

Microrobotics

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Week- 1

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Scaling Laws of Microrobots - Module 02

We have been discussing the scaling laws for designing micro robotic systems. In fact, we have discussed a lot about the different configurations, how we scale up and scale down the system from a macro to a micro level, and how the system behaves. We had some detailed interactions about rigid body dynamics with reference to the micro robotic perspective, and we also had some discussions about the usage of these electrostatic actuators for micro robotic-related applications, especially the fundamentals of these electrostatic actuators towards micro robotics development. Now we will discuss the scaling of electromagnetic forces. As far as these electromagnetic forces are concerned, they play a vital role in Microrobotics applications. The key motivation in considering these electromagnetic forces is that most of you might be aware of these origami-based robots. When it comes to these origami-based robots, they assume a reconfigurable shape tailored to the specific application we seek. For example, we have a tube, and inside the tube, if you want to make a structure, these structures are reconfigured. It tries to roll into the tube so that it can be used for inspection, for cleaning, or for a complete structural analysis, etc. Now, as far as scaling in electromagnetics is concerned, when we consider electromagnetic actuation, it can be effectively used for shrinking a microrobot.

For example, let us consider this as a tube, and we have a robotic structure that has a petal type. When we try to supply an appropriate actuation to it, it gets thin and then tries to

move into the system. So, what happens is that this structure can easily get contracted, and it can easily pass through the tube for appropriate movement. Here, electromagnetic forces play a vital role in bringing a macro system to a micro system; it also has the capability of facilitating locomotion. So, to have precise locomotion or micron locomotion, such electromagnetic forces play a vital role. As discussed, unlike in a macroscopic system where gravity is dominant, these electromagnetic forces become substantially stronger at small scales. When we investigate the fundamentals behind electromagnetic forces, these forces follow a fundamental physics law that determines how they scale with the size of an object, which is one of the key functionalities that we will be addressing for micro-robotic design or development. So, when we investigate the charges of these scaling laws, if an object's surface area scales as k^2 , then the total charge it can hold, assuming a constant surface charge density, also scales, which we can represent as $q \propto k^3$. The scaling of electrostatic force, which we call Coulomb's law, states that the electrostatic force between two charged particles is given by this law: $F \propto \frac{q_1 q_2}{r^2}$. If the charge scale has k^3 and the distance scale has k , the force can be represented as

$$F' = k \frac{(k^3 q_1)(k^3 q_2)}{(k^2)^2}$$

So, if we try to simplify it, we can represent it as k^4 , $k^4 F$, and $k^4 F$. So, this is the overall governing equation that can be used whenever we are trying to consider an electromagnetic force or electromagnetic actuation for micro robotic device development. What is the key motivation for considering this electromagnetic scaling? These electromagnetic scaling matter highly in micro robots. Some of the key salient features of considering this electromagnetic scaling factor are that, since electric and magnetic forces dominate at small scales, the gravitational force becomes negligible, allowing the electrostatic and magnetic actuators to work efficiently. With reference to the charge perspective, energy management in a micro robotic system is considered one of the key challenges that need to be addressed. In fact, people are attempting different types of methodologies. In our lectures, we will also be discussing more about such kinds of power management for Microrobotics systems and how those problems are addressed. For instance, miniaturization limits the onboard batteries in the system. There is a need to adopt

an inductive capacitive wireless charging method, which is considered crucial. Now, when we consider the optical and quantum effect-based systems, these optical and quantum effects become significant.

Especially when we try to consider the effect and the photonic interaction, which basically influences micro-robotic communication. In addition, there are a kind of quantum tunneling and Casimir forces that may also become a relevant system from a micro-robotic publication perspective. When we investigate the application of these electromagnetic scaling in micro-robots, we consider these electromagnetic actuations, which are used in MEMS, especially in MEMS-based micro-robots, with reference to the magnetic micro-robot perspective. One of the key advantages of using these magnetically based micro robots is that they can be remotely controlled by an external magnetic field. For instance, this is a kind of micro robot that is used for targeted drug delivery. So, in this micro robot, to cater to locomotion or movement, we can effectively use an electromagnetic system for appropriate resolution. Next is with reference to the optical tweezer's perspective. The optical tweezers are one of the most efficient systems that are effectively used for micro-robotic related applications. In fact, in our entire series, we will be discussing opto-mechatronic systems, how these opto-mechatronic systems are effectively used to develop micro robotic structures, and light-driven micro robots. In fact, I will also be discussing these light-driven microrobots, their overall functionality, and the fundamentals of these light-driven microrobots in detail.

