Micro Robotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

Indian Institute of Technology, Indore

Week-08

Lecture- Lec40

Microsystems for Microrobots (Actuators) - Module 05

So today we will discuss the last module, the last part of these microsystems for micro-robotic related developments, basically like we have been discussing the different actuator-based systems. We have been discussing piezoelectric-based ultrasonics; we have also discussed micro motors, and in the last class, we discussed thermal-based actuation. Now in today's lecture, we will discuss the chemical micro engines. As far as these chemical micro engines are concerned, they derive their power from chemical reactions that often mimic the biological system. So, some of the examples include the catalytic engine. In the case of a catalytic engine, ideally, the surface reactions are taken into consideration to generate motion in the fluids, and then there are certain osmotic engines that are also being delivered.

So, these osmotic engines are highly used for harnessing the osmotic pressure differential within the system. There are some fuel-based engines which are mainly meant for converting chemical energy directly into electrical and mechanical energy. So these engines offer the potential for autonomous operation in a specific environment, which is one of the key aspects we may need to consider while using such engines. But there is an issue with fuel storage, and then there is a reaction control at the microscale.

So ideally, let us consider a certain amount of chemical reactions or a type of chemical plant where such systems can be deployed to propel or actuate micro robots for different applications. However, from a research perspective, there is very little focus in this particular domain. So ideally, due to its challenges, which are involved in it, one of the key domains is the optical-based micro engines. So, as far as the name suggests, optical microengines use light energy to generate motion either directly through photon pressure or indirectly through the photothermal effect. Some of the examples include optically driven micro-turbines, light-activated polymer actuators, and photovoltaic power-based micro-engines.

So, as far as these optically driven micro-turbines are concerned, let us consider a small micro turbine that is fabricated using a shape memory alloy. So, the overall fins of this micro-turbine are fabricated using a shape memory alloy, and these shape memory alloys are highly strained during the fabrication. Now what happens is, when the laser light interacts with this micro-turbine, these micro-turbines will try to get actuated. When these micro-turbines get actuated appropriately, there will be a shift in the center of gravity, which will result in a rotation. The overall actuation is done using a kind of optical means so that the light which is incident on this surface is completely absorbed and acts as a source for actuation. So, this is one mode in which we can have a kind of actuation through light. In most cases, a monochromatic source, ideally "lasers," will be used for such actuation for efficient rotations. Then, we have the light-activated polymer actuator. So, in fact, when we were studying the different types of actuators, we saw some of these kinds of light-activated polymers, i.e., light-activated polymers. These polymers, when the light interacts with them, try to get displaced, and when the light is cut off, they return to their original shape. For example, let us consider that we have a light-activated polymer like this, which is being trained in an ohm shape. Now, what happens is that when the light falls on it, it becomes straight. So, ideally we are trying to switch from one shape to another shape based on our requirements or based on the propulsion for specific applications.

Here, the actuation is the light. The on and off of the light will have direct control over the movement of these structures. So, these are called light-activated polymer actuators. Then, there is a certain amount of photovoltaic-powered micro engines. So, as far as these photovoltaic-powered micro engines are concerned, these are a kind of solar cell that is available, so when the light falls on it, appropriately, the energy is going to get generated. So, this energy is capable enough to activate the micro-engines based on the requirement. So, one of the key advantages of using this system is, it offers a kind of a non-contact actuation. This is one important point. Another point is that these optical micro-engines typically provide a low power output compared to the other types. So, from the actuation perspective, precise actuation is possible by appropriately shining a light on a particular point.

So, as we all know, if we need to have a concentrated beam of light, we may use a lens system to focus the beam at that point, and then we can appropriately actuate. So ideally, what happens is that the control of the actuation is well taken care of using this optical-based system, and appropriately, we can expect an actuation. Now this is quite an interesting problem; it is a kind of split comb drive design that is completely fabricated using a light-actuated polymer. So basically, these polymers are integrated in the form of a split comb drive, and then these split comb drives ideally allow the waveguide to be placed near the translation stage when other features, such as an extended counterweight on the micro-engine and the linear actuators, are not available. So, the multimode waveguide design includes a polymer substrate layover.

