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Research into Passive Magnetic Field-Based Actuators

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Contents

1 Introduction

Actuators are key parts of mechatronic systems. They turn energy into movement and are used in many machines, robots, and control systems. One important group of actuators uses magnetic fields to create motion. These are called magnetic actuators, and they are often divided into two types: active and passive. Active magnetic actuators need electrical power to work and can change their magnetic field. On the other hand, passive magnetic actuators use permanent magnets and do not need continuous power to operate.

Passive magnetic field-based actuators take advantage of the natural forces between magnets, such as attraction and repulsion, to move or hold parts in place. Because they don't need a constant power supply, they are very useful in systems where saving energy, reducing heat, or avoiding electrical noise is important. For example, they are used in aerospace systems, medical devices, magnetic bearings, and vibration isolation platforms.

These actuators are often simple, quiet, and reliable. However, they also have some limits. Since they use fixed magnets, it is harder to control their force or behavior in real time. Also, their design must be very precise to make sure the magnetic forces work as expected.

In this paper, we will explore how passive magnetic actuators work, the types that exist, and where they are used. We will also look at some recent research and new ideas in the field, such as improved magnet arrangements and hybrid systems that combine passive and active elements. Finally, we will discuss the main challenges and future directions in this area of actuator technology.

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2 Theoretical background

2.1 Magnetism, Magnetic Fields and Forces

When talking about magnetism, one of the most common, and in our case most important concept is that of a magnetic field. Two possible ways of a magnetic field forming are as a consequence of an electrical charge in motion, and the other one being a magnetic field of a permanent magnet, created by spin of electrons and orbital motions inside of the magnet [1]

To understand how passive magnetic field-based actuators work, it is important to define several key magnetic quantities: magnetic field strength, magnetic flux density, magnetization, and magnetic flux. These quantities describe how magnetic fields are generated, distributed, and interact with materials.

Magnetic Field Strength (H) Magnetic field strength describes the intensity of the magnetic field created by electric currents or magnetic materials. It is measured in amperes per meter (A/m). This vector field shows how strong and in what direction the magnetic influence is at a particular point in space, independent of the medium it passes through.

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M} \tag{1}$$

This equation relates the magnetic field strength $\mathbf{H}$ to the magnetic flux density $\mathbf{B}$ and the material's magnetization $\mathbf{M}$, with μ_0 being the permeability of free space.

Magnetic Flux Density (B) Magnetic flux density, also known simply as the magnetic field, represents the total magnetic effect—including contributions from both free currents and magnetic materials—at a specific point. It is measured in teslas (T). The field $\mathbf{B}$ determines the magnetic force experienced by moving charges or magnetic dipoles.

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \tag{2}$$

This shows that $\mathbf{B}$ depends on both the externally applied field $\mathbf{H}$ and the material's response to it, described by $\mathbf{M}$.

Magnetization (M) Magnetization is a vector field that expresses the density of magnetic dipole moments within a magnetic material. It reflects how much a material becomes magnetized in response to an external field. Its unit is also amperes per meter (A/m). Magnetization contributes to the total magnetic flux density inside a material and is a key parameter in designing magnetic actuators.

$$\mathbf{M} = \chi_m \mathbf{H} \tag{3}$$

Here, χ_m is the magnetic susceptibility of the material, a dimensionless parameter that shows how easily the material becomes magnetized.

Magnetic Flux (Φ) Magnetic flux represents the total magnetic field passing through a given surface. It is a scalar quantity and is measured in webers (Wb). Magnetic flux is calculated by integrating the magnetic flux density $\mathbf{B}$ over a surface:

$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{A} \tag{4}$$

Magnetic flux is an important concept in Faraday's law of induction, and it plays a role in the behavior of magnetic circuits and actuators. In passive actuators, the control and redirection of magnetic flux through ferromagnetic materials and air gaps are essential to producing forces and motion without active current control.

