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Original Paper

Application of PID and self-tuning fuzzy PID control methods in the control of non-linear magnetic levitation system

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ABSTRACT

Because of the Magnetic Levitation System's (MLS) low energy consumption and little friction two factors that are deemed crucial for unstable and nonlinear systems MLS research is now being conducted in the engineering area. This article discusses the comparison of the performance of control theories used by applying advanced control theories to cope with the complexity of the structure and controllability difficulties of MLS. The control methods compared are Proportional–Integral–Derivative (PID) and Self-Tuning Fuzzy PID (STFPID) methods. These methods were developed in the MATLAB environment. The MLS model created in the MATLAB environment was subjected to the suggested control methods, and the outcomes were compared. The outcomes unequivocally demonstrate that MLS location control may make use of PID and STFPID techniques. Four criteria were used to compare the developed control approaches performances. These are the criteria; rise time, settling time, percent maximum overshoot and overshoot value. It is clearly seen in the results that the STFPID control method provides control of the MLS with greater stability than the PID control method.

Nomenclature	
MLS	Magnetic Levitation System
PID	Proportional–Integral–Derivative
STFPID	Self-Tuning Fuzzy PID
FLC	Fuzzy Logic Control
Kp	Proportional gain
Ki	Integral gain
Kd	Derivative gain
m	Mass of ferromagnetic ball,
g	Gravitational acceleration
L	Inductance of the coil
R	Coil resistance
C	Constant value
X_{01}	Position of ball
X_{02}	Velocity
X_{03}	Current

I. INTRODUCTION

MLS has a significant advantage due to the absence of friction losses due to its non-contact working principle. It has wide application areas in transportation, aviation, healthcare sector and other industrial organizations. However, since the system is unstable in open-loop control and has a non-linear characteristic, the difficulty of system control increases, and the control algorithm must have higher requirements. Therefore, research on the control algorithm of MLS has very important theoretical value and practical importance.

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In applications designed and currently used for MLS, various control methods have been suggested by many scientists in order to increase the fast dynamic response of the system, minimize the steady-state error and prevent the disruptive effects caused by external factors [1-4]. Fuzzy Logic Control (FLC) increases understandability thanks to the simplicity of the structure of the underlying rules and their linguistic expression, reduces the complexity of the algorithm design and provides the ability to produce strong and stable results. In addition, the self-adjusting fuzzy PID control structure, which is formed by combining fuzzy control and PID control, is widely used in many control systems by updating the gain coefficients online [5], which ensures that the system used operates with the same stability in variable conditions [6, 7]. In the literature [8] fuzzy PID control structure was applied for frequency control of power systems, and fuzzy control was used in online adjustment of PID control gains. When the reconstructed control system is compared with the standard PID control, it can be seen that the designed control system has a stronger anti-distortion ability. In literature [9], an adaptive PID control system is proposed for position control of MLS. In the proposed system, the parameters of the adaptive PID controller are adjusted online according to the derived adaptation laws. Literature [10] proposes fuzzy logic controller and PID control methods for position control of MLS. He interprets the performance performances of both control methods comparatively and states that the fuzzy logic controller produces better temporary and permanent state results in the results found. In literature [11], a fuzzy logic controller-based PID control method was designed and presented to effectively control MLS. In the literature [12], real-time application of the fractional order PID control system for MLS has been carried out, and the results clearly state that the developed control algorithm is applicable in MLS. In the literature [13], performance comparisons of fuzzy logic controllers and PID controllers in a test setup with feedback MLS are interpreted depending on various criteria. The results revealed that the fuzzy logic controller is more stable in the control of MLS because it has a much lower steady-state error than the PID control method for dynamically changing sine and square wave inputs. A study was carried out on the optimum control of the MLS by calculating PID parameters with a genetic algorithm [14]. It is clearly seen in the literature that various systems can be controlled using intelligent control methods [15-18]. Additionally, many systems have been developed to provide solutions to MLS's control problems [19-24].

PID control method is frequently used in control systems when it has a simple structure. The gain coefficients inherent in the PID control system are determined based on expert knowledge or using various calculation methods to ensure that the system can operate within the desired limits under certain conditions. However, in cases of unforeseen working conditions and uncertainty, it has difficulty in producing the desired results and is insufficient to compensate for the error that occurs. If these coefficients in the structure of the PID control method are changed online, the performance of the control method is increased. Various control algorithms are applied in online updating of these coefficients [25-30]. One of these control algorithms is the fuzzy logic controller. With the PID control method created using a fuzzy logic controller, PID gain coefficients are updated online, ensuring that the system operates with the same stability under variable operating conditions [31, 32].

As can be clearly seen in the literature study, MLS is one of the areas that researchers pay attention to. Therefore, every effort made to develop MLS is very valuable. Researchers who want to make significant contributions to the field of control systems are carrying out serious development work in this field.

It is known that MLS has an unstable structure and nonlinear dynamics that should be taken into consideration due to its characteristic structure. It requires position, speed, and electrical current measurements and therefore attitude observers must be used to estimate the MLS's current control signals. In addition, complex systems must be designed to perform the control process, and some of these systems are costly. Considering the mentioned work, the development of a controller that will stabilize the MLS becomes of great importance.