This isolating nitride layer of a typical SMM structure processes and relies upon variations in the reflected power coupled back over the moving stage into the waveguide input, which is subsequently split and collected as output. So, as far as this particular case is concerned, we have an optical input, and this optical input is made to pass through a multimode wavelength. If you see the construction of it, this is a kind of comb drive-based polymer structure that is available whenever the light falls on it, and there is going to be an actuation that it exhibits. So, with reference to time t, when the intensity increases, there is going to be an increase in the displacement, and then there is going to be a drop, okay. So, if I try to term it as a D, this is going to be like if the intensity is considered as on and off, on and off.

So, when the intensity is on, we get a displacement, and when the intensity is off, there is going to be a decrease in the displacement. Again, when the intensity is on, there is a displacement, and then there is going to be a decrease in displacement (when the intensity is off). So, this switching behavior can happen within the system. So, that is why it is a kind of resonator that is being fixed over here. So that appropriately, we can have control over the frequency, and by controlling the frequency, we can use it for different applications.

For example, by giving a particular sequence, I can load a kind of cantilever on top of it, and this cantilever can be vibrated appropriately with this resonator. So, the on and off of the light will take care of the requirement, and appropriately, you can see a moment coming out of it. So, these are some kind of polyamide wavegates that are fabricated in the form of a split comb resonator, and the actuation is through a laser or through light. Now, let us just brush up on some of the different fabrication techniques that have been deployed for developing such micro-engine related applications. So, as far as these micro engines are concerned, with reference to different micro engines, these are the different fabrication techniques that are being effectively used.

So, either it might be a laser-based micro-machining or, in certain cases, there is a chance of opting for a mechanical micro-machining; a lithography-based system is highly effective, and 3D printing at a micro scale can be effectively used, while a certain amount of surface micro-machining can also be employed. As far as this is concerned, material selection for micro-engines is critical, balancing its mechanical properties with good fabrication compatibility and application requirements. Some of the common materials include silicon (Si), for which we have quite a good amount of data, and which has excellent mechanical properties and an established fabrication process. From a metal perspective, we have nickel (Ni), gold (Au), etc., which have good conductivity, suitable for electromagnetic engines.

From a polymer perspective, we have SU-8 and PDMS structures, which provide flexibility and biocompatibility. As far as the piezoelectric perspective point of view, there are a wide variety of materials that exhibit piezoelectric capability. Recently, lead-free zinc oxides have also been efficiently used for piezoelectric-related applications, and there are also a certain amount of shape memory alloy materials that have been exhibited. Now, let us discuss some of the key design considerations for and optimization relevant to this micro-engine. As far as effective microengine design is concerned, it requires careful consideration of various factors.

Some of the factors include power output and efficiency requirements, operating environment, temperature, humidity and chemical compatibility, fabrication constraints and material limitations, and integration with control and power systems; reliability and lifetime expectations are one of the key parameters. So, as far as these optimization perspectives point of view, this optimization often involves a multi-physics simulation considering coupled electrical, mechanical, and thermal effects at a microscale. So, these are considered to be some of the key design considerations that are effectively contributing to the development of a micro system for the appropriate functionalities. Now, as far as these micro engines are concerned, they play a crucial role in the development of micro robots. So, one of the crucial roles includes a locomotion mechanism for terrestrial micro-robots and articulated joints for micro-manipulator related applications.

So as far as these locomotions are concerned, it might either be stick-slip based or sometimes comb based, and there are some mechanisms where, with reference to vibration, we can have a kind of locomotion with high frequency vibration. For example, if we can have a structure like this, it is a kind of cantilever; when these cantilevers vibrate at a very high frequency, this will induce a kind of forward motion in the system. Next is a kind of articulated joint for micromanipulators that is considered to be one of the effective ways to provide appropriate constraints, which will give a type of input with reference to different reach-outs, and is considered to be one of the key points. Next is the kind of propulsion system for swimming micro-robots, and then the power source for autonomous operation. So, as far as these autonomous operations are concerned, even though we had discussed some kind of micro-energy harvesters, there is still a need to work on the overall characteristics and behavior.

So this is one of the key aspects that we may need to look into. Okay. Now, as far as these challenges are concerned, it has improved power density and efficiency. It has enhanced reliability and lifetime. When we try to look into the overall fabrication cost, there is a reduction in the fabrication cost, primarily with reference to mass production, and integrating multiple functionalities in a single device is considered to be one of the key challenges in this regard.

