

Microrobotics

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Micro-Mechanics System Design (Design of Microrobots)- Module 04

In the last class, we discussed the different micro mechanics-related concepts related to Coriolis components, related to the dynamics of a system, and related to the torsion of the beam. We have also discussed the Poisson effect and the negative Poisson effect, i.e., how the negative Poisson effect can be efficiently used in the case of a micro robotic system where we have taken an auxetic structure as one example. With reference to this auxetic structure, we have investigated how a negative Poisson ratio can be demonstrated. We had also discussed this micro mechanism, the bending moment arising due to the residual stresses, which has a direct relevance to the kind of biomorph application.

Whenever we are trying to design the micro-mechanics systems, there is a need to understand the design and selection of materials for a micro-robotic system, which we will discuss in today's lecture. As we have seen in the earlier lectures, the auxetic structure has played a vital role in the creation of this negative Poisson ratio, and this negative Poisson ratio is generated not only because of the material, but also depends on the structure. In the case of an auxetic structure, the structure is in the form of a pentagon, and when we apply load, there is a kind of elongation that persists. In the case of an auxetic structure, one of the key points which we may need to consider is not only the material but also the overall structural capability, as well as the overall manufacturing capability, which plays a vital role in fabricating and in giving the functional properties based on the requirements.

As far as overall classifications or overall parameters are involved in the design and selection of a micro robotic system, we may need to classify it based on different challenges, different properties, and different parameters. Let us classify the materials for a micro robotic system. As we all know, materials play an important role in the functionality, performance, and durability of the various components of the micro robot. The selection of the material depends upon multiple factors, and one of the key factors is

mechanical property. As far as mechanical properties are concerned, we are all well aware of them.

Whenever we design a micro robotic system, we may need to consider the strength of the system based on its actual functionality and flexibility. In fact, we have also discussed these flexible structures. In certain cases, we may need to go for a flexible structure, and in certain cases, there is a need to go for a rigid structure based on the requirement where toughness and resistance to wear will play a vital role. When we talk about wear, as in the case of an actuator, a sensor, or a micro robotic system, there is regular contact of these systems with the surfaces, having an impact on the functional characteristics; i.e., there is going to be wear and tear of the system, and appropriately, our surface also needs to be realized to take care of this particular requirement, and this is where exactly the mechanical properties play a vital role. Next, we will discuss the electrical and magnetic properties. In most micro-robotics cases, there are energy-related challenges. In most micro-robotics systems, we go for contactless charging. Appropriately, the material we are selecting should have both electrical and magnetic characteristics.

When we talk about electric and magnetic properties, it should be a good conductor for sensing-related applications, and when we talk about magnetic materials, these magnetic materials are incorporated into the system for remote actuation. A discussion about micro magnetic actuators for micro robotic applications will be presented in detail in subsequent sections for better clarity. There are some case studies where selective magnetic fields are applied to these particular structures to create a mixed domain to obtain appropriate displacements. The next most important point, as far as the application of micro-robotic structures is concerned, is the biocompatibility of these structures. Biocompatibility is another essential element in the case of micro-robotics applications; if we consider it for medical applications, it might be more related to drug delivery, surgery, etc.

In the case of other applications, non-toxic and non-reactive based systems can also be deployed. The most important point is with reference to ease of manufacturing. So, whatever micro-robotic system we are planning, it should get well adapted within the process of microfabrication, so that this microfabrication technique is efficient enough to fabricate the kind of structures we are looking for. The conventional microfabrication techniques include lithography, 3D printing, micro etching, chemical etching, etc., which will be discussed in detail. In fact, there will be a detailed lecture on different microfabrication techniques that are available, and we will also discuss the concept of micro 3D printing in detail. Then, there is a need to talk about environmental sustainability. In today's conditions, environmental sustainability plays a vital role with reference to manufacturing, material selection, or system design. As far as environmental sustainability is concerned, one of the important aspects is, firstly, the corrosion resistance of the structure. Secondly, it should withstand thermal change and finally should also be able to withstand chemical degradation.

