

## **Micro Robotics**

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**Week -11**

**Lecture-51**

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

This is the last module of this micro robotic course, where we are going to discuss the bio-inspired micro robots. This bio-inspired robot is at a slightly advanced level compared to the earlier model. Here we discuss some important case studies where it works on the principles of bio-inspired locomotion or bio-inspired related mechanisms. This content comprises the gecko-inspired climbing robots, bio-inspired febrile adhesive robots, lizard-inspired water runner robot, water strider-inspired water walker robot, and a magnetic swimming micro robot for biomedical applications. We will also discuss some medical micro robots for endoscopy and other applications. Further, we will discuss some of the key challenges involved in these biomedical-based robots, micro robots, or in the domain of biomimetic-based micro robots. Now, in bio-inspired robots, these bio-inspired micro robots represent a field that takes inspiration from biological organisms to design and develop small-scale robotic systems. These micro robots have been proposed for future biomedical applications, in which they can navigate in a viscous fluidic environment. Nature has inspired numerous micro robotic locomotion designs that are suitable for propulsion at low Reynolds numbers. We have seen different types of locomotion that have been catered to the biome, which have been addressed by the micro robotic system.

So, the various swimming methods, with particular focus on helical propulsion including the *E. coli* bacteria, can mimic its propulsion characteristics. There are various magnetic actuation methods for biomimetic and non-biomimetic micro robots, such as rotating fields, oscillating fields, or field gradients. So, when we try to closely observe the mechanisms, we can classify these mechanisms under the rotating field, the oscillating fields, and the field gradient. They can also be categorized as force-driven actuation or torque-driven actuation. In force-driven actuation or torque-driven actuation, torque-driven actuation scales better to the micro and nano scale than force-driven actuation. Now, if we try to closely observe, the need for studying these bio-inspired systems is concerning. It is always considered that nature has been an inspiration for robot locomotion in the form of swimming. It is a kind of wiggling motion or sometimes a need for walking or flying. One of the main challenges in engineering the locomotion methods of robots is to copy or mimic the essential functions of their natural counterparts while keeping the complexity low in order to build the system.

So building complex devices becomes increasingly difficult on the micro and nano scale because the integration of various parts is more challenging, and it is therefore crucial to capture the essential functionalities of nature while keeping the complexities minimal. In micro robots, when we propose these micro robots for certain drug delivery-related applications or biomedical applications, or sometimes when we propose them for minimally invasive procedures, or when projected for targeted drug delivery or in vitro cell manipulation and characterization. Most of these applications use these micro devices in a fluidic or soft environment with reference to different applications in which they have to be propelled. So, propulsion is considered to be one of the key factors for the movement of the system. It is therefore natural to investigate the locomotion method at a micro scale in nature for inspiration when building these micro robots. We had discussed earlier the actuation of the micro robot, an electrostatic-based system, and magnetic-based systems, etc., which are coupled in this particular arrangement. Now, biomimicking capability, with reference to a microscale point of view, starts from the bacterial aspect. It can mimic some of the structures from living organisms, including a lizard, etc. In Gecko, we will be discussing a type of lizard that we can mimic the overall mechanism of, and based on that, we can see how the system moves.

Now, from these bio-inspired motions, these micro robots mimic the locomotion and help in sensing and adaptability of microorganisms, insects, and other biological systems to operate efficiently in a microenvironment. So these are AI-generated micro-robots that provide information about locomotion. So, in this case, there are jellyfish-based micro robots, bacterial-based micro robots, jelly-inspired micro robots, flagella-based micro robots, etc. This is a kind of imagination that talks about how such flagella-based systems can be deployed. However, when we try to look into the overall fabrication, it has its own challenges because fabricating such structures has its own challenges. Now, what is the need for going to such bio-inspired designs? Nature has evolved highly efficient microscale locomotion, sensing, and adaptive strategies over millions of years by studying biological organisms such as bacteria, insects, and microorganisms. Especially with effective mobility, for example, a bacterium uses a flagellum for propulsion. This flagellum for propulsion will be discussed in detail. If you closely observe, the flagellum there has a passive part of motion and an active part of motion over here. So the active part of motion comprises a flagellum, which is like a swinging arrangement that tries to create a certain amount of force, and this force will be helpful for the exertion of locomotion.

