

Micro Robotics

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Lecture 55

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

We have been discussing this biomimicking-related propulsion. We had discussed various types of biomimicking-related propulsion. We have been discussing E. coli-based biomedical propulsion and bacterial-based biomedical propulsion. In fact, it has potential applications for this targeted drug delivery. In all these cases, the actuation is based on either magnetic, pressure, or, in some cases, chemical reactions.

In this series, algae-based or algae-inspired micro-robots are considered a domain where there is quite a good amount of potential, and the most important aspect is that these kinds of algae-based micro-robots have potential applications in drug delivery and other biomedical-related areas. These algae-inspired micro-robots have attracted intense research over the past decade owing to the abundant desired properties of natural microalgae, such as biocompatibility, autofluorescence, and pharmaceutical activity, which make them ideal candidates for biomedical and related applications. With the deepening and widening of applied research, the functions of these algae-inspired micro robots have been greatly enriched and enhanced to meet the needs of demanding application scenarios, including targeted drug delivery, anti-cancer therapy, antibacterial therapy, cell simulation, wound healing, and biomolecule sensing. Withstanding, it also has multiple challenges that remain to be tackled for transformative advances and clinical translation.

These algae-based micro robots are classified into three different categories; one is called microalgae flagellated robots. These are some of the varieties of these microalgae flagellated robots, and from the perspective of manufacturing these microalgae flagellated robots, they are either produced through biotin-streptavidin binding, electrostatic interaction, or a concept called click chemistry. With reference to the application perspective point of view, they have potential applications in micromanipulation, active drug delivery, anti-cancer therapy, antibacterial therapy, biological detoxification, on-cell enzyme catalysis, and wound healing. With reference to a functional perspective point of view, it works on the functionality related to phototaxis, magnetotaxis,

photodynamic/photothermal, biocompatibility, degradability, oxygen generation, and immunoregulation. With reference to the perspective of microalgae hybrid robots, we have a certain series of such microalgae hybrid robots, which are being successfully deployed.

One is a kind of Kalmar-Donova base structure. From the manufacturing perspective, it can be manufactured through simple techniques like dip coating, solder electrolysis deposition, surface polymerization, and electrostatic interaction. With respect to the functional perspective, drug loading and release, off and on fluorescence sensing, enhanced photothermal effects, selective cytotoxicity, tunable biodegradability, piezoelectric effects, and opto-hydrodynamic effects. With reference to the application perspective, it is widely used in active drug delivery, anti-cancer therapy, antibacterial therapy, disease diagnostics, cell stimulation, and biological detoxification. When we consider this, there is another set of microalgae that is being effectively used for micro-robotic-related applications, which we call a microalgae-templated robot.

These microalgae-templated robots are concerned that they are called a kind of diatom base, which is available. So, with reference to a manufacturing perspective, biomineralization, annealing treatment, physical vapor deposition, and electrostatic interaction are considered to be some of the key manufacturing techniques that catered to this microalgae-templated robot. With reference to the functional perspective point of view, it has a high payload capacity, a photo-thermal effect, quite a good amount of remote biosensing, and heavy metal ion absorption. As far as the actual application perspective is concerned, it is widely used for active drug delivery, anti-bacterial therapy, biological detoxification, and biomolecule detection, which are some of the key areas where these alliaes are being effectively used. Now let us see the types of algae and their overall construction.

First, let us discuss this microalgae-based hybrid robot. This microalgae-based hybrid robot is a kind of non-living bio-hybrid algae with optional functional modification and algae surface or within the cells. The morphological structure and the biological substance of the microalgae will be preserved, but the cell activity is forfeited. With externally coated materials, most of these act as a kind of surface anchor, or in some cases, they also act as a kind of antibiotic structure. By using externally coated materials, mostly magnetic substances like Fe_3O_4 nanoparticles, it is possible to confer magnetic attributes to the microalgae for remote actuation and steering using a magnetic field.

