Micro Robotics

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Lecture 58

Inspired Micro Robots (Propulsion and Locomotion) - Module 01

So, in the last class, we discussed the different biomimetic-related systems. where we discussed this gecko robot and the overall mechanism involved in the gecko robot, including the locomotion and related applications. And we have also discussed some of the key adhesive-related mechanisms that were involved in these kinds of gecko-based robots. So, in today's lecture, we will discuss this magnetic swimming micro robot. So, as far as these magnetic swimming micro-robots are concerned. So, these are a class of microscale robots that navigate and operate inside the human body using an external magnetic field. We can have control over the locomotion by applying an appropriate magnetic field to this system so that we can move these objects appropriately. So, these robots are particularly useful in targeted drug delivery, minimally invasive surgeries, blood clot removal, and a certain amount of microscale diagnostics. In fact, this is a kind of AI-generated image, which will give you a clarity similar to how these magnetic swimming robots are deployed for different applications. Like it includes a kind of rotating flagellum.

These rotating flagella are mainly meant for a kind of drug delivery. So, it can be emphasized that it is a kind of targeted drug delivery using the system. We will have different parameters involved, which can be appropriately addressed by these magnetic swimming micro robots. So, as far as locomotion on this micro scale is concerned. Before going into the magnetically based micro robots, there is a need to understand the phenomenon behind this microscale locomotion influence. So, in this regard, it is important to consider the Reynolds number when studying the propulsion mechanism in the fluidic environment. So, as far as these Reynolds numbers are concerned, these Reynolds numbers are defined by the density, the velocity, the characteristic length, as well as the viscosity.

$$Re = \frac{\rho v L}{\mu}$$

When we construct this Reynolds number, it is a measure of the ratio of inertial to viscous force in a liquid. For small Reynolds numbers, which are Reynolds numbers less than 1, the inertial forces become negligible, and the viscous force ideally dominates. However, at a micro scale, both U and L are small, and even in water, which is not viewed as a viscous fluid itself, the Reynolds number is much smaller than 1.To understand how these microorganisms move in water, we would have to imagine ourselves swimming in a pool of honey or tar. It then becomes intuitively obvious that the swimming techniques must be adapted to be able to move in such a viscous environment. So, these are some of the points that we may need to consider. Now, when we try to look into the inertial term, without the inertial term, the flow can be described by the Stokes equation. So, ideally, if we look at the parameters of the stroke equation, it depends on the pressure.

The velocity field of the fluid and the external forces on the fluid are considered. So, this is the overall Stokes equation.

$$\nabla p = \eta \nabla^2 \boldsymbol{U} + \boldsymbol{f},$$

This equation is only exact for Re = 0, but it is considered a valid approximation for Re less than 1, and it does not contain any kind of inertial terms, making the flow perfectly reversible. As it is a linear equation, the superposition of fundamental solutions is possible. The direct outcome of the reversibility of the stroke flow is the fact that the motions are perfectly reciprocal, but they do not create any kind of net motion. There is a kind of theorem which we call the Scallop theorem. So, basically, the Scallop theorem is relevant to the selection of the Reynolds number. So, in that particular aspect, it states that as the Reynolds number Re, it is only the geometric configuration that matters, and it is not the speed and the reciprocating motion, which may lead to a net displacement. Ideally, this theorem is only true for r equals 0 and in a fluid with a constant velocity. Now let us see some of the different propulsion mechanisms of microorganisms and analogous artificial propulsion systems of magnetic microdevices.

If we observe closely, we can classify these microorganisms into three categories. One is a kind of planar flexible tail, another is a kind of helical rigid tail, and the third is called cilia. When we try to look into this planar flexible tail, it is a kind of beating of a flexible flagellum, and it is called Spermatozoa. It has a kind of tail that is available over here. This tail will create a kind of propulsion. Ideally, when we try to talk about micro devices, for example, let us consider this as a micro device that is meant for targeted drug delivery. It has a kind of top head and base, and then we have a kind of movement for an appropriate system. We will have a planar beating that moves back and forth. Next, we can talk about the rotating, rigid, helical flagella, which are actuated by a molecular motor. An example of such a system is called, and it is derived from a system which is a kind of E.coli bacteria.