When we investigate these optical tweezers, they are used for trapping, and the main fundamental behind the usage of these optical-based micro robots, optically actuated micro robots, is that if we integrate a nanoparticle along with the structure appropriately, we can actuate the system. Next, when we talk about wireless power transfer, this is where inductive and capacitive charging for untethered robots comes into the picture. Next, which we discussed, is a kind of plasmonic nanorobot that talks more about the use of light-matter interaction for movement. In fact, in this structure, there is a small micro robot to which a small gripper kind of arrangement is attached. The actuation of this gripper is high through an electromagnetic structure, so that we can have an appropriate coil. By applying an electric field or by applying a magnetic field, we can achieve precise manipulation in this

system. Now, one of the key aspects that we have addressed here is more to do with micromanipulation and system takes care of the power transfer. In addition to this, adhesion also plays a vital role. When we try to investigate the adhesion perspective, as we discussed earlier, a part of locomotion will also be considered for adhesion because we should consider a gecko-based robot, which is a kind of lizard-based structure that is trying to walk on a wall. So, there will be suction or adhesion with an actuation, which will be helpful for appropriate movement in the system.

Now, as far as the nature of adhesion for these micro robots is concerned, there are four different forces that are exhibited here, i.e., Van der Waals forces, electrostatic forces, gravitational forces, and surface tension, which are exhibited in this aspect. Now, as far as electrostatics, we have discussed a lot about gravitational forces, and we are more aware of them; in certain cases, they need to be overcome either through electromagnetic means or through electrostatics. With reference to the van der Waals perspective, one of the important aspects is that these van der Waals forces are present in all materials, resulting in an interaction between the instantaneous dipole moments of atoms.

So, when we try to closely observe the overall fundamentals behind these Van der Waals forces, we can classify these Van der Waals forces into three categories. One is called the Keesom force. The Keesom force basically relates the average angle, average dipole, and the dipole interaction between two atoms or molecules. Next, when we talk about the Debye force, the Debye force is the angle-averaged dipole that induces a dipole interaction between two atoms or molecules. Next, we have the dispersion force. The dispersion force essentially contributes to the van der Waals forces, which relates to the instantaneous dipole that induces dipole interactions. The force of quantum mechanics in nature acts at more than 10 nanometers. So, basically, from the micro robot, the overall adhesion actuation capability will lie in the nanometer domain, which will result in a kind of interaction. So, ideally, if you see in the system, there is a certain amount of microfibers. It basically corresponds to a locomotion mechanism of a gecko-inspired climbing robot, which we will discuss in detail when we come to these bio-inspired robots.

A gecko-inspired climbing robot will have certain nanofibers, and we have microfibers and micro- and nanoscale-based structures. These nanofibers have complete control over

adhesion, and this is exactly where the Van der Waals forces come into play. Ideally, all these forces will contribute to movement or locomotion. If we investigate the overall configuration of the force that is being derived, we can gain insights. Potentials that are derived from these forces can be represented as u_{Dw} ,

$$u_{Dw} = (-C_k + C_d + C_l)/6$$

which is minus C_k plus C_d plus C_l by R_6 , where these three parameters represent that C_k corresponds to the key sum and the Debye force represents C_d , and the dispersion force corresponds to C_l . So, this is basically how such kinds of adhesion forces are taken into consideration. Now, whenever we try to design these micro-robotic structures with reference to adhesion forces, these plots help us create the structure based on our requirements. So, ideally, based on the diameter or size appropriately, we can determine how much force will be applied or which will fall on the surface. Based on that, the relations can be appropriately taken from this plot, which would be highly useful whenever we are designing the system.

