

Micro Robotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

Indian Institute of Technology, Indore

Week-09

Lecture- Lec43

Microsystems for Microrobots (Manipulation) - Module 03

We have been discussing microsystems for micro-robots. So, in today's lectures, we will be discussing micro-manipulation for microsystem robots. In fact, we have been discussing this AFM (Atomic Force Microscope). So, in today's lecture, we will discuss the different modes of AFM and how an AFM is used as a kind of micro- and nano-robot from a characterization perspective. So, as far as the modes of AFMs are concerned, one mode is called contact mode. So, as far as this contact mode is visualized, it has a tip that will never leave the surface, used for very high-resolution imaging.

So, the maximum vertical force is also controlled to minimize the compression of the sample, it has a fast scanning speed, and it is highly used for good surface roughness analysis. So, ideally, this particular tip will try to move along the surface, and it will try to trace the profile; from the profile, we can observe a kind of roughness pattern that comes out of it. So, the secondary concern regarding contact mode systems is that these contact mode systems have the possibility of damaging the surface. So, for example, if you have some kind of porous, soft structures or porous auxetic structures, there is a chance that they may damage this surface if the measurement is done in the air atmosphere.

And as far as these lateral forces are concerned, these lateral forces can also distort the image, which will have an impact on the system. So, ideally, these contact modes are effectively used for a type of coating or a type of thin filling that is exhibited. Now, let us discuss the second mode, which is called tapping mode. As far as this tapping mode is concerned, in this tapping mode, the tip will not be in touch with the system. So, ideally, the tip will not be in contact with the surface; there will be a gap between the surface and the tip, and we can almost observe a kind of oscillating cycle, as shown over here.

So, as far as this particular case is concerned, there is a kind of charge transfer that happens between the tip and the surface. Accordingly, we can study the overall orientation of this charge transfer. So, it is used for imaging the samples that are not firmly stuck to the surface, such as molecules, and the cantilever is driven close to the resonance of the system to provide an amplitude for oscillation. The cantilever oscillates, and the tip makes a

repulsive contact with the surface at the lowest point of the oscillation. So, ideally, when we try to observe the tip at the lowest point of oscillation, we will have a repulsive force, and at the top edge, we will have an attractive force.

So, there will be a kind of deviation or repercussion between the peak and the valley. At the peak, we will have a kind of attraction, and at the valley, there will be a kind of repulsion. So, based on that, we can generate a kind of profile, and these profiles will give an indication of the traces of the overall surface features that are being deployed. Oscillation can be achieved with a small piece of element in the cantilever holder, which we discussed a lot in the last class, and it has a kind of AC magnetic field and a piezoelectric cantilever or periodic heating with the laser beam. One of the important key aspects of this particular mode is that it has an imaging force that is a bit lower.

Now let us discuss the next mode, which is called force modulation mode. So, as far as this force modulation mode is concerned, in this mode the tip does not leave the surface, but it makes a small oscillation. This is a kind of dynamic form of contact mode called force modulation mode. So, the cantilever is kept oscillating with a fixed amplitude, its resonance frequency is being monitored, and an image is formed by a constant frequency shift, while the difference between the current frequency and the free resonant frequency is being deployed. So ideally this is a kind of force spectroscopy mode which is being deployed. So, wherever kind of corrugated structures are present, such force-operated AFM modes, i.e., force-modulated AFM modes, can be efficiently deployed. Now, let us talk about the non-contact mode-based system. So, as far as this non-contact mode-based system is concerned, the cantilever in it is almost equivalent to a kind of tapping mode, whereas in the case of a non-contact mode system, the cantilever oscillates close to the sample surface at a resonance frequency but never makes contact.

So, there is a kind of force that is exerted. So, there will be a kind of attractive force and a capillary force in air that create a possibility of the tip touching the surface. It requires very stiff cantilevers to overcome the attractive forces and operate without touching the surfaces. A long range of forces between the tip and the surfaces decreases the resonant frequency of the cantilever, and this decrease in resonant frequency, combined with the feedback loop system, maintains a kind of constant oscillation amplitude or frequency by adjusting the tip to a sample distance. This tip to sample distance data at each point is used by software to construct a kind of topological image.

