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A STUDY OF EXPERIMENTAL FUZZY CONTROL FOR BALL AND TUBE SYSTEM

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ABSTRACT: This paper presents a fuzzy logic control approach for a real ball-in-tube system, which is a classical single-input, single-output (SISO) nonlinear system. The primary objective is to balance the ball's position at a fixed set point while ensuring effective tracking when the reference value changes over time. The results demonstrate the controller's ability to maintain stable ball positioning and provide smooth and responsive tracking behavior in real-time conditions.

KEY WORDS: *ball-in-tube; fuzzy control; SISO system; intelligent control.*

1. INTRODUCTION

Single-input single-output (SISO) models are a popular class of models in control engineering. They are popularly used in engineering education and research. The magnetic levitation system is a well-known SISO model developed by the Quanser company to support universities in training algorithms [1],[2]. However, it is not easy to make, and it is very expensive. Moreover, it is controlled by a professional control card. Therefore, cheaper equivalent models should be developed. The ball-in-tube system is one SISO model developed from the magnetic levitation model [3]. that was recently introduced. It consists of a vertical transparent tube that contains a lightweight ball. The position of the ball is influenced by the airflow generated by a fan located at the base of the tube. By varying the input voltage to the fan, the airflow changes, which, in turn, alters the vertical position of the ball. The behavior of this system is governed by nonlinear interactions among airflow, gravity, and aerodynamic drag, making it a challenging platform for testing control algorithms. This model has been well-tested through PID control [4]. However, the linear structure of a PID makes the controller easily usable in real-world situations. We can test real systems directly to calibrate PID parameters [5]. These advantages overcome the limitations of nonlinear methods, such as sliding control and back-stepping control, because nonlinear controllers require exact dynamic equations and system parameters to operate successfully.

Besides the PID method, fuzzy logic, introduced by Zadeh [6], provides a robust framework for controlling nonlinear systems, such as the ball-in-tube setup. It is obtained from the experiences of experts in real controlling. Unlike traditional PID control [7], fuzzy logic controllers (FLCs) do not require precise mathematical modeling, as demonstrated in recent studies **[8]**, **[9]**. Instead, they rely on a set of linguistic rules based on the system's behavior and expert human knowledge.

Additionally, there should be a low-cost, easy-to-build model that facilitates popularization in university laboratories. With the development of Arduino [10][11], various systems have been created for educational and training purposes in universities and for individuals interested in research, such as heating ovens [12][13], DC motors [14][15], to utilize intelligent MATLAB blocks in control, MATLAB provides tools that can help users embed MATLAB block programs for Arduino. Therefore, this direction holds promise for a broadened forum of developing controllers for popular models at a low cost. Before the MATLAB embedding helps for Arduino, only the STM32F4 chip [16] and the TMS320F28335 chip [17] were used to embed MATLAB blocks for these chips. However, they are expensive, while Arduino is much cheaper [18].

The objective of this study is to develop a fuzzy logic controller for a real ball-in-tube system, a low-cost and easy-to-build model created in the Automation and Control Laboratory of Ho Chi Minh City University of Technology and Education (HCMUTE), to control the ball's position at desired locations. Additionally, the study aims to implement the controller on a physical setup and evaluate its performance through experimental tests. Experiments are examined to confirm the calibration rules of fuzzy theory. Thus, it confirms that this experimental model is useful for testing control intelligence in university students.

2. EXPERIMENTAL MODEL

The experimental model and Block Diagram Control System of the Ball-Tube are shown in Fig. 1 and 2.

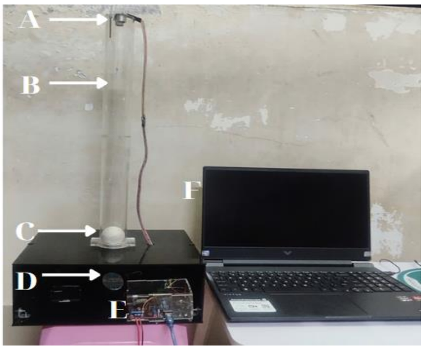

Fig. 1. The experimental Ball-tube model

where A is an ultrasonic sensor, B is a tube, C is a ball, D is a fan motor, E is Arduino Uno and L298, and F is a PC.

