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Lecture No- 47

Microsystem for Microrobotics (Integrated approach) - Module 02

So we have been discussing the micro system for micro robots. We have discussed the different micro assemblies and associated techniques involved with reference to these micro assemblies, including the forces exerted in these micro assemblies, such as surface tension, van der Waals forces, electrostatic charges, and gravity. The overall mechanical microsystems, the overview of the technologies, and our classification of them with reference to the different building blocks, techniques, and applications. Additionally, we have discussed the application of the electric field, related technologies, and the different features of the technologies in detail. Now we will discuss the overall forces that are participating in a micro assembly for micro robotic applications. So, among these forces, first let us discuss the electrostatic forces.

The electrostatic forces can be studied as the force between a charged sphere and a conducting plane. So, the overall generalized equation is

$$F = q^2 / (4 \pi \epsilon r^2),$$

where q is the charge, ϵ is the dielectric permittivity of the medium, r is the object radius, and the assumed charge density is approximately $1.6 \times 10^6 \text{ C/m}^2$. Working on this principle, let us consider that there is a microgripper holding a spherical object. The overall force being exerted is considered as F_{grip} . The microgripper consists of two layers: one is a kind of oxide layer, and then there is a gripper layer; by appropriate electrostatic forces, these oxide layers and the gripper layer will be actuated and generate a force along the diameter of the object. Also, Van der Waals forces act between the sphere and the micro gripper. These van der Waals forces are considered for a sphere and a plane arrangement, and they are approximately estimated by the following equation.

$$F = hr / 8\pi z^2,$$

h is the Lifshitz-van der Waals constant, and z is the atomic separation between the surfaces.

These forces also participate in gripping-related applications. Then we have these hydrophilic surfaces. There may be a liquid film between the spherical object and the planar surface, which is contributing a large capillary force that is the surface tension force. The surface tension force is given as

$$F = \gamma (\cos \Theta_1 + \cos \Theta_2) A/d.$$

Where γ is the surface tension, A is the contact area, d is the gap between the surfaces, and θ_1 and θ_2 are the contact angles between the liquid and the surfaces. Now the comparison between the different forces in a micro gripper is shown in the figure. The participation of different forces and their impact is discussed. The figure gives us clarity about the influence of gravity, Van der Waals forces, electrostatic forces, and surface tension. For a spherical part of silicon, the gravitational force is

$$F = (4/3) (\pi r^3) (\rho_{si} g).$$

For accurate placement, the adhesion forces should be an order of magnitude less than the gravitational forces.

So the capillary forces basically dominate and must be prevented to allow accurate placement. The Van der Waals forces can start to be significant (with smooth surfaces) at about a 100-micrometer radius, and they can generate an electric charge from the contact, which could prevent dry manipulation of power less than 10 micrometers in size. Now, considering the influence of the size of the object on the forces: for a smaller object radius, Van der Waals forces and surface tension forces dominate the gripping. As the object size increases, the significance of gravity becomes greater compared to surface tension and electrostatic forces. Now let us see different types of micro assemblies that are being exhibited for micro robotic applications. First is serial micro assembly. Serial micro assembly is a kind of sequential process where micro components are assembled one at a time. The key features are that it uses a micro manipulator, a micro gripper, and a positioning system. It also requires real-time feedback from the microscope or force sensors. Additionally, we can perform offline calibration or sensory feedback control, which enhances the precision.

Some of the key challenges include a time-consuming process for micro-assembling and a high precision requirement that increases the cost of the system. The applications of serial micro assembly include the MEMS integration, such as in micro optical benches, micro spectrometers, and micro robots. The subsystem for serial micro assembly includes a micro manipulator, a micro gripper or tool, a micro part, and a micro structure as key components. Micro manipulator and micro gripper tools communicate through a micro interface. The micro gripper tool and micro part involve communication via a temporary micro interface,

and from the micro part to the micro structure, there is a permanent joint interface.

Now let us discuss the parallel microassembly. The overall schematic of a parallel microassembly is shown in the figure, where the simultaneous assembly of multiple components using a multi-gripper system or self-assembly can be deployed. The key features of these systems are that they use a kind of gripper array, electrostatic or magnetic force, or fluidic self-assembly systems. Secondly, it has an increased throughput compared to the serial method. The advantage of this microassembly includes its high efficiency and high productivity. Also, it is a cost-effective method for large-scale production. Applications of parallel microassembly are flip chip technologies, and it is also widely used for the self-assembly of microstructures. Now, let us take a look into the comparison of serial microassembly and parallel microassembly. With reference to the speed perspective point of view, the serial microassembly is slow, whereas the parallel microassembly is fast. Serial microassembly can produce highly precise microassemblies, while parallel micro assembly gives moderate precision.