Now let us talk about or have a brief overview of scaling in electricity. As far as electricity is concerned, at a micro scale, it follows a different scaling law than in macroscopic systems. So as the object becomes smaller, properties like resistance, capacitance, and inductance scale differently, which affects the performance of microelectronic circuits and micro robots. When we consider a micro robot, there is a need to have a kind of electrical system, a type of micro electrical pulse, which needs to be integrated into the system, and these micro electrical pulses will be effective enough to create an appropriate micro propulsion system. Some of the scaling laws related to electricity may be derived from a simple law that is discussed. That is, if we try to investigate the parameters, we have electrical resistance, power loss due to resistance, and electric field energy. In addition, we have the capacitance and the inductance. Now, if we observe the influence of inductance on capacitance, let us understand the different common parameters that are being deployed. Some of the parameters include the ρ , which is the electrical resistivity of the material. L and A , which correspond to the length and the cross-sectional area, respectively, of the

conductor; V is the applied voltage; ϵ is the permittivity of the dielectric; E is the electric field strength; D is the separation distance; μ is the permeability of the core; N is the number of turns in the coil; and L is the length of the coil. Now, why do we require these electrical scaling matters in micro robotic systems? So we may need to consider the following parameters: one is with reference to power efficiency and heat dissipation. As the circuit gets smaller, the resistance will increase and there will be higher power losses. It is highly useful for managing heat dissipation, which is crucial in microprocessors and micro activities. Now, with respect to the signal integrity perspective, it has a lower capacitance and inductance effect. It has signal propagation and filtering and is mainly meant for making high-speed communication, which is a bit difficult.

With reference to breakdown voltage and reliability perspective, it has miniaturized circuits that are more vulnerable to electrical breakdown, and it requires stronger dielectric materials. One of the key aspects with reference to micro robotic actuation and energy storage is electrostatic forces, which dominate a small-scale influence on micro robotic movement. A miniaturized battery stores less energy, so these micro robots rely on wireless power transfer. When we try to investigate the applications of electrical scaling in micro robotics, we have an electrostatic actuator that is used in MEMS and micro robots for precise motion. There is a certain amount of microelectronics that include small-scale capacitors and inductors that impact the circuit design. Then we also have energy harvesting, where microrobots use inductive and capacitive power transfer, which is being exhibited. There are biomedical devices where microscale sensors and implants rely on low-power electronics. As far as the fundamentals of the scaling laws in electricity are concerned, if we try to map the electrical property with reference to the scaling size and the scaling effect, the electrical resistance, which is represented (K^{-1}), decreases with miniaturization. With reference to the resistance power loss perspective, it is represented as (K^1), which increases and affects circuit efficiency. The electrical field energy, represented as u , which is (K^{-2}) decreases, and with reference to capacitance, represented as (K^1), the capacitance increases with miniaturization.

With reference to the inductance perspective, k power minus 1, the inductance decreases, limiting the electromagnetic energy storage. So, to summarize what we have been

discussing about the electromagnetic-based system, the scaling laws of electromagnetic systems, and how these electromagnetic systems are effectively used for different micro robotic designs or from a micro robotic perspective. So, we also have some discussion about the electrostatic actuations, how these electrostatic actuations are deployed, and how they are being effectively used for different applications. The adhesion force in micro robotic systems is a separate study. There are different adhesion forces that participate whenever we are trying to design these micro robotic structures.

If we try to classify these adhesions, we have Vander Waals forces, electrostatic forces, gravitational forces, and surface tension, which play a vital role. Now when we try to classify these Van der Waals forces, we have the Keesom forces, the Debye forces, and the dispersion forces, which exhibit. Now, electrical-related aspects with reference to micro-robotics are highly challenging. There is a need to understand the phenomenon of scaling of electricity, what the parameters are involved with reference to the electric perspective, and how it behaves when it comes to a miniaturized level. In that aspect, if we investigate it, we have summarized it in such a way that, with reference to different parameters and the scaling effect or in the micro domain, how these miniaturizations will have an impact on the different parameters. Appropriately, these are some of the points that we may need to take up whenever we are trying to design a micro robotic system. We have been discussing the different parameters. One of the key aspects of a micro robotic system is the process of developing a micro robotic system from a biomedical perspective. We are focusing on some kind of targeted drug delivery. In that aspect, there is a need for these micro robots to interact with the fluid medium.

