Microrobotics

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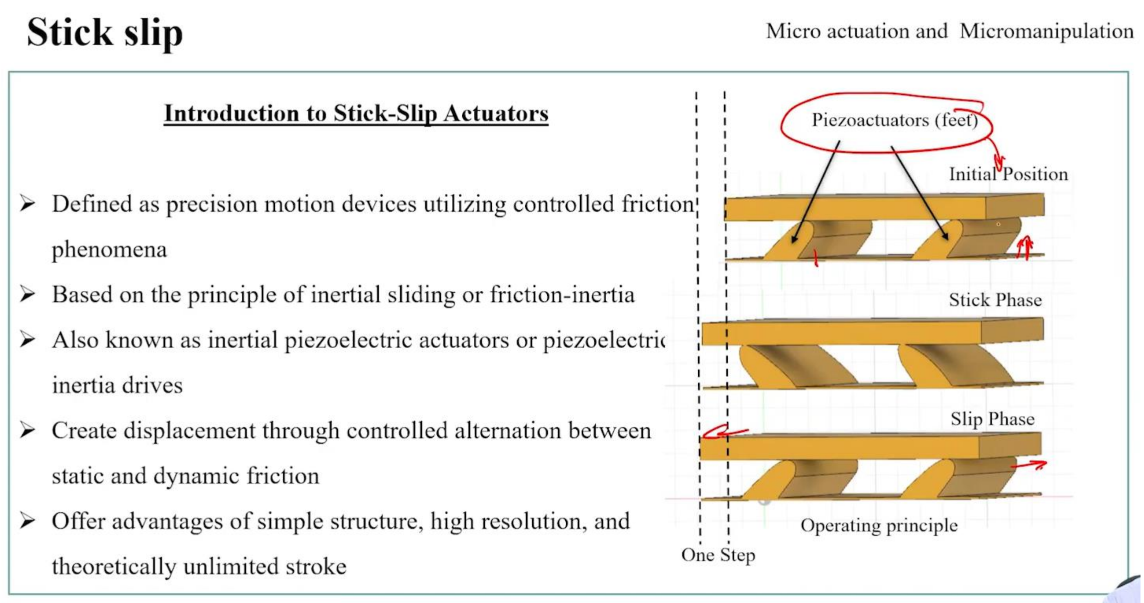
Week- 05

Lecture No- 25

Micro actuation and Micromanipulation - Module 10

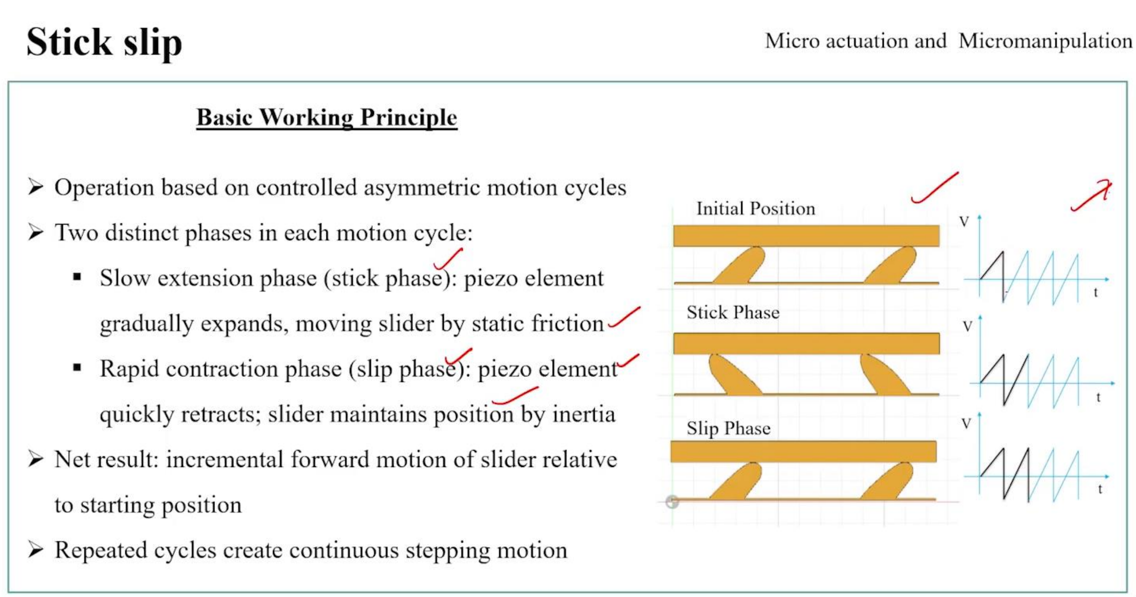
We have been discussing the different micro actuation. Now let us discuss the various micro actuation configurations and the overall mechanisms involved in micro robotic applications. So, as far as this case of Microrobotics applications is concerned, one of the key important micro-manipulations is called a stick-slip actuator. So when we take the example of the stick-slip actuator, this stick-slip actuator is efficiently used for achieving less than 1 micron resolution. It can be used for creating less than 1 micron resolution. So, that is one advantage of this stick-slip actuator.



