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유연한 단일링크 로봇 팔의 퍼지제어

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Fuzzy Logic Control of a Single-link Flexible Arm

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Abstract

The flexible arm has considerable structural flexibility. Because of its flexibility, the dynamic nodel is very complex and difficult to get. In this paper, fuzzy logic controller (FLC) of the single-link flexible arm is proposed, for FLC does not require any mathematical model of the plant. Noncolocated control is used and the choice of linguistic variables are examined. The simulation results are presented to show the possibility of FLC for flexible arm.

1 Introduction

Robot manipulators have been widely used both in dangerous circumstances and for industrial applications. They have been traditionally modelled as a chain of rigid links with colocated actuators and sensors, to ensure stable and reliable control. Moreover, the robot arms are generally made large and massive in order to remain its rigidity while carrying an assigned payload. Present generation manipulators are limited to a load-carrying capacity of typically 5-10% of their own weight by the need of structural rigidity.

For higher productivity, it is demanded faster speed. And for high operating speed, the manipulator should be made lightweight, but lighter members are more likely to deform elastically. If the controller could compensate for link flexure it would be possible to increase greatly the ratio of load to arm weight. Alternatively, for a given load, a large increase in speed would be possible. There are also other potential advantages arising from the use of flexible links[1].

- lower energy consumption
- smaller actuators required
- safer operation due to the reduced inertia
- compliant structure
- possible elimination of gearing
- less bulky design
- lowered mounting strength and regidity requiments

But, it is difficult to obtain its mathematical model and they have a limit of response time[1],[2],[3].

It has been known that if one attempt to control a flexible arm by applying control torque at one end that are based on a sensor at the other end, the problem of achieving stability is severe[5]. This noncolocated control has the nonminimum phase nature of the transfer function because of sensor actuator noncolocation[4][5].

Many investigators have looked into the usability of various flelxible arm control methods[2][5][6][7][8][9]. These methods have one or more problems as follows : sensitivity of the control to parameter variations and disturbances, requirement of a fairly exact model, necessity of load forecast, accurate estimation or measurement of the states of the system and complexity of the control algorithm. To overcome these problems, fuzzy logic controller (FLC) is proposed. Because of the ability to emualte the behavior of a human operator, an FLC can handle nonlinear system as well as it does not need mathematical model of the plant.

2 Design of the FLC

2.1 Control strategy.

Theoretically, any flexible system has an infinite number of elastic modes. Due to physical limitations, a finite number of sensors and actuators can be applied. But, the use of many measurements of sensors leads to heavy computational burden. Hence, the simple controller uses only directly measurable outputs. Figure 2 shows the geometry of the flexible arm. The directly measurable outputs are tip position error, its derivative, hub angle error and its derivative denoted by e_{tip}, $\dot{e}_{tip}$, e_{hub}, $\dot{e}_{hub}$, respectively. Using the PD controller, simulation is performed with e_{tip} and $\dot{e}_{tip}$. Figure 3 shows the vibrational phenomenon. And it is prone to diverge. The control results inserting e_{hub}, $\dot{e}_{hub}$ and both are depicted in figure 4, figure 5, figure 6, respectively. From these figures, the control strategy is evident. An additional damping is needed. In addition, the stable and reliable operation with respect to the payload variation must be appended.

2.2 Selection of linguistic variables

As seen in figure 4, e_{hub} causes the variation of output frequency. The factor of e_{hub} also has the effect of increasing rise time. Comparing figure 4 and figure 5, $\dot{e}_{hub}$ factor has a role of reducing the overshoot or introducing an additional damping. It is investegated rigorously that the factor of $\dot{e}_{hub}$ has a role of increasing system damping[13]. This fact will be illustrated in section 4.

In fuzzy control, as the number of linguistic variables increases, the overall number of rules increases tremendously. Thus, the number of linguistic variables is recomanded to be suitable and minial. From the previous discussion about the factors e_{hub} and $\dot{e}_{hub}$, e_{hub} is discarded because reducing the vibrational phenomenon is more important than increasing the rise time because of the flexture of the flexible arm. Hence in this paper, the following four linguistic variable are used.

