Microrobotics

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Lecture No- 23

Microactuation and Micromanipulation - Module 08

From the earlier lecture with reference to shape memory alloy, the fundamentals of shape memory alloy, you might have observed that one of the tedious processes in applying this shape memory alloy for different functional applications is the training of shape memory alloy. Because as far as this training cycle is concerned and most of the cases, since it works on the principle of the austenite phase and martensite phase, we may need to prepare a die, and we may need to immerse it inside or put it in a muffle furnace, and then we have to immediately quench it either in liquid nitrogen or in cold water conditions. And one more point is that we may need to repeat this cycle close to 50 to 60 times to get a higher recovery or recovery percentage. From an energy efficiency perspective, this is a kind of waste of energy, and secondly, it's a highly tedious process. In order to avoid this, we can integrate this SMA with a kind of material. That is what we have been discussing in terms of bimorph.

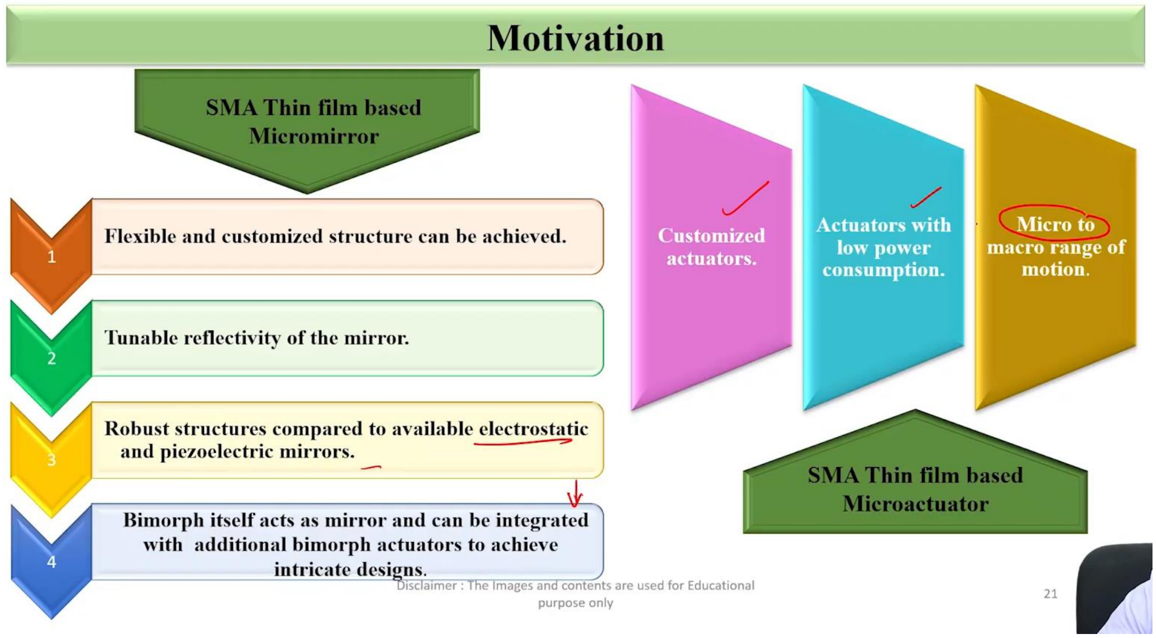
In the earlier composite case, what we have done is program the material and integrate the material with a composite structure. So what happens is this composite structure will work along with the shape memory alloy to achieve appropriate actuation or the appropriate characteristics. Now, as far as this realization of shape memory alloys is concerned, we can introduce this new concept called SMA biomorph. So as far as this SMA biomorph is concerned, what we can do is use a shape memory alloy and Kapton polyimide.

The shape memory alloy is integrated with Kapton polyimide so that the shape memory alloy takes care of the actuation, and then for the return stroke, this Kapton polyimide will participate with the shape memory alloy for the return stroke. Now with this as an idea, we have developed a small steward platform for micro robotic applications, which is used for beam steering. So let us see this particular case study. We can discuss the different processing steps involved and the different evolutions in this particular process in detail. Now the key motivation of this particular case study is, like in most flexible mirrors, that if you have a mirror of a large area, normally these mirrors are where we are looking for some kind of dynamic actuation.

So, these mirrors are integrated with a kind of actuator. In most cases, it might be a kind of hydraulic actuator. In some cases, it might be a kind of mechanical actuator; it might be a kind of linear electrical actuator. In certain cases, it might be a kind of piezoelectric actuator based on the response that is normally considered. The element of reflectivity is different; the actuator is different; the actuation characteristics will take care of the overall reflection behavior.

Now, in this particular case, what we thought is, if we need to make the system simple, why don't we prepare a deformable mirror that has its own capability for actuation? That is, if we can use a highly reflective shape memory alloy thin film, so that this thin film has the capability to be adapted appropriately. So one of the key concepts that we thought of is that we will make a flexible and customized structure which can be achieved, and then we can develop a mirror with a kind of tunable reflectivity so that this tunable reflectivity can be efficiently deployed for the deflection of or for manipulating the beam based on the requirements. The third important point is with reference to the robust structure compared to the available electrostatic and piezoelectric mirrors. So it can act as a kind of alternative to the electrostatic and piezoelectric mirrors because, in the case of electrostatic or piezoelectric mirrors, of course, it has a higher order frequency. However, with respect to linkages from a perspective point of view, what we may need to do is connect an actuator to the mirror.

So what is happening is these become two different elements, and these two different elements get actuated to get the required motion. Now, if we can design a system where a bimorph itself can act as a mirror and be integrated with an additional bimorph actuator to take care of the intricate design, the overall load of this dual platform can be considerably reduced, and it should have higher flexibility. So one of the key objectives or one of the key outcomes of this project is to develop a customized actuator. Then second, an actuator with low power consumption and the actuator designed is on a micron order. However, it has the capability to go for macro range motion.