These magnetic microalgae hybrid robots are versatile in varying scenarios because they can perform complex tasks even in harsh and toxic environments. Additionally, the biological compound inherited from a microalgae cell can equip MHR with desired functionalities such as autofluorescence, magnetic resonance signals, and anti-cancer activity. Through the integration of additional components, other functions such as

photoacoustic imaging and antibacterial therapy can be enabled by polydopamine. Benefiting from diverse functionalization strategies, these microalgae hybrid robots can be customized to accommodate a plethora of functions in a single package suited to the target applications. When choosing the chemical compositions of these microalgae hybrid robots for in vivo applications, there are some crucial aspects, including their cytotoxicity, biodegradation, imaging capability, and potential immune response that should be considered.

Whenever we try to look into these kinds of microalgae-based systems. Now, if you closely observe this microalgae-based system, the microalgae hybrid robotic system, we have the kind that will be integrated with the system. The other one is a kind of anchor that is used to reach a particular target, stick to that target, and diffuse medicines or biocompatible drugs, which will be managed by this anchor component. Now, in a similar fashion, when we try to talk about this kind of microalgae-based templated robot. So this is ideally the structure of these microalgae-based template robots.

In this structure, if you see, there are wide varieties of strokes. Wherever we need to have a forward stroke of algae, there are some kinds of tentacle-like structures. These tentacle-like structures are effectively used for appropriate propulsion. Whereas if you need to have a reverse stroke, these tentacle structures are appropriately reversed to create a reverse stroke. In this particular case, for example, if you take a forward stroke of an algae, then 1 to 7 will be helpful for giving a forward stroke.

Wherever there is a reverse stroke, the sequence from 8 to 11 or the tentacles from 8 to 11 will be involved in such a kind of reverse stroke. As far as these microalgae-templated robots are concerned, these microalgae are defined as synthetic micro-robots merely replicating the microalgal morphology with both the structural matrix and contained compounds removed after fabrication. These microalgae-templated robots rely on electrochemical deposition, like a process in the sense that the microalgae mainly provide a biological template for shaping the microrobot, regardless of their cell activity and intrinsic functionalities, which are eventually eliminated. Owing to the internal cavity space during the fabrication procedures, such as through annealing treatment, a large quantity of micromolecules or drug payload can be loaded into such microalgae-templated robots. These microalgae-templated robots are mainly meant for targeted drug delivery and controlled release.

During the fabrication process, the microalgae structure is susceptible to excessive damage, potentially affecting the locomotion performance of these MTRs. Therefore, factors such as temperature and reaction time need to be precisely controlled to preserve the microalgae-based morphology. Now, when we look into the overall manufacturing methods involved in such micro things, microalgae-based structures are concerned. There are two mechanicals, two important aspects that we may need to look into. One is they

should have the capability to swim in fluid environments and glide on the surface with a continuously propulsive force generated to empower locomotion.

When we try to consider the second part, they need to demonstrate a certain tropism for controllable steering motion toward a targeted location. As far as these kinds of things are concerned, these are meant to enable MFRs to desiccate the functionalities and modify the microalgal surface with exogenous materials through various strategies. There are different types of microstructures that exhibit such kinds of microstructures. Most of these cases involve microalgae that grow through a cellular structure or through chemical systems so that they can be decorated or integrated with such structures. As far as this microalgae is concerned, it has a kind of electrostatic interaction, and then there is a magnetic microbe.

If you closely observe this, as I discussed earlier, in order to have appropriate propulsion, there is a need to decorate these structures with suitable elements. When we try to give actuation to these elements, they will be capable enough for appropriate locomotion. In this particular case, this is the overall microalgae. In this overall microalgae, this entire microalgae is decorated using a kind of magnetic microbead. These magnetic microbeads are appropriately actuated using this electrostatic interaction, through a kind of charge, so they can be used for a micropropulsive action.

As far as this micropropulsion action is concerned, we have microalgae, and then there is going to be a magnetic microbead. With the integration of this microalgae and a microbead, we finally get a micro robot that is exhibited here. So these are some of the different examples of the different classes of algae-based micro robots, which also have potential applications in drug delivery. However, this area is not much explored. Just to give you an overview, I thought that I would just explain these basic concepts to you.

