Micro Robotics

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Week-4

Lecture-16

Micro actuation and Micromanipulation - Module 01

Here we will discuss micro-actuation and micromanipulation. We have discussed a lot about the actuators in micro-actuation. There is a wide variety of actuators available. However, on a micron level, smart material-based actuators have their own potential applications in micro-robotic-related development or micro-robotic-related design. Here, we will discuss three important topics. First is about magnetic-based micro actuation and how these magnetic-based micro actuators are incorporated into a micro robotic system for micromanipulation.

Let's consider some case studies and demonstrations of micro-magnetic, micro-robotic systems, and magnetically actuated micro-robotic systems. Thereafter, we will discuss piezoelectric material as a Microactuators for Microrobotics systems. Further, we will also discuss the electrostatic characteristics, which are a key factor for micro actuation in Microrobotics systems. In the case of an electromagnetic actuator, we are aware of the overall fundamentals of magnets. Now, with an electromagnetic perspective on robotic applications, we have observed a solenoid and a relay, which are efficiently used in different robotic applications. A solenoid has an electromagnetic coil, and it is used for direction-related applications. Basically, it's a kind of macro-level actuator that is incorporated with a relay that acts as a switch. These electromagnetically driven micro-actuators have significant benefits for manufacturers due to the improved three-dimensional production methods for a variety of materials. In electromagnetic actuators, electrical energy is transformed into mechanical energy in the form of forces or torques.

The classical example of such kinds of actuators includes relays, solenoids, motors, etc. So they can produce linear and rotational motion, which is suitable for many microsystem tasks. Further, to miniaturize these electromagnetic actuators, the properties of the magnetic materials must be improved, and new manufacturing methods for micro-winding must be developed. These are some of the key challenges we need to address with reference to an electromagnetic actuator. Application of an electromagnetic actuator is used in contactors, circuit breakers, and relays to control electric motors and circuits.

It is also used in switchgear and relays for electric power transmission and distribution. It is also used as a head positioner in computer disk drives, loudspeakers, fuel injectors in engines, automobiles, trucks, and locomotives. So the electro-hydraulic systems in airplanes, tractors, robots, automobiles, and other vehicles are being efficiently used. Further, in biomedical prosthetic devices like artificial limbs, hearts, ears, and other organs, such kinds of electromagnetic actuators are being efficiently used. Now, to realize the fundamentals of electromagnetic actuators, we need to understand the overall functionality and classification of these magnetic materials for their application towards micro actuators.

With reference to the micro-actuator point of view, we need to understand the concepts of diamagnetism, ferromagnetism, antiferromagnetism, paramagnetic, and ferrimagnetism. The magnetic susceptibility, which is termed Xm, is defined through the relationship between the magnetic induction B and the magnetic field H. Thus, the magnetization M is B equals μ_0 plus Xm H. Mu naught plus h plus m and mu naught is 1 plus xr; h equals mu h. So, xm is the magnetic susceptibility, mu naught is the permeability of vacuum, mu is the permeability of the material, and xr is xm minus mu naught, which is a kind of relative magnetic field susceptibility that exists.

Magnetic Materials for Microactuators :