So, ideally, this topological image will have complete information about the peaks and valleys. From the peaks and valleys, we can estimate the overall undulation that comes from it. Now, with reference to all these modes, it is observed that this feedback plays a vital role. So, when we try to observe this feedback system with reference to the AFM perspective point of view, it is a bit critical; in fact, in the earlier classes, we have also seen that these feedbacks are taken from both the piezo layers and the piezo scanners. Within

the piezo layers and the piezo scanners, the feedback loop is embedded, and the signals are taken care of appropriately.

Let us discuss the strategies that are followed for a feedback loop, or we will have a detailed insight into the overall parameters that are being considered for a feedback loop. So, in the case of AFM operation with reference to the feedback loop, AFM operation is based on the ability to keep parameters like deflection, amplitude, and phase shift constant. This is done by an AFM control system, which is usually a kind of proportional integral differential (PID) system. So, the digital controllers have built-in timers which provides the time base for interruption. It is a code which ensures a well-defined and a consistent timing.

So, which is represented as dt . A PID feedback loop consists of three correction terms that contribute to the Z-scanner position at a given time (Z_t). Thus, z of t is represented as $P \epsilon_t + I \sum_{i=0}^t \epsilon_i + D \frac{\epsilon_t - \epsilon_{t-1}}{dt}$. Therefore, t equals $t-1$ means $t-dt$, and ϵ_t is the error signal at time t , the difference between the measured value and the set value. So, as we all know, the proportional part of the PID is nothing but the proportional, integral, and derivative gains, respectively.

- A PID feedback loop consists of three correcting terms, which contribute to Z-scanner position at a given time (Z_t).

$$Z_t = P\epsilon_t + I \sum_{i=0}^t \epsilon_i + D \frac{\epsilon_t - \epsilon_{t-1}}{dt}$$

Where,

$t-1$ means $t-dt$; ϵ_t is error signal at time t (difference between measured value and set value); P, I, D are proportional, integral and derivative gains respectively.

Now, let us go into detail about the overall feedback loop. So, most of the AFM employs P and I only because the differential control leads to instabilities, thus considering a kind of proportional integral feedback.

This can be rewritten as $Z_t = Z_{t-1} + a \epsilon_t + b \epsilon_{t-1}$. So, a equals $p + i \Delta t$, and b equals $-p$. So the proper feedback control requires the fine-tuning of these PI parameters.

As far as these atomic force microscopes are concerned, with reference to the feedback loop, the fine-tuning of the PA signal is done by overlapping the forward and backward scan signals. So, low values of a and b indicate the different profiles for forward and

Atomic force microscope as micro/nano robot

Feedback Loop

- Most AFMs employ P and L only because differential control leads to instabilities. Thus, considering PI feedback,

$$Z_{t-1} = P\varepsilon_{t-1} + I dt \sum_{i=0}^{t-1} \varepsilon_i$$

Thus, relation between Z_t and Z_{t-1} can be written as,

$$Z_t = Z_{t-1} + (P + I dt)\varepsilon_t + P\varepsilon_{t-1}$$

This is rewritten as,

$$Z_t = Z_{t-1} + a\varepsilon_t + b\varepsilon_{t-1}$$

$a = P + I dt$ and $b = -P$.

Proper feedback control requires fine tuning of PI parameters.

Thus, a system response will be a very slow. So, system response for low values of a and b will be very slow and for two high values of a and b which makes the system unstable. So, the Z piezoelectric system oscillates at a very high frequency. So, in the commercial system, the optimized values of A and B are derived by an inbuilt algorithm that takes care of the overall compensation within the arrangement. So, these are some of the key aspects with reference to AFM as micro and nano robots.