In this study, a simulation study developed only in the Matlab/Simulink environment is presented, without the need for an MLS created in the real environment. Controlling MLS through simulation allows researchers to obtain faster results. This advantageous situation allows faster development of control methods. PID and STFPID control methods have been developed for position control of the ferromagnetic ball in the simulated MLS. The gain coefficients used in the PID control method are determined by the developer using various methods. However, disturbances caused by environmental factors have a negative impact on the operation of the system, and the PID control method cannot compensate for these negativities. It is possible to compensate for these negativities by updating PID earnings online. The STFPID control method developed within the scope of this study constantly changes the PID gain coefficients according to the needs of the system with FLC. With the results found, MLS can be checked more quickly and efficiently. In this way, the importance of updating PID gain coefficients online is clearly seen. It is understood that using constant gain coefficients in the PID method alone is not sufficient for the control of MLS.

This study will shed light on the selection and design of appropriate control methods for scientists who want to conduct research on MLS in the future. In this way, it contributes to scientists having an idea about what to pay attention to in the design criteria of the control methods they will use. Expressing MLS mathematically also allows researchers to carry out research and development activities on this subject without conducting experimental studies.

II. EXPERIMENTAL METHOD

The system discussed in Figure 1 represents the MLS created by suspending the ferromagnetic ball in a magnetic field with a typical voltage control. The subject addressed in this study consists of checking this MLS using mathematical equations.

The current used in the control of the electromagnet is denoted by I. The position of the ferromagnetic ball is determined by the optoelectronic sensor. The Vsensor signal received from the optoelectronic sensor is applied to the controller as position information. The result of the developed control system, denoted by U, serves as the reference value for the MLS's current control block. The ferromagnetic ball's weight should be equal to the electromagnetic attraction force that the electromagnet creates on it with the current I determined based on the reference U value. The ball is raised into the air in equilibrium when the buoyant force acting upon it equals its weight. Without a feedback control system, it is a highly unstable and nonlinear system. Therefore, it is very important to design an efficient control system that is stable, has low steady-state error, and has optimum performance in case the operating conditions change, in accordance with the characteristic structure of the system.

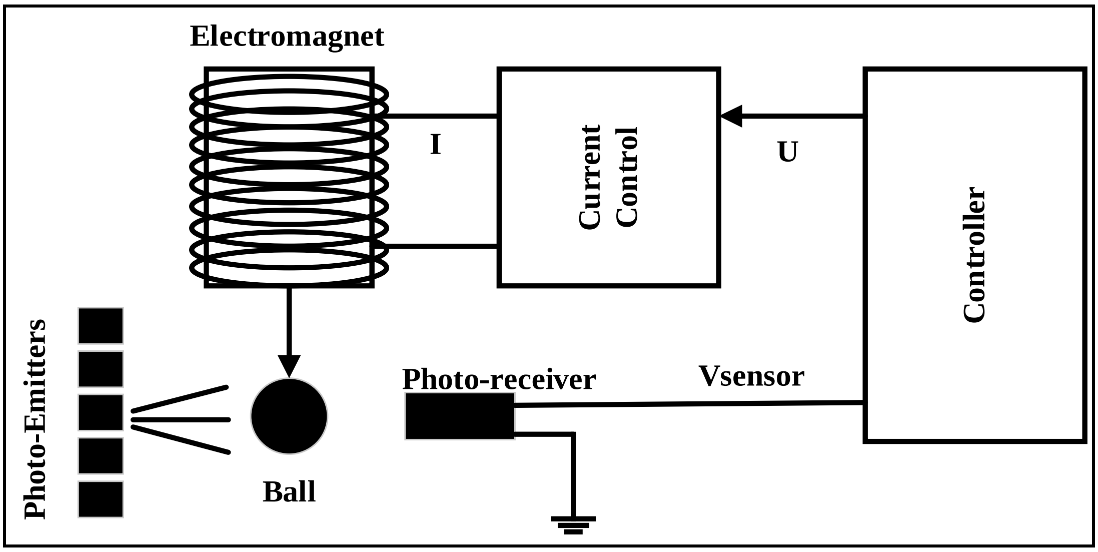

Figure 1. Block model of MLS

2.1 MLS Dynamic Equations and Modeling

In this section, the mathematical equations of the MLS mechanism examined, and the control modeling of these equations are explained. To model the motion of the MLS, the electromagnetic and mechanical system dynamic equations need to be examined. Here, the equations obtained from the mathematical modeling of this electromechanical system are used to produce a linear model.

The differential equation below can be used to express the MLS nonlinear model. Electromagnetic modeling is the foundation of this model [33].

$$V = \frac{dx}{dt} \tag{1}$$

$$m\ddot{x} = mg - C\left(\frac{i}{x}\right)^2 \tag{2}$$

$$u = iR + L\frac{di}{dt} - C\left(\frac{i}{x}\right)^2 \frac{dx}{dt} \tag{3}$$

Here V is the speed of the suspended ferromagnetic ball. U is the voltage value applied to the system. x is the position of the ferromagnetic ball, m represents the mass of the ferromagnetic ball, C is expressed as the magnetic force constant, g is expressed as the gravitational acceleration, L and R are expressed as the inductance and resistance of the coil, and i is defined as the current of the coil.

The following can be used to write Eqs. 1, 2, and 3 assuming that $x=x_1$, $v=x_2$, and $i=x_3$.