So, how does it behave in a fluid medium and what are the parameters that impact this fluid medium? With reference to the fluid domain perspective, there are different biomimicking-based micro robots that have been developed. In fact, we will be discussing this in the different modules, how these biomimicking-based micro robots are developed, how locomotion is exhibited in these biomedical robots, and how it has been deployed for different applications. Just to give you an overview, when we consider a fluid domain, there are micro robots developed by mimicking nature. Like this helical micro robot with

a soft magnetic head, by applying a magnetic field and since there is a helical moment, this helical moment will catalyze the overall motion of these structures, allowing for locomotion. Then we have a kind of flexible tail oscillation. As far as this flexible tail oscillation is concerned, it is a type of sperm-based actuated micro robot that almost mimics a sperm moving in a fluid domain. So here there is a flexible tail, and the movement of the oscillation will capture the locomotion. It also has a potential application in targeted drug delivery. Next, we have the Celera-based micro robots. It is almost inspired by the micro-robotic structure called Celia.

If we closely observe how these systems move either in a blood domain, a fluid domain, or any other liquid domain to take care of the functionalities. So, there is a need to understand the different parameters that exhibit. As far as fluid mechanics is concerned, it plays a crucial role in micro-robotics. As the behavior of the fluid changes drastically at small scales, forces such as viscosity, surface tension, and drag become dominant while inertia and turbulence become negligible. Ideally, if you investigate the configuration of a fluid, the shear deformation of the fluid can be appropriately categorized into two types. One is called a stationary fluid structure, and the other is called a displaced fluid structure. As far as these stationary fluid structures are concerned, they dominate in a particular domain, and in the case of a displaced fluid structure, let us consider that we have an oily layer which tries to get displaced. Some of the key parameters of this fluidic structure are governed by this velocity profile, which has a direct intervention on the volume of moving fluid. In that aspect, we have a velocity profile in place; this is the overall area and a shear stress that is being induced into it, and then there is a non-slip boundary that exhibits here. Now, as most of us are aware of this Reynolds number, the Reynolds number Re basically takes care of the flow behavior.

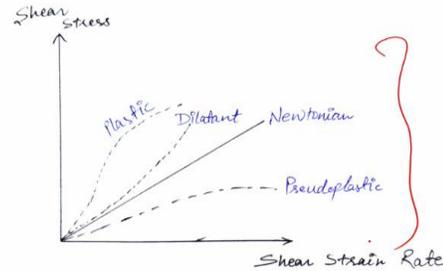
So there are different parameters that scatter these Reynolds numbers. One is rho, the density, which remains constant. V is the velocity, which usually scales as k⁰ or k¹. L is the characteristic length, which scales as k, and mu is the viscosity, which remains constant. This figure gives us a kind of clarity about the different types of fluids that are available

□ **Reynolds Number Scaling(Re) (Flow Behavior)**

$$Re = \frac{\rho v L}{\mu}$$

$$\Rightarrow Re' = \frac{\rho(k^0 v)(kL)}{\mu} = k Re$$

Here,
 ρ (density) remains constant.
 v (velocity) usually scales as k⁰ or k¹.
 L (characteristic length) scales as k.
 μ (viscosity) remains constant.



Classes of fluids.

for actual applications.

One is a kind of plastic base, another is called a dilatant base, then we have the Newtonian fluid and the pseudoplastic system. So, the selection of these fluids is determined by this shear stress and the shear strain rate. Now let us consider this drag force. The drag force is given by the equation $F_D = C_D (1/2) \rho V^2 A$, where the cross-sectional area A scales as k² and the drag coefficient C_D is referred to as F_D. Similarly, there is a velocity squared that you call V squared, which is scaled at k⁰ or k squared and at density rho, and it is governed by the equation $F_D' = C_D (1/2) \rho k^2 v^2 k^2 A$, which can be appropriately represented as k squared F_D.