However, by reducing the overall configuration of the probe appropriately, we can have control over the motion of this thick slip actuator. So, these thick slip actuators are defined as precision motion devices utilizing controlled friction phenomena, based on the principle of inertial sliding or friction inertia. They are also known as inertial piezoelectric actuators or piezoelectric inertial diodes. It creates a displacement through a controlled alteration between static and dynamic friction.

And it offers an advantage in simple structures, higher resolution, and theoretically unlimited strokes. So in this particular case, let us consider that this is a kind of initial portion where there is a stick face. And then, with the stick facing through an inertial force, it is slipping to the next level so that we can have a kind of displacement that persists over here. Now the generation of this thick face to the slip face is happening because of the piezoelectric actuation that is being deployed here. So what is happening is that either the piezoelectric can be incorporated in such a way that in a single stretch you can push the actuator, or in multi-stage stretches, when one leg actuates, the other leg can come down, or when the other leg is actuated, the one leg, that is one foot, can come up, and the other foot can have less force exertion while it has a higher force exertion through this process; also, we can have a higher operating process.

So, as far as the historical development perspective is concerned, it was first introduced in the late 1980s basically for scanning tunneling microscopy applications. So originally, the stick-slip phenomenon was designed by Niedermann and Emch for precise positioning, which evolved from a simple design to a sophisticated mechanism with an amplification structure. So the major advancement occurred in the early 2000s with the introduction of the structural hinge mechanism. So modern design incorporated multi-degree freedom and bidirectional capabilities has been deployed. When we look into the overall working principle of this thick slip phenomenon, it operates based on a controlled asymmetric motion cycle.



Two distinct phases in each motion cycle can be exhibited; one is called the slow extension phase, also known as the stick phase, where a piezo element gradually expands and moves a slider by static friction. Another one is called a rapid contraction phase, which is referred to as a slip phase. So as far as this slip phase is concerned, a piezo element quickly retracts, and a slider maintains a position by inertia. Now, the net result of this is a kind of incremental forward motion of a slider relative to the starting position. There is a kind of repeated cycle that creates a continuous stepping motion.

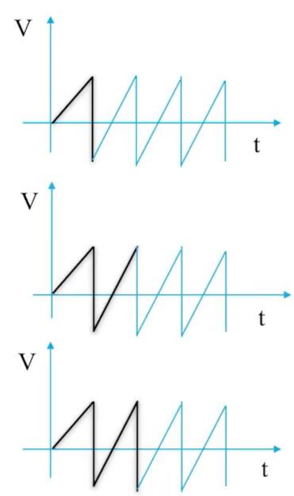
So if you observe over here, this is the overall configuration of a stick slip, and this is the overall configuration of the features. In this particular case, we have an increase in voltage, and then there is a slip that is observed; in the case of a stick phase, there is again a kind of increase, and then a slip is observed in this particular system. So as far as this is concerned, when we closely observe the sawtooth waveform, which is typically used as a driving signal during a slow ramp of 90 percent of the cycle, piezoelectric elements gradually extend. Static friction between the driving foot and the sliding platform moves them together and displaces equally in the piezo displacement multiplied by the lever ratio. However, during a rapid return that is around 10% of the cycle, the piezoelectric element rapidly contracts and inertia keeps the slider in position while driving the foot return.