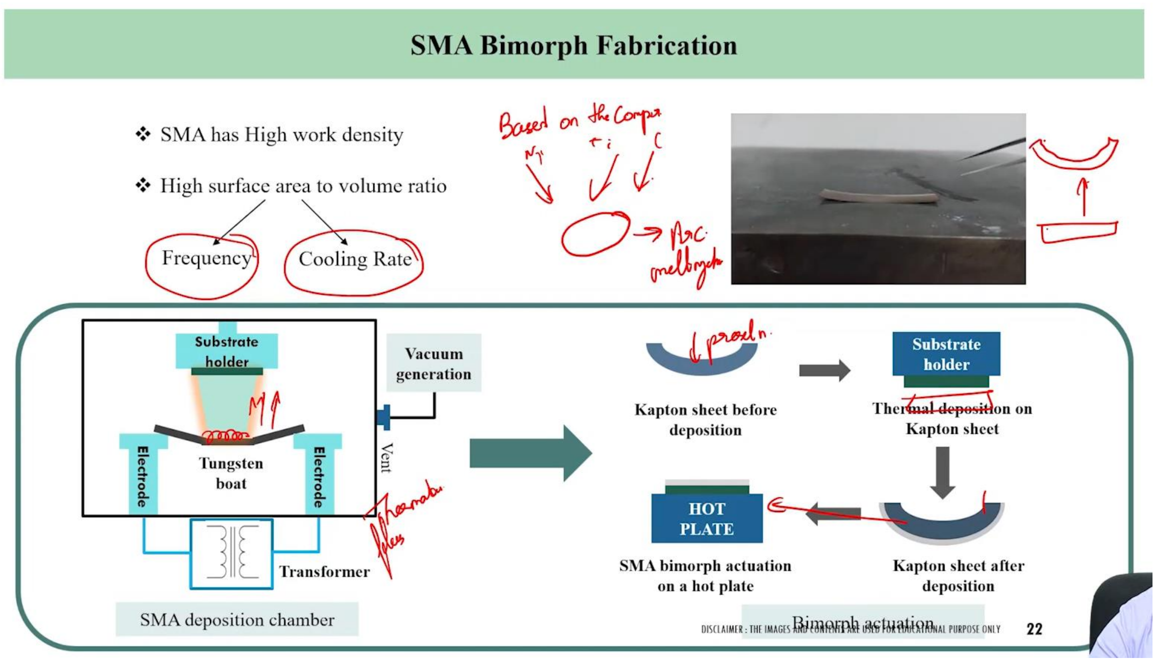
Now, let me just introduce you to this shape-memory alloy bimorph. The shape memory alloys have a high work density and a high surface area to volume ratio; they have a capability for high frequency and cooling rate. This is a kind of SMA deposition chamber; in this SMA deposition chamber, there is a tungsten boat. This is a kind of thermal deposition unit. This thermal deposition unit can be used to deposit a shape memory alloy structure.

Now, one of the important points that you may need to consider is our feed material that we are planning to use. Based on the composition, we get powders; for example, if I want to make a quaternary alloy or a ternary alloy, I can take Ni, Ti, Cu, etc., and make it in the form of a pellet in an arc melting chamber. In an arc melting chamber, we try to make a pellet, and this pellet can be integrated with the tungsten board, and then we try to supply a kind of electrical biasing through this. Through this electrical biasing, the material melts and is deposited on a substrate holder.

So the entire thing will happen in a vacuum environment since this system is called a flash system, where the power is applied instantaneously to the tungsten board, resulting in rapid heating of the material and rapid evaporation of the material on the surface. Now, if you try to see the overall mechanism that is happening in this. So this is the kind of Kapton sheet that is used. So this Kapton sheet is initially in a curled form. So when we try to put it on a substrate holder, we attempt to straighten it.

So, a shape is already preset in this kept-on sheet, and now, using a substrate holder in this preset condition, we are trying to straighten it and then proceed with thermal deposition. This thermal deposition, the thickness of the material will be in the order of less than 1 micron, close to around 0.25 to 0.5 micron, where the deposition happens so that it takes the curled shape of a Kapton sheet after deposition gets curled, and when we try to put it on a hot plate, it tries to get biased. As far as this bimorph actuation is concerned, you can see over here that this is on a hot plate; when we try to put it on a hot plate, it becomes straight, but when it is taken into an open environment, it takes a curved structure; that is the switching between the actuation domains.

Now, in order to preset this particular shape setting on the SMA biomorph, two different techniques have been followed. So one technique is to take a kapton polyamide, strain it using a fixture, and then complete the straining in a tensile testing machine. In that tensile-testing machine, it is further being placed within the two-pulley arrangement in this particular fashion. And this pulley arrangement is such that the shape setting will be continuously deployed during the deposition. So what happens is this pulley will always be in a kind of strained condition.



So this is what we call programming the shape memory alloy for our requirements. So, how much is the frequency that we require? How much displacement do we require while appropriately straining is deployed over here? Now we have a kind of arrangement. So in this bot kind of arrangement, we have already kept the pellet that has been manufactured or is required to make an appropriate composition. Now a kind of electrical biasing is applied to it. This electrical biasing is capable enough to ensure that there will be a kind of evaporation that persists, and this deposition will be a kind of continuous deposition.

So what happens is that since you have a pulley arrangement, these pulleys are connected to the motor and the motor to the idler pulley. When the rotation happens, there is going to be a continuous deposition of the material. This continuous deposition will result in a kind of deposition belt over here. Overall deposition is in the form of a sample size that is closer to 2 centimeters than to 50 centimeters. The deposition bar is in the range of 2 into 10 to the power of minus 5 millibar.

The deposition current used is approximately 380 amps, and then only 1 gram is used. So, based on the weight, we can have a kind of varying thickness that we are going for. Now, this is the case in which, like in the earlier case, we have used a flasher operation. So, wherever we want to make a bimorph, we go for this flash evaporation. That is, wherever we want to go for a low-density film, this film will not be highly reflective.

