**Microrobotics**

**Prof. Palani Iyamperumal Anand**

**Department of Mechanical Engineering**

**Indian Institute of Technology, Indore**

**Week- 12**

**Lecture No- 59**

# Bio Inspired Micro Robots ( Integrated Approach) - Module 04

We have been discussing the different bio-inspired propulsion methods and have discussed the different actuation behaviors that are involved. One of the bio-inspired processes is this febrile adhesive. As far as this fibrillar adhesive is concerned, let me just introduce you to this particular concept. We have discussed the different types of adhesive in the last lecture. However, this is slightly specific, and it has an impact and almost mimics a lizard or a kind of spider structure. Ideally, if we observe the mechanism in a lizard or in a spider, there are technologies that exhibit such behavior.

As far as these bio-inspired fibrillar adhesives or synthetic adhesion systems are concerned, they mimic the micro and nanoscale structures found in nature, such as gecko feet, insect pads, and spider silk. We have discussed in detail the adhesive mechanism in geckos. However, this particular mechanism is more focused on insect pads and spider silk. These adhesives do not require glue or suction but rely on Van der Waals forces and capillary interaction or electrostatic adhesion, making them reversible, reusable, and highly efficient for robotics, biomedical, and industrial applications.

When we investigate the overall mechanism of this, we have different membranes with nanochannels being placed, and inside these nanochannels, we have adhesive liquid being filled. The adhesive liquid will act as an interactive medium. These bio-inspired fibrillar adhesives work based on the physical adhesion principles rather than the chemical bonding. The mechanisms include van der Waals forces, capillary adhesion, and mechanical interlocking. Ideally, we have discussed more about this van der Waals forces, which play a key role in the adhesive perspective.

The effectiveness of these adhesives depends on the micro and nano structure of rubbers, material properties, and surface interactions. When we talk about these van der Waals forces, especially with reference to dry adhesion, these van der Waals forces are weak intermolecular attractions that occur when molecular dipoles interact at a very short distance. In the case of fibrillar adhesives, it has microscopic fibers that increase the contact area with surfaces and enhance the adhesion. In fact, we had discussed a small structure where there are some kinds of fibrillar structures like gecko feet. We have discussed it in detail and some of the key characteristics; that is, these are dry and irreversible.

So, there is no glue required for it, and it has an easy attachment as well as an easy detachment. With reference to the directional adhesion perspective, the adhesion is strong when pulled in one direction and weak when pulled in another direction, like a gecko peeling its feet as it tries to detach from the surface. Now, when we try to talk about capillary adhesion, which is a wet adhesion mechanism, this capillary adhesion relies on the liquid bridges between the fibrillar structure and the surface, creating adhesion via surface tension and capillary force. For example, if we keenly observe how the tree frog moves, it basically relies on a liquid bridge between these structures, which we have also seen in the earlier slide. The liquid bridge will try to interact with the structure, and it will have a hold over the surface so that interaction is obtained. When we investigate the key characteristics, it works in humid and wet conditions. Unlike Van der Waals adhesives, which fail in wet environments, these are kind of soft and flexible, so they can adapt to uneven and rough surfaces as well. It is pressure-sensitive adhesion, and it can be tuned by adjusting the liquid viscosity. When we look into the interlocking mechanism, instead of relying on molecular forces, interlocking adhesives physically grip onto rough surfaces using a febrile microstructure. Some examples of interlocking mechanisms are beetles and spiders.

The key characteristics include high strength adhesion. So ideally, it is used for heavy load applications. As far as roughness is concerned, it works on rough surfaces, unlike van der Waals forces or capillary adhesives. From a durability and wear resistance perspective, it is designed for long-term usage. Some of the key design features of these fibrillar adhesives are hierarchical fibrillar structures. It maximizes the surface contact for strong adhesion, like gecko-state directional adhesion, and it allows easy detachment when needed, as well as the gecko's food peeling motion. As far as key features include the self-cleaning ability, when we look into its function, it prevents dust and debris accumulation. Some of the bio-inspired examples include the kind of gecko city regeneration and a water-resistant design perspective. It maintains adhesion in humid environments, like how a tree frog or the insect pack works. Like this, it maintains adhesion and has a soft, flexible material. It enhances the capability of a curved surface. It is one of the key advantages where we could observe with reference to this tree frog's footpaths.

