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Fuzzy Logic Control for Flexible Joint Manipulator: An Experimental Implementation

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Abstract—This study presents an intelligent control algorithm for a flexible robotic arm. Fuzzy control is used to control the motion of the arm to maintain the arm tip at the desired position while reducing vibration and increasing the system speed of response. The Fuzzy controller (FC) is based on adding the tip angular position to the arm deflection angle and using their sum as a feedback signal to the control algorithm. This reduces the complexity of the FC in terms of the input variables, number of membership functions, fuzzy rules, and control structure. Also, the design of the fuzzy controller is model-free and uses only our knowledge about the system. To show the efficacy of the FC, the control algorithm is implemented on the flexible joint manipulator (FJM) developed by Quanser. The results show that the proposed control method is effective in terms of response time, overshoot, and vibration amplitude.

Keywords—Fuzzy logic control, model-free control, flexible joint manipulators, nonlinear control.

I. INTRODUCTION

FLEXIBLE joint manipulators are the backbone of industrial robots. The applications of these manipulators are enormous and have ranged from automotive industries [1], [2] to medical fields [3], [4] to space [5], [6] with the requirement of high precision and fast speed of response. Although they are lighter and cheaper than rigid joint manipulators, their applications come with a few challenges such as structural optimization, system design, and oscillation suppression of the flexible arm [7]. From a control system design perspective, arm vibration is the most prominent problem as it degrades positional accuracy and causes nonlinear dynamics of the linkage [8], [9]. As a result, controlling the FJM's tip angular position while suppressing the vibration of the flexible arm has been receiving much attention.

Many model-based control strategies have been developed and implemented on flexible joint manipulators. These strategies encompass however are not restricted to the classical PID control [10], linear quadratic regulator (LQR) [11], H_∞ control [12], input shaping [13], time delay control [14], and state feedback control [15].

Because of the increased complexity of FJMs and their elasticity, classical model-based control algorithms are complex and challenging to synthesize [16]. To this end, we present a model-free control approach based on the Mamdani-type fuzzy logic control. Fuzzy controllers are frequently semi-heuristic and thus nonlinear, do not require prior development of an analytic system model, and are effective methods of converting an expert's knowledge of the plant into an actual control [17], [18]. Also, the synthesis of a fuzzy control law does not rely entirely on the plant's mathematical model [19], [20]. Thus, FCs are ideal for controlling complex and highly uncertain systems such as the system at hand. Even if a model-based controller exists, fuzzy controllers may be more robust and easier to modify [21].

The literature records several works about the application of Mamdani FCs on rotary flexible joint robotic arms. For instance, a composite control that is based on the combined computed torque control using a rigid robot model and fuzzy control was applied to the FJM to achieve global trajectory tracking and active damping [19]. Computer simulations demonstrated that the controlled system is robust against payload or joint stiffness variation. Another composite controller was introduced in [16]. Therein, a collocated proportional derivative (PD) was combined with a fuzzy logic control for the tip angular position control of an FJM. The input to the PD controller is the error between the tip's actual and desired position; while the fuzzy logic control uses the deflection angle of the manipulator as its input. The results showed a satisfying performance in terms of input tracking, vibration control, settling time, and overshoot. A fuzzy proportional integral derivative (PID) controller for a flexible-joint robot arm with uncertainties from a time-varying load was developed in [22]. Experimental results revealed that the control algorithm is robust with remarkable tracking performance. To control the tip position of the manipulator, the authors in [23] developed three controllers: a PD-FLC, a fuzzy model reference controller, and an adaptive neuro-fuzzy controller (NFC) for situations where there is payload variability. The NFC was used to online tune the input and output scale parameters of the fuzzy controller. Numerical simulations demonstrated that the NFC performs better than model-based control schemes. Another NFC for end-point vibration damping of a flexible single-joint manipulator mounted on a two-degree-of-freedom platform was presented in [24]. The angular position of the hub and the endpoint deflection of the flexible beam were used as inputs to the FLC. The neural network was used to predict the arm deflection using a set of strain gauge sensors and a linear-variable differential transformer placed at the tip. Experimental results showed that the FLC is effective in suppressing the end-point oscillation of the flexible beam. A control algorithm that

