International Journal of Dynamics and Control (2023) 11:441–451
https://doi.org/10.1007/s40435-022-00971-z

Control techniques for electromagnetic levitation system: a literature review

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Received: 9 April 2022 / Revised: 1 May 2022 / Accepted: 3 May 2022 / Published online: 6 June 2022

Abstract
Electromagnetic levitation is a cutting-edge technology with a wide range of applications in several fields. Because of the increasing demand for this technology, an in-depth investigation of its dynamics and control technologies is required. This article aims to provide a detailed review of the control techniques that are available for controlling the performance of an electromagnetic levitation system. Furthermore, the merits and demerits of existing control methods that have been investigated for the electromagnetic levitation system are also drawn in this survey.

Keywords Electromagnetic levitation system · Nonlinear system · Control techniques · Robust control · Modelling equation of EMLS · Inductance approximation

1 Introduction

In the past many decades, the interest in research in nonlinear systems has grown significantly. Nonlinearity is exhibited by systems that exist physically. In addition, a large spectrum of complex systems, such as ball and beam, rotary inverted pendulum, electromagnetic levitation system, and many more fall under the category of unstable nonlinear dynamical systems. The electromagnetic levitation system is considered a highly nonlinear system; however, various control techniques have been established to provide the required control for the system's nonlinear behavior. Magnetic levitation is a technique for suspending an object in the air using just the magnetic field as a support. Samuel Earnshaw investigated the difficulty of levitating an object stably using the inverse square law in 1842 [1]. This analysis was extended by Werner Braunbeck on uncharged dielectric bodies in static electric field and also on magnetic bodies in static magnetic field; hence it was observed that eddy current induced in the conducting body can have stable equilibrium state. The EML system has varied application such as magnetic levitation train, magnetic bearings, launching rockets, electromagnetic aircraft launch systems, maglev wind turbines, magnetic micro-robots, and many more.

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2 Evolutionary background

2.1 Electromagnetic levitation system

The use of permanent magnets can be traced back to 1890. Evershed utilized to the shafts of wattmeters in 1900 [2]. In 1937 a controlled ac supply electromagnet was invented to sustain an very high-speed rotor employing speed beams and centrifuges [3]. Arkadiev, in 1945, investigated the first instance of levitating objects via the superconducting effect [4]. An electromagnet was suspended using active control demonstrated by kemper in year 1937 [5]. Simon devised the magnetically suspended gyroscope in 1953 [6]. During 1966 levitating a vehicle over a conducting rail by connecting a super conductor to the vehicle's base was proposed by Powell et al. [7]. Multiple ideas for adopting magnetic levitation as a means of transportation were proposed in the 1960s and 1970s. Shanghai Transrapid, which employs the German approach, began commercial operations in April 2004, while HSST "Linimo" began commercial operations in March 2005.

2.2 Control techniques

During the eighteenth century, James Watt coined the concept of speed control of a steam engine using the centrifugal governor. In 1932, Harry Nyquist proposed the regeneration theory to determine the stability of a closed loop system on the basis of the response of an open loop system [8]. The servomechanism was developed by Hazen in 1934 for position control systems [9]. A major contribution to the stream of control systems happened in the year 1938 when the frequency domain analysis in terms of magnitude and phase was introduced by Hendrik Wade Bode [10]. Ziegler and Nichols introduced tuning rules for tuning PID controllers in 1942 [11]. The zeros and poles of a system can be determined by using the root locus method. The method was introduced by Evans in 1951 [12]. Ever since 1950s, the focus in control design issues has evolved away from designing one of many working systems and toward designing one optimal solution in certain significant sense. Modern control theory, focused on time-domain analysis and synthesis utilising state variables, has been developed around 1960, when digital computers came into existence. Optimal control of both random and fixed systems, as well as adaptable and learning control of complicated systems, were thoroughly explored between 1960 and 1980. First from 1980s through the 1990s, the focus of modern control theory was on robust control [13].

