NONLINEAR TRACKING MOTION CONTROL BASED MULTI-VERSE OPTIMIZATION FOR MAGNETIC LEVITATION SYSTEMS

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Abstract - Magnetic levitation (Maglev) systems are employed in a wide range of applications and are therefore of significant practical importance, which has led to growing research interest. This paper presents the design of a terminal synergetic control (TSC) and feedback linearization-based proportional-integral-derivative plus second-order derivative (FL-PIDD2) controller for the Maglev system. For developing the control law of both controllers, the mathematical model of the Maglev system is converted into a canonical system where the expression of the nonlinearity is displayed in the last differential dynamic equation of the system. The determination of the TSC and FL-PIDD^2 gains for achieving the desired dynamic response is carried out using the multi-verse optimization (MVO) approach. Computer simulations on MATLAB are used to examine the performance of the proposed controllers. The simulation outcomes reveal that the TSC has superior response performance and a lesser effect from external disturbances compared to the results of the FL-PIDD^2 controller. Furthermore, compared to the published results of the classical synergetic control (CSC) and the feedback linearization based state feedback controller (FL-SFC), TSC have also shown better than the CSC and FL-SFC in terms of performance and robustness.

Keywords: Magnetic levitation, Nonlinear control, Terminal synergetic control, Multi-verse optimization; Computer simulation.

1. Introduction

Magnetic levitation (Maglev) systems have numerous industrial applications due to their contactless and frictionless properties which increase the efficiency and reduce mechanical wear and maintenance costs [1]-[6]. The system includes a ferromagnetic ball of a given mass. The magnetic field of a ball is maintained suspended in an air gap by an adjustable strength that can be controlled by an applied voltage, as in references [7]-[10]. Due to its inherent nonlinearities and highly unstable nature, designing a control algorithm that can maintain stable control of the Maglev system is challenging.

In this context, many linear and nonlinear control mechanisms are offered to stabilize the system. As an example, Ahmad et al. [11] propose a proportional-integral-derivative (PID) controller for a magnetic levitation (Maglev) system. An adjustment of the PID tuning parameters was performed with the genetic algorithm (GA). The simulation outcomes showed that the tuning of the PID by the GA is superior to the conventional Ziegler Nichols (ZN) tuning technique. The most efficient linear-quadratic-based regulator was suggested by Benomair [12], who used an improved spiral dynamic regulator to actively control a Maglev system with full-state feedback linearization, and simulations have been done based on the nonlinear mathematical model of the system. Roy et al. [13] carried out a comparative analysis between a fractional-order PID (FOPID) controller and a classical PID controller to control the ball position in a Maglev system. To optimize the controller parameters, three swarm-optimization algorithms, including the gravitational search algorithm (GSA), particle swarm optimization (PSO), and a hybrid version of the Particle Swarm and Gravitational Search, PSOGSA, have been used. It has been

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established that the PSOGSA hybrid algorithm gives a better performance in comparison to the corresponding standalone algorithms and that the FOPID controller is better than the conventional PID controller. Moreover, Ataşlar-Ayyildiz and Karahan [14] proposed fuzzy-PID, which is a PID-like, strong fuzzy logic controller, to gain a better understanding of the dynamics and stability of the system. The cuckoo search (CS) algorithm was used to tune the parameters of the controller based on time-domain response properties, which is considered the objective function. The simulation experiments with disturbed conditions proved that the CS-based Fuzzy-PID is superior to both the FOPID and PID controllers with regard to steady-state error, settling time, overshoot, and control effort required. Ekinci et al. [15] also designed a second-order derivative of the PID (PIDD^2) controller for the Maglev system, and optimized the design variables of the controller using the Manta Ray Foraging Optimization (MRFO) algorithm in conjunction with the Generalized Opposition-Based Learning (GOBL) algorithm and Nelder-Mead simplex search method. Besides, the Maglev system was introduced as a linear feed-forward controller using a fuzzy logic controller (FLC) by Chiem and Thang [16]. The proposed controller provides stability to the system and achieves a fast response. Comparative performance appraisals of a conventional PID controller and a standalone FLC indicate a rapid and steady response despite the presence of noise. Nevertheless, these investigations only considered the linear model of the Maglev system.