Now let us discuss some of the factors that are affecting this adhesion performance. One of the factors basically includes the surface roughness, where Van der Waals adhesives work best on smooth surfaces and interlocking adhesives perform better on rough surfaces. From an environmental condition perspective, humidity plays an important role, and the capillary adhesive performs better in a humid environment. As far as dust and contamination are concerned, these van der Waals adhesives may lose efficacy as and when required based on the different environmental conditions. With reference to the material property perspective, these are soft elastic materials that improve adaptability and have a nanostructure with increased surface contact area. So these are some of the key properties that come into play with reference to adhesion performance. Now, let us see some of the applications of these bio-inspired fibular adhesive structures. One important application is the climbing robot.

If we are designing a gecko-based robot, these robots use gecko-inspired footpaths for wall climbing. So, there are several examples. In fact, there is a NASA-based gecko, i.e., NASA has developed a gecko gripper robot, which is used for some space-related applications. With reference to the biomedical device perspective, when we talk about the working, these soft adhesives replace the harmful glues in surgical patches and bandages. Some examples include a gecko-inspired wound dressing, and with reference to the space application perspective, these fibrillar adhesives help astronauts grip objects in zero gravity. So, this is one good application where NASA dry base adhesive technologies are being deployed. From a manufacturing and assembly perspective, it maintains adhesion in a humid environment, and some good examples include robotic arms for microchip handling, where adhesion-based structures can be deployed. From a wearable sensor and prosthetic perspective, these enhance adaptability to curved surfaces and are used in smart bandages and biosensors.

Some of the key challenges observed in this fibrillar adhesive are loss of adhesive overtime, which includes the use of self-healing materials to restore the fibrillar structures, scaling to a larger load, designing a multilayer febrile array to contribute weight efficiently, and dust and contamination buildup. To develop a self-cleaning, fibrillar-like gecko, feed is one of the established solutions. With this as a fundamental, let us now discuss a lizard-inspired water runner robot. As far as these lizard-inspired water runner robots are concerned, this is a good example showing a chameleon-based lizard. If you closely observe this, we may need to mimic three different portions of this water runner robot. One portion is the head portion, the other portion is the abdomen portion, and the third portion is the portion that is used for pushing it forward. The overall buoyancy and equilibrium are maintained by the head portion as well as the abdominal portion. The abdominal portion takes care of the overall center of gravity, while the head portion has a kind of movement that takes care of the overall direction of the system. In this particular aspect, for this abdominal portion, we can have a servomechanism that will be helpful for continuous locomotion in the system. Similarly, we have a direction mechanism, and the direction mechanism will take care of the overall movement of the structure.

This structure talks about the overall load capability. With reference to the load capability perspective, we can have two sets of motors scattering the limb structure. In this limb structure, we can have one set of motors capturing this particular moment and the other set of motors capturing this particular moment. So appropriately, we can have theta orientation. The theta orientation will give a load that acts as load-bearing motors, so that the load can be easily calculated, and we expect a moment coming out of the structure. As far as this lizard-inspired water runner robot is concerned, it is a biomimetic robotic system designed to replicate the remarkable ability of certain lizards, such as in this operation, and we are considering this basilisk lizard. In fact, this basilisk lizard is used because it is a kind of lizard, and some different micro-robotic structures have been developed using this. So, this basilisk lizard will run across a water surface at high speed. It has the capability to run across the water surface at high speed without sinking. So, these robots leverage principles of surface tension and hydrodynamics.

It is a kind of food-slapping mechanic and lightweight structural engineering to achieve rapid locomotion over the water. By integrating this bio-inspired limb motion, a hydrophobic material, and energy-efficient actuators, robots have potential applications in surveillance. It also has potential applications in search and rescue operations, environmental monitoring, and military-related applications, especially in the case of amphibious areas, basically focusing on water-based terrains. Let us discuss some of the key principles behind the biological inspiration of the basilisk lizard. This basilisk lizard has an extraordinary ability to run on water at a speed of approximately 1.5 meters per second for several meters before sinking and switching to swimming mode. So, this is one advantage. It cannot be categorized directly as an amphibian, but it can be used as a lizard that can walk on the water's surface and can also go for a swim. So if you closely observe the locomotion of these particular basilisk lizards, the key principle behind this unique locomotion ideally includes high-speed limb locomotion. So the lizard's hind leg moves at 5 to 10 steps per second, creating sufficient lift and propulsion to keep it above the water.