2.2 Maxwell's Equations

Maxwell's equations describe the fundamental behavior of electric and magnetic fields and their interaction with matter. These four equations form the foundation of classical electromagnetism and are essential for understanding how magnetic field-based actuators operate, including passive systems.Together, these equations describe how electric and magnetic fields are generated and altered by each other and by charges and currents. In the context of passive magnetic field-based actuators, Maxwell's equations help explain the distribution and behavior of magnetic fields in space, which is crucial for understanding force generation, motion, and energy transfer without active current control.[2]

1. **Gauss's Law for Magnetism:**

$$\nabla \cdot \mathbf{B} = 0 \tag{5}$$

   This equation indicates that there are no magnetic monopoles; in other words, magnetic field lines always form closed loops, and the net magnetic flux through a closed surface is zero.

2. **Gauss's Law for Electricity:**

$$\varepsilon_0 \nabla \cdot \mathbf{E} = \rho \tag{6}$$

   This law states that the electric flux out of a closed surface is proportional to the total electric charge enclosed within that surface. It explains how electric charges produce electric fields.

3. **Ampère-Maxwell Law:**

$$\frac{1}{\mu_0} \nabla \times \mathbf{B} = \mathbf{j} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{7}$$

   This equation describes how a magnetic field is generated either by electric current ($\mathbf{J}$) or by a changing electric field. The second term, added by Maxwell, explains how electromagnetic waves can propagate through space.

4. **Faraday's Law of Induction:**

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{8}$$

   Faraday's Law shows how a time-varying magnetic field can induce an electric field. This is the principle behind electromagnetic induction, which is key to how many actuators and electrical devices work.

2.3 Magnetic Dipole Moment and Torque

The concept of the magnetic dipole moment helps us understand how magnetic materials react to external magnetic fields. A magnetic dipole moment **m**, describes the strength and orientation of a magnetic source. It arises either from current loops or from magnetic properties of particles like electrons.

For a current-carrying loop, the magnetic dipole moment is given by:

$$\mathbf{m} = I\mathbf{A} \tag{9}$$

where I is the current and **A** is the vector area of the loop (with magnitude equal to the area and direction perpendicular to the loop surface according to the right-hand rule). In permanent magnets or magnetic materials, the dipole moment represents the net alignment of microscopic magnetic domains.

When a magnetic dipole is placed in an external magnetic field **B**, it experiences a torque $\boldsymbol{\tau}$ that tends to align the dipole moment with the field. This torque is described by the vector cross product:

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B} \tag{10}$$

The torque causes the dipole to rotate such that its magnetic moment aligns with the external field direction. This principle is used in many magnetic actuators, where the interaction between magnetic fields and dipole moments generates useful mechanical motion.

2.4 Permanent Magnet Materials

Permanent magnets are materials that produce a constant magnetic field without the need for an external power source or current. They are essential components in many passive magnetic field-based actuators, as they provide a stable and long-lasting source of magnetic flux. A permanent magnet can be modeled as a collection of tiny magnetic dipoles. The net magnetic field **B** at any point is the vector sum of fields from these dipoles. Similarly, magnetic force arises from dipole–dipole interactions, where the force depends strongly on relative orientation and distance between blocks of magnetization.

Most high-performance passive actuators employ NdFeB (neodymium-iron-boron) magnets[3, 4, 5] because they offer strong remanence B_r and high coercivity. Ferrites and Alnico are used when lower cost or higher temperature stability is needed. The choice of material directly affects performance and design constraints.

The magnetic behavior of a permanent magnet can be described using the **B-H curve**, which shows the relationship between the magnetic flux density **B** and the magnetic field strength **H**. The point at which the magnet retains magnetization even after the external field is removed is called the remanent flux density (B_r), and the field required to demagnetize it is known as the coercive field (H_c).

In passive actuators, permanent magnets are used to generate a constant magnetic field that interacts with magnetic or conductive materials. This interaction can produce forces, torques, or controlled displacement. Since they do not consume energy during operation, permanent magnets enable efficient, compact, and low-maintenance actuator designs.