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is based on the fuzzy Lyapunov synthesis and assumes no prior knowledge about the system dynamics, except for some structural properties of the model, was proposed in [25] for tip position tracking. The implementation of the FLC on an FJM showed that the control algorithm is effective regardless of system uncertainties. Similarly, a robust fuzzy control approach for manipulators using direct methods of Lyapunov functions was introduced in [26]. Another novel FLC for trajectory tracking and vibration control of a flexible joint manipulator was presented in [27]. To reduce the number of rules and control structure complexity, the rule base of the FLC was divided into two sections such that the first section accepts the error of tip angular position and the error of deflection angle as its inputs, while the second section uses the first-time derivatives of mentioned errors as its inputs. The control algorithm was implemented on the Quanser flexible joint and the results showed that the FLC is quite effective. In another study, an FLC is developed such that the error between the desired and actual tip position is the input and the outputs are the setup parameters of a classical PID controller [7]. Experimental results showed that the control algorithm could effectively reduce the vibrations and is robust against parametric model variations. In [28], a cascade fuzzy logic controller consisting of three subsystems called FLC-I, FLC-II, and FLC-III was presented to reduce link vibrations and enhance trajectory tracking performance. The FLC-I's inputs are the motor angle error and its first-time derivative, and the output is a virtual signal called θ. The FLC-II accepts the deflection angle error and its time derivative as inputs, and its output is a virtual signal called α. The outputs of the FLC-I and FLC-II are used as inputs to the FLC-III, which computes the required motor voltage to drive the arm to the desired position. Experimental results showed that the control system is robust against parametric variations and internal and external disturbances.

It is evident that some of these studies did not include the deflection angle of the flexible link in the control decision [7], [22], used the deflection angle as an input to the FLC but had to simplify its complexity by dividing the rule base into two sections [27], used information about this angle for the deflection angle's prediction [24], or utilized it to build a complex and cascade FLC [28]. Since the control objective is to bring the arm's position to its desired value and reduce its vibration to zero, we propose a simple FC that uses the error between the sum of the hub's angular position and the arm's deflection and the arm's desired angular position as its input. As a matter of fact, the sum of the hub's angular position and the arm's deflection represent the arm tip position as it will be delineated in the next section. This justifies the use of their sum as an input to the FC. A similar idea was introduced in [5] such that the sum of the hub's and arm's angular rate is used as an input to a strictly positive real parallel feed-forward controller to track a desired angular velocity of the flexible arm. However, such an approach has not been used for position control and tested using an FC.

This paper is organized as follows. Section II introduces the flexible joint manipulator used for control implementation. Section III details the design of the FC. Discussion of the experimentation results is presented in Section IV. Finally, Section V presents our concluding remarks.

II. FLEXIBLE JOINT MANIPULATOR

A flexible joint is formed when the robot arm's anchor bends at its pivot point. As an experimental setup, the arm's flexibility can be achieved by connecting the arm to springs [15]. Fig. 1 shows a simulation benchmark with a flexible joint module developed by Quanser. The module was used as a physical analog for many applications such as flexible surgical robots [4], and spacecraft carrying a payload [5], [6]. As shown in the figure, the module includes a rotational flexible base (1), thumbscrews (2), rotational flexible arm (3), arm encoder (4096 counts/rev) to measure the deflection of the flexible linkage, α as shown in Fig. 2, (4), base anchor points (5), arm anchor points (6), springs (7), adjustable load (8), encoder connector (9), rotational flexible pivot (10), adjustable load anchor points (11), and direct-current (DC) servomotor motor (12). The servomotor module is equipped with an incremental encoder (4096 counts/rev) to measure the angular position of the flexible base, θ indicated by the schematic diagram in Fig. 2. The variable $\gamma = \theta + \alpha$ denotes the tip position of the arm that is to be tracked. The DC motor voltage is between -15 and 15 V and the maximum input current is 1 A. Taking these constraints into consideration, the controller scheme was designed in Simulink® and embedded in the USB-2 Quanser control board.