- e_{tip} : Error of tip angular position
- $\dot{e}_{tip}$: Error ratio of tip angular position
- $\dot{e}_{hub}$: Error of hub angle
- τ : Control input torque

2.3 Rule Table

Fuzzy rules are presented in Table 1. In this table, "- -" stands for "don't care".

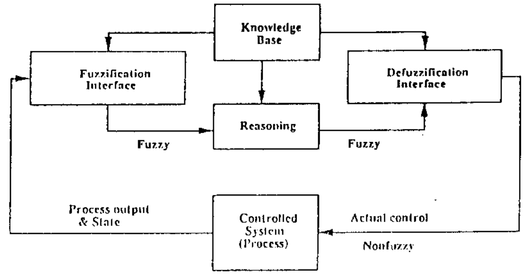

Figure 1. Basic Configuration of fuzzy logic controller

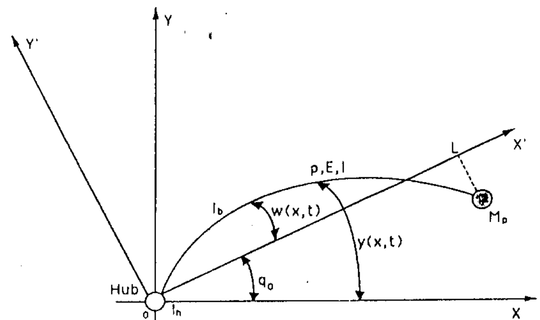

Figure 2. Geometry of the single-link flexible arm

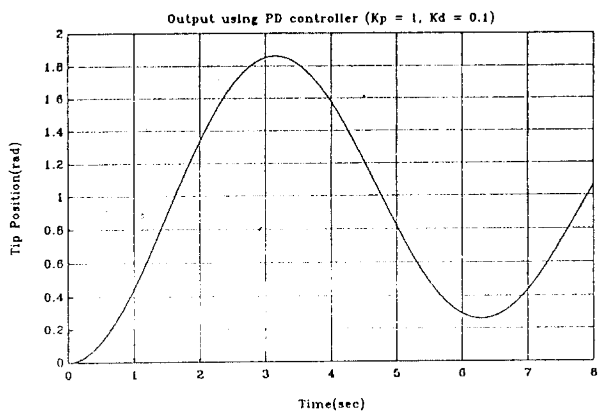

Figure 3. The result of PD Controller (using e_{tip} and $\dot{e}_{tip}$)

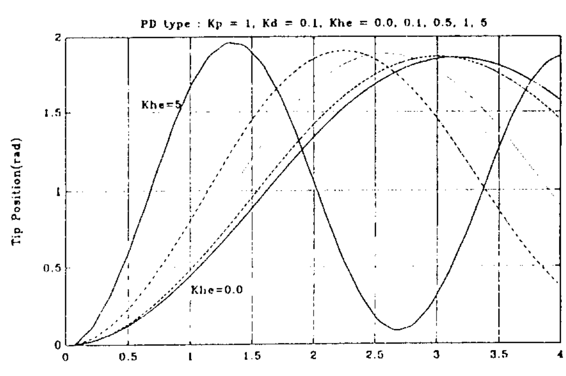

Figure 4. The result of PD Controller (using e_{tip}, $\dot{e}_{tip}$ and e_{hub})

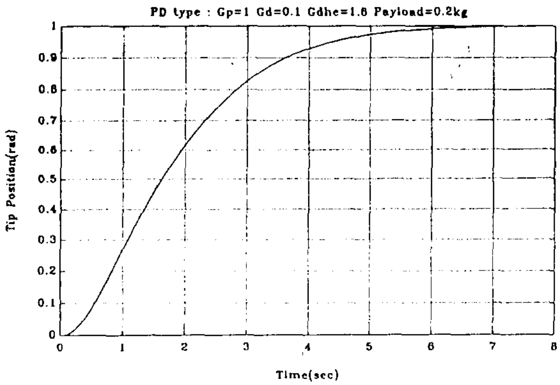

Figure 5. The result of PD Controller (using e_{tip}, $\dot{e}_{tip}$ and $\dot{e}_{hub}$)