Now, when we try to look into the theoretical perspective point of view, we are attempting to design such kinds of bio-inspired micro robots. As we discussed earlier, we need to have a very low Reynolds number of less than 1. Let us see what the different parameters are that basically try to participate in relation to such low Reynolds number structures concerning these bio-inspired micro robots. One is low Reynolds number hydrodynamics, which we call Stokes flow. Since micro-scale robots operate at a Reynolds number less than 1, the Navier-Stokes equation can be written and is considered.

$$\mu \nabla^2 \mathbf{u} - \nabla p = \mathbf{0},$$

So here, if you observe closely, we have the fluid viscosity in place, we have the pressure in place, and \mathbf{u} is the velocity. Since the inertia is negligible, the moment must be non-reciprocal; in fact, it is governed by this Purcell-Skalob theorem. Now, the next aspect

refers to the fluid domain perspective point of view. Next is with reference to the flagellar motion. If you observe that we have a flagellar whip through the flagellar whip, there is a kind of huge frequency being generated that is helpful for appropriate locomotion.

If you look into the resistive force theory for this flagellar motion, it is basically determined by the resistance coefficient and the velocity components that are normal and parallel to the flagellum.

$$\mathbf{F}_{\perp} = -C_{\perp} \mathbf{v}_{\perp}, \mathbf{F}_{\parallel} = -C_{\parallel} \mathbf{v}_{\parallel}$$

These resistance coefficients, these velocity components, and this system will participate in this particular structure for the appropriate moment. Now, when we try to look into the helical propulsion model for magnetically actuated systems, we consider a similar perspective point of view. We have the rotation frequency that is participating in this; r is the helical radius, λ is the wavelength, and θ is the helix angle used for appropriate participation. The overall equation is governed by these parameters to obtain a particular value.

$$\mathbf{v} = (\omega r^2 / \lambda) \tan(\theta)$$

Now, when we try to look into the jet propulsion model, we have a kind of jellyfish-inspired motion. This thrust generated by the expelled fluid volume V is

$$\mathbf{F}_{\text{thrust}} = \rho V d\mathbf{v}_{\text{jet}} / dt$$

So, V_{jet} is a kind of jet velocity, ρ is a kind of fluid density, which is being effectively used. Here in this particular case, we have discussed the parameters involved in helical propulsion and the parameters involved in the jet propulsion method. Now, when we try to consider surface walking and rolling, so far in rolling robots, the force balance includes adhesion and rolling resistance.

$$\mathbf{F}_{\text{propulsion}} = \mu \mathbf{N} - \mathbf{F}_{\text{resistance}}$$

So the $F_{\text{propulsion}}$ basically includes that it is in the order of micronewtons with $F_{\text{resistance}}$; μ is the friction coefficient, N is the normal force, and F is the resistance, which includes the Van der Waals force for adhesion. Let me just introduce you; until now, we have been discussing most of the cases on a micron level. One of the methodologies or one of the modules is related to this water-running robot. As far as this water-running robot is concerned, the basilisk lizard is considered to be one of the key creatures, from which

we can extract some mechanisms that cater to the needs of this water-running robot. As far as these water-running robots are concerned, it is a kind of small, lightweight animal that has a large variety of flotation mechanisms available to them.

There are spiders and insects that float using a kind of surface tension. They propel themselves using a meniscus in water and because of the meridional flow. So, larger animals have few options like lizards, aquatic birds, and marine mammals; with their larger bulk and higher masses, they utilize buoyancy, viscous drag, and momentum transfer. As far as these kinds of basilisk lizards are concerned, they are capable of running across the surface of water at approximately 1.5 meters per second. A stepping rate, if I try to tabulate the overall characteristics of it, is that the running speed on the water surface is 1.5 meters per second and the stepping rate is 5 to 10 hertz. There are 4 factors which influence the lizard's ability to stay afloat. One is the body mass, second is the characteristic length, third is the running speed, and fourth is the shape of the foot. So all these variables are interrelated, and the morphological relation of the lizards' water running is being considered for different applications.

