

## **Micro Robotics**

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**Lecture-52**

### **Bio-Inspired Micro Robots (Propulsion and Locomotion) - Module 02**

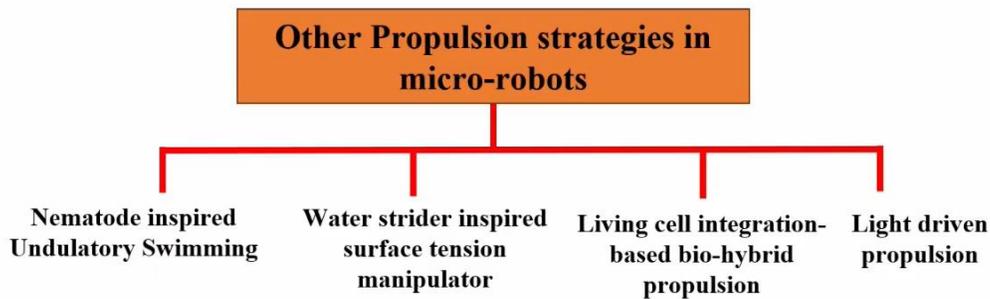
We have been discussing the micropropulsion mechanism. Specifically, we have discussed bio-inspired micro-robots, various microscale propulsion mechanisms, and the need for these mechanisms. In the micropropulsion mechanism, we have discussed this bacterial-inspired flagellar-based micropropulsion mechanism and a ciliary-based propulsion mechanism. And we have also discussed some of the key parameters that are involved with reference to bacterial-inspired flagellar propulsion. We have discussed in detail the different configurations involved in this bacterial-inspired flagellar system. Furthermore, we discussed the different dimensionless parameters that are involved, the magnetic actuations, the overall swimming velocity, and the direction controls.

We have discussed in detail the key outcomes of these systems, the different fabrication steps involved in these systems, and the parameters related to force perspective, magnetic propulsion, and actuation, in detail. Now, here we will discuss the other propulsion strategies in micro robots. In propulsion strategies, we can classify micro robots into four categories. One is called a nematode-inspired undulatory swimming motion.

It is a kind of propulsion-based system. And the water strider-inspired surface tension manipulator, living cell integration-based bio-hybrid propulsion, and light-driven propulsion. In bio-inspired models, we will be discussing in detail these kinds of propulsion mechanisms and how they are deployed for different applications. In nematode-inspired undulatory swimming, it mimics the movement of worms. It has a small aquatic organism that makes wave-like body motions.

It is achieved using a soft actuator that deforms and responds to stimuli such as light or an electric field. In nematode-inspired undulator swimming actuators, electroactive polymers are efficiently used for such kinds of nematode-inspired structures. Now, inspired by water striders' surface tension, it takes advantage of the interfacial force to move efficiently on the liquid surface. It is a kind of small aquatic life, like a small micro worm, which tries to move in stored water or in stagnant water. Such a kind of propulsion is inspired by a nematode-type system.

On the water strider surface, it tries to stick to the water, or it tries to float on the water. Hence, we can see the forces that are being generated through which these robots alter the surface tension gradient, temperature, and chemical release. So, these are effectively used actuators based on the surface tension gradient as well as the temperature gradient. In living cell integration-based bio-hybrid propulsions, it mimics the function of living cells, such as muscle cells, sperm cells, or bacteria, as actuators. There are different examples, like a bacterial-driven micro robot, which is effectively used for targeted drug delivery, so it almost mimics a microorganism.



It almost has a structure similar to that of a muscle cell or a sperm cell, and it can move in a particular direction. Here, we will be discussing algae-based propulsion. Then we will discuss the light-driven propulsion system. In this light-driven propulsion system, a light-responsive material is used to generate movement in a micro-scale robot. Some examples of these light-driven propulsion systems are called soft micro robots that bend or contract when exposed to a specific light wavelength. So, when a light falls on it, it appropriately bends or contracts, and a kind of actuation is exhibited. In locomotion in liquids, this movement and the liquid are known as aquatic locomotion or swimming locomotion. So, if we closely observe the movement of an organism in this liquid medium, it can occur by swimming or by moving in contact with the bottom or other surfaces. Some of the examples of aquatic motion include fish, arthropods, mollusks, amphibians, reptiles, birds, and mammals, which are used for movement. If we closely observe the overall mechanism, let us take an example of cilia and flagella.

