INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

VOL 04. ISSUE 02 . (2026)

http://ijirjournal.com

Advancements in Non-contact Force Perturbation Sensing within Magnetic-levitation Control Loops

Julian J. Bennett[1], Alexandra Sanders[2]

[1] Department of Mechanical and Aerospace Engineering, Herbert Wertheim College of Engineering, University of Florida, Gainesville, Florida, USA

[2] Department of Electrical and Computer Engineering, Pratt School of Engineering, Duke University, Durham, North Carolina, USA

Abstract.

The precise regulation of magnetic-levitation systems is inherently dependent on the accurate estimation and rejection of external force perturbations. As these systems operate without physical contact, traditional contact-based force and torque sensors cannot be deployed, necessitating the development of advanced non-contact sensing methodologies integrated directly into the control loop. This paper provides a comprehensive investigation into the mechanisms, algorithms, and practical implementations of non-contact force perturbation sensing. By synthesizing principles from electromagnetic theory and modern control engineering, the research details how variations in the magnetic air gap and coil currents can be transformed into reliable estimates of external disturbances. The analysis explores the limitations of standard position-derivative feedback and advocates for the implementation of advanced observer-based architectures, specifically focusing on extended state observers and disturbance observers. Extensive experimental and analytical discussions elucidate the impact of sensor noise, unmodeled system dynamics, and environmental variables on sensing fidelity. Through a robust methodological framework and detailed comparative analysis, this study demonstrates that integrated algorithmic sensing can achieve disturbance rejection capabilities comparable to physical sensors, thereby enabling high-precision positioning in vibration-sensitive applications such as semiconductor manufacturing and precision aerospace instrumentation.

Keywords: *Magnetic Levitation, Force Perturbation, Disturbance Observers, Non-contact Sensing*

1. Introduction

1.1 Context And Motivation

Magnetic levitation technology has emerged as a cornerstone for modern advanced engineering applications requiring zero friction, high-speed motion, and extreme precision. By suspending an object entirely through electromagnetic forces, systems such as high-speed transportation networks, precision rotary bearings, and ultra-clean manufacturing environments eliminate the mechanical wear and tribological limitations associated with conventional contact bearings. The foundational advantage of this technology lies in its reliance on non-contact interactions, which drastically reduces maintenance requirements and allows for operation in extreme environments,

including vacuums and highly corrosive atmospheres. However, the absence of physical contact inherently removes the natural mechanical stiffness and passive damping that traditional bearings provide. Consequently, a magnetically levitated object is highly susceptible to external force perturbations. These perturbations can arise from a multitude of sources, including aerodynamic drag, structural vibrations, mass unbalances, and electromagnetic interference. Without a robust control system capable of detecting and compensating for these forces, the levitated object can easily deviate from its equilibrium position, leading to instability or catastrophic failure. The motivation for this research stems from the critical need to maintain nanometer or micrometer level precision in modern industrial applications despite the presence of highly dynamic and unpredictable environmental disturbances. Because physical force sensors cannot be attached between the stator and the levitating rotor without defeating the purpose of non-contact operation, researchers and engineers must rely on extracting perturbation information purely from the available non-contact state variables, primarily position and current. This creates a complex challenge in signal processing and control theory, as the estimation must be performed in real-time with minimal latency to prevent phase lag from destabilizing the closed-loop system. For a broader comparison, related research addresses design of a novel Self-Test-on-Chip interface ASIC for capacitive accelerometers [1].

1.2 Problem Statement

The central problem addressed in this academic investigation is the accurate and rapid estimation of exogenous force perturbations in a magnetic-levitation control loop without the use of direct physical force transducers. In a typical active magnetic bearing or levitation system, the controller relies on proximity probes, such as eddy current sensors or capacitive displacement sensors, to monitor the air gap between the stator and the rotor. When an external force acts on the levitated mass, it causes a microscopic deviation in this air gap. Traditional proportional-integral-derivative control schemes attempt to correct this deviation by adjusting the electromagnetic coil current proportional to the error, its integral, and its derivative. However, standard control schemes react only after a significant positional error has already accumulated. Furthermore, differentiating a noisy position signal to obtain velocity and acceleration for force estimation amplifies high-frequency measurement noise, which saturates the control actuators and induces severe chattering. The challenge is therefore twofold. First, the control system must mathematically infer the exact magnitude and direction of the perturbing force by decoupling it from inherent system nonlinearities and measurement noise. Second, the system must feed this estimated force back into the control loop as a feedforward compensation signal rapidly enough to counteract the physical disturbance before the levitated mass deviates beyond its stringent operational tolerances. Standard approaches often struggle to balance the bandwidth required for rapid disturbance rejection with the necessary noise attenuation, leading to compromises in overall system robustness. Another relevant line of investigation concerns design of magnetic sensor Array-Based PUFs for IoT security [2].