When we try to focus on future directions, the exploration of novel materials, such as 2D materials and metamaterials, is considered to be one of the key directions we may need to focus on, from a micro-robotic perspective. Bio-inspired and soft micro-engines are one of the domains. Self-assembling and reconfigurable micro-engines are considered to be one of the domains. Integrating artificial intelligence for adaptive behavior is one of the key aspects. From the perspective of propulsion mechanisms, we have different domains. One domain is related to steam. The other domain is with reference to a liquid. In certain cases, we may also need to go for magnetic field-based systems. In those conditions, such adaptive behavior will help to fulfill some of the appropriate functionality. From the perspective of biomedical applications, we have seen many micro-pumps. When we closely observe these micro-pumps for drug delivery-related applications, we find that they are suitable for minimally invasive surgeries.

They have artificial muscles for prosthetic applications and microfluidic devices for lab-on-chip diagnostics, as well as implantable sensors and actuators. So as far as these micro-pumps for drug delivery systems, it has one good aspect which we may need to look into: these micro-pumps, as we have seen in one case study, can ideally be used for targeted drug delivery applications and for implantable applications. Now, if we try to look into the strategic areas where such kinds of micro-engines contribute, we can see that micro-engines contribute to miniaturization and enhance functionality in aerospace and defense applications. Some of the aspects include the micro-thruster for satellite positioning. So, ideally, wherever based on the requirement, such kinds of adaptive micro thrusters get activated, and they can be used for the locomotion of the satellite.

Second adaptive optics imaging system. This is considered to be one of the key domains where there is a good amount of research focused on these optomechatronic systems. Further, there is more focus on micro optomechatronic systems where such micro engines or micro actuators are integrated with optics so that the overall focal point of the optics can be manipulated. Thus, the required focal point can be adjusted to achieve the desired application, such as the auto-focus feature currently available in cameras. So this auto focus basically works on the principle that we have a kind of image stabilization program.

Based on the image stabilization program, the actuator moves, and appropriately it will try to get the signal coming out of it; from these signals, we can observe the overall construction behavior, etc. Then there is a certain amount of micro gyroscopes that are used for navigation-related applications. So, as far as these micro gyroscopes are concerned, these micro gyroscopes are effectively used for a kind of stabilization perspective. So, energy harvesters for autonomous sensors are also considered to be one of the key elements that are effectively used for autonomous-related applications and a microfluidic cooling system for electronics. So, ideally, wherever we have a kind of electronic system, such microactuation with microfluidic behavior will have its own advantages for taking care of adaptive-related structures.

Now, when we focus on energy harvesting-related applications, micro engines play a role in microscale energy harvesting, ideally with reference to power generation. So, from a power generation perspective, we have vibration-based energy harvesters, such as a piezoelectric system. From the vibrations, we can harness energy. Then, there are a kind of thermoelectric-based micro engines. Because of the variation in the temperature gradient, we can get these structures.

Then there are a few micro fuel cells that are available, and piezoelectric energy-based scavenging devices are being effectively used for micro-robotic-related applications. So, these technologies ideally aim to develop a self-powered micro system for applications like wireless sensor networks and implantable medical devices, which are some of the key applications where such energy harvesting and power generation-related applications are focused. As far as the application perspective point of view is concerned, in the case of applications in MEMS devices, the integration of micro engines enables a MEMS device to perform a complex function in a compact form factor. So some of the systems, some of the micro systems are listed over here. So one important microsystem is the kind of micro pump that has valves for fluid control, and then there is a kind of micro actuator that is ideally used for precise positioning.

There are a few energy harvesting devices that are being effectively used for harvesting-related applications, so there are several micro energy harvesters. These harvesters have a potential application in harvesting energy from thermal sources, from vibration, from shock, and sometimes from chemical reactions as well. Then we have the inertial sensors, which are effectively used for motion detection-related applications. So, which is considered to be one of the prime focus in the case of micro robotics is concerned. Even a sudden change or in the minor change in the system can be effectively monitored using this arrangement.

So ideally, motion detection is used in most cases through cameras; however, in this particular case, we have the capability to use a kind of inertial system that can be effectively used for monitoring the system based on the applications. Then we have the micro mirror arrays for optical switching and display-related applications. Such kinds of micro mirrors are concerned; we can have a kind of switching behavior. So, these switching behavior can be effectively used for the movement of the system and then, we can divert the beam for certain amount of optical manipulation related applications. So, in those areas, such kinds of micro mirror arrays are also available.