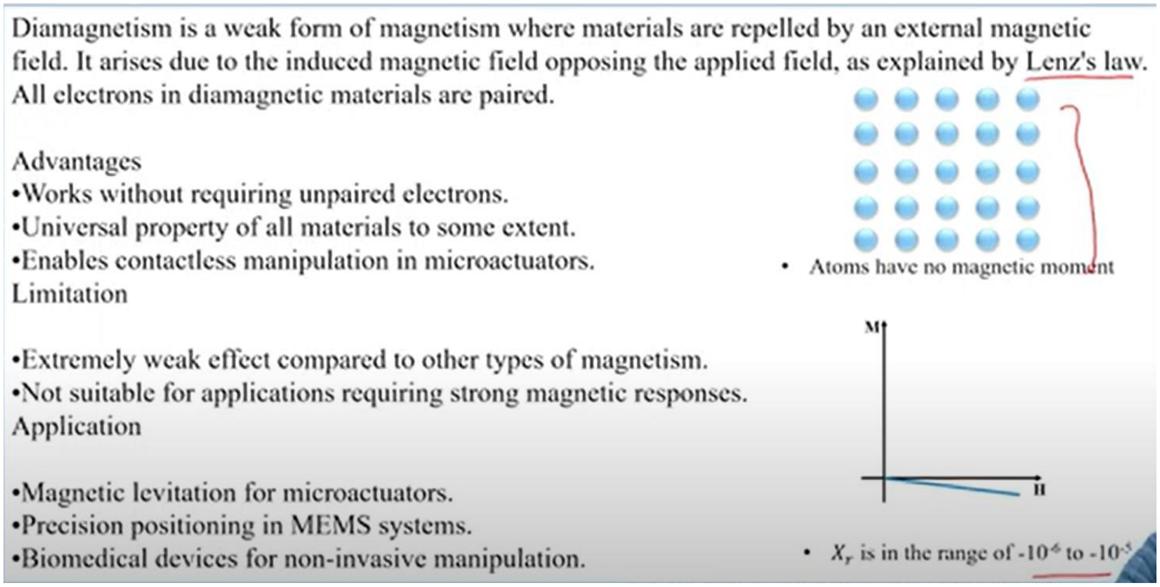
- Diamagnetism
- Ferromagnetism
- Antiferromagnetism
- Paramagnetism
- Ferrimagnetism

Magnetic susceptibility (X_m) is defined through the following relationship among the magnetic induction (B), the magnetic field (H):, and the magnetization (M):

$$B = (\mu_0 + X_m)H$$
$$B = \mu_0(H + M)$$
$$B = \mu_0(1 + X_r)H = \mu H$$

- X_m- Magnetic susceptibility
- μ_0 - Permeability of Vacuum
- μ- permeability of the material
- $X_r = \frac{X_m}{\mu_0}$- relative magnetic susceptibility

Now, when we try to understand the type of magnetism that is being employed for Microrobotics systems, diamagnetism is present. It is a weak form of magnetism, where materials are repelled by an external magnetic field. It arises due to the induced magnetic field, which opposes the applied field based on standard Lenz's law. So, all electrons in a diamagnetic material are paired. For instance, an atom that has no magnetic moment and Xr is in the range of minus 10 to the power of minus 6 to 10 to the power of minus 5.