The Fig. 1 shows the key features of the control system. However, the control system can be separated as classical, modern, and post-modern control systems. There are different techniques available to analyse the classical control system. Stability analysis can be done by using the Routh–Hurwitz criteria and root locus technique. Gain and phase margin analysis can be carried out by the Bode and Nyquist plot. Stability analysis of modern control systems is related to eigenvalues. Furthermore, controllability and observability analysis can be done with eigenvectors and vector spaces. Subspaces and eigenvectors are used to analyse the reachability and detectability. Different classical controllers and compensators are available to obtain the required control action, such as proportional (P), integral I, derivative D, proportional–integral (PI), proportional–derivative PD, proportional–integral–derivative PID, lead compensator, lag compensator and lead-lag compensator. Using the pole placement technique and a linear quadratic regulator, modern control actions can be designed. The estimation can be achieved by using the Kalman filter and the Luenberger observer. Nonlinear system control action requires modelling, which can be done by using ordinary differential equations. Global analysis is required for such systems, and design can be achieved by employing techniques like sliding mode control, backstepping, feedback linearisation, Sontag controller design and many more.

The next section of this article will discuss the importance of mathematical modelling in systems. It will also present the different models that have been established for the electromagnetic levitation system.

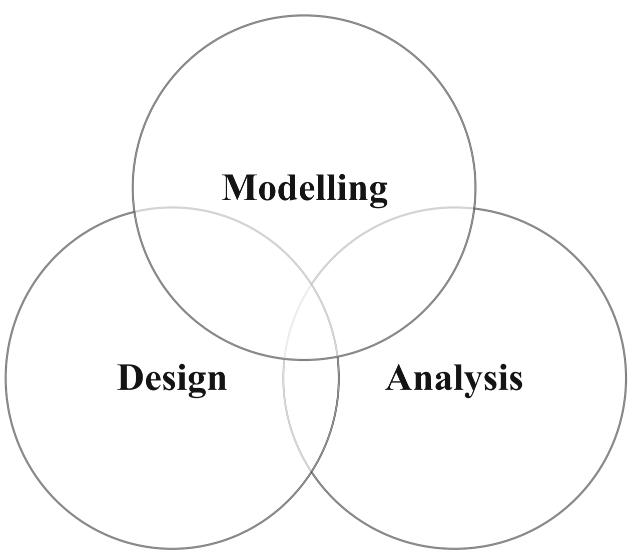

Fig. 1 Features of the control system

3 Modelling of electromagnetic levitation system

A mathematical model is a set of mathematical equations that are used to depict control systems. Such methods are important for control system design and analysis. With the known input and mathematical model for a control system, the output can be discovered. Differential equations, transfer functions, and state space models are frequently used to model any system. Modelling of the EML system is done on the basis of a nonlinear differential equation, which is then transformed into the state space model. Some of the mathematical equations of the electromagnetic levitation system are discussed in the table below.

Table 1 illustrates the different approaches to model the electromagnetic levitation system while taking into account the various system parameters. However, the electromagnetic levitation system (EMLS) modelling is not confined to the discussed methodologies only. The model equation of the EMLS can also be addressed based on the variation caused by parameters such as inductance. The attractive force which is generated in a magnetic levitation system is a function of the inductance of the coil [19]. Factors like time delay, instability, and uncertainty can be generated in the system if an inaccurate approximation of inductance is present in the system [20]. Hence some of the inductance approximation are discussed in Table 2.

