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Design and Hardware Implementation of Combining PD with HSSC for Optimizing Behavior of Magnetic Levitation System

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Abstract*—This paper presents the design and implementation of a hybrid control system that uses Proportional-Derivative (PD) and High-Speed Switching Controller (HSSC) methods to enhance Maglev system performance. The goal is to design controllers that properly follow input references and improve system stability and reactivity. The PD controller is fast and easy to install, but it cannot handle system disturbances and nonlinearities, which might cause instability. HSSC integration addresses these issues. The HSSC makes the PD controller more resilient to external forces and nonlinear dynamics. The combined PD-HSSC approach ensures stable levitation, precise positioning control, and system reliability in various conditions. The hybrid system reduced steady-state error and maintained system stability under dynamic input conditions, although it over-shoot more than PD alone. The computer-aided real time simulation of system dynamics is done, and the control rules are formulated out of a combination of PD Control for normal control processes and the HSSC for enhanced robustness. The total control current is given by the algebraic addition of the PD control action going, the equivalent control going, and the switching control going. However, the proposed PD-HSSC technology is possible to provide a stable levitation state for the control of precise position, even in the nonlinear and disturbance conditions The experimental results showed an 89% enhancement in the efficiency of the hybrid control system. The integration of PID (Proportional-Integral-Derivative) and HSSC has been developed in this system using MATLAB Simulink. The real-time findings demonstrate that the PD-HSSC system is higher in stability for operating the maglev system. This is due to its much lower steady-state error compared to the PD system, regardless of the kind of step input or dynamically fluctuating sine and square wave inputs. However, PID_HSSC exhibited a greater degree of overshoot in comparison to the PD.

***Keywords*—Magnetic Levitation; Optimize; HSSC; PD controller; Maglev.**

I. INTRODUCTION

Due to its frictionless operation, high accuracy, and efficiency, magnetic levitation (Maglev) systems are used in high-speed transit, precise manufacturing, and vibration isolation [1]-[6]. However, magnetic levitation systems are nonlinear and unstable, making it difficult to build a control system that maintains system behavior. Wang et al. [4] present a novel Adaptive Fixed-Time Controller (AFTC) that uses disturbance compensation technology to improve magnetic levitation system position accuracy [7]-[11]. This controller optimizes magnetic levitation systems with high position precision control. Wu [12] presents the IPSO and HSSC technique, which combines particle swarm optimization, High Speed Switching Controller, and adaptive linear active disturbance rejection control [13]. This solution addresses traditional control strategy constraints by improving single-point magnetic levitation ball system control system stability and anti-interference. Mughees and Mohsin [14] employ a Fractional Order PID (FOPID) controller to improve the stability control of a levitating item in a magnetic levitation system [15]. The work improves the magnetic levitation apparatus by improving the FOPID controller with an ants colony optimization Algorithm. Awsaj et al. [16] design and build a linear state changing feedback microcontroller for a Maglev vehicle to address the complexities of the magnetic levitation technology. It also indicates that a system of this sort is unlikely to be linear and stable, necessitating the controller's adjustment to parameter changes. A systematic parametric effect study shows that the combination of a proportional-integral controllers for current management and the lead compensator for position control improves stability and performance. Thus, this study contributes to the development of intelligent systems for controlling and maximizing the magnetic levitation system. Luan et al. [22] noted that the cascaded configuration of an integrator, regulator, and controller with including the local current feedback in the magnetic levitation systems lowers the steady-state error, increases the stability, bandwidth, and position accuracy [24]. This method also determines the dynamic performance of Magnetic Levitation actuator. The so popular magnetic levitation system optimization reference is Bauer and Baranowski's PIÎ»D controller design [20]-[25]. In this study, an understanding of how an intelligent controller can be developed to optimize system performance through the application of artificial intelligence is explained. Our comments on this research rely on state-of-the-art techniques of magnetic levitation system control. Magnetic levitation systems were studied by Abdalhadi et al. [26] and they applied optimum proportional integral derivative (PID) tuning. This paper investigates the enhancement in the performance of the magnetic levitation system through the use of PID controllers and which directs the designer and implementer of an intelligent controller towards the right direction [27]. Satria's Proportional-Integral-Derivative (PID) controlling prototype demonstrates that magnetic levitation devices must be supplemented with a magnetic field management system to prevent [28]-[30]. This reference emphasizes the importance of suitable intelligent controllers, such as PID, in improving magnetic levitation systems while also laying the groundwork for future research. Deepa et al. found that controllers improve the transient reaction of the magnetic levitation system. The current study's comparative analysis of controllers for lifting magnetization objects demonstrates how different control strategies improve magnetic suspension systems. This shows how 'smart' controllers may help make magnetic levitation applications operate. A deep neural network forward-looking compensation controller to improve magnetic levitation system position control [31][32]. This improves the control of the magnetic levitation ball's behavior based on an improved an optimization which enhances the degree of precision [32]-[36]. A Magnetic levitation actuation and Motion control system with active levitation is developed and integrated in [37]-[41]. Active control is enhanced in magnetic-levitation system stability through the use of a neural-network PID control for actuation and a force-imbalance concept for step-motion mode. The study reveals yet again the integrated electromagnetic actuators and the double-hall-structure sensors may enhance the magnetic levitation system functionality and manageability by maintaining homogeneous and stable electromagnetic force in the levitating object. In [42][43], show how Takagi-Sugeno fuzzy model-based integral state feedback control method can be applied to optimize the magnetic levitation ball system. The paper discusses generating a fuzzy model from the system's nonlinear dynamics, designing local and global controllers, and using the integrated state feedback controller for position control. Simulations and tests show that the suggested controller achieves stable levitation with improved control performance. The developed and analyzed a feedback-controlled magnetic levitation device for additive manufacturing [44]. The article discusses Laser Directed Energy Deposition via Powder Feeding (LDED-PF) and how magnetic levitation may eliminate the requirement for a substrate and reduce post-processing. Two newly developed, optimized, and tested levitation systems outperform prior prototypes [45]. The paper also discusses the construction of a feedback PID controller for the levitation system, which controls levitation height and can sustain it with an additional mass. The suggested integrated driving control algorithm overcomes semiconductor process problems by constructing a system without shaft and bearing, following Jung and Lim's 6-DOF magnetic levitation system control technique research. The method optimises magnetic levitation systems by controlling levitation, rotation, tilt, and X-Y axis movement via current vector control [46]. The compare nonlinear and linear controllers for magnetic levitation systems. Robust discrete-time pole-placement and feedback linearization are used to study nonlinear unstable magnetic levitation system control [47]. These control algorithms are tested for efficiency and competitiveness to optimize magnetic levitation systems. In [48][49] propose self-tuning predictive control for ship repulsive magnetic levitation damping devices to stabilize levitation. Position imbalances under external shocks are addressed by predictive control with state and input limitations, whereas self-tuning using recursive least squares solves problems with fixed parameters in classical controllers. Simulations show better precision, dynamic reaction, and anti-interference. This study helps optimize magnetic levitation devices using sophisticated control algorithms. The static forces are extremely nonlinear, and for control engineers, they are difficult to stabilize [50]-[54].

