Single axis control of ball position in magnetic levitation system using fuzzy logic control

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Abstract: This paper presents the design and real time implementation of Fuzzy logic control (FLC) for the control of the position of a ferromagnetic ball by manipulating the current flowing in an electromagnet that changes the magnetic field acting on the ball. This system is highly nonlinear and open loop unstable. Many un-measurable disturbances are also acting on the system, making the control of it highly complex but interesting for any researcher in control system domain. First the system is modelled using the fundamental laws, which gives a nonlinear equation. The nonlinear model is then linearized at an operating point. Fuzzy logic controller is designed after studying the system in closed loop under PID control action. The controller is then implemented in real time using Simulink real time environment. The controller is tuned manually to get a stable and robust performance. The set point tracking performance of FLC and PID controllers were compared and analyzed.

1. Introduction
Magnetic levitation is a technique in which gravitational acceleration is negated which in turn leads to free suspension of objects without any support of mechanical system. Since magnetic levitation provides a near frictionless environment, this particular trait makes it a popular choice in many research fields, such as high speed transportation, mechanical engineering, automatic control and biomedical engineering [1-5]. The maglevs however are inherently nonlinear and open loop unstable in nature. Therefore, in order to achieve desired performance such as excellent setpoint tracking, minimum overshoot and minimum steady state error, stabilizing feedback controllers are required which are based on a linearized model. Since there could be many disturbances acting on the operational maglev system and the performance of linearized model can be affected when it deviates from the linearized point, classical control approach is not effective, therefore an intelligent control technique is demanded for handling disturbance rejection and parameter variations [6-8].

The current research article encompass the design of a fuzzy logic controller (FLC) using fuzzy logic toolbox and then implementation of the FLC in real time environment for the magnetic levitation system using SIMULINK. The performance of FLC is compared with the existing PID controller. The remainder of the paper is structured as follows. Section 2, section 3 represents the modeling of the system and design of FLC respectively. While, section 4 represents the experimental analysis of the
present research work which shows the comparative performances of FLC and PID. The last section of the paper i.e. section 5, presents the conglomeration of the whole research work.

2. Mathematical Modelling of Maglev
Figure 1 gives a pictorial view of Laboratory setup of magnetic levitation system, also including the auxiliary components of the system such as IR Transmitter & receiver for measurement of ball position, the electromagnet which acts as actuator, the iron ball and the data acquisition card connected to a personal computer provided by Feedback instruments(33-210).

2.1. Characteristics of magnetic levitation system
The Maglev device consists of three important components: an infrared (IR) sensor, an electromagnet which acts as an actuator and a feedback controller which operates around a linearized point from the tip of the electromagnet. The physical parameter values of Maglev (33-210) shown in figure 1 are as follows: the iron ball used has a mass of 20 g and the electromagnet coil has a resistance of 22 Ω, inductance of 227 mH at 1kHZ .The core diameter, coil diameter are 25 mm and 80 mm and having 2850 number of turns. The mean crosssectional area of the coil is 21.5 cm² and the length of the coil is 65 mm.

In the linearized zone the photo detector of the Maglev gives a voltage $Z$ which is proportional to the amount of IR light it senses, has a relation with the distance $X$ of the levitating object(a ferromagnetic ball or iron ball) from the tip of the electromagnet can be expressed as [9]

$$Z = \beta X + \bar{Z} \tag{1}$$

Where $\beta > 0$, $\bar{Z}$ are constants such that $Z \in (-1.5 V, 1.5 V)$

The current $I$ in the electromagnet is varied by an inner control loop and have a liner relationship with input voltage $E$ as

$$I = \sigma E + \bar{I}, \quad \sigma > 0 \tag{2}$$

Where constant $\bar{I}$ is the magnitude of current that is necessary for keeping $Z = \bar{Z}$.