If you remember, we had discussed this SMA-based high reflectivity mirrors. So, these SMA-based high reflectivity mirrors are integrated with a type of steward platform arrangement, and here we have a type of SMA bimorph. So, this SMA bimorph is effectively used for operating in such a way that this actuation moves, and we can see a kind of deflection, and we can also monitor the deflection. So, there are micro pumps and micro valves that we discussed in detail.

Now let us discuss one of the key aspects, which is called magnetic helical-based micromachines. So, as far as these magnetic helical-based micromachines are concerned, this is considered to be a kind of NAVE system. It is a type of system that is effectively used for displacement-related applications. So ideally, such kinds of systems are inspired by bacterial flagella. These micro machines utilize a helical propulsion mechanism to perform tasks such as cargo transport, biofilm disruption, and drug delivery.

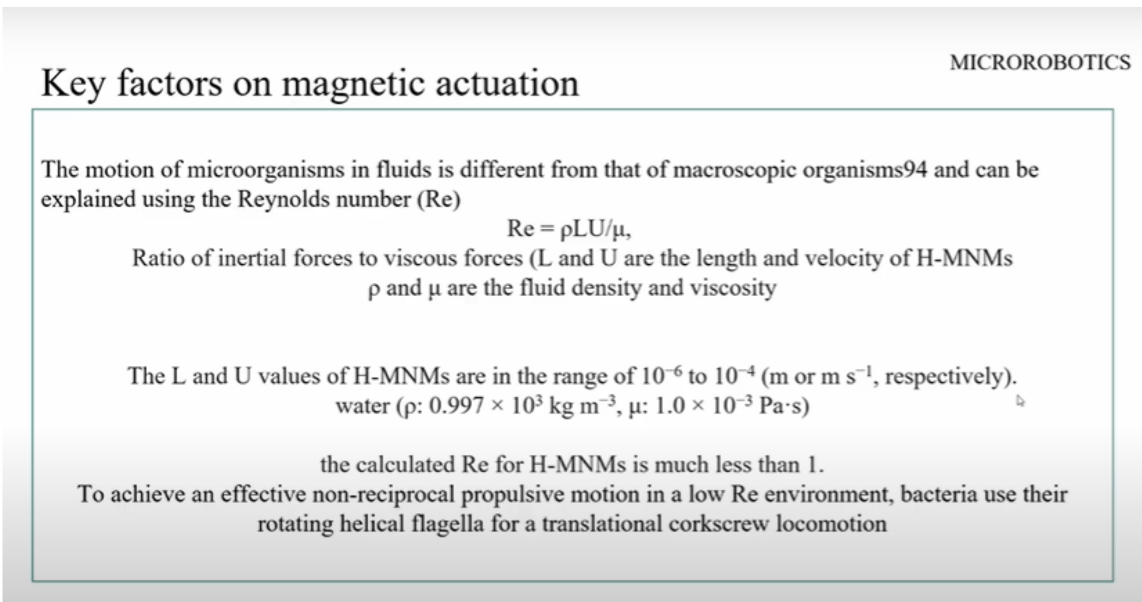
In this particular case, there is a helical arrangement. This helical propulsion will be helpful for us in such a way that whenever we try to activate it and when the helical rotation is appropriately achieved, we can expect a displacement that is exhibited here. So, if we try to look from the application's perspective, it has potential applications for biofilm disruption as well as targeted drug delivery. So, from the modal perspective, it has a helical shape. It enables a corkscrew-like motion for efficient propulsion.

So basically, this corkscrew motion is the overall principle for this helical shape. Then there is a kind of magnetic actuation that it exhibits. These are powered wirelessly using a rotating magnetic field, so as we try to actuate the magnetic field appropriately, there will be a rotation in this process. From a versatility perspective, it operates in a diverse fluid environment that includes water, bodily fluids, and tissue, which are considered to be some of the key advantages of using such magnetic-based helical micromachines for different applications. Therefore, for propulsion and manipulation in a fluid environment, a low-strength rotating magnetic field can be used, which can be considered harmless to humans and other living organisms.