However, it has better actuation. So, for these better actuation properties, such kinds of thermal evaporation are deployed. However, wherever we want to go for high-density film, we can deploy a kind of E-beam based system. In this E-Beam based system, try to put the source over there, and then, using an E-Beam, the source is evaporated, resulting in a kind of continuous evaporation that occurs, and because of this continuous evaporation, there will be a thickness in the overall structure. So this thickness will result in a greater amount of high-density structures being fabricated per unit area here.

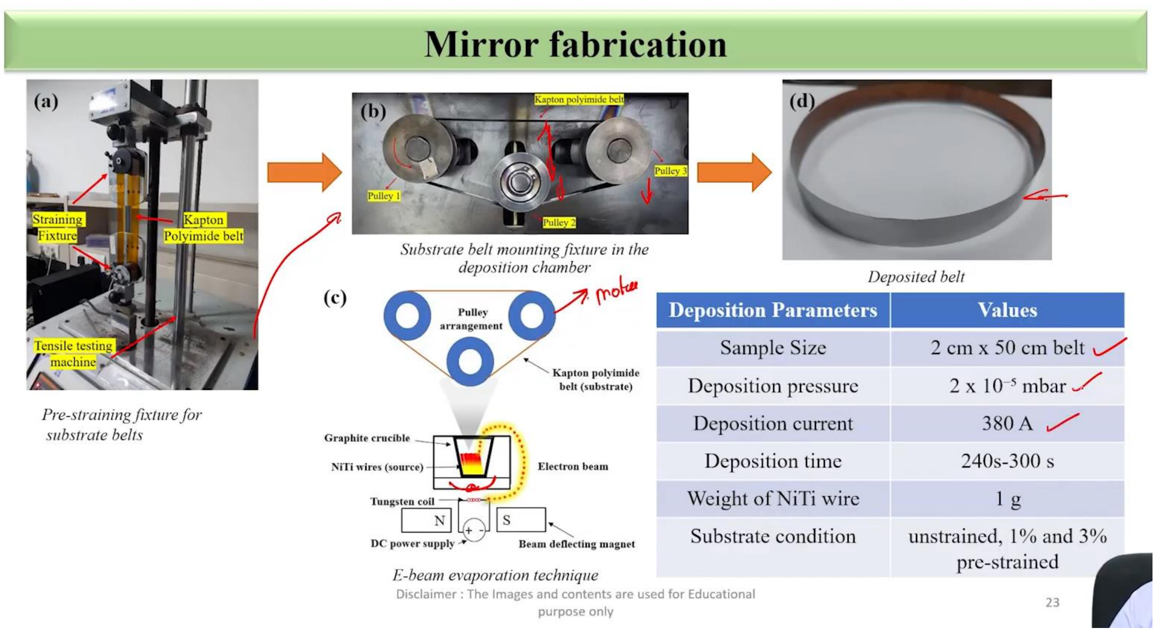
So because of these high-density structures, you get a high-density film that exists. So in this high-density film, these are the different process parameters that are employed. Since an E-beam is used, these E-beams are capable enough that a good amount of energy is imparted on the material, and this material will start depositing. Finally, as shown before, here we also have a kind of kapton polyamide; these kapton polyamides are strained appropriately so that there will be continuous deposition, which is exhibited over here. So because of this continuous deposition, you can have a thicker, high-density film, which is almost equivalent to a kind of mirror that can be established over here.

This is a customized system; it's a PVD-based system that is being deployed. In fact, regarding PVD, we have discussed a lot in microfabrication. Now, let us see the characterization of this electrical actuation. As far as this electrical actuation process goes, if you closely observe the cycle, it is initially in a certain state, and this is the representation of tip displacement. So what happens is that as the tip increases, the displacement also increases with reference to time t, and then there is a decrease in the tip displacement.

So this cycle is called a repeatability cycle; that is, we can call it a kind of reliability cycle. So, in order to get the cycle, we normally have a kind of setup that we will be showing during the demonstration as well. So, in order to achieve this repeatability cycle, we keep the SMA bimorph, and then the overall repeatability of the structure can be monitored using a laser displacement sensor. In this laser displacement sensor, the light is made to interact with the tip, and when continuous actuation occurs, there is a reflection that persists, from which we can estimate the overall cycle. The voltage supplied is around 25 volts, and 0.

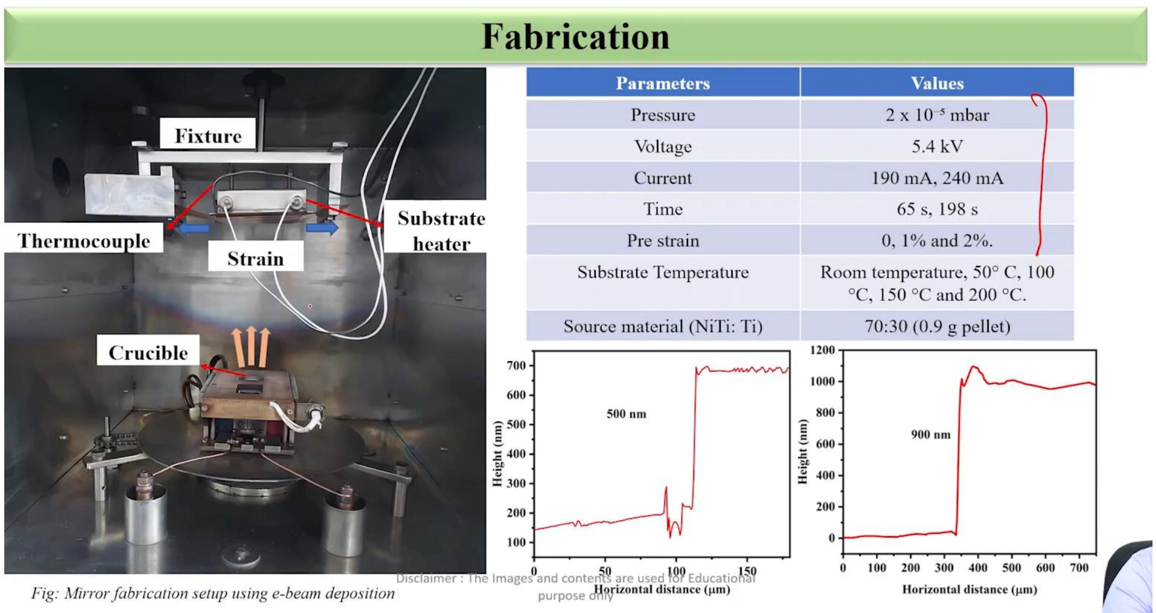
25 amps is the overall input to this particular system, with a frequency close to 0.25 hertz. As far as this displacement is concerned, we can have control over the displacement; roughly, the displacement is on the order of micrometers. So, basically, a range from 60 micrometers to 75 micrometers can be easily established using this particular SMA biomorph. However, the overall actuation characteristics or the frequency characteristics can be efficiently catered to by changing the thickness.