A deviation from the equilibrium point is shown by using lower case, hence equations (1) and (2) can be rewritten as

$$z = \beta x \tag{3}$$

$$i = \sigma e \tag{4}$$

The nonlinear differential motion equation which governs the single axis movement is given by

$$m \frac{d^2x}{dt^2} = mg - p \frac{i^2}{X^2} \tag{5}$$

Where $p > 0$ is an electromechanical conversion coefficient, $m$ is the mass of the sphere, $g$ is the acceleration of gravity, and $I$ is the current fed to the coil. With $I$ kept constant, the equilibrium distance from the tip of the electromagnet is expressed as

$$X_o = I_o \sqrt{\frac{p}{mg}} \tag{6}$$
This nonlinear dynamic equation of the MAGLEV is linearized around the equilibrium position $X_o$ using first order Taylor’s expansion gives rise to the following expressions.

$$m \frac{d^2x}{dt^2} = \lambda x - \tau I$$

(7)

where,

$$\tau = \frac{2pl_o}{x_o^2} = \frac{2qmg}{x_o}$$

(8)

$$\frac{d^2z}{dt^2} = \omega z - D e$$

(9)

where

$$\omega = \frac{2g}{x_o} \text{ and } D = \frac{2eB}{x_o} \sqrt{\frac{p}{m}}$$

The resulting transfer function after linearization around equilibrium point is given by

$$G(s) = \frac{L[z]}{L[e]} = -\frac{D}{s^2 - \omega}$$

(10)

As seen from equation (10) the system has a pole in the right hand side of the S-plane, therefore the system is open loop unstable, hence we need to develop a suitable stabilizing controller. The parameters used for modelling and its values for magnetic levitation system is as follows height to voltage multiplier (B) is given as 143.48, the electromechanical constant (p) has a value of 2.501779922×10⁻⁵. The height to voltage constant (Z) and sensor gain (σ) has a value of -2.8 and 1.045 respectively and $g$ represents acceleration due to gravity having a value of 9.8 m/s². Where $E$, $I$ and $X$ represents controller output, current fed to the coil and output height respectively. The next section describes how to design and implement a fuzzy logic controller for the magnetic levitation system.

3. Design of Fuzzy Logic Controller (FLC)

As discussed in the introductory section, magnetic levitation systems are naturally nonlinear and unstable. The nonlinear magnetic levitation system is first linearized around an operating point and then position control is done by employing a PID controller. Since the stability of nonlinear system degrades when initial condition deviates from the equilibrium zone and to achieve a large stable region with desired performance specification application of fuzzy logic for a robust controller design is reasonable[10]. The next section describes the implementation of fuzzy logic controller.

3.1. Implementation of fuzzy logic controller (FLC) for magnetic levitation system

In this research work, a two input fuzzy controller is designed and applied to a laboratory-scale magnetic levitation system (Feedback, 33-210). FLC uses the error and rate of change of error for calculating the controller output. The goal of using FLC is to minimize the error. The error here is the difference between reference position and available position of the steel ball. The output of fuzzy controller is created by rules which are composed of these two inputs with linguistic definitions of the system. The general rule is that if error value is negative and change of error value is negative then output of controller is negative or if the error value is positive and change of error value is positive then the output of controller will be positive.

Figure 2 represents the two inputs error and change in error to the FLC. The error and change in error have seven membership functions, five triangular and two trapezoidal: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive small (PS) in order to get desired value with high accuracy. The range of these two inputs are taken to be [-1 -1].

Figure 3 represents the output of the FLC. The output is also having seven membership functions five triangular and two trapezoidal: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive small (PS) in order to get desired value with high accuracy. The range of this input is taken to be [2-2].
3.2. Fuzzy rules
The general rules for position control of steel ball in magnetic levitation system is that if ball position is below the reference position then increase the voltage across the electromagnetic coil (control voltage) hence current flowing in the coil will also increase and if ball position is above the reference position then bring it down to reference position by decreasing the control voltage. In the process of producing output voltage with fuzzy controller the position error must be minimized. The bigger position error causes the bigger controller input. So two inputs make 49 rules in order to get accurate value and efficiency. Table 1 represents the fuzzy rule base used for control of the ball position in the magnetic levitation system.