2.5 Earnshaw's theorem

Earnshaw's Theorem is an important concept in magnetostatics and plays a critical role in understanding the limitations of passive magnetic systems. It states that it is impossible to achieve a stable static equilibrium using only inverse-square law forces, such as those from electrostatics or magnetostatics, in free space. In simpler terms, this means that you cannot use only permanent magnets or static electric charges to hold an object completely still in all directions without it eventually moving or falling.

This theorem is especially relevant when designing magnetic levitation systems or passive magnetic bearings. It explains why a small magnet cannot float steadily in mid-air above another magnet unless there is some additional stabilizing force or constraint involved. For example, if you try to balance one magnet above another, the levitating magnet will tend to flip, slide, or fall off to one side. This instability is a direct result of Earnshaw's Theorem.

2.6 Halbach Arrays

A Halbach array is a special arrangement of permanent magnets that focuses the magnetic field on one side while almost canceling it on the other. This clever configuration enhances the magnetic field where it is needed most, without requiring additional power or complicated electronics. The idea behind it is to rotate the direction of magnetization in each magnet block in a specific way so that the fields reinforce on one side and cancel out on the opposite side.[4]

This property makes Halbach arrays especially useful in applications where a strong, concentrated magnetic field is required, such as in magnetic levitation systems, linear motors, magnetic bearings, and brushless electric motors. Since they naturally direct most of the magnetic field to one side, Halbach arrays improve efficiency and reduce stray fields that could interfere with nearby electronics or components. Halbach arrays are also one of the ways that overcome limitations posed by Earnshaw's theorem and overall inprove stability of a system.

2.7 Eddy Currents

Eddy currents are circular electric currents that are created inside conductive materials when those materials are exposed to a changing magnetic field. This phenomenon occurs because a varying magnetic field can generate an electric field, which then causes electrons in the conductor to move in loops.

Although eddy currents happen naturally in any conductive object exposed to a changing magnetic environment, they can have both positive and negative effects. On one hand, they can cause energy losses in devices like motors and transformers because they produce heat as they flow through the material. This heating is often unwanted and needs to be minimized. On the other hand, eddy currents can also be very useful in some applications. For example, they can create a force that resists motion, which makes them suitable for use in magnetic brakes or damping systems where no physical contact is needed.

2.8 Magnetic force modeling

Force between magnets can be accurately estimated through dipole approximations and numerical methods like finite element analysis (FEA). Analytical models combined with FEA enable parameter optimization, such as magnet spacing, geometry, and material grade, to maximize flux density and force output while controlling nonlinearity .

3 Types of Passive Magnetic Field-Based Actuators

Passive magnetic actuators can be classified by the way they utilize magnetic fields to generate force, motion, or constraints without active control or continuous energy input. Each type is suited for specific applications based on its advantages and limitations.

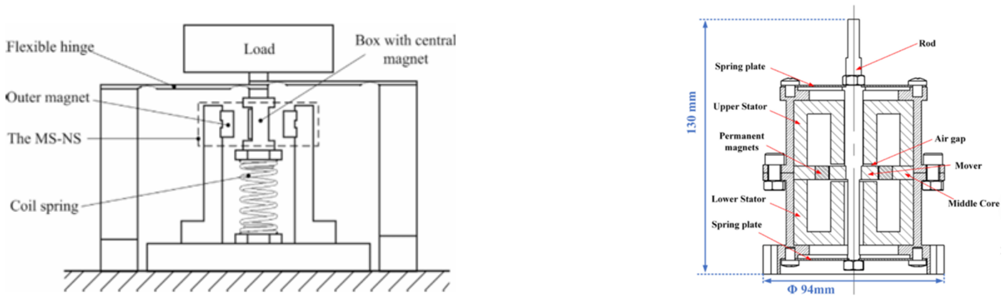
3.1 Magnetic Springs

Magnetic springs rely on the repulsive or attractive force between permanent magnets to produce a restoring force, similar to mechanical springs. Their main property, differentiating them from classical mechanical springs, is the absence of friction while operating, as well as no material wear, operating noise, and negative effects on reliability that are normally present with mechanical springs[6]. Qian at al. in their paper propose use of a simple magnetic spring, consisting of a bigger and smaller magnetic ring kept concentric with a axis in the middle. The anti-push/anti-pull properties of a magnet pair behave similarly to a mechanical spring. Their proposed use for such a system is in a magnetic suspension for a train, that utilizes existing form of railway and locomotives, with the change od metal springs for magnetic ones. They claim this would support