By appropriately changing the thickness and the strain percentage of the Kapton polyamide, we can achieve the higher order frequency that we are looking for. Now, how? So, this is a kind of initial trial. This is a kind of SMA bimorph mirror that has been fabricated using this technique, and since it is used for beam steering, the incident beam is made to strike the mirror, and the reflected beam is collected on the screen. This is a kind of power source that is being employed for the biomorph, so basically, since the actuator has the capability to actuate at a high frequency, we can also deploy a programmable power supply. This programmable power supply can be integrated with the bimorph for a higher order frequency, so you could observe in this particular video.

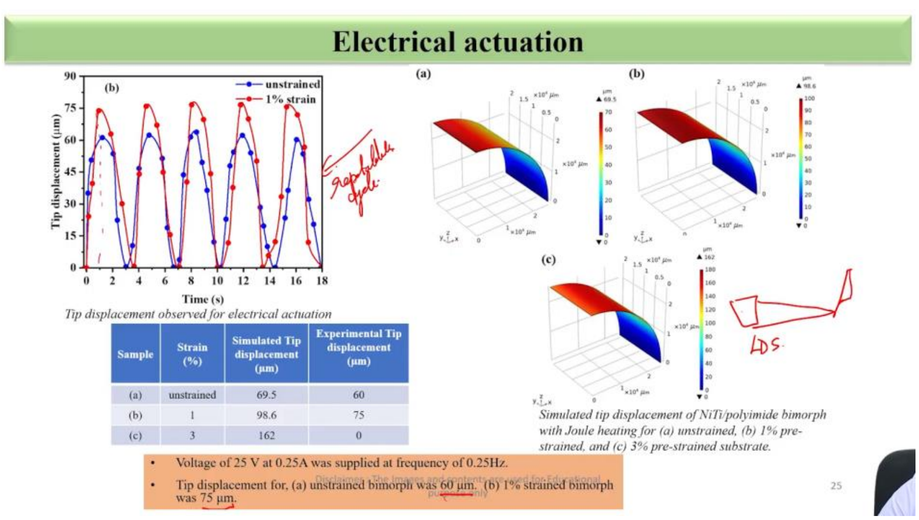


This is a kind of laser that is interacting with the bimorph, and this bimorph is reflecting. So, the bimorph is over here. The connection for the bimorph is taken through these leads, and from the reflection, you can see the overall sweeping of the mirror that occurs. So the mirror gets swept and appropriately it is used for reflecting the beam. Now, one of the microfabrication techniques that was followed here is that we have induced a kind of roughness on these polyamide substrates in order to improve the efficiency.

You may ask a question like, whenever such kinds of bimorphs are prepared, there is a question of adhesion. Because these are completely two materials that are being bonded using a coating technology, there is a chance that these films may get peeled off when we try to actuate it. When we are discussing this substrate selection, I had discussed two different types of substrate selection. One is the substrate integrated with the SMA, and another is where both the substrate and the thin film will work together, resulting in a kind of actuation. And the other technique is something like the substrate and the SMA, where the SMA can be peeled off and the substrate can be used separately.

