Review of Disturbance Suppression Methods for Magnetic Levitation Worktables

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Abstract: The traditional micro-machining process is revolutionized by maglev systems, which can provide friction-free support, high precision (below 1μm), low friction wear, etc. in the machining processes of micro electrical discharge machining (micro EDM), additive manufacturing, etc. However, the interaction of tools and the workpieces will cause system parameter uncertainties, impacting the stiffness and precision of the whole system. This paper presents a review of disturbance mitigation technologies of maglev worktables between 2022 and 2025 with regard to structural design, adaptive control techniques and applying novel technologies, such as artificial intelligence (AI). As promising examples, we can also appreciate 5-DOF actuators with resolution at the level of 1 μm, the final surface roughness after micro-EDM operations improved, the rate of material removed increased. Issues remain in controlling nonlinear motions, lowering construction expense, and making devices compatible with varied manufacturing environments. Further research involves supervised-learning enabled control, cyber-physical systems, and low cost machine development for achieving higher accuracy and reliability, to realize maglev as revolutionary devices in precision manufacturing.

Keywords: Magnetic Levitation; Disturbance Suppression; Micro-Machining; Adaptive Control; Artificial Intelligence

1. Introduction

1.1 Background and Significance

Maglev machine drastically redefines the perception of precision machining by transporting machined parts in free air without mechanical contact, thus offering unprecedented ability to eliminate sliding friction and vibration problems arising in traditional mechanical driving. In micro-machining tasks where most parts tolerances have to be below micron scale, maglev machine demonstrates powerful capabilities in micro-machining such as microelectrode discharge machining (micro-EDM) [1], micro-milling machining, and 3D additive manufacturing [2]. Such devices use electromagnetic forces to hold constant the inter-electrode gap, suppress perturbations, and achieve a high level of stability and precision [3,4]. A 5-DOF maglev actuator with a permanent magnet ring and a void coil has been used to hold a simulated payload up to 12.93 N at 101 and 51 Hz bandwidths for the X and Z axes, respectively [3]. Reported maximum loads on experiments in the test bench were much smaller, such as 0.8 kg spindle mass to emphasize the difference between the theoretical and actual performance [3]. These are just the abilities needed to micro-EDM materials which are difficult to machine such as the expensive Inconel-625, where consistent voltage-current profiles mean we are never facing arcing and a surface finish consistent with that of a material where good cutting requires a positive plate with zero current [1].

The frictionless nature of maglev systems offers unparalleled advantages in precision manufacturing. By eliminating mechanical contact, these systems reduce tool wear, minimize vibrational noise, and enhance positional accuracy, which are essential for achieving sub-micron tolerances. In additive manufacturing, maglev platforms enable substrate-free material deposition, reducing post-processing requirements and streamlining production workflows [2]. However, tool-workpiece interactions introduce disturbances—load fluctuations, vibrational noise, and parameter shifts—that compromise system stiffness, leading to positional inaccuracies and diminished machining quality.

These challenges necessitate robust disturbance suppression strategies to maintain the precision and reliability of maglev worktables.

Structural improvements and control algorithms of complex nature have been devised in recent years to reduce disturbances arising from deviations in the structure, most notably optimized magnet arrangements [4] and advanced control algorithms [5]. Development of novel Halbach array designs and planar motors have led to substantial lift and thrust increases of the effectors and enhanced operating envelopes of maglev systems [4]. At the same time adaptive control methods are intensively studied, for instance in the realm of intelligent control techniques based on machine learning [5,6]. Moreover, the applications and development of maglev machinery in additive manufacturing are another demonstration of the disruptive potential of maglev technology and their use in PEM by opening new avenues for this manufacturing paradigm [2]. It has been reviewed here and explained how they influence the micro-machining and pave the way for future advances.

1.2 Review Objectives

In this paper, the works published in the years 2022 to 2025 are summarized to analyze the fundamentals, control methods and applications of disturbance suppression in the control system of maglev worktable for micro machining. Moreover, the structural optimization (Halbach array configuration and EM micromanipulator) and control method (adaptive robust control and learning control with AI) are addressed respectively. Special emphasis was paid to solving nonlinear dynamics, the most recurrent nuisance on the maglev systems and to the existence of scalable and cheap solutions for its industrialization. Future works that deserve being investigated in detail are also presented, including the employment of deep reinforcement learning methods for autonomous rejection of disturbances and hybrid maglev-mechanical systems. Figure 1 shows the process of maglev system in micro-machining, including disturbance, sensor feedback and control.