They have the simplest propulsion system for aquatic locomotion. When we look into the undulatory swimming perspective, this involves wave-like bending of the body that travels down the body axis. When we want to discuss the active drag perspective point of view regarding swimming or paddling concerns, the limb or tool that generates propulsion also creates drag. Then it is used for initiating such a micro propulsion system. Now, if we look into the overall fundamentals that are involved in locomotion in liquid at a small scale, we can consider the Reynolds numbers of the stokes law.

These Reynolds numbers are represented as  $Re$ , which is a kind of dimensionless parameter that determines whether a flow is dominated by inertia or viscosity. So, if we look into the key parameters that are involved,  $\rho$  is density,  $v$  is the velocity,  $l$  is the characteristic

length, and  $\mu$  is the viscosity. For micro robotics, the Reynolds numbers are always expected to be less than 1, which means the inertia is negligible compared to the viscous force. Most importantly, the flow is linear and time-reversible. It is a kind of reciprocal motion that does not generate a net displacement.

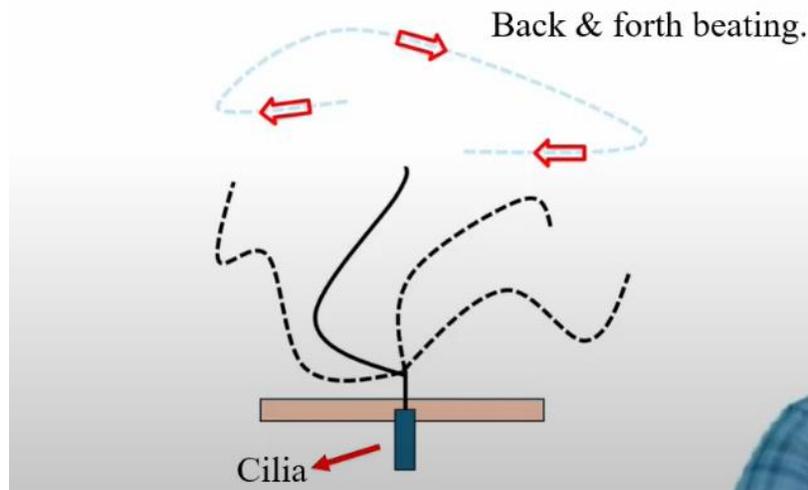
### □ Reynolds Number and Stokes Flow

The **Reynolds number (Re)** is a dimensionless parameter that determines whether a flow is dominated by inertia or viscosity:

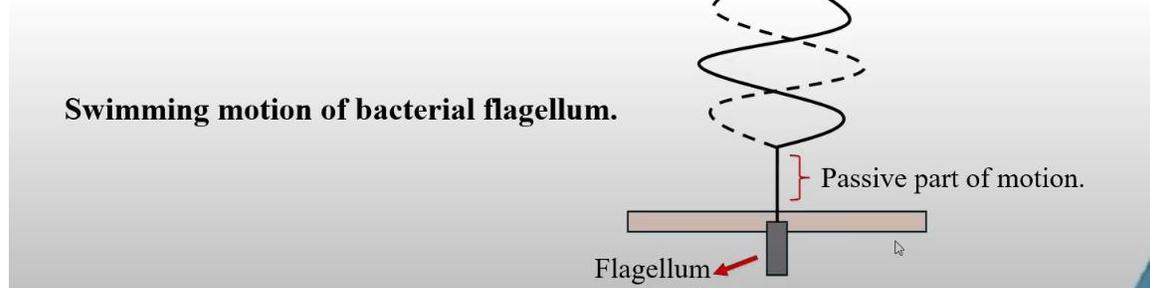
$$Re = \frac{\rho v L}{\mu}$$

Here,  
 $\rho$  = density  
 $v$  = velocity  
 $L$  = characteristic length  
 $\mu$  = viscosity

In movement perspective point of view, the movement must follow a non-reciprocal strategy, which we call the scallop theorem. Now let us discuss in detail the locomotion of such kinds of micro robots, especially in a liquid environment. The first locomotion that we are going to discuss is called flagellar propulsion, which is a kind of helical swimmer. These flagellar propulsions or helical swimmers are basically inspired by bacterial flagella. This method uses a kind of rotating helical filament from a propulsion point of view. The key principle involves a bacterium such as *E. coli*, which uses a rotary motor to spin a helical flagellum, creating a kind of screw-like motion through the fluid. So these microrobots mimic this mechanism by using artificial magnetic flagella that rotate under an external magnetic field. Some examples of such systems basically include helical magnetic microrobots or soft artificial flagella.