□ **Drag Force Scaling**

Drag force is given by: $F_D = C_D \frac{1}{2} \rho v^2 A$

Here,

- Cross-sectional area (A) scales as k².
- Drag coefficient (C_D)
- Velocity squared (v²) scales as k⁰ or k².
- Density (ρ)

$$\Rightarrow F_D' = C_D \frac{1}{2} \rho (k^2 v^2) (k^2 A) = k^2 F_D$$

As far as these viscous forces are concerned, when we try to investigate the viscous force scaling, the viscous force is given by F equals μA dv/dy. Where we have the surface area scaling as k squared and the velocity gradient, which is represented as dv dy, as k. So, it

can be represented as $F \sim v$, which is the k of $F \sim v$, considered to be the final equation with reference to the scaling of viscous force. Similarly, when we try to investigate the other parameter, which is called surface tension scaling, this surface tension scaling has a direct relevance to shear as well as the length scales, k , which is represented by this particular equation, and the capillary number scaling is concerned. The capillary number scaling is given by $Ca \propto \mu \gamma$.

□ *Viscous Force Scaling*

Viscous force is given by: $F_V = \mu A \frac{dv}{dy}$

Here,

- Surface area (A) scales as k^2 .
- Velocity gradient (dv/dy) scales as k^{-1} .

$$\Rightarrow F'_V = \mu(k^2 A)(k^{-1} dv/dy) = kF_V$$

So, where μ is the dynamic viscosity, velocity u , which scales as (K^1) , is assumed to be similar to the kinematic viscosity, and as far as the surface tension is concerned, σ remains constant or scales as (K^0) . So, this can be represented as Ca , which is the inverse of k^1 by k^0 or k^1 .

□ *Surface Tension Scaling*

Surface tension is given by: $F_S = \sigma L$ Here,

- L(length) scales as k.

$$\Rightarrow F'_S = \sigma kL = kF_S$$

□ *Capillary Number Scaling*

Capillary No. is given by: $Ca = \frac{\mu U}{\sigma}$ Here,

- Dynamic Viscosity (μ) remains constant.
- Velocity (U) scales as k^1 (assuming similar kinematics).
- Surface tension (σ) remains constant or scales as k^0 .

$$\Rightarrow Ca \sim \frac{k^1}{k^0} = k^1$$

Now, when we investigate the influence of these scaling laws from the fluid mechanics perspective, let us take out the different fluid properties. So, one of the fluid properties includes the Reynolds number, the drag force, the viscous force, which is represented as F_v , the surface tension, which is represented as F_s , and the capillary number Ca . So, the scaling with size can be represented as K^1 , which indicates that the scaling effect is low RE viscous dominant at small scales.

In the case of a drag force, the drag dominates, affecting the micro robot's movement. As far as viscous force is concerned, this viscous force increases, preventing free motion from a surface tension perspective; these surface forces dominate and affect locomotion. When we investigate the capillary number, these capillary effects remain significant even at small scales. Now, when we try to correlate the fluid scaling matter in micro robotics, we see that these micro robots cannot move like macro robots. So, these traditional swimming high Reynolds numbers do not work and require a low Reynolds locomotion, like we have seen in cilia or flagella-based motion.

Similarly, when we try to talk about the Visco-dominant over inertia perspective, these micro robots, when they try to move in such a liquid domain, experience high drag and resistance. In fact, this also has a direct impact on the power consumption perspective. There is a need for specialized automation and for either a helical rotation or a peristaltic

rotation in the system. By appropriately having a helical rotation or a peristaltic rotation, we can save overall power consumption, and because of the momentum of this helical or peristaltic motion, we can have control over the resolution of the locomotion we are looking for. So, in fact, helical rotation is the one that we have seen over here.

