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Research Article

PROTOTYPING AND CONTROL OF A 2-DOF SERIAL FLEXIBLE-JOINT ROBOT BY USING FUZZY CONTROL SYSTEM

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ABSTRACT:
Challenging in control of a flexible-joint robot is residual vibration due to non-linearity and flexibility of a joint. Furthermore, in a 2-DOF serial flexible-joint robot, there is interaction of Link-1 control and Link-2 control. In this research, the prototype flexible-joint robot was designed and tested. The flexible-joints have springs and flexible couplings. Conventional PID controller, which is widely used in industry, can be used in the robot with limited performance. Two PID controllers separately control the Link-1 and Link-2 link position. From the experiment tests, there is high interaction between each link. Control action of the Link-2 link affects higher residual vibration of the Link-1. Fuzzy controller was designed as a parallel compensator to reduce the oscillation. The movements of the Link-2 link are used as the fuzzy inputs. The controller generates the control input of the Link-1 that cancels the residual vibration of the Link-1. The proposed controller showed superior performance of position tracking and less vibration compared to the PID controller.

Keywords: *Fuzzy control, Flexible- joint Robot, Residual vibration*

1. INTRODUCTION

According to their efficiency, repeatability, and reliability, industrial robots are widely used in industry. Joint flexibility can be found in the most industrial robots due to backlash in gears, transmission belts, and frictions. There are some benefits from the joint flexibility such as force reduction of the joints during transient operations and also less fatigue of the moving parts. Drawbacks of the joint flexibility are oscillations from the joint resonant frequencies and time-delay that limits the control performance. Due to the complex dynamics of the flexible system, there is a control challenge of the robot. Those complexities come from non-linearity, interaction between links and flexibility of the joints [1]. There is some conventional control technique such as input shaping technique which was originated by [2]. The technique can suppress residual vibration, occurring at the end of move of flexible system, by using the principle of destructive interference of the impulse responses. The input shaping technique proved to minimizing residual vibration of a linear system by using appropriately shaped forcing functions [3].

Because of the complexity of its model, the resonant frequencies of the two-link flexible-joint robot manipulator vary with the configuration of the manipulator. In order to reduce residual vibration at the end-effector. [4] introduced two shaped command profiles, based on ramped sinusoidal basis function and a basis function. The segmented

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versine basis function was proved to be the most effective compare to the unshaped bang-bang command profile. Yaovaja et al. [5] proposed a novel technique to handle the overshoot due to the time delay by combining the Smith predictor inside the loop to remove the effect of time-delay from the loop. Chatlatanagulchai et al. [6], the quantitative feedback controller was used as the inner-loop feedback controller to match the uncertain flexible plant to an exact reference model. The input shaper is placed before the inner-loop system and is designed from the exact reference model. A proportional-integral controller is used in the outer-loop system for reference signal tracking.

Fuzzy controllers were proved to be intelligent controllers for many applications; such as in an internal combustion engine, a Stewart platform, and a flexible joint manipulator. Fuzzy control system is different to the other intelligence systems; such as artificial neural network (ANNs) which does not provide understandable knowledge but only accumulates data in numerical weight values between neurons. Yaovaja and Chatlatanagulchai [7], experimental results of a knock control system applied to a DF-PCCI engine were presented. The fuzzy control system was designed and tested in a test cell with an engine dynamometer on the new European driving cycle (NEDC). In [8], fuzzy supervisor of PID controller for ball balancing on a Stewart platform (ball and plate system) was implemented. Small-size Stewart platform was built and used for demonstrating the application of the controller. [9] designed robust stable fuzzy control by using fuzzy modeling and feedback linearization to control a uncertain single-link flexible joint manipulator.

In this research, Fuzzy controller was implemented with a 2-DOF serial flexible-joint robot. The trajectory control results were improved in better efficiency and reliability comparing with a conventional PID controller.

Section 2 demonstrates a novel hardware design of the robot. Dynamic model of the developed robot is describes in the section 3. Control problem of the robot, which experimental results showed interaction between the links, is discussed in section 4. Proposed Controller, consists of fuzzy controller and PID control loops, is described in Section 5. Section 6 demonstrates experimental results compare between a well-tuned PID controller and the fuzzy controller. the Section 7 is conclusions section.