It describes how to create efficient PID control algorithms for a magnetic levitation benchmarking system and compute steady-state gains while the parameters and function transfer are uncertain. As a result, systems such as magnetic levitation require intelligent controllers such as the PID controller with derivative filter coefficients to provide long-term stability [55]-[59]. When compared to other conventional displacement measuring devices, the magnetic levitation ruler is stable in a magnetic field, highly controlled, integrated, and precise. These features are required for an intelligent controller that is designed and implemented to improve the operational efficiency of magnetic levitation systems [60]. In [61] provide develop and implement a model predictive control system for a magnetic levitation system, which is indispensable for Maglev train operations. The proposed control method is to employ state feedback and there are quantitative measurements for state variables for instance air gap and magnetic acceleration hence enhancing system dynamic characteristics and disturbance rejection.

This study proves that this strategy can help in mapping the most appropriate behavior for magnetic levitation systems concerning air gap variation. The design and modeling of a conical energy harvester that enables the levitating magnet to translate in either the vertical location of the cone or the angle of the cone raises the amount of power produced. This brand-new approach replaces two anchored magnets with a spring that permits the levitating magnet to ingest vibrations in each direction leading to conical coils. An improvement 8 times greater than that of LBEH systems has been obtained from this Conical Energy Harvester (CEH) to prove that the intelligent controller design and implementation add value to magnetic levitation systems.

II. Problem Statement

The problem statement for the design and implementation of an intelligent controller for optimizing the behavior of a magnetic levitation system can be formulated as follows: Develop a robust and time-varying control strategy that will facilitate the manipulation of the position of the levitated object and its staking with regard to interference and uncertainty and variation of the system parameters and with a fast response time that does not have oscillatory, over-shoot, or steady state error. The key objectives for the intelligent controller design include:

- Gaining the ability to maintain highly accurate and stable lifting of the object throughout the processes of its functioning.
- Mainly, improving on the system's transient performance; this refers to the system response time, the amount of overshoot and the steady state error.
- Maintaining the controller's immunity to external

interferences, sensor noise, and variations of the system parameters.

- Using the controller and making it computationally less complex and more efficient for real time applications.

For these considerations, the design of the intelligent controller adjoins the implementing high order control methodologies like adaptive control, robust control and data mining facility of optimizing control which are not available in the model control methodologies due to the flaw of modeling which does not have enough capability to model the nonlinearity present in the magnetic levitation system.

III. METHODOLOGY

In developing and applying an intelligent controller of enhancing the operations of a Maglev system, the following key steps are observed. This involves, Requirement specification of the system, specification of the system model, Selection of the most suitable control strategy Control system design and development Integration of the control system and System testing. There are a lot of steps corresponding to the process of the development and utilization of an intelligent controller for a maglev system. The procedure is carried out starting by defining the system requirements specifying stability, accuracy, response time and ruggedness. Following this, mathematical modeling takes place with a view of understanding the behavior of the system. Often the design of the controller is eased using this model where the plant is linearized. The choice of an appropriate control technique is therefore very crucial. They are conventional ones like PID and there are advanced controllers like Fuzzy logic controllers and neural network controllers as well as the combinations of the above. Choosing a control strategy defines the controller, and the real-time programming environments are used in its construction. It is then applied on the right hardware like micro controllers or digital signal processors (DSPs).

The integration process ensures that all of the software and hardware components function properly since they were meant to work together. Thus, a sequence of tests and confirmations are undertaken, beginning with simulations and progressing to actual practice. System evaluation includes the following parameters: stability margin, settling time, overestimation, and steady-state error. Finally, optimization techniques are used to fine-tune the settings for the controller and, if necessary, add adaptive control procedures to maintain optimal performance. An supporting flowchart will be designated as Fig. 1 to demonstrate the method stated in Fig. 1. Magnetic levitation (maglev) is a way of suspending an item using only magnetic fields as support. The forces acting on the object are precisely controlled to counteract gravitational and other forces, allowing for stable levitation. Here’s an overview of the physical concept and mathematical model behind maglev systems.