1.3 Scope And Objectives

This paper comprehensively examines the theoretical foundations, methodological designs, and practical implementations of non-contact force perturbation sensing embedded within magnetic-levitation control loops. The primary objective is to detail how modern state observation techniques can effectively replace physical force sensors by utilizing the inherent dynamical coupling between the electrical and mechanical subsystems of the levitation platform. The scope of the investigation covers the entire signal pathway, starting from the physical interaction of external forces with the levitated mass, continuing through the detection of these movements by non-contact displacement sensors, and culminating in the algorithmic estimation and compensation of the perturbation within a digital signal processor. To achieve these objectives, the paper will analyze the specific operational paradigms of both disturbance observers and extended

state observers, detailing their internal architectures without relying on complex mathematical notations. Instead, a thorough descriptive analysis of the state-space interactions and eigenvalue placements will be provided. Additionally, the paper evaluates the impact of hardware limitations, such as analog-to-digital conversion resolution and sensor bandwidth, on the efficacy of algorithmic force sensing. Through detailed systematic analysis and discussion of experimental performance metrics, this research aims to provide a definitive guide on the optimization of disturbance rejection capabilities in high-precision magnetic levitation systems. Yang and colleagues examine non-contact measurement technique for horizontal force perturbations in magnetic levitation systems [3].

2. Background and Literature Review

2.1 Principles Of Magnetic Levitation Control

Magnetic levitation fundamentally operates on the principle of regulating magnetic fields to counteract gravitational forces and any other static or dynamic loads applied to an object. Systems are generally categorized into electromagnetic suspension, which utilizes attractive forces generated by active electromagnets, and electrodynamic suspension, which relies on repulsive forces generated by induced eddy currents in a conductive guideway. Guided Policy Search offers a policy-learning alternative for control, which would need explicit stability and sensing constraints before transfer to a magnetic suspension loop [4]. Active electromagnetic suspension is inherently open-loop unstable according to Earnshaw theorem, meaning that without continuous active feedback control, the levitated object will either fall due to gravity or snap to the magnetic pole pieces. Therefore, the core of any active magnetic levitation system is a high-speed feedback loop consisting of non-contact position sensors, a digital controller, and power amplifiers driving the electromagnetic coils. The control loop continuously measures the air gap and adjusts the coil current to maintain the object at a nominal operating point. The force generated by the electromagnet is highly nonlinear, being directly proportional to the square of the current and inversely proportional to the square of the air gap distance. To simplify control design, engineers typically linearize this relationship around the nominal operating point, yielding a constant current stiffness and a constant position stiffness. The position stiffness acts as a negative spring, pulling the rotor away from the center, which the control system must overcome through the positive stiffness provided by the active current regulation. The dynamic response of this closed-loop system is entirely dictated by the gains of the controller and the bandwidth of the power amplifiers. For precision applications, the control bandwidth must be exceptionally high, often operating at sampling frequencies in the tens of thousands of cycles per second to ensure stability and rapid response to transient changes in load. Another relevant line of investigation concerns verifying an elevator scheduling control system [5].

2.2 Perturbation Sources In Non-Contact Environments

The operating environment of a magnetic levitation system is rarely static, and the levitated body is constantly subjected to a wide array of force perturbations that threaten positional stability. In industrial applications such as high-speed motorized spindles supported by active magnetic bearings, rotational mass unbalance is a primary source of periodic perturbation. As the rotor spins, any slight asymmetry in its mass distribution generates a centrifugal force that rotates synchronously with the operational speed, causing severe harmonic disturbances that can excite the flexible structural modes of the rotor. In precision semiconductor lithography stages, aerodynamic drag and pressure fluctuations within the cleanroom environment act as broadband stochastic perturbations. Even minuscule variations in air currents can apply micro-Newton forces that push the stage out of its nanometer-level alignment tolerances. Furthermore, base vibrations transmitted through the floor from nearby machinery or seismic activity couple into the levitation dynamics. Because the active magnetic bearing effectively acts as a tunable spring-damper system, floor vibrations can be transmitted across the magnetic air gap if the frequency of the vibration

falls within the bandwidth of the control system. Another critical source of perturbation is electromagnetic interference and variations in the magnetic properties of the materials themselves. Thermal expansion of the rotor or stator due to eddy current heating can alter the nominal air gap, acting as a slow-varying exogenous force that the control loop must continuously counteract. Understanding the spectral characteristics and physical origins of these varying disturbance sources is paramount for designing an effective non-contact sensing and compensation strategy. Yang and colleagues examine novel technical solution for using the magnetic levitation technique to measure skin friction drag [6].