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix}x_2\\ g-\frac{C}{m}\left(\frac{x_3}{x_1}\right)\\ -\frac{R}{L}+\frac{2C}{L}\left(\frac{x_3x_2}{x_1^2}\right)\end{bmatrix}+\begin{bmatrix}0\\0\\ \frac{1}{L}\end{bmatrix} \tag{4}$$

$$y=[x_1 \quad x_2 \quad x_3]^T=[1 \quad 0 \quad 0] \tag{5}$$

$$\dot{x}=f(x)+g(x)u \tag{6}$$

The state equations for a nonlinear system can be written as in Eq. 7 [34, 35].

$$\frac{dx(t)}{dt}= f[x(t),r(t)] \tag{7}$$

In this case, the state vector x(t) has dimensions of (nx1), and the input vector r(t) has dimensions of (px1). In general, f[x(r), r(t)] is written as a vector function of input vectors and a (nx1) dimensional state.

In a given initial state, it can be written as the nominal operating trajectory $x_0(t)$ vs the notional input $r_0(t)$. Eq. 8 with i=0, 1, 2,...,n is obtained if the nonlinear state equation given in Eq. 7 is enlarged based on a Taylor series around x(t)=x0(t) and all higher order terms are removed.

$$\dot{x}_i(t)=f_i(x_0,r_0)+\sum_{j=1}^{n}\frac{\partial f_i(x,r)}{\partial x_j}|_{x_0,r_0}\left(x_j-x_{0j}\right)+\sum_{j=1}^{p}\frac{\partial f_i(x,r)}{\partial r_j}|_{x_0,r_0}\left(r_j-r_{0j}\right) \tag{8}$$

Moreover,

$$\Delta x_i=x_i-x_{0i} \tag{9}$$

and,

$$\Delta x_i=x_i-x_{0i} \tag{10}$$

If differences are detected between Eq. 9 and Eq. 10,

$$\Delta\dot{x_\iota} = \dot{x_\iota} - \dot{x_{0\iota}} \tag{11}$$

The relationship with the expression given in Eq. 11 is provided.

Eq. 8 can be expressed as Eq. 13 because of the expression given in Eq. 12.

$$\dot{x_{0\iota}} = f_i(x_0, r_0) \tag{12}$$

$$\Delta\dot{x_\iota} = +\sum_{j=1}^{n} \frac{\partial f_i(x,r)}{\partial x_j}|_{x_0,r_0}\Delta x_j + \sum_{j=1}^{p} \frac{\partial f_i(x,r)}{\partial r_j}|_{x_0,r_0}\Delta r_j \tag{13}$$

If Eq. 13 is expressed in vector-matrix form, Eq. 14 is produced.

$$\Delta\dot{x} = A^*\Delta x + B^*\Delta r \tag{14}$$

Here,

$$A^* = \begin{bmatrix} \frac{\partial f_1}{x_1} & \cdots & \frac{\partial f_1}{x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{x_1} & \cdots & \frac{\partial f_n}{x_n} \end{bmatrix} \tag{15}$$

$$B^* = \begin{bmatrix} \frac{\partial f_1}{r_1} & \cdots & \frac{\partial f_1}{r_p} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_p}{r_1} & \cdots & \frac{\partial f_p}{r_p} \end{bmatrix} \tag{16}$$

is defined as.

The following equation can be used to find the velocity and acceleration parameters that will maintain the system in balance when the MLS control problem is linearized around the $x=x_{01}$ equilibrium point.

$$x_{02}(\mathrm{t}) = \frac{dx_{01}(t)}{dt} = 0 \tag{17}$$

$$\frac{d^2x_{01}(t)}{dt^2} = 0 \tag{18}$$

Eq. 19 can be produced by writing the expression given in Eq. 3 as the nominal value of the current value i(t), which will maintain system equilibrium. This expression is given in Eq. 18.

$$x_{03} = x_{01}\sqrt{\frac{gm}{C}} \tag{19}$$

Eq. 20 represents the linearized state equations for the planned MLS.

$$\Delta\dot{x}(\mathrm{t}) = A^{*}\Delta x(t) + B^{*}\Delta\mathrm{u}(t) \tag{20}$$

In this instance, the linearized state equations $A*$ and $B*$ matrices are constructed in the manner shown in Eq. 21.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ Cx_{03}^{2} & 0 & -2\frac{Cx_{03}}{mx_{01}^{2}} \\ 0 & 2\frac{Cx_{03}}{Lx_{01}^{2}} & -\frac{R}{L} \end{bmatrix} \; B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} \tag{21}$$

Eq. 22 provides an expression for the C matrix of the output function.

$$C = [1 \quad 0 \quad 0] \tag{22}$$

The space state equations of MLS are expressed by the equations found in Eqs. 21 and 22. The system has a transfer function according to the parameters determined for the designed system.

Table 1 lists the specifications of the MLS that has to be examined [36]. Unlike other applications in the literature, the precision of the developed controllers and the uniqueness of the study are conveyed here through the weight and position of the ferromagnetic ball.