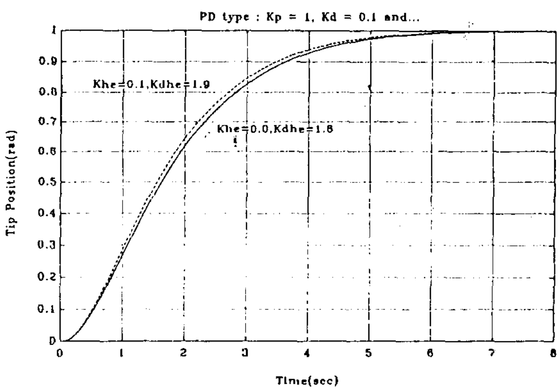

Figure 6. The result of PD Controller (using e_{tip}, $\dot{e}_{tip}$, e_{hub} and $\dot{e}_{hub}$)

Table 1. Fuzzy rules for single-link flexible arm

e_{tip}	$\dot{e}_{tip}$	$\dot{e}_{hub}$	τ	e_{tip}	$\dot{e}_{tip}$	$\dot{e}_{hub}$	τ	e_{tip}	$\dot{e}_{tip}$	$\dot{e}_{hub}$	τ
PB	--	--	PB	ZR	NS	NS	NS	NS	ZR	ZR	NS
PM	--	NM	NM	ZR	NS	ZR	NS	NS	ZR	PS	ZR
PM	--	NS	NS	ZR	NS	PS	ZR	NS	ZR	PM	PS
PS	NM	NM	ZR	ZR	ZR	NS	NS	NS	PS	ZR	PS
PS	NS	NS	NM	ZR	ZR	ZR	ZR	NS	PS	PS	PM
PS	NS	ZR	NS	ZR	ZR	PS	PS	NS	PM	PM	ZR
PS	ZR	NM	NS	ZR	PS	NS	ZR	NM	--	PS	PS
PS	ZR	NS	ZR	ZR	PS	ZR	NS	NM	--	PM	PM
PS	ZR	ZR	PS	ZR	PS	PS	PS	NB	--	--	NB

2.4 Fuzzification , Reasoning, Defuzzification and Membership functions

Fuzzy singleton is used as an fuzzifier operator, and the simplified method as an defuzzifier operator and reasoning. In literature, these operators have the advantages of simple and small computational load, and does not critically affect the performance of the overall system. From the similar reasons, isoceles shape is served as a membership function.

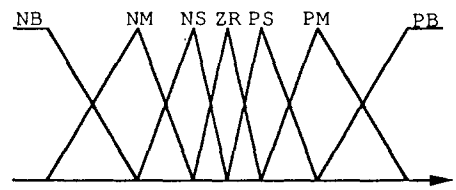

Figure 7. Membership functions for fuzzy logic controller

3 Simulation Results

Numerical parameters of simulation for the flexible one-link arm are given as follows:

Table 2: Parameters for the flexible manipulator

Parameters	Symbol	Numerical Value
Modulus of elasticity	E	$6.9 \times 10^{10}\ N/m^2$
Cross-sectional area moment of inertia	I	$8.31934 \times 10^{-11}\ m^4$
Length	L	$1.0\ m$
Linear density	ρ	$0.233172\ kg/m$
Inertia of the beam	I_b	$7.7724 \times 10^{-12}\ kgm^2$
Hub inertia	I_h	$5.176 \times 10^{-3}\ kgm^2$
Mass of gripper		$0.3\ kg$
Mass of payload		$[0,\ 0.4]\ kg$
Mass of total payload	$\hat{M}_p$	$[0.3,\ 0.7]\ kg$
Maximum total inertia	$I_{T_{max}}$	$0.7829\ kgm^2$
Minimum total inertia	$I_{T_{min}}$	$0.3829\ kgm^2$
Estimated total inertia	$\hat{I}_T$	$0.5475\ kgm^2$
Margin of I_T ($= \sqrt{I_{T_{max}}/I_{T_{min}}}$)	β	1.4299

In this paper, the model based on first three modes is used because the model based on at most three or four modes are suitable for simulation and other controller design methods. Control input torques are generated every 10msec.