As far as these foot slapping and lift generation are concerned, the lizard slaps the water surface forcefully, generating an upward thrust by trapping an air pocket under its feet. As far as the hydrophobic capability of this is concerned, this hydrophobic skin and toes have a specialized scaly food structure, and the hydrophobic skin prevents excessive water drag. When we study the body weight distribution, keeping it at the center of mass forward, the lizard maintains stability while running. In fact, this is what we had discussed when we try to consider it as three different components. So, the overall mass or weight distribution is what we are considering under the abdomen; appropriately, we may need to design mechanisms to take care of the overall equilibrium in these structures.

Then, transitioning to swimming, when the speed decreases, it switches to swimming using a kind of lateral undulation technique, which is considered a biological inspiration. Now, let us consider some of the key components of these lizard-inspired water runner robots. We categorize these structures into two different categories: one is for structural design, and the other is for actuation and locomotion design. So, when we look into the structure and design of the body material, it is an ultra-lightweight material such as carbon fiber and a titanium alloy, and it has a high-strength polymer to minimize weight and maximize buoyancy. As far as these coatings are concerned, it is a hydrophobic coating that does not stick to the surface and does not have any impact on the electronic structure. So the robot surfaces and the feeds are coated with a superhydrophobic, ideally a PTFE-based graphene or a nanocoating, to reduce the drag, similar to the drag in the leg design. When we investigate the leg design perspective, it is a long-jointed length with flexible feet that replicate the foot-slapping motion of the basilisk lizard. In fact, we had discussed the slapping motion and the recovery motion. Here, this leg design will capture the slapping motion for efficient movement. Then we can also talk about a webbed footpad.

These webbed footpads are mainly meant to increase the surface area for maximum lift. Now, when we look into the actuation and locomotion mechanism perspective to replicate the lizard's fast foot-slapping motion, the robot uses different types of actuators that are ideally chosen based on the type of energy density. So we have the electromagnetic actuators, and when we look into these electromagnetic actuators, they are high-speed motors that generate a kind of rapid leg oscillation. Then we have the piezoelectric actuators. As far as these piezoelectric actuators are concerned, they enable a precise and energy-efficient movement. We have shape memory alloy actuators. The shape memory alloy actuators are a type of soft robotic actuator for flexible foot movement. Then we have the bio-inspired joint mechanism. Ideally, it has a kind of adaptive rotational and vertical motion to replicate the natural leg movement. Now when we investigate the propulsion perspective, this hydrodynamic foot slapping creates an air pocket under the feet for lift and forward momentum. It has an adjustable gate cycle. These robots adapt a step frequency and force for different water conditions. When we look into the gyroscopic perspective, these gyroscopic sensors ensure balance by preventing excessive tilting or sinking. Now when we look into the overall power source and energy management, there are micro batteries called lipo-based batteries. They provide lightweight and compact power. When we analyze the wireless power transfer perspective, these systems enable a continuous operation for surveillance related applications.

In addition to this, the system also has a provision for solar energy integration, which enhances autonomy in field operations. Now, if you closely observe the other kinds of systems, like sensor and navigation systems, we may need to look into the different sensors that are deployed for such kinds of navigation. Some of the sensors include the inertial measurement units (IMUs), which monitor acceleration and stability. The optical flow sensor tracks movement relative to the water current, while Lidar and ultrasonic sensors help avoid obstacles in the water environment, and AI-based control systems, which are a form of adaptive learning, allow the robot to improve balance dynamically. When there are two modes of working environments, the robot is made to work in both modes. The appropriate inputs can be attracted, and appropriate decisions can be made using these AI-based control systems. Now, when we are considering the running-on-water environment, ideally we expect that it should have a high-speed limb motion. Ideally, the quantified value is in the range of 5 to 10 hertz, which ensures the robot generates a sufficient amount of lift to avoid sinking behavior. There should be precise foot impact, which timing allows for a forceful water slapping to support the weight. In addition to this, there is a kind of hydrodynamic lift enhancement that ensures the robot can maintain speed efficiently.