Table 1. MLS parameters

Parameters	Unit	Value
Mass of ferromagnetic ball, m	*Kg*	0.5
Gravitational acceleration, g	*m/s2*	9.8
Inductance of the coil, L	*H*	0.01
Coil resistance, R	*Ohm*	1
Constant value, C		0.0001
Position of ball, X01	*m*	0.024
Current, X03	*A*	0.84

Eqs. 23 and 24 are produced by applying the parameters listed in Table 1 to the state space equations presented in Eqs. 21 and 22.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0.0001 & 0 & -0.5833 \\ 0 & 29.17 & -100 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 100 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \tag{23}$$

The matrices given in Equation 23 were defined in the Matlab/m-file environment and the linearized transfer function was calculated. The calculation was carried out using the 'ss2tf' and 'tf' functions in the Matlab program. Control methods were developed by transferring the found transfer function to the Matlab/Simulink environment.

$$T(s) = \frac{-58.33}{s^3 + 100s^2 + 17.01s - 0.007056} \tag{24}$$

PID and STFPID control methods were designed according to the transfer function given in Eq. 24.

2.2 Design of PID and STFPID Controllers

The PID and STFPID control methods design criteria for MLS are covered in this section. In the PID control method, three mathematical calculations are made: proportional, integral and derivative. The result expression is created by adding the values found as a result of these calculations. Since P, I and D operations do not want to affect the output expression at a constant rate, they are multiplied by Kp, Ki and Kd coefficients and collected in the output expression. Many methods have been developed to determine these coefficients. As in the Ziegler Nichols method, which is one of these methods, Kp, Ki and Kd parameters can be calculated by applying certain inputs to the system input and evaluating the information obtained from the output [37]. Eq. 25 illustrates how the transfer function in the s domain of PID control can be expressed:

$$T_{PID}(s) = \frac{K_D s^2 + K_P s + K_i}{s} \tag{25}$$

The integral gain constant is represented by the Ki value, the derivative gain constant is represented by the Kd value, and the proportional gain constant is represented by the Kp value in Eq. 25. Figure 2 shows the block diagram depiction of the PID control system's fundamental architecture.

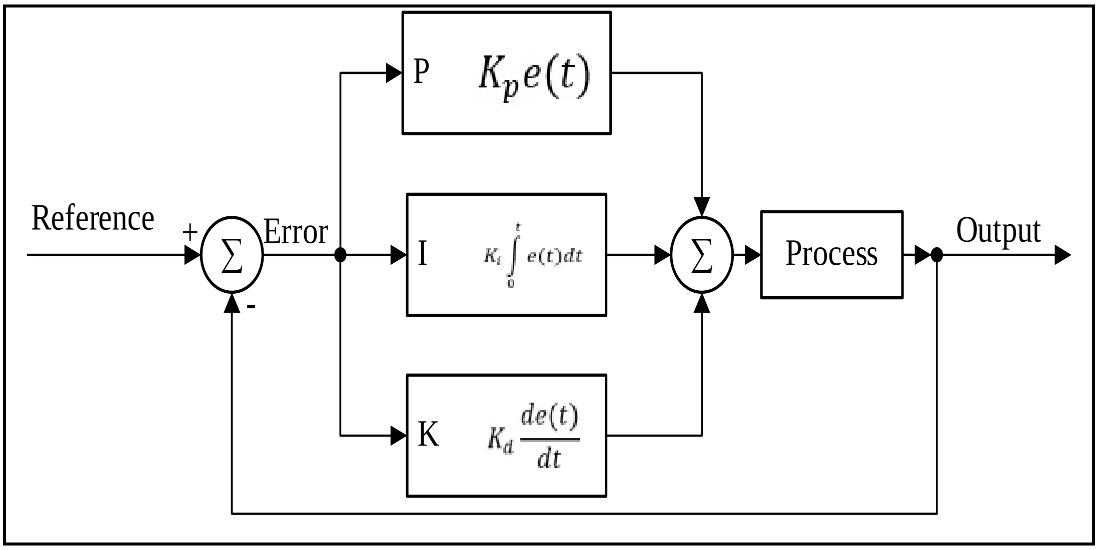

Figure 2. Basic structure of PID control system

MLS, which is designed according to the transfer function given in Eq. 24 in the Matlab/Simulink environment and has a PID control structure used in controlling the position of the ferromagnetic ball, is given in Figure 3.

