Micro Robotics

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Week 11

Lecture 51

Bio Inspired Micro Robots (Propulsion and Locomotion) - Module 01

We are in the 11th week, and we are going to discuss this bio-inspired micro robots. As we all know, these bio-inspiring-based structures or bio-inspiring-based systems have their own fascination. The second important aspect with respect to this bio-inspiration perspective is that it is a kind of proved concept. So already it is a well-established, nature-adapted proven concept, and it has its own advantages with reference to particular locomotion, system development, or system functionality, etc. So, with reference to that, it would be better if we could understand the overall behavior of it, and based on that, we could pursue a biomimicking capability to incorporate some of the key aspects involved in this bio-inspired design. Then we try to implement it appropriately in an engineering domain so that we can use it for different applications, like you might have heard about this sunflower tracking the sun.

So, this is one of the bio-inspired concepts, which is being catered to by different solar panels where they also follow a similar concept of tracking the sun. From the bio-inspiring perspective, let us look into the micro-robotic domains. With reference to micro robotics, we can take up different micro activations and different micro sensing elements from this bio inspiration and then appropriately implement them. This particular module is highly focused on this bio-inspired micro robot.

Basically, as far as the key content of this bio-inspired micro robot involves micro-scale propulsion, it also includes locomotion in a liquid. In most cases, we have seen that these micro robots are effectively used for drug delivery-related applications. So with reference to a biomedical perspective, there is a need to understand these biomimicking-based locomotions in the fluidic environment, which we will be discussing in this particular module. With reference to the modeling perspective point of view, let us discuss the key technical aspects involved in the modeling of this propulsion system. So, we will be discussing this in detail with reference to different domains, including the mechanical domain, the electrical domain, the fluid domain, etc.

We have been discussing UAVs. However, with reference to a biomimicking perspective point of view, there are some micro robotic structures that work on the principle of micro mechanical flying insects. So those structures can also be effectively used for different applications, especially for a micro aerial perspective point of view. So, let us look into the mechanism of it and let us look into the complete detail of it with reference to different functionality. Now, as far as this particular module is concerned, first we will focus more on this microscale propulsion. As far as these microscale propulsions are concerned, it is similar to when we try to talk about nature. Nature consists of numerous solutions to overcome challenges in designing artificial systems. There are various actuation mechanisms that have been implemented in microrobotics to mimic the motion of microorganisms. So such bio-inspired design has contributed immensely to micro-scale development. Among the actuation mechanisms, magnetic actuation, which we discussed in detail in the earlier modules, is widely used in bio-inspired micro-robotic systems.

Especially from a propulsion perspective, such a micro magnetic-based system has smooth propulsion, which is considered to be one of the key advantages, and it also has the flexibility to be used for different complex structures. So, these micro magnetic-related propulsion mechanisms used by micro robots, which can be navigated using an appropriate magnetic field, can also be analyzed. In addition to this, considering the robots are at a micro scale, they can swim inside a fluidic environment with a low Reynolds number. So in relation to micro robots mimicking a kind of bacteria or a kind of fish, it has its own significance. Now, with reference to a micro robotic perspective, we have the bacterial flagella, the sperm flagella, cilia, and fish, which are significantly considered to be prospective candidates for analyzing micro propulsion in a micro robotic system.

So due to this fact, these biological matters consist of a different propulsion mechanism. So in this particular model, we will be discussing in detail the different micro propulsion mechanisms that have been exhibited by such kinds of micro robotic structures. How these micro robotic structures are effectively used from a different functional application perspective. How these robots are designed and developed to navigate in a complex environment such as the human body for medical applications or for confined spaces in the case of a microengineering task. Second, with respect to micro-scale propulsion in bio-inspired robots, it is a crucial area, particularly for applications targeted towards drug delivery.

The minimally invasive surgeries, as well as the environmental monitoring, of such micro propulsion mechanisms are exhibited. These tiny robots basically operate in a low Reynolds number regime where the viscosity dominates over inertia, requiring a specialized propulsion mechanism that is inspired by biological organisms. Now let us see the first case study, which is like a bacterial-inspired flagellar and ciliary propulsion mechanism. As far as these bio-inspired mechanisms are concerned, especially with reference to such a bacterial system, macro-scale robots have mimicked the shape and locomotion of biological species. This mimicry is challenging when the size of the robot is reduced.