Stick slip

Micro actuation and Micromanipulation

Stick-Slip Motion Mechanism

- Sawtooth waveform typically used as driving signal
- During slow ramp (90% of cycle):
  - Piezoelectric element gradually extends
  - Static friction between driving foot and slider moves them together
  - Platform displacement equals piezo displacement multiplied by lever ratio
- During rapid return (10% of cycle):
  - Piezoelectric element rapidly contracts
  - Inertia keeps slider in position while driving foot returns
  - Dynamic friction insufficient to pull slider backwards



So the dynamic friction is insufficient to pull the slider back. Some of the core components of this particular stick-slip mechanism are concerned; one is called piezoelectric stacks, which provide a primary actuation force to the system. So this is the overall figure for the stick-slip mechanism, where there is a piezoelectric stack with the stator motor, there is a flexural hinge stator, there is a driving foot, a slider change, and a base structure. These piezoelectric stacks provide a primary actuation force, a flexural hinge mechanism that converts and amplifies a piezo displacement, a driving foot that serves as a contact interface with the friction surface, and a slider stage that acts as a moving element receiving the net displacement, along with a base structure that supports and aligns the components. So these are some examples of the type of stick-slip actuator.

So it's a kind of linear actuator that achieves high linear motions, and a rotary actuator that produces a kind of angular displacement. And when we try to classify the same with reference to degrees of freedom, it is a kind of single-axis system that exhibits. Then there is a kind of multi-access system that exhibits a six degrees of freedom, which can be established with high-precision platforms using this particular system. Now, as far as the classification perspective point of view, the classification of these kinds of stick-slick actuators can be either unidirectional, bidirectional, or in a cooperative mode. So unidirectional means one way, and you may need to manually move the return.

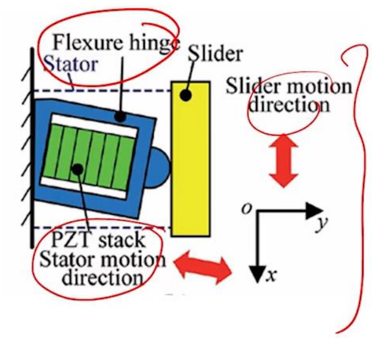
Bidirectional is something like in both directions. Cooperative mode is something like this; it's a kind of adaptive structure. In this adaptive structure, based on the kind of obstacle that is being avoided, it can be appropriately used for movement. So with reference to the operating characteristics perspective point of view, the stick-slip actuators have a direct relationship between the voltage and the displacement. As the velocity increases with the driving frequency, it reaches a mechanical limitation, and the performance varies with the preload force that is applied between the driving foot and the slider.

From the perspective of the coefficient of friction, the coefficient of friction at the contact interface is studied, and the driving waveform parameters, specifically the frequency and amplitude, are asymmetric to the system. With reference to the application perspective, this kind of stick-slip phenomenon and stick-slip based actuators are efficiently used in precision positioning systems for optics and microscopy. As mentioned, it was used for the scanning tunneling microscope. It is effectively used for the manufacturing of semiconductor equipment, such as semiconductor-based systems, and it is also used for medical devices requiring precise motion. In certain cases, it is also used for scientific instruments for nanoscale research and in the area of metrology, as well as in the area of inspection; it is used for a camera focusing mechanism, and it also has adaptive optics for astronomy and a micromanipulation tool.

