

## **Micro Robotics**

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### **Micro Mechanics System Design (Design of Microrobots) - Module 05**

The different aspects of micro robotic systems, especially in terms of the selection of materials, the parameters involved in the selection of materials for different domains and subdomains, which are being efficiently used for micro robotic designs. Now, we had discussed the selection of the sensor material, the selection of the actuator material, the selection of the structural material, the different types of materials used for sensing applications in micro robotics, the different materials used for actuators in micro robotics, and the different materials that are used for structural purposes in micro robotics, etc. We have been discussing the power source materials, the parameters required for power source materials, including energy density, charging and recharging capability, weight, and flexibility, which is one of the major requirements for these power source materials. Now, as far as the power source materials are concerned for a micro robotic application, materials like lithium have potential applications. So basically, for kind of thin film batteries for energy storage, graphene for supercapacitors for fast discharge applications, biocompatibility like self-powered micro robots, and a copper and silver structure for antennas for remote powering, etc. So, these are some of the different power source materials that are commercially available.

Sometimes these are developed based on the requirements or based on the functionality. For developing all these power source materials, microfabrication plays a vital role in most of these thin film battery-related applications. So, people used to use a sputtering technique; people used to use an e-beam based technique. Lithographic techniques are efficiently used for fabricating such power source materials, making them compatible with micro-robotic related applications. So, a thorough exposure to these micro fabrications, microfabrication-related applications, and microfabrication-related methodologies is required to appropriately tailor these materials based on the application or based on the characteristics. Now, when we try to talk about control and communication materials, control and communication play a vital role with reference to micro robotics. Either it might be a one-

to-one communication from the control to the concerned actuation of the micro robotic system, or it is a kind of communication between two micro robots, especially when we are talking about swarm robot-based applications or the coordination of micro drones related to the applications we saw in the introductory slide. So, those are some examples where we can directly deploy such kinds of micro drones or micro systems where communication and control play a vital role. These control and communication materials have certain parameters that we may need to consider. One parameter refers to power consumption. So, as far as power consumption for control and communication materials is concerned, it should be low to achieve a long duration of operation for battery-operated micro robots. From a processing speed perspective, it requires high processing speed and is necessary to achieve real-time control and response of a micro robot. As far as the miniaturization perspective is concerned, its size should be minimal for proper integration of the system. And then we have a kind of thermal stability.

So thermal stability plays a vital role. Ideally, whenever such an actuation or sensing occurs, or wherever such a system operates, there is a need for thermal stability. So a control and communication system should be thermally stable and prevent overheating in the micro robot. The most important aspect is with reference to electromagnetic compatibility, i.e., the signal generated from such actuators or sensor systems should not interfere with the external electrical components we are working with. From this material perspective point of view, there are different types of materials that are being efficiently used for control and communication. As far as antennas are concerned, it is highly required that these antennas are a kind of wireless communication circuit. So in the case of antennas, most of the material that is used is gold, silver, and copper. In the case of flexible chips, we have graphene in place that is efficiently used.

In the case of antennas, since we have such kinds of materials, in most of these micro robotics-related applications, the antennas used for communication are a kind of patch-based system. These patch-based systems are kind of a lightweight system that has the capability to be integrated within the system. Next, in the case of an integrated circuit, we have silicon. Silicon is considered to be a dominant material with reference to any kind of microelectronics-related application. From a micro-robotic perspective, this kind of material has potential aspects related to behavior.

Then we have a kind of ultrasonic communication. Ultrasonic communication is concerned with how piezoelectric crystals play a vital role; especially, PZT and zinc oxide-based piezoelectric crystals are efficiently used for a kind of ultrasonic communication and related applications. Then we have flexible antennas in place as far as these flexible antennas are concerned. The conductive polymers are used efficiently, and in addition to conductive polymers, a certain amount of metallic interconnects is also being used efficiently for the fabrication of such kinds of flexible antennas. In fact, from a manufacturing perspective in fabricating these antennas, micro 3D printing has potential

applications in fabricating these antennas directly on the devices or on the micro robotic system based on the application or functional behavior. When we try to talk about future materials, the materials we are focusing on should be lightweight and possess high strength to ensure energy efficiency and durability. The system should have high durability as well as the capability to meet higher order requirements. One of the most important parameters is biocompatibility and biodegradability. From a biocompatible perspective, the system we are fabricating or emphasizing should have biocompatible capabilities. In the meantime, when we are talking about the sustainability of the system, the biodegradability of the system also plays a vital role in the requirements as well as characteristics.

