

Article

Development of an Active Micromagnetic Bearing with a 300 μm Outer Diameter Permanent Micromagnet

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Abstract

Micromachines, MEMS and actuators suffer from much more significant relative friction and wear issues than their equivalent macroscopic devices. Active magnetic bearings can be a good option to mitigate friction issues; however, their construction at microscale is still an open research topic. In this work, we have developed a micrometric-size active magnetic bearing with a simple configuration and one vertical degree of freedom. This active magnetic microbearing is composed of a coreless coil with 1 mm outer diameter, 0.3 mm inner diameter and 0.5 mm length that holds a 0.3 mm outer diameter, 0.5 mm length NdFeB N52 micromagnet. Stable magnetic levitation is achieved by regulating the coil current based on precise position measurements of the magnet obtained using the smallest commercially available Hall-effect microsensor. The microprobe integrates between the coil and magnet, reducing the total size of the device. A maximum axial load capacity of 1.16 mN/A has been demonstrated. This micromagnetic bearing is one of the smallest active magnetic bearings developed to date, demonstrating the viability of this kind of system at the micrometric scale.

Keywords: active magnetic bearing; magnetic levitation; micromagnet; MEMS; active micromagnetic bearings

1. Introduction

Electromagnetic actuators and machinery present unique characteristics such as compactness, high efficiency and reliable easy control. Thanks to this, they are the one of the most attractive solutions to create complex machines for a wide variety of applications at the macroscale. However, the current performance of electromagnetic actuators at the microscale is very far from optimal. Current micromachines and microactuators show typical figures of performance (like power-to-weight ratio, torque/power density, or efficiency) several orders of magnitude lower than the macroscopic equivalent ones [1]. One of the main reasons why they show such a poor performance is their relatively high friction forces compared to inertia forces.

Friction and wear phenomena at the microscale are primarily controlled by surface forces (such as capillary, van der Waals, electrostatic or frictional forces) and surface properties (i.e., surface roughness and adhesion) [2]. Friction and wear determines the reliability of micromachines, which is a crucial aspect as it can be the difference between a successful or totally missed product [3]. This affects any type of micromachine, whether electrostatic,



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piezoelectric or electromagnetic. The problem of wear and friction in micromachines has been faced mostly using techniques from the surface engineering field [4,5]. Scale [6], coating and lubricant influences on the friction and wear properties of the devices were studied, explaining the differences in tribological behavior from micro- to nanoscale [7]. But in the end, the effectiveness of all previously proposed friction-reduction techniques is physically limited as long as mechanical contact is maintained.

A radically different approach to friction is to completely separate moving elements using different types of magnetic levitation [8]. Active [9], passive [10], magnetic and superconducting levitation [11] is being explored and used to mitigate friction issues at different scales, micro and macro, and different harsh environmental conditions, even at cryogenic temperatures [12]. Focusing on the millimetric and micrometric size, magnetic microbearings could mean critical breakthroughs for their application in emerging fields such as microrobotics [13], precision medical devices [13–17], aerospace and micro-power systems. However, these advancements are still constrained by challenges in the micro-manufacturing [18,19], microassembly [20] and integration [21] of magnetic elements and sensors in the device [22], electromagnetic topology optimization, thermal management, and multi-physics coupling considerations [23].

More specifically, recent advances in active magnetic microbearings have been published. The reviewed works present several miniaturized magnetic bearing systems distinguished mainly by their compactness and performance. A micromagnetic bearing with a 2.6 mm outer diameter (OD) rotor and 2.1 mm stator, separated by a 10 μm air gap, achieving 45 μN axial maximum restoring force through active radial and passive axial control is shown in [24]. Kuroki et al. proposed an even smaller 2 mm OD rotor bearing, levitating at 39,000 rpm with 4.7 N/mm stiffness and only 20.4 mW power consumption, demonstrating highly efficient single-axis control using minimal components [25]. Okada et al. [26] scaled up to a 28 mm outer diameter axial self-bearing motor, capable of 7600 rpm, 8.7 mNm torque and 67% efficiency, showing applicability in compact fluid systems such as artificial heart pumps despite hydrodynamic limitations.

Larger but still compact designs include Ueno et al. [27], who introduced a 32 mm $\times$ 114 mm six-pole active bearing integrated into a brushless DC motor, optimizing energy efficiency with minimal copper losses. At the sub-millimeter scale, Boletis and Bleuler [28] achieved a breakthrough with a three-axis AMB micromotor stabilizing spherical rotors from 1 mm to 0.4 mm, reaching 2.88 million rpm under vacuum using five electromagnets and optical sensors for precise control. Together, these developments illustrate a clear trend toward reducing system dimensions—from tens of millimeters down to the sub-millimeter scale—while maintaining or even enhancing dynamic stability, control accuracy and operational speed.

In this article, we present a micrometric size active magnetic bearing with a simple configuration and one vertical degree of freedom. This active magnetic microbearing is composed of a non-ferromagnetic core coil with 1 mm outer diameter (OD), 0.3 mm inner diameter (ID) and 0.5 mm length that holds a 0.3 mm diameter and 0.5 mm length cylindrical NdFeB N52 micromagnet. Not only are the magnetic elements micrometric in size, but we have also used a Hall-effect microsensor which is the smallest commercial Hall sensor available. This ends in a very compact full micromagnetic bearing that is axially levitated, smaller than 2.5 mm long and 1.2 mm in outer diameter including the sensor, which is several times smaller than any previous development to date. In the article, we present the design and manufacturing process, specifically developed for it, a model of the control system, and the experimental setup and test results characterizing the micromagnetic bearing. We describe special considerations due to small size as well as the

influence of hardware parameters like frequency, resolution or noises in the control of the levitating magnet. Table 1 compares the strengths of this development with previous works:

Table 1. State-of-the-art summary table.

Ref.	Size	Load Capacity	Control Strategy	Sensing Approach
[13]	Magnetic ball $\varnothing$ 12.7 mm	Suspension of 8.15 g	NN-PID tuning	Dual Hall-effect sensor array
[14]	H = 15.8 mm D = 65 mm	4.4 N/A	Virtual zero power control	Eddy current based gap sensors
[16]	H = 33 mm D = 22 mm	2 N/A	PID/PI controller	Eddy current and Hall effect sensors
[24]	H = 0.25 mm D = 2.6 mm	45 μ N	PD controller	Eddy current sensors
[25]	D = 2 mm	0.54 N/A	One-axis controller	Capacitance micrometers
[28]	D = 1~0.4 mm	$2.88 \cdot 10^6$ rpm	-	Optical sensors
This work	H = 1.9 D = 1 mm	1.16 mN/A	PD controller	Hall-effect microsensor

2. Design and Manufacturing

2.1. Electromagnetic Design and Simulation

The micrometric-size active magnetic bearing is composed of a microcoil with a micromagnet positioned beneath it that provides an upward attractive force, counteracting the effect of gravity. The coil, wound around a resin core, has an inner diameter (ID) of 0.3 mm, an outer diameter (OD) of 1 mm and a height (H) of 0.5 mm. The magnet is a NdFeB N52 cylinder with a 0.3 mm diameter (D_M) and 0.5 mm in height (H_M), positioned at a levitation height (L_H) between 0.9 and 1.3 mm from the lower end of the coil. A simplified scheme and a dimensional drawing of the magnetic levitation system are shown in Figure 1.