As far as these lizard-based water running is concerned, there are different phases that are exhibited. Some of the phases basically include the slab phase, stroke phase, recovery up, and recovery down. What do you mean by this slab of face? So, let us consider this as the basilisk lizard. In this basilisk lizard, when it wants to move on the surface, it tries to maintain an equilibrium on top of the surface. There will be a kind of slab face exhibited here, and then, with reference to a slab face, it will try to move to a stroke face.

Then this is a kind of stroke face, and then again it will try to come up with a recovery up and a recovery down. So, if I try to represent it in the form of a small figure, this is a kind of slab face. In this slab face, this lizard is going to rest like this, and then in the stroke phase, it is going to push in this direction during the recovery up and in the recovery down. So, all these correspond to the foot motion. In order to have a better understanding of stroke face and recovery, let us see some of the key parameters involved with reference to this slab face and recovery face.

Now, as far as these slab faces are concerned. So during each step on the water, an initial slap at the interface pushes against the basilisk foot. So, for a younger, lighter lizard, this slap phase can provide all of the lift necessary to stay afloat. The lizard's ability to generate excess lift during the slap phase of the stroke declines as the mass of the lizard increases. So the slap phase begins when the foot first contacts the water.

Foot motion is primarily downward, and the magnitude of the upward force is much greater than anywhere else in the step. So the maximum slap impulse, which we call I_{max}

slap, is a function of the effective radius of the foot, which we refer to as REFF. The peak velocity during the slab U_{peak} is,

$$I_{slap}^{max} = \frac{4}{3} r_{eff}^3 U_{peak}$$

When we try to consider the stroke face, this is a kind of slab face. As far as these stroke phases are concerned, after the slab phase, the lizard pushes against the water beneath its foot.

So stroke downward and create an air cavity in the water. The momentum transfer from the lizard's foot to the water during this force stroke phase generates the rest of the lift force necessary to stay afloat, most of the forward thrust. While basilisk lizards do apply a significant force to the water in a lateral fashion, it is felt that this is done for balance and stabilization and not for lift. This lateral motion may be an anatomical limitation imposed by the created posture. So for heavier lizards, most of the lift comes from the stroke phase.

The drag on the foot is the combination of the hydrostatic drag due to an increase in depth. So, we can represent something like this:

$$D(t) = C_D \times \left[0.5 \rho v^2 S + \rho g h(t) S \right]$$

$d(t)$ is the time-varying drag force. C_d is the constant drag coefficient, and G is the acceleration due to gravity. We can represent it as

$$S = \pi r_{eff}^2$$

S is the area over which this drag is occurring, and $h(t)$ is the time-varying depth along the foot.

When we try to consider this recovery up and recovery down, during the recovery up phase, the basilisk lizard will curl its toe inwards when pulling its foot out of the water, as shown here. To prevent accidental drag on the cavity walls, this takes place entirely within the air cavity and must be completed before the cavity collapses. So during recovery, the speed of the stride increases as the lizard prepares to slap the water surface in the next

stride. So no significant forces are experienced by the lizard's foot in either of these phases. In this particular aspect, timing is considered to be one of the important parameters.

So if you consider the timing, the period of time during which the cavity is open, which we call T-seal. It basically depends on the shape of the lizard's foot. For a circular disc, the relationship is

$$T_{\text{seal}} \rightarrow 2.285 \sqrt{r_{\text{eff}} / g}$$

It is the period set for an absolute minimum frequency at which the lizard must slap down, stroke, and remove the foot from the cavity in less than a T-seal second.

This response corresponds to the frequency. With reference to this frequency, it doesn't allow the lizard to move down. Instead of that, there is a kind of periodic set with an absolute minimum on the frequency, and the lizard must slap down to reach higher order frequencies so that it does not allow it to sink. So, this is the overall correlation. These are some references related to this particular aspect. Overall, in this module, we discussed a lot about propulsion, specifically about biomimicking-based propulsion on a macro level and slightly on a micro level.

How the mechanisms are adapted from a naturally available system to the conventional system, and how they can be translated appropriately for microrobotic-related applications. As far as the water runner robot's perspective point of view, we will be discussing in detail with an application in the next upcoming module. Thank you.