Microrobotics

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Scaling Laws of Microrobots - Module 03

We have been discussing the different scaling laws that are involved in designing a micro robot. In fact, this module will give us clarity about the different parameters that cater to or govern the actuation of a micro robot or the development of a micro robot for different applications. So we had discussed in detail the different parameters that are involved, such as what all the different domains are, and we also had a detailed discussion about the different parameters that have an influence on the domain. Among the different domains, heat transfer is also considered to be one of the key parameters for a micro robotic system. So, when we consider a micro robot, one aspect is the power perspective and the loading. When we power up the system and have an appropriate load on the system, there is a certain amount of energy dissipation in the form of heat. One of the key challenges is the drag force, which is generated when a microrobot is moving in a fluid domain. The drag force will also have an impact on power dissipation. With reference to this heat transfer perspective, when we design a micro robotic system, there are different modes of heat transfer that also come into play. Now, before going into this, let us discuss why we need to have a heat transfer scaling that has a direct impact on the micro robotic system.

The first case is the miniaturization challenges, i.e., if we investigate the miniaturization challenge, heat dissipation is harder at small scales due to reduced conduction and convection. When we investigate the thermal management of micro robots, this material with high thermal conductivity is required to prevent overheating. Secondly, it has a kind of active cooling method. For example, microfluidic cooling or radiation-based cooling is essential. From an energy efficiency perspective, these micro robots must balance power consumption and heat dissipation to avoid thermal damage. From a biomedical perspective, these biomedical micro robots can damage biological tissue, and proper thermal control is essential for this system. So, in that aspect, these are some of the key challenges that need to be addressed with reference to the thermal management perspective. Now, to understand thermal management, let us take an example of this application of heat transfer in a micro-robotic system. One of the key aspects is the kind of thermoelectric generators, as we discussed regarding this electrostatic charge. The case of electrostatic charges will involve a certain amount of heat dissipation. So, there is a need to convert this heat into electricity, which can be used for a certain amount of temperature gradient. Next, with reference to heat-driven micro actuators. We have shape memory alloys and bimetallic materials that rely on thermal expansion for motion. As far as the shape memory alloys or bimetallic materials are concerned, when we try to actuate them, they will have a certain amount of locomotion. By applying thermal expansion, we can expect a kind of locomotion that is exhibited here. Next is with reference to the temperature-sensitive drug release mechanism. There are a certain number of configurations whereby actuating these micro robots with the temperature allows us to have overall control over the targeted drug delivery. Whenever we use a kind of heat responsive polymer, these heat responsive polymers will have an impact in such a way that they get actuated when we supply heat to them.

In fact, in that aspect, we have these shape memory alloys and shape memory alloy polymers as well. These shape memory alloys or shape memory alloy polymers are highly responsive to heat, so that when heat is applied, they automatically become responsive. Next, we have microfluidic heat exchangers, which are efficient for cooling in biochemical assemblies. Basically, wherever there is a certain amount of biochemical assemblies, supplying heat can have a responsive system. Next, we have a thermoresponsive hydrogel. This thermoresponsive hydrogel changes its volume with temperature variation. Now, let me just give you a small demonstration or a kind of small insight into these shape memory alloy biomorphs that are being developed in our laboratory. So, as far as the shape memory alloy biomorphs are concerned, we are all aware of shape memory alloys. These shape memory alloys come under the category of smart materials. Let us consider that we have a spring.

So, when we try to deform the spring, it will take the form of a wire. Now, to bring it back to its original shape, when we try to supply heat to it, it comes back to its original shape. Ideally, we are trying to incorporate a kind of conduction mechanism into this kind of shape memory alloy. When we try to integrate a conduction mechanism, the shape memory alloy will try to contract, and then we call it actuation. So, the shape memory alloy gets actuated and is displaced. Now, if you closely observe the actuation of these shape memory alloy structures, the actuation is happening because of the heat transfer capability and the switching between the austenite and the martensite phases. When we switch between the austenite and martensite phases, it appropriately exhibits a kind of displacement, which can also be used as a temperature sensor for different applications. So, one of the key challenges involved in such shape memory alloys is the training of these structures. This is exactly where we demonstrated. So, we integrated it with a Kapton polyimide polymer, and it became a bimorph structure.