If we look into the propulsion mechanism or the overall key systems, there is a flagellum in place.



Then, there is a passive part of motion and a kind of propeller mechanism. So this propeller mechanism rotates and creates a kind of swimming motion for bacterial flagella. In fact, we had discussed that the overall frequency generated from the structure is close to 100 hertz. It is capable of generating appropriate swimming behavior. Now in the cilia-based propulsion mechanism, it is called ciliary beating.

It is inspired by the paramecium, which uses a coordinated beating of tiny hair-like cilia. In the last model, we have seen a structure, something like a kind of hair. This hair is used for appropriate propulsion or appropriate actuation for forward movement. When we look into the principal, these cilia move in an asymmetric manner, and it is a kind of time-inversible pattern. A power stroke pulse pushes the fluid, generating a thrust, and the recovery stroke brings the cilium back to its initial position with minimal resistance.

So this motion breaks the time and the reversibility. It always enables the propulsion in this particular system. There are different examples; one is called a magnetically actuated cilium and the other is called an electrically driven cilium. So, in the case of magnetically actuated cilia or in the case of electrically driven cilia, there is going to be propulsion that takes care of the back-and-forth beating. Now let us discuss magnetic field-driven propulsion.

In this magnetic field-driven propulsion, it utilizes an external magnetic field to manipulate a micro robot embedded with a magnetic nanoparticle. From the principal point of view, it has a rotating magnetic field that causes a screw-like motion in the helical robot, and an oscillating field drives the cilia-like beating or a kind of undulatory movement. With reference to the gradient perspective point of view in the magnetic field, it creates a pulling force that enables the direction of the motion. Some examples of these helical magnetic swimmers, or magnetically steered microrobots, featured a kind of soft-headed structure. So these helical robots have a spring-like structure.

When the spring rotates, we can expect a kind of linear displacement. So we call it a car screw-based system where rotary actuation is converted into linear motion. Now let us discuss flexible or undulatory swimming. From a flexible or undulatory swimming perspective, it is inspired by eel-like or spermatozoa-based locomotion, where it travels like waves along the body, creating thrust. So the principle of a flexible filament or a soft



body, which propagates undulatory waves along its length, interacts with the surrounding fluid and generates a kind of forward motion. So, in the case of a micro device and microorganism, some examples, like electroactive-based swimmers and thermally actuated-based swimmers, are the key propulsion systems that are effectively used for creating such flexible or undulatory swimming. Now, from the application perspective of these micro-robotic liquid motions, they are effectively used for biomedical-related applications. The biomedical-related application includes targeted drug delivery, where it has a magnetically guided robot that can carry a drug to a precise location and can be used



for minimally invasive surgery. So, these microbots can navigate through the blood vessels, or they can be used for some kind of microsurgery. So, in propulsion, it might be a kind of microorganism or a kind of helical micro robot that works especially for targeted drug delivery, where these drugs can be encapsulated at a particular point.

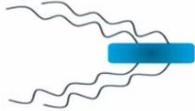
So the locomotions, especially the proportions, are exhibited in such a way that they reach a particular point, and then they will try to release the drug. For those locomotions, such kinds of structures are effectively used. Now, with reference to the minimally invasive surgery point of view, these micro robots can navigate through a blood vessel, or they can also perform some kind of micro surgery. Now, for environmental monitoring, it is highly used for detecting pollutants and contaminants in water. From an environmental monitoring perspective, it is also used for exploring confined or hazardous liquid environments.

From a lab-on-chip perspective, these kinds of manipulated microfluidic flows are used effectively for diagnostics as well as chemical analysis. Now, if we try to make a comparison with reference to these bio-inspired mechanisms used in locomotion, the working window is something like less than 1 mm. It has a traditional means of movement, or it has an additional interdisciplinary field that will be helpful for appropriate locomotion. So, in certain cases, it might be through magnetic fields, pressure, or effective fluid flow.