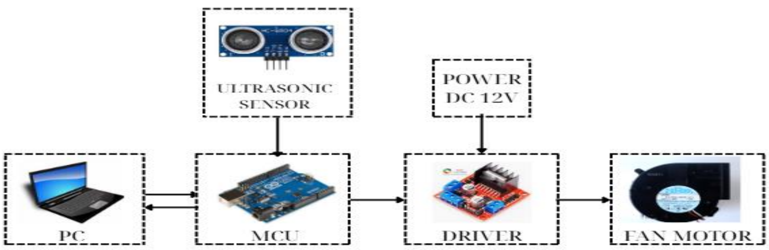

Fig. 2. System Overview

Description of Blocks in Fig. 1:

- PC block: This is the key component of the system. The computer allows users to control and monitor the system through the MCU block, which is an Arduino Uno, using the USB communication protocol.
- MCU Block: The main control unit of the system is the Arduino Uno microcontroller, which communicates with other components via the USB communication standard. It receives data from the sensor block and sends it to the PC block to help maintain balance. Additionally, it sends signals to the Driver for further implementation.
- Driver (L298): Receives signals from the MCU block and converts them into voltage values to perform motor control.
- Actuator Block: This block consists of a DC brushless fan motor that receives adjusted signals from the Driver to regulate the desired airflow.
- Sensor Block: This block collects and processes information about the ball's position, sending signals to the MCU block for further processing.

3. CONTROL METHOD

To design and implement a fuzzy controller, we will utilize the Fuzzy Logic Designer tool available in MATLAB Simulink.

3.1. Fuzzy Logic Controller Structure

The structure of the Fuzzy Logic Controller (FLC) consists of three main components: input fuzzification, rule-based inference, and output defuzzification.

The controller uses two input variables:

- Position Error (e): This is the difference between the reference position (yd) and the measured ball position (y), defined as

$$e = y_d - y \quad (1)$$

- \- Change of error (e_dot): This represents the rate of change of the error and is computed as

$$\dot{e} = \dot{y}_d - \dot{y} \quad (2)$$

The output of the FLC is the control signal (u), which is converted into a pulse-width modulation (PWM) signal. This PWM signal is then sent to a microcontroller, and subsequently, an Arduino will transmit signals to a driver (L298) to regulate the voltage supply for the fan motor.

3.2. Membership Functions

In this work, both input variables of the fuzzy controller – namely, the error and the change of error – are normalized and fuzzified within the range of [-1, 1] using triangular and trapezoidal membership functions. Each input variable is assigned five linguistic terms: Negative Big (NB), Negative (N), Zero (Z), Positive (P), and Positive Big (PB). The fuzzy inference engine is implemented using the Sugeno method [19]. Unlike Mamdani-type systems, the Sugeno controller produces crisp outputs directly from the rules, which is why it is adopted due to its computational efficiency and suitability for real-time control, as evidenced in similar hardware implementations [20]. Specifically, the rule outputs are constant singleton values selected from the set {0.2, 0.4, 0.6, 0.8, 1.0}, which correspond to increasing levels of control effort. The final output is calculated using a weighted average of the rule outputs based on their respective firing strengths.

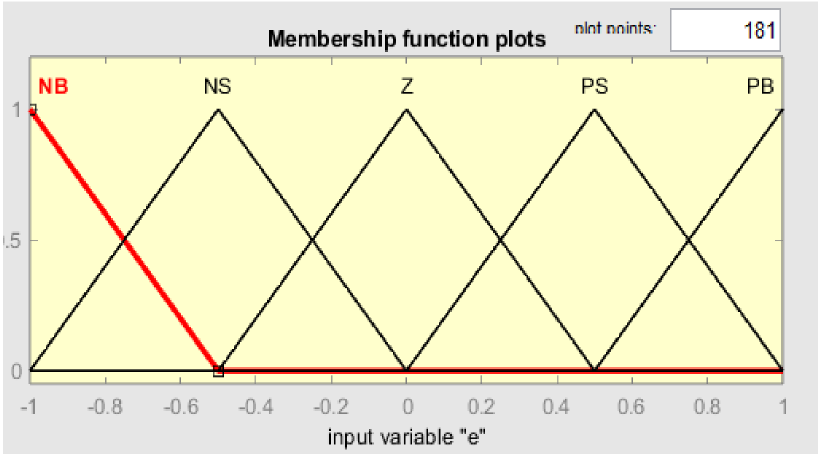

Fig. 3. Membership function of input “e”