Next, when we try to talk about energy consumption from a point of view, it should be the energy consumption; it should be operational with minimal input power. That is like we discussed a lot about this energy consumption. Still, there is a huge amount of requirement for the usage of these materials or the selection of these materials, which can consume or operate at minimal input power. We have a self-healing and self-assembly capability, as well as a self-healing or self-assembly capability. Therefore, this is one of the prominent properties that are in recent demand.

So, in this prominent property, if you see that whenever there is a defect, the material should automatically have the capability to self-heal and to restore its functionality based on the requirement. So, when we try to talk about functionality, which includes the structures, electrical behavior, and other characteristics, what we are looking at. There are wide varieties of self-healing materials. So when we try to talk about the biodegradable perspective, one of the important points is with respect to temporary implants, bio-integrated robots, and muscle-powered robots. A bio-integrated robot means these kinds of micro robots that are implanted along with the tissue, and they work with the tissue for the required characteristics.

Muscle power robots are concerned; these muscle power robots are polymer-based robots that are available, which basically provide the required energy density for different applications. So, in this particular aspect, there are some materials that have a relevant application towards biodegradability. One is called a biodegradable-based system, and another set of robots is called a bio-inspired material. Silk, fibroin, and gelatin are considered to be some of the promising materials that have a direct application toward temporary implants, a bio-integrated robot, and muscle-powered robot systems. The smart and responsive material, stimuli-responsive polymer, plays a vital role.

In Stimulus response polymer is concerned; stimulus action or the immediate response action has a direct relevance to the response time of the system. These micro robots function by responding to changes in external stimuli such as light and humidity, which can be appropriately used for generating or establishing smart and responsive materials. There are wide varieties of materials that have a kind of capability towards these stimulus-

response polymers. When we discuss the different types of these polymeric materials for actuator applications, we will also discuss these polymers. Self-healing materials, such as polymers and hydrogels that can achieve self-repair, come under the category of this self-healing material.

The self-healing materials are concerned; they should have the capability to retain functionality even when a defect state is observed, and appropriate characteristics can be retained by these self-healing properties. There are a certain number of polymers and hydrogels that have a capability for this self-healing capability. To summarize, we discussed the overall key factors for material selection: mechanical properties, electrical properties, magnetic properties, biocompatibility, ease of manufacturing, and environmental stability. With reference to the structural material perspective, different process parameters affect the structure of the material. We have also discussed the overall different types of materials and their applications, actuator materials and their applications, and sensor materials and their applications.

The power source materials and this application, basically focused on the type of externally energy-based power sources and energy-efficient power sources, etc., control and communication materials and their appropriate applications. And then we have also discussed the future materials in which some of the key components, including the biocompatible and biodegradable materials, energy consumption, and self-healing, are considered to be additional materials that come into the picture. Now, we will discuss one of the important aspects of this micromechanical system design, which is the control of the surface walker, i.e., a kind of propulsion like the micro robot used for walking on a surface that can show various kinds of motion such as walking, crawling, rolling, and jumping, which are considered to be major characteristics. We can also say that the propulsion of these micro robots has various classifications based on the kind of environment we are using, or based on the type of functionality we are using. It is necessary to select an appropriate mechanism for these micro control micro robots to generate a kind of motion. The surface walking of micro robots is concerned; we may need to look into some of the key parameters, and we may also need to study the different parameters that influence the control of the surface worker. The surface walking of a microrobot experiences various forces during motion.