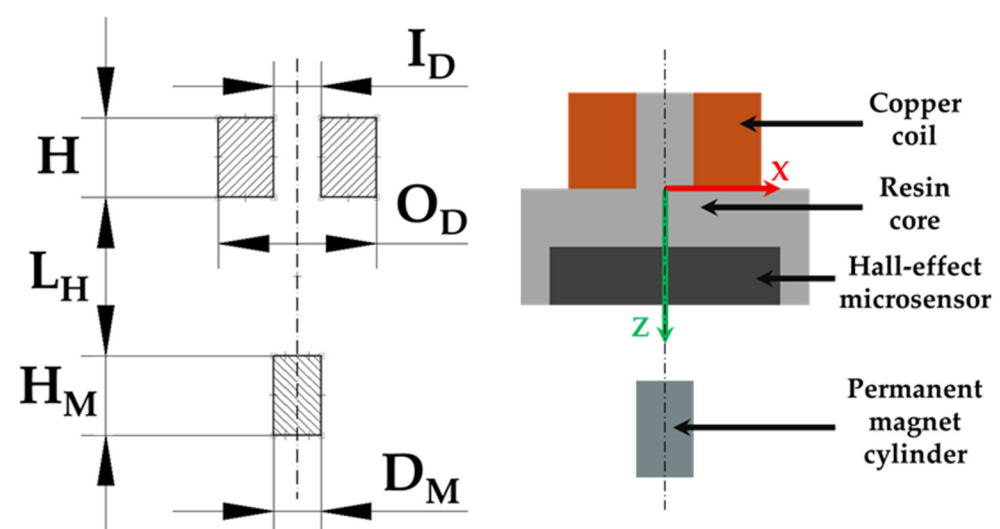


Figure 1. Simplified scheme of the magnetic levitation system.

The electromagnetic attraction between the coil and the magnet counteracts the gravitational force acting on the magnet, resulting in a force equilibrium. Therefore, active control of the current through the coil is required to regulate the magnet's height and to compensate for the influence of noise and vibration perturbances.

The levitation system was modeled in Ansys Electronics 2024 R1 using a Maxwell 2D configuration. An axisymmetric magnetostatic finite-element method (FEM) simulation was performed about the z-axis, with perfect axial alignment, assuming that any residual imbalances will be compensated by auxiliary elements such as external magnets. An equivalent representation of the real electromagnet was constructed by modeling the coil as a solid copper block, using the copper material from the ANSYS material library and including an internal air gap (vacuum). A current-density excitation was directly applied to this coil geometry, enabling the simulation of the magnetic force required to levitate the magnet.

The permanent magnet was modeled by assigning the NdFe52 material from the ANSYS material library to the corresponding geometry, thereby accurately reproducing the characteristics of the magnet used in the physical prototype. All elements were enclosed within an air region, whose outer edges were assigned a balloon-type boundary condition.

The initial mesh was generated using a length-based criterion, setting the maximum element size in both the magnet and the coil. The magnetic force acting on the magnet was defined as the primary simulation output. Several mesh refinement iterations were performed, progressively reducing the element size until convergence was achieved under a 0.001% error criterion, resulting in a final energy error of 0.00046%.

To analyze the magnetic force, a parametric study was conducted by varying the levitation height from -0.9 mm to -1.3 mm. The resulting data were subsequently used to linearize the equations describing the levitation system. The simulation model is shown in Figure 2.

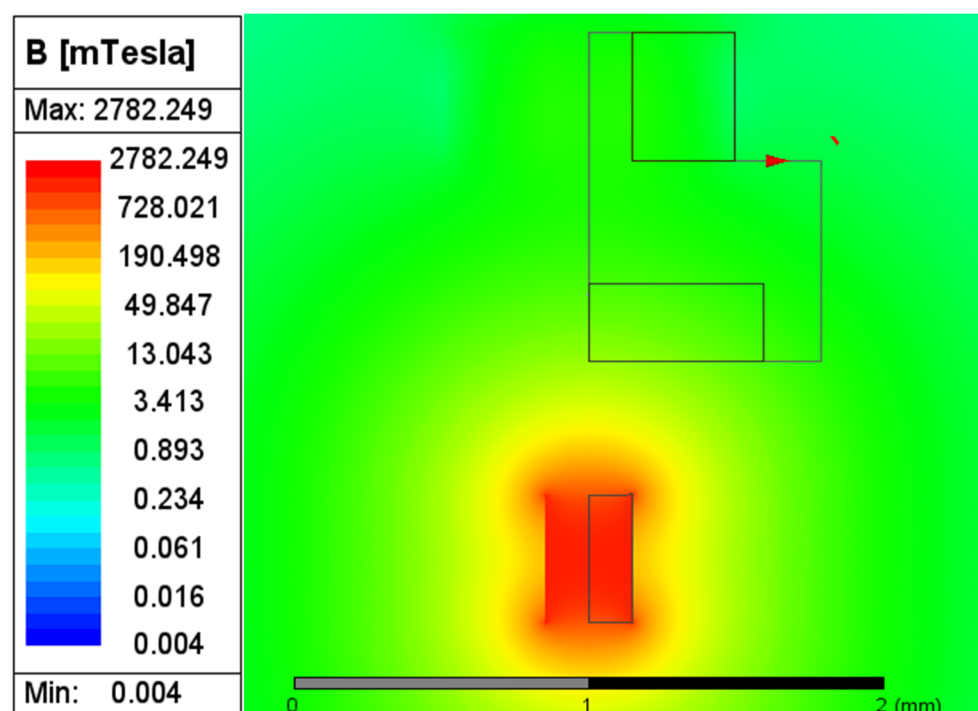


Figure 2. Micromagnetic levitation system axisymmetric simulation modeled in Ansys Electronics.

The simulation results of the dependence of the electromagnetic force on both the distance between the magnet and the coil base and the current density applied to the coil

are shown in Figure 3. It is important to remark that the current density values imposed in the simulation are only an approximation of the actual values applied in the physical prototype, since the model assumes a different effective cross-sectional area for the coil. This discrepancy arises from the fill factor of the real coil, which is approximately 44.88% of the cross-sectional area considered in the simulation. Consequently, the simulated current densities of 10, 15, and 20 A/mm² correspond to real current densities of 22.28, 33.42, and 44.56 A/mm², respectively.