Stick slip

Core Components

- Piezoelectric stack: provides primary actuation force
- Flexure hinge mechanism: converts and amplifies piezo displacement
- Driving foot: contact interface with friction surface
- Slider/stage: moving element that receives net displacement
- Base structure: supports and aligns components



Some of the key advantages and challenges of this particular system are that it is a simple structure with few components. In fact, if you keenly observe the overall construction of this thick slip mechanism, it has only two feet, as mentioned there. The appropriate actuation of these two feet is highly simple in such a way that it can control the micropositioning level as well as achieve a higher order. It has a high resolution and positional capability. Theoretically, it has an unlimited travel range.

It has low power consumption, and there is no backlash or mechanical play. Challenges from a perspective point of view include backward motion during a slip phase, wear at a friction interface, limited load capacity, speed limitations, and environmental sensitivity. So when we try to observe the future research direction of this particular system, so enhancing the speed of it through an optimized flexure design is one of the need which can be expressed. Second is improving load capacity. As of now, this thick slip phenomenon is being effectively used for micro-robotic related applications.

Stick slip

Types of Stick-Slip Actuators

- Linear actuators: achieve straight-line motion
- Rotary actuators: produce angular displacement
- Classification by degrees of freedom:
  - Single-axis systems
  - Multi-axis systems
  - 6-DOF precision platforms
- Classification by motion mode:
  - Unidirectional
  - Bidirectional
  - Cooperative motion mode

However, from a larger perspective, it may have its own impact. Developing a multi-degree-of-freedom actuator is a challenging task. So of course this thick slip, as I mentioned earlier, may either be unidirectional, bidirectional, or adaptive. A multi-degree freedom system is one of our challenging tasks. So what we may need to do is, when there is a leg, to provide a kind of small cushioning arrangement.

If this cushioning has an adaptive structure, then by appropriately adjusting the cushioning, we can achieve a rotation. With reference to the implementation perspective, implementing a closed-loop control system is one of the important aspects, as is exploring an alternative driving waveform beyond the sawtooth. Miniaturization of microrobotic applications is one of the challenging tasks using this stick-slip system. In summary, the stick-slip piezoelectric actuator provides precision motion through the ingenious use of frictional dynamics. Various design approaches offer flexibility for specific application requirements.

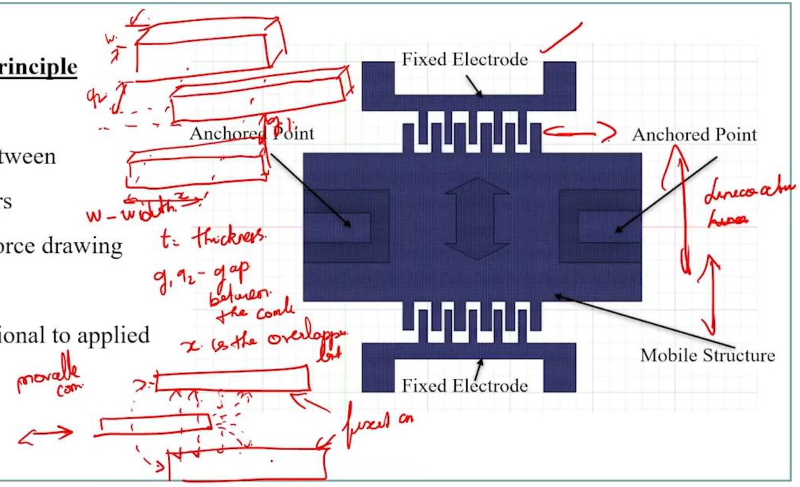
The performance continues to improve through research advancements and represents an important class of positioning devices bridging micro and macro scales. Future developments are likely to expand applications in the case of emerging devices, and the emerging technologies are some of the key aspects. Now, let us discuss the next type of actuation system, which is called a comb drive-based actuator. As far as this comb drive-based actuator is concerned, when we discussed this electrostatic process, we talked a lot about this comb drive actuator. And now in this particular lecture, we will discuss the overall configuration of this comb drive actuator and its behavior.