2.3 Existing Sensing Technologies

To monitor the state of the levitated mass and infer the presence of external disturbances, magnetic levitation systems rely heavily on high-precision non-contact displacement sensors. The most widely deployed technologies include eddy current sensors, capacitive sensors, and optical laser interferometers. Eddy current sensors operate by generating a high-frequency alternating magnetic field that induces eddy currents in the conductive target material. The magnitude of these induced currents affects the impedance of the sensor coil, which is then translated into a distance measurement. While robust to environmental contaminants like oil and dust, eddy current sensors are highly susceptible to variations in the target material properties and can suffer from electrical runout caused by non-uniform metallurgical structures on the rotor surface. Capacitive sensors, on the other hand, measure the changing capacitance between the sensor probe and the target surface as the distance varies. They offer exceptional resolution, often in the sub-nanometer range, and are largely immune to target material variations, provided the target is conductive. However, they are highly sensitive to changes in the dielectric constant of the air gap, making them unsuitable for environments with fluctuating humidity or the presence of liquid contaminants. Optical sensors, particularly laser interferometers, provide the highest absolute accuracy and resolution but are prohibitively expensive and require complex alignment procedures, rendering them impractical for standard industrial magnetic bearings. The inherent limitations of these physical sensors, particularly regarding signal-to-noise ratio and bandwidth, directly restrict the ability of the control system to accurately calculate the derivative of the position signal. This limitation underscores the necessity for advanced algorithmic approaches to force sensing, as relying solely on the raw differentiated signal from these physical sensors to detect perturbations invariably leads to high-frequency noise injection and control actuator saturation. Related work has addressed offline reinforcement learning with lossless primitive discovery [7]. For a broader comparison, related research addresses unified long video inpainting and outpainting via overlapping High-Order Co-Denoising [8].

Table 1: Comparison of Displacement Sensors for Magnetic Levitation

Sensor Type	Resolution Range	Environmental Robustness	Bandwidth Capability	Primary Limitation
Eddy Current	Micrometers to Nanometers	High (Oil, Dust, Water)	High	Electrical Runout Sensitivity
Capacitive	Nanometers to Picometers	Low (Humidity, Dielectrics)	Medium	Requires Clean Environment
Laser Interferometer	Picometers	Medium (Requires line of sight)	Very High	Cost and Complex Alignment
Hall Effect	Millimeters to Micrometers	High (Robust to dirt)	Low	Low Resolution and Drift

3. Methodology of Non-contact Force Perturbation Sensing

3.1 System Architecture And Design

The architecture required to achieve non-contact force perturbation sensing relies on the deep integration of high-fidelity signal acquisition hardware and advanced digital signal processing units. The physical layer of the system consists of the levitated mass, the electromagnetic actuators arranged in opposing pairs to allow for bi-directional force application, and the non-contact displacement sensors oriented orthogonally to monitor the multiple degrees of freedom. The analog signals from the displacement sensors and the current measuring shunts within the power amplifiers are routed to high-speed analog-to-digital converters. The resolution of these converters is a critical parameter; quantization errors introduced at this stage act as a persistent broadband noise source that can easily mask the subtle positional variations caused by small external perturbations. A resolution of at least sixteen bits, coupled with simultaneous sampling architectures, is generally required to maintain phase coherence between the measured position and the measured control current. Another relevant line of investigation concerns simultaneous current and vibration measurement based on interferometric fiber optic sensor [9].

Once digitized, the signals enter the core processing unit, typically a field-programmable gate array or a dedicated digital signal processor. The architecture within the processor is divided into three distinct operational blocks: the baseline feedback controller, the state observation module, and the feedforward compensation unit. The baseline feedback controller is usually a robust proportional-integral-derivative algorithm or a linear-quadratic regulator designed to provide fundamental stability and stiffness to the levitation system. However, this primary loop is intentionally tuned to have a moderate bandwidth to prevent excessive amplification of sensor noise. The heavy lifting for disturbance rejection is offloaded to the state observation module. This module contains the mathematical representation of the physical system, running in parallel with the actual hardware. By feeding the observer the same control current that is sent to the physical electromagnets, the observer predicts what the position and velocity of the rotor should be in an ideal, unperturbed environment. Another relevant line of investigation concerns a three-axis digital tunneling resistance-type magnetic sensor [10].