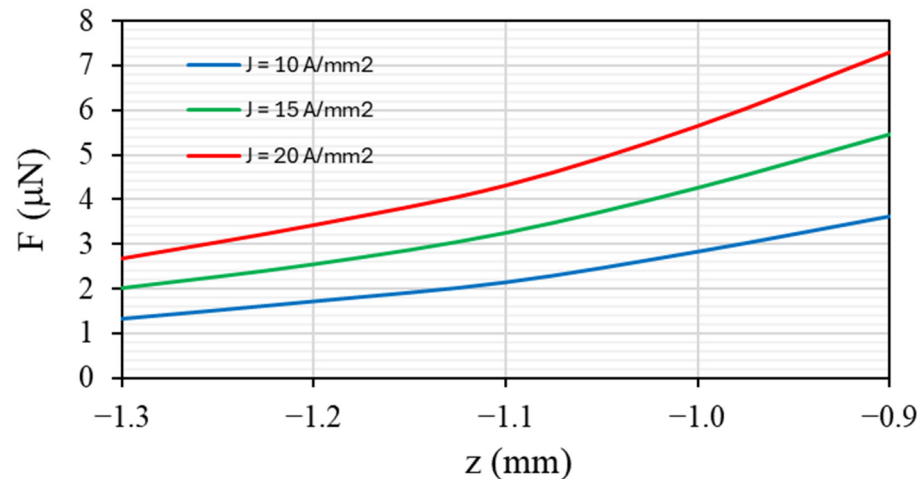


Figure 3. Attractive force between the coil and the magnet as a function of magnet height and the current density flowing through the coil.

From this analysis, the expression of the current that must flow through the coil at different levitation heights can be derived such that the resulting attractive force equals the weight on the magnet (mass = 0.27 mg, weight = 2.75 μN):

$$I \text{ (A)} = -0.0114 \cdot z \text{ (mm)} - 0.0087 \quad (1)$$

The magnetic field at the Hall-effect microsensor location, 680 μm below the bottom surface of the coil, has also been simulated. Based on the magnetic field measurements as a function of the current density applied to the coil and the magnet–sensor separation distance, it is possible to establish a correspondence between the magnetic field detected by the Hall-effect microsensor in the physical prototype and the field predicted by the simulation. This equivalence enables a direct comparison between the experimental data and the numerical model, thereby supporting the validation of the simulation framework.

Finally, the force model is obtained simulating the equilibrium point as a function of the distance of the magnet in millimeters, with the current applied to the coil. The force model is derived by approximating the dependence of the force on the distance using a second-order polynomial function. This expression is subsequently generalized with respect to current, given that the force exhibits a strictly linear relationship with the applied current density:

$$F \text{ (}\mu\text{N)} = \left(15.959 \cdot z^2 + 46.526 \cdot z + 36.224 \right) \cdot \frac{I}{0.00628} \quad (2)$$

Linearized expression around the equilibrium point ($z = -1.312$ mm, $F = 2.65$ μN):

$$F \text{ (}\mu\text{N)} = 4.395 \cdot z + 8.3729 \quad (3)$$

Finally, the simplified expression for the force model is obtained, which will be used to tune the controller in the MATLAB R2024b model:

$$F (\mu\text{N}) = (699.84 \cdot z + 1333.264) \cdot I \quad (4)$$

2.2. Mechanical Design and Manufacturing Process

The fabrication process of the micrometric components of the levitation system is described below. The first step is the printing of the coil core using a Phrozen Sonic Mighty Revo 14k, a high-resolution resin printer with a pixel size of only $16.8 \times 24.8 \mu\text{m}$. The resin used is the Aqua Hyperfine Graphite, a UV-curable acrylic resin composed of a mixture of acrylated monomers, oligomers and additives, especially for high-resolution pieces. The core has a 0.3 mm diameter and 0.5 mm height, and it has a special shape for placing the Hall-effect microsensor in one of its ends (Figure 4). The design incorporates a 20 mm long, 4 mm diameter stem that facilitates handling and enables its insertion into a micro-winding system and the experimental test bench.

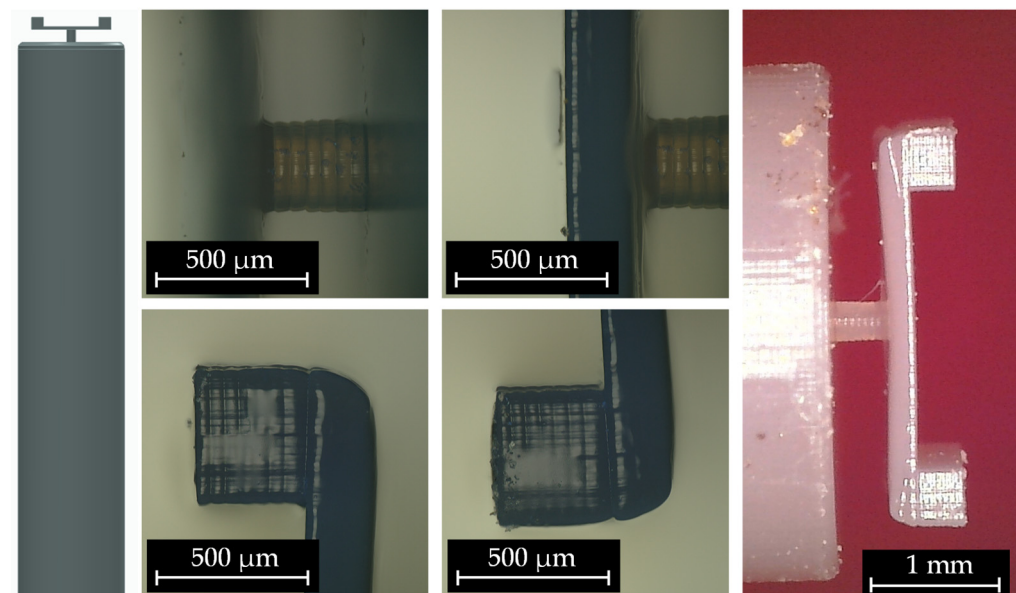


Figure 4. 3D mechanical model of the coil (left); resin-printed core coils (right, with scale).

Once the core has been manufactured, the coil is wound using a micro-winding system designed for some previous works [29,30] which ensures an organized helical winding. The coil has 250 turns of a 0.02 mm diameter copper wire, and its dimensions are 0.3 mm inner diameter, 1 mm outer diameter and 0.5 mm height. This results in a fill factor of 44.88% for the coil cross-section. Then, the ends of the coil are soldered to standard wires with easy plug connections, and they are glued to 3D-printed adapters which allow them to be mounted in micrometric translation stages. Finally, they are electrically characterized using a high-precision LCR meter, obtaining resistance values between 45 and 55 Ω and inductance values between 33 and 36 mH. The variation in the measurement range is mainly due to differences in the length of the wire leads emerging from the coils, which are used to connect them to the electrical terminals. These terminals may also exhibit different impedances. In any case, this only affects the voltage level required to achieve the same current in the different coils, which are otherwise identical and share the same geometric characteristics. Figure 5 shows some pictures of the cores, winding process and final manufactured coils.