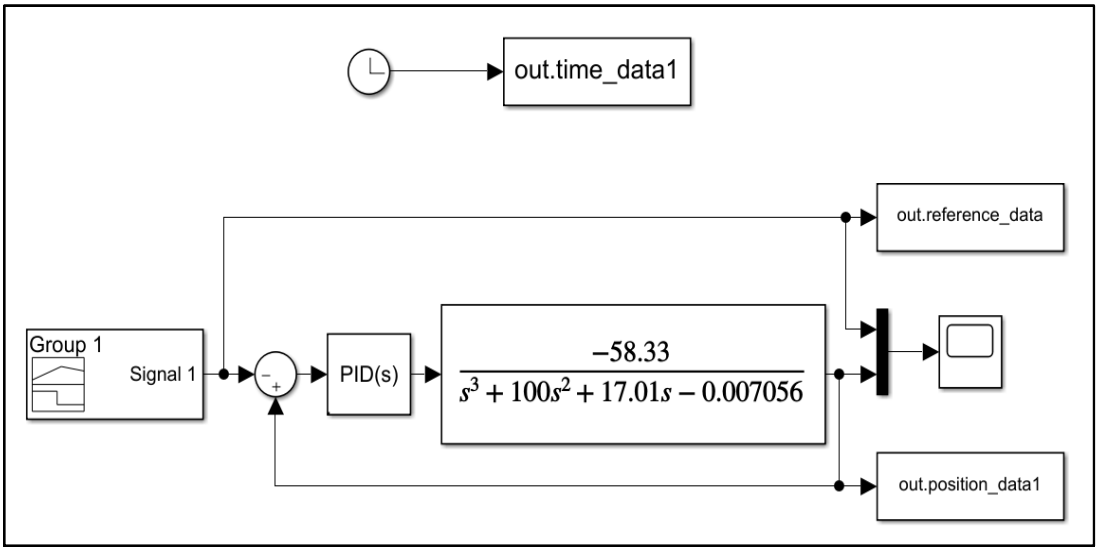

Figure 3. Matlab/Simulink structure modeled with the PID control method of MLS

Calculation of PID parameters was carried out by rearranging the results obtained with the help of Matlab/PID/Toolbox tuning feature through simulation study. As a result of the calculations, for PID gain coefficients; Values of P=11, I=0.1, D=64 was found.

In the STFPID control method, the gain coefficients of the PID controller are constantly updated online. FLC is used to update PID controller coefficients. The general structure of the STFPID control method is given in Figure 4.

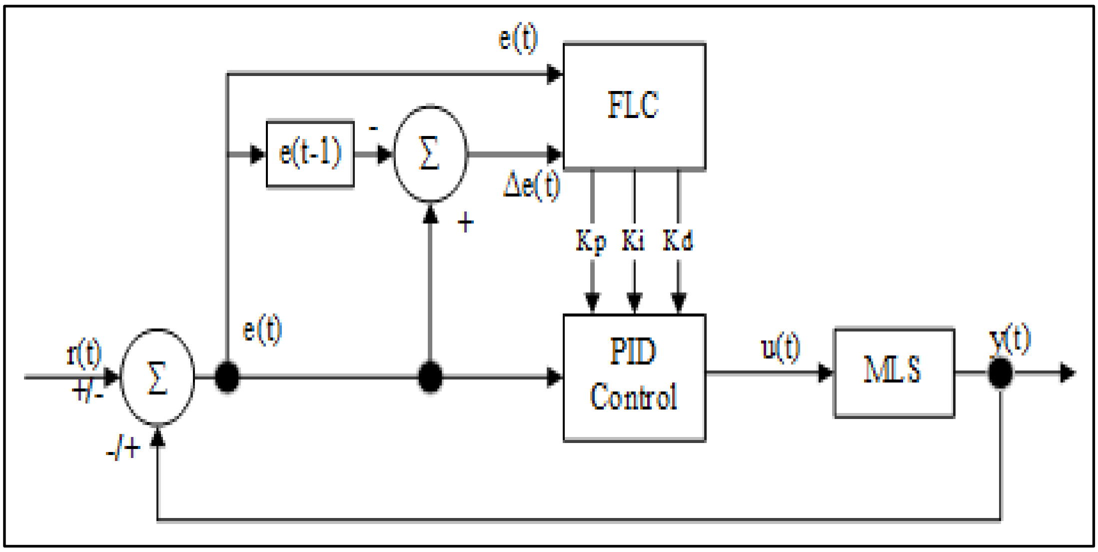

Figure 4. General structure of the STFPID control method

The inputs of FLC are the error occurring depending on the position information of the ferromagnetic ball and the change values of the error over time. The limits of the input membership functions used for FLC are given in Figure 5. The linguistic definitions expressed here are chosen as Negative Big (NB), Negative Middle (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Middle (PM), Positive Big (PB).

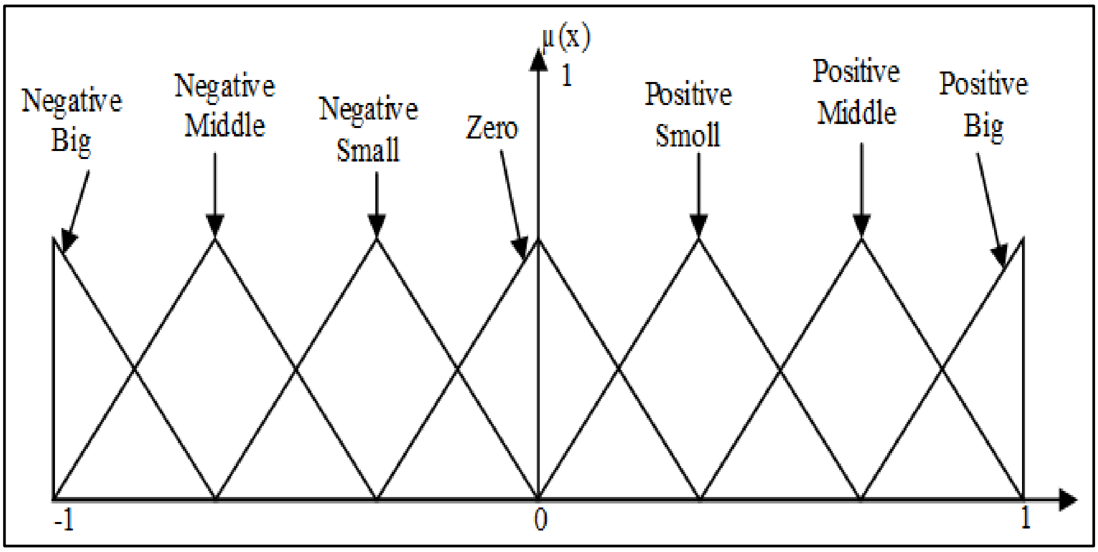

Figure 5. Input membership functions used for FLC

The output expressions of FLC are the gain coefficients of the PID controller. The limits of the output membership functions used for FLC are given in Figure 6. Membership function definitions of the outputs defined for the kp, ki and kd gain coefficients of the FLC; Seven membership functions were selected: Very Very Small (VVS), Very Small (VS), Small (S), Middle (M), Big (B), Very Big (VB), Very Very Big (VVB).