2. PROTOTYPING OF A 2-DOF SERIAL FLEXIBLE-JOINT ROBOT

In this work, we designed and built a small-size 2-DOF Serial flexible-joint robot (Fig. 1) to perform the controller tests. The material of the robot's structure is aluminum. The robot (Fig. 2) has a pneumatic gripper installed at the end-effector. The flexible-joint robot consists of two 12V DC geared motors and four encoders. The motors are 12V Maxon DC motors. The Encoder-1 and Encoder-2 model are HEDS 5540, 500 CPT and 600 CPT, respectively. The motor-1 is attached with encoder-1 and mounted with the stationary base. The motor is coupled with a Flexible-Joint-1 with a flexible coupling and bearing housing. Inside the flexible-joint, there are two springs engaged motor axis and output axis. The spring constant of Spring-1 (k_5) is 1,226.25 N/m.

The Encoder-3 measures the angular different between the flexible joint and Link-1 which is the extension and compression of the both springs. The output axis connects to Link-1 of the robot with a flexible coupling and bearing housing. To move the robot's link, the motor generates power through the flexible-joint and transfer to the link.

The Motor-2 is mounted in opposite direction of the end-effector in order to counterbalance the payload. The Motor-2 drives the Link-2 of the robot through the flexible-joint-2 which is similar to the first joint. But the output axis connects to the pulley which transmits energy through timing belt before moving the Link-2 and payload. The spring constant of Spring-2 (k_6) is 387.24 N/m.

Two DC motor drives are H-Bridge/Power Mosfet 80-160A. NI myRIO-1900 as a real-time controller was implemented. The controller sends two PWM commands and four digital commands to control the link's positions of the robot. The encoder's A-B-Z-signal as Quadrature phase signal are sent to the controller to indicate positions of the axes.

