Micro Robotics

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Lecture 53

Bio Inspired Micro Robots (Propulsion and Locomotion) - Module 03

We have been discussing this bio-inspired micro-robot. We have covered the different propulsion mechanisms, the fundamentals behind these propulsion mechanisms, the different characteristics involved in this propulsion mechanism, and the parameters involved with reference to this propulsion mechanism. We were focusing more on this bio-based fact, particularly on the microorganism-based structures and how the propulsion mechanisms are extracted, and transformed into a kind of mechanical micro-robotic system or in the micro-robotic domain for an appropriate application in detail. Now let's discuss the cilia-based structure. The cilia-based structure, the core structure of the cilium was identified as axoneme. The single cilium can beat rhythmically, and its motion can be divided into two stages. One we call an effective stroke stage and the other a recovery stroke stage. The ciliary motion of it is a kind of effective recovery stroke of the cilium. We have seen a kind of whip arrangement.

This whip arrangement will have three or four different nodes, so it starts from this effective stroke, reaches this point three, and then comes back to the one stroke. So, it is something like through an effective stroke it tries to push the whip in the forward direction and then, in the recovery stroke, it has a pulling node. So, with reference to a pulling node, you have a kind of backward motion that tries to get generated out of it. During the effective stroke, the cilium is straight and pushes a large amount of fluid, and in the recovery stroke, it pulls a small amount of fluid as it closes to the cell surface. In the case of a recovery stroke perspective, it has a direct relevance to the fluid. When it tries to push a large fluid, it gives a kind of propulsion forward, and then when it tries to give a small amount, it will be a kind of precise moment that is closer to the system. When the cilia arrange in an array, the hydrodynamic interaction makes the adjacent cilia beat out of phase. This motion is like a wave motion and it is called a metachronal wave, which is shown here. This is a kind of metachronal wave that is being generated, and then there is a cilium-like structure present. These cilia, due to the alternative effective stroke and the recovery stroke, can move in an

appropriate direction through these metachronal waves, which govern appropriate movement. So, like flagella, several microorganisms use cilia to generate drag-based propulsion within a fluid. Some of the microorganisms, which include the paramecium and the stentor, are such microorganisms that use cilia for propulsion. This image will give you a kind of clarity that discusses the effective stroke and the recovery stroke in such micro robots. Now, when we try to look into the perspective of the actuation force, the cilia beating cycle generates a net translational force due to the difference in the magnetic actuation force between the power stroke and the recovery stroke. The magnetic stroke torque Tm of cilia in an external magnetic field is determined by Tm, where m is the magnetic moment of the cilia, and B is the magnetic field intensity.

When we try to look into the magnetic torque, this magnetic torque has a maximum value when the field is applied orthogonally to the magnetic moment. So the equation of the magnetic force on a cilium along the longitudinal axis of the cilium body can be simplified using a backward power stroke and a forward recovery stroke to the following equation.

$$T_m = M \times B$$

$$F_m = mB \, Sin(\,Y-\theta)\, /L,$$

We have the Fm equals Mb sine (gamma minus theta) L. So this corresponds to the applied field angle. Theta corresponds to the angle, cilium angle, and L corresponds to the cilium length.

$$\Theta = \frac{TL}{EI} = mB \, Sin(\,Y-\theta)L/EI$$

The cilium angle is evaluated using a simple cantilever deflection model. These simple cantilever deflection models can be represented as theta equals T L / E I, which is nothing but M B sine (gamma minus theta) L by E I. So, T is the magnetic torque of a planar component of a ciliary micro robot. E is Young's modulus of the cilium. I is considered to be the moment of inertia of the structure. Now, when we try to look into the application of these micro-robotic perspectives, point of view. The surface locomotion of these cilia-inspired micro robots crawls over the surface, mimicking epithelial cell movement. It is highly used for navigation inside ducts, blood vessels, and on tissues. With reference to the microfluidic control perspective, the cilia array can control fluid flow in lab-on-chip devices. It enables the mixing, transport, and sorting of liquids or particles.