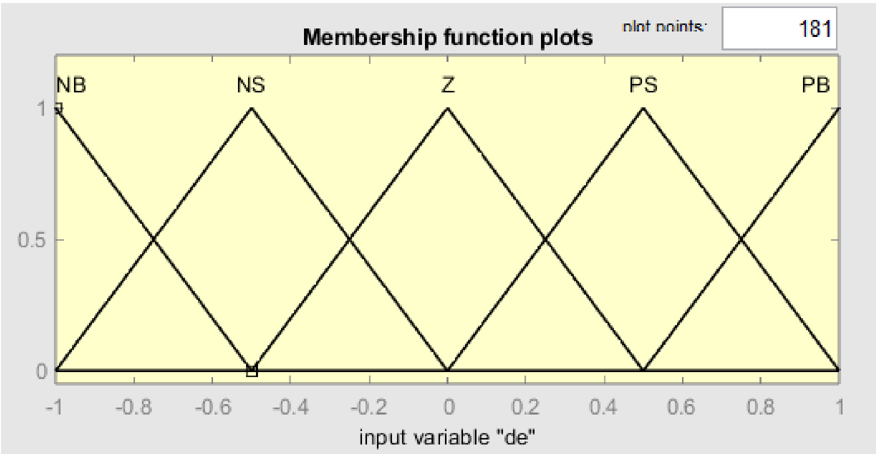

Fig. 4. Membership function of input “e_dot”

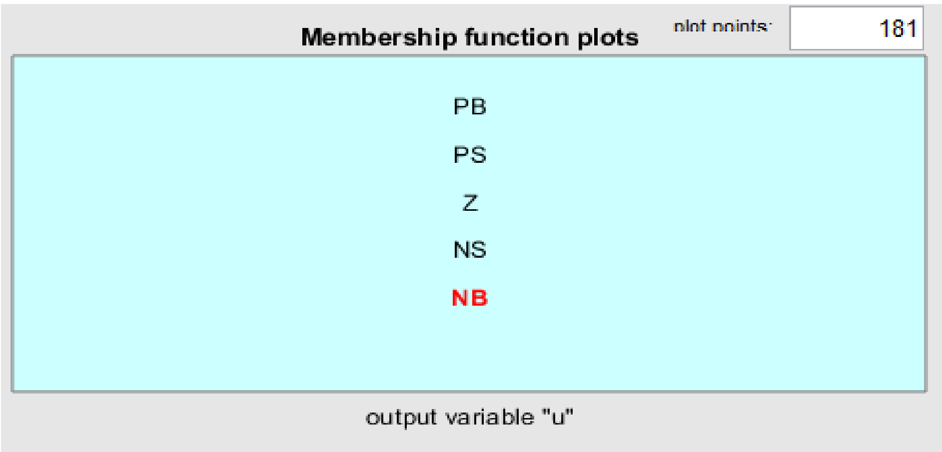

Fig. 5. Membership function of output “u”

Note: NB=0.2; NS=0.4 ;Z=0.6; PS=0.8; PB=1

3.3. Fuzzy Rule Base

The Fuzzy Rule Base is designed following the table below:

Table 1: Fuzzy Rule Base

e dot	e				
	NB	NS	Z	PS	PB
NB	PB	PB	PS	PS	Z
NS	PB	PS	Z	Z	NS
Z	PB	PS	Z	NS	NS
PS	PS	Z	NS	NS	NB
PB	Z	Z	NS	NS	NB

4. EXPERIMENTAL RESULTS

Structure the FLC system the ball in tube system by MATLAB/SIMULINK as follows:

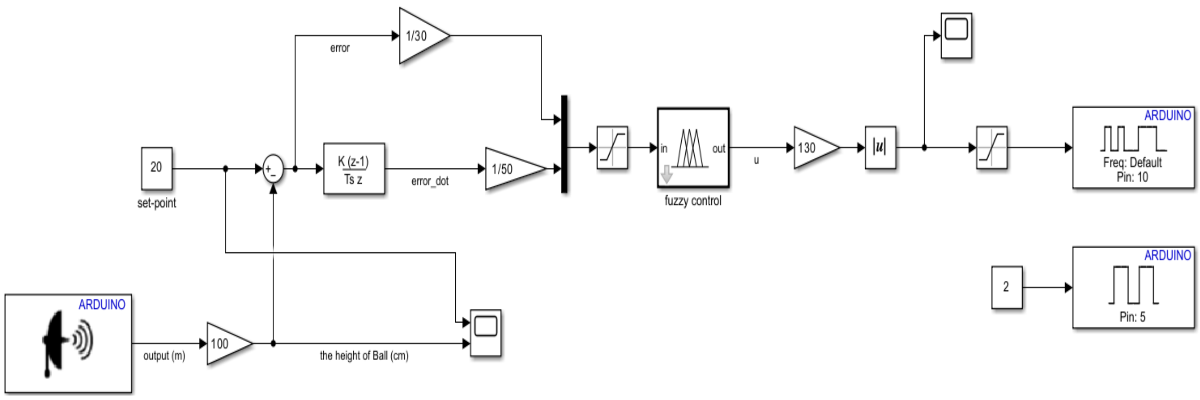

Fig. 6. Block diagram of the Fuzzy control for the experimental ball-in-tube system

Figure 7 shows the simulation results when the set point changes over time, with K_1 set to 1/30, K_2 to 1/50, and K_3 to 120. The graph illustrates the tracking performance of the Ball-in-Tube system as it controls the ball to reach the desired positions. The black line represents the set values, while the red line represents the actual position of the ball relative to the sensor.

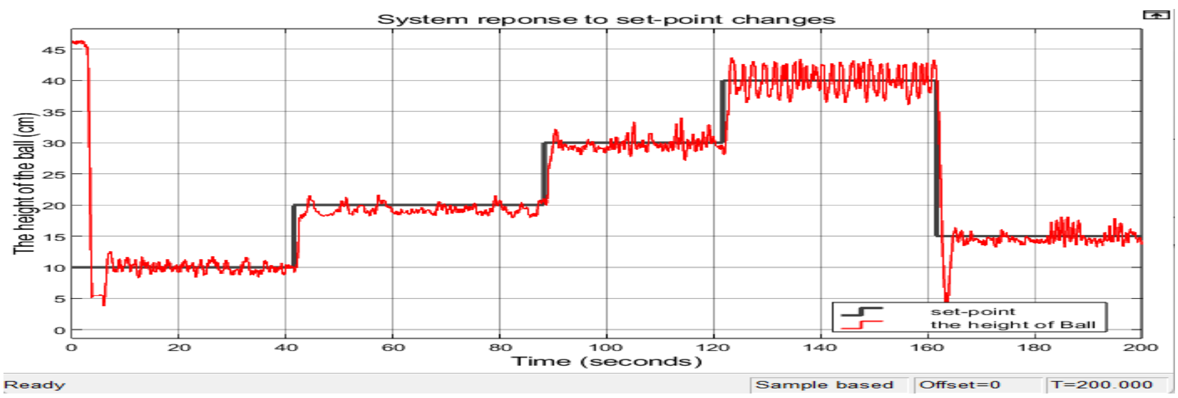

Fig. 7. The Set-point varies from 10 cm to 40 cm.