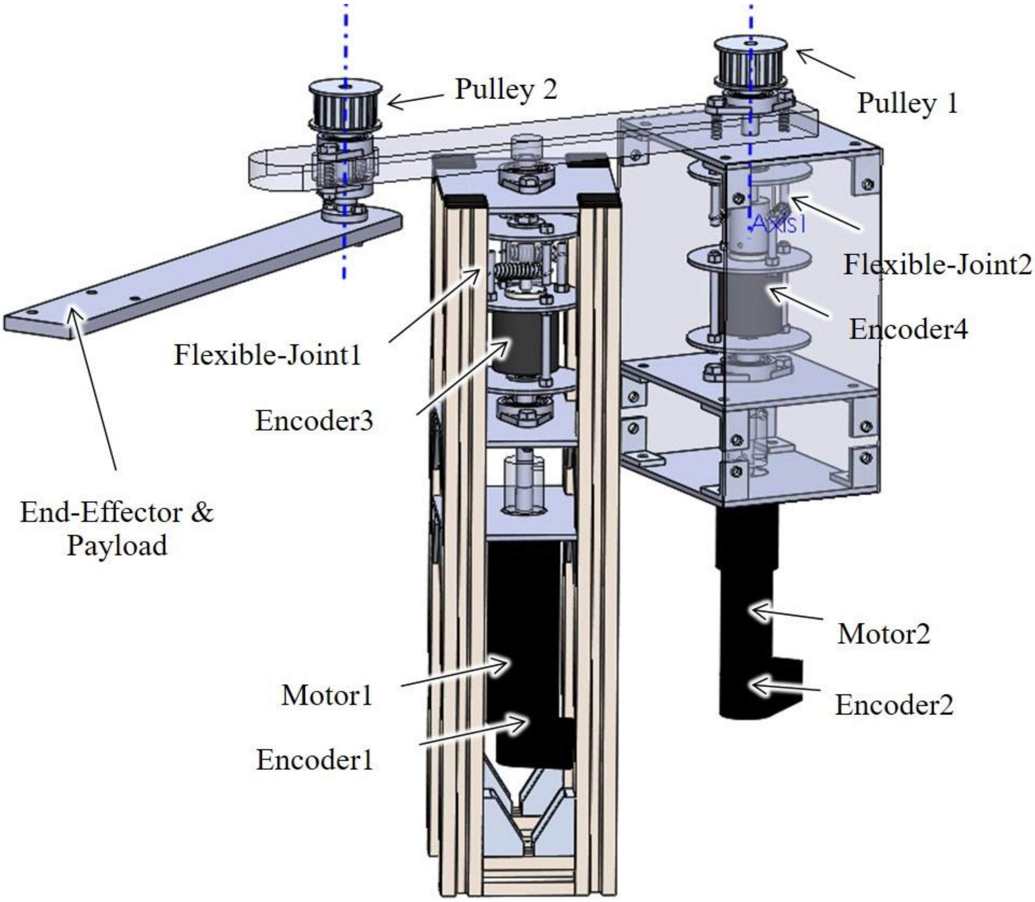

Fig. 1 3D model of a 2-DOF Serial Flexible-joint Robot

Fig. 2 a 2-DOF Serial Flexible-joint Robot

3. DYNAMICS MODEL OF SCARA FLEXIBLE-JOINT ROBOT

Consider the two-link flexible-joint robot as shown in the Fig. 3.

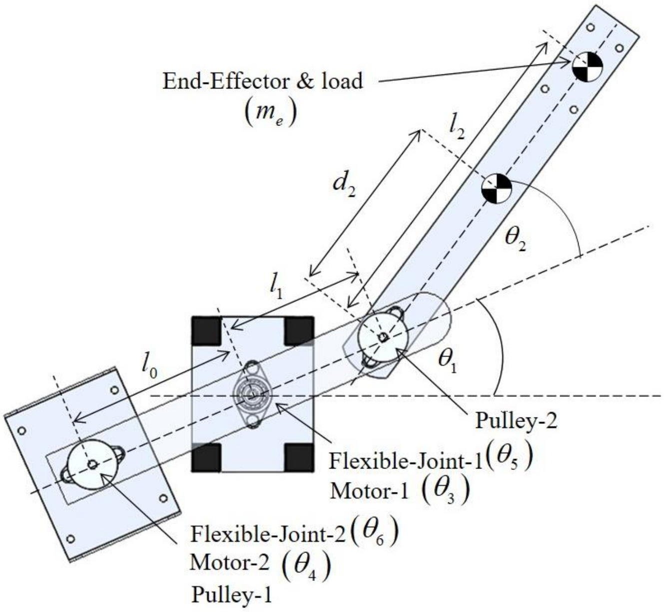

Fig. 3 Schematic diagram of the Flexible-joint Robot

θ_1 : Absolute Angular of Link-1

θ_2 : Angular between Link-2 and θ_1

θ_3 : Absolute Angular of motor-1

θ_4 : Angular between motor-2 and θ_1

θ_5 : Absolute Angular of flexible-joint-1

θ_6 : Angular between flexible-joint-2 and θ_1

$T = [T_1, T_2]^T$

T_1 : Torque of motor-1

T_2 : Torque of motor-2

l_1, l_2 are lengths of Link-1 and Link-2

Distance between COG of Link-1 and flexible-joint-1 assume to be zero. d_2 is the length between COG of Link-2 and flexible-joint-2.

Mass ($m_1$tom_6) and Moment of Inertia (J_1toJ_6) are properties of Link-1, Link-2, Motor-1, Motor-2, Flexible-Joint-1, and Flexible-Joint-2, respectively. m_p is mass of the pulley. c_1, c_2 are coefficient of friction in the bearing of the Flexible-Joint-1 and Flexible-Joint-2. c_3, c_4 are coefficient of friction in the bearing of the Motor-1 and Motor-2. c_5, c_6 are internal damping of the Spring-1 and Spring-2. k_5, k_6 are coefficient of the Spring-1 and Spring-2. r is gear ratio of motors. m_e and J_e is mass and Moment of inertia of end-effector and payload.

Total length of Link-1 and Link-2 is 300 mm. Servo Motor weight is 366.4g. Encoder weight is 218.2g. Link-1 and Link-2 mass are 371.7g and 170.7g. Gripper weight is 418g.