higher speeds, and at the same time be more cost-effective because of the minimal change to the structure.
In the research for integrating magnetic springs on ends of an oscillatory linear motor's stator [7], they found that a structure utilizing permanent magnet springs benefited from the lack of material wear, friction noise, and mostly from the compactness of said spring. The magnetic spring allowed long strokes without axially elongating the build of the motor. In comparison, the use of mechanical springs of a similar spring rate and dynamic stroke would result in a need for more axial space to fit those springs.

Vibration Isolators and Absorbers

One big use of magnetic springs is found in vibration isolators and absorbers. Vibration isolation is, in today's age, more and more demanded, finding its use in fields such as semiconductor manufacturing, engine mounts for automotives, and support systems with very low supporting frequencies, which are needed in the aviation industry for grounded planes. In researches on this topic [5, 3, 8], different approaches were commented. Design made in [3], is based on Maxwell magnetic normal stress, placing a disk of magnets around a mover, that is connected to the actuating rod. The combination of spring plates with the magnetic negative stiffness isolator (MSSI) provides the wanted isolation. There are similarities in design shown by Wu et al. [5], with the combination of mechanical spring with the magnetic spring with negative stiffness (MSNS), although here, a coil spring is used, and the MSNS is composed of three magnets placed in a repulsive interaction. All three researches pointed towards the increased range for vibration isolation in the lower frequency ranges. With that said, active actuation is proposed to be connected as well because of the difficulties with control.



(a) Prva izveba

(b) Druga izvedba

Figure 1: Comparison of two ways of realizing magnetic spring

3.2 Magnetic Shape Memory Alloy (MSMA) Actuators

Magnetic Shape Memory Alloys (MSMAs) are a special type of smart material that can change their shape when exposed to a magnetic field. This change in shape is caused by the movement of different parts (called twin variants) within the crystal structure of the material. The most commonly used MSMA is made from a combination of nickel, manganese, and gallium (Ni-Mn-Ga), which can produce large strains, sometimes up to 6-10%, just by applying a moderate magnetic field [9, 10].

What makes MSMAs different from other materials is that they don't need heat or complex mechanical systems to move. Instead, the magnetic field itself causes parts of the crystal to shift, changing the length or shape of the material. This allows for fast, silent, and energy-efficient actuation. The shape returns to normal when cristal is out of the magnetic field, often with the help of a small spring or mechanical load. Because of this, MSMAs can work well in compact devices that need reliable and quick movement [1].

There are some challenges, such as hysteresis (lag between input and output) and sensitivity to temperature. However, researchers are developing ways to control these effects using smart algorithms and control systems [11]. MSMAs have already been used in micro-pumps, small actuators, vibration dampers, and even in aerospace systems.

Although they are still being developed for wider use, MSMAs show great potential for passive magnetic actuators. They do not need electric motors or coils during operation, and in many cases, they can hold their position without using energy, making them a useful and efficient solution for future mechatronic systems.

3.3 Maglev Systems

Maglev, short for **Mag**netic **Lev**itation, is a method of suspending an object with the use of magnetic fields. Maglev systems rely on the interaction between magnetic fields generated by permanent magnets or electromagnets. In passive maglev systems, the levitation is achieved without active control or power input, using only the static magnetic forces from permanent magnets or induced currents.[12] A key theoretical limitation in passive magnetic levitation is Earnshaw's Theorem, but despite this, stable levitation can be achieved through: geometric constraints or mechanical guidance, active control system[13], diamagnetic materials which repel both poles of a magnet, induced eddy currents in conductive, non-magnetic materials, and Halbach arrays.