This swimming motion of the bacterial flagellum, where the passive part is mainly meant for holding, involves these particular propulsion motions. So, if you clearly observe this propulsion motion, where the system rotates in a particular direction, this propulsion motion will create a kind of elliptical force. To understand this elliptical force, suppose this system is inside a water body and a kind of propulsion is generated. Therefore, a vortex motion will be generated. This vortex motion will be helpful for appropriate locomotion. So when this vortex motion is generated, it makes the body move in one direction, or sometimes it will be helpful for the targeted system to propel in a particular direction. We will discuss in detail the different types of proportions that have been exhibited with this flagella-based system. Next is the smart sensing. So, as far as these smart sensors are concerned, some of the key examples include the antenna for environmental perception, like you might have seen in a cockroach; a cockroach has an antenna-like structure. So,

these antennas are mainly meant for sensing the antibodies that are available next to them or the enemy system that is attached to them. Once they send a signal, they may automatically rush away. So the antennas are there, which are used for smart sensing applications. In fact, the antennas themselves and their functionalities can also be studied and explored to investigate the overall behavior of this type of micro robot. Besides, there are different energy-efficient mechanisms where biomimetic muscle actuation is observed. In this case, there is a structure that will try to open and close.

When it tries to open and close, it gets actuated and propulsion occurs. So this is an energy-efficient mechanism that has adaptability in complex environments. In certain cases, we may need to use such kinds of micro robots for biomedical-related applications. In certain cases, we may need to use these biomedical robots for inspection-related applications. Sometimes it may need to flow in a liquid environment, sometimes it may need to flow in an air environment or in a cloud-based environment. So when we are trying to design the mechanism or when we are trying to train the mechanism, we may need to ensure that a certain amount of adaptability is employed and that this adaptability is capable enough to cater to the complex mechanisms. Some of the soft-bodied organisms navigating confined spaces are examples of bio-inspired design. Now let us discuss the different locomotion mechanisms. In this particular case, there are some biologically inspired micro robots that have a certain locomotion mechanism. If we consider the bacterial and flagella-based swimming, which is used for designing a micro-robot that can move in a helical manner, ciliary movement is observed, which we call paramecium movement.

So this is a kind of ciliary movement. Here, a propeller-like mechanism was observed, similar to what we have in a helicopter. When the fan rotates over the helicopter, it tries to generate a kind of motion that would be helpful for forward or backward movement; sometimes, it can also be helpful to create Z-axis movement. Similarly, in order to have a back-and-forth movement, we may need to opt for ciliary movement. The cilia movements, which are called a paramecium-based system, are applied for micro robots that require surface interaction and coordinated movement. So, it's like you have a whip when you try to move it. The base is kept fixed. However, the whip is designed to move in a particular direction. Based on the movement of the whip, a force is generated that helps the base to move. So, this is a combination of back-and-forth beating.

When we have a back beat and a forth beat, accordingly we can expect a kind of forward motion or backward motion. So a certain amount of vibrations arise. These vibrations are encased in the form of a displacement. This is called a kind of back-and-forth system or cilia-based movement. Now another set of locomotion mechanisms includes insect-like walking and jumping. These kinds of mechanisms are inspired by grasshoppers. So if you see a grasshopper, it has a kind of legged structure. It tries to give a push from the base towards an anti-gravity structure. So it is like against gravity; it tries to move. It will give a kind of jumping nature that results in motion. So, like we have a base. Over the base, the grasshopper is sitting and then it tries to jump and fly towards the moment. So, this kind of inspiration happens with reference to grasshoppers for terrestrial microrobots. It is also used by ants. In ant structures, when they try to move, they have a kind of walking behavior and a kind of jumping behavior. So, walking and jumping will be deployed on the ant.