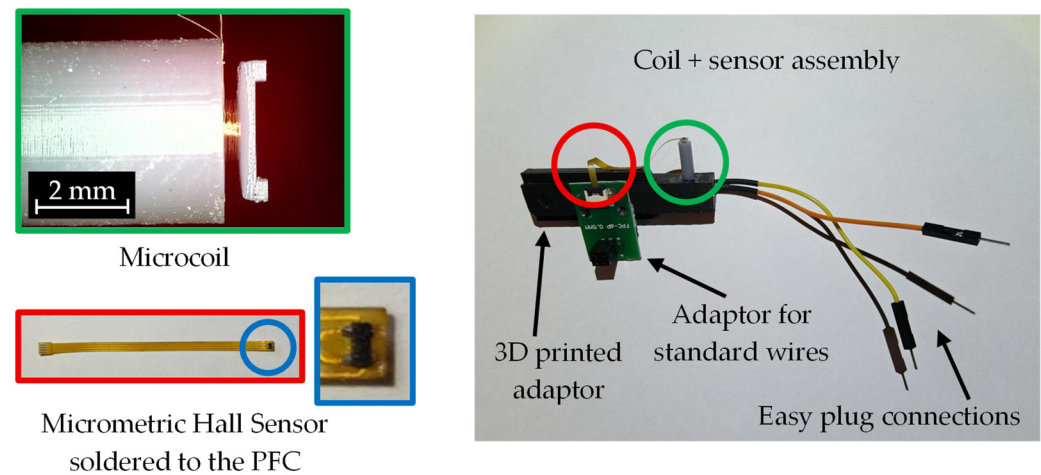


Figure 5. Winded coil (**top left**). Hall-effect microsensor soldered to an FPC (**bottom left**) and final assembly of the coil and Hall-effect microsensor on the 3D-printed adaptor with easy plug connections (**right**).

After that, a HG-0711 Hall-effect microsensor from Asahi Kasei Microdevices Corporation, Tokyo, Japan, of only $1.2 \times 0.5 \times 0.3$ mm is soldered to a flexible printed circuit (FPC), acting as a cable, which is glued to the end of the coil core. The other end of the FPC is connected to an adaptor for standard wires, which is also glued to the 3D-printed adapter. The FPC does not introduce dynamic loads or asymmetries, as it is firmly bonded and rigidly fixed to the experimental bench. The assembly of the coil and the sensor is shown in Figure 5.

3. Control Model

3.1. Description of the Magnetic Levitation Control System

The current through the coils must be modulated to achieve stability in magnet levitation. It will be performed with a proportional–derivative (PD) control system, having the magnet position error as input and the modulated current as the output. The actual height is measured with the Hall-effect microsensor, which gives a proportional voltage depending on the distance to the magnet. Therefore, the desired height must be traduced to voltage to calculate the position error.

The modulated current will be added to a fixed bias current that compensates for the effect of gravity at the equilibrium position and is traduced to voltage knowing the resistance of the coil. The control scheme is depicted below in Figure 6.

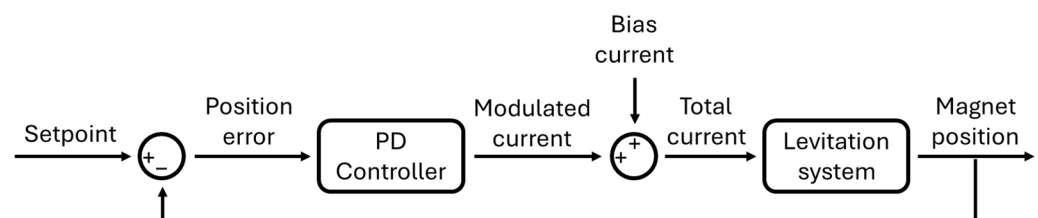


Figure 6. Control scheme of the magnetic levitation system.

3.2. Matlab Model Description

The system has been modeled in Matlab using the results from Ansys simulations to tune the PD controller. The following subsection describes the system architecture. The simulated behavior is equivalent to that of the physical prototype, relying on a proportional–derivative (PD) control strategy to achieve stable magnetic levitation.

As shown in the schematic (Figure 7), the selected setpoint is converted into a reference voltage which, when applied to the coil, generates a current that produces the magnetic force required to levitate the magnet. The voltage associated with the setpoint obtained by modeling the Hall-effect microsensor is compared with the voltage corresponding to the measured position of the magnet, yielding the instantaneous position error. The PD controller processes this error to compute the corrective action needed to drive the magnet toward the desired position. The PD law is defined as follows:

$$K_P e(t) + K_D \frac{\Delta e(t)}{\Delta t} \quad (5)$$

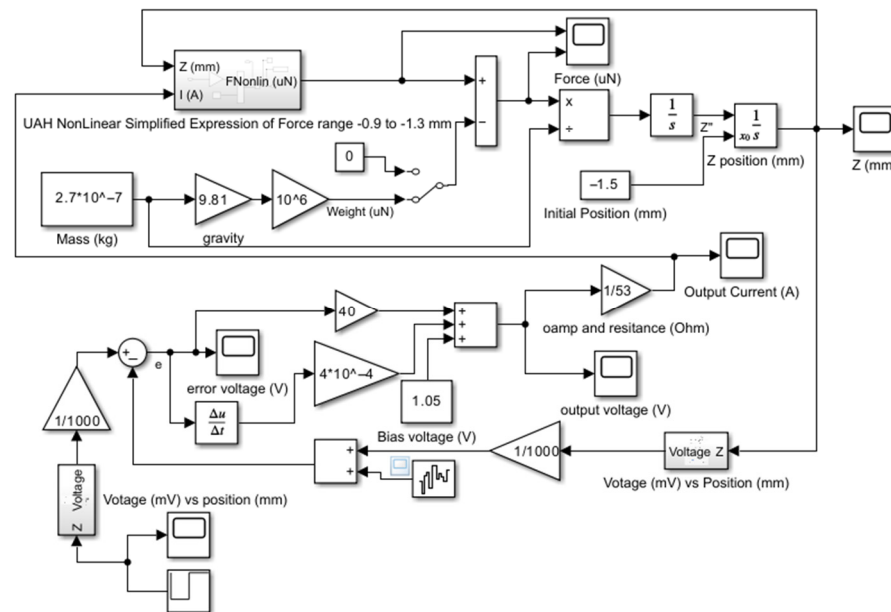


Figure 7. MATLAB/Simulink R2024b schematic of the levitation system model.

Additionally, a bias voltage is added to the controller output in order to introduce the steady-state bias current required at the equilibrium point. The resulting control voltage is then amplified and applied to the coil, which is modeled as a resistive load of 53 Ω . Based on this current, the magnetic force generated by the coil is obtained through a simplified (locally linearized) nonlinear force expression derived from the ANSYS Electromagnetics simulations. This nonlinear model establishes the relationship between magnetic force, coil current and magnet position. The gravitational force acting on the magnet is also included, as it represents the disturbance that must be overcome to achieve levitation.

By subtracting the magnet's weight from the magnetic force, the net force acting on the magnet is obtained. Dividing this net force by the magnet's mass yields the resulting acceleration. A double integration of this acceleration—incorporating the initial conditions—provides the instantaneous magnet position, which is subsequently used to compute both the position error and the net force applied to the magnet.

A PD controller was selected in order to achieve a fast and well-damped response of the magnet's motion, rather than to eliminate the steady-state error, which is instead compensated for by a bias current. The sensor model was assumed to be linear, since a Hall-effect sensor with a linear voltage–magnetic field response is employed. The current flowing through the coil is not directly controlled; instead, a low-power voltage signal is generated and the corresponding current is increased through the use of a voltage follower. The electrical dynamics introduced by this configuration were neglected in the control

system design, as the operating frequencies of both the control hardware and the voltage follower are sufficiently high so as not to affect the levitated magnet dynamics.

The MATLAB model exhibits stable behavior, characterized by a pronounced initial damping that drives the system toward its equilibrium position. The response converges with a non-zero steady-state error. The initial overshoot is approximately 60%. The system's behavior was simulated under variations in the levitation height setpoint, achieving stability in 2 ms with an overshoot of 2.2% (Figure 8, left). Finally, the system's stability was verified by introducing a noise signal at the input (Figure 8, right).