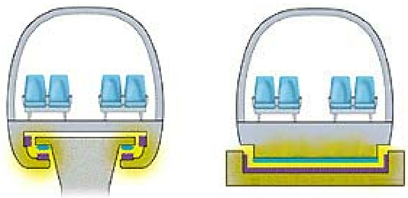


Figure 2: Comparison of maglev systems

Passive Maglev Techniques

Several configurations are used in passive maglev designs:

1. Halbach Array Suspension Halbach arrays are arrangements of permanent magnets that enhance the magnetic field on one side while canceling it on the other. They are widely used in maglev trains and bearings to create strong, directional levitation forces. These systems typically require a moving conductor, for example, an aluminum rail, in which eddy currents are induced, generating a repulsive lift force.

2. Diamagnetic Levitation Certain materials, like pyrolytic graphite or bismuth, exhibit strong diamagnetism and can stably levitate small permanent magnets due to their intrinsic property of repelling all magnetic fields. Although limited in strength, this method is entirely passive and requires no power input.

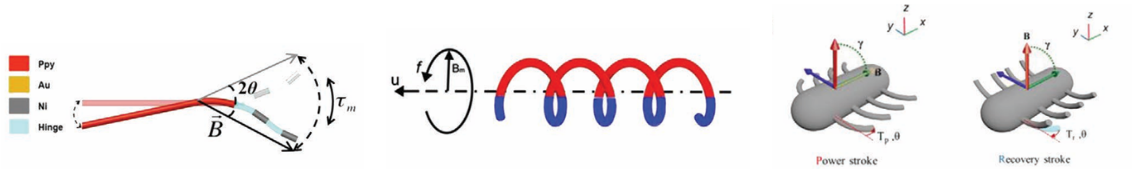
3. Inductive (Eddy Current-Based) Levitation When a magnet moves relative to a conductive surface (like copper or aluminum), it induces circulating currents (eddy currents) that create an opposing magnetic field according to Lenz's law. This results in a repulsive force that can be used for passive stabilization or levitation.[14]

This principle has found the most use in land transport and is practically best known for high-speed train systems like the Japanese *JR-Maglev* and experimental EDS (Electrodynamic Suspension) platforms. In other applications, besides transport, passive maglev systems are often used in: contactless bearings (flywheel energy storage systems), precision optical platforms for vibration damping, and biomedical devices, including magnetic drug delivery platforms or lab-on-chip modules.

3.4 Miniature and Biomedical Actuators

The world of biomedicine is constantly going to smaller and smaller scales. It has gotten to the point of developing micro and nano robots, which can be used for a wide variety of uses such as targeted drug delivery, internal curing, manipulation of small objects [15], getting access into vasculature, gastrointestinal tract, eye, and the brain [16]. While there are many methods of actuating these miniature robots like chemical, optical, ultrasonic, and electrostatic, magnetic actuation is by far the most preferred as it's relatively safe and offers good controllability [17].

Paper by Ebrahimi et al. proposes many different ways of fabricating a microrobot that can be actuated with the use of magnetic fields[18]. The first three designs take ideas from biological microscopic sources. One is a planar locomotion, made with a gold "head" and a nickel "tail". Magnetic nickel tail is moved by a magnetic field and makes the microrobot move in fluid. Second one is of a helical, spring-like design, that has a soft ferromagnetic head diametrically magnetized. By rotating the magnetic field, the robot itself starts rotating and moving in a direction perpendicular to the axis of rotation. This version of the robot lacks the appropriate ability of package carrying (micro-objects and particles), so it needs improvements in that field, and a possibility of adding microholders to the model is discussed. Last biological design is a robot with cilia, hair-like structures on the body that are used for movement. While in nature this presents a good option, with magnetic actuation only a synchronous movement is achieved, which produces unstable fluid propulsion, and in turn results to limited movement.