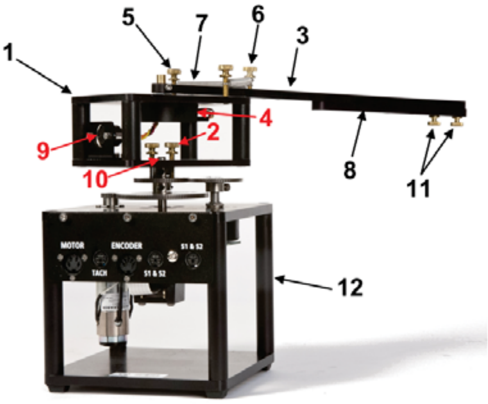


Fig. 1 Rotary Flexible Joint-Quanser Manual

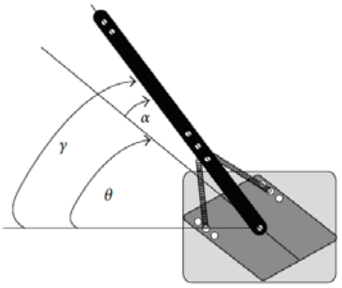


Fig. 2 Schematic representation of the rotational flexible base [29]

III. FUZZY CONTROL SYSTEM

As shown in Fig. 3, the FLC includes two inputs: the error, $e = \theta + \alpha - \theta_d$, and its rate of change, de. The variable θ_d is the reference tip position of the flexible arm since the desired α_d is zero. The output of the FLC is the DC motor voltage, v_o. The variables k_p, k_d, and k_o are the normalizing factors of e , de, and v_o, respectively. Following the work proposed in [30], seven Gaussian membership functions in the names of "NB," "NM,", "NS,", "Z," "PS," "PM," and "PB" are selected for each input and output variable as shown in Figs. 4, 5, and 6. Fig. 7 shows the fuzzy rule base using these linguistic variables. Based on these rules, the relationship between the FLC inputs and output is depicted in Fig. 8, which portrays a relatively smooth control surface.