So, that one way of actuation is taken care of by the shape memory alloy, and the return stroke is taken care of by the biomorph. If we look at this video where there is an actuation in the SMA biomorph, the sample is kept on it, and then it actuates, and when we try to remove it, it returns to its original state. Ideally, we have a kind of SMA biomorph, and then there are pads; when these pads are exposed to an electrical pulse, they get actuated, and consequently, we can see a kind of system. Now, if we closely observe the different process parameters, such as those that cater to this shape memory alloy requirement, this heat transfer requirement, or heating-related aspects. So, when we investigate scaling and thermodynamics, this thermodynamics governs energy conversion, heat transfer, and work in a system of all sizes. So, when systems are miniaturized to the micro and nano scale, the thermodynamic properties do not scale linearly, which will lead to different behavior in energy exchange efficiency and heat dissipation. In that aspect, we have a thermodynamic quantity, an equation, and the scaling width size. So, when we investigate the thermodynamic quality, we have a volume in place, the surface area, the mass, the heat capacity, which is represented as Cp, the work done W, the energy storage U, and the entropy change. Appropriately, we have appropriate equations that are being integrated over here, and the scaling in size is represented with reference to the different parameters. Ideally, it depends on the process of how we are taking it out.

Now, when we try to look into the specific scaling laws of thermodynamics. The first law of thermodynamics basically talks about energy consumption and energy conservation, which is ΔU equals Q minus W. So, the internal energy U scales with mass K3, meaning the micro robot stores less thermal energy, while W is PV, which also decreases, making energy storage and conversion challenging.

First Law of Thermodynamics (Energy Conservation): $\Delta U = Q - W$

Internal energy (U) scales with mass (k^3), meaning microrobots store less thermal energy.

These micro robots require high-energy-density materials for efficient operation. Similarly, when we look at the second law of thermodynamics perspective, we have entropy and efficiency where ds equal ΔQ by T.

Second Law of Thermodynamics (Entropy & Efficiency): $dS = \frac{\delta Q}{T}$

So, at micro scales in heat exchanges, which occur more through conduction and radiation than convection, the entropy fluctuation increases because of the thermal energy, which is limited to it. Similarly, when we investigate the scaling of heat transfer from a thermodynamic point of view, it is governed by the equation Q equals m Cp del T. The heat capacity Cp decreases, making micro robots more sensitive to temperature changes. From a radiation perspective, it dominates at the micro scale, making the thermal coating and the emissive material crucial.

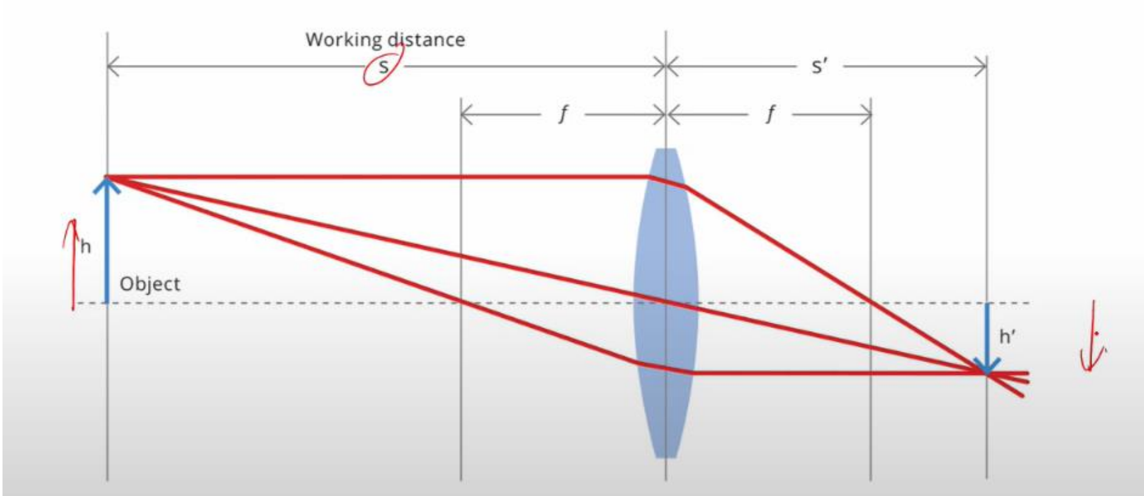
Scaling of Heat Transfer in Thermodynamics: $Q = mC_p\Delta T$