Figure 1. Summary of how the influences coming from the external disturbances and the contact-induced ones are managed via a sensor-based approach and through a change in the structure in order to work effectively under several machining conditions.

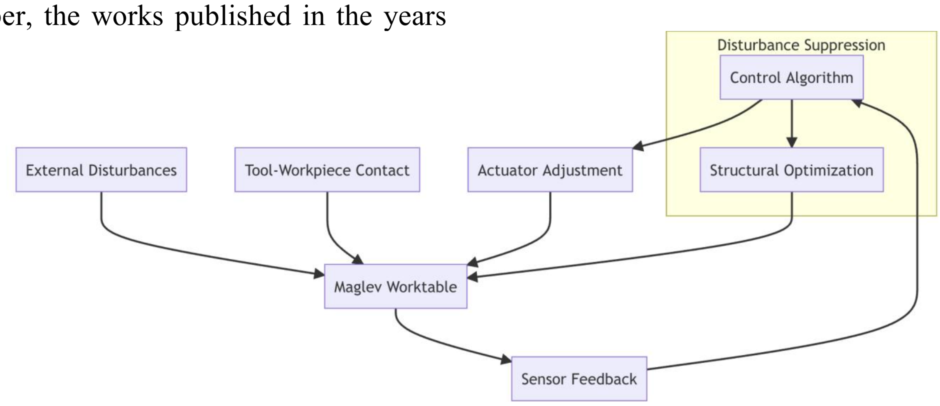

Figure 1. Schematic Workflow of a Magnetic Levitation System for Disturbance Suppression in Micro-Machining

2. Literature Review

2.1 Principles of Magnetic Levitation in Precision Machining

Electromagnetic levitation is a technology for carrying out levitation using electromagnetism opposed to gravity to achieve ‘no contact’ motion that is necessary for micro-systems to acquire high resolution operations [6]. Levitation eliminates the force of friction, mechanical interaction, wear and noise that can result in mechanical vibrations, suitable for a high resolution micro-machining applications that demands low micron tolerances. One such high resolution micro machining is micro-electro-discharge machining (micro-EDM), where EDM electrodes levitated using levitation platform to maintain the inter electrode gap enables producing uniform electro discharge and high surface finish [1]. Likewise, with micro-milling and additive manufacturing [2], magneto-levitation systems also improves position accuracy and extends tools wear, allowing the fabrication of sophisticated geometries and glossy surfaces

[2].

Maglev micro-machining systems commonly use 5-DOF actuators consisting of permanent magnet rings and a copper wound coil (0.7 mm wire, 670 turns, ±3.08 A, 1 μm position resolution [3]). The simulated maximum load capable of being handled by these actuators has been published as high as 12.93 N [3], however, in a 0.8 kg spindle mass-based experiment [3], the maximum experimental load was reported as 0.8 kg [3]. The Lorentz force defines the electromagnetic force in such a system as equation (1):

$$F = I \times B \cdot L \quad (1)$$

where (F) is the electromagnetic force, (I) is the current, (B) is magnetic field strength and (L) is conductor's effective length. An accurate modulation of the current guarantees the suspension stability that plays a crucial role in retaining positional accuracy under dynamic conditions.

The design aspects of the maglev have also developed, which include planar motors of 2 dimensional Halbach array alongside PCB coils (72mm × 72mm) which amplify the force output and the torque by 50.31 % and 70.65 % respectively against ordinary harmonic designs for prolonged use [4]. The electromagnet-based micromanipulator with concentric coil for object manipulations in a low–permeability material may perform with minimum 28% of working envelope of that for a conventional substrate-based DMD-IC106 [2] system, which proves that high-precision manufacturing utilizing maglev might change the existing manufacturing paradigm by bringing both operation flexibility and manufacturing precision into the same system.

2.2 Control Methods for Magnetic Levitation Systems

Controlling maglev systems is a nontrivial problem because of the nonlinearity and external disturbances that are subject to the dynamics. Control techniques from linear to nonlinear like proportional-integral-derivative (PID) and state feedback, sliding mode control (SMC), feedback linearization and the like in the presence of system uncertainties [5,7]. While linear approaches such as PID are convenient for both design and tuning of controls, they suffer in performance when dealing with nonlinear dynamics and uncertainty [5]. The robust performance of SMCs however is faced with chattering issues that lead to undesired shaking [7].