The kinetic energy is given by

$$\begin{aligned}K =& \left(\left(m_4 + m_p + m_6\right) l_0^2 + \left(m_2 + m_p + m_e\right) l_1^2\right) \dot{\theta}_1^2 / 2 \\ &+ J_1 \dot{\theta}_1^2 / 2 + \left(J_3 + J_5 / r^2\right) \dot{\theta}_3^2 / 2 \\ &+ J_4 \left(\dot{\theta}_1 + \dot{\theta}_4\right)^2 / 2 + J_6 \left(\dot{\theta}_4 / r + \dot{\theta}_1\right)^2 / 2 \\ &+ \left(m_2 d_2^2 + J_2 + m_e l_2^2 + J_e\right)\left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 / 2 \\ &+ l_1 \left(m_2 d_2 + m_e l_2\right) \dot{\theta}_1 \left(\dot{\theta}_1 + \dot{\theta}_2\right) \cos\theta_2\end{aligned} \tag{1}$$

The potential energy is given by

$$P = \left(k_5 \left(\theta_3 / r - \theta_1\right)^2\right) / 2 + \left(k_6 \left(\theta_4 / r - \theta_2\right)^2\right) / 2 \tag{2}$$

Dissipative is given by

$$\begin{aligned}D =& \left(c_1 \dot{\theta}_1^2 + c_2 \dot{\theta}_2^2 + c_3 \dot{\theta}_3^2 + c_4 \dot{\theta}_4^2\right) / 2 \\ &+ \left(c_5 \left(\dot{\theta}_3 / r - \dot{\theta}_1\right)^2 + c_6 \left(\dot{\theta}_4 / r - \dot{\theta}_2\right)^2\right) / 2\end{aligned} \tag{3}$$

Input is given by

$$\delta W = T_1 \delta\theta_3 + T_2 \delta\theta_4 \tag{4}$$

The Lagrange equations are

$$\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{\theta}_i}\right) - \frac{\partial K}{\partial \theta_i} + \frac{\partial P}{\partial \theta_i} + \frac{\partial D}{\partial \dot{\theta}_i} = Q_i \tag{5}$$

Let $q_1 = [\theta_1, \theta_2]^T, q_2 = [\theta_5, \theta_6]^T, T = [T_1, T_2]^T$

The Lagrange equations can be put in the form as in the work of [10]

The equation of motion can be written as

$$\begin{aligned}T_1 =& \left(J_3 + J_5 / r\right) \ddot{\theta}_3 - c_5 / r \dot{\theta}_1 \\ &+ \left(c_3 + c_5 / r^2\right) \dot{\theta}_3 - k_5 / r \theta_1 + k_5 / r^2 \theta_3 \\ T_2 =& \left(J_4 + J_6 / r\right) \ddot{\theta}_1 - c_6 / r \dot{\theta}_2 - k_6 / r \theta_2 + k_6 / r^2 \theta_4 \\ &+ \left(J_4 + J_6 / r^2\right) \ddot{\theta}_4 + \left(c_4 + c_6 / r^2\right) \dot{\theta}_4\end{aligned} \tag{6}$$

4. CONTROL PROBLEM

This section describes the system response of the 2-DOF Serial Flexible-joint Robot. The well-tuned PI controller was applied to the flexible-joint robot. Ziegler-Nichols Tuning Parameters of PI controller was selected by using from the ultimate Gain (K_u, T_u). The controller Gain is $K_p = 0.01 = 0.45K_u$ and $T_i = 0.02 = 0.85T_u$. In Fig. 4A, only the Link-1 position, blue solid line, is controlled to track the square-wave set-point; red dotted line. The black thick line shows the position of the Link-2 with no control. The Link-1 control produced the vibration of the Link-2. In Fig. 4B, there is a similar test but control the Link-2 position. The set-point is red dotted line. The Link-2 position is blue solid line. Without the Link-1 control, the Link-1 has a large oscillation causes by the movements of the Link-2.