Model parameters of first three modes with various payloads are provided in Table 3, 4 and 5 .

Simulation results are provided in figures 8 through 16. Figures 8 through 11 are for regulation and figure 12 through 16 for tracking. Figure 8 shows the nonminimum phase phenomenon(undershoot at the beginning) of flexible arm and the robustness for the unknown payloads. Note that the mass of the arm is about 0.33kg including the mass of gripper. But, the chattering phenomenon of control input does not disappear. Using more control rules for fine control near the ZR, this chatterring phenomenon tends to vanish[12]. Comparing figure 9 and 11, the shape of $\dot{e}_{hub}$ are in the opposite direction of control input. This seems to mean that $\dot{e}_{hub}$ prevents rapid variation of control input torque. As a result, $\dot{e}_{hub}$ has a role of increasing system damping and prediction. Except for the robustness, all the above arguments are also given to the tracking control result.

Table 3: Modal parameters for the first three modes with no payload

Mode i	Natural frequency ω_i (rad/sec)	$\phi_i'(0)$	$\phi_i(L)$	Damping ξ_i
0	0	1	1	0
1	42.0	5.478	-0.359	0.0015
2	108.2	5.929	0.217	0.002
3	261.0	2.387	-0.178	0.002

Table 4: Modal parameters for the first three modes with 0.2 kg payload

Mode i	Natural frequency ω_i (rad/sec)	$\phi_i'(0)$	$\phi_i(L)$	Damping ξ_i
0	0	1	1	0
1	41.1	6.731	-0.286	0.0015
2	107.4	7.367	0.167	0.002
3	259.7	2.965	-0.135	0.002

Table 5: Modal parameters for the first three modes with 0.4 kg payload

Mode i	Natural frequency ω_i (rad/sec)	$\phi_i'(0)$	$\phi_i(L)$	Damping ξ_i
0	0	1	1	0
1	40.6	7.788	-0.244	0.0015
2	107.1	8.565	0.140	0.002
3	259.1	3.446	-0.113	0.002