It is a kind of fundamental where AFM characterization is used. Now, let us discuss in detail how an AFM is used for a kind of fiber pulling. So as far as these fibers are concerned, we all know that we are aware of it. Fibers are widely used for sensing-related applications, and they have the potential to be used for diagnostics in certain cases; they are also used for improving strength, etc. Now, in this particular case study, we will discuss this 3D micro and nano fiber pulling, which is a kind of microfabrication technique in which thin fibers are pulled in a controlled manner to achieve a diameter in the micrometer or nanometer range to generate three-dimensional structures.

So, these micro- and nano-fibers are useful in biomedical engineering; they are also used in fiber optics, micro and nano electronics, etc. Some of the commonly used micro and nano fiber pulling techniques are AFM tip-controlled pulling, flame-heated taper drawing, tungsten probe pulling, and polymer drawing. So, in all these cases, one of the key aspects that we may need to consider is that the overall coil diameter and overall length need to be taken into consideration. Let us look into the overall methodology of how these pulling capabilities are deployed and how they have an impact on different fabrication processes. Let us see the first concept.

It is a kind of AFM tip control pulling process. So, in this AFM tip control pulling process, we have an AFM tip and then there is a polymer in place. This polymer will interact with the heated substrate where the material that the fiber needs to be pulled from is kept, and then a kind of micro-nano fiber pulling is done with an AFM tip when it touches the surface and tries to pull it. AFM tip control pulling is a concern. Let us consider a type of thermoset polymer that is coated on a glass substrate.

The substrate is heated to a temperature of around 90 degrees Celsius, which is mainly meant for curing the polymer. Now we have a silicon AFM tip that is used to pull the fiber in a vertical direction, as shown here. So what happens is, this is a kind of tip that is being inserted into the cured polymer, and there is going to be a certain amount of curing that results in nanofiber formation between the substrate and this tip. After a certain waiting time, the nanofiber itself cures at room temperature due to its high aspects. In the case of the application perspective, it is highly used for electronic circuit sensors as well as robotic mechanisms.

This is a concept where AFM is used. So some of the key parameters that are taken into consideration are the overall diameter of the fiber, the length of the fiber, and the density per unit area of the fiber, which will heavily contribute to the kind of manipulation exhibited here. Now let us discuss the next concept, which is called flame heated taper drawing. As far as this flame heated taper drawing is concerned, if we try to look into this particular process, there is a kind of standard fiber that is of a particular diameter. Ideally, there is a flame that is being introduced into it. So, with reference to the flame, the complete material gets heated up, and then you can pull the fiber. So the fiber is pulled with a kind of pulling force that is exerted here. So there is a kind of feedback system that exhibits an input signal, and then the overall change in the input signal is measured from the output signal system. So what is happening is that when the flame heats this fiber, the fiber is pulled up or deformed, and finally we get a thin structure coming out of it. So, here in this particular case, a hydrogen flame is used for heating the optical fiber.

A constant pulling force is applied to the fiber during the heating to reduce the heat diameter to a desired value. As far as the optical signal is concerned, the optical signal is passed through the fiber during the pulling process. This is ideally done for a kind of in-situ monitoring of waveguiding properties such as propagation loss, multi-mode interference, and group velocity delay. So, this kind of system is mostly used to draw silica with this kind of pulling process for a standard optical fiber. And one of the key aspects, since heat is involved in this, is that the flame heat can lead to a kind of turbulence and can also result in a kind of contamination in the nanofiber.

So, in order to avoid that, ideally what is done is that it is wrapped with an insulating medium so that the contamination can be appropriately eliminated. This is one way, or the other way is something like it is completely done in a controlled environment, so that the

contaminations can also be controlled. So, this kind of contamination can also be eliminated by using an electric heater or laser heating in a sapphire tube while pulling. Now, let us discuss the next configuration, which is a kind of tungsten probe pulling. As far as this tungsten probe pulling is concerned, it is a manipulation process in which a solution phase of the material is taken into consideration.