So, this is an important point that we need to consider with reference to the environmental system. Overall, when we consider the key factors for material selection of micro robotic systems, these are the key factors that contribute to the overall system development. Now, considering the factors that we have discussed earlier, these materials have been utilized for different applications of microrobots, one of which is with reference to structural material. The material used for the frame and body construction in micro-robots should be lightweight, and it should have the capability to reduce energy consumption and facilitate fast motion. In fact, propulsion in a micro robotic system is one of the key aspects that need to be considered. Considering the case of propulsion, for example, the overall body construction and the lightweight will come into the picture for effective propulsion or effective micromanipulation. The next important point is the strength-to-weight ratio. The frame and the material in the micro-robotic system should have the strength to bear the additional components. Basically, the payloads that we work on, as well as the system's capability to maneuver with the available load or onboard systems that are being deployed. If we develop a small micro robot for biomedical applications, there is a need to carry drug along with it so that it can be used for drug delivery application.

So, the strength-to-weight ratio plays a vital role in such a way that the payload characteristics, carrying capability, as well as the propulsion of the system will also come into the picture. Next, when we talk about corrosion resistance, it should withstand varying operating conditions for a longer period, which is normally called a reliable system. So, at different conditions, it is mandatory to look into the overall operational capabilities of the system. It might be used in biomedical applications or sometimes in surveillance applications. In the case of oceanography and its applications, these microrobots have their own advantages.

Next, when we investigate the manufacturing capability, it should be easy to manufacture, and this fabrication is based on either a top-down approach or a bottom-up approach. In fact, there will be a detailed discussion on the bottom-up approach and the top-down approach. Any fabrication should follow a bottom-up approach, a top-down approach, or it may use a combination of both for the efficient manufacturing of these micro-robotic systems. Now let us discuss the structural materials that are efficiently being deployed for micro-robotic applications. So, if we observe these structural materials, one of the key structural materials that are used in micro robotics or any MEMS-based structure is silicon and is a dominant material for MEMS and microstructures as well as micro sensor applications. These MEMS-based rigid structures are efficient enough to handle these microrobotic structures. Other materials include polymers, for instance, parylene and Poly-Di-Methoxysilane (i.e., PDMS). We can also use PET and polyimide structures as substrates for flexible applications.

In fact, in our micro mechanic systems, we have also discussed Kapton polyimide, which is used for bimorph actuation-related applications. Wherever we talk about soft micro-

robots or flexible systems and wearable structures, these polymer structures will efficiently contribute to the behavior and its associated characteristics. Next, when we talk about shape memory alloys (SMA), they come under a special category of smart materials. Like SMA, there are different other smart materials that contribute to this particular system. For instance, we have a thermal actuator for the fabrication of flexible micro robots that use electrical actuation.

With reference to the electrical characterization, there is a need to incorporate a certain amount of metal interconnects into the system. These metal interconnects basically include Al, Ni, Pt, Au, etc., that act as interconnects or as electrodes for the circuits. Furthermore, as far as hydrogels are concerned, hydrogels have potential applications in the case of soft robotic systems. In the case of semi-liquid layers or semi-fluid layers that have the capability to induce compression on the structures, we can have an actuation or force that is exerted by these hydrogels. Nowadays, hydrogel-based actuators are efficiently used for different biomedical-related applications. Further graphene and carbon nanotubes hold potential applications in sensors and energy storage-related applications and have direct relevance to their functionality. If we look at the actuator's material, there is a lot of discussion going on. Just for a recap, what do you mean by an actuator? An actuator is a system or a device where we can have different types of input; however, our output will always remain in terms of displacement. The displacement can be either a mechanical displacement, an electromechanical system, an automatic system, or a hydraulic system.