In the context of the nonlinear model of the Maglev system, Al-Muthairi and Zribi [17] introduced a sliding-mode control (SMC) scheme to ensure the asymptotic control of the system states to the required values. Two modifications of the traditional structure of the SMC were made to reduce the phenomenon of chattering, and the control schemes obtained were demonstrated to be resilient to changes in the parameters of the system. Ma'arif et al. [18] handled the problem of controlling the Maglev system using the SMC. The proposed approach shows a rapid response of the output with a significant reduction in the steady-state error. However, the work did not address the problem of chattering. Uswarman et al. [19] compared traditional SMC with an SMC that uses gain-scheduling. The simulation results show that the SMC-based gain-scheduled controller has better performance due to external disturbances, but the chatter is still a problem for both controllers. Al-Ani et al. [20] proposed a trajectory tracking control of the Maglev system by applying optimal synergetic control (SC) and a feedback-linearization-based state-feedback controller (FL-SFC). Controller gains were optimized using the Swarm Bipolar Algorithm (SBA) based on the Integral Time Absolute Error (ITAE) performance index to achieve the targeted response. Computer simulations are conducted to evaluate the performance of the proposed methodology. The results indicate that in normal conditions, the SC controller is more effective than the FL-SFC controller in controlling the Maglev system. Both controllers exhibit zero maximum overshoot and eliminate steady-state error, but SC responds faster compared to FL-SFC's. Additionally, when the Maglev system experiences external disturbances, SC exhibits better performance than that of the FL-SFC in terms of reducing the ITAE index. This study makes the following key contributions:

1. The design of two nonlinear controllers, Terminal synergetic control (TSC) and feedback linearization based proportional-integral-derivative plus the second-order derivative (FL-PIDD^2), for stabilizing and tracking the trajectory of a Maglev system based on its nonlinear dynamics across different operating scenarios.
2. The multi-verse optimization (MVO) is introduced as an optimization tool to determine the optimal controller parameters and improve system dynamic behaviour.

The rest of the paper is structured as follows: Section 2 describes the mathematical modeling of the magnetic levitation system. Section 3 explains the design procedure of the proposed controllers. Section 4 introduces the Multi-Verse Optimization. Section 5 discusses the obtained results of the simulation. Finally, Section 6 summarizes the conclusion of the paper.

2. Mathematical Model

The magnetic levitation is composed of a ferromagnetic ball that is suspended in a magnetic field controlled with the voltage [21]. The goal of the control is to perform high positional accuracy of the steel ball, which is ensured to be in a steady levitation position [22]. The schematic of the system is shown in Figure 1 [18]. These parameters and the symbols which are relevant to the system are: electromagnetic force (f_e), gravitational force (f_g), inductance (L), resistance (R), ball position (x), source voltage (V), ball mass (m), and current (i). The equations of motion of the mechanical components can be written in the following way using the second law of motion [10]:

$$m\frac{d^2x}{dt^2} = f_g - f_e \quad (1)$$

where the electromagnetic and gravitational forces are given by:

$$f_g = mg \quad (2)$$

$$f_e = \frac{1}{2}i^2\frac{dy}{dx}\left(L(x)\right) \quad (3)$$

$L(x)$ is an operating non linear operational mathematical relationship that can take the form as:

$$L(x) = L + L_0x_0 \quad (4)$$

Equation (4) can be approximated as [17]:

$$L(x) = \frac{2k}{x^2} \tag{5}$$

where k is the force constant. Substituting the result of Eq. (5) in Eq. (3) gives:

$$f_e = k\left(\frac{i}{x}\right)^2 \tag{6}$$

Substituting Eq.s (2) and (6) in Eq. (1) gives:

$$m\frac{d^2x}{dt^2} = mg - k\left(\frac{i}{x}\right)^2 \tag{7}$$

By rearranging Eq. (7), we get:

$$\frac{d^2x}{dt^2} = g - \frac{k}{m}\left(\frac{i}{x}\right)^2 \tag{8}$$

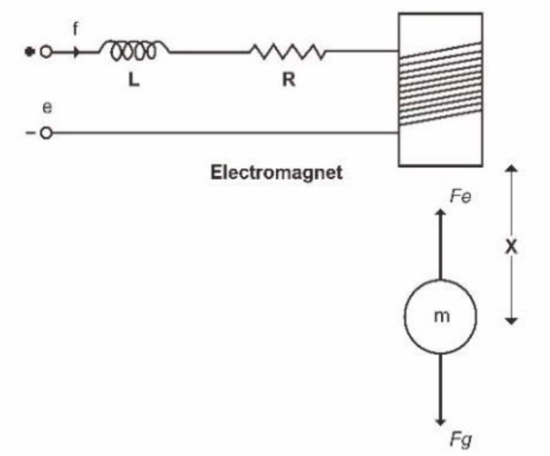

Figure 1: The Maglev system

Other than the mechanical analysis, the Kirchhoff law of voltage in the electrical system may be applied to derive Eq. (9).

$$e = iR + \frac{d}{dt}L(x)i \tag{9}$$

Using simple mathematical operations, the equation can be rewritten as:

$$\frac{di}{dt} = -\frac{R}{L}i - \frac{2k}{L}\frac{i}{x^2}\frac{dx}{dt} + \frac{1}{L}e \tag{10}$$

With the assumption that the states of the system are $x_1 = x, x_2 = \frac{dx}{dt}, x_3 = i$, and the control input to the system is $u = e$, then the dynamics of the Maglev system are governed by the following nonlinear differential equations:

$$\frac{dx_1}{dt} = x_2 \tag{11}$$

$$\frac{dx_2}{dt} = g - \frac{kx_3^2}{mx_1^2} \tag{12}$$

$$\frac{dx_3}{dt} = -\frac{Rx_3}{L} + \frac{2kx_2x_3}{Lx_1^2} + \frac{u}{L} \tag{13}$$

where $x_1 > 0$ and $x_3 > 0$.

The system's output can be described as:

$$y = x_1 \tag{14}$$

Specifically, it is possible to see the nonlinearity aspects in the form of the equation, as it can be observed in the dynamics of Maglev system, Eq. (12) and Eq. (13). In order to formulate the model of the Maglev into an equivalent canonical system, the model is converted into a simpler canonical system, a form that actually displays the nonlinearity in an expression of a single dynamic equation. The nonlinear transformation of the coordinates is defined as follows:

$$z_1 = x_1 \tag{15}$$

$$z_2 = x_2 \tag{16}$$

$$z_3 = g - \frac{kx_3^2}{mx_1^2} \tag{17}$$

Thus, the equivalent model in the new coordinates can be expressed as:

$$\dot{z}_1 = z_2 \tag{18}$$

$$\dot{z}_2 = z_3 \tag{19}$$

$$\dot{z}_3 = f(x) + g(x)\,u \tag{20}$$

where

$$f(z) = \frac{2kR\,x_3^2}{mx_1^2L} - \frac{4k^2\,x_3^2x_2}{mx_1^4L} + \frac{2kx_2x_3^2}{mx_1^3} \tag{21}$$

$$g(z) = -\frac{2kx_3}{mx_1^2L} \tag{22}$$

The functions $f(z)$ and $g(z)$ are obtained by differentiating z_3 with respect to x and substituting $\dot{x}_1$ and $\dot{x}_3$ according to Eqs. (11) and (13), respectively.

3. Tracking Motion Control

Feedback control algorithms have the ability to adjust the dynamics of the systems to the predefined performance [23]-[25]. Over the years, many types of control systems have been introduced to cover a wide range of systems [26]-[29]. This section present the procedure to design two nonlinear control approaches for deriving the control law of the Maglev system, namely terminal synergetic control (TSC) and feedback linearization–based proportional-integral-derivative plus the second-order derivative (FL-PIDD[2]) controller. These controllers are particularly appropriate for Maglev applications, as they effectively address the inherent nonlinear dynamics, enabling fast and stable positioning of the levitated object while preserving robustness against disturbances. For the purpose of designing the two nonlinear controllers, let define the tracking error e as the difference between the desired position x_d and the actual position x_1 of the Maglev as follows:

$$e = x_d - z_1 \quad (23)$$

The 1st, the 2nd and the 3rd derivatives of e are given in Eq. (24), Eq. (25) and Eq. (26) respectively:

$$\dot{e} = \dot{x}_d - \dot{z}_1 = \dot{x}_d - z_2 \quad (24)$$

$$\ddot{e} = \ddot{x}_d - \dot{z}_2 = \ddot{x}_d - z_3 \quad (25)$$

$$\dddot{e} = \dddot{x}_d - \dot{z}_3 \quad (26)$$

- ***Terminal Synergetic Control***

Synergetic control (SC) technique has been widely used to control numerous systems [30]. For further enhancement in the SC performance, the SC has been integrated with the terminal technique [31]-[32]. In this subsection, the procedure to design Terminal SC (TSC) for the Maglev system is presented. One of the advantages of designing the TSC is that they do not require the linearization of the Maglev system. In the context of terminal technique, the marco-variable φ is defined as follows:

$$\varphi = c_1 e^q + c_2 \dot{e} + \ddot{e} \quad (27)$$

where $0 > q > 1, c_1$ and $c_2 > 0$
The result of the first derivative of φ gives:

$$\dot{\varphi} = qc_1(e^{1-q})\dot{e} + c_2\ddot{e} + \dddot{e} \quad (28)$$

Select state trajectories of φ as:

$$\dot{\varphi} + c_3\varphi = 0 \quad (29)$$

Substitute $\dot{\varphi}$ gives:

$$qc_1(e^{1-q})\dot{e} + c_2\ddot{e} + \dddot{e} + c_3\varphi = 0 \quad (30)$$

Substitute $\dddot{e}$ as given in Eq. (26):

$$qc_1(e^{1-q})\dot{e} + c_2\ddot{e} + \dddot{x}_d - \dot{z}_3 + c_3\varphi = 0 \quad (31)$$

Substitute $\dot{z}_3$ as given in Eq. (20):

$$qc_1(e^{1-q})\dot{e} + c_2\ddot{e} + \dddot{x}_d - f(x) - g(x)\,u + c_3\varphi = 0 \quad (32)$$

To find the control law of TSC (u_{TSC}), solving Eq. (32) for u:

$$u_{TSC} = \frac{1}{g(x)}(\dddot{x}_d - f(x) + qc_1(e^{1-q})\dot{e} + c_2\ddot{e} + c_3\varphi) \quad (33)$$

- ***Feedback Linearization–based Proportional-Integral-Derivative plus Second-Order Derivative***

Feedback linearization (FL) is one of the most extensively studied methodologies for the design of trajectory tracking controllers in nonlinear systems [33]. The control law in FL is designed such that the nonlinear system is transformed into an equivalent linear form as follows:

$$u_{FL} = \frac{1}{g(x)}(-f(x) + u_l) \quad (34)$$

where u_l can be any linear controller. In this paper, a proportional-integral-derivative plus the second-order derivative (PIDD²) is selected as follows [34]:

$$u_l = k_p e + k_i \int e + k_d \dot{e} + k_{d2}\ddot{e} \quad (35)$$

where k_p, k_i, k_d and k_{d2} are the PIDD² gains that are designed such that the desired tracking performance is achieved. Substitute u_l into Eq. (34), the control law of FL-PIDD² ($u_{FL-PIDD^2}$) is given by:

$$u_{FL-PIDD^2} = \frac{1}{g(x)}(-f(x) + k_p e + k_i \int e + k_d \dot{e} + k_{d2}\ddot{e}) \quad (36)$$

4. Multi-Verse Optimization

Swarm optimization methods can be described as a category of optimization algorithms that could be used to handle complicated and difficult engineering problems. These algorithms are inspired by human natural processes, social processes and enhance version of the heuristic strategies [35]-[36]. In control systems, calibrating controller parameters to ensure desired system performance is a significant challenge. The optimization algorithms are employed by so many researchers in place of the conventional trial-and error methods since the former possesses more effective and efficient solutions in determining the best controller settings [37]-[42].