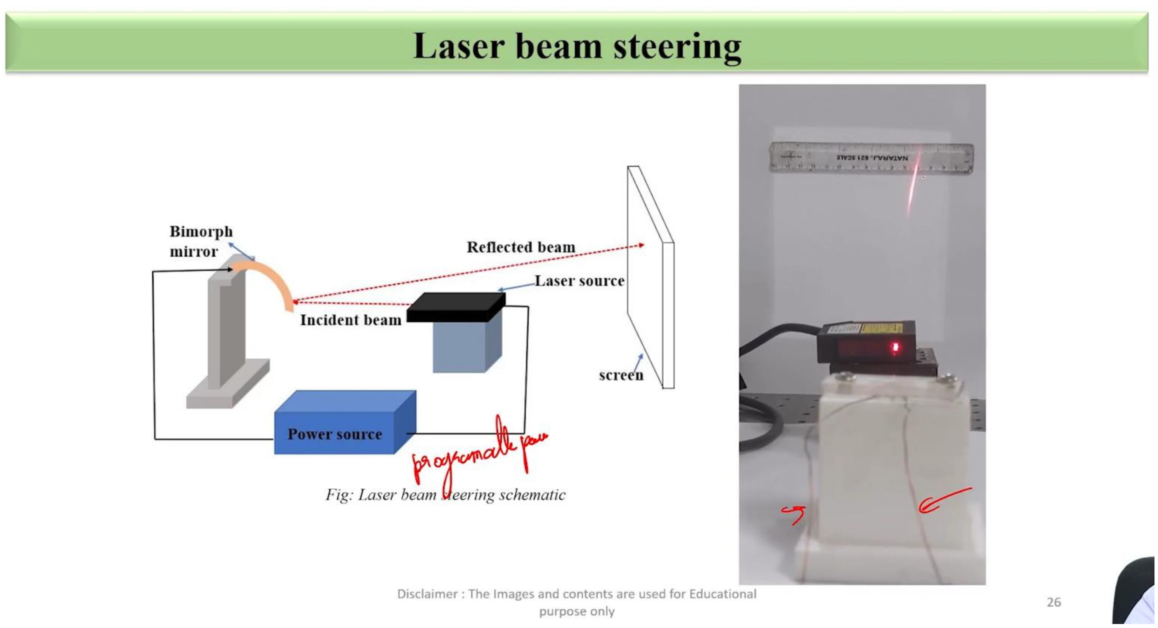


Now, in this particular case, in order to improve the frequency, we are trying to work on it. So if you are trying to use it for a mirror application, one important aspect is that we may need to run it at a higher frequency. So at this higher order frequency, at any cost, there should not be any peel off of the material. That is one important aspect. There are different techniques that are deployed to improve adhesion.



So one property can be that we can go for a plasma treatment of this polyamide so that the adherence of the polyamide will be improved, and when we go for a coating, we can appropriately get a characteristic. Another method is something like we can go for a kind of pulsed laser crystallization. Using pulsed laser crystallization, what we can do is modify the surface based on the requirements, and then we try to go for a coating. Once we go for a coating, what happens is these modified layers will act as a kind of anchoring medium. In this anchoring medium, once you go for a coat, these anchoring mediums will hold and will have a greater amount of adhesion.

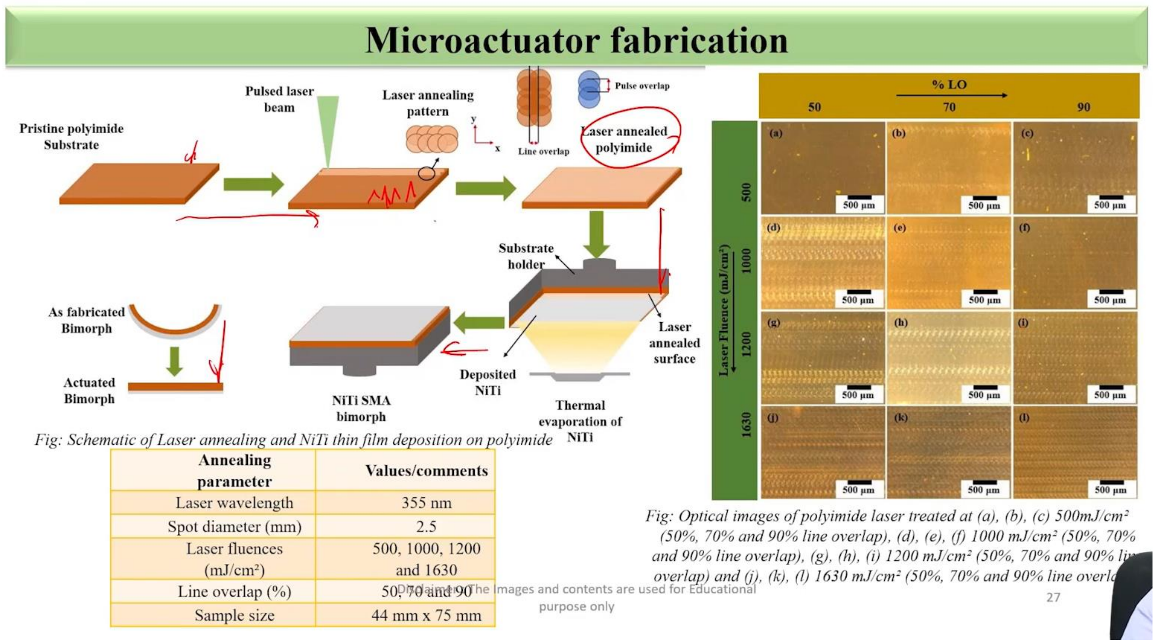
That is like we are trying to manipulate the surface-to-volume ratio appropriately so that you can have a greater amount of adhesion. So with a greater amount of adhesion, you can appropriately achieve a larger life cycle, which is what we are looking for. These are the overall steps that are being followed. This is a kind of pristine polymer substrate that is integrated with the laser handling, and then, with the laser handling, the deposition is performed using thermal evaporation. The thermal evaporation, NiTi-SMA biomorph, as-fabricated biomorph, and actuated biomorph are integrated here.



Now, like in this particular case, we have different parameters that are being established over here. So it's a kind of surface treatment that has been done to improve the capability. Now, this is the system which has been fabricated. So this is a kind of micro position-based steward platform that has been fabricated. So, in this micro position-based steward platform, there is an SMA bimorph mirror.

The mirror is in the form of an SMA bimorph-based actuator, which is integrated with the mirror, and these are individually connected to a relay system. In order to monitor the position and orientation of these SMA bimorph mirrors appropriately, a certain number of

ArUco markers are being placed here. So these ArUco markers act as a reference in such a way that when we try to actuate them appropriately, they move. So in this particular construction, if you see, there is a kind of micro-positioning stage with the ArUco marker and a mirror, and then there is a camera that is being placed, a motion controller, and a computer. This camera is used for observing the overall mirror, and there is a micro motion controller available.



Annealing parameter	Values/comments
Laser wavelength	355 nm
Spot diameter (mm)	2.5
Laser fluences (mJ/cm²)	500, 1000, 1200 and 1630
Line overlap (%)	50, 70 and 90
Sample size	44 mm x 75 mm

Through this micro motion controller, we can observe the behavior. So, we can have a kind of deflection in this plane. Let us consider this as the Z axis and this as the X axis, and then the deviation in the X axis between the Z axis is mentioned as theta x. So this theta x is like it is on a micron level for shifting the beam. So, if you see the overall response to this, it is a kind of micron inclination that has been observed.