When we discuss actuators for a micro robotic system, we need to consider certain parameters that fit into the requirements of micro-robotics or capture the functionality of the micro robots for different applications. One of the important parameters is the energy efficiency, i.e., the actuator material should have a high energy efficiency to reduce power consumption and work for a longer period of time with a limited power supply. For instance, when we use a simple micro robot for drug delivery-related applications, the injected unit will reach a particular point and then disperse the drug. For this process, it would require a non-contact-based actuation, and these energy systems should be capable enough to reach a particular point and deliver their functionality. This is one of the key parameters that need to be considered. Next, with reference to the actuator, another important parameter is the force-to-weight ratio. The material required for the actuator should provide a high force with as light a weight as possible. This improves energy efficiency and provides better locomotion.

As far as the force-to-weight ratio is concerned in reference to a micro-robotic perspective, most of our systems used for micro-robotic applications will fall under the category of either thin films or nanomaterials. Sometimes it might be an integrated material combination. The thin films will be appropriately embedded into the structure to achieve actuation, and nanomaterials can be embedded into the structure for functional

characteristics. For instance, ferrofluid-based structures are a kind of nanomaterial that is integrated or dispersed inside the liquid medium, and these liquid mediums are being actuated with the magnetic field that finally tries to take the intended shape. Furthermore, an integrated system has a coil present in it. When a magnetic field is applied around the coil, there should be an actuation that exhibits, and we can study the overall deflection. Further soft robots require high flexibility. Most importantly, they should have the capability or a realization of biomimicking. It is one of the most important parameters that need to be considered with reference to the system's flexibility. There are different types of actuator materials contributing to micro robotic applications, especially at a micron and nano level. If we closely observe these actuator materials, one of the actuator materials that is efficiently used is a piezoelectric material. The major used materials include PZT or PVDF. PZT is not widely used today because of the presence of lead content. However, PVDF is efficiently used as a flexible material. In lieu of piezoelectric, there is a new concept that is taking on a new shape, and we call it triboelectric. We might have heard of this concept called electrostatic charge. For instance, whenever we wear a woolen cloth and remove it from our body during the winter season, we hear a spark that gets generated. This spark is generated because of triboelectric behavior or electrostatic induction between two electropositive and electronegative surfaces. When these two bodies with different charge affinities rub against each other, it appropriately generates a spark. Triboelectricity is now observed as an alternative to piezoelectricity. In piezoelectric structures, when the crystal is exposed to an external load, a bias is formed, and vice versa; when we apply biasing, we observe an actuation that persists. However, in the case of triboelectricity, there is a constant need for contact and separation. With reference to contact and separation, there will be a charge transfer and its overall diffusion that will be sufficient for energy applications. Not just actuators, these piezoelectric and triboelectric structures are also efficiently used for sensing-related applications. While triboelectric is more focused on sensing, piezoelectric has more applications in precision actuators.

A detailed discussion about the overall configuration of piezoelectric materials and piezoelectric actuators is scheduled in subsequent lectures, i.e., how these piezoelectric materials and piezoelectric actuators are being efficiently deployed for micro-robotic related applications. Moving ahead, we have magnetostrictive material or magnetic-based systems. Like piezoelectric material, magnetostrictive material also works on a similar principle: when we supply a magnetic field to it, it will exhibit actuation. Vice versa, when a load is supplied, a magnetic field is generated. Terfenol D is one of the standard materials used for magnetostrictive applications. As far as magnetic micro robots are concerned, there are other wide varieties of magnetic materials exhibited. For instance, neodymium-based magnets, paramagnetic magnets, and ferromagnetic magnets are available and very much in use. These paramagnetic magnets and ferromagnetic magnets can be efficiently used for actuation-related applications.

Next, when we discuss shape memory alloys, SMAs might either be a nickel-titanium combination or copper-based shape memory alloys, depending on their functionality and utility. Commercially, when we look at shape memory alloys, these shape memory alloys are either available in the form of wires, powders, sheets, or springs. However, for micro robotic applications, we may need to tailor these shape memory alloys based on the requirements. There is a need to focus on certain shape memory alloy structures towards their structural and compositional manipulation based on their capability or functionality, and that is how the concept of bimorph evolved. There is also a way for micron-level printing of SMA using laser micro 3D printing for microrobotic applications.