Table 1 Modelling equations of EMLS

1.	$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 3\frac{C}{m}\frac{i_0}{d_0^4} & 0 & -\frac{C}{m}\frac{1}{d_0^3}\\ 0 & 0 & -\frac{R}{L}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{1}{L_c}\end{bmatrix}u,\ y = \begin{bmatrix}-2x_1\frac{\beta}{d^3}0\gamma x_3\end{bmatrix}$
2.	$\begin{bmatrix}\dot{x}\end{bmatrix} = \begin{bmatrix}x_2\\ g + \frac{Fd}{Mb} - C_1\left(\frac{x_3}{x_1}\right)^2\\ -C_4x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ C_5\end{bmatrix}u,\ y = \begin{bmatrix}x_1 & 0 & 0\end{bmatrix}$
3.	$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix}x_2\\ -\frac{F_{em1}}{2m} + g\\ \frac{1}{f_i(x_1)}\left(c_i - x_3\right)\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{k_i}{f_i(x_1)}\end{bmatrix}u,\ y = \begin{bmatrix}x_1 & 0 & 0\end{bmatrix}$
4.	$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix}x_2\\ g_c - \frac{C}{m}\left(\frac{x_3}{x_1}\right)^2\\ -\frac{R}{L}x_3 + \frac{2C}{L}\left(\frac{x_2x_3}{x_1^2}\right)\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{1}{L}\end{bmatrix}u,\ y = \begin{bmatrix}x_1 & 0 & 0\end{bmatrix}$
5.	$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\\ \dot{x_3}\end{bmatrix} = \begin{bmatrix}\frac{R}{L}x_1\\ x_3\\ g - \frac{1}{m}\frac{x_1^2}{b_0+b_1x_2+b_2x_2^3+b_3x_2^4}\end{bmatrix} + \begin{bmatrix}\frac{1}{L}\\ 0\\ 0\end{bmatrix}u,\ y = \begin{bmatrix}0 & x_2 & 0\end{bmatrix}$ [14–18]

Table 2 Inductance approximation

Equation of force	Equation of inductance
$F_c(x, i) = -\frac{1}{2}i^2\frac{\mathrm{d}L(x)}{\mathrm{d}x}$	$L(x) = L(\infty) + \frac{a}{\left(1+\frac{x}{\beta}\right)^2}$
$F = -\frac{i^2}{2}\frac{\mathrm{d}L}{\mathrm{d}x}$	$L = L_1 + \frac{L_0x_0}{x}$
$f(i, x) = -\frac{1}{2a}L_0\exp^{-\frac{x}{a}}i^2$	$L(x) = L_1 + L_0\exp^{-\frac{x}{a}}$ [21–23]

Therefore, it becomes essential to investigate and study the different techniques that are available to control unstable nonlinear dynamical systems. The next section of this article will focus on the detailed study of different control methods that have been established to provide the necessary control to an electromagnetic levitation system.

4 Electromagnetic levitation system control techniques

With the availability of varied control techniques, it has become easy to control the highly unstable nonlinear dynamical systems like electromagnetic levitation system (Fig. 2). In last several years the controlling of EML system has been done. Some of those techniques are discussed in this section.

4.1 Classical control of EML system

Classical control techniques mostly employ the PID controller. This controller is a feedback-based controller which works on the difference between the desired value and the obtained value. The authors in [24] have designed a PID controller for an electromagnetic levitation system and tested the performance of the controller with different test inputs. However, the designed controller is simple as the disturbance in the system is not considered. With position and velocity as the variables of the system, the required control input is obtained by using the exponential function whose value is less than unity, which implies that when the system deviates from its operating point, the feedback coefficient of position and velocity will decrease [25,26]. The nonlinear PID controller has been built to achieve the lowest air gap and assure suspension security when the magnetic levitated train operates at high speeds. However, the controller's robustness in terms of performance is not achieved [27]. Since PID controllers are linear, employing them in nonlinear dynamic systems such as electromagnetic levitation causes the system's performance to vary. Tuning the PID controller can prevent the overshoot, but it may result in increased settling time and decreased system performance. Therefore, it becomes necessary to study better controllers that are capable of handling such dynamical systems.