These E. coli bacteria cause a rotation in this system with reference to the movement of this spring-like structure; this rotation will help us create locomotion in a particular direction. Now what happens is that there is going to be a contraction and expansion that is exhibited in this rotary movement, owing to which there is going to be a kind of translation mechanism that is exhibited here. Either it has a kind of theta orientation, which exhibits, or you can also have a kind of x and y movement that can be used for the motion of the system. Now, we have cilia, which is a kind of organism called paramecium. So, as far as this cilium is concerned, there is a certain number of small nodes that are available. The main functionality of these small nodes is that when they get actuated, they have the capability for movement. This is a kind of cilia structure which is exhibited. Paramecium is a very good example of this kind of cilia structure. Now, let us talk about the other with reference to the micro device perspective point of view.

This is a kind of flexible beam actuated by a torque at a spherical head. The moment of the flexible beam is actuated by a torque with respect to this motion. Then this talks about the rotating rigid helical tail that is fixed to a magnetic head. So, what happens is this rotation moves at an appropriate moment. This can be used to move the structure in a particular direction. As far as these artificial cilia arrays are concerned, it has flexible micro rods or beams. The actuation of this structure will be helpful for us to achieve appropriate locomotion, which is expected. When we try to talk about the materials that are used for this magnetic robotic perspective point of view. We have a material type that is called a magnetic nanoparticle. Some of the examples include Fe_3O_4, iron oxide, or cobalt-based structures, which are used for these magnetic nanoparticle-based applications.

Then some of the key purposes basically include that it provides external controllability. With reference to a biocompatible perspective, there are certain biocompatible polymers. Some of the biocompatible polymers ideally include PEG, PLGA, and hydrogel, and the main purpose of such a biocompatible structure is to ensure a safe interaction with body fluid and tissues. Then the most important perspective point of view is the soft and flexible material. These elastomers are shape-memory alloy polymers. It helps with smooth movement and takes care of the adaptability of the structures. Now let us see the overall working principle of these magnetic swimming micro robots. These magnetic swimming micro-robots are fabricated with magnetic materials like iron, cobalt, or nickel-based nanoparticles. They are being exhibited; they respond to an externally applied magnetic field to generate a kind of control motion. So, this movement is achieved via magnetic torque or oscillation, or a helical rotation mimicking biological microswimmers, such as bacteria and sperm cells.

There are different types of magnetic actuation. One is called a helical propulsion, like you might have seen with a rotating corkscrew when we try to rotate it under a magnetic field. As far as this corkscrew is concerned, it will have a programmed path, and when we try to apply a magnetic field appropriately, this square screw will rotate, resulting in a kind of movement. Some of the examples are bacteria where we have the equally magnetotactic bacteria which are being established. Then, in addition to this, we have a flexible tail oscillation. As far as these flexible tail oscillations are concerned, the major mechanism involves a wave-like tail moment under an oscillating magnetic field. Some of the examples basically include a sperm-like motion. And then when we try to talk about the other type, where we have the surface rolling or walking system. As far as these mechanisms are concerned, it has magnetic adhesion, which enables a kind of surface climbing inside the vessel or tissues. Some of the examples in this include a bacteria-like crawling that is exhibited here, or some of the examples that exhibit.

So, this is how the actuations are classified overall, and the propulsions are classified appropriately for different applications. This is the overall notation of such a kind of magnetic-based propulsion, which we have discussed earlier. This is a kind of helical propulsion with exhibits, and this is a kind of flexible tail oscillation. Basically, the moment of the oscillation is termed here. If we have an oscillation something like this, we can have control over the moment as well as theta. Similarly, the Celia micro robot also has an oscillation in this particular direction for appropriate movement. In the case of a helical micro robot, we have a helical kind of structure. So, this kind of helical structure will appropriately expand and contract. The expansion and contraction will have a kind of influence on the overall movement of the structure. Now, let us see some of the applications of such a kind of magnetic robot.

As far as these magnetic robots are concerned, they are widely used for targeted drug delivery. So, like these micro robots that deliver the drugs, which are directly affected by tissues or tumors, which reduce the side effects. It is highly used for minimally invasive surgery, which is used for precise micro-scale interventions inside arteries, eyes, and the digestive tract. It has potential applications in this cancer therapy. So, when you try to consider a cancer therapy, it can carry the chemotherapy drugs directly to the tumor and increase the treatment effectiveness. From an application perspective, blood clot removal is considered to be one of the applications where micro robots break down clots inside the blood vessels, preventing strokes or heart attacks. And then when we try to talk about the cell and tissue engineering. These micro robots help in cell transport as well as tissue regeneration and are some of the key applications of this biomedical magnetic-based actuation in the field of biomedical-related applications. Now, let us discuss some of the challenges that are observed with reference to this magnetic swimming micro robot. One of the major challenges is the biocompatibility issues.