However, serial micro assembly is costly compared to parallel microassembly. The automation of serial microassembly requires real-time feedback, while parallel microassembly requires a self-organizing or multi-gripper system. Serial microassembly is used in high-precision MEMS applications. On the contrary, parallel microassembly is utilized for large-scale microdevice assembly. In summary, serials are highly used for high precision and small-scale applications. Parallel is ideal for high volume and cost-effective manufacturing. The future direction of these microassemblies is toward hybrid systems for higher efficiency and greater flexibility. Now let us discuss the different relationships that exist in microassembly for micro robotic applications. So one of the key aspects is called the stochastic effect. Here, the relationship between the part and its destination is unknown or random. So the parts are self-assembled during the stochastic process. This involves fluidic agitation and mating part shapes, vibratory agitation and electrostatic force fields, vibratory agitation and mating part shape, and mating patterns of self-assembling monolayers. The mating patterns for self-assembling monolayers comprise a number of microparts, and there is a certain number of receptor sites available. These microparts are fed close to the receptor sites. After agitating the part, most receptor sites are filled by a micro part. However, there is always a possibility of error. For example, there may be unfilled receptor sites. Usually, more micro parts than receptor sites are used for such a kind of system. This was a stochastic process in which the micro part is assembled on a receptor site. Thus, appropriate mating or bonding is required for proper assembly.

Now let us talk about self-assembly. So self-assembly leverages physical forces such as capillary, magnetic, and electrostatic forces to automatically position the components without direct manipulation. This approach offers high throughput but reduced pressure

compared to deterministic methods. The key techniques include shape-directed assembly. Another is fluidic self-assembly.

The third is surface tension-driven assembly. The fourth is magnetic self-assembly. The primary advantage of this system is parallel operation, allowing many components to assemble simultaneously. An illustration is given in the figure. Here, we have multiple balls dropping inside a cup. A ball is released into a cup, and potential energy is converted into kinetic energy. Also, the ball is attracted toward the energy minimum, which is at the bottom of the cup. Slowly, the kinetic energy is dissipated as heat, and the ball settles to the center of the cup. Now, considering the four key techniques mentioned above, this is a shape-directed assembly where, based on the shape or geometry, we can orient the assembly for a particular alignment. In fluidic self-assembly, let us consider a hemispherical structure where there is a fluid. In most cases, because of the fluidic interaction in the available circular curvature, the particles will try to accumulate in the circular curvature region. Next is the surface tension-driven assembly. Here, based on the surface tension of the fluid, assemblies can be formed. Then we have a magnetic self-assembly where a magnetic field is utilized to align the microcomponents, thereby forming the assembly. As discussed, the major advantage of this system is that it allows parallel operation and enables many components to assemble simultaneously.

Since the overall assembly is controlled by shape, fluid, surface tension, or magnetic field, it is easy to automate the system to obtain the required assembly models. Now we will discuss directed microassembly. It is a controlled approach to assembling microscale objects by leveraging specific interactions. Let us take an example here; the figure shows a system of an inverted microscope, and fluidic interactions are involved. An electromagnet is placed at the boundaries and in the fluid. Now, by giving an appropriate field to this electromagnet, these fluidic interfaces will get aligned, creating a sub-assembly, and the leveraging of this assembly is taken care of by the magnetic field. The importance of such assembly is that it enables precise micromanipulation for manufacturing complex microstructures. Some of the techniques that are used include capillary interaction and magnetic microrobots. Now let us take a kind of capillary interaction in microassembly. It falls under the category of a fluid domain. The concept involved is that the microparticles at the fluid interface disturb the interface shape and migrate to minimize the interfacial area. So it is independent of the material property and it allows the assembly of diverse particles. Such microassemblies find application in microfabrication, biomedical devices, and smart materials. Now considering magnetic micro robots. This mechanism involves mobile micro robots that distort fluid interfaces and generate attractive capillary forces.