However, due to space limitations, placing an actuator inside the robot is very challenging. These challenges have been addressed by using an untethered actuation mechanism such as magnetic actuation. Apart from that, the domination of viscous force highlights the requirement of non-reciprocal motion for a Newtonian fluid. When we try to talk about the mimicry of motion. The first mimicry of motion with reference to a micro-robotic perspective is the bacterial flagella, sperm flagella, cilia, and fish, which have shown a promising solution to control micro-robots in the low Reynolds number flow regime.

We will be discussing the overall motion of these living organisms, analyzing how it actually works and how to adapt it in micro robotic applications or from a micro robotic perspective. As far as this bacterial flagellum is concerned, this is the kind of bacterial flagellum. It is inspired by this bacterium called E. coli and other motile bacteria that use a rotating helical flagellum for movement. These magnetic or electrical fields are often used to drive these artificial flagella. There are some examples, such as helical micro robots that rotate under an external magnetic field. These bacteria are a kind of living organism that can move inside a lower Reynolds number fluidic environment. A helical-shaped filament called a flagellum is used. This is a kind of flagellum that is used by the bacteria for locomotion. When we try to look into the key technical aspect of this flagellum, it has the capability to rotate at 100 hertz by a rotary motor connected to the cell body.

It acts as a kind of biomimicking motor, resembling a whip, allowing it to rotate at a frequency of 100 hertz, which will be helpful for appropriate locomotion. These rotary motors and flagella are connected through a short flexible hook, which is shown over here, and it has an arrangement that is almost similar to a kind of universal joint. In general, the diameter and the length of the helical flagellum are about 20 nanometers in diameter and 3 to 10 micrometers in length. These are some of the key characteristics of systems like flagella-based systems and artificial flagella-based systems. We will discuss more insight in detail.

When we try to look at the overall design perspective. Many computational models have been developed. To analyze the swimming dynamics of this artificial flagella, we need to consider having a kind of whip that is rotating at a high frequency of around 100 hertz. We may need to understand the parameters that are involved, and we may need to translate those parameters appropriately for our micro robotic system. These swimming dynamics of an artificial flagellum are what we are terming micro swimmers.

The model accounts for fluid-structure interaction between the deforming swimmer and the surrounding fluid while incorporating the applied magnetic field. Now, if we closely observe the equation behind this, the mathematical framework basically integrates solid mechanics, fluid mechanics, and magnetostatics. When we look at the solid mechanics perspective, the flexible polymer film undergoes deformation due to external forces. With reference to a fluid dynamics perspective, the fluid drag is modeled using a Stokeslet-based boundary element method. With reference to the magnetostatic perspective point of view, the external magnetic field generates magnetic body couples that influence propulsion.

Now, if we closely observe the overall equation that is involved, we have Km, the material stiffness matrix. Kg is the geometric stiffness matrix, and Kd is the drag matrix. Now, del D is considered to be a kind of displacement increment, F external is a kind of external force which exhibits, and F internal is a kind of internal force which exhibits.

So, when we try to equate it,

$$(K_M+K_G+K_D)\Delta d=F_{ext}-F_{int}$$

Since we have already discussed these dimensional parameters to describe the interplay between elasticity, viscosity, and magnetism. Three key dimensional numbers are identified with reference to these bacterial-inspired flagella, or it is a kind of ciliary proportion. So we will discuss the ciliary proportion in the upcoming lectures. It is almost similar to a bacterial-inspired flagellum. Now, but it works on the principle of a magnetic field. Here we have three different systems and three different parameters that we are considering.

One is a fraction of the magnetic field. Then we have the magnetic number. These are highly catered towards the propulsion perspective point of view. With reference to the type of fluid, we use the fluid number. Now, as far as this particular magnetic perspective point of view is concerned, let us discuss the fraction of the magnetic film.

Fraction of Magnetic Film:

Lo/L

When we try to look into the fraction of the magnetic film, we need to consider two important parameters. One is the length of the magnetic portion, and the other is the total length of the film. So, this fraction of the magnetic film is the ratio of the length of the magnetic portion to the total length of the film. When we try to look into the fluid number perspective, it is represented as Fn equals

Fluid Number (Fn):

$$F_n=(12\mu\omega/G)\ WL^2/h^3$$

Basically, it represents the ratio of fluid drag to elastic forces, where μ is the fluid viscosity, ω is the angular frequency of the rotating field, and h is the thickness of the swimmer. Now, the fluid level changes with reference to the domain, to which we are constrained in relation to the different fields we are limited by. So in certain cases, if you are considering oil as a domain, these parameters will be exhibiting based on that. If you consider something like a biomedical fluid as a domain, then the appropriate parameters will be incorporated. Now we have a magnetic number which we term Mn. In this magnetic number, M is the permanent magnetization, B is the magnetic field strength, G is the shear modulus, H is the thickness of the swimmer, and W is the width of the swimmer.