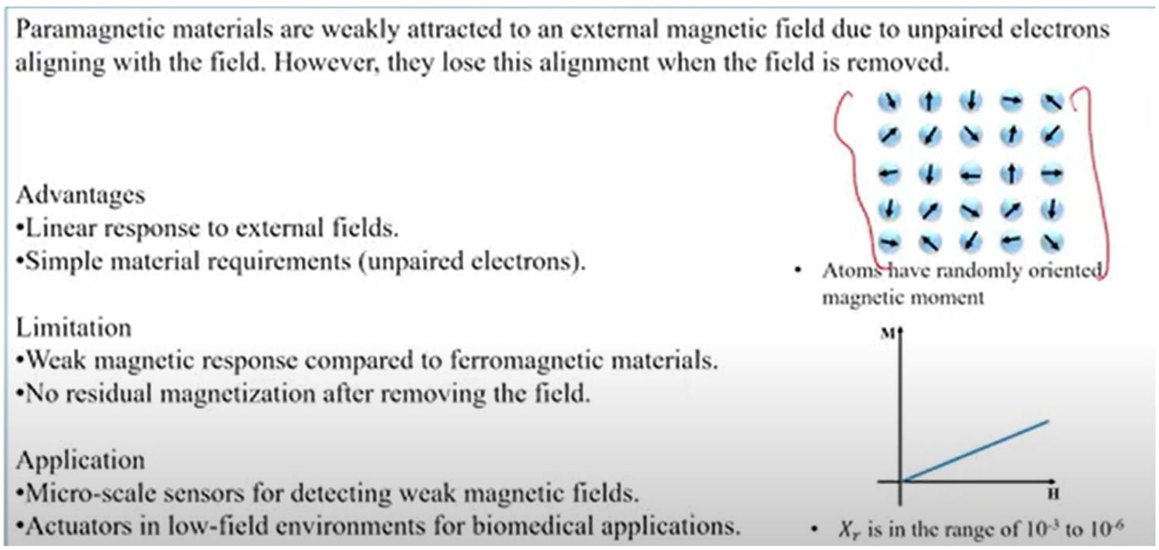


The main advantage of using such a kind of diamagnetism for a Microrobotics application is that it works without requiring an unpaired electron. The universal property of all materials is maintained and enables contactless manipulation in the case of a Microactuators. However, the limitations are that it is extremely weak and shows a comparable effect with respect to other types of magnetism. So it has very little value for micro-actuation. Hence, it is not suitable for applications requiring a strong magnetic response.

According to the application point of view, magnetic levitation for micro-actuators, precision positioning in MEMS systems, and biomedical devices for non-invasive manipulation are some of the key applications and examples of this diamagnetism. In the case of a biomedical application, magnetism is considered to be promising, and this diamagnetism has direct relevance to biomedical-related applications. Now in discussion of a paramagnetic system, the paramagnetic materials are weakly attracted to an external magnetic field due to an unpaired electron aligning with the field. Further, they lose this alignment when the field is removed. So here, the figure shows that the atom has a randomly oriented magnetic moment.

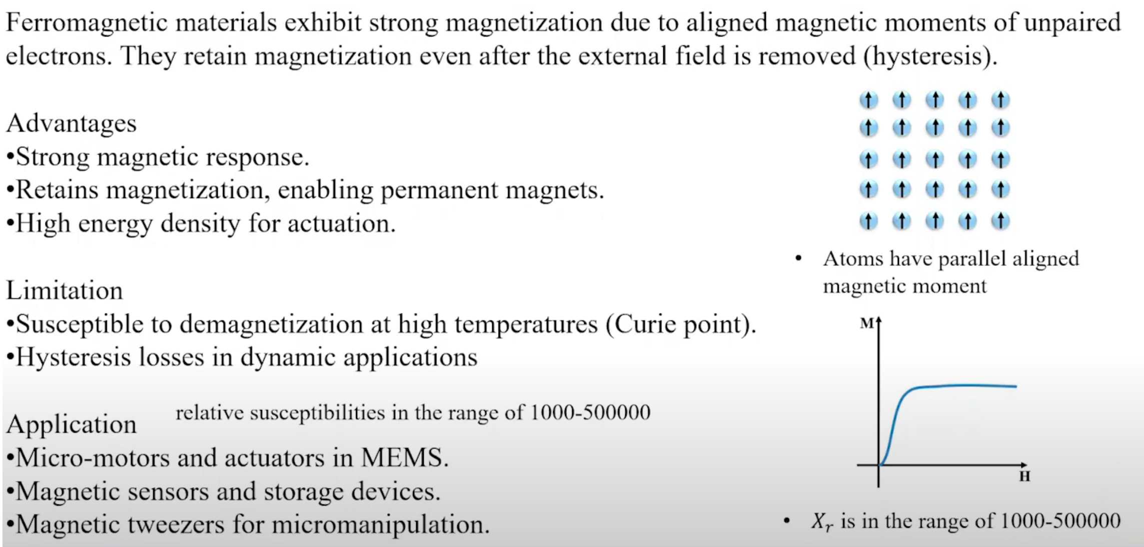
It can be aligned by applying an external magnetic field, so we can align the domains based on the requirements. So the XR is in the range of 10 to the power of minus 3 to 10 to the power of minus 6 based on the requirement. It has a linear response to external fields. It's a simple material that requires an unpaired electron. From a limitation point of view, it has a weak magnetic response compared to ferromagnetic materials and no residual magnetization after removing the field.