Two trends are adaptive robust controls, and fuzzy logic controllers [8], which adapt themselves to the variation by dynamically modifying control parameters but such controllers would need heavy computations [8]. Internal model regulators augment the steady state performance by modeling and compensating for known disturbances and adaptive robust control by using online parameter estimation for stability [9], whereas PI controllers incorporate a compensation in the current feedback loops to improve the dynamic performance by decreasing the settling time and tracking error [5].

More recent works have tackled these problems with advanced methods for control. Neural PID controller is designed with the help of NN to reject noises and follow better complicated dynamics but it needs sufficient training samples [10]. A new form of tracking differentiator based on inverse hyperbolic sine function is devised to reduce chattering of a SMC and thus enhance smoothness and accuracy of control [10]. Iterative learning PID with disturbance compensation (LPIDDC) combines iterative learning control (ILC) and disturbance observer techniques for trajectory tracking in repetitive tasks, e.g., maglev rotary tables [11], that is expected to provide benefits in applications where system dynamics is determined by periodic disturbances of repeated tasks, e.g. those caused by tool-workpiece interaction. Comparative summary of these control techniques in terms of their advantages, disadvantages and their usage in maglev systems are presented in Table 1.

These comparisons lead to choice of controls methodologies according to machining needs and system limitations, between performance and computation capabilities.

Table 1. Comparison of Control Strategies for Magnetic Levitation Systems

Control Method	Key Advantages	Limitations	Applications in Maglev
PID	Simple implementation, easy tuning	Limited nonlinearity handling	Basic stability control
Sliding Mode Control	Robust to uncertainties	Prone to chattering	Disturbance rejection

Adaptive Fuzzy	Adapts to parameter variations	High computational demand	Nonlinear system control
Neural Network PID	Superior noise rejection, adaptive learning	Requires extensive training data	Precision trajectory tracking
Iterative Learning PID	Enhances repetitive task performance	Complex implementation	Rotary table trajectory tracking

2.3 Disturbance Suppression in Magnetic Levitation Systems

Variations in the stiffness and position accuracy of maglev systems (e.g., tool induced parameters variations, environmental vibrations, force varying loads and so on) are resulted from disturbances, which usually arise during machining between both objects due to dynamic friction during machining (e.g., contact force in micro-EDM or vibration noise in micro-milling etc.). They will cause large errors in the system position. To solve these problems, integrated methods should be developed that are composed of structural optimizations and active compensations.

Structural modifications have the benefit of increasing the structural stiffness and the force. For example, newly arranged structures of magnet and coils can obtain a structural stiffness as high as $\delta_x \approx 256.45$ and $\delta_z \approx 256.50$, which greatly reduces the system's sensitivity to disturbances [3]. The array form of Halbach has larger magnetic field size, allowing planar motors to provide larger forces and larger torques which is crucial for the system stability under heavier load, as well as higher speed motion [4]. Such structures guarantees satisfactory disturbance rejection, especially for high-accuracy missions.

Structural design combined with active control is an attractive solution for some of the drawbacks. While force-balancing methods apply real-time corrections to EM forces to stabilize the load change, hybrid methods of nonlinear stiffness compensation and deviation compensation can better compensate the complicated dynamic [12]. Adaptive robust control combined with ILC allows low- to medium-speed maglev systems to deal with nonlinear challenges while enhancing disturbance rejection without using overly sophisticated algorithms [8]. For maglev system in additive manufacturing, it has been used to avoid substrate-induced vibration when levitating the workpieces and simplify the post-processing [2]. Another requirement for suppressing disturbances is the capacity for nonlinearities because of coil inductance and variation in the magnetic fields and environmental vibrations. Here model predictive control (MPC) has demonstrated encouraging results in suppressing nonlinearities by optimizing control input using predictive models to outperform conventional PID or SMC in trajectory tracking [7]. Similar to the previously mentioned robust controllers, artificial intelligent controllers like using deep reinforcement learning, provide some adjustable controllers whose optimal response to noises (disturbances) adapt to environment over time and increase the robustness of systems in a dynamic environment [6].