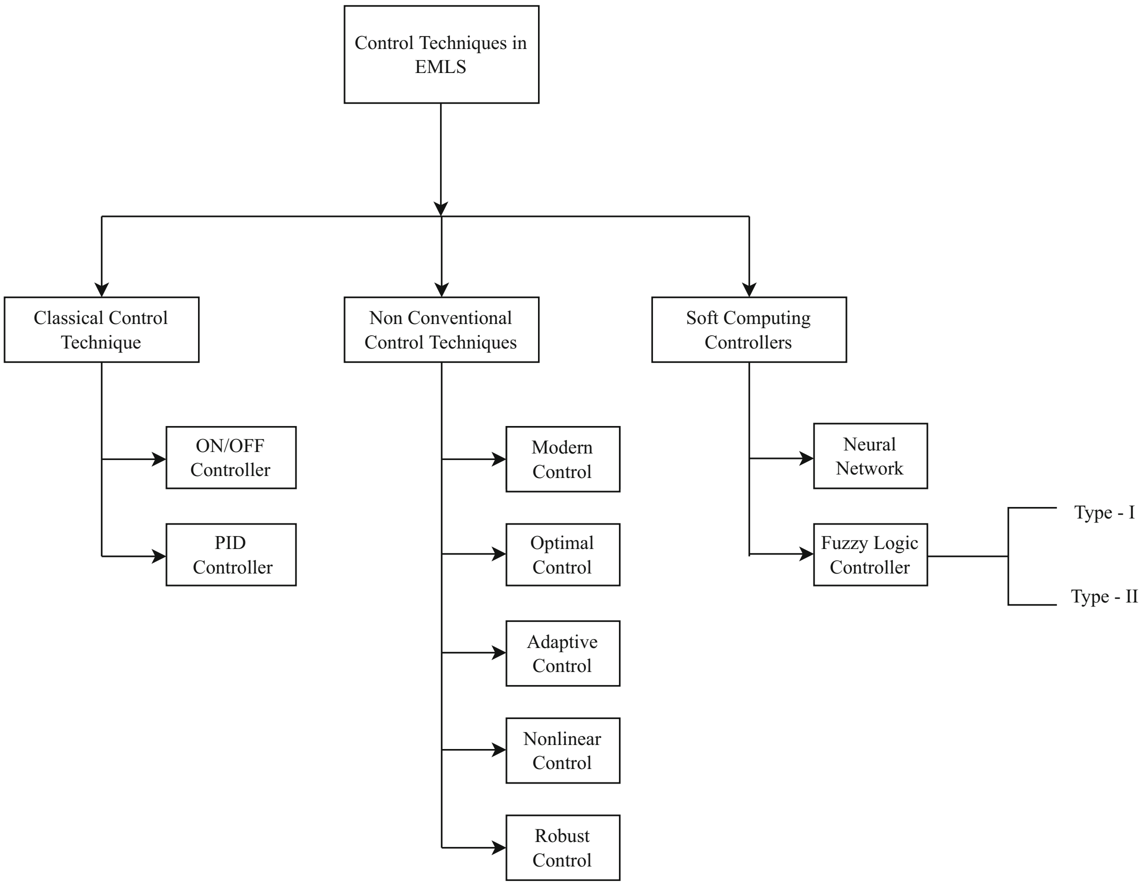

Fig. 2 Diagrammatic representation of various control techniques used in the electromagnetic levitation system

4.2 State feedback and observer based control of EML system

With the design of digital computers, it became easy during the 1960's to design modern control techniques, and hence, with that development, it became easy to compute and implement state feedback and state observers. A full order state feedback observer is developed for electromagnetic levitation system to track the reference step input [28]. Multi-degree of freedom for position control of maglev systems is designed by employing observer-based nonlinear model predictive control (NMPC). The benefit of this design is that it reduces the computational burden by excluding the stability-related factors [29]. A state-feedback robust integral controller based on signum of error is designed for the EML system. The signum function is used to design the state feedback controller, which guarantees a better control signal [30]. The authors of the article [31] have designed a hybrid observer, which is a combination of an extended state observer-based controller (ESOBC) and a generalised extended state observer-based controller (GESOBC). The hybrid observer is capable of estimating and controlling the multi-channel lumped disturbances with non-ICF. The authors have carried out the construction of a conventional ESOBC. A hybrid extended state observer-based controller (HyESBOC) is proposed for the SISO system with distinct matched and unmatched dynamics. The disturbance observer is proposed for nonlinear systems in [32] using the internal model concept to reject disturbances with established model structure.