IV. PHYSICAL CONCEPT

Both magnetic repulsion and attraction are used in magnetic levitation devices. Diamagnetic levitation occurs when superconductors reject magnetic fields and levitate in strong magnetic fields. Eddy current levitation uses conductive materials traveling through a magnetic field to induce currents that produce an opposing magnetic field. However, electromagnetic suspension (EMS) employs electromagnets to attract and elevate a ferromagnetic item against gravity, requiring precise feedback management for stability. Electrodynamic suspension (EDS) uses superconducting magnets or electromagnets and induced currents in a conductive track to lift an item [28]-[30].

A. *Magnetic Repulsion:*

- Diamagnetic Levitation: Certain materials, like superconductors, exhibit diamagnetic properties, meaning they repel magnetic fields. When placed in a strong magnetic field, they can levitate due to the repulsive force.

- Eddy Current Levitation: Conductive materials moving through a magnetic field induce currents that create a magnetic field opposing the movement, allowing levitation.

B. *Magnetic Attraction:*

- Electromagnetic Suspension (EMS): Uses electromagnets to attract a ferromagnetic object upwards, countering gravity. This method requires feedback control to stabilize the levitated object.

Electrodynamic Suspension (EDS): Relies on the interaction between magnetic fields generated by superconducting magnets or electromagnets and the induced currents in a conductive track, leading to repulsive forces that lift the object.

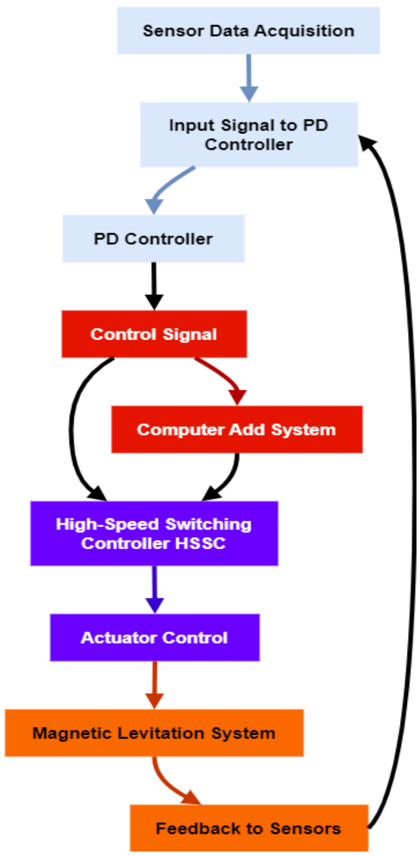


Fig. 1. Integration of Proportional-Derivative (PD) Controller with High-Speed Switching Controller (HSSC) in a magnetic levitation system physical concept

V. Mathematical Model

The mathematical model of a magnetic levitation system involves several key principles from electromagnetism and mechanics.

A. *Forces in Magnetic Levitation*

For a simple system, consider an electromagnet creating a magnetic field to levitate a ferromagnetic object. The relevant forces are:

– Magnetic Force (F_m): The force exerted by the magnetic field on the object [31].

– Gravitational Force (Fg):

The weight of the object,

$F_g = m \times g$, where m is the mass and g is the acceleration due to gravity. For stable levitation, the magnetic force must balance the gravitational force:

$$F_m = F_g \tag{1}$$

B. *Magnetic Force Calculation*

The magnetic force can be derived from the magnetic field B and the properties of the materials involved [32]. For an electromagnet, the magnetic field strength B depends on the current I through the coil and the number of turns N:

$$B = \frac{(\mu o.I.N)}{l} \tag{2}$$

where μo is the permeability of free space, and l is the length of the coil.

The force F_m exerted on a ferromagnetic object in a magnetic field gradient is given by:

$$F_m = \frac{\chi.V}{2\mu_o}(\nabla B^2) \tag{3}$$

where χ is the magnetic susceptibility V is the volume of the ferromagnetic material, and (∇B^2) is the gradient of the square of the magnetic field.

C. *Dynamic Model*

To achieve stable levitation, dynamic stability needs to be considered. The system can be described by differential equations representing the balance of forces and the control of the magnetic field [33]. Consider the vertical motion of the levitated object:

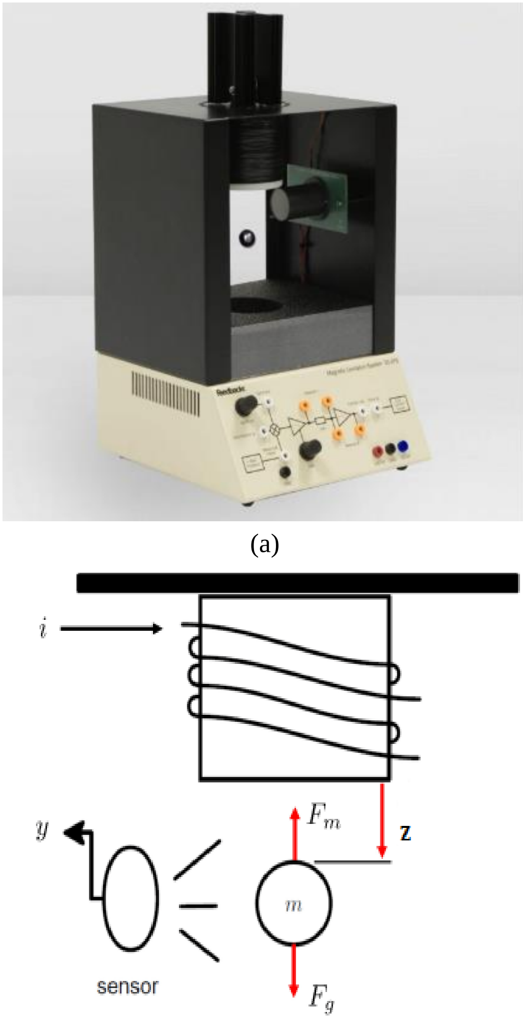
$$m\ddot{z} = F_m(z, I) - mg \tag{4}$$

where z is the vertical position of the object? The magnetic force F_m depends on the position z and the current I.