In this micron inclination, the overall system is designed in such a way that the maximum inclination of the mirror achieved was close to around 28.76 degrees Celsius, and about the X axis it is around 8.46 degrees, about the Y axis it is around 1.19 degrees, and about the Z axis it is around 27.76 degrees along the X axis. So, appropriately, the steward platform will create a work volume over the portion and the mirror inclination with a single bimorph and two bimorph actuations for 8-volt input, and it has a cycle of 0.25 hertz that is being kept over here. Now in this particular case, we have the angle about the z-axis, the angle about the y-axis, and the angle about the x-axis, which are being represented in this particular domain. Now, here you can see this is the overall construction, in fact, which is deployed for actual conditions. So in this deployment, what we are trying to do is place a mirror over the steward platform.

Fabrication and Calibration for position detection

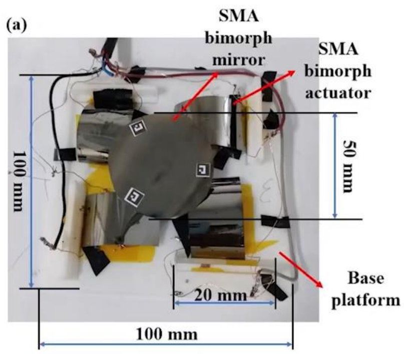


Fig: Stewart platform arrangement with SMA bimorph mirror and actuators

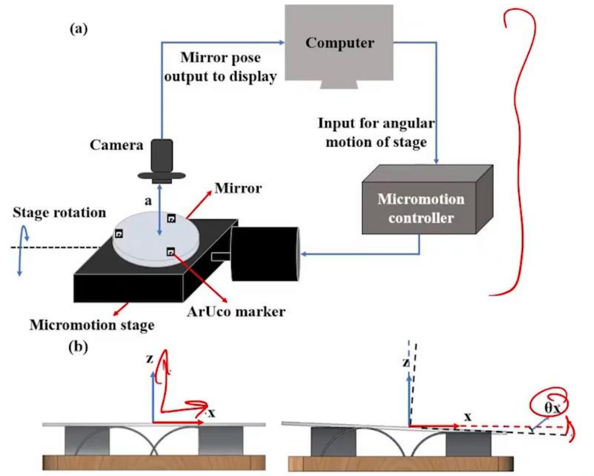


Fig: (a) Setup for camera calibration (b) Side view of angular motion of the mirror.

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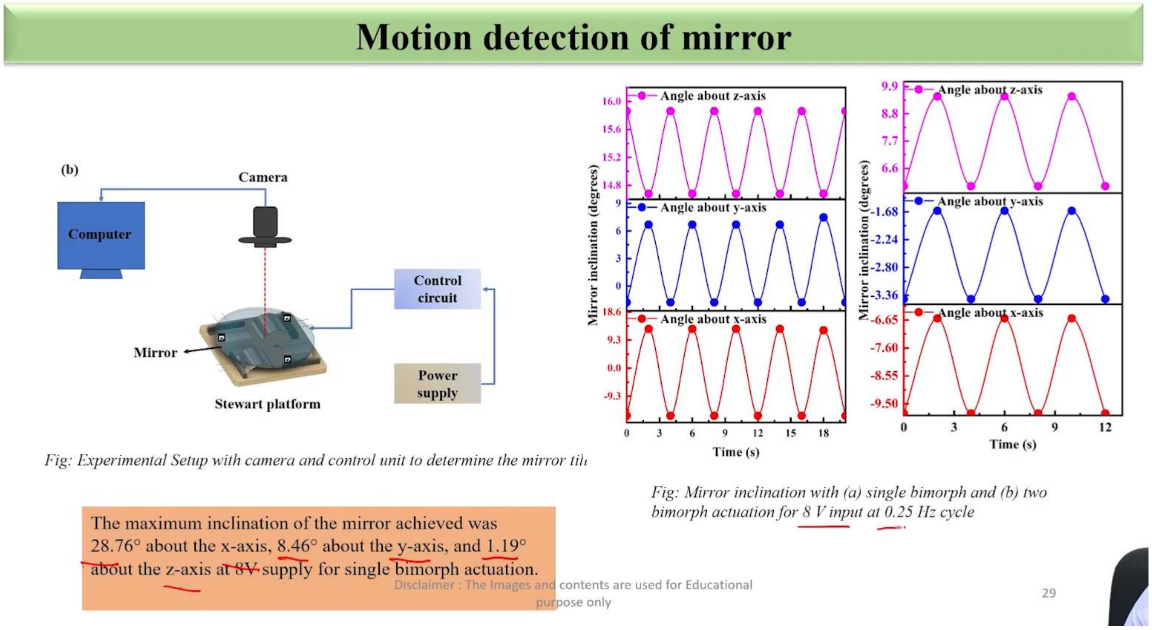
This mirror is a kind of rigid mirror that is being placed. Since we have the capability to fabricate a mirror with an SMA bimorph, which is a kind of static bimorph. From an actuation perspective, these mirrors are integrated in this particular fashion so that the actuations can be appropriately controlled, which has a direct relevance to the degrees of orientation along the X, Y, and Z planes. This is the incident laser beam, and a camera is used to capture the overall orientation of this particular beam and its appropriate characteristics. So in that aspect, it has three different types of orientation: one is along the theta x orientation, and the other one is along the theta z orientation.

So, as far as the theta x orientation is concerned, a degree of around 1.01 degrees plus or minus 0.18 degrees could be achieved, and with reference to the z direction, 0.42 plus or minus 0.05 could be achieved. The direction has a direct relevance to the degree, and appropriately, a laser beam is being diverted over here. Now, let us see the overall fabrication procedures which are being involved in this. Now, in the earlier case a kind of a parallel mechanism has been fabricated. Now, we will see a mechanism where, like an optical shutter, an optomechatronic shutter has been developed. So, it has the capability to open and close in such a way that it can restrict the light entering this optical shutter.