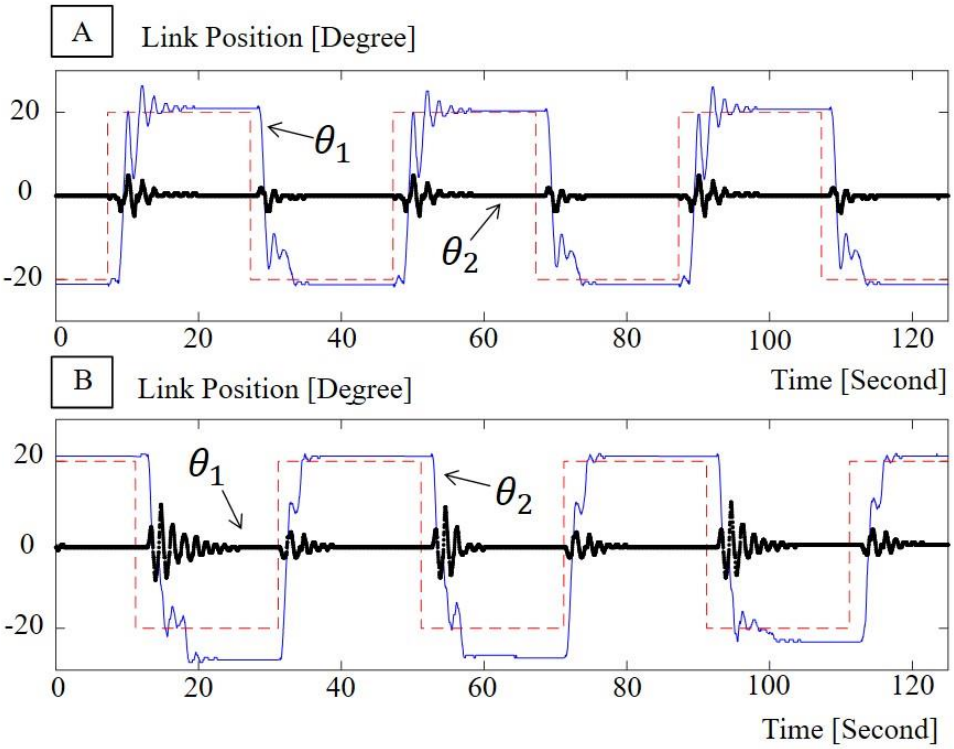

Fig. 4 Residual vibration from the interaction

In a practical case, the serial robot arm moves from point A to point B and the both links must simultaneously be operated in the same direction. This experiment is one of the practical cases that each link simultaneously moves from - 20 degrees to 20 degrees. The proposed controller consists of the well-tuned PID controller for each link. This is assumed that the main controllers handle the vibration of the links. However, the vibration effect from another link will be compensated by the proposed fuzzy controller. From the results in Fig. 4, it can be seen that the amplitude of the vibration of the Link-1 is larger than the Link-2. And the phase of the vibration of the uncontrolled link is the similar to the residual vibration of the controlled link. In order to enhance the position accuracy of the end-effector, the vibration of the Link-1 should be removed by adding control to the Link-1. The speed and acceleration of the Link-2, as a dynamic behavior of the link, were chosen as the fuzzy input. The fuzzy controller was designed as a mapping from the input to generate proper motor control input.

5. FUZZY CONTROL DESIGN

Feedback control system is discussed in this section. In the flexible-joint robot control problem, the Link-1 position control and Link-2 position control can be decentralized and are separated into two control loops; shown in Fig. 5.