1) *Proportional-Derivative (PD) Controller:*

$$I(t) = K_p\big(z_d - z(t)\big) + K_d(z_d - \dot{z_d} \tag{5}$$

where K_p and K_d are the proportional and derivative gains, respectively, and z_d is the desired position. This diagram illustrates the magnetic ball levitation apparatus and its essential elements. An electric current $i(t)$ is applied to a coil, generating a magnetic pull on the ball. The location of the ball is represented by the variable z, measured in meters [34]-[36]. An infrared sensor detects and determines the vertical position of the ball, denoted as y. The goal is to achieve levitation of the ball at a certain vertical position, denoted as z. The ball is subject to two primary forces: the gravitational force, Fg, and the magnetic force, Fm. As shown in Fig. 2.



(a)

(b)

Fig. 2. (a) The figure shows Maglev, (b) diagram of the magnetic levitation system

$$mb\,\ddot{z} = m_b\,g - \alpha\frac{i(t)^2}{z(t)^2} \tag{6}$$

2) *Conditions of Equilibrium*

The equation characterizes an equilibrium condition, also known as a steady-state condition, where the height of the ball is denoted as z, from equation (6).

$$0 = m_b\,g - \alpha\frac{i(t)^2}{z(t)^2} \tag{7}$$

$$m_b\,g = \alpha\frac{i(t)^2}{z(t)^2}$$

$$z(t)^2 m_b\,g = \alpha i(t)^2$$

$$z(t)^2\frac{m_b\;g}{\alpha} = i(t)^2$$

$$i(t) = z(t)\sqrt{\frac{m_b g}{\alpha}} \quad (8)$$

D. High Speed Switching Controller (HSSC) for Magnetic Levitation System

High Speed Switching Controller (HSSC) is a robust control method particularly effective for systems with uncertainties and non-linearities. It forces the system's state trajectory to "slide" along a predetermined surface (the sliding surface), providing robustness against parameter variations and external disturbances.

1) System Dynamics

Starting from the vertical motion equation and incorporating the magnetic force, we have [37]:

$$m\ddot{z} = \alpha\frac{I^2}{z^2} - mg \quad (9)$$

2) Sliding Surface

The sliding surface s is typically defined as a function of the error e and its derivative:

$$e = z_d - z$$

$$\dot{e} = \dot{z_d} - \dot{z} \quad (10)$$

A reciprocated choice for the sliding surface is:

$$s = \dot{e} + \lambda e$$

$$s = \dot{z_d} - \dot{z} + \lambda(z_d - z) \quad (11)$$

Where λ is a positive constant that influences the convergence rate [38].

3) Control Law

The control objective is to drive the sliding surface s to zero and keep it there. When $s = 0$ the system's behavior is governed by the dynamics of the HSS. The High Speed Switching Controller law typically has two parts: an equivalent control and a switching control [39]-[41].

4) Equivalent Control Study Stat

The equivalent control is designed to keep $s = 0$:

$$I_{eq} = z\sqrt{\frac{mg}{\alpha}} \quad (12)$$

This matches the equilibrium condition derived earlier.

The switching control I_{hssc} is added to handle deviations from the sliding surface. It typically has the form [42]-[44]:

$$I_{hssc} = -k.sign(s) \quad (13)$$

where k is a positive gain that determines the strength of the switching action [45]-[48].

5) Total Control Input

The total control current $I(t)$ is:

$$I(t) = I_{eq} + I_{hssc} \quad (14)$$

Substituting the expressions:

$$I(t) = z\sqrt{\frac{mg}{\alpha}} - k.sign(s) \quad (15)$$

6) Complete Dynamic Equation with HSSC

Substitute the control current $I(t)$ into the dynamic equation:

$$m\ddot{z} = \frac{\alpha(-ksign(s) + z\sqrt{\frac{mg}{\alpha}})^2}{z^2} - mg \quad (16)$$

By integrating the HSSC approach, the magnetic levitation system gains enhanced robustness and performance, ensuring precise and stable levitation even in the presence of system variations or external disturbances. The HSS control rule consists of two components: the equivalent control eq. (12) and eq. (13).

7) Current Level of Complete Control

The total control current $I(t)$ is the result of combining the PD control and the HSSC components.

$$I(t) = I_{PD}(t) + I_{eq} + I_{hssc} \quad (17)$$

$I_{PD}(t),\ I_{eq},\ and\ I_{hssc}$ are all variables that may be defined as part of the set of all possible equations.

$$I(t) = (K_p\, e + K_d\, \dot{e}) + z\sqrt{\frac{mg}{\alpha}} - k.sign\ (s) \quad (18)$$

Final Dynamic Equation Using PD-HSSC Combination Change the overall control current using $I(t)$ in the equation for dynamics:

$$m\ddot{z} = \frac{\alpha((K_p\, e + K_d\, \dot{e}) - ksign(s) + z\sqrt{\frac{mg}{\alpha}})^2}{z^2} - mg \quad (19)$$

Flowchart in Fig. 3 depicts the integrated control method for a magnetic levitation system, which combines Proportional-Derivative (PD) and HSS Controllers. The figure illustrates the collaborative functioning of position and velocity feedback, proportional-derivative control, and sliding surface design to regulate the electromagnetic force and implement the switching control law, so achieving efficient levitation.