Now, why does thermodynamic scaling matter in micro robots? In the case of thermodynamic scaling, the thermal management challenges arise because heat dissipates differentially at small scales, requiring specialized cooling strategies. So, these micro robots must use radiation and conduction-based cooling instead of convection. From an energy storage and efficiency perspective, its limited volume reduces energy storage capacity, and the micro heat engine is less efficient, so alternative energy conversion methods are required. When we look into the actuation and motion perspective, the thermal expansion actuators behave differently at small scales, as we discussed about the overall design of shape memory alloys and thermoresponsive polymers, which can be used for movement. With respect to the biological and biomedical microrobotic perspective, there will be a controlled temperature in medical and microrobots, which is considered crucial for safe operation, and the heat transfer affects the drug release mechanism, which is regarded as a type of biocompatible structure. So, in summary, if we try to investigate these thermodynamic structures, these thermodynamic structures are well governed by different applications as well as different actuation perspectives.

When we investigate the application perspective, either with reference to energy efficiency or locomotion, there is going to be a certain amount of heat generated. Sometimes it is due to the friction that the amount of heat needs to be generated. So that can be efficiently controlled by capturing different parameters, appropriately aligning the geometries, and having an effective power management system for control. In fact, this thermoresponsive system, from the perspective of shape memory alloys or electrical thermal resistance, has a considerable amount of applications in designing these micro robots with these systems. If we look at different thermal management challenges. One of the thermal management challenges regarding heat dissipation, which differs at a small scale, is that it requires specialized cooling strategies. Now we will discuss scaling in optics. As far as optics is concerned, with reference to the micro-robotic perspective, these optics are going to play a vital role, especially in actuation. In certain cases, they are also used for sensing-related applications. For example, if we need to study the overall locomotion of a micro robot, optical-based systems can be effectively used.

The applications of these optical-based systems will have an impact on understanding or monitoring the behavior. In optics, when we try to investigate the scaling laws, they refer to the mathematical relationship that describes how the optical properties, like beam size, focal length, or diffraction pattern, change when the physical dimensions of an optical system are scaled up and down. Now, let me just introduce you to the different parameters of these optical laws where we have an object in place; this S is the working distance, and F is the focal point. So, we have an erect image, and we have an inverted image in place.

From the erected image, the structures are projected, and it is being fed into an inverted image.



Some of the key points about the scaling loss in optics are concerned; we have a geometric scaling. The fundamental concept behind this geometric scaling is that all the lengths in optical systems are scaled proportionately, allowing for the design of a similar system at different sizes. So, this is one part with reference to geometric scaling. From a diffraction scaling perspective, as the size of an aperture decreases, the diffraction pattern spreads out proportionally, impacting the resolution of the imaging system. Next, we have the lens scaling. So, in the case of lens scaling, when scaling a lens system, the focal length and the diameter should be scaled proportionally to maintain good image quality. This is exactly where these lens scalings will have an impact. When we discuss this beam propagation scaling, if we investigate beam propagation, we have a beam waist size and the divergence angle of a laser beam, which scale down with the size of the source of the aperture. Ideally, if we try to investigate the conventional configuration of a beam, it is represented in the form of a Gaussian beam profile. So conventionally, any light, if you take it, will be in the Gaussian beam profile, where the energy is focused to around 85 percent, which can be used for having a responsive behavior in actuating a system.