As far as advantages from a perspective point of view, the main key advantages of cilia-inspired micro robots are that they are designed to work in a low Reynolds number regime, which is basically inside the human body, and cilia allow a micro robot to crawl or glide along surfaces, walls, and tissues. It also enables local fluid control without an external

pump and is mainly meant for ideal untethered operations inside the body. As far as flexibility and conformity are concerned, it is mainly meant to make them safe for a win-win use. These are some of the advantages of this cilia-inspired micro robot. Let's discuss a case study where we have used a kind of jellyfish-inspired jet propulsion system.

In this jellyfish-inspired jet propulsion system, the mechanism is concerned. So this jellyfish-inspired jet propulsion model is based on the interaction between the deformable belt structure and the surrounding fluid. Ideally, in the case of the jellyfish, we have a structure something like this. You can see it over here. This is a kind of bell structure, and then there are kind of flagella structures that are available. By giving an appropriate frequency to this kind of flagella structures, the dome moves, and these dome movements are appropriately captured. If you closely observe this dome moment, or if you want to mimic such dome moment-based structures. So, this propulsion mechanism comprises two phases: one is called a contraction phase, where it is referred to as a power stroke-based system. The jellyfish contracts its bell, expels the water, and generates thrust. The expelled water forms a kind of vortex ring that contributes to the forward motion.

When we try to look at the expansion phase from a different perspective, this is a kind of recovery stroke. In this recovery stroke, a bell passively expands, drawing water into the sub-umbrella cavity, and the vortex dynamics ensure a continuous moment transfer, enhancing a kind of good propulsion efficiency. These are considered to be the two phases that are being effectively catered to in the propulsion mechanism. Let's see a simple example where shape memory alloy-based structures can be integrated to create a kind of propulsion mechanism.

In fact, this case study we discussed earlier also concerns this structure, which is integrated with a shape memory alloy. It has two different components. One is a kind of polymeric structure, and the other is a kind of shape memory alloy structure. These polyamide sheets or shape memory structures are integrated in such a way that the shape memory structures are carved or stitched into these particular polyamide structures, and these shape memory structures are programmed to achieve the required displacement. So in order to capture this displacement, ideally we have a kind of structure that is flexible, and then we have a kind of integrated shape memory loss structure. The actuation motion is scattered by the kind of elastic structure that is available here.

It has a kind of medium that takes care of the entire buoyancy and movement of the system. Inside this medium, it has a kind of actuator. These actuators are ideally a type of shape memory alloy actuator, so as we all know, these shape memory alloy actuators are programmed to create a kind of linear actuation, and then During this linear actuation, there is an expansion and contraction that exhibits a kind of contraction phase recovery or expansion phase recovery, which caters to the overall movement of the structure. In order

to cater to the frequency, one way actuation is taken care of by the shape memory alloy, and the return stroke is taken care of by the rubber string. So ideally, your structure looks something like this: this is kind of a kept-on polyamide. This is an SMA structure. This SMA structure has the capability to actuate in a straight phase. Now, what we are trying to do is integrate a string. So, this is a kind of rubber string. So this actuation is taken care by the potential difference applied.

As the potential difference, it becomes straight, and the return stroke is taken care of by a rubber band, which is exhibited over here and takes care of the overall motion of the system. So, that is how this system works. The overall kinematics involved are modeled appropriately with reference to a plane and with reference to an axis. It has q1, q2, and q3, which take care of the angular movement theta, and a0, a1, a2, and a3 take care of the overall length between the link and the appropriate movement in the structure. This is a kind of model simulation that is being incorporated.