So basically, it represents the ratio of magnetic to elastic forces, where m is the permanent magnetization, b is the magnetic field strength, and g is the shear modulus. With reference to thickness and the swimmer's perspective, this is the relation that is followed, which basically states that,

Magnetic Number (Mn):

$$Mn= (12\ MB/G)\ (LW/h^2)\ (Lo/L)$$

So, we are considering the magnetic number as well as the fraction of the magnetic field. Now, let us discuss the other parameters that contribute to magnetic swimming or the perspective of magnetic actuation, highly focused on bacterial-inspired flagellates or ciliary proportions. In this particular case, the swimming motion is chirality-induced, meaning it is a kind of helical shape that forms dynamically due to computing magnetic torque or fluid resistance.

Almost the system looks something like this. We have chirality-based structures, which can take care of the overall fluid resistance at the expense of the magnetic torque. So, here if you closely observe the magnetic forces per unit volume, it is given by

$$N=M\times B$$

N represents the magnetic body couple acting on the structure. B is considered the magnetic field strength. In this particular case, since we are considering the chirality-induced structures, the twisting angle theta comes into the picture. In order to model this twisting angle theta, the twisting angle theta follows the form of torsion theory, which is nothing but theta

$$\theta = TL/GJ$$

T is the applied torque, G is the shear modulus, and J is the polar moment of inertia. If we try to equate it, we can come up with this relation, which basically gives the overall twisting angle that will be highly helpful for locomoting the structures based on our requirement. Now, in the earlier case, we have been talking about magnetic actuation and chiral shape formation. Now, we will discuss the different parameters that contribute to swimming velocity and directional control. As far as the perspective of swimming velocity is concerned, the swimming velocity is derived using resistive force theory, assuming a balance of magnetic and hydrodynamic forces. When we try to consider the dimensionless swimming velocity, it is approximated as

$$U_{\text{analytical}} = \omega \theta_{\text{max}} W^2/12L\ (C_{dh}/C_{dL} - 1)$$

where, since we are considering the swimming velocity, the properties of the overall fluidic domain need to be appropriately incorporated. So in that aspect, we have C_{dh} and C_{dL} as the drag coefficients in the width and length directions, respectively. C_{dh} corresponds to the drag coefficient along the width, and C_{dL} corresponds to the drag coefficient along the length.

This mathematical model effectively describes how a flexible, polymer-based artificial swimmer can be actuated using a magnetic field. The computational approach basically provides key insights into optimizing swimming velocity, controlling directions, and tuning the magnetic and fluidic properties for real-world applications. Some of the applications include the targeted drug delivery and the micro robotic applications. Now let us discuss some of the key outcomes of this system. We closely observe these bacteria, bacteria-inspired flagella, and ciliary propulsion, as they have potential applications, especially from a bio-inspired micro swimmer perspective.

Basically, it presents a kind of artificial microswimmer that can mimic bacterial propulsion through magnetically driven chirality-induced motion. Now, when we try to look into the computational approach, a computational model was developed to analyze the swimming dynamics and constrain the interaction between the elastic, viscous, and magnetic forces.

Now, if we closely observe the perspective of magnetically controlled motion, the micro-swimmer's movement is regulated by an external rotating magnetic field influencing its chiral shape and swimming velocity. Now, with reference to the dimensionless parameter perspective, when we try to look into the dimensional parameters that are identified. So the key dimensional parameters that govern the propulsion were identified, including the magnetic, viscous, and elastic contributions, which are considered to be the key parameters contributing to the dimensionless parameter-based system.

Now when we look into the other key outcomes, some of the key outcomes basically include the viscosity-induced versus magnetically induced chirality, where we have a two-propulsion mechanism that is compared. One is a kind of viscosity-induced chirality and the other is magnetically induced chirality, with the latter providing an advantage for bidirectional motion. In this particular case, we have a kind of bidirectional swimming that is achieved; it is a novel design used for two magnetic sections with opposite permanent magnetization, which allows for forward and backward swimming by reversing the magnetic field rotation. When we try to look into the influence of a fluid dynamics perspective, the microsumer's performance is strongly affected by a type of fluid force, with higher viscous forces leading to shape deformation, and it also has an impact on the reduced velocity. This is exactly where, if you see, we have the drag force that contributes to this picture, which appropriately has a resistance to the overall flow.