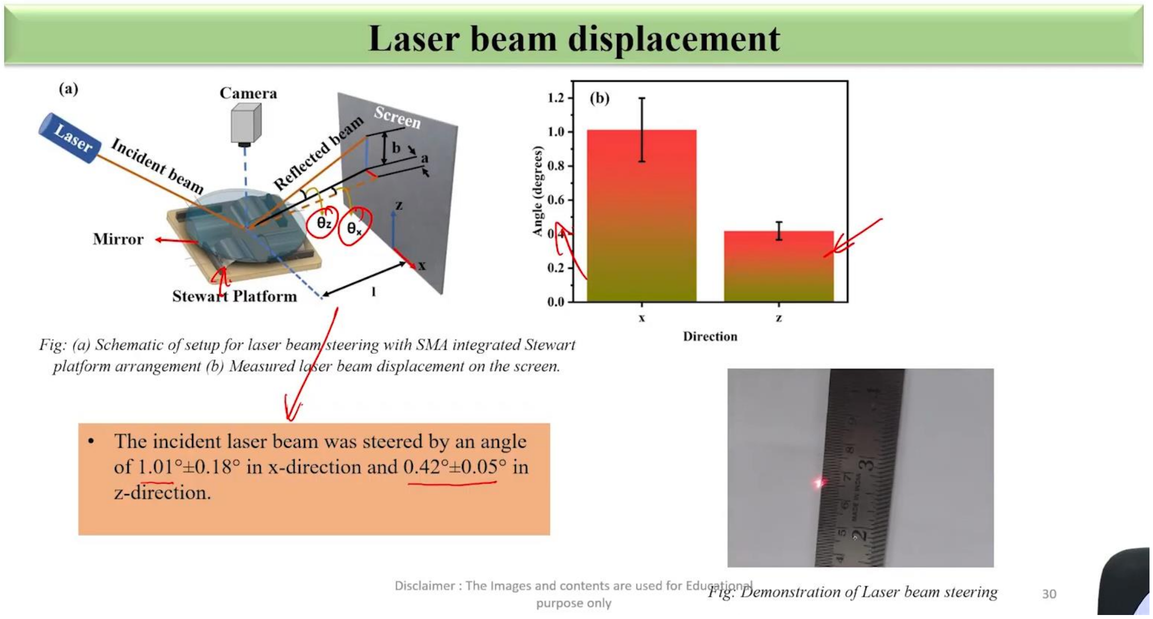
So, this is a closer view of the laser beam's steering. So, if you closely observe, the overall deviation is well controlled. So, there is no undulation in the system, and all the theta X and theta Z are well recorded, and the overall micromanipulation is on the order of less than 100 microns, which is the observation. Let us take one of the sub-case studies in this. So in this case study, what we are trying to do is plan to fabricate a kind of SMA-based optical shutter. So the main application of this optical shutter is that it opens and closes and restricts the overall interaction of light inside a particular system.



So, in fact, the optical shutter looks something like this. So in order to fabricate this, again, so we are fabricating the SMA biomorph. In this SMA biomorph configuration, what we are trying to do is, through vacuum arc melting, to make the concerned pellets, and then these pellets are used as source material for thin film deposition. So in this thin film deposition, there is a graphite crucible, and then the source material is applied. And since it is used for optomechatronic applications as discussed earlier, we may need to have a high-density film. To achieve a high-density film, an E-beam evaporation technique is deployed.

Now, in this E-beam evaporation technique, we get a strip of SMA biomorph. Now we may need to derive this SMA biomorph based on the requirement. Since we are looking for a kind of micro-level actuation, it is easy to fabricate such a micro-level process using a laser. So this is a kind of fiber laser that is used. During the overall process, these kinds of SMA biomorphs are strained, and a laser beam is used to interact with the biomorph, and then it is appropriately cut.

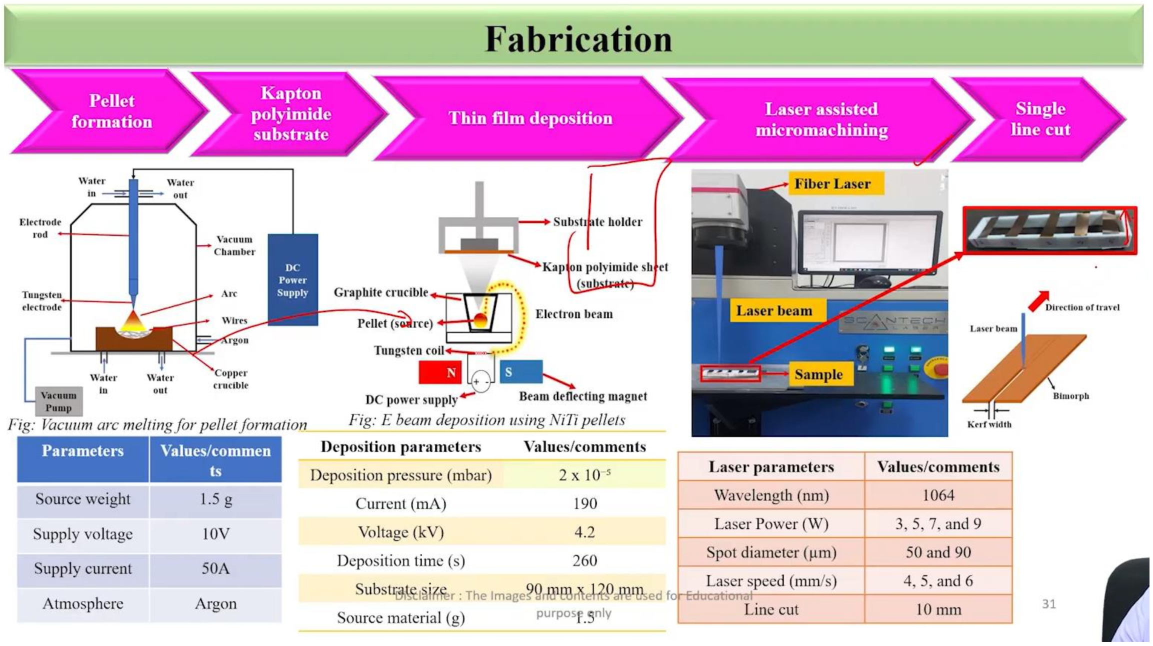
The different laser parameters are used, and this is a kind of SMA biomorph that is being fabricated. So you can see a closer demonstration over here, and a closer video over here. This is an SMA biomorph in which the concerned features are cut using a laser. This acts as a petal; these petals are fabricated using a laser. So, based on the type of configuration, different molds are used for fabricating such structures.