So, in this particular case, it is driven by a rotating magnetic field that generates a torque on the magnetized helical body. This results in a kind of corkscrew motion, allowing the micromachine to swim through the fluid efficiently. Such a system will be integrated with cavities and can carry drugs to a specific location within the body. So, this is one advantage of this particular system and their precise control and it allows a localized delivery without damaging the surrounding tissue which is considered to be one of the key aspect of this system. As far as these helical propulsion mechanisms are concerned, they have low Reynolds number dynamics.

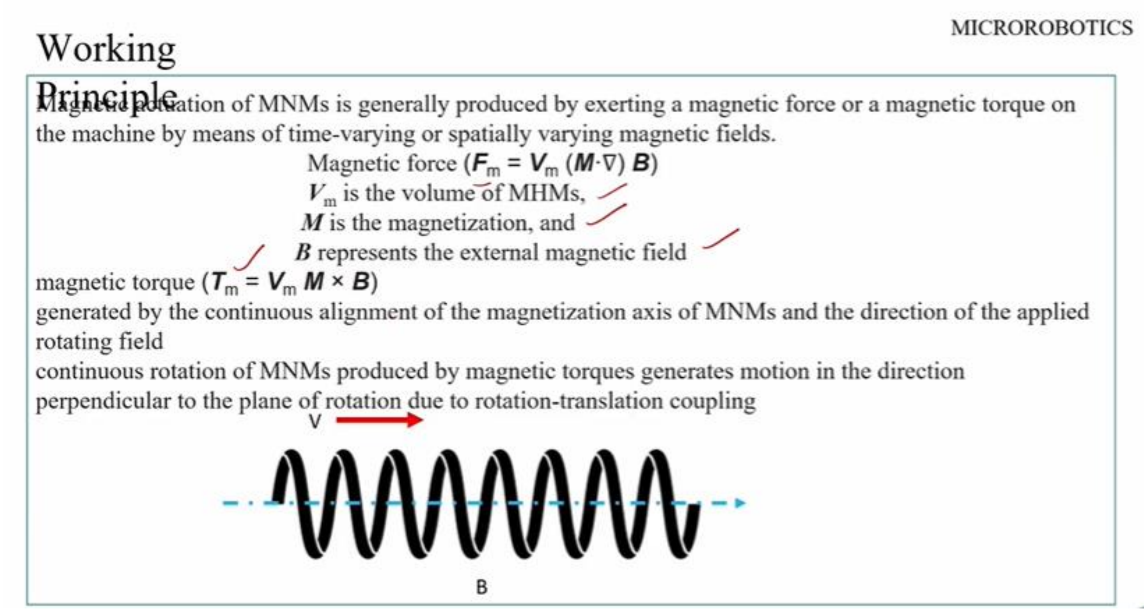
They operate in an environment where viscous force heavily dominates. As far as this core screw motion is concerned, it converts rotational motion into a kind of appropriate translational motion, and considering the efficiency factor perspective, some of the key parameters involved in this are the helix pitch, the diameter, and the magnetization direction, which influence the propulsion speed and are considered to be some of the efficiency parameters. So, some of the key factors in magnetic actuations are that the motion of a microorganism in fluid is different from that of microorganisms, which can be explained with the concept of a Reynolds number. So, we all know that as far as the Reynolds number is concerned, it is a ratio of inertial force to viscous force. L and U are the length and velocity of this helical system, and ρ (rho) and μ (mu) are the fluid density and viscosity that are involved in this system.

$$Re = \rho LU/\mu$$



The values of L and U for H-MNR are in the range of 10 to the power of minus 6 to 10 to the power of minus 4, with reference to the different parameters. So, overall, the Reynolds number is less than 1. To achieve an effective non-reciprocal propulsive motion in a low Reynolds environment, bacteria use their rotating helical flagella for translational corkscrew locomotion. Now, as far as the working principle perspective point of view, this magnetic actuation is generally produced by exerting a magnetic force or a magnetic torque on the machine by means of time-varying or spatially varying magnetic fields. So, when we try to look into these magnetic forces, let us represent the magnetic force as Fm, and then we have Vm as the volume, M as the magnetization, and B as the external magnetic field.

$$F_m = V_m(M.\nabla)B$$



$$T_m = V_m M \times B$$

So ideally, when we try to look into this magnetic torque, we have the volume, the magnetization, and B, which is represented as the magnetic field. This is generated by a continuous alignment of the magnetization axis and the direction of the applied rotating field. So, this continuous rotation of this system produced by a magnetic torque generates motion in the direction perpendicular to the plane of the rotation due to the rotation-translation coupling. So this is going to be V, and this is going to be the magnetic field B. So, the motion of this H-MNM under a rotational magnetic field is primarily determined by two aspects: one is called a magnetic field control system, and as far as this magnetic field control system is concerned, it involves a magnetic field strength with the velocity of the helix.