Now a certain set of locomotion mechanisms was observed, which is called jellyfish and soft-bodied motion. So, if you closely observe a jellyfish, it has tentacle-like structures. These tentacle structures are very soft, lightweight, and flexible. These tentacle structures can create a kind of push or pull force appropriately. So, in jellyfish or in an octopus, this tentacle behavior will either create a kind of cilia-based motion or a flagellum-based motion. A flagellum-based motion can be deployed for rotary movement, or cilia-based motion, which can be deployed for a kind of forward stroke. So, in jellyfish structure, there is a kind of bigger layer or a heavy-headed system followed by a simple system, so that these simple systems are capable enough to give a thrust to the system for appropriate movement. So, these are some kinds of basic classifications. Now, let us discuss sensation and perception. So, in sensory systems, we have a kind of compound eye insect that is a miniaturized optical sensor for micro-robots.

In the sensory system, we have discussed the sensors that are used in micro robots. In fact, we have classified different types of sensors; from a biomimicking perspective, there are certain limitations or challenges in selecting the sensors for these biomimicking-related applications or biomimicking-related work. So, the sensor selection basically depends on the type of adaptiveness that is considered for this micro robot. Secondly, the propulsion of the micro robot also plays a vital role in selecting the sensor as well as in implementing the number of sensors in the structure. So, in that particular aspect, when we try to consider a compound eye in an insect-based system, we have a miniaturized optical sensor for micro robots.

Then there are electroreception-based sensors. These electroreception-based sensors are mainly meant for a touch feel, like when an external object starts coming near a kind of amphibious structure. Automatically, their responsiveness increases. Such a kind of electroreception, which is identified in some fish and amphibians, is explored. Appropriately, such mechanisms or such sensory functionalities are deployed, which are used in bio-inspired underwater Microrobotics applications. So, in addition to this, there is a type of tactile sensor, which is a type of touch sensor. For example, in the case of spider hairs, they have antennas, which we have discussed. When we see a cockroach, it has two antennas, which are mainly meant for tactile sensing. So, when some kind of object or body comes near it, these antennas will detect and appropriately give feedback to the environment in a micromanipulation task. So, these are mainly meant for sensing the overall functionality as well as the overall behavior.

So, it is mainly used for environmental feedback in a micromanipulation task. One of the key challenges with reference to these biomimicking micro robots is energy actuation. There are different types of energy that are being used to activate these robots. We have discussed this kind of energy actuation. With reference to a biomimicking perspective, it has its own aspects. For example, in the case of energy actuation, there is a magnetically actuated robot. This magnetically actuated robot is inspired by bacteria that align with the Earth's magnetic field; basically, it is a kind of magnetotactic bacterium. So, a magnetic compass is aligned for a particular direction. Similarly, such bacteria also align with the magnetic field. Therefore, we can tailor the locomotion based on our requirements.

Next is light-driven actuation, which is a kind of mimicking of plant phototropism at the moment. Here, we have the capability to control the frequency of light. So, turning the light on and off will be helpful for us to provide appropriate locomotion in the system. This actuation can be easily controlled using this light-driven actuation. Then there is a soft robotic structure using a shape memory alloy. In this mechanism, we have integrated a shape memory alloy for inspired actuation. It might either be an octopus or a kind of jellyfish that has been deployed for movement. One of the important case studies with reference to this biomimicking perspective is the gecko-inspired surface climbing robot. The gecko-inspired surface climbing robot was first established in 2004 by one of the key groups involved in this, which was Carlin Menon City. They were involved in developing this Gecko-inspired robot.