So, the inertia that is generated is negligible, and here, it is almost a kind of viscosity that is dominant. So, when we try to closely observe the moment, this moment must overcome a high resistance in liquids. So, these kinds of bio-inspired mechanisms are heavily characterized for a kind of low Reynolds number environment. So,  $Re$  is less than 1. Here, bio-inspired mechanisms that are used in locomotion. So one is a bacterial flagellum, the other one is a sperm flagellum, and this is a kind of cilia-based structure.

So in the case of bacterial flagella, the bacteria are living organisms that can move in low Reynolds number fluidic environments. Since it has a kind of helical filament, called a flagellum, it is used by the bacteria for locomotion. So these bacteria have one or more flagella, which are located at the pole or the lateral side of the cell body. This is a kind of classification. So we can classify it based on the number of flagella and the placement of the flagella.

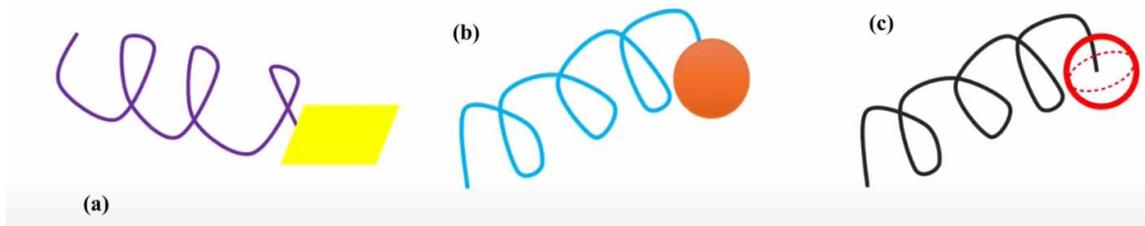
In bacteria like *E. coli*, which use a kind of flagella to swim effectively at lower Reynolds

Type	No. of Flagella	Placement of the flagella	Layout
Monotrichous	1	One Pole	
Peritrichous	>2(more than two)	Lateral	
Amphitrichous	2	Two Poles	
Lophotrichous	>2(more than two)	One Pole	

**Classification of the bacteria according to the placement of flagella.**

numbers, this is considered to be one of the critical parameters for their movement mechanics, which involve rotating a helical filament via a rotary motor. It is also powered by a kind of proton motive force or sometimes a kind of sodium ion gradient. In fact, these proton motive forces or sodium ion gradients are a kind of chemically stable structure. So, these chemically stable structures heavily participate in the structure to create locomotion. In this particular case, we have different rotation directions that involve forward tumbling.

It is a random orientation generated from these structures. Now let us discuss the different classifications of bacteria according to the placement of the flagella structure. If we closely observe, there is a monotrichous-type structure. So in the case of a monotrichous type structure, it is considered to be a one-flagellate where the placement of the flagella is at one pole. The overall layout looks like this: one pole is where it is placed.



There is another type which we call the peritricus base structure. In the peritricus base structure, two or more types of flagella are present. So the placement of the flagella is lateral. In this configuration, there are two or more flagella present. There is a third type, which we call the Ampetriaticus type flagella structure.

It has two flagella; basically, it has two poles that can be used for appropriate rotary movement, as well as appropriate linear movement. Then we have the Lopotricose base structure, which has more than two flagella. As far as the placement of the flagella is concerned, it has one pole, and the overall layer looks like a structure; these structures are effectively used for locomotion. So these are some classifications of bacteria according to the placement of the flagella. Now, these micro robots that mimic the Monotrichus bacteria can be classified as micro robots with a head or without a head.

These micro robots, having both a head and a tail, are fabricated using a magnetic material that improves the magnetic effect. Because of the nature of the helical structure, these magnetic robots can swim inside these fibrous environments, which lead to an in vivo experiment. To classify this helical microrobot, there is a soft magnetic head. We can classify the structure based on the type of magnetic head. One is called a soft magnetic head, which has a kind of flexible structure.