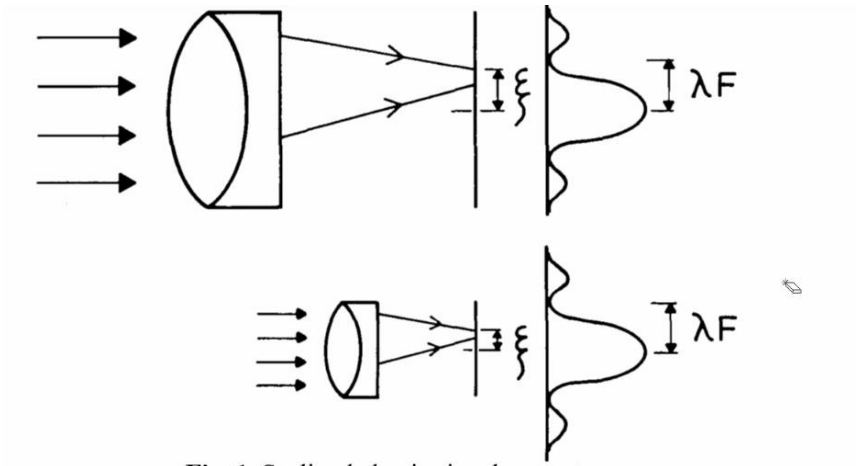


Fig. 1. Scaling behavior in a lens system.

One good example is light-driven systems; wherever we are trying to use a light-driven system, we can use this Gaussian beam profile-based laser for appropriate actuation. The beam wave size and the divergence angle of these laser beams scale with the size of the source of the aperture. When we look into the fundamentals of these optical scaling laws, different optical parameters contribute to this fundamental optical scale. One is with reference to wavelength. As far as wavelength is concerned, it is independent of the scaling. Next, we have the refractive index, which is represented as n, and it has no scaling impact. We have a Rayleigh criterion which is represented as theta. So, theta is 1.22 lambda divided by d, which is the inverse of k to the power of minus 1. When we have a diffraction limit represented as D, D equals $\lambda/(2n \sin \theta)$ where it is inverse K inverse.

Fundamental Optical Scaling Laws

Optical Parameter	Equation	Scaling with Size (k)
Wavelength (λ)	$\lambda = \frac{c}{f}$	Independent
Refractive Index (n)	$n = \frac{c}{v}$	No Scaling
Rayleigh Criterion (θ)	$\theta = \frac{1.22\lambda}{D}$	k^{-1}
Diffraction Limit (d)	$d = \frac{\lambda}{2n \sin\theta}$	k^{-1}
Focal Length (f)	$f \sim D$	k
Light Intensity (I)	$I \sim P/A$	k^{-2}
Absorption Cross-Section (σ)	$\sigma \sim \lambda^2$	k^{2}

We have a focal length F, where F is directly correlated to D, which is at K, and then we have a light intensity I, which has a direct relevance to P by E. Then there is the absorption cross-section, which is represented as sigma. When we correlate the scaling with size k, it is represented as k squared. Now, when we investigate the scaling laws for a lens system, designing a lens is trivial, at least in principle, if the focal length f, the lens diameter b, and other length parameters are enlarged by a factor m. So, there is a parameter called lateral aberration. The lateral abrasion is denoted by a symbol, which will be enlarged in proportion to M. So here we have a travel time del t of the light that scales with m. The size of the image field del x del y scales, which is represented as m squared. volume and the weight scale, which is represented as m^3. The resolution del x due to diffraction does not change with m since del x equals lambda f, which depends on the wavelength lambda and on the aperture angle, which is represented by a number called stop number, f.