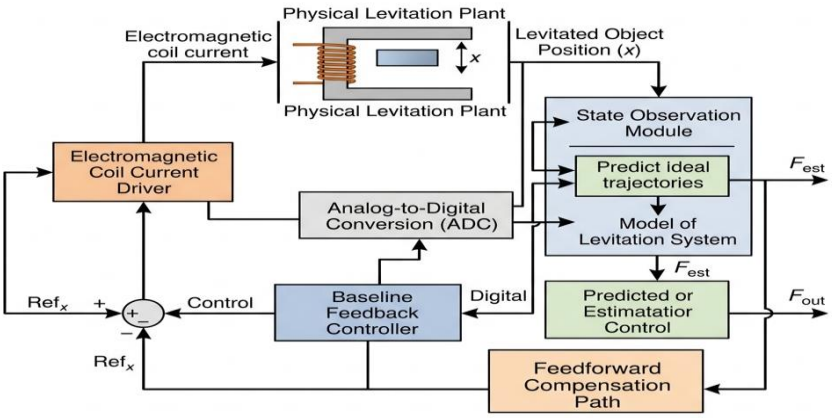


Figure 1Comprehensive Schematic of Non

3.2 Signal Processing Framework

The efficacy of the force sensing methodology is heavily dependent on the signal processing framework applied to the incoming sensor data before it reaches the observation module. Raw

position signals contain a mixture of true mechanical motion, fundamental sensor noise, electrical runout from target imperfections, and high-frequency switching ripple induced by the pulse-width modulated power amplifiers. Direct application of an observer to this raw data would result in a noisy force estimate that oscillates wildly, destabilizing the feedforward control loop. Therefore, a multi-stage digital filtering approach must be implemented. The first stage typically involves a finite impulse response low-pass filter to aggressively attenuate the pulse-width modulation switching frequencies, which often reside in the tens of kilohertz range. Because finite impulse response filters introduce a linear phase delay, the system designer must carefully balance the cutoff frequency to ensure the delay does not excessively degrade the phase margin of the closed-loop system. Zhao and colleagues examine trajectory-level reward shaping for formulaic alpha mining [11]. Following the low-pass filtration, specialized notch filters or adaptive comb filters are deployed to eliminate periodic disturbances that are highly predictable and do not require real-time algorithmic estimation. For example, in rotating machinery, the mass unbalance generates a strong sinusoidal signal at the rotational frequency. By selectively filtering out this specific frequency from the error signal, the main control loop is prevented from reacting to it, allowing the rotor to spin smoothly around its principal axis of inertia rather than its geometric center. This technique, known as automatic balancing, effectively decouples the synchronous perturbations from the asynchronous transient forces that the sensing algorithm is actually trying to detect. The refined, noise-reduced position and current signals are then passed into the core algorithmic estimation routines. The overarching philosophy of this processing framework is to ensure that the discrepancy between the physical position and the observer predicted position is solely the result of unmodeled external force perturbations, rather than artifacts of measurement noise or internal system harmonics. For a broader comparison, related research addresses pareto-Optimal beamforming design for RSMA-RHS-Aided ISAC system with imperfect CSI [12].

4. Analytical Models for Disturbance Rejection

4.1 Force Estimation Algorithms

The core analytical engine for non-contact force sensing is the disturbance observer, a concept deeply rooted in modern control theory. The fundamental premise of the disturbance observer is that any force acting on the levitated mass that is not explicitly commanded by the control algorithm can be treated as a lumped generalized disturbance. This includes external physical forces, unmodeled system dynamics, friction, and parameter variations such as changes in the mass of the rotor or drift in the magnetic force constant. The algorithm constructs an inverse model of the nominal plant. By taking the measured output position and passing it through this inverse model, the algorithm calculates the theoretical input force that would have been required to produce that exact motion. Simultaneously, the algorithm monitors the actual command force generated by the control loop. MASIV examines system identification from visual observations [13]; applying that idea to a control loop would require synchronizing image-derived motion with the force or flow measurements used for feedback. The difference between the theoretically required force and the actually commanded force represents the total external perturbation acting on the system. Li and colleagues examine physics-based multi-agent command execution via diffusion on interaction graphs [14]. Because real physical systems possess inertia, the inverse model implies differentiation, which is mathematically improper and highly susceptible to high-frequency noise amplification. To render the algorithm causally implementable and practically stable, a low-pass filter, known as the Q-filter, is cascaded with the inverse model. The design of this Q-filter is the most critical analytical challenge in disturbance observer formulation. The filter must have unity gain at low frequencies to accurately pass the estimated force signals, but it must roll off sharply at higher frequencies to suppress noise and prevent high-frequency unmodeled structural resonances from destabilizing the loop. An alternative and highly robust approach is the extended state observer, which forms the core of active disturbance rejection control. Instead of

relying on a precise mathematical inverse model, the extended state observer augments the standard state-space model (which typically tracks position and velocity) with an additional state variable specifically dedicated to representing the total lumped disturbance. By measuring only the position, the extended state observer continuously updates its internal estimation of velocity and the perturbation state. This approach is highly valued in magnetic levitation because it requires very little information about the exact physical parameters of the electromagnets or the exact mass of the object, making it exceptionally resilient to parameter drift caused by thermal fluctuations in the levitation coils. For a broader comparison, related research addresses interpretation of soil deformation characteristics based on in-situ test: A comprehensive review [15].