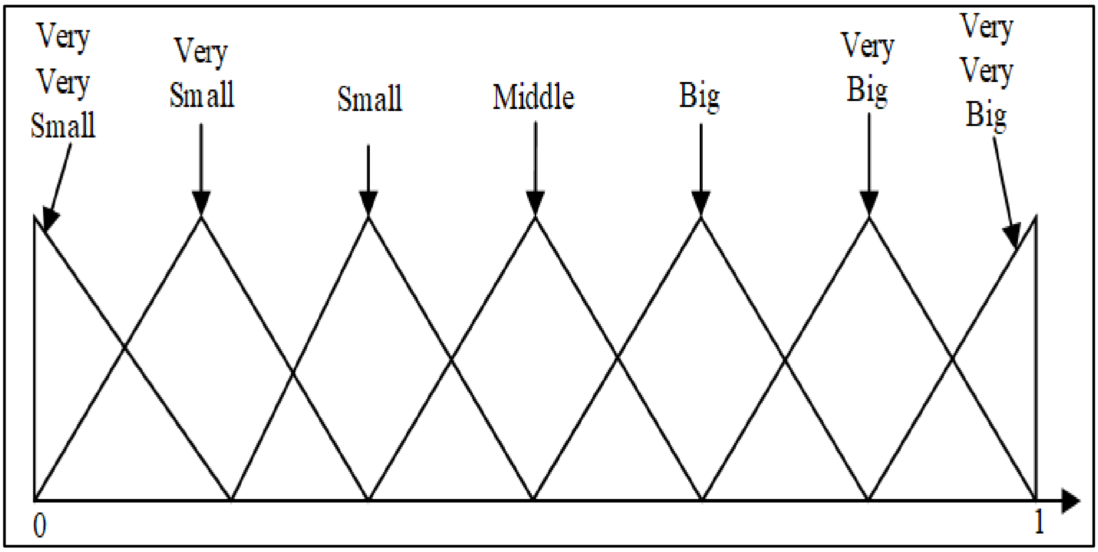

Figure 6. Output membership functions used for FLC

Using the "Fuzzy Logic Toolbox" package in the MATLAB environment, the FLC design for the STFPID control mechanism was produced. After being constructed, the model was evaluated on MLS and moved to the Simulink environment. Table 2 provides the Kp and Ki coefficients, while Table 3 provides the Kd coefficient. These tables comprise the rule foundation of the FLC created for the STFPID control mechanism. MLS with STFPID control structure, designed according to the transfer function given in Eq. 24 in the Matlab/Simulink environment and used to control the position of the ferromagnetic ball, is given in Figure 7.

Table 2. Rule table created for Kp and ki gain coefficients.

de \ e	NB	NO	NK	S	PK	PO	PB
NB	M	S	VS	VVS	VS	S	M
NO	B	M	S	VS	S	M	B
NK	VB	B	M	S	M	B	VB
S	VVB	VB	B	M	B	VB	VVB
PK	VB	B	M	S	M	B	VB
PO	B	M	S	VS	S	M	B
PB	M	S	VS	VVS	VS	S	M

Table 3. Rule table created for Kd gain coefficient.

de \ e	NB	NO	NK	S	PK	PO	PB
NB	M	B	VB	VVB	VB	B	M
NO	S	M	B	VB	B	M	S
NK	VS	S	M	B	M	S	VS
S	VVS	VS	S	M	S	VS	VVS
PK	VS	S	M	B	M	S	VS
PO	S	M	B	VB	B	M	S
PB	M	B	VB	VVB	VB	B	M