Comb Drive Actuator

Micro actuation and Micromanipulation

Basic Working Principle

- Electrostatic attraction between interdigitated comb fingers
- Applied voltage creates force drawing combs together
- Net displacement proportional to applied voltage



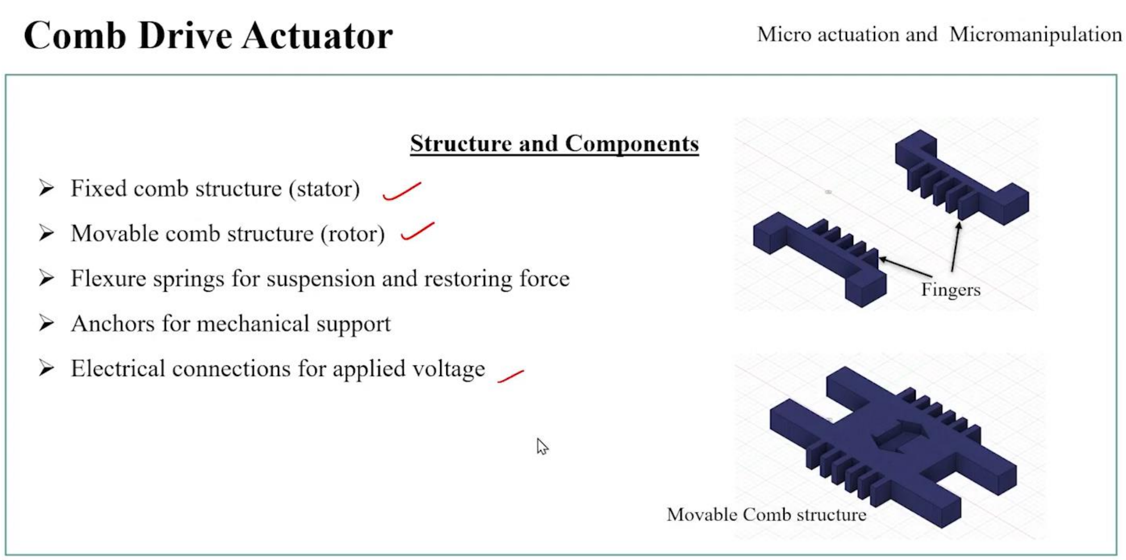
So with reference to the comb drive perspective point of view, it's a kind of micro-mechanical system that actuates using electrostatic forces. The key features of these comb drive actuators include a simple structure, easy fabrication, and low power consumption. So it has two basic components: one is a fixed electrically conductive comb, and the other is a movable one. So this, either this might be fixed, and this will move in any domain. Now, this is the overall working principle of a comb-drive actuator.

So in this comb drive actuator, we have a fixed electrode in place, anchor points, and a mobile structure that exhibits linear actuation. That is either it can be moved in this direction or it can be moved in another direction. So the electrostatic attraction between the interdigitated comb fingers and its applied voltage creates a force drawing the comb together, and the net proportional force is applied to the field. Now, if we try to see the overall mechanism of this, we have two fixed combs and then there is a movable comb. This is a kind of fringing field that passes between these combs.

So, when we try to look into the parameters of it, like if this is the structure, we have W, G2, and G1. So, these are the two fixed combs and this is a movable comb. So, this can be nominated as W. W is considered to be the width, T is the thickness; this is G1 and this is G2. So, G1 and G2 are the gaps between the combs, and x is the overlapping length of the combs.

The comb drive actuators have a movable and a stationary structure, which splits into the fingers with the attached combs, and the stationary parts are connected to a ground-fixed suspension. The coulomb forces deflect the moving comb structure and generate an output displacement, and the comb drive electrostatic actuator can have a lateral and a vertical design, which relates to the layout of the comb. The voltage-controlled comb drive actuators are quite attractive in micropositioning because of the laterally exposed electrostatic force independent of the portion contrary to the parallel plates. So the biggest disadvantage of a comb drive actuator is a moderate driving voltage, the small offset in the direct current driving mode, and a larger layout area. However, they can be compensated by a higher displacement rate than other actuators.