One is a type of external force that exists. The external forces include the gravitational force, represented as  $F_g$ ; the normal support, represented as  $F_n$ ; frictional forces, represented as  $F_r$ ; and the air resistance drag force, represented as  $F_d$ . The internal forces generated by the robot include a propulsive force  $F_p$ , an adhesion force  $F_a$ , and a torque for legged motion known as  $\tau$ . Let's discuss the parameters that influence the overall propulsion of a micro robot. The external forces are the gravitational force, which is

represented

as

Fg.

$$F_g = mg$$

The weight of the micro robot is pulling it downwards due to gravity, and it is given as  $F_g$  equals  $mg$ , where  $m$  is the mass of the micro robot and  $g$  is the acceleration due to gravity. Similarly, the normal forces known as  $F_n$  are the normal forces that are being generated, and this is due to the gravitational force. The normal reaction to the weight is given as

$$F_n = mg \quad \text{- For motion on horizontal surfaces.}$$
$$F_n = mg \cos\theta \quad \text{- For motion on inclined surfaces}$$

where  $F_n$  is the normal force and  $\theta$  is the angle of inclination of the surfaces. Now, let's consider the frictional forces. It is the resistance force of the surface on the micro robot; it provides the necessary traction for walking. It is given as  $F_f$  equals

$$F_f = \mu F_n$$

$F_n$  is the kind of normal force that exists;  $F_f$  is a kind of frictional force that is represented here.  $F_d$  is the kind of drag force that is being generated over here.  $F_n$  is the normal force, and  $\mu$  is the coefficient of friction for the frictional force, which is exhibited here. Now, let us consider the drag force. As the size of the micro robot is very small, the force acting on it due to the surrounding air becomes significant during motion. So, it gives  $F_d$  equals to

$$F_d = \frac{1}{2} C_p A v^2$$

where  $C$  is the drag coefficient,  $\rho$  is the density of the surrounding air. Since it is on a micron level, of course, the density of the surrounding air will have an impact on the propulsion of these kinds of micro robotic systems.  $A$  is the surface area of the micro robot that is in contact with the air, and  $v$  is the velocity of the motion that occurs in the system. The internal forces exhibited in an internal condition are known as proportional forces. The proportional forces are concerned; it is the force generated by the leg, wheel, or the other actuator during the locomotion of the microrobot. To achieve a significant movement, the proportional forces must be greater than the sum of the resistive forces. So, let us consider the motion of  $F_p$ , which is greater than  $F_f$  plus  $F_d$ . If this is our system, where  $F_p$  is the proportional force, which is the total force generated by all the legs. The parameters of  $F_p$ ,

$$F_p = N \times F_1$$

where  $N$  is the number of legs and  $F_1$  is the force generated by each leg.

So, for motion, when  $F_p$  is greater than  $F_f$  plus  $F_t$ , that is when the proportion of the force is the total forward force generated by all the legs of a legged micro robot. Similarly, let's have a different kind of micro robot. In some cases, there is a kind of electrostatic adhesion force that sticks to the surface.

Let us consider a legged robot. The adhesion of this legged robot to the surface will have an impact on the motion. In those conditions, there is a need to consider the adhesion force. The adhesion force,

$$F_a = \frac{\epsilon A v^2}{2 d^2}$$

where  $\epsilon$  is the permittivity,  $A$  is the area of the contact,  $v$  is the voltage applied, and  $d$  is the distance between the surfaces. So, in most cases, these adhesions are taken care of by the electrostatic adhesion forces. Now, let's consider the torque; the torque is a kind of force for legged motion, which is represented as  $\tau$ . The torque is useful when the legs of the micro robots rotate around a hinge to generate motion. For a leg with length  $L$  and leg force  $FL$ , the torque generated is considered as

$$T = Fl \times l$$

Now, one of the important aspects that come into such a kind of walker robot is called stability control. In most cases, the surface walker always moves. So, let us consider this as a kind of surface walker. This is a kind of load that is available, and here it is a kind of two-leg system, though. So, initially, the surface walker is at this particular portion, and it is pushing the surface. The surface walker moves due to pushing locomotion, where the force is generated by the micro-robot pushing against the resistance and the surface to achieve walking. The surface walker is usually a slow mover; thus, static stability is required. The static stability is derived by using support polygons. A leg position and the stability of the micro robot are controlled by adjusting the forces and the torques dynamically. Ideally, the control stability of such a simple surface worker, when it tries to move forward, involves two different strategies. One strategy is called PID control and the other is called force control. So let us discuss the generalized strategies that are being employed for control stability. Now, let us talk about the overall control stability of a micro robot.