In this figure, we can have a representation of the cap F and the lambda. So, with a lens system, we can have control over the aberration, and then it is the overall f that gives a stop number. So, the wave abrasion is represented by W, which describes the deviation of the actual wave front from a perfect spherical wave front, and the scale is represented as m. The wavelength lambda remains unchanged. So, this is the scaling behavior in the case of a lens system where the different parameters are being addressed. Here, the lateral abrasion varies, while the scale change, curvature angles, and diffraction blur remain constant. Now, why there is a need to go for optical scaling matters in the case of a microrobotic system. In the case of a miniaturized optical sensor, these microrobots rely on the optical sensor for navigation, obstacle avoidance, and biochemical sensing. When we look into optical communication from a micro robotics perspective, whether there are two robots or two micro robots, or when there is a span of micro robots, there is a need to have a kind of communication. These optical signals are used for data transmission, wireless power transfer, and swarm coordination. At small scales, higher frequencies, UV, visible, and infrared are preferred for compact optical devices. So, these are some of the key applications where optical communications in micro-rovers can be deployed. From a micro robotics perspective, optical actuation can be used to move or deform micro robots using optical tweezers or photo-thermal actuation. So, at small scales, optical force becomes dominant over the mechanical forces. Next, with reference to diffraction and limited images in the micro robotic perspective, these miniaturized imaging systems suffer from diffraction limitations, and these micro robots highly require a type of higher resolution imaging for precise operation.

This is considered one of the key requirements for considering this diffraction-limited image. Now, when we investigate the application of these optical scalings from a micro robotic perspective, these optical scalings are effectively used in endoscopic micro robots, especially in the case of non-invasive surgery. Infrared-based optical communication for micro robotic swarms, as discussed earlier. So, for a kind of interaction between two micro robots, or if we need to govern a swarm of micro robots appropriately, we can be deployed. There are optical tweezers for manipulation where there are a cell and a nanoparticle being kept. A photothermal actuation for soft microrobot movement is one of the key aspects with reference to the system. We have plasmonic heating for microfluidic propulsion. As far as this plasmonic heating is concerned, it is deployed for appropriate light-wrapping-related activity. We have a micro-ladder system for mapping small-scale environments. A laser-driven micro-robot that is used in optical retinas. So, like you might have seen in a cockroach where it has a kind of retina. So, for those things, such kinds of laser-driven systems are deployed. In fact, when we discuss these biomimicking-based micro-robots, we will be discussing these concepts. Now we discuss the influence of quantum effects on a micro robotic system. As far as the case of a quantum effect is concerned, first we need to have some understanding of the different parameters that are related to the quantum effect. One of the parameters includes quantum tunneling. It is a quantum mechanical phenomenon that occurs when a particle passes through a barrier that would normally be impossible to pass. It is also known as barrier penetration. Then we have the Casimir effect. The Casimir effect is a quantum force that causes attraction between two uncharged conducting plates held very close together.

Next, we have a kind of quantum entanglement. Quantum entanglement is a process whereby energetically degenerate states cannot be separated, and an electron or photon in these states is essentially linked. Next, we have wave-particle duality. It is an idea that matter and light can exhibit properties of both waves and particles depending on how they are observed. This concept is a fundamental principle of quantum mechanics. Next, we have a superposition. The superposition refers to the ability of quantum particles to exist in multiple states simultaneously, meaning they can be in a combination of different possible states as and when they are measured. As far as these quantum effects are concerned, the quantum effect in micro robots refers to the phenomenon where the behavior of the micro robot is significantly influenced by a quantum mechanical principle, such as quantum tunneling or superposition, due to its extremely small size. It leads to unique capabilities that are not possible with larger robots, particularly in areas like precise manipulation, as we will be discussing AFM as a micro robot. So where these quantum effects have an impact, especially with reference to precise sensing and manipulation at a micro scale level, in certain cases, if you need to have a kind of micromanipulation, such quantum effects will have a potential impact on micromanipulation. Unlike classical physics, these quantum phenomena, such as tunneling, superposition, and entanglement, play a crucial role in sensing, energy transfer, actuation, and communication in micro robotic-related systems.