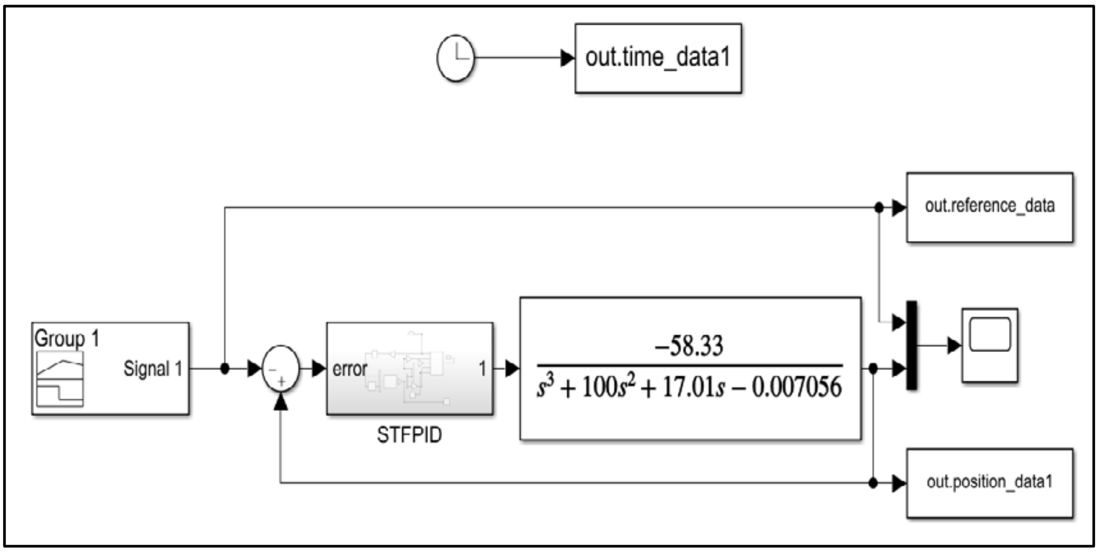

Figure 7. Matlab/Simulink structure modeled with the STFPID control method of MLS

III. RESULTS AND DISCUSSIONS

To examine and contrast the performance outcomes of the PID and STFPID control techniques established for the regulation of MLS, experimental investigations were conducted, and a simulation environment made using the Matlab/Simulink software was used. The desired height value for the ferromagnetic ball to hang without contact was applied to the controllers as a reference input value. Equitable attainment of the reference value by both controllers is the intended outcome. The trials showed that PID and STFPID controllers could successfully and evenly move the MLS to the reference position. Examined were the controllers' performances created using various tests. Reference values in the form of constant function, step function and ladder function were applied in the experiments. The constant function was applied separately for both control methods and the results are shown in Figure 8.

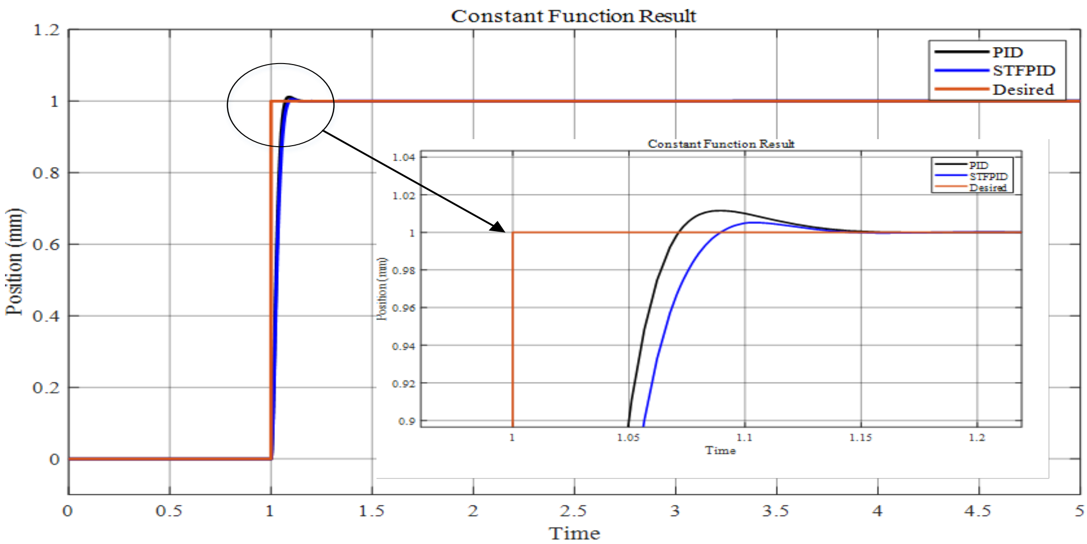

Figure 8. Results of PID and STFPID controllers for constant function.

With the results, it is clearly seen that both control methods reach the MLS to the desired reference value. However, the STFPID control method reached the reference value faster and with less overshoot than the PID control method. This result is considered as a desired result in control methods.

A step function was applied separately for both control methods and the results are shown in Figure 9.

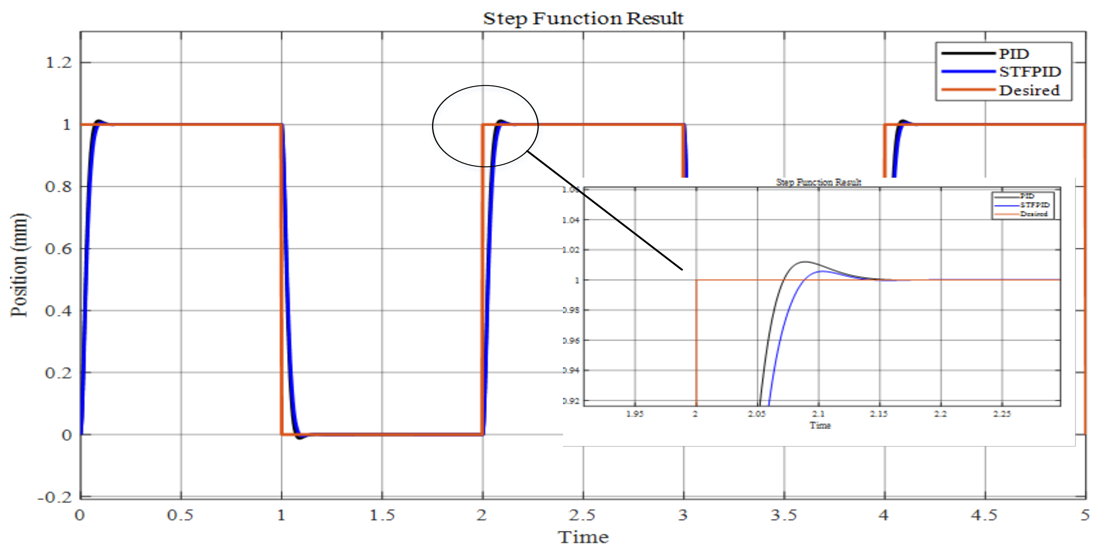

Figure 9. Results of PID and STFPID controllers for stepper function.