One of the key strategies for considering the micro robot stability is called the polygon for micro robot stability. The support polygon is the area enclosed by the contact points of the micro robot with the surface. For continuous walking without tipping of the micro robots, their center of mass should lie inside the support of the polygon. Consider a quadruped

four-legged micro robot. In this quadruped micro robot, it has four legs as mentioned, and the center of mass stays over here, and then there is a rectangle, this one. All the legs are on the surface, so we get a kind of rectangular shape, and the center of mass of the micro robot shifts towards the most stable position while walking. The stability depends upon the position of the center of mass with reference to the support of the polygon; i.e., when all the legs are on the surface, a rectangular profile is generated. When one more leg is moving, we get a triangular profile.

So, that is how this kind of micro stability is studied. Now, one of the key parameters involved in this stability perspective is the stability margin. The stability margin is the minimum distance of the projection of the center of mass from the support polygon boundary. The center of mass is available here, and  $M$  is a kind of stability margin that is represented in this direction. As previously mentioned, it has two different conditions. One is when all the legs are spaced at the point; we get a kind of rectangle domain, and when one leg is at the free end, we get a triangle or one-leg domain. In this case, a quadruped robot is deployed under these conditions for a quadruped micro robot. When  $m$  is positive, it is inside the support. If  $m$  is greater than 0, the micro robot is stable, whereas when  $m$  is less than or equal to 0, the micro robot basically tips over. Thus, a higher positive value of the stability margin provides better stability to the micro robot during motion.

This stability margin plays a vital role in studying the stability of the micro robot in relation to motion or requirements. Next, let us consider a hexapod. So, in this particular hexapod, considering  $M$  and all the legs are grounded, now trace a hexapod in that entire region. Similarly, it has three legs on the ground and three positions. These three positions are appropriately grounded here, and then the mass is placed in this particular position.

In a static position, all slick legs are on the ground, and the stability of the polygon is exact. The center of mass of the micro robot is at the geometric center of the hexagon. While moving, three legs are in contact with the ground at a time for a stable gait. Thus, the stability polygon reduces to a triangle, and the center of mass of the micro robot shifts away from the geometric center of the body.

That is, if  $m$  is greater than 0, the micro-robot is stable. If  $m$  is less than or equal to 0, the micro robot tips over. This acts as a base condition for micro-robot stability on the surface. Now, when we try to talk about the control strategies of a surface walker as discussed earlier, when we consider a PID control, which is the proportional-integral-derivative control, the leg portion is controlled based on these generalized equations.

$$u(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt}$$

where  $e(t)$  is the error in position, and  $k_p$ ,  $k_i$ , and  $k_d$  are the proportional, integral, and derivative gains of the leg position.  $y(t)$  is the desired position of the leg and  $y'(t)$  is the actual position of the leg. So, the error in the position can be represented as  $E(t)$ ,

$$e(t) = y(t) - y'(t)$$

Let's consider a proportional term; it generates an output that is proportional to the error. It is usually a fast response, but high values can lead to a steady-state error.

$$u_p(t) = k_p e(t)$$

The integral term, which is available,

$$u_i(t) = k_i \int e(t) dt$$

It accumulates the past error to eliminate steady-state error. It reduces the error over time. The derivative perspective point of view,

$$u_d(t) = k_d \frac{de(t)}{dt}$$

It reduces oscillation and also increases system stability. These are some kinds of general terminology. Now let's consider the force control; earlier, it was the PID control.