2.4 Applications in Micro-Machining

The advance of micro-EDM using a maglev system has yielded surface roughness of Ra 0.899–1.057 μm while employing servo gap control, as repulsive and restorative forces act for balancing their ratio on gap for R and F respectively, and helps in maintaining a uniform spark thereby easing all the arcing issues. Similarly has put forth a solution of how to opt for best materials (Inconel-625, a nickel-based superalloy) [1]. By employing these functions with the help of maglev [1], the energy consumption is recorded as 1.2245–1.6284 J/μg and MR is calculated as 39–57 μg/min [13]. All this helps in the removal of all the arcing-related issues and maintaining a relatively uniform spark gap for a uniform spark generation thereby yielding a finish surface for certain grades of difficult-to-cut-material like Inconel-625 [1]. Analogous benefits have been achieved in duplex stainless steel (DSS-2205), where a removal rate of 117.6–223.8 μg/min and surface roughness ranging from 1.614 to 2.370 μm are achieved, illustrating also the applicability of the maglev systems for other materials [13].

For micro-milling and micro-turning, maglev machines create less tool wear and vibration, and thus, smaller features and better surface finishes compared to machining tools using micro-EDM [4]. Because of their high implementation costs, setup complexities, etc.

the application of maglev machines to high-precision milling has largely not been explored compared to micro-EDM [4]. Planar motors that use arrays of Halbach magnets have demonstrated precision milling applications [4], but their operation is not as well documented for applications involving larger workpiece scale [4]. The use of maglev micromanipulators for material deposition in additive manufacturing is advantageous as it is material-based (no substrate involved), it only takes the space of 28 % of the working envelope as in the examples of the DMD-IC106 [2] thus minimizing material waste and also simplifying manufacturing process, making maglev-based systems an interesting option for metal additive manufacturing.

Other recent applications concern with mixed machine machining [6], such as the mixed machine tool machining approaches, wherein a combination of a maglev apparatus and another more specific machine (e.g., laser machine and/or ultrasonic machine) is employed. Examples comprise mixed machine machining wherein in some ways the processing quality of a laser micromachining can be enhanced by some kind of mixed machined micro-machining - i.e., a mixing of two types of machine machining approaches - in the sense of coordinating the motion of the workpiece using some mechanical tool, such as the lifting magnet, while it is processed in a maglev format. A typical example [6] is combining maglev for micromachining and laser micromachining. Here the mechanical tool is represented by a laser that acts upon the processing of the workpiece (target). Both approaches offer several distinct advantages to account for, one of them is of supporting a certain functionality that may not be achieved if just one machine approach is employed, in addition, an active way to reduce thermal distortion during the process can be supported in a relatively simple and cost-effective manner. Therefore, support for a wide range of materials (such as plastics, metals, glass, etc.) with comparatively high precision and low cost as well as high flexibility is enabled. This is especially true in view of an overall machining solution concept, which does not limit the machine movement to planar-level machine motion [6], but employs a sophisticated arrangement of various tools to achieve the highest dimensional stability of both the machine and the process itself [6]. These integrated processes reveal the capability of maglev devices beyond micromachining to becoming integrated manufacturing technologies.

3. Discussion

3.1 Summary of Current Research

The application of maglev in micromanufacturing has an explosive development in the following 3 years starting from 2022 to 2025. Both the design (e.g., Halbach array and coil on a PCB) and the control (e.g., adaptive fuzzy inversion and MPC) methods have been continuously enhanced [4]. Force/torque can be powered to its maximum by optimizing their structures, and thus extended travelling range is realized and no base is required; the nonlinearities can be effectively regulated through the control techniques [5,7]; so as to achieve excellent trajectory tracking. Micro-EDM This is to say maglev systems can bring positioning accuracy up to about 10 μm, which can greatly improve stability and performance factors, like surface roughness and material removal rates [1,13]. LPIDDC can be applied to the maglev rotary table, because it can deal with the unmodeled dynamics and periodic disturbances in the repetitively operated maglev rotary table [11]. For additive manufacturing, the substrate-free maglev system can generate a friendly environment for material generation and thus simplify the production process and avoid some procedures after the manufacturing process [2]. These advancements reflect a multidisciplinary approach, combining electromagnetics, control theory, and materials science to address the challenges of precision manufacturing. The integration of AI, particularly deep reinforcement learning, has emerged as a promising avenue for enhancing system adaptability, enabling maglev worktables to respond dynamically to unpredictable disturbances [6]. Such innovations position maglev systems as critical enablers of next-generation manufacturing technologies.

3.2 Challenges and Limitations

Though considerable work has been done, there are still many open issues preventing the use of maglev in micro-machining systems to be standardized. In order to be implementable, maglev devices rely on expensive materials and high control hardware complexity, limiting the number of entities capable of implementing the system [5,8]. Moreover, even the implementation of linearization and control in non-linear dynamics of magnetic systems, for instance considering non-linearity of the coils inductance [11], magnetic fields variations [9] or oscillations externally introduced, has proven to have limited success [11]. However, most existing models are simple assumptions not realistic enough to reflect the actual machine circumstances.