VI. HARDWAR IMPLEMENTATION

The Magnetic Levitation System shown in Fig. 4 use electromagnets to achieve levitation of an item without any kind of physical touch. The object's location is manipulated by adjusting the current flowing through the electromagnets.

Fig. 4 shows how electromagnets may levitate an object without touching it. Electromagnet current controls object position. The PD controller adjusts current based on positional error (the difference between desired and actual locations) and velocity [49]-[52].

Hardware components: Electromagnets supply the magnetic field for item levitation. Position Sensor: Locates levitated object. Typical sensors include optical encoders, laser distance sensors, and Hall-effect sensors.

Current Driver: Controls electromagnet current. The microcontroller/processor analyzes sensor data and conducts the PD control algorithm to generate control signals.

Power supply: Powers electromagnets and other components. Magnetic levitation uses the Proportional-Derivative (PD) control system and the High-Speed HSS (HSS) controller to increase performance.

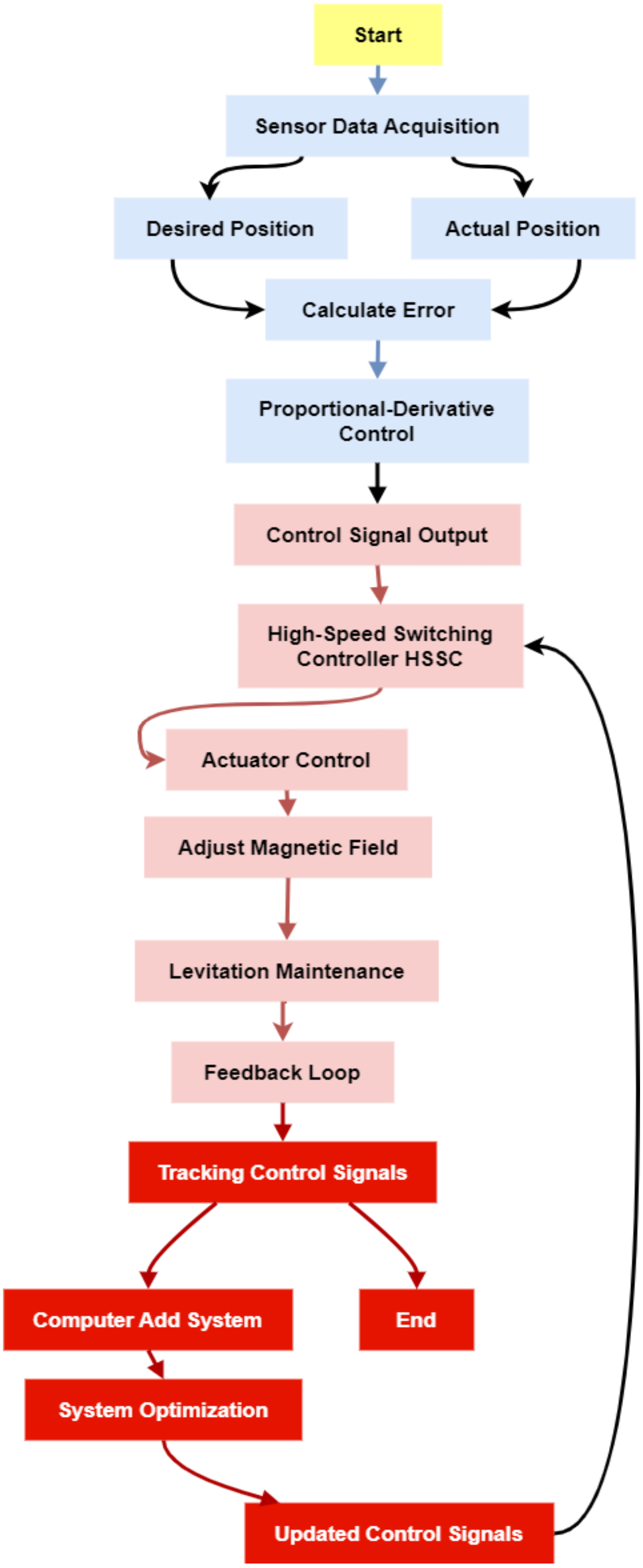


Fig. 3. Tracking control signals for integration of PD controller with HSSC

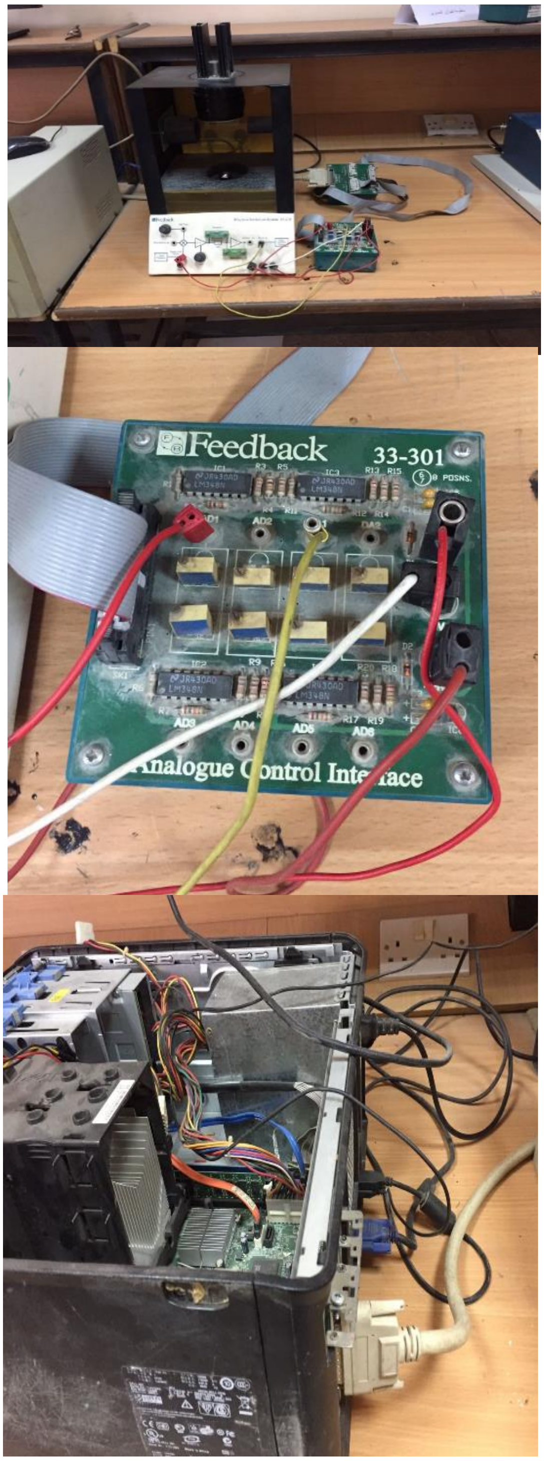


Fig. 4. Library magnetic levitation system

This integrated control system is created sequentially as shown in Fig. 5, Using the Generalized Composite Controller, which combines the Proportional-Derivative (PD) controller with the High-Speed Switching (HSS) controller in the levitation project, needs the construction and operation of both control systems. PD controls position and velocity-dependent fundamental control motions, whereas HSS stabilizes and controls disturbances. Proper calibration, tweaking, and testing are essential to guarantee the integrated system performs effectively and keeps the levitated object floating. PD may be attached to HSS Controllers using these steps:

- Integration of sensors:

– Position Measurement: Mount Position Sensor: To measure the vertical position of any levitated item, use an optic encoder or laser distance sensor.

– Calibration: Standardize the sensor for accurate location readings.

– Signal Conditioning: Increase and filter the sensor signal before sending it to the controller to reduce noise.

- Designing the PD Controller:

– The controller's quantitative reaction to the position error—the difference between the present and necessary positions—is called proportional gain (Kp).

– Adjustment: Kp, a proportional gain control parameter, enhances system sensitivity to control input but creates oscillations.

– Adjustment: Reduces volatility and stabilizes system.

- Developing the HSS Controller (HSSC):

– Definition of Sliding Surface: Create a sliding surface to ensure system stability and strength. More typically, the surface is created to meet performance criteria and system dynamics.

– The HSS control's interaction with sliding surface changes is determined by HSSC Gain(k).

– Adjustment: Accurate k selection enhances control aggressiveness while maintaining system stability.

– Equivalent Control: Implementation: Determine the control signal value for a steady sliding surface.

– Control Switching: Use a switching technique to handle disturbances and keep the system on the sliding surface.

- Implemented Combined Controller:

– Programming the microcontroller/processor: PD and HSS control methods should be included to the code.

– PD Control: Proportional actions are position errors and derivative actions are position error rates of change.

– HSS Control: Assess HSS control using the sliding surface and gain.

– Merge Control Actions: PD and HSS control actions are merged to generate the best control signal.

– Control Signal Creation: Currently Reg: Use the combined control signal and variable current to drive the electromagnets.

– Digital-to-Analog Conversion: Use DAC or PWM to control or regulate the current driver.

- Current control:

– Current Driver Circuit: Design a current driver circuit for this level's current values. These components may be finished using MOSFETs or transistors.

– Feedback Mechanisms: Use feedback to manage current and avoid circuit saturation.

- Evaluating and Adjusting:

– System Optimization: To fine-tune performance, try alternative Kp, Kd, and HSS values.

– System Response: Evaluation of the combined PD and HSS controller for levitated item position, velocity, and stability.

– Protective measures: Current constraints are: Avoid exceeding current limits to avoid damaging electromagnets and other equipment.

– Fail Safe Mechanisms: Model unanticipated system behaviors or failures.

- Integration and Debugging:

– Hardware integration: Establish Links: Confirm appropriate connection and communication between sensors, controllers and the currently.