The force control in a micro robot ensures that it moves as a result of pushing against the surface without slipping. It needs to consider the propulsion force, the normal force, and the coefficient of friction. So, in the case of proportional force,

$$F_p \leq \mu F_n$$

where  $\mu$  is the coefficient of friction,  $F_n$  is the normal force, and  $F_p$  is the proportional force. The proportional force is monitored with a force feedback sensor, and it is adjusted as per the requirement. Until now, we have discussed the control for surface walkers, the different parameters involved, such as various forces during motion, including the external forces, the gravitational forces, and the normal support forces, as well as the frictional forces and the air resistance forces. The internal forces are the proportional forces, adhesion forces, and the torque forces, which exhibit over the system. These are generalized formulations of how the gravitational force and the normal force will exert force on the

micro robotic system. In addition to this, a frictional force and a drag force will try to contribute to this particular system. In the case of internal forces, a proportional force plays a vital role. Let's discuss the legs of the micro robot and the force generated by all the legs.

$F_1$  is the force generated by each leg and  $N$  is the number of legs, while the adhesion forces need to be considered. From an adhesion forces perspective, the area of contact, the voltage applied, and distance play a vital role. So, two important parameters need to be considered. One is the kind of adhesion force as well as the torque that is being generated here. This is a kind of arrangement for a surface walker. In a surface worker, it is a kind of pushing locomotion that it exhibits. In order to take care of control stability, two important strategies are followed. One is a kind of PID and the other one is a kind of force. In addition, from a structural perspective, two types of micro robot stability are exhibited.

One is a kind of support polygon-based system. It is a quadruped, four-legged micro robot, and by considering the center of mass, let's discuss the stability when the legs are moving. So appropriately, these quadruped micro robots will try to deflect, and finally, it will form a triangular base. One of the key parameters to understand this process is the kind of stability margin. From the stability margin's perspective, all the legs on the surface are present, and the boundary condition is set with reference to the micro robot's stability.

A hexapod, with all legs on the ground and the three-leg system. As far as control strategies are concerned, we have discussed the PID, the proportional term, the integral term, the derivative term, the generalized equations that are being deployed, the force control, and the overall propulsion forces that are being exerted in the system. These are some of the references that are used for preparing the slides, and I acknowledge the authors for the support. Thank you. The thin film biomorph has been fabricated using different physical vapor deposition techniques such as thermal evaporation or electron beam evaporation, which can be used in various applications, such as Stewart platform assembly. The different structures such as circular or triangular structures, have been cut with the help of laser micro machining.

These structures are used for the fabrication of the Stewart platform assembly. This Stewart platform assembly is basically a fixed base and moving platform, which in this case is a mirror which is a lightweight mirror which is in the central part. This is our central part which has movable platform as the mirror and it is supported using four different four different actuators. All the parts are NiTi SMA based, and they have been machined using laser machining and then this structure in which the mirror is being moved with the help of the motion of these four actuators individually or in combination. When the electrical energy is supplied to any one of the actuator, it will actuate in the forward direction as shown in in electrical actuation video.

When the energy is supplied to the actuator, it will move in the forward direction and because of that forward motion our mirror will tilt in upward direction or downward direction. According to the motion of the actuator and because of that motion, or mirror tilting, it can be used for further application of laser beam steering such as optical scanning or optical communication applications. Here, ArUco markers are placed over the mirror. These ArUco markers are basically used for position detection of the mirror so that we can accurately determine the position and angle of the mirror. For simplification, three different ArUco markers at different positions of the mirror are placed for single plane of reference.

There is a camera on the top so that the camera continuously monitors the position of the ArUco marker. Initially the mirror is at horizontal position, the camera takes the position of these three aruco markers generate the equation of a plane which corresponds to the horizontal position of the mirror. As power is supplied to any one of the actuators, this mirror will tilt. Due to tilting, the position of the aruco markers with respect to our camera changes, and as it changes the new position will be detected by the camera. Then it again generates an equation of a new plane and will give the final angles of the plane or the mirror with respect to the initial position.

So when the mirror is moving, the X and Y positions are changing. So, these red, blue and green lines, they are the X, Y and Z axis of the ArUco markers. With mirror movement, these positions are changing, and angles are also changing. Here a live feed of angles of the plane with the initial condition and current position of mirror can be observed. The same can be used as feedback to control the input power to the actuator so that we can control the final position of the mirror.