From an application point of view, it is a micro-scale sensor for detecting weak magnetic fields and actuators in low-field environments for biomedical applications. These are some of the key aspects with respect to paramagnetic-related systems. Now, in the case of ferromagnetic materials, they exhibit a strong magnetization due to the aligned magnetic moments of unpaired electrons. They retain magnetization even after the external field is removed; thus, this is a kind of hysteresis. In this figure, atoms are aligned parallel to the magnetic moment, and the Xr is in the range of 1000 to 5 lakh.



The major advantage of this is that it has a strong magnetic response, so it retains magnetization. It enables a permanent magnet with a high energy density of actuation. From a limitation point of view, it is susceptible to demagnetization at high temperatures, and hysteresis loss occurs in dynamic applications. From an application point of view, it has potential applications in micromotors and actuators in MEMS systems, magnetic sensors, and strong devices. Magnetic tweezers for micromanipulation are some of the key applications with reference to this ferromagnetic system. Basically, ferromagnetic systems are standard systems that are being efficiently deployed for Microrobotics applications; especially, these magnetic tweezers for micromanipulation are one of the key applications. Now, let's discuss anti-ferromagnetic material. It is a kind of adjacent atomic magnetic moments aligned in opposite directions. Therefore, they cancel each other out and result in net magnetization. In the figure, one set of domains is aligned in one direction, and the other set of domains is aligned in another direction, resulting in the cancellation of the overall magnetic field.

So as far as its XR is concerned, the XR is in the range of 10 to the power of minus 6. Advantages: It has high stability under external fields. It is useful for spintronic devices due to minimal stray fields. Limitations: limited application in spintronic devices and memory systems, and high-frequency micro-actuators for precise control. Application: micromotors and actuators in MEMS devices, magnetic sensors, and storage devices.



Further, it is used for magnetic components in micromanipulation-related applications. In ferrimagnetic materials, The material has an opposing magnetic moment like antiferromagnets, but the moments are equal, resulting in no net magnetization. Common examples include ferrites like magnetite, Fe3O4, which are efficiently used for this ferrimagnetic property. So, it has positive magnetization, but it is less than the ferromagnetic material. So, when we observe the overall atoms and their magnetic domains, the atoms have mixed parallel and antiparallel aligned magnetic moments.

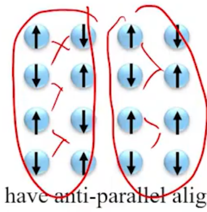
Advantages: it has a high resistivity and reduced eddy current loss. It is suitable for high-frequency applications and is stable under moderate temperatures. Limitation: It has a lower saturation magnetization compared to the ferromagnetic material, limiting its use in high power applications due to flux density constraints. These kinds of ferrimagnetic materials are efficiently used for microwave devices like isolators and circulators, as well as magnetic cores for inductors and transformers in MEMS. Thermal energy storage systems in micro-scale applications are some of the key applications from the perspective of micro robotics and MEMS.

In antiferromagnetic materials, adjacent atomic magnetic moments align in opposite directions, canceling each other out and resulting in no net magnetization.

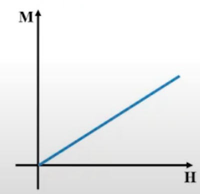
Advantages
•High stability under external fields.
•Useful for spintronic devices due to minimal stray fields.

Limitation
•Spintronic devices and memory systems.
•High-frequency microactuators for precise control.

Application
•Micro-motors and actuators in MEMS.
•Magnetic sensors and storage devices.
•Magnetic tweezers for micromanipulation.