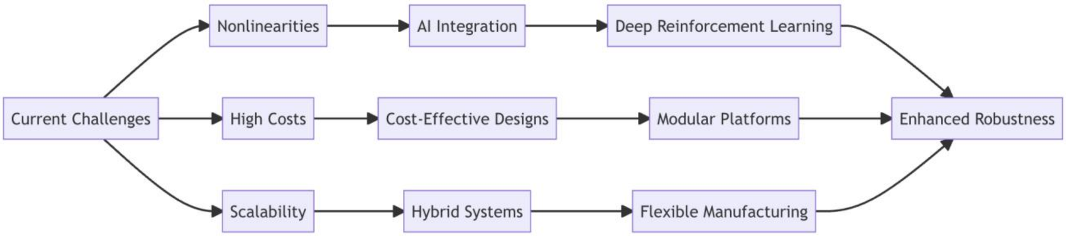

Figure 2. Flowchart of Future Research Directions for Disturbance Suppression in Magnetic Levitation Systems

Another important issue is scalability. The vast majority of these maglev applications have been designed for a dedicated process e.g. micro-EDM with few being applied in micromilling or turning where force outputs are inadequate for use on larger sized work-pieces [4]. This, therefore, will require a retrofit of maglev system with major potential logistic and economic hurdles. Further, complex control algorithms, such as a NN-based PID or MPC, are computationally intensive, and could impair the real time computing resources, especially when applied in limited resource environments [7,10]. External disturbances, including temperature variations, electromagnetic noises, and others, also pose serious challenges to the functioning of a maglev system. For instance, coils will have resistance variations and magnetic state variations as the temperature changes, which could cause the system parameters varying and degrading the control performance [9]. Effective solutions would demand efficient, adaptive control strategies and affordable controllers and transducers for actual applications on various mass productions.

3.3 Future Research Directions

The need of future research is to better integrate maglev systems with modern manufacturing paradigms as e.g. additive and hybrid manufacturing. The substrate free maglev systems could be powerful for minimizing the material waste while simplifying the production processes, specially in metal additive manufacturing [2]. The design of low-cost systems like modular platform or simple coil arrangement [2], may create equality to acquire the maglev devices for local small-and medium-scale businesses.

The use of AI based controllers, such as Deep RL, have the potential to change that paradigm by allowing the maglev system to adapt autonomously to perturbations and learn about the best response through trial and error interactions with environment [5,6]. This kind of applications could be employed to increase system robustness under the very time varying machining conditions that are challenging to manage using standard approaches. A practical route to larger industries for maglevs is towards hybrid systems in which maglev elements are integrated into the conventional mechanical hardware that form part of production machinery. A case-in-point is the combining of maglev worktables with robotic arms – this would allow for flexible manufacturing machines that have the required precision to work with any complicated geometry and across wide variety of materials. Another potentially fruitful path is to create multi-physics models involving the interplay between heat, electromagnetism and mechanics in maglev systems which allows enhancing the accuracy of the perturbation prediction and compensation as opposed to the limitations in the current nonlinear dynamics [9]. Further, effort towards low energy consuming implementations of controllers, i.e., low power electromagnetic actuators, can even decrease usage costs and make manufacturing green in line with worldwide processes of becoming environmentally friendly. Theoretical research lines described here are shown in Figure 2, with the depicted algorithms in AI and hybrid systems a key way to overcome existing difficulties.

The scenarios summarized above demonstrate how today's problems can be addressed with new technology innovations such that AI can be extremely disruptive, lightweight systems can be quite inexpensive, or hybrid approaches can be appropriate.

4. Conclusion

As this disturbance rejection is the key to tap the performance potential of the magneto-gravity levitated worktable in a high-precision micro-processing field, in the meantime, a series of latest advancements that combined structural optimization (Halbach arrays and electromagnetic micromanipulator) with intelligent control algorithms (adaptive robust control, AI algorithm) have improved the system rigidity, precision and capability. Their achievements are small-scale positioning resolution, enhanced surface quality in micro-EDM, and simplified productions in additive manufacturing. However, the existing issues such as their high cost, the nonlinear dynamics and the lack of the scale-up make the innovation urgent. AI controls, hybrid system and energy-efficient design etc. shall be some of the future studies that may solve the limitation and make maglev as backbone technology for the advance era of precision manufacturing.

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