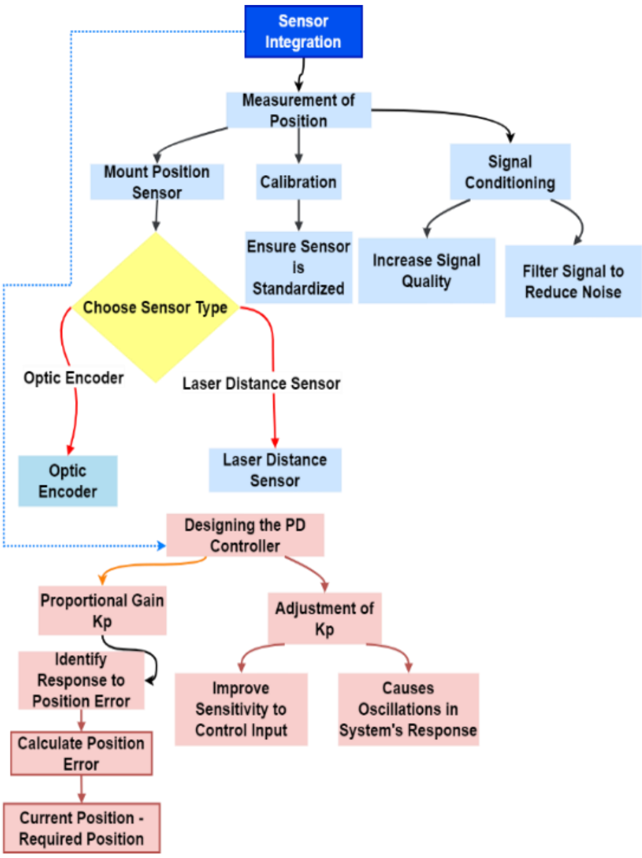
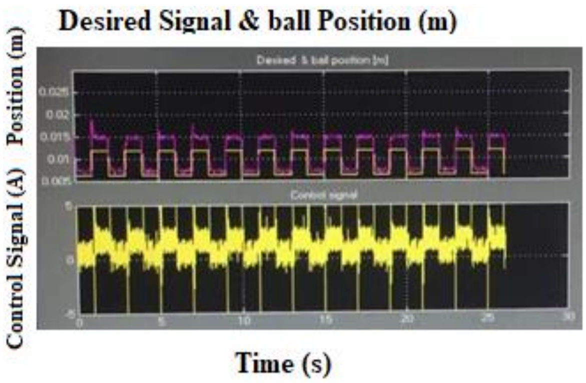


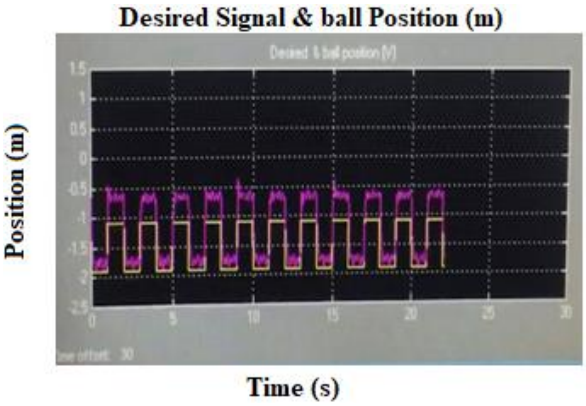
Fig. 5. Flowchart for integrating PD Controller with High-Speed Signal Conditioning (HSSC) in a magnetic levitation system

VII. HARDWAR TESTING AND SIMULATION

In this section the performance analysis of the magnetic levitation system is done independently by only using a Proportional-Derivative (PD) controller. These are illustrated in Fig. 6(a) and Fig. 6(b). That give the hardware results obtained by using the PD controller for magnetic levitation. Fig. 6(a): Use the PD Controller in order to get the output. As it can be observed in Fig. 6(b) this is the role of the position and the control signal.



(a)



(b)

Fig. 6. (a) Hardware results obtained from implementing the PD controller in for magnetic levitation. (b) The hardware results represent the response (position of ball in (m) and control signal)

– Stability and Response Time: - The PD controller offers a direct method for preserving the levitated position of the steel sphere. By manipulating the proportional (Kp) and derivative (Kd) gains, the system reacts to the discrepancy in position and its rate of change. The sphere's position stabilizes well, but there could be some remaining oscillations caused by the PD controller's limited capacity to efficiently manage system nonlinearities and external disturbances.

– Error Reduction: The proportional gain aids in diminishing the steady-state error, while the derivative gain enhances the damping properties, hence minimizing oscillations. Nevertheless, it is necessary to make adjustments in order to achieve a harmonious equilibrium between reactivity and steadiness. An excessively high proportional gain (Kp) may result in overshooting, but a high derivative gain (Kd) can lead to excessive damping, hence decelerating the reaction.

– Limitations: The PD controllers may struggle to deal with non-linarites with unmolded movements in the magnetic levitation system, resulting in inferior performance when confronted with changing scenarios. Output in Fig. 7 The output of a controller that combines a proportional derivative (PD) and an analogous harmonic suppressing strategy (HSS).

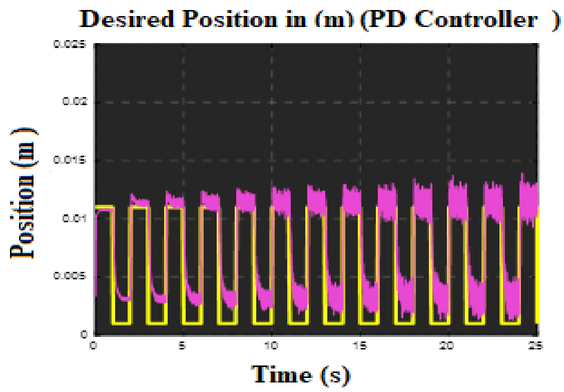
– Improved Stability and Endurance: By integrating the PD controller with the High-Speed Sliding Mode Controller (HSS), the system's stability and durability are increased. The has controller is used to control nonlinearities and disturbances that the PD controller cannot handle. The HSSC part gives a robust control action in dictating the system states to the wanted sliding surface, and retaining them there, in presence of huge shocks and uncertainties.