From the solution, you try to achieve wetting of a particular tip, and then when we manipulate it, we get a thin nanofiber coming out of it. We might have observed how, when we have the tip of a pencil dipped in a particular liquid, and when we try to pull it back, we see a thin film layer that comes out of it in the form of a thread. So this is a kind of concept that exhibits in such a way that you have a probe, and through the probe, you are trying to get it. So as far as this tungsten probe pulling is concerned, it is mainly meant for polymer or biological samples that are put on a glass slide in a kind of bulk solution, as shown here. The glass slide is heated to reduce the viscosity of the polymer solution. So, the tip of the tungsten probe is approached in the solution at one end, and the probe is retracted in this direction along the surface of a glass slide at a constant speed to produce a nanofibre. So, if you closely observe this schematic, we have a glass slide and a provision for heating the sample, heating the slide to have control over the viscosity. This should be done in a kind of controlled environment, and one of the most important aspects is that it is expected that there is no airflow within this particular domain. So, in case there is air flow appropriately, there is a chance that this nanofiber may break, and we would not have any kind of lattice deformation exhibited on this nanofiber. So, this is a kind of simple manipulation technique where a tungsten probe is used to pull the fiber based on its adhesion characteristics and its wetting property.

So, here one of the key points that we may need to look into is that the tip plays a vital role. The overall surface characteristics of the tip play a vital role in wetting the particular liquid and then pulling the particular liquid in appropriate directions. Now, let us discuss this polymer wire drawing process. So, as far as this polymer wire drawing process is concerned, from a mechanical perspective, this tungsten probe pulling and this polymer drawing are almost the same. However, in the case of polymer drawing, it is a kind of wire drawing process that is deployed.

So, in this particular case, if we closely observe the overall construction of the system, we have an iron silica rod in place, then there is a hot plate with a molten polymer placed over here; this iron silica is made to dip into the molten polymer and then it is kept in a static phase. So, this polymer, such as polytrimethyl terephthalate (PTT), is put on a heating plate. It is heated and maintained at 250 degrees Celsius during the drying process. Iron and a silica rod are approached, and their tips are immersed in the molten PTT layer. Then the rod is retracted in a vertical direction at a constant speed of approximately 0.1 to 1 meter per second, producing a PTT nanowire between the molten PTT and the tip of the rod. So, as far as this particular case is concerned, the diameter of the wire and the overall density

of the wire depend upon the rod retraction in the vertical direction. So this is a concept that is being successfully established, especially for drawing wires, which is involved in a kind of polymer drawing that is being established. Now, as far as these applications' perspective points of view, these kinds of optical fibers are highly used for gas absorption spectroscopy. So, if you look at the overall construction of it, let us consider a crucible filled with molecules, which is a kind of gas that needs to be investigated.

Now, we have a kind of fiber in place where there is going to be an input signal and an output signal, and the numerical aperture of this is close to around 125 micrometers, and then in between we have a kind of 500 nanometers, which is pulled by using either of these synthesis processes. The optical input is passed through double-tapered optical fiber. So, the diameter of the waste section is usually close to or less than the wavelength of light. So, the waste section is exposed to the species under observation. The molecules of the species are absorbed on the fiber substrate surface and absorb a fraction of the optical signal.

So, the absorption of light by the molecule leads to the attenuation of the signal received at the output. So, ideally, the strength of the gas absorption lines can be used to find the gas concentration, that is, I equals $I_0 \exp(-\alpha lc)$.

$$I = I_0 \times e^{-\alpha lc}$$

So, I is the output intensity, I_0 is the input intensity, and α is the optical absorption coefficient. l is the length of the fiber, and c is the concentration of the gas. So, ideally, this acts as a kind of generalized equation to investigate the overall gas concentration in the system.

Now, such kinds of fibers are also used for other kinds of sensing elements. So, one of the sensing elements includes a Mach-Zehnder interferometer. So, as far as this Mach-Zehnder interferometer is concerned, it utilizes a kind of evanescent wave for sensing, and this evanescent wave is a small portion of light that comes out of the optical fiber during total internal reflection. So, when we try to observe this Mach-Zehnder, we have two sets of wires that are placed, and these are couplers, and there is a kind of sensitive arm that is available. So, in the case of a nanowire arm, the sensing arm with a certain length of a sensing area and nanowire refers to the reference that is used to keep isolated formation.