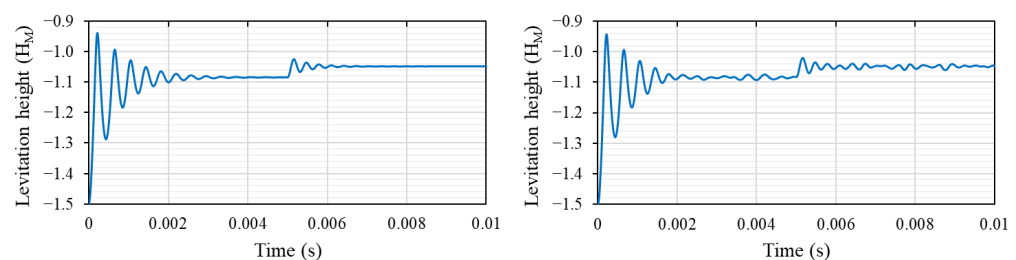


Figure 8. MATLAB/Simulink simulations results of the control with (right) and without (left) noise in the input signal).

3.3. LabVIEW Control Software Implementation

Signal processing and control is performed with an NI myRIO-1900 portable reconfigurable I/O device, from National Instruments Corporation, Austin, Texas. Within the board, three main processes are executed concurrently:

- (i) Acquisition of the voltage signal from the Hall-effect microsensor via analog 12-bit 5 V range input channel, and generation of the coil control signal via analog (not PWM) 12-bit ± 10 V range output channel, implemented on the board's FPGA through an optimized program capable of sustaining a stable operating frequency of 320 kHz.
- (ii) Processing of the input signal by a PD controller to compute the required control output at each magnet height, which is added to a fixed bias current intended to ideally compensate for the magnet's weight, also implemented in a frequency-optimized program, but in this case following a real-time execution methodology.
- (iii) Storage of the acquired and generated signals in a text file for subsequent offline analysis, performed at a low sampling rate on the host PC. Communication between the FPGA and the real-time application is achieved through direct read and write access to shared variables, resulting in high-speed data exchange since all processes are executed locally on the myRIO platform. Communication between the FPGA and the host PC is implemented via Direct Memory Access (DMA), with data written to FIFO buffers and retrieved as low-frequency data packets.

A high-resolution data acquisition and output board was employed, but the control system could in fact be implemented using more basic hardware with lower performance specifications. Only 25 input and 410 output codes out of 4096 were utilized. With appropriate offset adjustment, a system operating at high sampling frequency and providing precision levels on the order indicated would be sufficient to implement the proposed control strategy.

4. Experimental Setup

Following the design of the acquisition and control system and the fabrication of the coil–Hall-effect microsensor assembly, all elements comprising the levitation system were integrated. The 3D-printed component housing the coil and the Hall-effect microsensor was mounted on a micrometric translation stage, enabling precise positional adjustment

and accurate regulation of the operating height. The Hall-effect microsensor power supply was connected to the 5 V output of the myRIO board, while the output was interfaced with one of the analog input channels. In the presence of excessive measurement noise, the application of analog filtering was considered. Likewise, due to the limited dynamic range of the measured signal, offset removal and analog amplification within the effective signal range could have been required. However, neither approach was necessary, as the mean value of the measured signal coincided with the exact position reference required by the controller. Therefore, owing to the high and stable acquisition, control and signal generation frequency of 320 kHz, fully stable control was attained despite the presence of noise measurement.

Subsequently, the coil terminals were connected to one of the analog output channels of myRIO. Although amplification of the output signal was not strictly required, a high-output-current operational amplifier (LM675T from Texas Instruments Incorporated, Texas, USA) was incorporated in a voltage follower configuration to ensure that the coil current was not constrained by the maximum current capabilities of myRIO. A diagram of the complete system is shown in Figure 9.

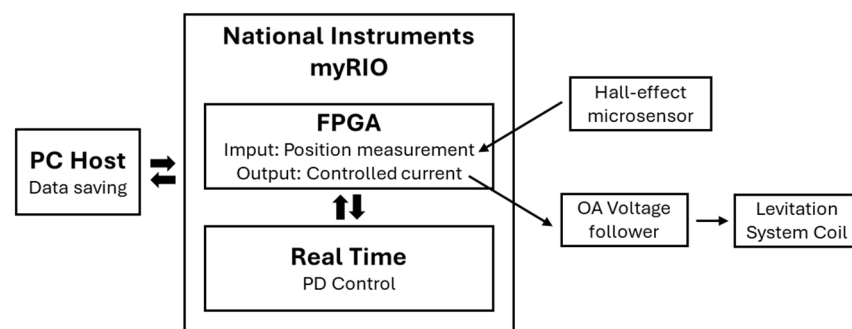


Figure 9. Levitation system diagram.

The experimental setup incorporates a microscope mount that monitors and enables increased precision in adjusting the relative positions of the magnet and the coil. Finally, an aluminum base is installed to support the micromagnet, which is electrically connected to the ground in order to mitigate electrostatic effects. This measure is critical in systems involving micrometric components, where electrostatic charges often generate forces of the same order of magnitude as those governing the system dynamics. The NdFeB N52 levitated magnet (N52 Nickel Plated Cyl0003-50, 0.3 mm diameter and 0.5 mm long) is placed above the aluminum base. The complete experimental setup is shown in Figure 10.

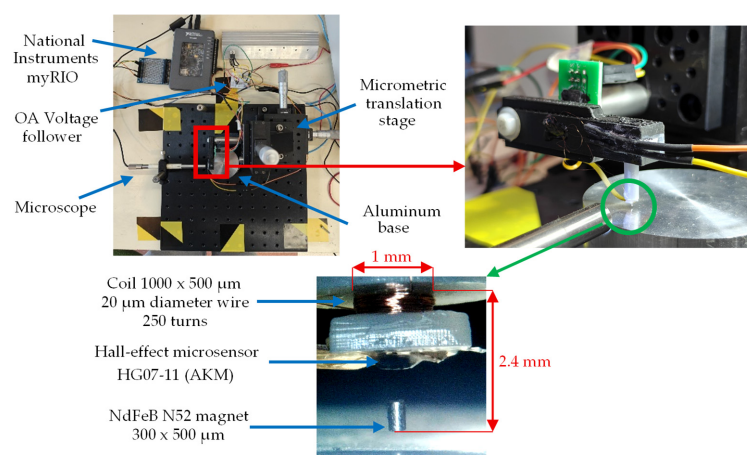


Figure 10. Micromagnetic levitation complete setup.