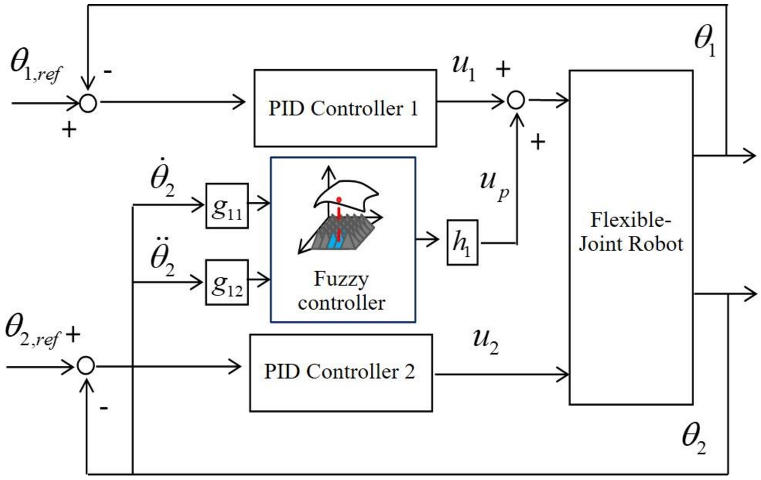

Fig. 5 PID controller with fuzzy controller

From mass-spring-damper system dynamics, residual vibration of each link depends on its natural frequency and damping ratio. In order to cancel the residual vibration, the compensated response should have 180 degree of phase lag of the residual vibration.

In this research, the natural frequency of the system is not measured but the 1st order low-pass filter with 0.8 Hz of cut-off frequency is used to generate the similar time-delay of the system. The filter of $\dot{\theta}_2$ and $\ddot{\theta}_2$ also reduces noise from sensors and numerical computational.

The inputs of the fuzzy controller are velocity and acceleration of Link-2. The input linguistic numeric values range from "-2" to "2", the output linguistic numeric values range from "-3" to "3" as shown in Fig. 6. Input linguistic variables of the controller are "Velocity" and "Acceleration". Output linguistic variable of the controller is "Output". The premise conjunction is "minimum". The defuzzification method is "center of area". Input scaling gain $g_{11} = 0.01$, $g_{12} = 0.001$ and output scaling gain $h_2 = 0.005$.

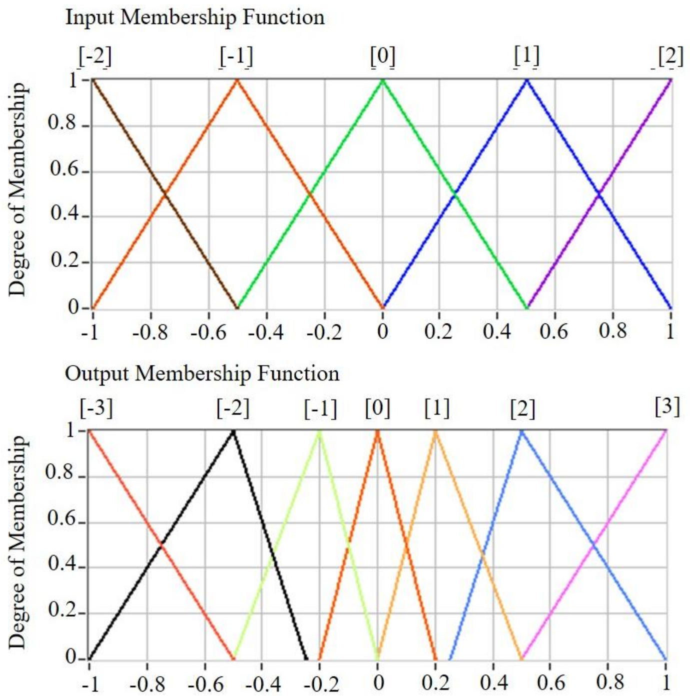

Fig. 6 Fuzzy Membership functions

Table 1 shows the fuzzy rule-based of the fuzzy controllers. Fig. 7 shows their corresponding surfaces; where the outputs of the controller are plotted against their two inputs. The output of the controller is multiplied by 100 to PWM commands.

Table 1: Fuzzy Rules

"u_p"		"Position"				
		-2	**-1**	**0**	**1**	**2**
"Velocity"	-2	-3	-3	-2	-1	0
	-1	-3	-2	-1	0	1
	0	-2	-1	0	1	2
	1	-1	0	1	2	3
	1	0	1	2	3	3