When we try to investigate the locomotion mechanism during a transition between running and swimming, if the robot loses speed, it automatically switches to swimming mode. Ideally, when it is running on land and when it tries to touch a water surface, there will be drag generated that will try to slow it down, and once it senses the speed and understands that the speed is getting reduced, it tries to switch us to swimming mode. In swimming mode, we have a lateral undulation with a snake-like movement. It also has propeller-assisted propulsion. In the propeller-assisted propulsion, we can engage induction, which gathers the propulsion mechanism. There is a kind of webbed foot paddling, and this webbed foot paddling has a sensory system that will try to actuate at a frequency so that it will be helpful for the system to move forward. Now when we look into the steering and the maneuvering mechanisms, this asymmetrical leg force application enables a sharp turn in the structure. The yaw control via differential limb motion allows for quick directional changes. The front leg for an additional control, like a kind of rudder in a boat, is ideally used for steering and maneuvering. Now, with reference to the application perspective, it is highly used for military and surveillance applications, such as in water-heavy terrains like river crossings, or it can be used in kind of swamp areas, etc.

It has potential applications for stealth movement in security operations in marine environments, and it also has the capability for autonomous intelligence in gathering information in flooded or difficult-to-access zones. So these are some of the areas where it can be focused on. With reference to environmental monitoring and wildlife search perspectives, it has some sensors that can be integrated, and such a robot can detect the pH, salinity, and pollution levels. Basically, it can be used for water quality assessment. It can be used for tracking the aquatic ecosystem. Thus, studying this waterborne species and the ecological changes can be easily accomplished using the system. And then we have a kind of wildlife surveillance. In this wildlife surveillance, we observe the behavior of a water-bound animal without disturbances. Now, when we try to look into the recreation and educational robotics perspective, it has advanced biomimetic robotic research for universities and research institutions. With reference to the educational perspective, it has an educational kit to teach biomechanics, hydrodynamics, and robotic principles. With reference to entertainment and robotic sport competitions, it is involved in water-based robotic challenges from a recreational and educational perspective. With reference to disaster response and search and rescue operations, it is mainly meant for rapid deployment in flood-affected areas. It is also used for monitoring the submerged or semi-submerged zones to detect the surveyors. It is also used for assessing water pollution and contamination in the post-disaster environment. So, these are some of the disaster responses for which such kinds of robots can be used.

Now let us see some of the challenges that are involved in developing this water runner robot. One of the key challenges is maintaining speed and stability. Achieving and sustaining a speed of over 1.5 meters per second is difficult with excessive energy consumption. In the expense of energy consumption appropriately, we may need to have control over the sustaining speed, and it is used for balancing between the water impact force and the stability, which is considered crucial to avoid tipping over. Next, with reference to the energy efficiency perspective, which is one of the key challenges involved in such a water runner robot, rapid movement requires a high-power input, making battery life a major challenge. Another important aspect is this alternative solution, which includes a wireless charging or an energy harvesting mechanism. This is considered one of the potential challenges that can be addressed by this energy efficiency. Now, with reference to controlling locomotion from varying water conduction perspectives and adjusting to different water surfaces, adaptive AI control is required. Dynamic leg force modulation is needed to maintain speed across a diverse water environment.

So, in the transition from water to land, these kinds of basilisk lizards can move seamlessly from water to land. They are used for replicating these features in robots, which require hybrid locomotion strategies. These soft robotic joints could enable the robot to adapt leg movement based on the different types of terrain as and when it is required. So, these are some of the challenges involved from the perspective of a water runner robot. Now we will discuss the next concept or the next technology, which is called a water strider-inspired water walker robot.

In the earlier cases, as far as this mechanism is concerned, what we have observed is that these kinds of lizards will be on land, and they will try to walk on water. They have the capability to swim in the water and then return to land. So, it has more attraction towards the land than the water. However, we can design a system where it can float on the water. Such mechanisms can be deployed by a type of water strider. As far as these water striders are concerned, they are inspired by a water-walking robot. As far as these water striders go, we have a water strider that will try to float on the water, and it can, so it does not directly swim. It can be used for standing on the water's surface and for movement on the water. The water-walking robot is a kind of bio-inspired robot system designed to mimic the unique capability and ability of the water strider.