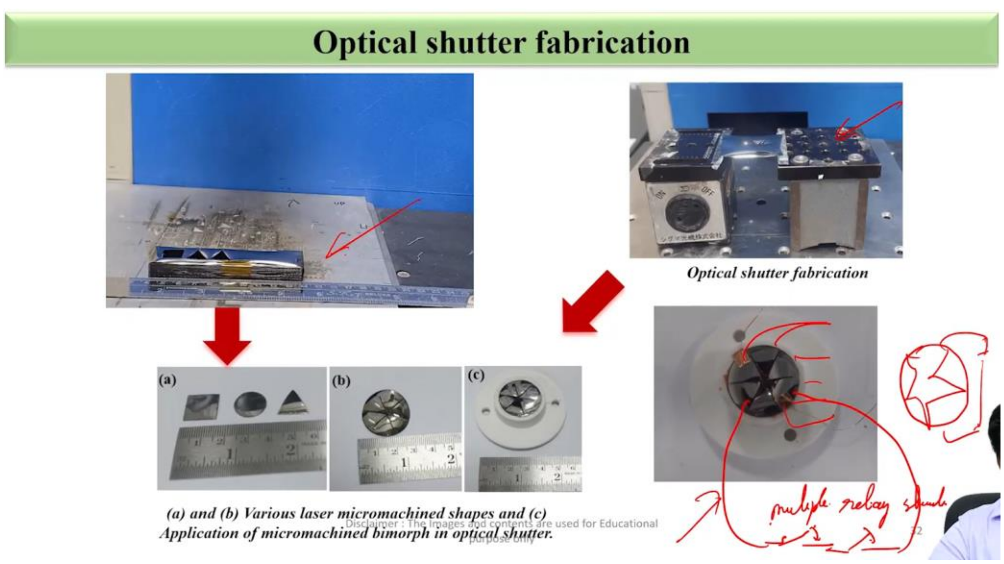
This is a kind of mold that is being deployed for the large area process. This is a kind of mold that is being deployed for a circular process. So these are some various configurations that are being deployed. So one set of configurations is in the form of a triangle. So one set of configuration is in the form of a kind of lotus petal shape.

And then the connections are established in such a way that the overall leads are taken in these particular dimensions, and the leads or contacts are established in such a way that instantaneous opening and closing take place. However, there is a possibility to have a different configuration in this. So in this particular configuration, what we can do is individually these systems can be connected so that there is a kind of an individual actuation which happens. For example, you can have multiple relay structures. So in these multiple relay structures, there is a kind of opening and closing of the relays.

With the appropriate opening and closing of these relays, there will be an opening and closure of these SMA biomorphs, and the actuation will happen appropriately. So in this particular case, if you keenly observe, in order to have control over the multiple micro actuations, we can have individual relay control, and these relay controls will give a signal for appropriate actuation. In fact, this talks about a kind of micro-robotic platform that is developed for optomechatronic applications, and what the stages involved in developing such a micro-robotic platform are. Especially the different stages involved in micro-fabrication, and then how the reliability and lifecycle behavior of these structures are assessed, as well as how closely the features are generated. So this is just to give you an overview and a feel for how micro-robotic structures can be fabricated.



Now, we will discuss the overall limitations of these particular shape memory alloy structures. In fact, we have discussed in detail the overall configurations, the types, and the reliability of the different devices, etc. So, one of the major limitations of shape memory alloys is that they have a high cost of production, especially from an internal perspective. That is the reason the raw material cost is quite high; secondly, there is a slight complexity in the machining of SMAs. So, as I mentioned earlier, for example, if you take a small rod or a small sheet and if I want to do a kind of drilling in this particular process.



So, whenever I try to apply heat to this particular material, it will try to deform and regain its shape. So, it is very difficult to hold this material for a longer period, which is one of the key challenges when we try to use such materials. They are highly sensitive to heat;

however, they have their own complexities and limitations regarding transformation temperatures, and there is complexity in controlling the SMA-based systems. So strategically, these materials are well represented in different defense and space-related applications, owing to their capability as smart actuators, smart sensors, smart microsystems, and smart microrobotics, etc. However, a future perspective point of view is that there is a possibility of exploring a cheaper alloy, and currently, 3D printing has taken shape in fabricating such kinds of shape memory alloy structures.

However, with the 3D printing process, there is a chance that it is very difficult to maintain the functionality of these particular shape memory alloys. Still, 3D-printed shape memory alloy structures are not commercially available, which may be a kind of future prospective direction where 3D-printed structures may emerge and take up a shape. Then, these kinds of 3D-printed structures can be integrated with materials for appropriate applications, allowing for a greater number of uses. The most important challenge from a field perspective is the training aspect. If so, currently the training is overcome through either this bimorph or through a kind of stretch strainability, etc.

However, if a simple training technique can be followed, this will open a new domain for the use of these kinds of actuators for different applications. The second important point with respect to shape memory is that, whether it is on a micro level or a macro level, it almost behaves in the same fashion.