Use of biocompatible coatings like PEG, hydrogel, or biodegradable polymers to make the micro-robot, which is safer for medical use. And the second point is with reference to control and precision. Implementing AI-based real-time control and optimizing the external magnetic field for adaptive navigation is considered to be one of the key solutions for control and precision. Next is the removal after use. So, we can design a biodegradable micro robot that breaks down naturally or use an external magnetic field for guided retrieval, which can be considered one of the key aspects. Next is drug release control. Use a stimuli-responsive drug carrier that releases drugs in response to pH, temperature, or external signals. Next is with respect to SWAM coordination. The implementation of a kind of SWAM intelligence algorithm for synchronized and autonomous movement is considered to be one of the key challenges that can be addressed with reference to this magnetic perspective point of view. Now, we will discuss the acoustic actuated micro robot. So, in the previous cases, wherever we had a magnetic base, it is appropriately used for targeted delivery.

From a biomimicking perspective, these are the three different proportions that are well explored and are being implemented for targeted drug delivery applications. Now let us discuss the acoustic actuated micro robot. As far as these acoustic actuated micro robots are concerned, the principal operation of these acoustic actuated micro robots is ideally driven by sound waves. Typically, sound waves in the ultrasonic frequency range are ideally considered for such kinds of acoustically actuated micro robots. So utilizing these acoustic forces for propulsion and manipulation, as we have discussed extensively in the earlier modules, is important.

Here, we will be focusing on acoustic-based actuation, in particular towards biomimicking-related applications. As far as the mechanical perspective point of view is concerned, they move through the mechanism like acoustic streaming, radiation forces, bubble oscillations, or resonance-induced vibration. As far as the key advantages are concerned, it offers a remote wireless control. The most important aspect from a perspective point of view is that it can operate in complex fluids, as it can be manipulated or propelled in the region of blood or biological media, making it a kind of minimally invasive system. From an application perspective, it has potential uses including targeted drug delivery, microsurgery, biosensing, environmental monitoring, and micro-assembly related structures. With reference to material choices, as far as these particular aspects are concerned, from the acoustic actuation perspective, there are certain sets of materials that we may need to consider for appropriate movement. These micro robots are often fabricated from biocompatible materials like polymers, metals, or composites to ensure safe interaction with biological environments. From a navigation and control perspective, precise motion control and swarm behaviors are easily achievable by tuning acoustic parameters like frequency and amplitude and using a phased array or pattern field. From a perspective point of view, some of the key challenges include controlling micro robots individually in swamps, achieving propulsion efficiency at small scales, and ensuring stability in variable biological conditions. Some of the recent advances are integration with other actuation methods, such as magnetic field and light, and the development of smart and multifunctional robots to enhance performance and versatility.

These are considered to be some of the recent advances regarding these particular systems. Now, let us discuss the overall classification of these acoustic actuated micro robots. So, when we try to classify these actuation-based micro robots based on acoustic actuation, we can classify them as a bubble propulsion system, a sharp edge propulsion system, and in-situ micro rotor-based acoustic actuated micro robots. Let us discuss in detail the mechanism and the principle involved in it. So first let me discuss bubble propulsion. As far as these bubble propulsion perspective points of view are concerned, like we discussed in our earlier micro propulsion mechanism, by creating a greater amount of high-frequency bubbles, we can create a kind of propulsion that can exert. For example, let us consider a kind of floating object by giving a bubble from the backside as well as from the side. Appropriately, we can have a kind of control over the manipulation of that floating object. In fact, let us consider the floating object that seems to be some kind of structure, something like this, where there is a kind of drug being kept in it, and it is a tube or capsule-like structure. In this capsule-like structure, by inducing a bubble in this particular direction appropriately, we can achieve manipulation.

As far as these bubble propulsions are concerned, they have a long-lasting armored micro bubble under a force vibration. Let us consider this as the structure. So, this structure comprises two different tubes. One is a short tube and the other is a long tube. There are two bubbles: one is a center bubble in the short tube, and there is an inner bubble along the long tube. There is a magnet which is also being placed in such a way that whenever there is a kind of deviation or precise control that needs to be implemented to capture the propulsion, then electromagnetic waves are deployed into it. If you closely observe the overall mechanism that is described in this schematic. Let us consider the payload system as follows. Basically, this is a kind of small micro robot that has the targeted drug placed over here. By applying a magnetic field as well as a forced vibration from the microbubble appropriately, we can observe a moment when these particular capsules move in a specific orientation or along a particular path.