These robots can precisely position and assemble the microparticles. The key advantages are non-contact manipulation; it works with passive microparticles that do not respond to electric and magnetic fields. Now, consider the behavior of the magnetic assemblies. The magnetic assemblies are formed with arbitrary geometries and functions. So these magnetic

assemblies can accomplish several configurations in different dimensions, designing devices with arbitrary structures, which remain a significant challenge because of unclear design and rules.

It enables the controllable and selective docking and assembly of magnetic devices with the desired microscopic pattern or mechanical structures. So the manipulation of microstructural units of these kinds of magnetic assemblies paves the way from micro devices to micro robots. Therefore, this section delves into the magnetic units and their magnetization under different magnetic fields. The key parameters pertaining to these systems are the force and torque of the magnetic unit in the magnetic field, which can be calculated as follows:

$$F(P) = \text{del}[m(P) \cdot B(P)]$$

Where $F(P)$ is the magnetic force, $M(P)$ and $B(P)$ are the induced magnetic dipole moment of the cluster and the magnetic field at point P , respectively. Thus, the magnetic torque $T(P)$ is given as

$$T(P) = M(P) \times B(P).$$

Let us take a simple case study where such kinds of magnetic assemblies are being deployed. In this case study, we have a reconfigurable self-assembly of photocatalytic magnetic microrobots. These kinds of microrobots are used for water purification. The overall structure has a lobe of a self-propelled, light-powered magnetic microbot. Inside this lobe-like structure, there is a core-shell arrangement.

This core shell arrangement comprises TiO_2 and $\alpha \text{Fe}_2\text{O}_3$. The lobe structure is controlled by two different mediums; one is a magnetic field, and the other is a kind of photocatalytic material that is converted through light. It works on three different kinds of interactions: one is a phoretic interaction, the second is an active cluster, and the third is a magnetic dipole and dipole interaction. It works in the form of a chain: firstly, there is a magnetic dipole-dipole interaction, then the active clusters, and finally phoretic interaction. The system involving the lobe kind of structure is a self-propelled light-powered magnetic robot, and the closed chain represents a reconfigurable system. These systems are mainly meant for the development of artificial small-scale robots, robotic spam with a nature-based biomimicking arrangement. They exhibit a collective behavior that represents the frontier of research in robotics. The micro robot moving under magnetic manipulation exhibits self-organization of micro-nano robots that can be deployed. The interaction is controlled, reconfigurable, and reversible. Also, it is a kind of active self-assembly of TiO_2 and $\alpha \text{Fe}_2\text{O}_3$ micro robots.

It is a peanut-shaped system, and these microparticles are synthesized by a different route. One of the major routes is the hydrothermal process, where the system is covered with a thin layer of TiO₂ by ALD deposition. There will be two layers: one is a core and the other is a clad. The core is alpha Fe₂O₃, and the clad is completely covered with a TiO₂ layer with the help of the ALD process. Due to their photocatalytic and ferromagnetic properties, these micro robots can autonomously move in underwater conditions using light irradiation.

The magnetic field precisely controls their direction. In the presence of H₂O₂ fuel concentration, the gradient along the illuminated micro-robots results in a kind of mutual attraction through the phoretic interactions, inducing their spontaneous organization into a self-propelled cluster. So in the dark, the cluster will reversibly reconfigure into a microchain where the microrobots are aligned and the photocatalytic properties can be appropriately used. It has more to do with the structure and the orientation or the self-alignment of the structure, which is taken care of by applying an appropriate magnetic field to the system. There are two different types of propulsion. This includes magnetic field and light-powered propulsion. Both collaborate to assemble these particles and appropriately configure these micro-robots for efficient photocatalytic applications. Now we are comparing directed assembly with traditional microassembly. Considering the manipulation mechanism, directed micro assembly is manipulated using capillary force and a magnetic field, while traditional micro assembly involves a mechanical or electrostatic mechanism. The precision generated by capillaries and the magnetic field is of high precision. However, the traditional micro assembly produces moderate precision, as we have seen earlier that with the electrostatic charge, there is a chance that the magnetic field and the gravitational force will also influence and resist the overall movement. Considering the compatibility of the assembly, directed microassembly works with passive particles, while traditional microassembly is material-dependent. Finally, direct microassembly can be controlled with an external magnetic field, while traditional microassembly is controlled by direct physical manipulation. In summary, the direct microassembly utilizes capillary force for precise assembly. The magnetic micro robots enable non-contact manipulation of micro particles. The different challenges regarding these microassemblies relate to micro manufacturing. Next, we will discuss the aspects related to this hybrid microassembly in the next class.