An adaptive robust-based disturbance observer controller is designed for control of the maglev system. It is designed in such a way that it can handle the class of time varying parametric uncertainty and mismatched lumped disturbance. The article aims to track the reference by using an error tracking method. The disturbance observer dynamics and robust adaptive controller are designed and its stability is proven by using the Lyapunov stability test [33]. To eliminate delays in supplying information in uncertain terms to the closed-loop system, a new adaptive disturbance observer with finite-time convergence has been designed. The observer is based on a dual-layer adaptive rule and a higher-order sliding mode observer. As a result, it can considerably minimise chattering phenomena and eliminate the necessity of the lumped certainty upper bound [34]. In [35] the authors have addressed the design problem of delayed output feedback controllers by optimizing a quadratic performance criterion from a novel viewpoint by using the delay Lyapunov matrix. The required gradient is computed from the sensitivity Lyapunov matrix with respect to the parameters of the controller. The advantage of the new technique lies in the restatement of the design problem as a minimization problem whose objective function is given in terms of a sum of delayed Lyapunov matrices. The study has investigated nonlinear model predictive control without stability-related limitations, which decreases the computational effort while ensuring stability [36].

4.3 Optimal control of electromagnetic levitation system

Optimal control covers the wide range of its usage in different domains and continues to be a major study context in the field of linear and nonlinear control systems. Regulating the system using its mathematical equation to obtain the desired solution, stating the performance index, all boundary criteria on states, as well as constraints that states and controls must meet are some of the requirements to formulate the optimal solution [37]. The sliding mode control and integral sliding mode control can provide robustness only for matched disturbance. To obtain the better performance the optimal integral sliding mode control technique is utilised in [38,39]. An output feedback with integral optimal sliding mode control (IOSMC) is designed to meet the robustness in the position control of EML system [40]. The linear quadratic Gussian control technique is incorporated with the optimised Jaya algorithm to achieve the better performance of the controller [41]. The optimal controller is designed with the model order reduction technique, which is based on the truncation method, to achieve the better performance of the magnetic levitation system [42]. The LQR technique can minimise the fluctuations between the state trajectories with less effort from the controller [43]. The infinite-time LQR-based optimal controller using the Hamilton–Bellman–Jacobi (HJB) equation is designed for the EML system [44]. The finite and infinite-time optimal controllers using the HJB equation are designed for the EML system [45].

4.4 Control based for varied inductance of EML system and nonlinear control technique

Since the EML system has considerable time-varying as well as nonlinear characteristics, linear control approaches cannot provide adequate stability and reliability, particularly above a broad working range and when the system's nonlinearity has a significant influence on its performance. Hence, to provide control over a wide operating range, nonlinear control techniques are required. To lessen the vibration in the ball, an linear matrix inequality (LMI)-based intelligent controller is proposed [46]. The controller is designed to minimise vibration while also achieving stability and reducing eddy current impact [47]. In [48] nonlinear controller with a quantitative feedback technique is designed for a magnetic levitation system. The design of a nonlinear state feedback controller for maglev is presented by Deepti et al. [49]. The purpose of this study is to construct a composite nonlinear feedback controller with a minimal rise time and no overshoots. The damping ratio is initially maintained low in this controller, but after the system achieves the required value, the damping ratio is increased via nonlinear control to limit overshoot. The linear matrix inequality is used to choose parameters for nonlinear control law formulation. Input output differential geometry feedback linearization, in combination with a linear state feedback controller, is used to control a magnetic levitation system. Using the pole placement approach, the position of the pole is determined. The lie derivative principle is used in the feedback linearization approach. As a result, a state transformed matrix is generated via feedback linearization and nonlinear control is designed to obtain the desired controller [50]. The tangent linearisation technique is used to develop the generalised PI controller near the random unstable equilibrium state. In comparison to a basic generalised PI controller, the proposed approach performs better [51].