Multi-verse optimization (MVO) is a swarm-based algorithm, which is based on the theory of the multi-verse in cosmology [43]. The algorithm is described using three major concepts diminished as white holes, black holes, and wormholes. The three concepts were applied to define the balance exploration, exploitation and local search in the optimization process [44]. MVO has demonstrated encouraging performance both on standard benchmark functions and on real-world engineering optimization problems [45]. Within the MVO framework, a universe functions as a search agent, i.e., a potential solution. Its fitness is assessed according to its inflation rate, where larger inflation values correspond to higher solution quality. The search mechanism of the algorithm needs the interaction between the white and black holes. Universe that have a higher inflation are the ones that contain white holes since they can transfer variables (objects) to other ones, whereas the ones with lower inflation rates have black holes, which mean that they are more likely to receive the variables. In mathematics, a roulette wheel selection process is used to simulate this exchange process. The universes are ranked based on their rate of inflation during each iteration and through this, one is chosen on the roulette wheel to serve as a white hole. The procedure continues as follows. Assume that:

$$U = \begin{bmatrix} x_1{}^1 & x_1{}^2 & \dots & x_1{}^d \\ x_1{}^1 & x_2{}^2 & \cdots & x_2{}^d \\ \vdots & \vdots & \vdots & \vdots \\ x_n{}^1 & x_n{}^2 & \cdots & x_n{}^d \end{bmatrix} \quad (37)$$

Here, d and n denote the number of design parameters (i.e. decision variables) and the universes' number, respectively.

$$x_j{}^i = \begin{cases} x_j{}^k & \text{if } r_1 < NI(U_i) \\ x_j{}^i & \text{otherwise} \end{cases} \quad (38)$$

Here, $x_j{}^i$ is denotes the j parameter of the i universe, U_i indicates the i universe itself, and $NI(U_i)$ is the normalized of the rate of inflation of that unit. The r_1 denotes a randomly selected value in a range of [0, 1] and [0, 1], while $x_j{}^k$ denotes a parameter of a universe k, which is selected in the form of a roulette wheel. Superior solutions influence the updating process of inferior ones, whereas population diversity is maintained by wormholes that permit random teleportation to any universe, regardless of inflation rate. This is to make sure that the search is guided with the best solutions without limiting the capability of exploration. The rule of wormhole update is stated as follows [46]:

If $r_2 < WEP$

If $\text{if}\, r_3 < 0.5$

$$x_j{}^i = x_j + TRD * (ub_j - lb_j) * r_4 + lb_j \quad (39)$$

Else

$$x_j{}^i = x_j - TRD * (ub_j - lb_j) * r_4 + lb_j$$

Else

$$x_j{}^i = x_j{}^i$$

In this model, x_j is the optimal solution that is found so far, and Traveling Distance Rate (TRD) determines the size of the step size. ub_j and lb_j are terms that are understood as the upper and lower limits of variable j respectively. Further, r_2, r_3, r_4 are arbitrary numbers that are randomly drawn with probability uniform distribution in [0, 1]. To effectively shift the search process from exploration to exploitation, the MVO algorithm employs two adaptive parameters. One of these is the Wormhole Existence Probability (WEP), which represents the likelihood of wormhole-based teleportation.

$$WEP = \min + \frac{l * (\max - \min)}{L} \quad (40)$$

In this context, l corresponds to the present iteration index, and L is the total iteration count. The TRD governs the precision of movement in the direction of the best solution [47]:

$$TRD = 1 - \left(\frac{l^{\frac{1}{p}}}{L^{\frac{1}{p}}} \right) \quad (41)$$

where, p defines the rate at which the process of exploration changes to the exploitation. The effectiveness of MVO stems from its exploration mechanism via white and black holes, which enhances the global search capability, and its exploitation strategy through wormholes, enabling local refinement around promising solutions. Moreover, adaptive parameter adjustment ensures a smooth transition between the exploration and exploitation phases.

The MVO employs to optimize tuning parameters $(c_1, c_2, c_2 \text{and } q)$ of the TSC's control law in the Eq. (33) and $(k_p, k_i, k_d \text{and } k_{d2})$ of the FL-PIDD²'s control law in the Eq. (36). For the purpose of comparison with the results of [20], the Integral Time of Absolute Error (ITAE) between the controller output x1 and the desired reference signal x_d is utilized as cost function as given in Eq. (42).

$$ITAE = \int_{t=0}^{t=t_{sim}} t|e|dt \quad (42)$$

where t_{sim} refers to the total time of the simulation.

