), so as to guarantee the stability of position closed loop. The transfer function of closed loop control of robot joint position control is as below:

$$\mathrm{G}_{mp}(\mathrm{S}) = \frac{\theta(S)}{R(S)} = \frac{b_0S^3+b_1S^2+b_2S+b_3}{a_0S^4+a_1S^3+a_2S^2+a_3S+a_4} \tag{3}$$

Still taking each joint of welding robot as the control object, establish the optimization model of single joint position controller parameters by Matlab, as shown in Figure 5.

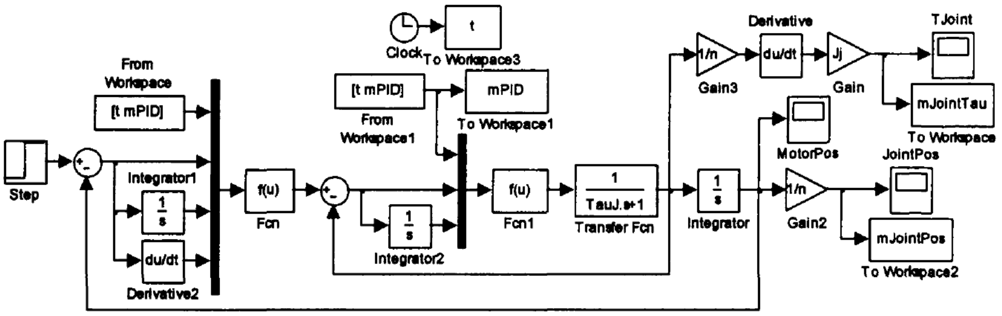


Figure 5: Optimization model of single joint position controller parameters

Table 4: Optimized PI controller parameters and step response performance of each joint

Joint	Inertia ($Kg{\cdot}m^2$)	Jump amplitude (°/s)	Overshoot (%)	Proportional gain	Adjustment time (s)	Steady-state error (°)
1	7.8238	1.00	0.0087	133.9	0.003	3.9e-6
		60.00	0.1873	2.231	0.129	2.1 e-5
		148.76	0.0429	0.090	0.364	-5.9 e-4
	58.6888	1.00	0.4906	92.39	0.020	4.3 e-6
		60.00	1.2437	1.54	0.751	3.1 e-8
		148.76	0.0068	0.62	2.712	-2.7 e-7
2	26.9309	1.00	0.4016	105.9	0.004	1.2 e-6
		60.00	2.4318	1.77	0.244	-2.7 e-4
		111.11	0.0064	0.95	0.435	1.8 e-4
	42.5914	1.00	0.6033	92.06	0.006	9.8 e-6
		60.00	0.0109	1.53	1.002	2.5 e-4
		111.11	0.0113	0.83	1.165	4.1 e-4
3	3.6440	1.00	0.0161	188.80	0.001	5.4 e-6
		60.00	0.0012	3.15	0.088	1.3 e-4
		148.76	0.3347	1.27	0.152	-1.2 e-4
	5.6005	1.00	0.2585	152.9	0.002	4.3 e-6
		60.00	0.0032	2.55	0.129	1.5 e-4
		148.76	0.0822	1.03	0.288	-8.5 e-5
4	0.9575	1.00	0.2909	87.8	0.0029	7.6 e-6
		60.00	0.0012	1.4627	0.1434	3.0 e-5
		150.00	0.0807	0.5851	0.2833	3.2 e-6
5	0.0180	1.00	0.0000	60	0.0008	-4.6 e-7
		60.00	0.0345	1.9457	0.0294	4.9 e-4
		225.00	0.9132	0.5185	0.0377	-2.6 e-4
6	0.0003	1.00	1.0000	124.8	0.0000	-2.6 e-7
		60.00	0.0000	86.4	0.0003	6.9 e-5
		225.00	0.0033	23.0376	0.0641	6.2 e-4

fffWe still use step response as an evaluation method for the single joint position controller, and the optimization objective is as below:

$$\min(t_s)$$

$$s.t.\, a_0 \geq 0.001, a_1 \geq 0.001, b_1 \geq 0.001, c_1 \geq 0.001, d_1 \geq 0.001$$

$$M_p \leq 1\%, e_{ss} \leq 0.1\%, \tau_{max} \leq \tau_{UP} \tag{4}$$

What is different from speed closed loop optimization index is that, the position closed loop requires the speed controller parameters and position PID controller parameters to be configured in order to ensure the stability of the system, and position closed loop requires small overshoot, to avoid the flutter phenomenon in the process of robot motion. Sequential quadratic programming algorithm was adopted for parameter optimization of position controller, and obtained the optimal parameters of each joint position controller, as shown in Table 5.

Table 5: Optimized parameters and step response performance of each joint

Joint	Jump amplitude (°/s)	Inertia (Kg·m^2)	Position loop K_{pp}	Position loop K_{pi}	Position loop K_{pd}	Speed loop $K_{vp}K_{I}$	Speed loop T_{vi}	Adjustment time (s)
1	7.924e-4	7.824	277.594	0.923	2.108	10.621	0.223	0.032
		58.689	277.110	0.577	5.920	7.339	0.076	0.045
2	5.917e-4	26.904	264.549	1.901	1.617	11.817	0.266	0.022
		42.591	224.890	1.910	1.787	11.972	0.297	0.026
3	7.924e-4	3.644	288.763	44.684	0.855	14.398	0.093	0.012
		5.601	305.885	64.799	1.325	11.007	0.066	0.017
4	7.990e-4	0.958	483.340	476.051	3.775	3.963	0.018	0.019
5	0.0012	0.018	383.741	417.428	0.811	4.428	0.114	0.016
6	0.0012	0.001	1882.600	1817.500	2.000	40.100	0.216	0.006

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