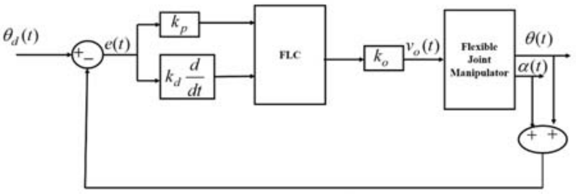


Fig. 3 Block diagram of fuzzy logic control for flexible joint robot

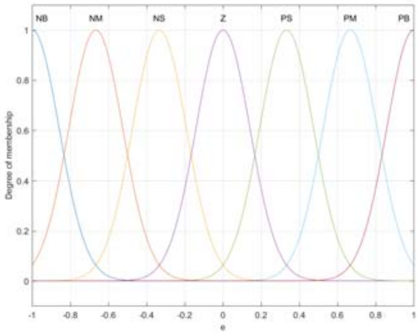


Fig. 4 Membership functions of the error

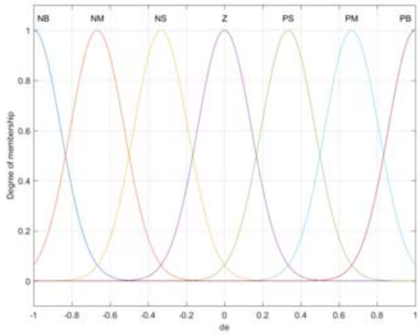


Fig. 5 Membership functions of the change of error

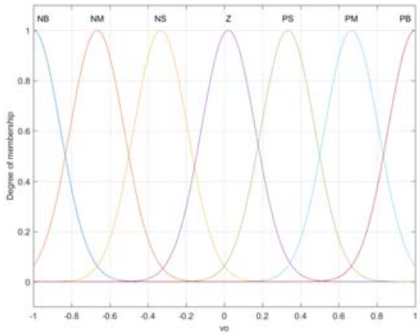
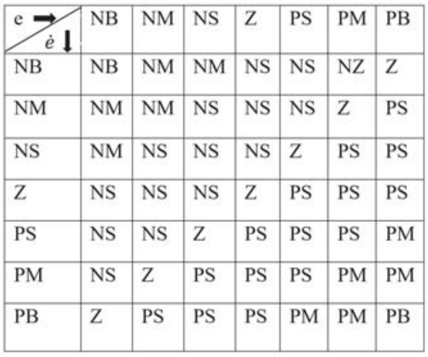


Fig. 6 Membership functions of the voltage



e ➡ / ė ⬇	NB	NM	NS	Z	PS	PM	PB
NB	NB	NM	NM	NS	NS	NZ	Z
NM	NM	NM	NS	NS	NS	Z	PS
NS	NM	NS	NS	NS	Z	PS	PS
Z	NS	NS	NS	Z	PS	PS	PS
PS	NS	NS	Z	PS	PS	PS	PM
PM	NS	Z	PS	PS	PS	PM	PM
PB	Z	PS	PS	PS	PM	PM	PB

Fig. 7 Rule base of the fuzzy controller

TABLE I
FUZZY SETTINGS

Method	Function	Method	Function
And	min	Aggregation	max
Implication	min	Defuzzification	centroid

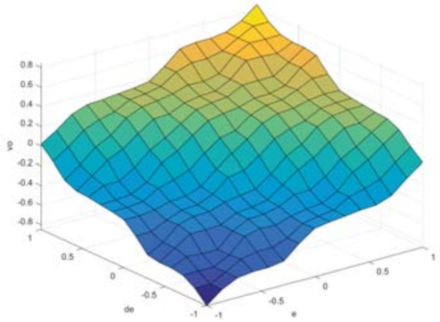


Fig. 8 Control surface

The proposed FC is simple, reduces the number of inputs to the fuzzy system from four to two, and brings down the number of rules from 98 to 49 if we assume seven membership functions are used. In this paper, the FLC is implemented in the MATLAB®Fuzzy Logic Toolbox. Membership functions and rule bases are created in the Fuzzy Inference System Editor. The settings of FLC are shown in Table I. Then, the FLC is applied directly to the flexible joint manipulator of the Quanser experimental set to show the efficacy of the proposed control algorithm in trajectory tracking reference position signals and reducing vibration sourced from the arm flexibility.

IV. RESULTS AND DISCUSSION

Fig. 9 shows the controlled system response to the desired position (θ_d) molded by a step input with $50°$ amplitude. As it is evident by this figure, the flexible joint manipulator tracks the desired trajectory well with a small overshoot ($M_p(\%) = 0.195\%$), fast response time (rise time (t_r)= 0.396 s, and the 2% settling time (t_s)= 0.556 s) as shown in Table II. That is, the response of the flexible joint manipulator under the FLC needs only 0.396 s to rise from 10% to 90% of its steady-state value and takes 0.55 s to reach with $\pm 2\%$ of its desired value. Fig. 10 shows the arm vibration represented by the deflection angle (α). It is worth noting that the deflection angle amplitude is small and reduced significantly by the control algorithm. Compared with the PD fuzzy logic with the non-collocated PID control developed in [31], we notice that our proposed control introduces a smaller overshoot and less deflection. On the other side, the settling time and rise time of the controlled system under the proposed control are bigger than those reported in [31]. In control system design, the objective of minimizing the overshoot conflicts with that of the settling time and rise time. This explains why less overshoot and thus less oscillations are associated with larger rise time and settling time. This also indicates that our proposed control method works well and tuning the control parameters in multi-objective settings will give better results.

The summation of two signals (γ), is shown in Fig. 11. It shows the behavior of the flexible joint concerning the fixed point of the system. As the figure demonstrates, there is not any unacceptable overshoot and undershoot in the response. So, the proposed FLC controller performs quite well. The profile of the motor voltage over time is shown in Fig. 12. The voltage stays within its saturation limits, -15 and 15 V.