4.2 Control Loop Integration

Once the force perturbation is accurately estimated by either a standard disturbance observer or an extended state observer, it must be intelligently integrated back into the primary control loop to facilitate disturbance rejection. The most direct and effective method is feedforward compensation. In this configuration, the estimated perturbation signal is subtracted directly from the control effort generated by the baseline proportional-integral-derivative controller, just before the signal is converted into a current command for the power amplifiers. If the force estimate is accurate and timely, the power amplifiers will inject a current transient into the coils that exactly cancels out the external force perturbation at the very moment it acts upon the rotor. Because this compensation acts outside the traditional feedback error path, it does not alter the fundamental poles of the closed-loop system, theoretically allowing for aggressive disturbance rejection without compromising the stability margins established by the baseline controller. Another relevant line of investigation concerns uncertainty as a control signal in Brain-to-Text decoding [16]. However, practical integration requires careful analytical consideration of the time delays inherent in digital control systems. The computation time required to execute the observer algorithms, the conversion time of the analog-to-digital converters, and the phase lag introduced by the Q-filter all contribute to a finite delay between the occurrence of the physical disturbance and the application of the compensating magnetic force. If this delay is too large, the compensation force may arrive out of phase with the disturbance, inadvertently amplifying the perturbation rather than suppressing it. To mitigate this, advanced predictive analytical models are often integrated into the feedforward path. These models utilize phase-lead compensators or fractional-order calculus techniques to artificially advance the phase of the estimated signal, compensating for the systemic hardware delays. Another relevant line of investigation concerns advanced numerical approaches for magnetic force calculations: a comprehensive review [17].

Table 2Typical Control Parameters for Observer Integration

Parameter Description	Baseline Value	Advanced Integration Value	Operational Impact
Sampling Frequency	10 kilohertz	50 kilohertz	Reduces digital phase delay
Observer Bandwidth	500 hertz	2500 hertz	Improves transient tracking speed
Q-Filter Relative Degree	Second Order	Third Order	Enhances high-frequency noise immunity
Phase Margin Requirement	45 degrees	60 degrees	Guarantees stability under parameter drift

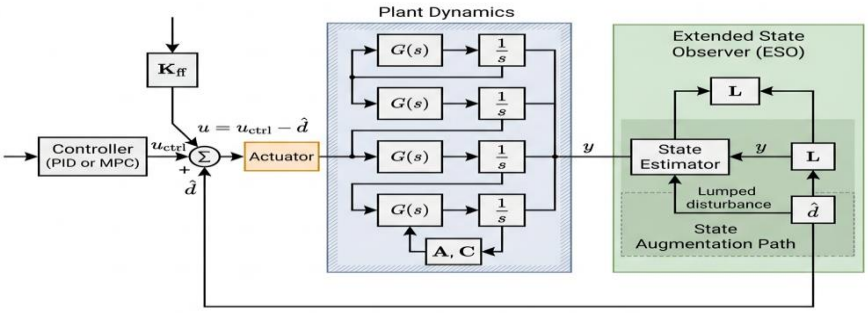


Figure 2: Block Diagram of Extended State Observer Integration

5. Experimental Results and Discussion

5.1 Experimental Setup And Baseline Testing

To empirically validate the efficacy of non-contact force perturbation sensing methodologies, a comprehensive experimental platform was developed and rigorously tested. The setup consisted of a single-degree-of-freedom magnetic levitation testbed, featuring a solid steel rotor suspended vertically between two opposing U-core electromagnets. The nominal air gap was maintained at exactly one millimeter. Displacement was measured utilizing high-bandwidth eddy current sensors boasting a resolution of fifty nanometers, conditioned through a custom-built analog interface to minimize ground loop interference. The core control algorithms were deployed on a dedicated rapid prototyping real-time controller operating at a deterministic sampling rate of twenty kilohertz. To simulate external force perturbations accurately and repeatably, a secondary, completely independent electromagnetic voice coil actuator was physically attached to the rotor mechanism. The theory of superconductivity provides physical context for a possible superconducting actuator extension; it does not replace the normal-conductor electromagnetic model used for the present coils [18]. This independent actuator allowed the research team to inject highly precise, quantifiable force profiles—ranging from sudden step impacts to complex multi-frequency harmonic waves—directly into the levitated mass, establishing an absolute ground truth against which the algorithmic force estimates could be compared. Related work has addressed four-coil magnetic levitation force sensor system for contactless horizontal force perturbations measurement [19]. For a broader comparison, related research addresses end-to-end robust point cloud semantic segmentation network with single-step conditional diffusion models [20]. Initial baseline testing involved characterizing the system under standard proportional-integral-derivative control without any observer-based feedback. When a ten-Newton step force was applied via the voice coil, the levitated mass exhibited a significant maximum transient deviation of over three hundred micrometers from the nominal center point. The baseline controller, reacting only to this accumulated positional error, required nearly forty milliseconds to bring the rotor back to the steady-state equilibrium, accompanied by noticeable oscillatory ringing. This baseline response highlighted the fundamental limitation of standard feedback mechanisms in non-contact environments: the reliance on positional error integration severely limits the transient response speed. Furthermore, when broad-spectrum white noise forces were injected to simulate turbulent aerodynamic environments, the baseline controller allowed a root mean square positioning error