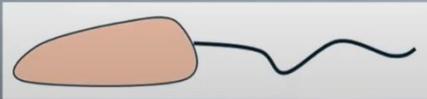
There is a small micro holder in place. The main function of the micro holder is to take care of the flexible movement and the spherical head. Even though locomotion is taken care of by this helical micro robot, from any perspective point of view the directions are well oriented with reference to such kinds of soft structures that are being applied. So it has a soft magnetic head, small micro holders, and then a kind of spherical holder that takes care of the locomotion. Now if we look into the application in real world micro robotics, it is used for biomedical applications, ideally for a targeted drug delivery where micro robots swim through the blood or tissue to reach the cancer cell. It is heavily used for minimally invasive surgery as it has the capability to navigate inside the human body for diagnostics, or it can be used for a kind of micro-intervention.

From a biofilm disruption perspective, these micro robots can destroy harmful bacterial colonies. For these applications, such structures can be deployed. From an environmental point of view, this is highly used for pollutant reduction and chemical cleanup. These flagella-inspired swimmers carry a sensor or a cleaning agent so that they can be used for pollutant detection, and they can be used for the cleanup of the structure. Now in water quality monitoring, these have autonomous navigation in a confined environment, allowing them to move in an appropriate fashion to collect these structures. From an advantageous point of view, these flagella-based micro robots are a kind of efficient swimming, and even in a viscous environment, they have high maneuverability and good directional control. It has a kind of energy-efficient propulsion with minimal mechanical complexity, which is considered to be one of the key aspects. From a scalable perspective, it is scalable to a nano or micro scale. Next, discuss this sperm flagellum. The sperm flagella mimic the animal sperm, which are motile main reproductive cells.

- The shape and propulsive performance of the tail depend on viscous forces.
- Sperm number,  $S_p = L(\xi_{\perp} \omega/A)^{1/4}$  can be used to describe the relative magnitudes of these forces.

Here,  $L$ ,  $\xi_{\perp}$ ,  $\omega$  and  $A$  are the length, transverse viscous drag, angular frequency of the driving action, and bending stiffness of the flexible tail, respectively.

- Also, **Transverse viscous drag** =  $\xi_{\perp} = 4\pi\mu[\log(2L/d) + C]$ , where:
  - $\mu$  = dynamic viscosity.
  - $d$  = tail diameter.
  - $C$  = constant (often taken as 0.5)



These motile sperm have a beating tail like flagella to propel themselves through the fluids. These human sperm cells beat at a frequency of 10 to 30 hertz, which varies depending on environmental conditions. These human sperm also have a swim velocity of around 50 micrometers per second, a beat amplitude of around 5 micrometers, and a beat wavelength of around 12 micrometers. So the shape and the propulsive performance of this tail depend upon the viscous force. So, this is an equation that is being deployed with reference to the sperm number perspective point of view; basically, it is a biological relation.

From the biological relation, a kind of mechanical relation is being derived. From a biological perspective, the different parameters involved are  $L$ , which takes care of the length, a transfer, a viscous drag, and an angular frequency that participates in the driving action and the bending stiffness of the flexible tail. So these can be used to describe the relative magnitude of these forces. Now, from the perspective of transverse viscous drag, a contributing dynamic viscosity is involved. There is a tail diameter that is being considered and certain constants that are being accounted for in this particular system. From an application perspective, they are highly used for reproductive medicines like assisted fertilization, especially in cases of male infertility and guiding sperm toward the egg in vitro. In the most important cases, it is highly used for targeted drug delivery. So these micro robots mimic a sperm to swim to a specific tissue where a tumor or a uterus is located, and then they are used for a targeted system. So, this is useful for localized delivery

in a narrow as well as a fluid-filled environment. From an advantageous point of view, the key feature is a wave-like motion that benefits smooth propulsion in a viscous medium.

It has a soft, flexible body that is safe for interaction with living tissues. It is highly biocompatible, so it is suitable for a kind of in vivo application. With respect to directional control, it has good directional control that is achievable via external fields. From a feature perspective, it is highly efficient and mimics one of nature's most optimized swimmers. So these are some of the characteristics that have been granted and engineered for microrobotic development.

<b>Feature</b>	<b>Benefits</b>
Wave-like motion ✓	Smooth propulsion in viscous media. ✓
Soft, flexible body ✓	Safe for interaction with living tissue.
Bio-compatibility ✓	Suitable for in vivo applications. ✓
Directional control ✓	Achievable via external fields. ✓
High efficiency ✓	Mimics one of nature's most optimized swimmers. ✓

So in the next session, we will discuss the cilia-type propulsion in detail.