The utility of shape memory alloys basically depends on the overall actuation condition; that is, based on the actuation condition, we appropriately classify these SMA structures. If the working range lies between 80 and 130 degrees Celsius, ideally we use nickel titanium-based shape memory alloy structures, and if the actuation range lies between 250 and 350 degrees Celsius, we use copper-based shape memory alloy structures. Further, the next important material is called electroactive polymers, of which the most widely used is polypyrrole. These electroactive polymers are efficiently used for artificial muscle generation or soft robotic-related structure generation. By appropriately incorporating these electroactive polymers, we achieve flexible actuation as required. Even gallium alloy-based liquid metals hold applications in actuations and have potential applications in the case of reconfigurable circuits as well as soft robotic-related applications. Now, when we talk about the sensor element, what is a sensor? A sensor is a device that has a sensing element and a transduction element. What are these sensing elements and this transduction element? Let us take an example of a simple thermometer.

In the case of a thermometer, we have mercury which is used for sensing the temperature and graduation in temperature based on exposure, so there is mercury that expands based on heat exposure and this expansion is marked or identified in the graduated readings. Here, mercury acts as a sensing element. It senses the temperature, and we have a transduction element that will try to manipulate the overall expansion in the form of a gradient. So, ideally, the transduction element will be helpful for us to translate the overall variation in the sensing element. This is a case of converting one set of parameters into another set of parameters to study the behavior of the system. In microrobotics systems, there are three parameters on which sensing depends. First, the sensor materials should have a high sensitivity to minute changes in the environment, such as force, high pressure, temperature, chemicals, and fluid flow.

Second, as far as the miniaturization point of view for the desired sensitivity is concerned, the sensor should be small enough to be integrated into the micro robotic structure. Finally, the last important parameter is payload, i.e., these sensors should be capable enough to be integrated with the system, and when we try to actuate it, it should not be a burden to the

system; rather, it should complement the system. Another important parameter is the minimal power required to ensure longer operation. Power consumption plays a vital role in these sensing systems, and appropriate characteristics can be deployed, allowing the overall characteristics to be studied in detail. Discussing the different sensor elements further, it is based on the application that we shortlist the sensing element. One of the applications includes chemical reduction. With reference to chemical reduction, we have graphene and carbon nanotubes in place that play an important role in biosensing applications. Furthermore, we have pressure and acceleration sensing that uses silicon-based structures.

So, in cantilever operations, we have discussed serpentine operations and beam-based operations; wherever silicon can be deployed, the actuators can be used appropriately to translate as per requirement. Next, when we talk about vibration sensing, we have discussed piezoelectric materials and triboelectric materials as promising materials for vibration sensing-related applications. Now, when we talk about biosensors for medical biorobotics, biocompatible polymers play a vital role. The biocompatible polymers are capable enough in such a way that they can be deployed for different applications as well as different characteristics, catering to the biological impedance matched without body challenges. The sensor materials are not incorporated with transduction material in the above discussions; however, in most cases, the sensor materials are well incorporated with the transduction materials appropriately for efficient transformation. Now discussing the power source materials. The power source materials in a micro robotic system are always expected to have a charging and recharging capability or non-contact-based charging that can be deployed. So, appropriately having non-contact charging will be helpful to actuate it in localized and specialized domains. So, when we talk about the power source material, the energy density plays a vital role, i.e., the material should have a high energy density to provide a longer operational life cycle.

The microrobots will at times be in a standstill condition, and the arrangement has to be such that stored energy is used when in operation, while the energy should be cut off from use or made leak-proof while not in function; hence, high energy density materials will be of great use and can power the system for longer operations. The second important parameter is with respect to charging and recharging capability. The power source should have the capacity to support fast charging, and the power arrangement in the micro-robot should be rechargeable. For instance, magnetic systems are used for charging applications in certain contexts, and electrostatic systems are used for charging and discharging in specific applications. Even thermoelectric-based systems can be used for charging the system.

As far as weight and flexibility are concerned, the material should be lightweight and flexible enough to integrate with the micro-robotic structures we are looking for. So, we

will discuss the different types of materials that can be deployed for power source materials in the upcoming classes. Thank you.