Basically, it comes under the family of Gerridae insects. It is mainly meant to walk, jump, and maneuver across the water surface without sinking. Ideally, it can float on the water. It can stand on the water, and it can float on the water by utilizing the principles of surface tension, hydrophobicity, and light field structural engineering. These robots enable efficient aquatic locomotion, offering potential applications in environmental monitoring, military surveillance, biological studies, and disaster response. So, these are the applications where such kinds of water strides can be effectively employed. So, these are the closer views of the water striders. In fact, there is a group that has published a video on these water striders; you can refer to this on YouTube. Now if we keenly observe the different mechanisms that are involved in the perspective of a water strider or water walker robot, we can categorize these mechanisms as we have discussed in the earlier module about the different types, such as the slab face and the stroke face. So first, there is a kind of recovery up and recovery down mechanism. We have the stroke phase, slab phase, final push phase, and loop shaping phase.

So let us consider this as a kind of water strider that is in the water. Initially, if you consider this as your reference, it is kept on top of the reference, and then there is a structure meant for a slapping phase, followed by a stroke phase that is exhibited here. Now, let us discuss the different phases that are exhibited in detail. As far as the recovery up and recovery down mechanism is concerned, in the recovery up phase, the foot, though submerged, is assumed to exit the water through the cavity that was formed during the slapping and stroking phase. Now, for this first, we need to have an understanding of the slapping phase and the stroking phase. So, as far as these slapping phases are concerned, during the basilisk slip, the slab phase can convey an extra amount of lift depending upon the speed, the contact, and the power abilities of the lizard.

This phase of the step is for all positions where the ankle height is lower than the water height and the velocity angle is less than the negative of 45 degrees. So at this time, the slab face is governed as it is hoped that it will yield a conservative estimate of the lift provided by the robot, as the slab face, in reality, provides a surplus amount of lift. Now, when we consider a stroke phase, the stroke phase begins when the ankle velocity angle is equal to or greater than negative 45 degrees, which depends on the water height and the loop shape. But in general, it occurs shortly after the ankle is submerged over here. So, this phase continues until the ankle has reached the lowest point of the loop, and the drag of the loop is assumed to be a kind of force that is exerted on it. Now we can create this loop shape in such a way that we can have a drag face and a lift face. Now when we try to talk about the recovery up and the recovery down, in the recovery up, the foot, though submerged, is assumed to exit the water through the cavity that was formed during the slap and the stroke phase. So the drag on the foot is thus considered zero. Consecutively, when we try to consider the force along the x and y planes at 0, this phase occurs during the recovery down phase of the step when the foot is above the water level and is entirely in the air. So, forces are assumed to be 0 and the phase lasts of all proportions where the ankle height is greater than the water height.

These are some of the mechanisms that are being deployed with reference to the water strider for the movement of the phases. Now let us discuss the different principles involved in this water strider locomotion to design an efficient water walking robot. The researchers have analyzed the biomechanics of the natural water striders. If we closely observe the different aspects of biomechanics that are involved, one is a kind of surface tension utilization. In this case, the water striders rely on a surface tension that prevents them from breaking the water surface, and their legs distribute weight evenly, preventing submersion. When we try to talk about the hydrophobic leg, the stridulating leg has a macroscopic, microscopic wax-coated hair structure which we had discussed earlier, also referred to as setae, that repels water and traps air, which enhances buoyancy. In fact, that is what we saw in the 4 to 5 slides before, where we could see there is a kind of column over which there is an interaction of the liquid along the surface. Then we have a kind of leg-based propulsion. In this leg-based propulsion, a water strider moves by pushing against the water with its middle leg while using the front leg for steering and the hind leg for stability. So appropriately, an equilibrium is maintained with reference to the steering and stability, and the equilibrium is established.

Next, when we try to talk about the jumping mechanism, they generate sufficient force to jump off the water surface without breaking it, leveraging their lightweight bodies and specialized joint mechanics. So, these are the different principles of water striders with reference to locomotion. So, let us discuss in detail the key components of this water walker robot in the upcoming classes.