| Change in Error | NB | NM | NS | ZE | PS | PM | PB |
|-----------------|----|----|----|----|----|----|----|
| NB              | NB | NB | NB | NB | NM | NS | ZE |
| NM              | NB | NB | NB | NM | NS | ZE | PS |
| NS              | NB | NM | NS | ZE | PS | PM | PB |
| ZE              | NM | NS | ZE | PS | PM | PB | PB |
| PS              | NM | NS | ZE | PS | PM | PB | PB |
| PM              | NS | ZE | PS | PM | PB | PB | PB |
| PB              | ZE | PS | PM | PB | PB | PB | PB |

3.3. Scaling factors
The scaling factors presented in table 2 for error, change in error and controller output was used in order to scale the desired inputs and outputs within the range of membership function’s range. They are calculated on a trial and error basis.

| Tuning parameters | Scaling factors |
|-------------------|-----------------|
| Error             | 0.22            |
| Change in error   | 0.01            |
| Controller output | -10             |

3.4. Hardware implementation
The real time analysis of the controller is performed in the magnetic levitation system supplied by Feedback Instruments, UK (33-210). A data acquisition system with inbuilt (Digital to analog converter) DAC and (analog to digital converter) ADC is used for communication between the controller (computer) and MLS. Figure 1 presents the pictorial view of FLC connected with maglev (33-210) when the device was operated in real time.
4. Performance Analysis of Controllers

The FLC parameters are tuned with trial and hit method. The criteria followed while tuning was to give a stable steady state performance with minimum error. The performance of FLC is analysed for various types of setpoints in the presence of many un-measurable disturbances affecting the process such as air circulation, moisture, change in coil resistance with time due to the generated heat in coil, magnetic field distortion due to other magnetic elements etc. Step input was given to the system for analysis and the performance of designed FLC was compared with the professionally tuned PID.

Figure 4 represents the step response of the maglev (33-210), for step input (Magnitude changing from 12.5 mm to 9 mm at t = 35 s); it was found that FLC is giving an over-damped performance with constant steady state error. Table 3 gives the time response specifications of the system when step input was applied, there is a step change at t = 35 s as seen from the table 3 PID have a high overshoot in comparison to fuzzy logic controller (FLC) which is giving an over damped response at the same time the FLC have a shorter settling when compared to PID controller. The error analysis was also done for both the controllers as shown in table3.

Table 3. Performance analysis of controllers for step change in setpoint.

| Performance Criteria                  | Controller |
|---------------------------------------|------------|
|                                       | PID    | FLC    |
| % Overshoot                           | 40     | 0      |
| Rise time - 0% to 100% (sec)          | 0.0418 | 0.135  |
| Settling Time (sec)                    | 1.16   | 0.4    |
| % Steady state error                  | 0      | 28.57  |
| ISE of MLS output (10^6)              | 192    | 627    |
| ISE of controller output              | 10708.7| 139.8  |

Figure 4. Step change response of magnetic levitation system.

Figure 5 represents the controller output of both the PID and FLC as shown in the figure FLC found to put maximum effort by continuous change in controller output. For PID; when rate of change of setpoint is high, output shows derivative kick.

Figure 5. Controller output for Step change in setpoint.
During the experiment it was observed that there is a huge scope in improving the performance of both FLC by using better tuning methods and by incorporating further intelligence through Neural Networks and Heuristic algorithms in the controller.

5. Conclusions
The paper gives theoretical description as well as the real time implantation about the design of Fuzzy controller for a laboratory scale magnetic levitation device. The nonlinear system is linearized about an operating point. The FLC was designed in the linearized zone. The performance of the controller was compared with already existing PID controller on the basis of time response analysis. After the comparison it is concluded that although the fuzzy logic controller shows constant steady state error but the FLC have better performance in terms of lower settling time and overshoot. The FLC takes only 0.4 sec to settle down as compared to 1.16 sec by PID controller also the fuzzy FLC has 0 % overshoot while the PID has a staggering 40 % overshoot. While the speed of response for both the controllers are nearly same. Error analysis was also done for both the controller output (Integral square error) ISE for FLC was found better than the PID. ISE for FLC is 139.8 while the ISE for the PID is at staggering magnitude of 10708.7. The scaling factors for the FLC which is equivalent to gain of the classical controllers are very important and are found by hit and trial method. The performances of FLC can be improved with certainty by proper tuning of membership functions and scaling factors in case of Fuzzy Logic controller.

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