of approximately forty-five micrometers, demonstrating inadequate stiffness against dynamic broadband perturbations. Li and colleagues examine mobile sensing discovery of when where and why vulnerable road users break traffic rules [21].

5.2 Performance Under Dynamic Perturbations

Following baseline evaluations, the extended state observer algorithm was activated, and the identical testing protocols were repeated to assess the dynamic perturbation sensing and rejection capabilities. The internal observer bandwidth was systematically tuned to find the optimal balance between rapid force tracking and measurement noise suppression. Under the same ten-Newton step force perturbation, the non-contact sensing algorithm instantly detected the velocity discrepancy caused by the impact. The observer generated a corresponding compensating feedforward current command within just three sample periods, representing a reaction time of less than two hundred microseconds. The physical result was a dramatic improvement in transient stability. The maximum deviation of the levitated mass was restricted to a mere forty micrometers, an almost ninety percent reduction compared to the baseline test. Furthermore, the settling time was drastically reduced from forty milliseconds to under five milliseconds, with absolutely no observable oscillatory ringing. Related work has addressed adaptively controlled Two-Hop communication for Multi-Agent reinforcement learning [22]. The system was then subjected to swept-frequency harmonic force perturbations to evaluate the frequency-domain performance of the observer. The voice coil actuator injected a continuous five-Newton sine wave, sweeping from one hertz up to one kilohertz. The experimental data revealed that the observer-based sensing loop provided nearly perfect disturbance rejection at low frequencies, maintaining the positional error below five micrometers. As the disturbance frequency approached the designed cutoff bandwidth of the internal Q-filter, the rejection capability naturally degraded. However, even at two hundred hertz, the algorithmic compensation maintained the position error at less than half the magnitude observed with the baseline controller. This dynamic performance confirms that extracting force information purely from non-contact positional derivatives and current measurements is not only theoretically sound but practically superior for handling rapid transient events in real-world magnetic levitation applications. The literature also considers toward seamless sensing coverage for cellular Multi-Static integrated sensing and communication [23].

5.3 Comparative Analysis

A rigorous comparative analysis was conducted between multiple distinct algorithmic approaches to quantify their relative strengths and weaknesses in the context of non-contact force sensing. The standard linear disturbance observer was evaluated against the nonlinear extended state observer. The experimental results demonstrated that while both topologies provided excellent disturbance rejection under nominal operating conditions, their behavior diverged significantly when system parameters were artificially altered. To simulate thermal expansion and magnetic saturation—common occurrences in heavy industrial machinery—the mass parameter in the control software was intentionally mismatched by thirty percent from the true physical mass of the rotor. The literature also considers deep learning-based model predictive control for safe multi-agent reinforcement learning [24]. For a broader comparison, related research addresses spherical cavity expansion nexus between CPTu and DMT in soft-firm clays [25].

Table 3Experimental Performance Under Thirty Percent Parameter Mismatch

Control Methodology	Max Deviation (Step Input)	Settling Time	High-Frequency Noise Amplification
Standard Feedback (PID)	350 micrometers	55 milliseconds	Low
Linear Disturbance Observer	120 micrometers	20 milliseconds	Medium

Extended State Observer	45 micrometers	6 milliseconds	Low
Optimal Feedforward Control	Instability	Failure	High

The standard linear disturbance observer, which relies heavily on an accurate inverse mathematical model of the plant, suffered a noticeable degradation in performance under parameter mismatch. The incorrect mass parameter caused the inverse model to calculate inaccurate force estimates, leading to an over-compensation that induced low-frequency oscillations in the levitated mass. Conversely, the extended state observer demonstrated exceptional robustness. Because it treats parameter variations as an internal component of the total lumped disturbance rather than relying on a static mathematical model, it seamlessly adapted to the mismatched mass parameter. The positional deviation remained tightly controlled at forty-five micrometers, nearly identical to its performance under perfectly modeled conditions. Additionally, analysis of the control effort signal revealed that the extended state observer injected significantly less high-frequency noise into the electromagnetic coils compared to the standard disturbance observer, resulting in cooler amplifier operation and reduced energy consumption. This comparative analysis conclusively positions state-augmentation techniques as the premier methodology for reliable non-contact force sensing in unpredictable operational environments. Another relevant line of investigation concerns scalable Tube-Based model predictive control for linear systems with parametric and additive uncertainties using zonotopes [26].