The control of the electromagnetic levitation system is also carried out on the basis of coil inductance approximation. As discussed in Sect. 3, it has been noted that the system equation and its working state are directly associated with the inductance of the coil [21]. With the elimination of the influence of coil inductance, it is possible that factors such as uncertainty and time delay would occur in the levitation system [19,20]. The approximation of coil inductance, which is used to model the voltage as well as current control of an electromagnetic levitation system, is discussed in [52]. The comparison of both the techniques is based on the varied specifications of the system. The controller designed for suspension of the EML system is an important factor for safety measures. The variation in coil inductance causes the nonlinearity in the transfer function, which in turn can be eliminated by decoupling the inductance from the air gap equation, hence the error will be reduced [53].

4.5 Artificial intelligence technique for control of EML system

Due to the nonlinear and complex nature of the levitation system, it is quite difficult to derive the exact state model, as many uncertain parameters exist in the system. As a result, finding an exact model while addressing all the uncertain parameters and conditions for an EML system is a difficult task. Hence, the use of artificial techniques provides the platform to control the system without having the exact model of it. Takagi–Sugeno based fuzzy control is designed for electromagnetic levitation system [54]. Neural-fuzzy driven optimal control strategy is proposed for EML system [55]. T–S fuzzy in discrete form is established in [56] which uses the switched parallel distributed compensator to control the position of a levitated object in the presence of uncertainty. The better control performance of the magnetic levitation (Maglev) system is achieved by fusing the proportional-derivative controller with a fuzzy controller [57]. The Kalman filter is combined with the T–S fuzzy system to estimate the nonlinear state and provide the suspension control [58]. In [59], the PID-fuzzy controller is proposed to provide the desired control for the suspension system in the Maglev train. The authors of the [60] proposed the combination of a fuzzy interpolative controller with a Kalman filter having the capability for noise estimation and reduction, along with the design of a stable controller that can provide robustness of up to 25% with different operating conditions. The Takagi–Sugeno fuzzy model describes the nonlinear plant model, and linear matrix inequality is designed to track the signal of the maglev system [61]. A T–S fuzzy-based control is proposed in [62] using a negative eigenvalue for an unstable nonlinear Maglev system.

Abbreviations	Full form
ML	Magnetic levitation
EML	Electromagnetic levitation
EMLS	Electromagnetic levitation system
Maglev	Magnetic levitation
PI	Proportional integral
PD	Proportional derivative
PID	Proportional integral derivative
NPMC	Nonlinear model predictive control
ESOBC	Extended state observer based controller
GESOBC	Generalised extended state observer based controller
HyESOBC	Hybrid extended state observer based controller
SISO	Single input single output
MIMO	Multiple input multiple output
LMI	Linear matrix inequality
SMC	Sliding mode control
IOSMC	Integral sliding mode control
LQR	Linear quadratic regulator
HJB	Hamilton Jacobi Bellman
ASMC	Adaptive sliding mode control
RBF	Radial basis function
MPL	Minimum parameter learning