5. Results and Discussions

In this section, computer simulations based on MATLAB are performed to evaluate the terminal synergetic control (TSC) and the feedback linearization based proportional-integral-derivative plus the second-order derivative (FL-PIDD²) controller that are applied to tracking control of magnetic levitation (Maglev) system. To conduct the computer simulations, the Maglev system that is described by Eqs (11-13) and the value of its main physical components that are listed in Table 1 [20] are used in the simulation to represent the dynamics of the system. The initial value of the states of the position, velocity and current was set as follows: 0.001m, 0m/s and 0.3A respectively. The desired position was set to 0.01m.

In order to optimize the performance suggested controller, a multi-verse optimization (MVO) is used to plate tune the design parameters of the TSC. The population size (N) and the number of Iterations (T_{max}) of the MVO is 20 and 30 respectively. Table 2 gives the values of the design parameters of TSC according to MVO.

Table 1. Parameters of Maglev System

Parameters	Values
Resistance (R)	4.2 Ω
Inductance (L)	0.02 H
Force constant (k)	8.25×10^{-5} Nm2/A2
Mass (m)	0.0221 Kg
Gravity acceleration (g)	9.81 m/s2

The structure of the optimized controlled system is shown in Figure 2. The convergence of the MVO for tuning the TSC based on ITAE is shown in Figure 2. In order to compare performance of the TSC, the results achieved of the classical synergetic control (CSC) and feedback linearization based state feedback controller (FL-SFC) is compared [20].

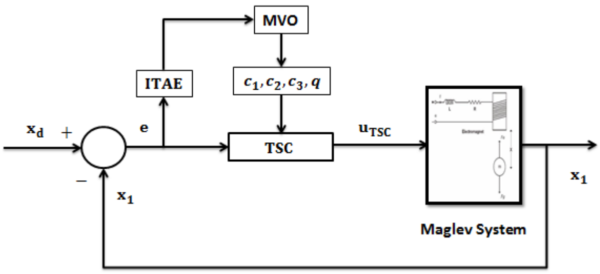

Figure 2: TSC optimized by MVO for Maglev system

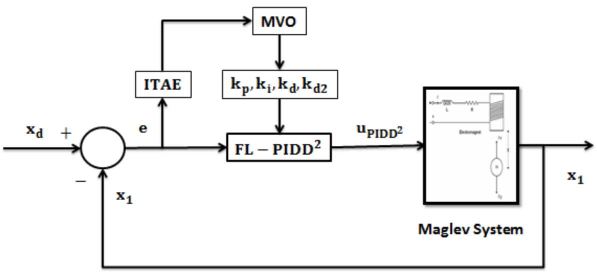

Figure 3: PIDD² optimized by MVO for Maglev system

- ***Normal Operation***

The performance of the controlled systems in this scenario is simulated for 6 seconds. The Maglev's position response with TSC and PIDD² methods is depicted in Figure 5. To determine the effectiveness of the TSC and FL-PIDD² approaches, a numerical value of the ITAE of TSC, FL-PIDD², CSC and FL-SFC is given in Table 3. The visualized result in Figure 5 with the help of the numerical result in Table 3 reveals that the TSC improves the overall performance of the system by reducing the value of the ITAE (0.0271) in comparison with the CSC (0.0374), FL-PIDD² (0.132) and FL-SFC (0.2728). This result show that the ITAE with TSC is reduced by 27.5%, 79.5% and 90% in compared with CSC, FL-PIDD2 and FL-SFC respectively. Moreover, the result show that the t_s with TSC (0.29s) is reduced in comparison with the CSC (0.35s), FL-PIDD² (0.8s) and FL-SFC (1.2s).

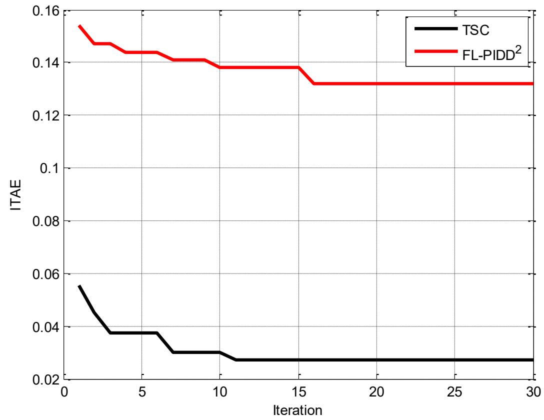

Figure 4: Convergence of MVO based on ITAE

Table 2. Optimal settings of TSC

Parameters	TSC	Parameters	FL-PIDD²
c_1	113.5	k_p	220
c_2	24.2	k_i	0.2
c_2	87.8	k_d	85
Q	0.9	k_{d2}	11