When we look into the fabrication feasibility perspective, the micro swimmers can be manufactured using inkjet printing and photolithography, which makes them viable for real-world applications. Now, some of the applications basically include, in the case of microfabrication and micro-manipulation perspectives, these kinds of fabrication feasibilities are deployed. Now, when we try to look into the applications from a biomedicine perspective, these micro swimmers hold potential for biomedical applications that basically include targeted drug delivery and micro-object manipulation, particularly in the form of lab-on-chip devices. Now, let us see the overall fabrication that is being deployed with reference to these micro robotic perspectives. Whenever we are trying to fabricate these structures, one of the key aspects that comes into the picture is how these actuations are being deployed and how it is being fabricated in the form of a resin.

These are the different steps involved in fabricating a type of paramecium-based micro-robot, which is designed for a cilia-based robot, and the overall fabrication involves a laser coupled with a lithography process. So here in this particular case, like in most of these cases, either photolithography or rapid prototyping is deployed. If you try to look into the features, they are in the range of 60 micrometers and 75 micrometers, and these are some kind of structures that are being built over here. In order to have appropriate actuations at certain times, shape memory alloy structures are also being deployed. Here we could see a kind of shape memory alloy structures that are being deployed here, effectively contributing to the structure.

In these shape-memorialized structures, we have a lead kind of behavior; this lead kind of behavior gets actuated, and appropriately, it can be used for movement. In this particular structure, we are concerned when we try to closely observe, so there are two important aspects that basically contribute to locomotion. One is called a kind of power stroke, and the other is called a recovery stroke. In both cases, either it is a power stroke or it is a recovery stroke; it is actuated using a kind of locomotion. In fact, this is a kind of ciliary-based micro robot where we have a type of locomotion.

So as far as this locomotion is concerned, we have two different types of locomotion that contribute to it; one is called a power stroke, which is used for propulsion in a forward stroke. Then we have a recovery stroke where there is going to be a lift, just as there is going to be a push or a recovery, which will take care of the micro-precise locomotion exhibited here. Now let us discuss the actuation force evaluation which is being deployed in this magnetic actuation, basically for the ciliera base lobe. As far as this particular case is concerned, the cilia beating cycle regenerates a net translational force due to the difference in the magnetic actuation force between the power stroke and the recovery stroke. So, let us consider the selenium angle theta and the magnetic force F acting on the xy plane to calculate the in-plane translation force in the celeria micro robot.

When an external magnetic field is applied along the long axis of the micro body at an angle with a gradual increase from 0 to 90 degrees. If you see in this particular case, at one particular point the cilia are bent, and in another particular case, the cilia are moved in a particular stroke. So here we have the cilium angle theta and the applied field direction, which is 0 degrees in the recovery stroke, and the force generated due to the difference between the maximum serial angle and zero degrees. So ideally, to calculate the actuation force, we assume the serial angle is zero degrees. After one beating cycle, the magnetic torque Tm of a cilium with an external magnetic field is described as Tm equals m times B, where m is the magnetic moment and B is the magnetic field intensity.

Now, this has a maximum value when the magnetic field is applied orthogonally. So the equation of the magnetic force on the longitudinal axis is simplified with the duration as two. One is like a backward stroke, which we call a power stroke, and forward we call a recovery stroke. So, we have the cilium length L and the field angle gamma. The actual cilium angle, which can be represented as F equals mb sine minus theta L, is considered only in the planar xy plane.

The force component is counted in this calculation, and we can represent it as

$$\theta = TL / EI = mb \sin(-\theta) L / EI.$$

where E is considered to be Young's modulus, I is the moment of inertia. The relationship between the applied magnetic field direction, represented as gamma, and the cilium angle, represented as theta, is that the magnetic force F is calculated appropriately. So let us see a small set of parameters of the calculated actuation force. So if you try to tabulate it with reference to the parameters, the first parameter we can consider is E, which is Young's modulus and is on the order of 4 GPa, and the cilium width is represented as 4 micrometers, which we can nominate as b. Cilium height is 10 micrometers; we can denote it as H, which is around 10 micrometers, and cilium length L, which is around 75 micrometers, and from a magnetization perspective, it is around 686,000 amperes per meter. The volume V can be represented as $B \times H \times L$, and the moment of inertia I is $B \times H^3 / 12$, a magnetic field intensity b which can be represented as 10 mT, and the magnetic moment m, which we call $V \times m$. So, these are the parameters that are being considered for calculating the actuation force. This is just to give you an overview of an equally based propulsion. What are the parameters involved with reference to this equally based propulsion? We have discussed the different key outcomes and the overall fabrication process equally, as well as the cilia-based propulsion. So, in the next class, we will discuss the Jellyfish Inspired Jet Micropublisher.