So a vertical comb actuator is used to achieve a higher and greater angular moment. And the design of the vertical actuator with a comb drive brings a higher deflection angle at low voltage. So, with reference to a structural and component perspective point of view, these are the different structures that exhibit. One is called a fixed comb structure, which we refer to as a stator, and the other is called a movable comb structure, which is essentially a rotor, a flexure spring for suspension and restoring force, an anchor for mechanical support, and an electrical connection for the applied voltage. So these are the different structures and components of the motor.



Now, when we try to talk about the overall comb drive actuator, the amount of force generated depends on the number of fingers, T is the thickness, epsilon is the permittivity of free space, V is the voltage, and D is the gap between the fingers. With reference to the comb drive operation perspective, as we discussed earlier, the comb drive operation basically depends on the gap between the fixed and movable systems, as well as the overall overlapping length, which is nothing but the x, and then the width of the finger. Now when we try to look into the key design parameters of this comb drive actuator, some of the key design parameters include the number of comb fingers, the finger dimensions which include the length, width, and thickness, the gap between the fingers, the overall spring stiffness, and the applied voltage. Based on the number of fingers, the thickness, the permittivity, the voltage, and the gap, these parameters will appropriately influence the overall electrostatic force being generated. However, with reference to performance characteristics from a perspective point of view, it typically has a displacement range of around 1 to 100 micrometers, an actuation voltage of close to 1 to 100 volts, and the force generated is in the range of micronewtons to millinewtons.

Comb Drive Actuator

Micro actuation and Micromanipulation

Force Generation

- Electrostatic force equation:

  $F = (n * t * \varepsilon_0 * V^2) / (2d)$

  - n (number of fingers)
  - t (thickness)
  - ε_0 (permittivity of free space)
  - V (voltage)
  - d (gap between fingers)

So there are different types of comb drive actuators; one is called a linear actuator, which is mainly meant for a kind of linear action, and the other is a rotary actuator. This is a kind of linear actuator, or it can also be considered an in-plane actuator, and this is a kind of rotary actuator. In this rotary actuator, there is an actuator, an anchor, and a flexure ring that is available with the rotary comb drive. This rotary comb drive moves in this particular direction along with the anchor. This is a kind of insert image for it, which gives clarity on how these systems can be deployed and how the overall angle theta can be easily represented in this case.

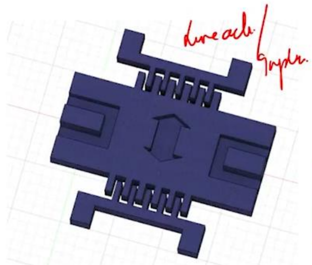
There is one more kind of actuator. So apart from this, there are also a kind of outplane actuators. Out-of-plane-based comb drive actuators are used effectively for different applications. Now we can also discuss one of the important types of actuators, which is called a single-sided actuator. This is a kind of electrostatic comb drive which is used in a movable microsystem with a non-linear spring. This is the movable actuator with a spring arrangement and a base, and a spring arrangement as a base Kx and Ky with area A.

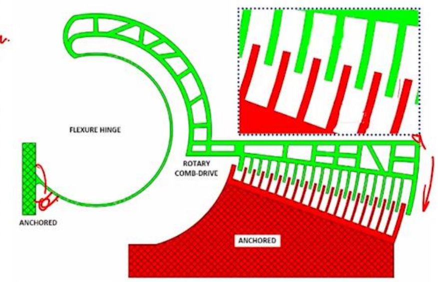
This is a fixed actuator, and this is a movable actuator. This is a kind of area which is being exerted, and there are two non-linear springs. These non-linear springs are capable enough to provide a type of dedicated manipulation. Basically, these kinds of systems are effectively used for biomedical-related applications where they are used for dedicated manipulation of tissue samples, and simultaneously, they can measure the displacement and probe tipping as well. So, like, it has different geometries and is being effectively used.