The membership function which is selected for the fuzzy and neural network, makes influence on the stability of EML system [63–65]. Based on the affine nonlinear model, a new sliding surface with an extra integral term is created. The exponential reaching law is used to construct a sliding mode controller that can assure the system state in the sliding surface. The Lyapunov stability is used to demonstrate the system's stability. An adaptive neural-fuzzy sliding mode control is presented to handle the problems of mismatched disturbance, parameter perturbation, and chattering in the SMC. The SMC and fuzzy are utilised to compensate for the approximate error [66]. An optimal control scheme is designed in [67] which is based on advanced adaptive programming. The proposed method considers two variables: one is the angular position of the ball, and the second is the electromagnetic parameter. A neural network is used to approximate the electromagnetic parameters. The stability is proved by using the Lyapunov method [68]. The method proposed in [69] does not require the exact model of the electromagnetic levitation system; instead it uses a radial basis function neural network to approximate the unknown dynamics of the ML system. A neural network based adaptive controller is employed in [70] as a robust term it uses sign function that rejects the unmatched uncertainty. The authors of the article [71] have proposed the online identification of an unknown mass of levitated ball. The designed scheme assures the input to be within the permissible limit. The radial basis function is used to estimate the nonlinear dynamics in the ML system, and an ASM controller is designed for the maglev system, which ensures the required robustness [72]. The authors designed a radial basis function proportional–integral–derivative (RBF-PID) controller for the maglev system. This method uses data from the maglev system to modify the controller's parameters in real time. The developed control scheme is efficient at controlling external disturbances and also effective at adjusting the changes that occur in system parameters [73]. The radial basis function neural network with minimum parameter learning adaptive sliding mode control (MPL-ASMC) is designed to estimate the unknown function in the maglev [72]. The article focuses on the research which is based on the control of the current to maintain the air gap. An amplitude saturation controller (ASC) is designed, which mainly generates the unidirectional attractive forces and trains the neural network. A Gaussian function is used as the activation function. The stability analysis of the proposed controller is studied using the Lyapunov method [74].

4.6 Robust control of electromagnetic levitation system

Developing a mathematical state equation of the system or control object is the primary stage in the design of any control system. Any model of the plant which is intended to be controlled can include errors in the modelling process. To guarantee the designed controller will perform suitably, one practical approach is to assume the uncertainty from the very initial stage between the actual system and its mathematical model, as well as include that uncertainty in the control process scheme [75]. A robust controller to maintain the air gap with the inner feedback loop of the maglev system is

Table 3 Merits and demerits of reviewed control techniques

Control techniques	Merits	Demerits
Classical control	1. One of the widely used controller	1. Less accurate for nonlinear and uncertain systems
	2. Easy implementation	2. Limited performance
		3. Cannot control system with uncertainty
		4. Tunning of controller parameter is difficult
		5. System can become unstable with improper selection of gain
Modern control	1. Initial condition of system is included	1. Requirement of Computation is high
	2. Analysis of system like time variant and invariant, linear and nonlinear, SISO and MIMO is possible with this technique	2. It is a complex method
	3. Independent of Input-Output relation	
Optimal control	1. The approach is simple to implement	1. For designing, a system model is necessary
	2. It is capable of handling a wide range of objective functions	2. Selecting a suitable system model is required
	3. It is not necessary for the target function to be quadratic and additive over time	
Adaptive control	1. Simple to use and Stability performance is better	1. Exact system model is necessary
	2. In relation to the change in system dynamics, parameters may be modified quickly	2. Implementation requires adequate design
Nonlinear control	1. The method is entirely different from other control techniques	1. Construction of Lyapunov function is difficult
		2. Hard to give stability proof
		3. In feedback design the dynamic range is limited
		4. All state variable has to be calculated
Neural network control	1. Robust in predicting model	1. Data needs to be trained
	2. Nonlinear classification and control have enticing characteristics	2. It is a time taking process
	3. Capable of handling a significant quantity of data	
Fuzzy logic control	1. Logical like human reasoning	1. For better performance it requires large rule base
	2. Better accuracy	2. Computational burden is high
	3. Efficient for nonlinear system	3. Use of input variables is limited
Robust control	1. The method include uncertainty between actual plant and mathematical model	1. In order to guarantee the robustness some performance of system may reduce
	2. System uncertainty can be addressed using this method	
	3. Efficient in handling matched and unmatched uncertainty	
	4. It can bound the uncertainty	
	5. Worst case analysis method [93]	