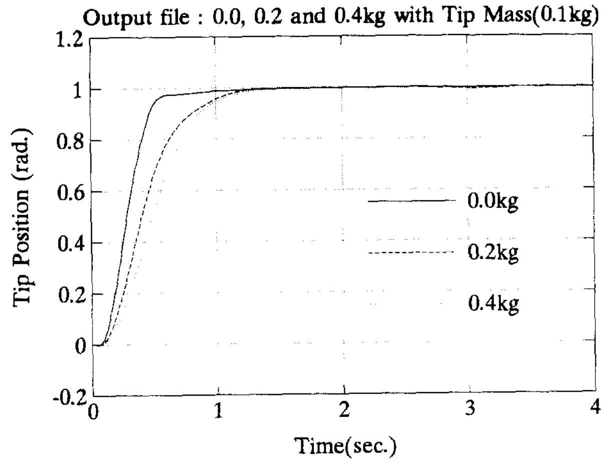

Figure 8. Tip position – Regulation

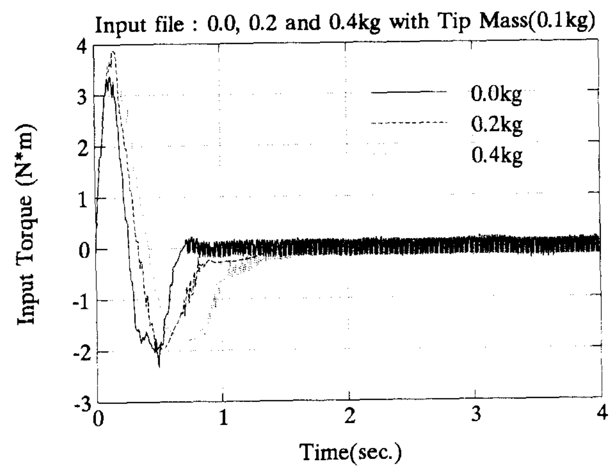

Figure 9. Control input torque – Regulation

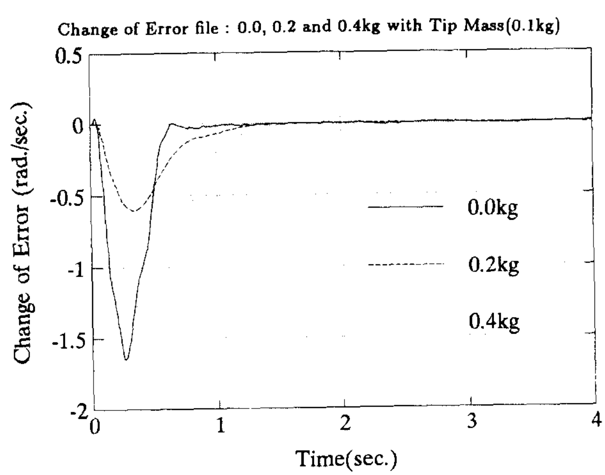

Figure 10. Error ratio of tip position – Regulation

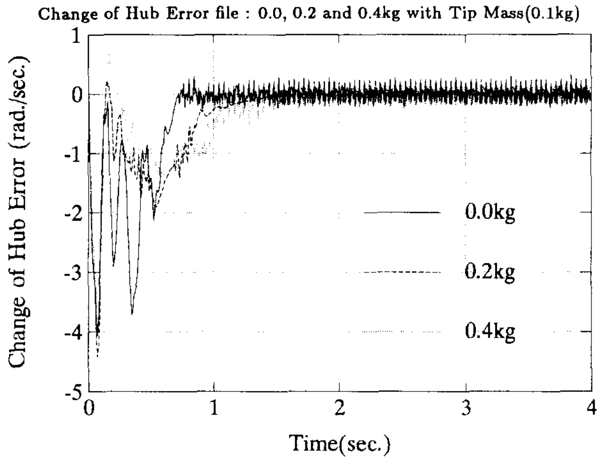

Figure 11. Error ratio of hub angle – Regulation

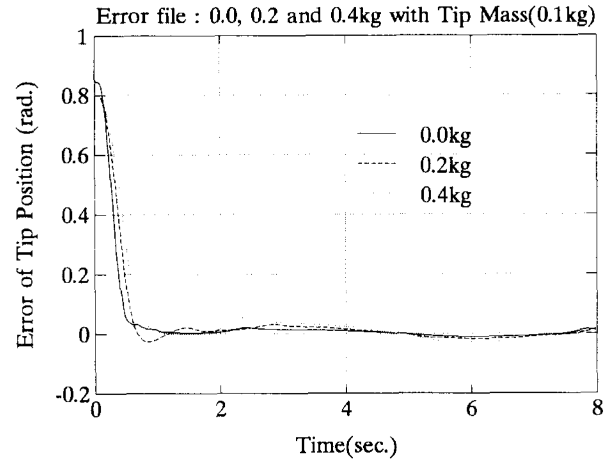

Figure 14. Error of tip position – Tracking

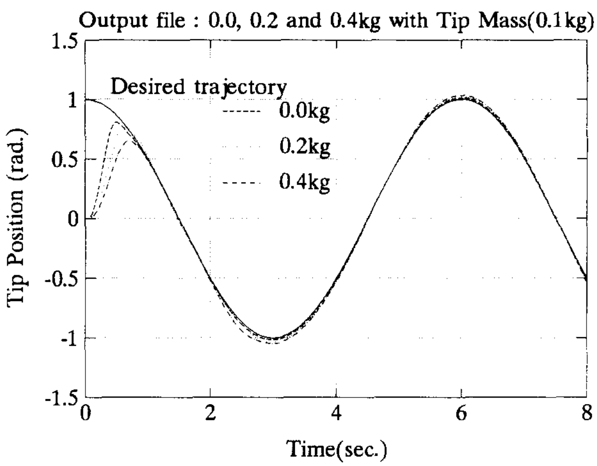

Figure 12. Tip position – Tracking

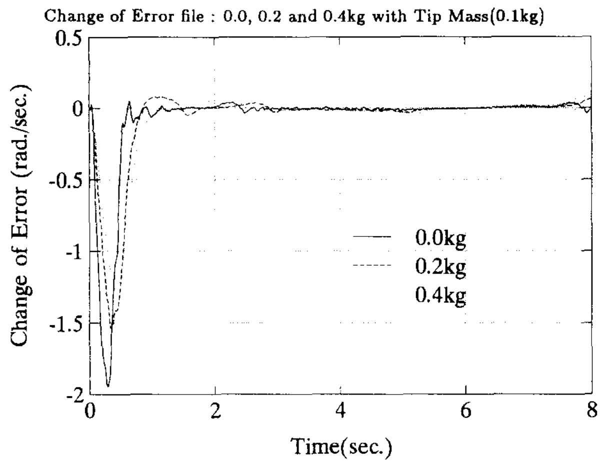

Figure 15. Error ratio of tip position – Tracking

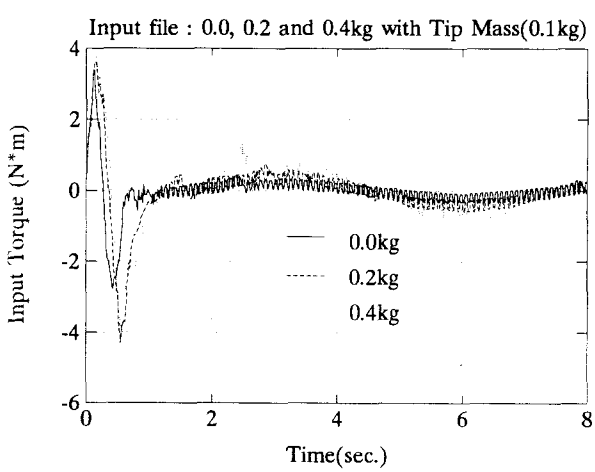

Figure 13. Control input – Tracking

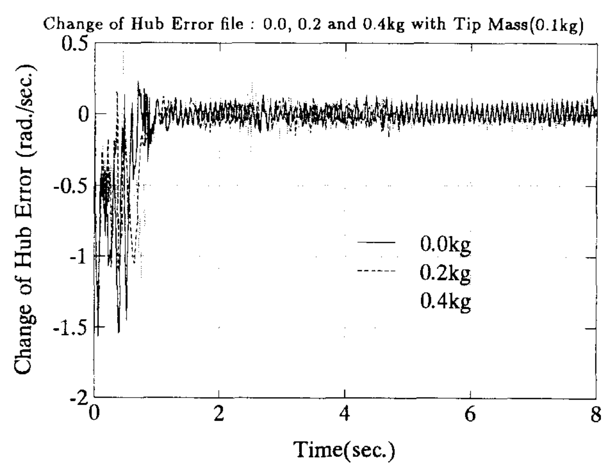

Figure 16. Error ratio of hub angle – Tracking

4 Conclusions and further studies

The proposed FLC of the single-link flexible arm works well for regulation and tracking, because of the effective use of noncolocated control method. The factor $\dot{e}_{hub}$ reveals the prediction ability and the increase of overall system damping. Using only 27 rules for the complex structure of the flexible link, the controller itself is very simple compared to the other control methods. But this simplicity leads to the chattering phenomenon of control input and the lack of robustness in the case of tracking.

The elimination of chattering, improvement of robustness and application to the multi-link flexible arm can be pointed out as further studies.

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