MNM increases the field strength; the direction angle of the magnetic field is adjusted to direct the movement of H-MNM, and its angle is a component of the direction angle that causes it to tilt at a certain angle from its origin. Horizontal state produces a vertical propulsion component to compensate for the force of gravity, which ensures a kind of free swimming; ideally, the direction is related to the propulsion, and the reverse and forward strokes of the propulsion will have an impact on the direction. From a low-frequency perspective, a low-frequency wobbling phenomenon will always be observed, which is basically a kind of misalignment in the axis of symmetry. From the velocity perspective, the velocity is proportional to the input frequency (f) in the intermediate range. So, ideally, in this particular case, a and b are related to the geometrical features of the helical system, and psi u (ψ) contains the geometrical parameter of the head attached to this system.

$$V = \frac{-b}{(a + \psi_u)} f$$

So, when we try to look into the structural design parameters, the key design parameters influencing the performance are the helical pitch, height, diameter, and the cross section of the structure. So, in fact, this image will give us better clarity where we have a filament diameter, a helical helix angle in place, a pitch diameter in place, and then the overall length being exhibited over here. As far as the structural design parameters point of view, this magnetic helical system tends to sink down or near the solid boundary, which results in a lateral force due to the drag imbalance. The externally applied non-fluidic force and torque must balance the fluidic force, and the torque generated by their rotation is represented by this equation, where it is considered that two sets of rotations or two sets of motions are taken into consideration.

One is called a translation, and another one is called a rotation. So, the drag coefficients involved in both translation (ψ_u) and rotation (ψ_w)are taken into consideration for the head effectively, and a, b, c are related to the geometrical parameters, which basically have a direct impact on the diameter, pitch, length, helical angle, and width of the filament diameter.

$$\begin{bmatrix} F_m \\ T_m \end{bmatrix} = \begin{bmatrix} a + \psi_u & b \\ b & c + \psi_W \end{bmatrix} \begin{bmatrix} u \\ w \end{bmatrix}$$

So, the wettability of such a helical system is another factor that influences locomotion, as a hydrophobic surface would cause a low drag force, which is exhibited here. Now, let us see some of the key performance metrics of the system. So, some of the key parameters include the proportional field speed, which is in the range of up to 390 micrometers per second, and from a stability perspective, stability under the varying magnetic field is the strength and efficiency; efficiently in a low Reynolds number environment is one of the key performance metrics.

Now let us discuss the different modes of motion. Some of the modes of motion of these particular systems are concerned. So, one is called a straight mode system. As far as this straight mode system is concerned, we have a rotating shaft, so it is like without a tilt. So when you try to move this rotating shaft appropriately, we get a displacement coming out of it. So, in this particular condition, it is without a tilted angle along the axis of the tube.

This is a kind of tilted mode. In the case of a tilted mode, it is kept at a particular angle with a constant tilt angle along the axis of the tube. In a wobbling mode, there is going to be a continuous change in the tilted angle. So when there is a continuous change in the tilted angle appropriately, we get the highest efficiency in disrupting the biofilms and occlusion into the debris. So as far as this particular case is concerned, it can break down the biofilm into debris while enhancing the diffusion of antibacterial agents like reactive oxygen species, etc.

These are the different modes of motion that are exhibited here. So when we try to look into the material consideration perspective point of view, we have the polymer materials. In the case of polymer materials, it is a kind of silicon-based polymer, so technically we represent it as SU-8. These SU-8 materials offer excellent mechanical stability and provide thermal resistance. The cross-linked SU-8 structures remain stable during the development drying process as well as during subsequent metallization steps. A magnetic material perspective, like nickel, is one of the key materials for actuation and control of helical micromachines, ideally in the range of 50 to 100 nanometers, and titanium, which is considered to be a kind of biocompatible material, is in the range of 5 to 10 nanometers.