– Enhanced Responsiveness: - The combined controller delivers a faster reaction time with less oscillations in comparison to the PD controller alone. The sliding mode control swiftly corrects irregularities, while the PD component guarantees seamless and accurate adjustments.

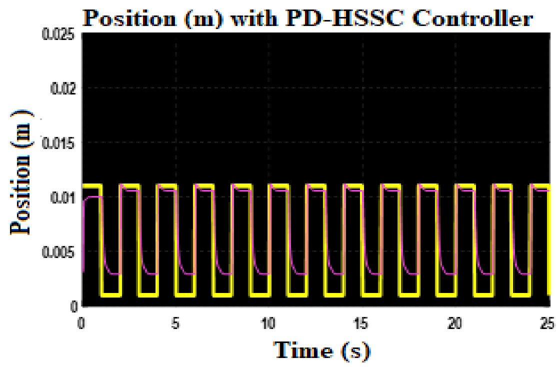
– Decreased Error and Overshoot: - The integration leads to a substantial decrease in both the error that persists over time and the excessive deviation from the desired value. The switching action of HSS control efficiently handles rapid changes, while the PD control enhances the precision of placement figure8.

– Adaptive Performance: - The integrated method demonstrates superior adaptability to changing circumstances and system dynamics, ensuring consistent performance in various operating situations.

To investigate many systems performance factors, the simulation replicates a magnetic levitation system employing PD and HSS controllers. A full discussion of each output figure follows. The intended location is z_d.



(a)



(b)

Fig. 7. (a) Ball Position for only PD, (b) Ball Position for HSS integrated with PD (PD-HSSC)

Fig. 8 shows how the levitated item's reference position changes over time. A 0.015-m square wave function at 0.5 Hz generates the signal. Levitated item elevation is shown by the square wave oscillating between 0 and 0.015 m. The signal switches between these levels to indicate location changes at each square wave half-period. Integrate HSSC and PD controllers for position (z). Fig. 8 shows how the levitated item's position varies over time. HSS Control and PD controllers control position. The graph shows the association between the actual location (z) and the projected position z_d from the first plot. The present position should closely match the desired position, and any variances demonstrate the controller's ability to stabilize the object at the proper heights. Velocity is dz. Integrate HSSC and PD controllers. Fig. 8 shows the object's velocity over time. It indicates the object's position change rate. Zero or low velocity is ideal when the object is stable. The system's response to square wave input and control actions may vary velocity. Fig. 8 in "Integrate HSSC with PD Controllers" shows how the magnetic system's current varies over time to achieve the required position. It is made up of PD control, equivalent and HSS control.

Fig. 8 indicates how control current interferes with desired location changes and the problem, which the system experiences in correcting it. The dynamic control current describes a capability of the system about the current control means to maintain the levitation in various inputs.

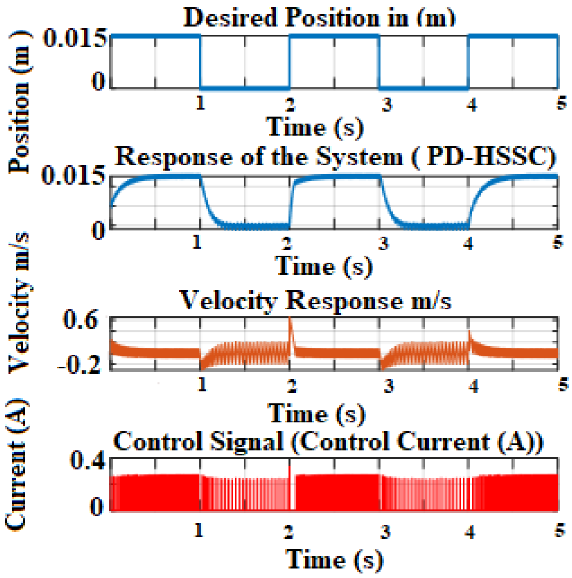


Fig. 8. Simulation results of Magnetic levitation system

VIII. CONCLUSION

This paper delineates the design and implementation of a comprehensive controller that integrates both PD and HSSC for a magnetic levitation system. The primary aim of this work was to attain a consistent and reproducible suspension of an object using the significant attributes of both control approaches. This was achieved to enable the PD controller to provide a smooth and straightforward control action to compensate for the positional inaccuracies of the levitated object. Nevertheless, the HSSC improved the system's stability and ensured its optimal performance despite existing instability. The modeling of system dynamics and the establishment of control algorithms were executed, proving the efficacy of integrating PD control with operational duties in HSSC. The total control current was therefore established as the PD control action, in conjunction with the equivalent current control and the switching control. The dynamics of the levitation state can be effectively regulated using the PD-HSSC technique, and the performance achieved is satisfactory regarding reliability for applications necessitating precise position control despite non-linearity and disturbances. The integration of PD with HSSC in hardware-in-the-loop simulation with the magnetic levitation system from Feedback Instruments was notably effective, hence reinforcing the efficacy of the suggested control technique. The implementation demonstrated that the positioning control formula of the proposed PD-HSSC approach is highly efficient and feasible in practical applications, making it suitable for systems that need precise and reliable position control. In summary, the use of PD and HSSC control methods in magnetic levitation systems provides substantial benefits, primarily including enhanced precision, robustness, and stability. This methodology guarantees system integrity and stability in control system operations and is strongly advocated for integration owing to its advantageous characteristics in many situations where uncertainty is unavoidable. Subsequent research may investigate the refinement of these control parameters and explore the broader uses of this method in other intricate control systems.

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