5. Experimental Results

5.1. Static Levitation

The verification and characterization of the levitation system are subsequently carried out. During the experimental campaign, a significant influence of the Earth's magnetic field on the levitated magnets was observed, causing them to rotate and align with the geomagnetic field. In the case of lighter magnets, this alignment occurred even when the magnets were resting on low-friction surfaces. Although this effect could, in principle, be mitigated by employing systems designed to shield or compensate for the Earth's magnetic field, this option was discarded because it may not be compatible with all potential implementations of the proposed magnetic microbearing. Consequently, an alternative solution was proposed and experimentally validated. This solution consists of placing a magnet of the same polarity beneath the experimental bench, with low magnetic flux density and positioned at a sufficient distance such that it does not exert a significant attractive force on the levitated magnet, while still providing a torque large enough to enforce vertical orientation. Experimental measurements confirmed that the magnetic field generated at the height of the levitated magnet, and therefore the resulting attractive force, was negligible. This auxiliary orientation magnet was incorporated into all experiments conducted. The orientation of the levitated magnet before and after the inclusion of the auxiliary magnet is shown in Figure 11.

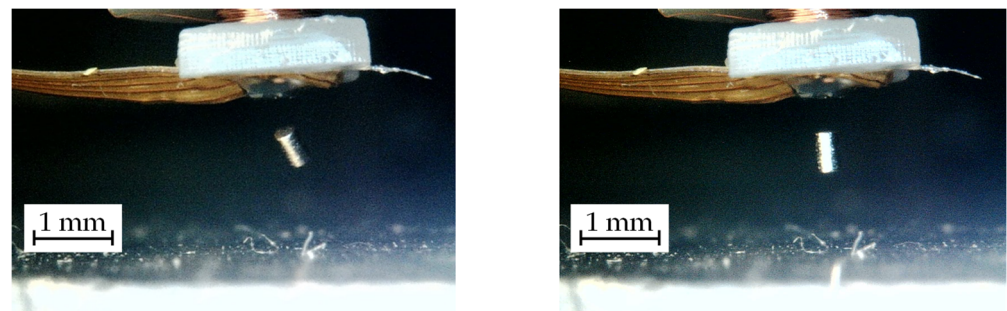


Figure 11. Compensation of the levitated magnet's orientation when it aligns with the Earth's magnetic field.

The following Figure 12 illustrates the system's response to an external disturbance—such as base vibrations or nearby air currents—acting on the levitated magnet. The controller compensates for these perturbations such that, for a height deviation of 22.47%, the magnet is re-stabilized in 44 ms. To enable clearer visualization of the experimental results, post-processing data filtering is applied, computed as the average of every 2000 measured samples. This filtering approach allows the mean value of the signal to be visualized while effectively suppressing noise effects.

5.2. Step Response

The system's response to different commanded levitation heights is analyzed below. Data were recorded for all heights within the stable levitation range, in which correct operation of the controller designed on the basis of the simulation data is guaranteed. In addition, system stability was investigated beyond the analysis range used for linearizing the governing equations. Under these conditions, the system was found to remain operational, albeit with increased error.

Figure 13 illustrates the system response to a step-type input. A brief transient response is observed (2.3 ms), along with a maximum overshoot of 18.3% following a change in the setpoint. The stabilization time is consistent with the results obtained from the Matlab simulations, although the observed overshoot is higher than expected. This discrepancy

may be attributed to sampling and control discretization effects, residual system instabilities or inaccuracies in the model. Nevertheless, a strong agreement between the simulation results and the experimental measurements is observed.

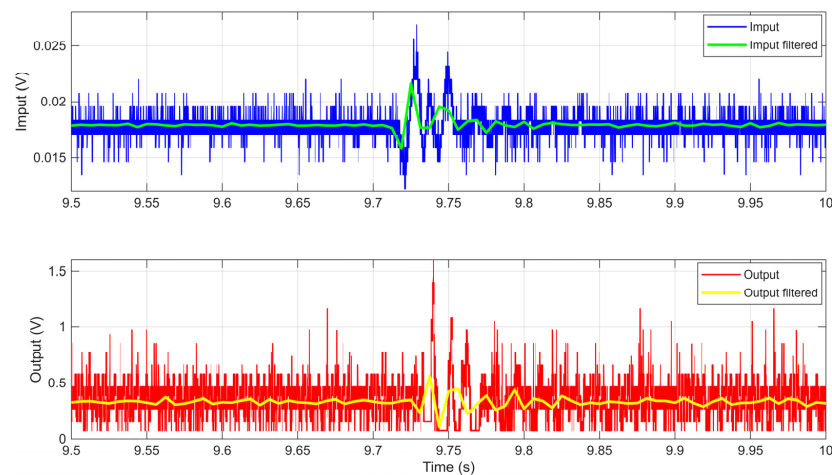


Figure 12. Magnetic levitation system's response to an external disturbance.

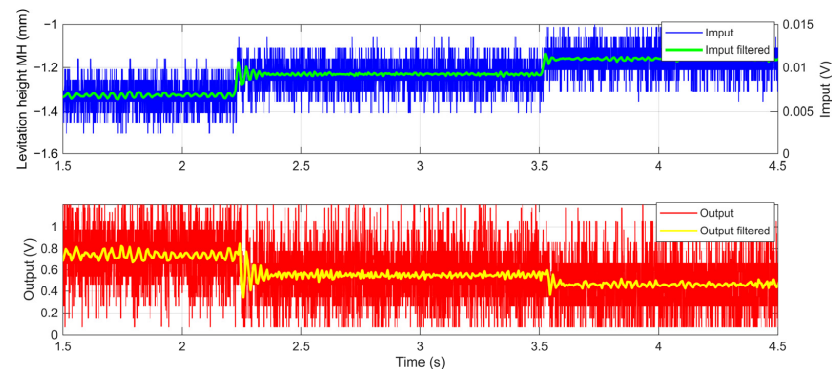


Figure 13. Magnetic levitation system's response to setpoint changes.

5.3. Experimental Evaluation Varying Levitated Mass Weight

The current density that can be supplied to coils of these dimensions in open air can reach up to 60 A/mm^2 , owing to the relatively high heat dissipation capability of micrometric copper coils [29]. Accordingly, a maximum allowable current density of 60 A/mm^2 is assumed, which ensures safe operating conditions for copper conductors of the cross-section employed. Considering that the attractive force generated by the coil at a given levitation height is directly proportional to the current flowing through it, the maximum force that the coil can exert and, consequently, the maximum mass that can be coupled to the levitated magnet can be determined.

For the largest levitation distance of -1.3 mm , at which the required current is highest, the maximum attractive force produced by the coil with the maximum current density is $8.14 \text{ }\mu\text{N}$. This force corresponds to a levitated mass of 0.83 mg ; subtracting the magnet mass of 0.27 mg yields a maximum allowable mass of 0.56 mg that can be attached to the magnet. This means an axial load capacity of $431.67 \text{ }\mu\text{N/A}$. Similarly, at a levitation distance of 0.9 mm , the attractive force increases to $21.84 \text{ }\mu\text{N}$, which would allow a mass of up to 1.95 mg to be coupled to the magnet, corresponding to a maximum axial load capacity of 1.16 mN/A . The stiffness has not been explicitly characterized because, given the active and levitation-height-dependent nature of the system, the axial load capacity provides a more representative metric, while always accounting for the current limitations imposed by the thermal dissipation environment of the coil.