Then, since it is magnetic, Fe2O3 and Fe3O4 offer alternative options as a kind of alternative magnetic material with excellent responsiveness to the external field. These Fe2O3-based helical micromachines achieved magnetic saturation at 35 electromagnetic units per gram, enabling rapid magnetic separation in an aqueous environment within seconds. Now, with reference to the metal oxide perspective, we have zinc oxide, copper oxide, CO3, O4, and NiO offering specific functional properties beyond basic magnetic actuation. From a graphene oxide perspective, it acts as a structural framework combined with metal precursor solutions, and from a high-temperature processing perspective, it transforms the metal ions into a metal oxide structure that retains the helical morphology, exhibiting catalytic and functional properties specific to each of these metal oxide types. So ideally, the material selection will fall under these particular categories.

Now let us discuss some of the key applications of these magnetic helical micromachines. So these magnetic helical micromachines can transport microparticles or biological samples in a 3D environment using microholders integrated into their structure. As far as the application's perspective point of view, the application is more focused on targeted drug delivery and manipulation tasks. These kinds of magnetic helical micromachines are well integrated with the cavities and carry drugs to a specific location within the body. So their precise control allows a localized delivery without damaging the surrounding tissue.

As far as cell biology is concerned, it is used for the manipulation of cells and biological samples, and as far as lab-on-chip is concerned, these microfluidic systems are highly useful for microfluidic transport and analysis. So this is a kind of configuration that is being deployed for magnetic helical micromachines. With reference to medical integration with endoscopy, this endoscope-assisted magnetic helical micromachine, combining visual guidance with precise magnetic actuation for biofilm eradication in sensitive structures like the tympanic membrane and ocelli, is considered to be one of the key applications of such a magnetic system. The system combines a helical micro-robot and an endoscope, a magnetic actuation unit with a robotic arm, and a specialized catheter. So, the endoscope is used to visualize and deliver the helical micro-robot via a catheter to the targeted site and remotely actuate the micro-robot using a programmed magnetic field to perform the biofilm eradication task, which is considered to be one of the key challenges.

So basically, this is a kind of schematic treatment procedure for biofilm eradication in the T-tube in a tympanic membrane under endoscopic surgery. Now, let us discuss the different fabrication techniques that are being used for such kinds of magnetic helical-based systems. So one is a kind of direct laser lighting that enables precise fabrication of helical structures. Another one is through physical vapor deposition techniques since we need to add a certain amount of magnetic coating for appropriate actuation. Then, there is also a possibility to have a kind of two-photon laser printing that generates a complex geometry with high resolution within the system.

Some of the challenges and limitations involve scaling up fabrication methods for mass production while maintaining consistent performance. It has precise control, and its localization means it has an absolute position error of 2.35 plus or minus 0.4 mm in the in-vitro models and 2.6 mm in ex-vivo environments. From the perspective of performance limitations, there is a difficulty in balancing competing requirements such as motion speed and drug carrying capacity. A stability of a magnetic control system has varying fluidic properties, such as temperature fluctuations and spatial constraints that impact the magnetic field's uniformity and effectiveness. From a biocompatibility perspective, it is highly biocompatible, has good safety considerations, and has a reliable recovery mechanism. It also has a reliable retrieval method for safely removing tasks from the completions. So, some of the future trends of such a magnetic helical system are; it enhances the biocompatibility for in vivo applications.

Basically, it is a kind of biodegradable material that can safely dissolve after completing the therapeutic mission within the body. Integration with AI for autonomous operation aims to incorporate decision-making capabilities that would allow the micro machine to navigate complex biological environments and respond to changing conditions independently. Exploration from a perspective point of view; it is used for the exploration of new materials like graphene for improved performance, such as smart materials that can respond not only to magnetic fields but also to environmental stimuli such as temperature, pH, and chemical signals. From a multifunctional capability perspective, it is capable of sequential operations such as targeted navigation, magnetic nanoparticle retrieval, and programmed dual drug release, as well as magnetic actuation with other stimuli like focused ultrasound and near-infrared light to trigger specific functions at predetermined times; significantly, it is also used for enhancing therapeutic efficiency. So, these are some of the references. We will discuss the manipulation of microsystems for microrobotics with reference to the manipulation perspective in the upcoming lecture.