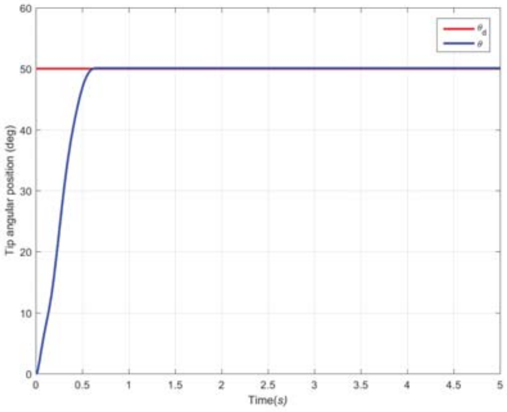


Fig. 9 Tip angular position of the flexible joint manipulator

TABLE II
CLOSED-LOOP SYSTEM PERFORMANCE INDEXES

	Our Work	PD FLC+PID [31]
Settling time	0.556	0.501
Rise time	0.396	0.222
Overshoot (%)	0.195	9.4
max(α)	4.2	7

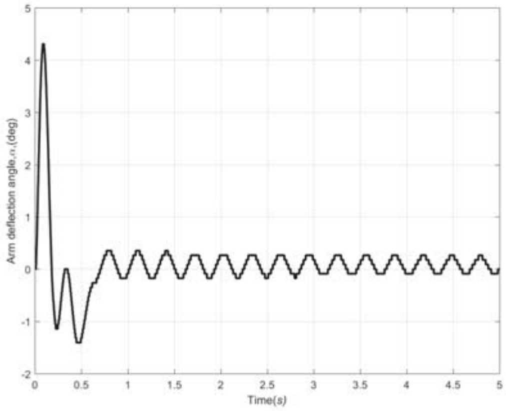


Fig. 10 deflection angle of the flexible joint manipulator

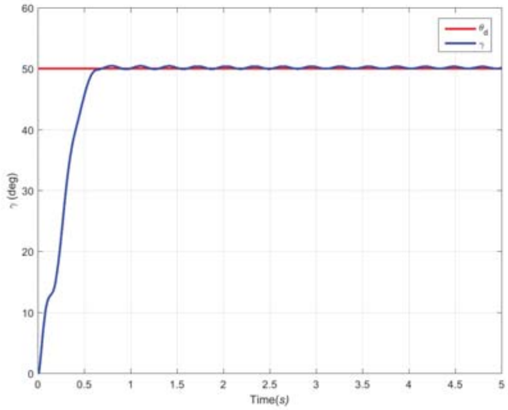


Fig. 11 Summation of the two signals($\theta + \alpha$)

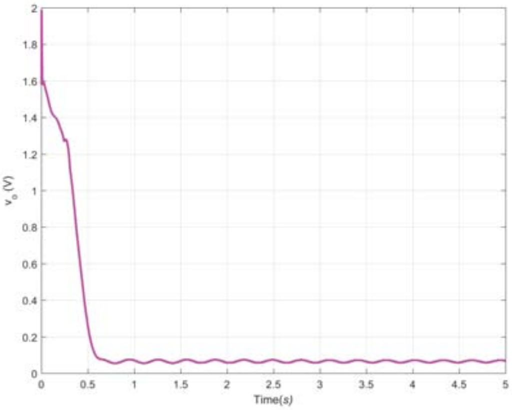


Fig. 12 Servomotor voltage

V. CONCLUDING REMARKS

In this paper, a simple but effective fuzzy logic controller is presented for trajectory tracking and vibration control of a flexible joint manipulator. The proposed controller simplifies the structure of the fuzzy system in terms of the number of inputs and rules and thus reduces its computational

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complexity. The control algorithm is implemented on the Quanser FJM. Comparing with work conducted on the same platform shows that the proposed control strategy is quite effective in terms of vibration reduction, response time, and overshoot. Future studies will include tuning the FC's setup gains to simultaneously achieve multiple design requirements.

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