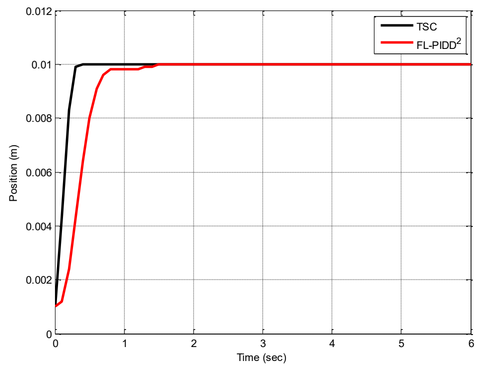

Figure 5: Position response of Maglev for step input

Table 3. Performances of system in normal operation

Controller	t_s(s)	ITAE
TSC	0.29	0.0271
FL-PIDD²	0.8	0.132
CSC (20)	0.35	0.0374
FL-SFC (20)	1.2	0.2827

- ***Uncertainty***

To illustrate the resilience of the designed control laws in the face of external disturbance, the TSC and FL-PIDD² are tested by subjecting the controlled system to a single external disturbance following the simulation of 5s where the overall simulation had 10s. Figure 6 indicates the response of the controlled systems in case of the disturbance. The resilience of the proposed controllers is measured based on the time of recovery (t_r) and the maximal undershoot (M_u). In this case, using Figure 6 and Table 4, it is evident that the position of the ball is recovered after being disturbed to the intended position and it also did not shift. Moreover, TSC has better disturbance rejection where M_u of the TSC was 3 compared to CSC (5), FL-PIDD² (10) and FL-SFC (19). However, t_r (0.1s) was same for the CSC and TSC which is less as compared to the FL-PIDD² (0.4s) and FL-SFC (0.65s).

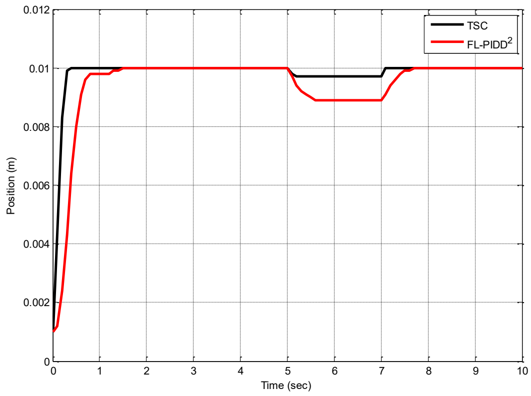

Figure 6. Position's response of Maglev under external disturbance

Table 4. Performances of system in the presence of external disturbance

Controller	$t_r(s)$	Mu(%)
TSC	0.1	3
FL-PIDD²	0.4	10
SC (20)	0.1	5
FL-SFC (20)	0.65	19

Based on these results, it can be observed that the additional terminal factor that has been added to CSC increased the capability of the controller in terms of performance and robustness. This improvement could be further cross-validated on other systems in the future.

6. Conclusions

Magnetic levitation (Maglev) systems have been widely adopted in a variety of industrial applications due to their significant practical importance. The control design of Maglev systems remains a valuable benchmark for evaluating control performance. In this paper, a terminal synergetic control (TSC) and feedback linearization-based proportional-integral-derivative plus the second-order derivative (FL-PIDD²) controller are presented for tracking motion control of the Maglev system. The performance of the proposed control was examined using computer-simulation (MATLAB software). Efficient comparisons in terms of normal operation and under external disturbance are presented. A step reference signal was selected in the simulation. Results analysis reveals that the TSC is more effective than FL-PIDD² for both cases. Moreover, the performance of the TSC is compared with the results obtained from the classical synergetic control (CSC) and the feedback linearization-based state feedback controller (FL-SFC). TSC exhibits a superior performance in normal operation and more robustness to external disturbance than CSC and FL-SFC. Future research could examine the performance of TSC in more complex conditions, such as time-varying disturbances or parameter variations, and investigate the implementation of TSC on real hardware for practical validation.

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