These are called long-lasting armored microbubbles that are being manipulated using a force vibration-based system. Now let us discuss the sharp edge propulsion system. As far as the sharp edge propulsion system is concerned, these are the different configurations that are available under the sharp edge propulsion system. Ideally, in this system, we have a kind of structure that is placed over here, and then the overall control over the propulsion velocity and the wave velocities is appropriately maintained. With reference to propulsion, velocity is concerned, as it is manipulated or propelled by the wave velocity, which is a kind of sharp object. In order to get a kind of no moment condition, ideally, we may need to go for such a feature, or in case we need to move in a direction. So we may need to have a wobbling kind of arrangement. This wobbling will have two sets of configurations. One is in the form of a clockwise direction and the other is in the form of an anticlockwise direction. Moving or wobbling in both clockwise and anticlockwise directions.

So we can expect a kind of propulsion in a forward stroke. When we try to observe the overall schematic, this is called helical wave propulsion; in fact, we discussed this in the last module. Then it is a kind of micro-scale swimming robot with a type of wave propulsion. These are some of the different designs with sharp edges. These sharp edges will be a point of contact with the microbubbles. When microbubbles start interacting with sharp objects appropriately, we can observe a kind of propulsion that can be easily monitored using this system. This is a kind of configuration that is called sharp-edge propulsion. Now this is called an in-situ micro rotor. As far as this in-situ micro rotor is concerned, the overall configuration, such as the shape of this micro rotor, can appropriately create a kind of micro bubble propulsion in different orientations. Appropriately, we can expect a kind of angular displacement that exhibits in this micro rotor. Wherever we are more concerned about the angular rotation, such kinds of sensitive micro rotors are deployed.

In this particular case, we have a pillar-like arrangement, and there is a need to take care of the micro streaming. We have a microbubble that is being placed, and there are some sharp-edged corners that are available. At the sharp edge corners, we have a micro bubble that will start interacting at the sharp edge corners. So appropriately we can expect a kind of a rotation which exhibits. This rotation will try to propel the targeted drug in an angular rotation form that can be used for a kind of targeted drug delivery. In certain cases, this can also be used for micro-rotation, or a kind of vortex generation can be created using such structures. Now let us discuss the different types of propulsion, especially with reference to acoustic-based systems. As far as this acoustic-based system is concerned, when we try to classify the propulsion type, we have a bubble propulsion system. The overall principle involved is that bubble vibration produces a source of net momentum. From an advantages perspective, it is fast and has a strong propulsion.

With reference to a disadvantaged perspective point of view, it has narrow frequency selection ranges, and bubbles may burst, and it might be a hand-operated system. As far as sharp edge propulsion is concerned, the sharp edge vibration generates propulsion, a wide frequency selection range, and simple manufacturing operations. With reference to a limited positional perspective point of view, it has a kind of low propulsion. Wherever we have a limitation in the propulsion, we will be using such a kind of sharp edge propulsion. Next, with reference to the in-situ micromotor perspective point of view. This is also similar to sharp edge propulsion, but there is a kind of fixed axis in the center. There is a kind of in-situ propulsion and low fluid influence, which it exhibits. With reference to a disadvantaged perspective, it can create a complex design. Now let us see some applications related to this acoustic-based system. One of the key applications that is involved is a kind of microfluidic configuration.

Let us consider a kind of PDMS structure or a PDMS channel that is placed here, so there are some fluorescent particles present. The main motto of this particular structure is that the fluorescent particle has to reach a particular portion, and it has to stick to some layers. For instance, a tissue is affected by cancer, and if we need to have a kind of imaging, we may need to appropriately propel this fluorescent particle. We direct the fluorescent particle directly to stick to the tissue, so that it gets stuck to the tissue, and appropriately we can have a kind of emission coming out of it. This is a kind of bubble region that is a PDMS structure, and these bubble regions will take care of the direction as well as propulsion of these structures to achieve the required functionality. This is a kind of microsurgery, so it is a bio-inspired acoustic magnetic microswarm. In this particular case, there are some bacteria and then there are bio-inspired structures that are available. In order to create a kind of acoustic-based structure, a piezo transducer is used. This piezo transducer will vibrate at a high frequency, and this frequency will create a type of vibration that is a pressure node existing from this pressure node.

There will be a kind of force that will be generated from it. This force is capable of transferring the structure from one particular portion to another. Ideally, there is a kind of shear flow that participates in this, and then there will be a capillary structure that will participate in it for an appropriate moment of the flow. In the next module, we will discuss the bio-inspired febrile-based adhesive structures, how these structures work, and how these structures activate with reference to different configurations. Let us discuss the details in the upcoming lecture.