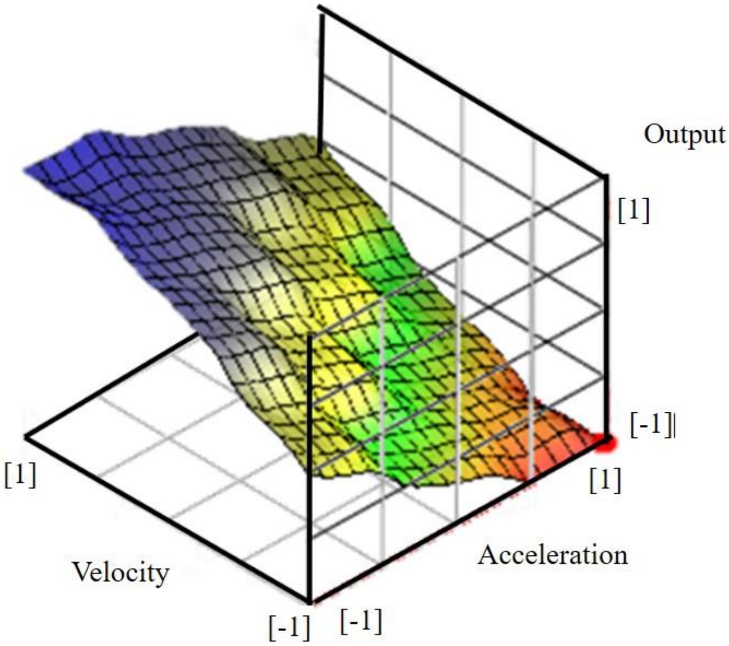

Fig. 7 Control surface of the fuzzy controller

The friction compensation was introduced to reduce the dead zone nonlinearity during -5 to 5 % of PWM for both motors.

6. EXPERIMENTAL RESULTS

In the first case, experiments by using the well-tuned PID controller showed in Fig 8. The robot links were simultaneously controlled with square wave reference signals. The Fig. 8A shows the position of the Link-1 link in blue solid line and the reference in red dotted line. In Fig. 8B, the position of the Link-2 link and the reference are plotted in blue solid line and red dotted line, respectively. Fig. 8C showed the control input of the DC motors. The blue solid line is control input of the Motor-1. The red dotted line is the control input of the Motor-2. The Link-1 position has large residual vibration and cause high settling time which takes 5.76 seconds. The steady-state error of the Link-2 is large due to friction of the system which is not able to handle with the conventional PID controller.

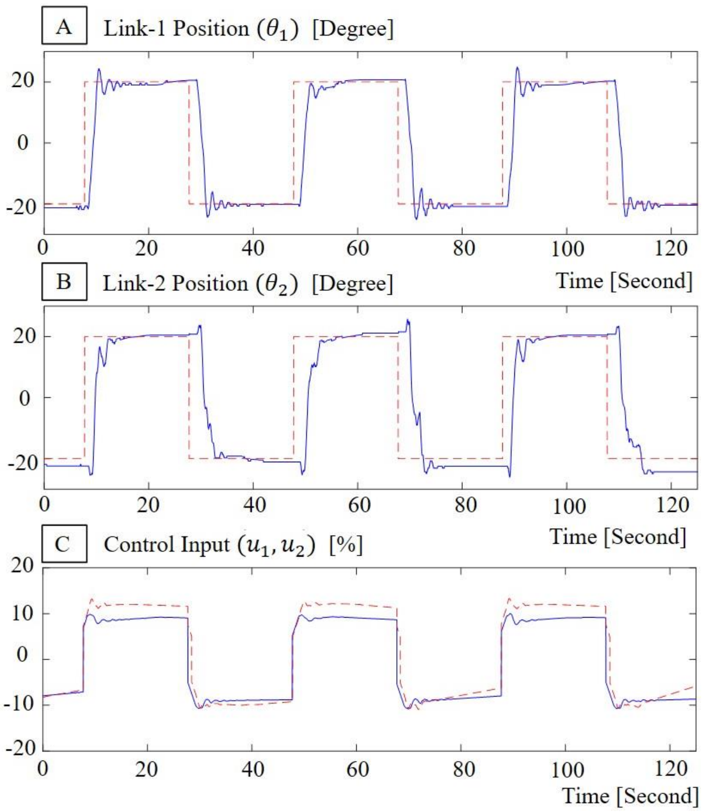

Fig. 8 Control performance without fuzzy controller

In the proposed controller case, similar test was done and showed in the Fig. 9 and Fig. 10. Position of the Link-1 in blue solid line and the reference in red dotted line are shown in Fig 9A. In Fig. 9B, the position of the Link-2 and the reference are plotted in blue solid line and red dotted line, respectively. Control input of the Link-1 in blue solid line and the control input of the Link-2 in red dotted line are shown in Fig. 10A. Fuzzy control input shows in Fig. 10B.