Now let us discuss some of the different quantum effects and how these quantum effects will have an impact on micro-robotic related applications. One of the quantum effects is called quantum tunneling, where we have a nanoscale sensor and actuator. It enables a nanoscale actuator, a quantum diode, and an ultra-sensitive sensor that is being impacted. Next, we have the Casimir effect. It is a kind of surface adhesion and energy harvesting. It has control over the micro-robot's interaction with the surfaces. We have quantum entanglement, which secures communication, computing, enhances micro-robot coordination, and cryptography. One of the key impacts with reference to the micro-robot perspective is superposition. It has quantum sensing and computing and enables quantum-based sensing and computing of a micro-robotic system. As far as the quantum effect is concerned, we have wave-particle duality. It has a photonic microrobot and imaging capabilities. It is used in nanoscale imaging and a photonic propulsion system. When we investigate the application of these quantum effects in microrobots, quantum tunneling is effectively used in micro robotic actuation and sensing. This quantum tunneling enables a nanoactuator that bypasses the constraints of classical motion. As far as the application perspective point of view is concerned, it is used in nanoscale MEMS switches for micro robot control, tunneling junction-based energy harvesting for self-powered micro robots, and a quantum tunneling sensor for detecting a single molecule in a biological environment. Similarly, when we have a Casimir effect for surface adhesion and energy harvesting, these quantum vacuum fluctuations create Casimir forces that affect micro robots that move near the surface. From an application perspective, these electrostatic adhesives are for a wall-climbing microrobot and a Casimir energy harvester for power generation in a nanorobot. Similarly, we have quantum computing for swan micro-robot coordination. This quantum algorithm optimizes a micro robot swan for efficient task execution. So, there are different applications. One of the applications includes the quantum-inspired optimization for micro robot navigation in complex environments.

Quantum neural networks for real-time micro robots and decision-making. Quantum-enhanced cryptography for secure data transfer in micro-robot networks. Quantum sensors for extreme sensitivity in micro robots are concerned; we have a quantum sensor leveraging entanglement and superposition for ultra-precise measurements. With reference to the application perspective, we have atomic scale accelerometers for micro robot stability control. A quantum magnetometer for precise magnetic field sensing; now let us discuss the different challenges that are evolving with reference to scaling quantum effects. So as far as the scaling quantum effects are concerned, the scaling quantum effect has potential with reference to real-world micro robots, especially in complex environments. It maintains quantum coherence in biological environments in challenging cases, and quantum computing for micro robots is at an early stage, but it has great potential. In fact, this is one of the key areas where more focus is currently being placed with reference to the usage of these micro robots for micro-manipulation as well as from a micro-sensing perspective. Some of the solutions with reference to these challenges are hybrid classical quantum micro robots that may integrate a quantum sensor while operating with classical mechanics. The second advance in nano-fabrication will have better control over these Casimir forces, quantum tunneling, and photonic interactions.

To give you an overview of this model, we discussed the different scaling laws that are being deployed. So, we discussed how these structures from a geometric perspective behave on a macro level and how they behave on a micro level. So, we also had some discussions about these rigid body systems. We also had some discussions about electrostatics, the influence of electrostatic structures, electromagnetic structures, electrical structures, fluid structures, thermal-based systems, and then we also discussed optical-based systems, scaling laws in optical-based systems, and finally we had some discussion about the quantum effect. So, we will be discussing the other aspect of these micro robotic systems in the upcoming classes. So, this module gives you a fundamental understanding of the overall parameters, fundamentals, and design considerations that we may need to consider when we are approaching micro robotic systems.