Evaluation: upon system startup, the ball quickly rises to its maximum height due to the fan operating at full power, then rapidly returns to its initial set point of 10 cm. After approximately 8 seconds, the system stabilizes, and the ball oscillates with a small amplitude around this set-point. As the set-point is increased to 20 cm and 30 cm, the ball continues to track the reference effectively, with minimal oscillation. However, at a set-point of 40 cm, the system remains stable but shows larger oscillations compared to the other levels, measuring approximately 3 to 4 cm. Finally, when the set-point is reduced to 15 cm, the ball quickly stabilizes again with small oscillations, demonstrating the controller's effective performance.

4.1. Case 1: Investigation of the Influence of K_1

In this case, we investigate the effect of the gain parameter K_1 on the system response, as shown in Figure 8. The set point is kept constant while K_1 is varied, with K_2 set to 1/50 and K_3 set to 120. The objective is to evaluate how changes in K_1 affect the stability and tracking performance of the ball position control system.

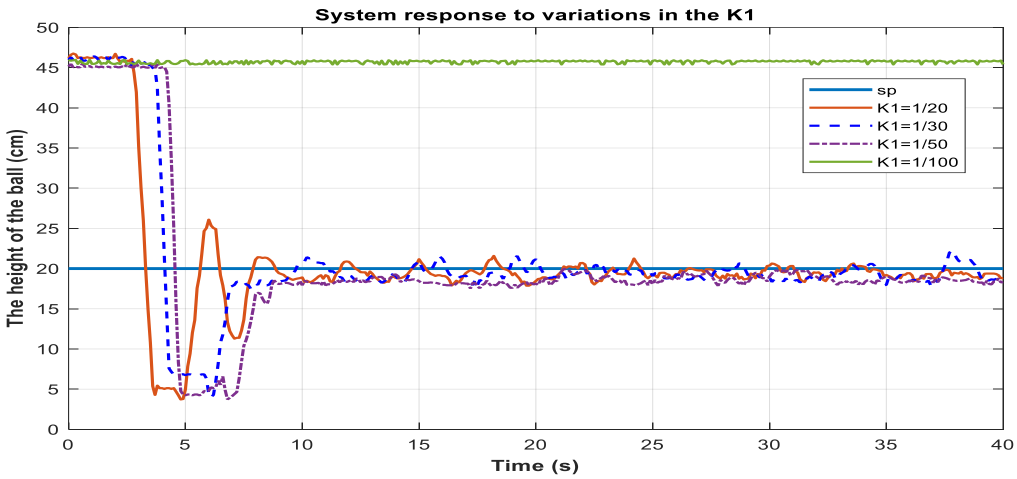

Fig. 8. Experimental system response to variations in the gain K_1

Evaluation: When K_1 = 1/20 (blue dashed line), the system exhibits a fast response with noticeable overshoot and oscillations before stabilizing. At K_1 = 1/30 (solid red line), the response becomes more stable, featuring a moderate settling time and reduced overshoot. With K_1 = 1/50 (purple dashed-dotted line), the response slows down, exhibiting minimal overshoot and good stability, albeit with a longer settling time. When K_1 = 1/100 (thin dotted black line), the system response becomes excessively slow, preventing the ball from reaching the desired set-point within the simulation period. These results indicate that increasing K_1 enhances responsiveness but also increases the risk of overshooting. Conversely, smaller K_1 values improve stability at the expense of speed.

4.2. Case 2: Investigation of the Influence of K_2

The set-point is kept constant while K_2 is varied, with K_1 set to 1/30 and K_3 set to 120.

Evaluation: when K_2 is set to 1/20 (blue dashed line), the system responds quickly but exhibits significant oscillations and poor damping. At K_2 = 1/100 (magenta dashed line), the system becomes underdamped and oscillatory, with larger amplitudes and longer settling times. With K_2 set to 1/50 (solid red line), the response is smoother, exhibiting smaller oscillations and faster convergence to the set point. Overall, K_2 = 1/50 provides the best performance in terms of stability and response time, while values that are too high or too low for K_2 result in increased oscillation and degraded control quality.