Fig. 9A shows the control input of the DC motors. The blue solid line is control input of the motor-1. The red dotted line is the control input of the motor-2. Fig. 9B shows the control input of the fuzzy controller which generates counter response. The settling time of the Link-1 is decrease to 4.18 seconds. The Link-2 control performance is similar to the previous test and is not focused in this research.

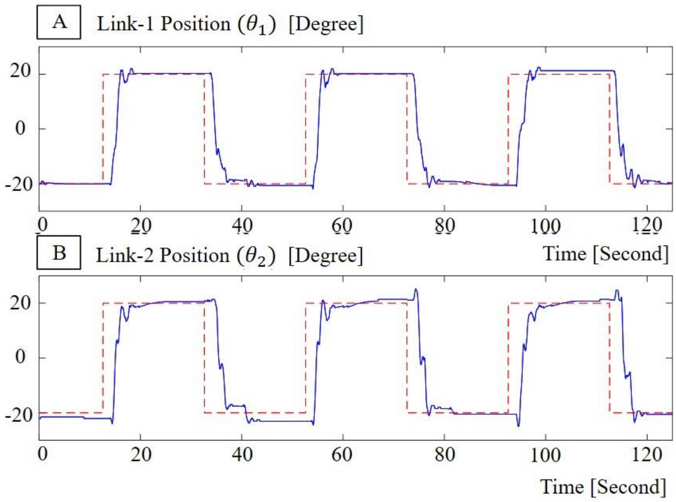

Fig. 9 Control performance with fuzzy controller

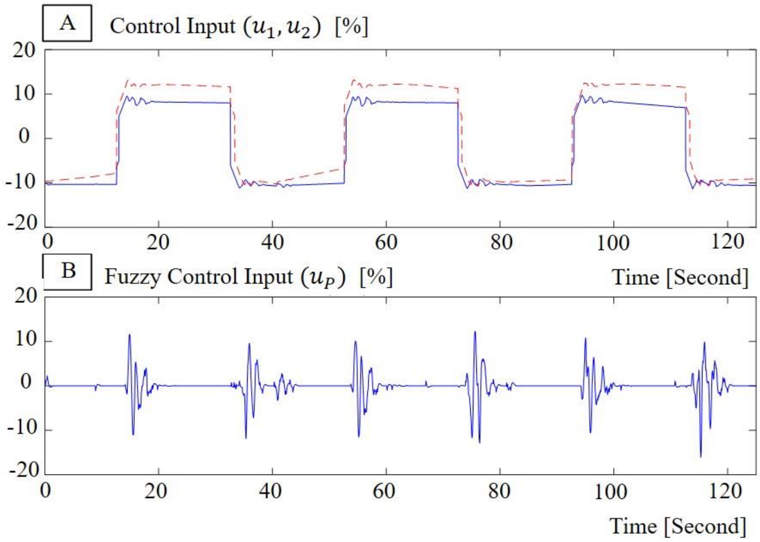

Fig. 10 Control input of the PID and the fuzzy controller

From the first step response, PID controller with fuzzy controller provides better results. The 5% settling time reduces from 5.76 to 4.18 seconds (27.47%). The overshoot reduces from 21.64 to 10.16% (53.04%).

7. CONCLUSION

The prototype flexible-joint robot was designed and tested. The mathematic model of the robot was described. The conventional PID controller has limited control performance. In this control problem, there was found that the action of the Link-2 generated high residual vibration of the Link-1. The fuzzy controller was design to cancel the residual vibration of the Link-1. The proposed controller reduced both overshoot and settling time compare to the PID controller. The future work is to integrate conventional vibration suppression methods using natural frequency, like input shaping or command shaping, and intelligence control system.

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