In this model, simulation is concerned; a kind of structure and the overall structure get actuated at a particular moment. The forward stroke and the return stroke are provided by the SMA plus the rubber string structure. So through SMA, we get a kind of forward actuation, and the return stroke is taken care of by a rubber string-like structure. As I mentioned earlier, when we try to model this structure, let us consider this as an axis where A and B are defined. B talks about the length in tension, and A talks about the overall elongation in the structure. K corresponds to the stiffness of the rubber spring, B corresponds to the length of the tension, and NL is the natural length of the rubber string under no load condition. E is the elastic modulus, and I is the moment of inertia. The schematic of the model basically discusses the extraction of the bending moment, which is shown in the actual image that we refer to as a tentacle. When we try to equate it with reference to these equations as well as with reference to the overall displacement that is being exhibited along the x axis. When we try to model the structure as far as the shape memory alloys are concerned, when it tries to actuate, an electrical pulse is applied to it.

$$\frac{k * (b - nl) * (a - y)}{E * I} = \frac{\frac{d^2y}{dx^2}}{\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{\frac{3}{2}}}$$

So this electrical pulse will cater to the actuation, basically kind of like a heating and cooling cycle. This heating will provide an appropriate displacement, and the cooling will take care of the reverse stroke, which is shown here. When we plot a graph with reference

to time and temperature. There is going to be a heating cycle, and then there is going to be a quenching cycle. This alternating heating and quenching cycle will try to cater to the overall biomimicking actuation in the SMA integrated tentacles. So that it has a kind of stroke moment which is exhibited here, which caters to the overall displacement. The overall variations, or the parameters that affect these particular tentacle movements, are based on the modulus variation during the phase change. We are all aware of the type of SMA phase change. Basically, it is a switching between the austenite and martensite kinds of structures. Switching between this austenite and the martensite kind of structure will greatly affect the overall actuation behavior.

This deflection, with reference to the change in modulus, can be modeled, and the overall deflection is restricted to close to a 30-degree angle, which basically caters to the requirement of the actuation. Now, this is a kind of simulation that basically discusses where exactly the actuation happens. If we have a jelly-like structure, the loading happens along the sides of the tentacles. When the loading occurs in these tentacles and when the forward and return strokes happen, what happens is there is a kind of lift and drag. Those who will participate in the system, and when there is lift and drag, participate appropriately; you can see a kind of moment that persists over here.

It has the pressure contour during bell contraction, a pressure contour during bell expansion, and then there is a kind of vortex formation, which is visualized via the streamlines. This is a kind of real jellyfish simulation, it swims by contracting its bell and the umbrella-shaped part at the top of its body, which forms a kind of vortex behind the animal and propels it forward. Either if we consider this appropriately, or if we try to manipulate this vortex motion, we get a kind of displacement either in the vertical direction or in the horizontal direction. Your overall propulsion with respect to vertical or horizontal movement is determined by the model of contraction and expansion. These are considered to be the key points where we try to focus the load; this will cater to the overall drag force and the lift force.

This alternative drag force and the lift force will be helpful in creating a vortex behind, and it will be helpful for propulsive motion within the system. This is a kind of structure. So, as far as this structure is concerned. It gives us clarity regarding the amount of thrust force exerted over time t. There are some restrictions when we try to use such kinds of soft actuators, basically such kinds of shape memory alloy-based soft actuators. Because when we use such kinds of soft actuators, there is a chance that the overall thrust that is integrated can be achieved. However, with reference to a frequency perspective, it has its own limitations. In order to cater to that frequency aspect, we may need to compromise on the thrust we are trying to generate from it. In fact, this is a kind of performance evaluation. So, in this structure, if you see, this is a kind of polyamide structure.

So, it is a tethered kind of system. It has have a system at rest and during actuation, it moves in this direction. In this particular case, we have an SMA wire diameter as we are pretty clear from an actuation perspective. So, when you try to switch between the martensite phase and austenite phase, so what happens is we may need to give a pulsed signal to this system. So, these pulse signals will be helpful for us to create a kind of actuation, and it also caters to the overall movement. Even though, especially in underwater conditions, the overall convection is protected appropriately because of the polyamide film, which is being kept over here.