Comb Drive Actuator

Types of Comb Drive Actuators

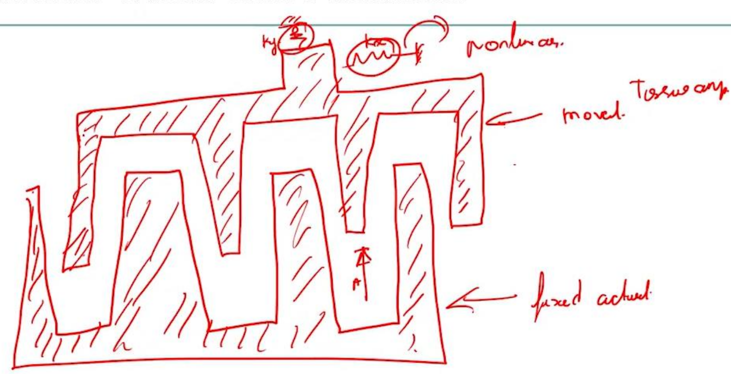
- Linear actuators
- Rotary actuators
- In-plane actuators
- Out-of-plane actuators





Ideally, the overall manipulation is taken care of by this linear spring, and along with the electrostatic comb, a non-linear spring will also participate in this particular structure. From an application perspective, comb drive actuators are effectively used in optical systems, primarily for mirror shelters and RF MEMS switches (variable capacitors and tunable filter applications), as well as in inertial sensors such as accelerometers and gyroscopes. They are also used in biomedical devices, including micromanipulators and cell sorters, and for precision stages, particularly in micro robotic systems. Additionally, they are utilized for self-starting, micromanipulation, and precision stages. These are the three applications that these kinds of comb drive actuators basically focus on.

Single sided Electrostatic Comb drive actuator



Now, with reference to the advantages from a perspective point of view, it has a simple fabrication process, is compatible with standard MEMS manufacturing, has low power consumption, large displacement capability, high force density, and a linear force-to-voltage relationship. Challenges from a perspective point of view include a pull-in stability at high voltage, a limited force output, high susceptibility to stiction, and wear and fatigue in moving parts because it is a kind of concentrated region. So in these concentrated regions, there are chances that it may lead to a kind of wear and tear on these particular parts. Now, with respect to recent advancements and optimization strategies, a novel spring design can be employed for generating a larger displacement, as mentioned in this particular single-sided electroactive system. Asymmetric comb-finger design for increased force.

It uses an alternative material, such as polymer for flexibility, increasing the number of comb fingers, reducing the gap between the fingers, and it has a good amount of implementation with respect to the closed-loop system. With reference to future directional perspectives, this has quite a good amount of integration with other actuation mechanisms. The development of a 3D comb drive structure is considered to be one of the key aspects. Applications in emerging fields, such as microfluidic-related applications and energy harvesting-related applications, are some of the focuses of this particular comb drive actuation and miniaturization for NEMS-based systems. So overall, in this particular module, we discussed in detail the shape memory alloy structures.

We have discussed the different configurations of shape memory alloy structures, the overall challenges involved, and the actuation involved, etc. So we have seen some micro-robotic applications related to shape memory alloy structures where we discussed a kind of steward platform that is used for fabricating a micro steward platform for manipulating a beam and then what the different microfabrication steps involved in fabricating such shape memory alloy-based structures are. Then we had a discussion about the conducting polymers, their properties, and the different actuation mechanisms involved in them. The key properties, device architectures, overall applications, and future directions. So we also had a discussion about the shape memory of live polymers and the electrorheological-based fluids.

So we had a detailed discussion on the stick-slip phenomenon, how this stick-slip phenomenon is impacted, its potential application towards micro-robotics, the different core components involved in this stick-slip phenomenon, overall operating characteristics, advantages, challenges, and future directions. So, we also had a discussion about this comb drive actuator. What are the different characteristics of a comb drive actuator, the structural components involved, the basic operation, the overall fourth generation, and key design parameters, as well as the different types of comb drive actuators that are being established with suitable applications, advantages and limitations, and the prospects of recent advancements and future directions? So, these are some of the references that we have used for preparing this particular model.