Later, these kinds of robots were taken up in a different ship. So, people started working on this inspiration and they have developed different mechanisms from it. In fact, they have drawn different mechanisms from this gecko, and they have implemented them in different robotic systems for various applications. Concerning these Gecko robots, many applications call for robots to perform tasks in workspaces where a traditional vehicle cannot reach. So, using a robot to perform this task can provide better human safety as well as low-cost operation. So, in this case, we have a robot that can operate on vertically oriented surfaces, allowing the possibility of automating the tasks that are currently accomplished manually. So, affording an extra measure of human safety is often a more cost-effective manner. Some of the wall-climbing robots that are used in industry today are for cleaning high-rise buildings, etc. They are performing inspections in dangerous environments such as storage tanks for petroleum industries and a nuclear power plant. In fact, there is more interest in using robots to inspect and repair these space vehicles as well.

From application aspects, one of the major features is a lizard-like structure. For lizard-like structures, if we can mimic a lizard's structure, it has some capability to climb the wall, and then appropriately, manipulator operations can be performed. So, This is one of the key mechanisms involved in this activation mechanism, which is being placed. So, when we try to relate to an actual lizard, a lizard possesses naturally built functional surface textures that enable it to walk and climb on versatile topographies. To bio mimic the surface characteristics, we may need to look into three important mechanisms. One is biomimicking the surface characteristics, the second is biomimicking locomotion, and the third is biomimicking suction. So, biomimicking the surface characteristics of these geckos has enormous potential to improve the accessibility of modern micro-robots. Therefore, these gecko-inspired adhesives have significant industry applications such as biomedical cleaning, medical bandage tapes, rock climbing adhesives, and tissue adhesives. So, we need to discuss the different adhesive properties and then the different elastomeric properties in detail. We have classified the different types of adhesive mechanisms that are followed by this gecko-inspired clamping.

So, if you closely observe the overall mechanism of this particular gecko-inspired climbing robot, it has a different fiber in place. This is called a gecko foot fiber, which we call setae. In this gecko foot fiber, it has a kind of micro and nanoscale. So, it has nanofibers and microfibers in place. These microfibers integrated with nanofibers are kept in such a way that they act as a kind of compliant mechanism with a high aspect ratio, which we can call

a beta keratin structure at their feet. So, if you closely observe the feet of a lizard, you can see some kind of integrated roughness. So, these roughnesses are sufficient for the lizard to create suction. We call it a beta keratin structure at their feet, and these geckos can manage to adhere to almost any kind of surface with a controlled contact area. This is one advantage of these gecko structures. The gecko-inspired climbing robots use the principle of dry adhesion, mimicking the gecko's ability to climb smooth surfaces like glass and walls.

So, these dry adhesions will be helpful for them to walk or climb on glass or any kind of slippery surface without any issue. These robots ideally use a kind of water wall force, which is used in a specialized material such as microstructured polymer adhesives to achieve adhesion without leaving residue. So, this is one advantage of using this system. Now the question is, why geckos? These geckos can climb vertically on a smooth, even, and inverted surface due to a special structure of their feet, and this adhesion is based on the setae, which are a kind of microscopic hair-like structure. These geckos' feet have a million nanoscale hairs, which we call setae, and each splits into 100 subtula-shaped tips.

From nano, we have a multilayer fibrous layer, which takes care of the adhesion with reference to the surface. Now, if we need to mimic this structure, we may need to develop such structures so that we can have control over the adhesion and appropriately control the movement. Now, one of the important mechanisms that cater to this adhesion includes the van der Waals forces. As far as Vander Waals forces are concerned, these subtle tips interact with the surfaces via weak intermolecular forces, allowing for strong yet reversible adhesion.

This will allow the structure to be held. Next, with reference to the directional adhesion perspective, the gecko can detect its feet effortlessly by changing the angle of its toes. So these are the three different mechanisms that is being followed by the geckos for the different adhesion. We will discuss the different mechanisms involved in gecko-inspired climbing robots in the next session.