However, with reference to the actuation perspective point of view, the frequency is constrained within the switching behavior of the austenite phase and martensite phase, which is evidently shown here. In fact, this is a kind of thermal image camera; it will give us clarity about how much illumination is happening or how much temperature variation is being exerted here. In fact, this is a kind of performance evaluation. So, as I mentioned earlier, like the frequency, the switching behavior between austenite and martensite will cater to the required frequency. So, for instance, when we try to look into the frequency of the tentacle, we have three different types of frequency.

One is with reference to 0.5 hertz, another is 1 hertz, and then there is 2 hertz. So, with reference to the 0.5 hertz perspective point of view, we have a very limited structure. So within the structure, we can see the overall frequency it exhibits. With reference to the 1 hertz perspective point of view, you are appropriately trying to tune the actuation behavior to get the structure, and with reference to the 2 Hz perspective point of view. So we can have an appropriate structure for what we are looking for. These actuation behaviors have a direct relevance to the functionality and characteristics of the system. Now this is the kind of actual structure. It has a camera and an electronic control system that is placed on top of the dome. Then there is a certain amount of flex sensors, and this is the kind of tentacle that is integrated with the SMI structure.

The actuation with these SMI structures is deployed, and the overall actuation behavior is studied using a kind of flux sensor. This flux sensor acts as a medium to study the deflection behavior as well as the characteristics. And then you have an onboard camera and an electronic control system that is placed on top of it, which is mainly meant for measurement-related applications. The overall bending angle and the time are measured using this system, so we have a kind of tentacle bending angle. In this tentacle bending angle, we can see a kind of deflection characteristic that it exhibits. With reference to these deflection characteristics, we can study the behavior. So it is a kind of system that has a sensor in place and an actuator in place. The actuator is a kind of shape memory alloy integrated polymer structure. The sensor is a kind of flex sensor. Other functional sensors are characterized using the camera and the electronic control system, which is placed on a dome-shaped structure.This can be used from a surveillance perspective. In fact, this is a kind of payload that is being integrated on top of the dome. Other condition monitoring

structures can have their condition monitoring behavior effectively monitored using these available flux sensors. In order to capture such performance evaluations, this is a system being deployed which has load cell, a rod, and a soft jellyfish with a water channel available. When a load is exerted on this jellyfish, we can see a movement, and these moments are being captured by the load cell, from which we can take measurements. So ideally, the measurement of thrust is catered to using this load cell. This is a kind of actual jellyfish where it has a head and tentacles. This is a kind of biomimicked jellyfish structure, even though it is used on a macro level; it can be reduced on a micro level appropriately by incorporating a certain amount of flexible bimorph-based actuators. These bimorph-based actuators can have their own appropriate frequency, which can be effectively used for motion. This is a kind of moment with reference to the horizontal perspective point of view, and this is a kind of moment that is observed with reference to the vertical perspective point of view.

We have seen this vortex motion, which is being created. These vortex motions are generated by the available tentacles. This is a kind of horizontal motion, and this is a kind of vertical motion where we have a scale-like structure. These vertical motions are appropriately opened and closed, and then you can almost mimic the behavior. When an expansion of tentacle happens, what occurs is that it will try to push the vortex force in this particular direction, which affects the overall movement in this domain. Almost in an actual condition, the jellyfish follows the same phase, where the vortex motion is created in this particular domain and then it is helpful for the appropriate propulsion of the system.

These are some of the different positions of these jellyfish-like structures with reference to the time domain and how the results are deployed. In order to cater to the different loading conditions, these are some of the tests being deployed in such a way that these SMA structures are integrated with these polyamide behaviors, the payloads are deployed, and the actuation is happening. This jellyfish prototype is slightly on a macro level, so appropriately it can be on a micro level for different applications or characteristics. Let's discuss the micro-mechanical flying insect in the upcoming class.