This behavior was verified experimentally by coupling different masses to the levitated magnet (Figure 14), with the corresponding results shown in Figure 15. The two attached masses consist of disks with a height of 0.25 mm, an inner diameter of 0.3 mm (matching the outer diameter of the magnet) and variable outer diameters, with masses of 0.112 mg and 0.218 mg. Stable levitation behavior is observed in both cases, accompanied by a proportional increase in the current required to levitate the magnet with the additional attached mass. In addition, a higher number of instability peaks is observed, which are effectively corrected by the control system and are likely induced by axial asymmetries of the elements attached to the magnet, arising from minor geometric imperfections. Finally, variations in the dynamic response are also observed, with increased maximum overshoot and longer stabilization time following setpoint changes. The Supplementary Materials include Video S1, “Magnetic levitation test varying levitated mass weight”, which shows the levitation experiments.

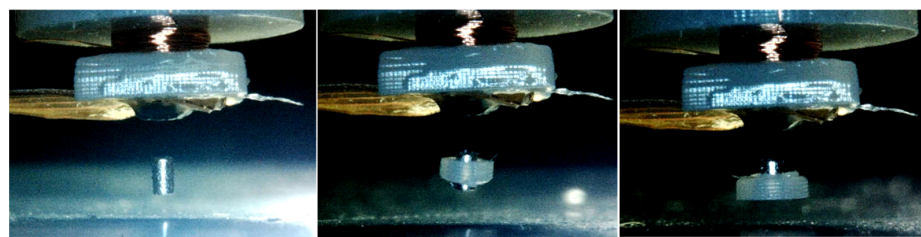


Figure 14. Different masses attached to the magnet. Magnet only (**left**); 0.112 mg mass (**middle**); 0.218 mg mass (**right**).

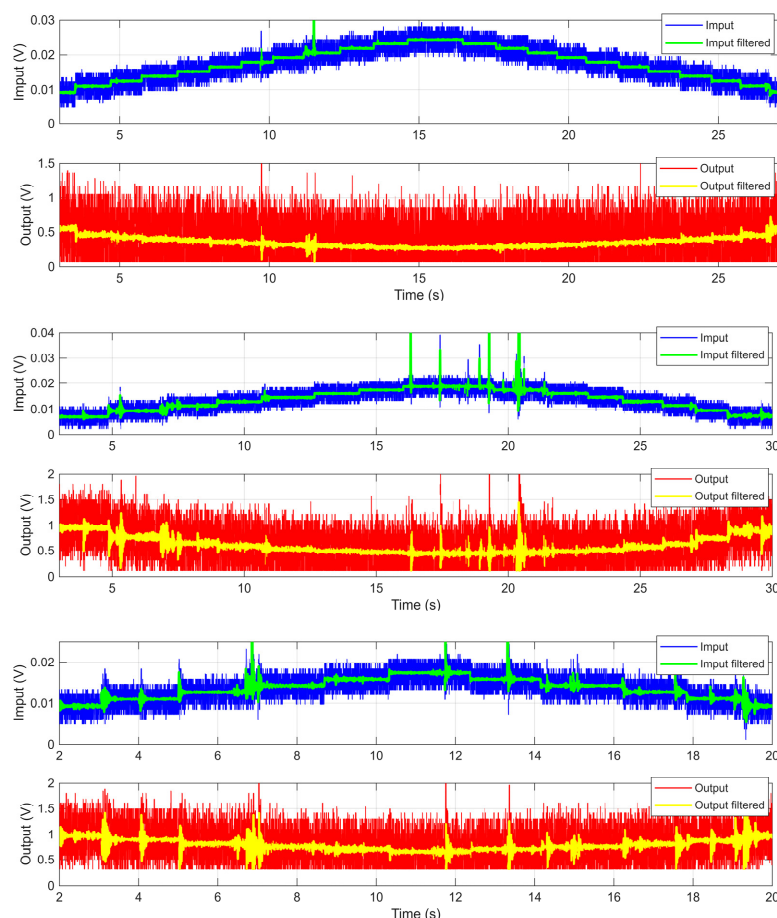


Figure 15. Magnetic levitation system’s response to different masses attached to the levitation magnet. (**Top**) Magnet only. (**Middle**) 0.112 mg mass. (**Lower**) 0.218 mg mass.

6. Conclusions

A micrometric-scale active magnetic bearing with a simple configuration and a single vertical degree of freedom has been developed. This work presents the design, simulation, fabrication and experimental validation of an active magnetic microbearing composed of a coreless coil with a 1 mm outer diameter, 0.3 mm inner diameter and 0.5 mm length, which levitates a NdFeB N52 micromagnet with a 0.3 mm outer diameter and 0.5 mm length. Magnetostatic finite-element (FEM) simulations were performed to extract the relationship between magnetic field and position over the magnet levitation range, enabling linearization of the governing system equations. Based on this theoretical framework, a PD controller was designed in MATLAB/Simulink R2024b to achieve a fast system response while minimizing overshoot. The fabrication process of the microcoil and its compact integration with a Hall-effect microprobe are described in detail, followed by the implementation of the control and data acquisition system and the assembly of the complete experimental setup. Stable magnetic levitation is achieved by regulating the coil current based on precise magnet position measurements. An axial load capacity of 1.16 mN/A is achieved, and correct system operation is demonstrated by successfully levitating the magnet with additional attached masses. This micromagnetic bearing is on the same order of magnitude as the smallest active magnetic bearings reported to date, while employing a simplified design and the smallest commercially available Hall-effect microprobe. These results demonstrate the viability of this type of system at the micrometric scale. Future developments will explore the integration of the active magnetic bearing into miniaturized actuators.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/act15020079/s1>, Video S1: Magnetic levitation test varying levitated mass weight.

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References

1. Diez-Jimenez, E.; Sanchez-Montero, R.; Martinez-Muñoz, M. Towards miniaturization of magnetic gears: Torque performance assessment. *Micromachines* **2017**, *9*, 16. [CrossRef]
2. Subhash, G.; Corwin, A.D.; de Boer, M.P. Evolution of Wear Characteristics and Frictional Behavior in MEMS Devices. *Tribol. Lett.* **2011**, *41*, 177–189. [CrossRef]