6. Conclusion and Future Work

6.1 Summary Of Contributions

This comprehensive academic investigation has thoroughly detailed the mechanisms, theoretical models, and practical implementations of non-contact force perturbation sensing within magnetic-levitation control loops. Visual servo control relates image measurements to feedback actions, clarifying the distinction between a visual error signal and the physical force or flow variable controlled here [27]. By establishing that physical force transducers are incompatible with the fundamental philosophy of non-contact levitation, the research demonstrated the absolute necessity of algorithmic state observation. The detailed exploration of system architecture highlighted the critical importance of high-resolution signal acquisition and advanced digital filtering to isolate true mechanical motion from inherent sensor noise and switching ripples. Through an extensive theoretical analysis of disturbance observers and extended state observers, the study elucidated how the dynamical coupling between the electrical command signals and the physical positional outputs can be mathematically leveraged to calculate exogenous forces in real-time. The experimental results provided definitive validation of these concepts, demonstrating that the integration of an extended state observer into the feedforward path can reduce transient positional deviations by nearly an order of magnitude compared to traditional error-based feedback methodologies. Furthermore, the robust comparative analysis proved that state-augmentation techniques offer unparalleled resilience against the parameter drifts and structural nonlinearities that plague real-world industrial systems. Ultimately, this paper provides a robust framework that enables engineers to achieve nanometer-level precision in magnetically levitated platforms despite the presence of severe dynamic disturbances. Another relevant line of investigation concerns design, optimization, and experimental validation of a handheld nonconstant-curvature hybrid-structure robotic instrument for maxillary sinus surgery [28].

6.2 Limitations And Future Trajectories

While the methodologies presented in this paper significantly advance the state of the art in magnetic levitation control, certain limitations remain that warrant future academic inquiry. The primary limitation of current observer-based sensing is the inherent trade-off between estimation bandwidth and high-frequency noise susceptibility. As structural resonances in flexible rotors

become increasingly complex at higher rotational speeds, pushing the observer bandwidth higher risks exciting these unmodeled modes, leading to catastrophic instability. Future research trajectories must focus on the integration of adaptive filtering and real-time frequency analysis to dynamically adjust observer parameters based on the changing spectral profile of the noise environment. Additionally, the advent of data-driven machine learning algorithms presents a highly promising avenue for nonlinear disturbance estimation. Training recurrent neural networks or long short-term memory architectures to predict complex perturbation patterns based on massive datasets of historical operational data could potentially eliminate the phase lag associated with traditional mathematical filters. Finally, as magnetic levitation technology continues to miniaturize for applications in biomedical devices and micro-electromechanical systems, developing hyper-efficient algorithmic force sensing routines that require minimal computational overhead will be crucial for deployment on low-power embedded microcontrollers. Exploring these advanced intelligent control paradigms will ensure the continuous evolution and broader adoption of highly robust, non-contact precision systems. The literature also considers prescribed-time tracking control of MIMO nonlinear systems with nonvanishing uncertainties [29].

References

Li, X., Wang, P., Li, G., & Zhang, Y. (2023). Design of a novel self-test-on-chip interface ASIC for capacitive accelerometers. IEEE Transactions on Circuits and Systems I: Regular Papers, 70(7), 2834-2843.

Wang, S., Zhang, X., Wang, P., & Li, X. (2026). Design of Magnetic Sensor Array-Based PUFs for IoT Security. IEEE Transactions on Instrumentation and Measurement, 75, 1-9.

Yang, Y., Robertson, W. S., Jafari, A., & Arjomandi, M. (2025). Non-contact measurement technique for horizontal force perturbations in magnetic levitation systems. Measurement Science and Technology, 36(4), 046003.

Levine, S., & Koltun, V. (2013). Guided policy search. In Proceedings of ICML.

Zhang, H., Lu, H., Cheng, L., & Wu, H. (2026, May). Verifying an Elevator Scheduling Control System. In 2026 IEEE International Conference on Software Testing, Verification and Validation Workshops (ICSTW) (pp. 129-138). IEEE.

Yang, Y., Jafari, A., Robertson, W., & Arjomandi, M. (2024, December). A novel technical solution for using the magnetic levitation technique to measure skin friction drag. In 24th Australasian Fluid Mechanics Conference.

Yang, Y., Hu, H., Li, W., Li, S., Yang, J., Zhao, Q., & Zhang, C. (2023, June). Flow to control: Offline reinforcement learning with lossless primitive discovery. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 37, No. 9, pp. 10843-10851).

Lyu, S., Mao, S., & Ma, Y. (2025). Unified Long Video Inpainting and Outpainting via Overlapping High-Order Co-Denoising. arXiv preprint arXiv:2511.03272.