(a) Planar (b) Helical (c) Cilia

Figure 3: Example of three related images shown side by side.

The direct contact of the robot to the objects it needs to carry is unwanted for its sticky properties, so a study by Ye at al. shows a technique of actuating by using magnets to tilt the robot, which creates a rotational fluid flow that is responsible for carrying the object[19].

Another method researched in [18] is the existence of Magnetotactic Bacteria (MTB), which are microorganisms that use magnetic particles for navigation along the earth's magnetic field lines. With introduction of a local magnetic field made with magnets, the bacteria is controlled to follow this field. In a paper talking about new colonoscopy methods, they made a capsule-like device consisting of a camera module, with permanent magnets and a magnetic field sensor. Capsule was controlled externally with a use of a permanent magnet. Two studies were done, comparing manual control of the magnet versus a utilization of a robotic assist system that held the magnet. Results showed that manual control had a lower completion rate with lower completion time, while robotic system had the opposite higher completion rate with much slower completion time[20, 21].

4 Magnetic Systems Linked to Actuation

4.1 Magnetic Couplers

Magnetic couplers are devices that transfer force or motion between two mechanical parts without direct physical contact, using only magnetic fields. They typically consist of two rotating or moving components, each containing permanent magnets, arranged so that the magnetic field from one part influences the motion of the other. When one part of the coupler rotates or moves, the magnetic interaction, through a magnetic push-pull effect that causes the second part to follow in sync.

The main advantage of magnetic couplers is that they allow motion and torque to be transmitted across barriers that would otherwise block mechanical contact. This is especially useful in systems where it is important to keep one area sealed or isolated, such as in pumps handling hazardous or sterile fluids, vacuum chambers, or underwater systems. Since there is no physical connection, there is also no wear between the coupled parts, which increases the durability and reduces maintenance needs.

Two main configurations of magnetic couplers are an axial type, where two rotors are placed face to face, and radial type coupling, where one bigger rotor is concentrically placed around the smaller rotor.

4.2 Magnetic Bearings

Magnetic bearings are devices that support and guide rotating parts, such as shafts or rotors, using magnetic forces instead of physical contact. Unlike traditional bearings that rely on mechanical rolling or sliding components, magnetic bearings use the attraction or repulsion between magnetic fields to keep the moving part suspended in space. This eliminates friction, wear, and the need for lubrication, making them especially useful in high-speed, high-precision, or clean environments.

Passive magnetic bearings rely entirely on permanent magnets or other magnetic materials arranged in a way that creates a naturally stabilizing force. While active systems offer precise control, passive magnetic bearings are simpler, require no external power, and are often more robust for certain applications.

However, designing a stable passive magnetic bearing is not straightforward due to limitations like Earnshaw's Theorem. To overcome this, combination of different magnetic configurations is used, with other possibilities being diamagnetism, or gyroscopic effects. For example, permanent magnets might provide radial support, while axial stability is handled by another mechanism or with help of innovative geometry.

Magnetic bearings are used in many advanced systems, including flywheels for energy storage, vacuum pumps, high-speed turbines, and precision instruments. Because they eliminate mechanical contact, they are ideal for situations where minimizing friction, contamination, or vibration is critical. In the context of passive magnetic field-based actuators, magnetic bearings demonstrate how magnetism can be harnessed not just to create motion, but also to support and guide it with exceptional smoothness and efficiency.

5 Recent Research and Future Possibilities

Research in passive magnetic actuators has grown rapidly in the past decade, driven by demands for efficient, contactless, and maintenance-free systems.

5.1 Advanced Halbach Array Designs

Some studies have focused on optimizing Halbach arrays to improve magnetic field strength, compactness, and force uniformity. For instance, Choi and Yoo proposed a topology optimization method to design segmented Halbach cylinders. They made models for attractive and repulsive force of two magnet layers, as well as 2-ringed and 3-ringed designs for torque.