3. Iannacci, J. Reliability of MEMS: A perspective on failure mechanisms, improvement solutions and best practices at development level. *Displays* **2015**, *37*, 62–71. [\[CrossRef\]](#)
4. Samsel, M.J.; Chá Nko, A.; Michałowski, M.; Fernandez-Munoz, M.; Diez-Jimenez, E. Tribological Characterization of Micro Ball Bearings with and without Solid-State Lubrication. *Micromachines* **2023**, *14*, 1775. [\[CrossRef\]](#)
5. De Pasquale, G.; Soma, A.; Barbato, M.; Meneghesso, G. Impact wear and other contact effects on the electro-mechanical reliability of MEMS. In Proceedings of the 2014 Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP), Cannes, France, 1–4 April 2014; IEEE: New York, NY, USA, 2014; pp. 1–6.
6. Villalba-Alumbreros, G.; Moron-Alguacil, C.; Fernandez-Munoz, M.; Valiente-Blanco, I.; Diez-Jimenez, E. Scale Effects on Performance of BLDC Micromotors for Internal Biomedical Applications: A Finite Element Analysis. *J. Med. Devices* **2022**, *16*, 031011. [\[CrossRef\]](#)
7. Tambe, N.S.; Bhushan, B. Scale dependence of micro/nano-friction and adhesion of MEMS/NEMS materials, coatings and lubricants. *Nanotechnology* **2004**, *15*, 1561–1570. [\[CrossRef\]](#)
8. Serrano-tellez, J.; Romera-juarez, F.; González-de-maría, D.; Lamensans, M.; Perez-Diaz, J.L.; Sanchez-Casarrubios, J.; Diez-Jimenez, E.; Valiente Blanco, I. Experience on a cryogenic linear mechanism based on superconducting levitation. *Proc. SPIE Mod. Technol. Space- Ground-Based Telesc. Instrum. II* **2012**, *8450*, 658–666. [\[CrossRef\]](#)
9. Sikora, B.M.; Piłat, A.K. Analytical modeling and experimental validation of the six pole axial active magnetic bearing. *Appl. Math. Model.* **2022**, *104*, 50–66. [\[CrossRef\]](#)
10. Shi, X.; Zhu, S. Magnetic negative stiffness dampers. *Smart Mater. Struct.* **2015**, *24*, 072002. [\[CrossRef\]](#)
11. Diez-Jimenez, E.; Perez-Diaz, J.-L. Flip effect in the orientation of a magnet levitating over a superconducting torus in the Meissner state. *Phys. C Supercond.* **2011**, *471*, 8–11. [\[CrossRef\]](#)
12. Perez-Diaz, J.L.; Diez-Jimenez, E.; Valiente-Blanco, I.; Herrero-de-Vicente, J. Stable thrust on a finite-sized magnet above a Meissner superconducting torus. *J. Appl. Phys.* **2013**, *113*, 63907. [\[CrossRef\]](#)
13. Liu, G.; Gao, M.; Sun, D.; Jiang, R.; Fan, L. Three-Dimensional Active Magnetic Levitation Actuating and Control System for Curved Pipes. *Appl. Sci.* **2024**, *14*, 871. [\[CrossRef\]](#)
14. Sreejith, M.R.; Vivek, S.A.; Sunil, K.M.; Sagar, D.; Ravichandran, M.H. Design of Magnetic Bearing and BLDC Motor for a Novel Third-Generation LVAD. In Proceedings of the 2022 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India, 14–17 December 2022; pp. 1–5. [\[CrossRef\]](#)
15. Zhang, C.Y.; Hu, L.; Su, R.; Ruan, X. Design method of bearingless permanent magnet slice motor for maglev centrifugal pump based on performance metric. *Actuators* **2021**, *10*, 153. [\[CrossRef\]](#)
16. Osa, M.; Masuzawa, T.; Orihara, R.; Tatsumi, E. Performance enhancement of a magnetic system in a ultra compact 5-DOF-controlled self-bearing motor for a rotary pediatric ventricular-assist device to diminish energy input. *Actuators* **2019**, *8*, 31. [\[CrossRef\]](#)
17. Andriollo, M.; Fanton, E.; Tortella, A. A Review of Innovative Electromagnetic Technologies for a Totally Artificial Heart. *Appl. Sci.* **2023**, *13*, 1870. [\[CrossRef\]](#)
18. Villalba-Alumbreros, G.; Soler-Morala, J.; Bollero, A.; Kanitz, A.; Hoppius, J.; Valiente-Blanco, I.; Diez-Jimenez, E. Microfabrication of Sm₂Co₁₇ micromagnets for MEMS and micromotors using ultrashort pulsed hydro laser micromilling process. *Int. J. Adv. Manuf. Technol.* **2023**, *129*, 4961–4970. [\[CrossRef\]](#)
19. Diez-Jimenez, E.; Lopez-Pascual, D.; Villalba-Alumbreros, G.; Valiente-Blanco, I.; Fernandez-Munoz, M.; del Olmo-Anguix, J.; Manzano-Narro, O.; Kanitz, A.; Hoppius, J.; Philipp, J.; et al. Micromanufacturing Process of Complex 3D FeCo Core Microwindings for Magnetic Flux Modulation in Micromotors. *Micromachines* **2026**, *17*, 115. [\[CrossRef\]](#)
20. Diez-Jimenez, E.; Bollero, A.; Valiente-Blanco, I.; Palmero, E.M.; Fernandez-Munoz, M.; Lopez-Pascual, D.; Villalba-Alumbreros, G. Integration of Sm₂Co₁₇ Micromagnets in a Ferromagnetic Multipolar Microrotor to Enhance MEMS and Micromotor Performance. *Micromachines* **2024**, *15*, 875. [\[CrossRef\]](#)
21. Ahmed, K.S.; Sendur, G.K.; Bediz, B. Integrated design optimization of a motorized active magnetic bearing spindle for micro-milling applications. *J. Mech. Sci. Technol.* **2025**, *394*, 2015–2027. [\[CrossRef\]](#)
22. Nehal, T.H.; Ahmad, M.; Shafiullah, M.; Islam, A. Advanced sensing technologies for active magnetic bearing systems: Trends and prospects. *Measurement* **2026**, *257*, 118515. [\[CrossRef\]](#)
23. Du, Y.; Zhang, G.; Hua, W. Review on Research and Development of Magnetic Bearings. *Energies* **2025**, *18*, 3222. [\[CrossRef\]](#)
24. Ghantasala, M.K.; Qin, L.; Sood, D.K.; Zmood, R.B. Design and fabrication of a micro magnetic bearing. *Smart Mater. Struct.* **2000**, *9*, 235–240. [\[CrossRef\]](#)
25. Kuroki, J. A micro magnetic bearing with a 2 mm-diameter rotor and its performance. In Proceedings of the Ninth International Symposium on Magnetic Bearings, Lexington, KY, USA, 3–6 August 2004.
26. Okada, Y.; Yamashiro, N.; Ohmori, K.; Masuzawa, T.; Yamane, T.; Konishi, Y.; Ueno, S. Mixed flow artificial heart pump with axial self-bearing motor. *IEEE/ASME Trans. Mechatron.* **2005**, *10*, 658–665. [\[CrossRef\]](#)

27. Ueno, S.; Arai, T.; Odagiri, K. Development of The Miniature Active Magnetic Bearing with 6 Concentrated Wound Poles. In Proceedings of the Ninth International Symposium on Magnetic Bearings, Lexington, KY, USA, 3–6 August 2004.
28. Boletis, A.; Bleuler, H. Three Axis Amb High Speed Micro Motor. In Proceedings of the Ninth International Symposium on Magnetic Bearings, Lexington, KY, USA, 3–6 August 2004.
29. Diez-Jimenez, E.; Valiente-Blanco, I.; Villalba-Alumbreros, G.; Fernandez-Munoz, M.; Lopez-Pascual, D.; Lastra-Sedano, A.; Moron-Alguacil, C.; Martinez-Perez, A. Multilayered Microcoils for Microactuators and Characterization of Their Operational Limits in Body-Like Environments. *IEEE/ASME Trans. Mechatron.* **2022**, *28*, 1789–1794. [[CrossRef](#)]
30. Fernandez-Munoz, M.; Sanchez-Montero, R.; Lopez-Espi, P.L.; Martinez-Rojas, J.A.; Diez-Jimenez, E. Miniaturized High Gain Flexible Spiral Antenna Tested in Human-Like Tissues. *IEEE Trans. Nanotechnol.* **2022**, *21*, 772–777. [[CrossRef](#)]

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