- Atoms have anti-parallel alignment magnetic moment



- X_r is in the range of 10^{-6}

Now, the governing law is used for magnetic material-based actuators for different functional applications. The Lorentz force actuator, which is the key thumb force used for quantifying the magnetic-based systems. So, these Lorentz force actuators generate force based on the interaction between a current-carrying conductor and an external magnetic field. The force F_L is given by F_L equals L dot LC dot B.

That is I · L · C · B. I is the current through the conductor, L is the effective length of the conductor, and B is the magnetic field strength. This is a Lorentz force actuator that consists of a micro-machined silicon structure with a diaphragm. The current-carrying wire is embedded within this structure, as shown in the figure. When the current flows through the wire in the presence of a perpendicular magnetic field, denoted as Bb, a force is generated that deflects the diaphragm. The force generated does not depend on diaphragm diffraction, unlike the electrostatic forces. The external magnetic field is assumed to be uniform across the diaphragm span, ensuring consistent operation in this particular system. So, these are some kinds of generalized Lorentz force actuators that are being systems discuss the middle ear implant hearing device. It is a micro robotic system where a magnetic-based actuator is used. These implantable middle ear hearing devices are powered by a magnetic actuation mechanism.

The device uses a coil to drive a permanent magnet attached to the suspension arm connected to the step board. When the current flows through the coil, it generates an electromagnetic force that moves the magnet and simulates a vibration in the step bone. The device is used as an implantable hearing aid for individuals with middle ear hearing loss. It provides high-fidelity sound reproduction with a wider frequency response compared to conventional hearing aids, which offer precise control over the vibration for improved auditory perception. It operates efficiently across a broad frequency range. Its compact design is suitable for implantation without significant discomfort. This kind of mechanism is being deployed by considering magnetic actuation. This is a simple system where bulk magnet-based structures are deployed. This innovative use of magnetic actuation demonstrates its potential in biomedical applications where precision and compactness are critical for enhancing human health and functionality. The implantable middle ear hearing device is powered by the magnetic actuation mechanism.

The device uses a coil to drive a permanent magnet attached to the suspension arm, which is connected to the stapes. When the current flows through the coil, it generates an electromagnetic force that moves the magnet and stimulates the vibration in the step bone. The main parameters that play a vital role in this system are the frequency of the system and the micro displacement. Another specific magnetic micro actuator with a planar coil is shown. Here, we try to understand the overall behavior.
It has spring arms that are interconnected between the stages. There is a small permanent magnet that is attached. Earlier, we discussed a serpentine structure that is used for the movement of the mirror. This is like a spring arm structure that is used for manipulating the permanent magnet. Here, the etching involves lithography and DRI etching to create such structures.

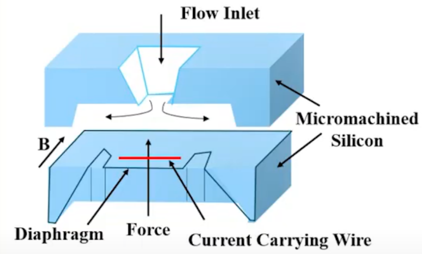
A Lorentz force actuator generates force based on the interaction between a current-carrying conductor and an external magnetic field. The force (F_L) is given by:

$$F_L = I.l_c.B$$

Where:

- I : current through the conductor,
- l_c : effective length of the conductor,
- B : magnetic field strength.

•The actuator consists of a micromachined silicon structure with a diaphragm.
•A current-carrying wire is embedded within this structure.
•When current flows through the wire in the presence of a perpendicular magnetic field (BB), a force is generated that deflects the diaphragm.
•The force generated does not depend on diaphragm deflection, unlike electrostatic forces.
•The external magnetic field is assumed to be uniform across the diaphragm span, ensuring consistent operation.