Another study by Lou et al. introduced a Halbach-array magnetic spring and with it, they aimed at achiving nearly linear stiffness, which they succeeded at, demonstrating its potential in passive suspension and vibration isolation systems.

5.2 Passive Magnetic Couplings for Industrial Applications

Magnetic couplings are increasingly replacing mechanical gear-based solutions in pumps, mixers, and motor drives. Their ability to work through sealed walls makes them ideal for chemical, food, and pharmaceutical industries.

A recent application involves magnetically coupled drives using concentric Halbach arrays to reduce stray field losses while maximizing torque transmission. Improvements in magnet segmentation and geometry modeling are helping to reduce cogging and vibration, improving long-term reliability.

6 Advantages and Limitations

Passive magnetic field-based actuators offer several unique benefits compared to traditional electromechanical systems. However, they also have limitations that must be considered during design and application.

6.1 Advantages

There are many advantages discussed over different papers mentioned in this work. The most obvious one is that with passive actuation, we are not using any outer source of power. This brings us in a positive position about energy efficiency. They are not only efficient energy-wise, as no direct contact of the parts that utilize magnets means that we have no friction between parts, which further means that there is no material wear. In return, we get components that have prolonged lifespans, and with that, less time and resources spent on maintenance and replacing the parts. Other than that, with no contact, these components bring considerable stability and noise reduction to the systems they are used in. No friction, as we can see in the example of maglev trains, is not just about material wear, as it also allows much higher speeds not attainable by conventional train track system.

In Bio-Medical science, advantage of using passive systems with permanent magnets is seen use of magnets for controlling the actuators, as well as being a building material for microscopic actuators. This is possible because a magnetic field up to $2T$ doesn't have any negative effects on a human body, and it goes up to $8T$ for healthy individuals[16], as well as the fact that, in comparison to electromagnets, permanent magnets gave a higher strength-to-size ratio for magnetic fields [18].This means that in micro and nano technology, it is really hard producing an electromagnet of a sufficient size. Permanent magnet also has the advantage of it's ability to be produced in any shape needed while retaining it's magnetic properties.

6.2 Limitations

While advantages of fully magnetic systems sound attractive, there are numerous limitations in theoretical and practical domains. Actuation and controlling of systems with permanent magnets is in most use-cases really complex and challenging. One of the core principles of permanent magnets, its continuous, non-powered magnetic field, can bring trouble in actuator systems, as in contrast to active systems (electro-magnets), the magnetic field can not be turned off, or changed and adjusted in real-time.

With magnetic levitation, as discussed before, there is a difficulty with keeping non-operating systems stable with only permanent magnets, which is shown in Earnshaw's theorem, but with combination of active systems, like we see in real life examples, this becomes managable. In spring-like systems, one of the main challenges is the magnets non-linear response of the negative stiffness, which has to be properly accounted for. In medical applications, there is a risk of using magnetic fields with patients that have implants like pacemakers and similar. The safe limit drops from $2T$ to $0.5mT$[16].

7 Conclusion

Passive magnetic field-based actuators offer a compelling combination of energy efficiency, mechanical simplicity, and contactless operation. By harnessing static magnetic fields, primarily through permanent magnets and magnet array configurations, these actuators can perform a variety of functions such as suspension, vibration isolation, torque transmission, and precise positioning without continuous power input.

Recent developments in Halbach array optimization, hybrid passive–active systems, and micro-scale biomedical devices show the growing versatility of these actuators across industries. At the same time, the rise of advanced manufacturing techniques and new magnetic materials is enabling more compact, efficient, and application-specific designs.

Despite their many advantages, passive magnetic actuators face important challenges, including nonlinear force characteristics, limited real-time controllability, and constraints imposed by Earnshaw's theorem. Future research will likely focus on improving modeling tools, integrating passive systems into smart mechatronic platforms, and developing safer, more sustainable actuator materials.

Overall, the continued evolution of passive magnetic actuator technology promises innovative solutions for a wide range of modern engineering problems, from industrial automation to biomedical devices.

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