Scaling Laws in Fluid Mechanics

Fluid Property	Scaling with Size (k)	Scaling Effect
Reynolds No. (Re) ✓	k^{-1}	Low Re (viscous dominance) at small scales..
Drag Force(F_D) ✓	k^2	Drag dominates, affecting microrobot movement. ✓
Viscous Force(F_v) ✓	k^1	Viscous forces increase, preventing free motion. ✓
Surface Tension(F_s) ✓	k^1	Surface forces dominate, affecting locomotion.
Capillary Number(Ca) ✓	k^0	Capillary effects remain significant at small scales.

So, this is a kind of helical rotation that exhibits a corkscrew motion, which will have direct control over the locomotion we are looking for. This is with reference to the capillary and surface effect perspective. These capillary and surface tension effects are strong. The water surface behaves like a kind of soft elastic membrane for small objects, and these micro robots need to exploit surface interaction for mobility. Even for micro-mobility or minor mobility, these kinds of capillary and surface tension effects are deployed.

With reference to the usage of these micro-robots or the application of fluid scaling in micro-robotics, it is concerned. First, let us consider the swimming micro-robot, which uses a kind of cilia or flagella to move in a helical motion at a low Reynolds number. These microfluids are used in a lab-on-a-chip device for biomedical applications. Now, with reference to the surface adhesion robot's perspective, it exploits the surface tension and the capillary forces. From the biomedical robot's perspective, these biomedical robots navigate through the blood cells and tissues using fluidic force. So ideally, we have kind of a microchannel; through these microchannels, such biomedical robots can be actuated, and

they have potential applications in the case of fluid scaling. So overall in this module, we discussed the electromagnetic forces and how these electromagnetic forces contribute. So, we also had some discussions about the adhesion forces. We also had some discussions about electricity, scaling loss of electricity, how these different parameters of the electrical system behave at the micron level, and how it can, so this will give us clarity on how we can deploy this electrical system for an efficient design of a micro robot. And then we had an overview of the fluid domain in a micro robotic system where we saw certain configurations of these biomimicking micro robots and how these biomimicking micro robots are helpful for appropriate locomotion.

□ Scaling in Electricity

- ✓ Electricity at the microscale follows different scaling laws compared to macroscopic systems. As objects become smaller, properties like resistance, capacitance, and inductance **scale differently**, affecting the performance of microelectronic circuits and microrobots.
- ✓ Some of the scaling laws related to electricity may be derived from simple laws of physics as shown below:

Electric Resistance(R):	$R = \frac{\rho L}{A} \propto (l)^{-1}$	Here, ρ = electrical resistivity of material ✓ L & A = length & cross-sectional area ✓ respectively of the conductor ✓ V = applied voltage $\propto (L^0)$ ✓ ϵ = permittivity of dielectric $\propto (L^0)$ ✓ E = electric field strength $\propto (L^{-1})$ ✓ d = separation distance ✓ μ = permeability of the core ✓ N = number of turns in the coil ✓ l = length of coil ✓
Resistive Power loss(P):	$P = \frac{V^2}{R} \propto (l)^1$	
Electric field energy(U):	$U = \frac{1}{2} \epsilon E^2 \propto (l)^{-3}$	
Capacitance(C):	$C = \frac{\epsilon A}{d} \propto (L)$	
Inductance(L):	$L = \frac{\mu N^2 A}{l} \propto (L)^{-1}$	

There are different parameters that exhibit scaling from a fluid mechanics perspective. In that aspect, the influence of Reynolds number scaling, drag force scaling, viscous force scaling, surface tension scaling, and capillary number scaling. When we investigate the scaling laws in fluid mechanics, we have a fluid property in place, the scaling with size and space, and the scaling effect in place. With reference to the scaling effect, we can have an interaction regarding fluid properties. While these fluids, scaling matters in micro robots. We can have different parameters that dominate the micro robot, such as movement in a macro robot, where viscosity dominates capillarity and the effect of surface tension. With reference to application perspectives, there are different fluid scaling in Microrobotics

systems. We have taken three different examples, such as cilia-based and flagella-based systems. With reference to how it works in the fluidic domain, of course, in the future models, we will be discussing in detail how it has been directly employed in the field and how design considerations are considered for developing such structures. In the next module, we will discuss scaling in heat transfer because heat transfer plays a vital role in the actuation of these micro room codes.