So this acts as a standard system and this acts as a sensing system. So from the standard system, we can see that we keep this as a calibration part, and from this calibration part, we can sense how much deviation is exhibited here, and by using a sensitive area, we can understand how sensitive this system is when deployed. So, for these applications, these kinds of MNF-pulled fibers can be efficiently used. Now let us take an application where

a fiber Bragg grating is deployed. So this is a process in which, by using a fibre, the fibre Bragg gratings are inscribed on the fibre-pulled samples.

So, this fiber-bragg grating is considered to be one of the successful fiber-based structures for optical sensing. It has high compactness and strong near-field interaction with the surrounding media, and it has a high resistance to mechanical and thermal shock, as well as high sensitivity and a small footprint with a larger dynamic range and faster response. So, to fabricate such a kind of MNF grating with a much smaller fiber diameter and a shorter overall length, femtosecond laser pulse irradiation is used. So, ideally, the XML laser with a wavelength of 193 nanometers, which is used for the scribe machine, and sometimes in certain cases, focused ion beam milling is also used. So, this laser beam is irradiated with this MNF grating at different points while increasing the refractive index of the core locally.

So, this is how these gratings are being deployed. However, from an application perspective, these gratings are efficiently used as a condition monitoring tool or for vibration analysis. In certain cases, it is also used for delicate measurements; it acts as a highly sensitive system that is used for delicate measurement. How are these fiber-pulled samples used for resonators? So, when such samples are concerned, we have a loop in place with an optical fiber, and these are MNF assembled samples. So, we have different configurations which are being deployed. One is a kind of loop-based system, another is called a knot-based system, and we also have a stack of coil-based systems.

So, in the case of a resonator, when an MNF is assembled into a closed loop, a ring resonator can be formed by an evanescent coupling at the overlapping area. So, the typical geometries are loosely assembled loops, either as a tied knot or as stacked multi-coil resonators. And MNF loop resonators are a type of Sagnac interferometer where the coupling between the adjacent MNF segments leads to almost a complete transfer of light from one segment to another. As a result, the electromagnetic wave makes several turns in the MNF loop, forming a resonance in the MLR transmission spectrum. So, as far as these particular systems are concerned, they are effectively useful for temperature measurement, humidity measurement, magnetic field sensing, as well as electric field sensing.

So, these are some of the key parameters which can be measured using such kind of resonators. Now let us discuss this MNF coupler. So as far as this MNF coupler is concerned, let us consider that we have the input P1, and then there is a waste region where exactly a transition region exists, and then there is going to be a reflective ring. So, a light is passing through it, and it passes through the waste region, and through the reflective region, it comes out of it. So, this is a kind of coupler, or this is a kind of transition region that works in this particular region, and MNF is bent while the two free ends are twisted together to form a Sagnac loop.

So, the twisted region is laterally fused and tapered, which will act as a kind of coupling region. It compresses a four-port. Two transition regions, one central base region, and a reflective ring formed by linking ports P3 and P4. So, the input light enters the waste region through the port P1, and the coupling process proceeds along with the coupling region. At the end of the coupling, the light continues to propagate within the Sagnac loop and finally enters the waste region again, but in the opposite direction.

So, this is how the system works. Now, in the case of the second coupling, that is when the second coupling happens; hence, the Sagnac loop in the proposed structure can be considered a kind of reflector. The corresponding output light at pore P2 is monitored and analyzed by an optical spectrum analyzer. So, these MNF couplers are a kind of useful structure for highly sensitive optical sensing, biosensing, and feedback systems in lasers, and these MNF couplers have been widely employed for the detection of micro force, magnetic field, current, sea water salinity, temperature, and humidity. So, these are the different parameters which can be measured using this particular system. So other applications and then and other important characteristics which we will be discussing it in the upcoming classes.