proposed [76]. Song et al. [77] proposed robust H∞ LMI-based controller for EML system. The optimal H∞ control issue is the challenge for determining the minimum disturbance attenuation level [78]. The robust H∞ controller based on convex optimization for multi-axis magnetic levitation system is designed [79]. A robust adaptive neural fuzzy controller with sliding mode control technique was proposed in [66] for position control of maglev train which achieved better dynamic performance. The authors of the article [80] have designed a robust adaptive controller based on the Riccati method and SMC technique. The article covers the due effect of the time delay in the maglev system. To keep the air gap in desired limit a digital signal processor based algorithm is proposed [81]. In a maglev system, when the electromagnet interacts with the suspension controller, the gap deviates from its ideal position due to the disturbance. Hence the signal from the sensor controls the suspension to keep the system stable [82,83]. In order to provide the robust control to suspension system in flexible track a sliding mode robust adaptive state feedback controller is designed based on the radial basis function [84].

Robust air gap control is proposed by using an inner feedback compensator, which ensures both stability and robustness [85]. $H\infty$ based model reference and robust controller is designed for EML system [86,87]. The technique proposed in [88] is a continuous, robust scheme which tracks the reference trajectory of mass in the presence of uncertainty. Pole placement based robust discrete time LMI controller is designed for maglev system [89]. The authors of the article [90] developed a robust controller design for maglev systems based on a coefficient diagram. The proposed controller provides sufficient robustness with all the uncertain parameters of the system. A combination of $H\infty$ and feedback linearisation technique is designed in [91] to provide the robust control to EML system. In reference [77] $H\infty$ centered robust LMI controller is designed for levitation system. The designed controller has the capability to cater to the robustness of the system and reduce the disturbance signal to zero. A three-stage state transformation robust control of magnetic levitation is proposed in [92] the control design is carried out iteratively by Lyapunov min–max analysis.

The strategies utilised to offer proper control scheme to an electromagnetic levitation system have been explored in this portion of the text. Section 5 concludes all the control approaches that have been used to provide the required control action to the electromagnetic levitation system. The Table 3 elaborates the merits and demerits of control methods which has been discussed in this article.

5 Conclusion

To conclude, this study article describes an analysis of the possible control mechanisms used in electromagnetic levitation systems. Multiple control mechanisms are grouped into traditional, non-conventional, and soft computing categories in the outline. Since non-conventional control methods are extensively employed and are still the primary selection in designing control, it appears that most of these schemes did not account for the diversity of constraints on controls and states to show the actual conditions. Traditional and nonconventional control methods have been widely employed, mainly due to their ease of application and low initial cost. However, the maintenance cost and reduced efficiency of classical and non-conventional control techniques for EML system has diverted interest towards the possibility of the use of soft computing techniques as well as hybrid techniques. The hybrid technique can be a combination of non-conventional and soft computing as well as classical, non-conventional, and soft computing techniques. The electromagnetic levitation, which is a nonlinear dynamical and complex system, intelligent controllers will be a better alternative as these controllers are model-free controllers.

The electromagnetic levitation system has different factors which affect the system performance and, in greater aspect, the uncertainty in mass, position of the levitated object, actuator, sensor, and internal circuit parameters leads to a major change in the system. Since non-conventional techniques are extensively utilised to regulate the EML system, the fusion of intelligent controllers and non-conventional techniques can provide better control performance. Hence, the design of a nonlinear robust intelligent controller can be significant for the entire control mechanism.

Acknowledgements The article presented is part of a full-time Ph.D. course in the Department of Electronics and Instrumentation at the Institute of Technology, Nirma University, Ahmedabad, Gujarat, India.

Author Contributions Both the Author's have reviewed the article and framed it. Right from developing the concept, flow of article till its final manuscript, both the authors have equally contributed.

Funding No Funding is provided.

Conflict of interest No conflict of Interest.

Data Availability No external data, material is used in the article.

Code Availability No code is used in the article.

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