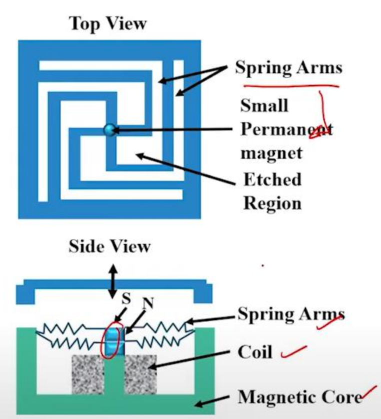


•When current flows through the coil, it generates a magnetic field that pulls down the spring.

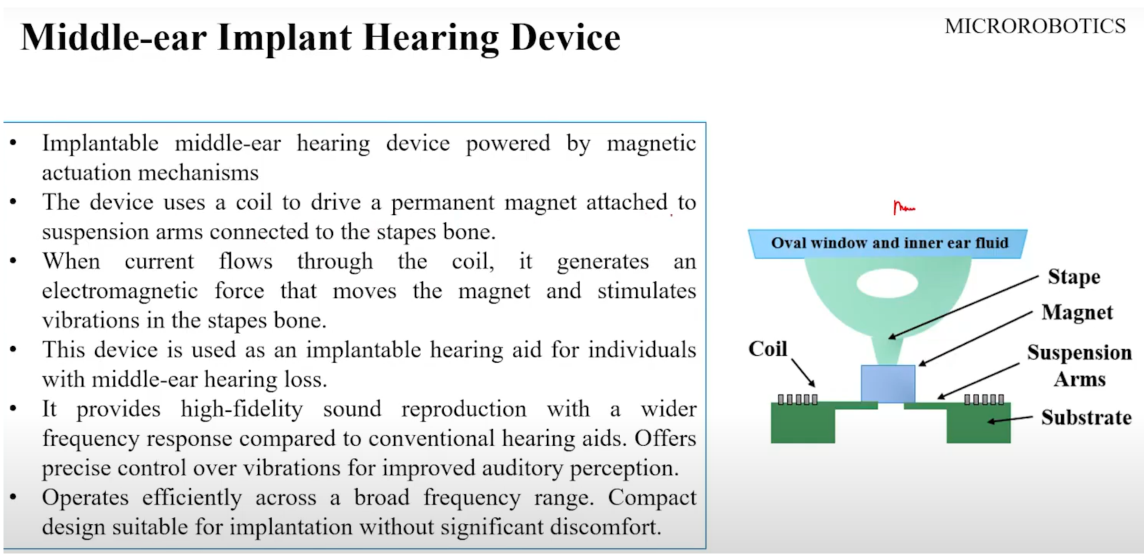
•The physical contact between the spring and the top of the coil creates an electrical connection, referred to as the "ON" position of the relay.

•The small permanent magnet ensures that the spring remains latched in the "ON" position even when the current is turned off.

•To release (un-latch) the spring, the coil is excited with a current polarity that generates a repelling magnetic field.



This is a side view. In this view, we have the magnetic coil and the springs and arms that are placed in the coil, and a magnetic course is placed. When the current flows through the coil, it generates a magnetic field that pulls down the spring. The physical contact between the spring and the top of the coil creates an electrical connection referred to as a relay; the small permanent magnet ensures that the spring remains latched in the "on" position even when the current is turned off. To release the unlatch, the coil spring is excited with the current polarity, which generates a repelling magnetic field in this system. These types of systems are efficiently used for planar coil-related applications or planar coil-related characteristics.



These give some overviews of the magnetic-based system or magnetic-based actuators that are efficiently available for the development of microsystem-related applications. If we closely analyze all these cases, we can see solid magnetic particles, and these solid magnetic particles can generate such kinds of levitation or magnetic structures that are being employed. Hereafter, we will discuss the overall classification of this magnetic-based actuation. How are these magnetic-based actuations classified with reference to the geometry and the manufacturing process? What are the different types of micromanipulations that exist with reference to the magnetic-based structures and magnetic-based actuators? We will also discuss in detail how these magnetic actuators are efficiently used for biomedical-related applications. The list of the applications and their characteristics is detailed in the following module.