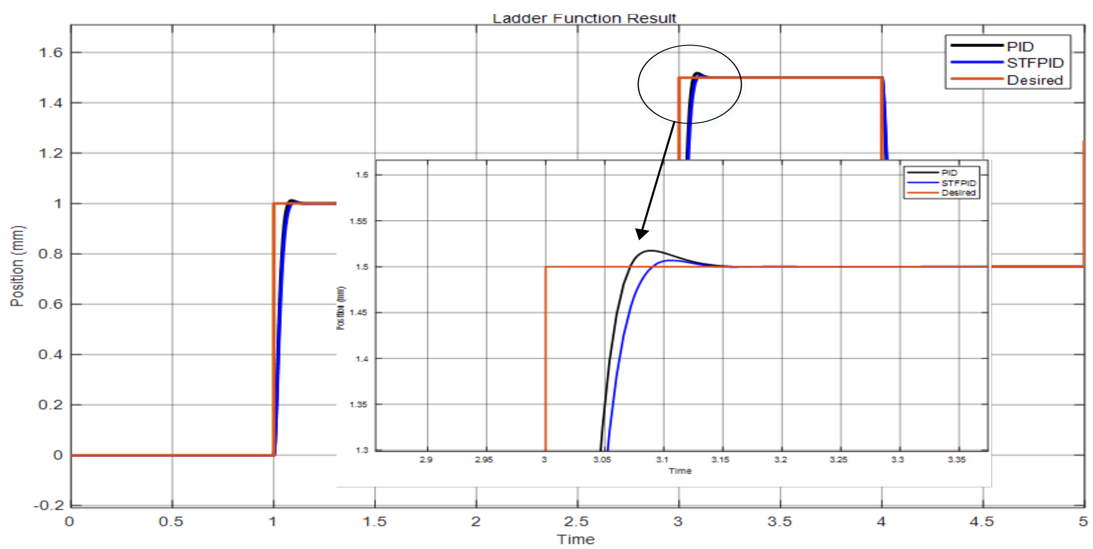

Figure 10. Results of PID and STFPID controllers for ladder function.

Table 4 displays the comparative outcomes of a performance study performed on the data collected from the tests carried out for both controllers.

Table 4. Comparison of the performances of PID and STFPID control methods

Parameters	PID	STFPID
Reference value	1	1
Rise time (sec)	0. 072	0.0885
Setting time (sec)	0.1675	0.147
Maximum overshoot (%)	1.15	0.55
Overshoot (mm)	0.0115	0.0055

Table 4 shows the performance comparison of the PID and STFPID methods developed for position control of MLS for four different parameters. Comparisons were made according to rise time, settling time, maximum exceedance percentage and exceedance values. In line with these results, it was observed that the STFPID method had the lowest overshoot value and the fastest settling time. It is clearly seen in the results that the STFPID control method gives faster dynamic responses than the PID control method for position control of MLS.

IV. CONCLUSIONS

Due to developments in technology, it becomes difficult to express many systems mathematically. This situation creates systems that are difficult to control and nonlinear. In order to cope with these problems, existing control systems need to be improved and thus more successful control methods need to be created. MSLs attract the attention of researchers working on development studies in this field due to their nonlinear structure and difficulty in controlling. In this study, PID and STFPID controllers were developed for an MLS modeled in a simulation environment. The created controllers were used on MLS, and four distinct factors were evaluated between the techniques and performance outcomes. Based on the information gathered from the simulation outcomes, both approaches successfully moved the ferromagnetic ball, which started out at zero position, to the intended location in a balanced way. The PID controller simulation research demonstrates that the system surpasses the reference point and attains the intended result. In the simulation study conducted with the STFPID controller, it is clearly seen in the results obtained by exceeding the reference point less than the PID controller. The STFPID controller reaches the reference point by overshooting by 0.0055 mm. The PID controller reaches the reference point by overshooting by 0.0115 mm. The STFPID controller reaches the reference point in 0.147 seconds. The PID controller reaches the reference point in 0.1675 seconds. In line with these results, it is clearly seen in the results that the STFPID control method gives faster and more dynamic responses than the PID control method. On the other hand, in application areas where very fast responses are required, such as magnetic suspension and balancing systems, the use of the STFPID control method allows precise positioning within the desired time. Using the STFPID controller for applications that require very precise positioning, such as magnetic valves, will enable more effective and stable system operation. Consequently, using the STFPID controller is advised in order to reach the reference value in MLS and to maintain system stability precisely, in line with the results found. The overall findings make it evident that using the STFPID controller to regulate nonlinear systems would enhance control performance and boost system stability. Simulation results confirm the effectiveness of the proposed control algorithm. In future studies, the effects of the STFPID controller on the system can be examined by applying it on various nonlinear systems.

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