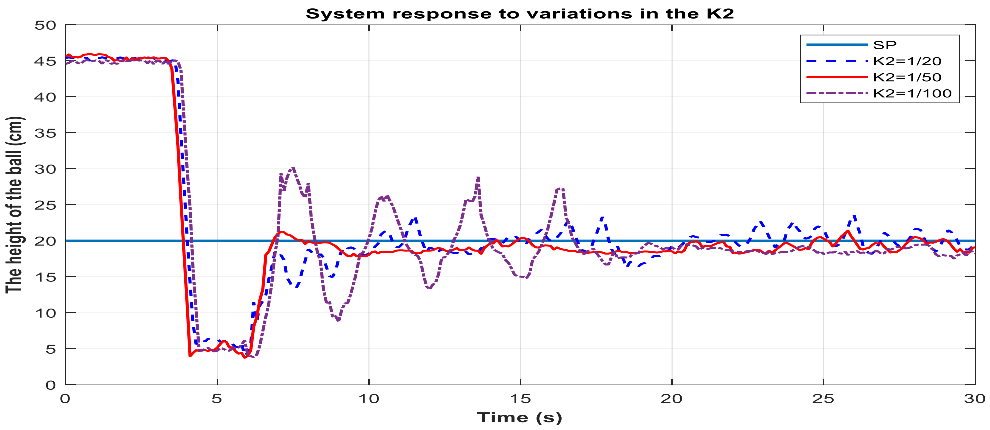

Fig. 9. Experimental system response to variations in the gain K_2

4.3. Case 3: Investigation of the Influence of K3

The set point is kept constant while K_2 is varied, with K_1 set to 1/30 and K_2 set to 1/50.

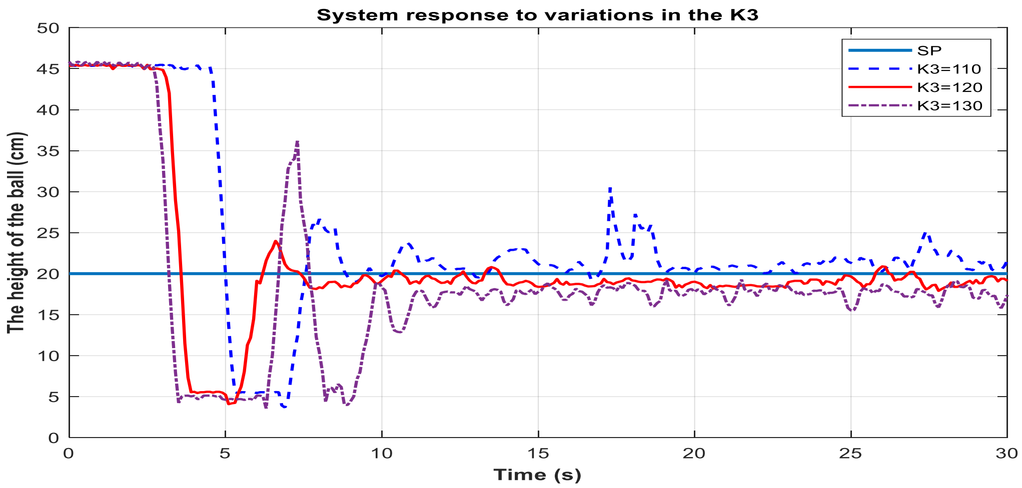

Fig.10. Experimental system response to variations in the gain K3

Evaluation: when K_3 is set to 110, the response is relatively sluggish and underdamped, resulting in a longer settling time with small oscillations. At K_3 = 130, the system becomes overdamped, exhibiting reduced oscillations but a slight increase in steady-state error. The best performance is observed at K_3 = 120, where the ball height tracks the set point more accurately, with minimal overshoot and faster settling times. These results suggest that selecting an appropriate value for K_3 is crucial for achieving a balance between responsiveness and stability. Values that are excessively low or high can degrade control performance.

5. CONCLUSION

Through this research, we presented a hardware platform for a ball-in-tube system. On this platform, we have built a fuzzy controller, and a survey of fuzzy parameter calibration is examined. Therefore, the rules of fuzzy calibration are confirmed through experiments. Iot suits the theory of fuzzy control. The popularity of the system is based on Arduino, which has a large community that can help popularize it. Therefore, it is a suitable model that can be provided for university laboratories.

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