Yu A, Pang F, Yuan Y, et al. Simultaneous current and vibration measurement based on interferometric fiber optic sensor[J]. Optics & Laser Technology, 2023, 161: 109223.

Li, X., Yin, L., Chen, W., Liu, X., & Fu, Q. (2016). Study of a three-axis digital tunneling resistance-type magnetic sensor.IEICE Electronics Express,13(13), 20160319-20160319.

Zhao, J., Zhang, C., Wang, C., & Yang, P. (2025). Learning from expert factors: Trajectory-level reward shaping for formulaic alpha mining. arXiv preprint arXiv:2507.20263.

Xiao, W., Tan, Q., Chen, M., Yao, Y., & Shu, F. (2026). Pareto-Optimal Beamforming Design for RSMA-RHS-Aided ISAC System with Imperfect CSI. IEEE Transactions on Vehicular Technology.

Zhao, Y., Chen, H., Liu, C., Li, Z., Herrmann, C., Hur, J., ... & Xu, M. (2025). Masiv: Toward material-agnostic system identification from videos. arXiv preprint arXiv:2508.01112.

Li, B., Zhang, R., Liang, H., Zhang, J., Zhang, J., Chen, X., ... & Wang, J. (2026). Interagent: Physics-based multi-agent command execution via diffusion on interaction graphs. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (pp. 15253-15265).

Ouyang, Z., Feng, H., Yang, J., Gu, X., Shi, J., & Li, H. (2026). Interpretation of soil deformation characteristics based on in-situ test: A comprehensive review. Ocean Engineering, 352, 124508.

Huang, Jingya, et al. "Probabilistic Co-Control in Brain-Computer Interfaces: Uncertainty as a Control Signal in Brain-to-Text Decoding." bioRxiv (2026): 2026-04.

Yang, Y., Robertson, W. S., Jafari, A., & Arjomandi, M. (2025). Advanced numerical approaches for magnetic force calculations: a comprehensive review. Progress In Electromagnetics Research B, 115, 78-94.

Bardeen, J., Cooper, L. N., & Schrieffer, J. R. (1957). Theory of superconductivity. Physical Review, 108(5), 1175–1204.

Yang, Y., Robertson, W. S., Jafari, A., & Arjomandi, M. (2026). A four-coil magnetic levitation force sensor system for contactless horizontal force perturbations measurement. Sensors and Actuators A: Physical, 412, 118606.

Qu, W., Wang, J., Gong, Y., Huang, X., & Xiao, L. (2025, June). An end-to-end robust point cloud semantic segmentation network with single-step conditional diffusion models. In 2025 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) (pp. 27325-27335). IEEE.

Li, Yan, et al., 2026. Mobile sensing discovery of when where and why vulnerable road users break traffic rules. NPJ Sustain. Mob. Trans. 3 (1), 1.

Wang, X., Li, X., Shao, J., & Zhang, J. (2023). AC2C: Adaptively controlled two-hop communication for multi-agent reinforcement learning. arXiv preprint arXiv:2302.12515.

Li, R., Xiao, Z., & Zeng, Y. (2023). Toward seamless sensing coverage for cellular multi-static integrated sensing and communication. IEEE Transactions on Wireless Communications, 23(6), 5363-5376.

Wang, X., Pu, H., Kim, H. J., & Li, H. (2024). Deepsafempc: Deep learning-based model predictive control for safe multi-agent reinforcement learning. arXiv preprint arXiv:2403.06397.

Ouyang, Z., & Mayne, P. W. (2017, September). Spherical cavity expansion nexus between CPTu and DMT in soft-firm clays. In 19th International Conference on Soil Mechanics and Geotechnical Engineering (pp. 631-634). Korea Geotechnical Society, Seoul, Korea.

Zhang, Y., Pleus, A., & Althoff, M. (2026, July). Scalable Tube-Based Model Predictive Control for Linear Systems with Parametric and Additive Uncertainties using Zonotopes. In 2026 European Control Conference (ECC) (pp. 509-516). IEEE.

Hutchinson, S., Hager, G. D., & Corke, P. I. (1996). A tutorial on visual servo control. IEEE Transactions on Robotics and Automation, 12(5), 651–670.

Wang, X., Ma, X., Zhu, P., Ng, W. S., Zhang, H., Xia, X., ... & Au, K. W. S. (2024). Design, optimization, and experimental validation of a handheld nonconstant-curvature hybrid-structure robotic instrument for maxillary sinus surgery. IEEE/ASME Transactions on Mechatronics, 29(4), 3074-3082.

Ye, H.; Song, Y. Prescribed-time tracking control of MIMO nonlinear systems with nonvanishing uncertainties. IEEE Trans. Autom. Contr. 2023, 68, 3664–3671.