Microrobotics

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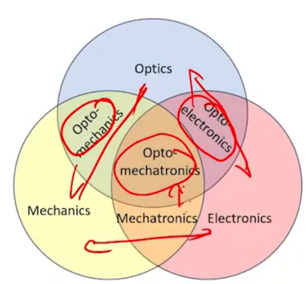
Micro Sensors and Micro Transducers - Module 03

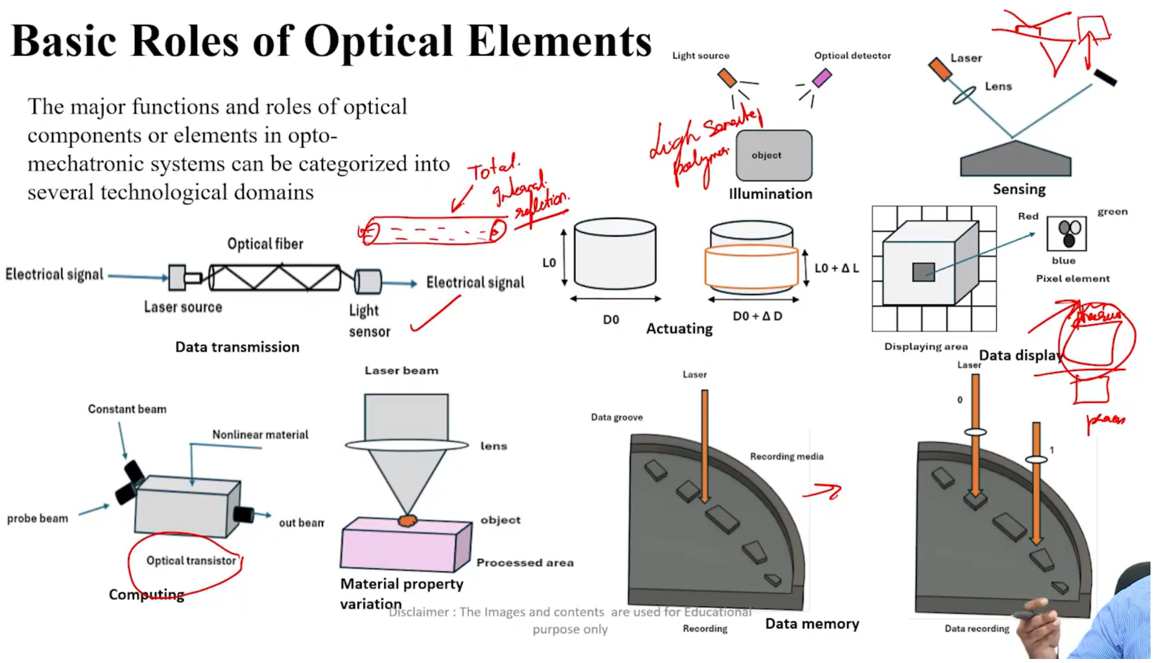
We have been discussing opto-mechatronic system design and the key motivation behind it, the overall evolution of opto-mechatronic system design, and some key examples of opto-mechatronic system design, which include optical fiber-based sensing, optical-based actuation, optical-based data display, and data memory manipulation. The opto-mechatronic systems are classified into three categories: one is called opto-mechatronically fused systems, another is optically embedded mechatronic systems, and the third is mechatronically embedded optical systems. Now, we will discuss some of the key components of the opto-mechatronics system. So, how do these opto-mechatronics systems cater to the entire microfabrication or micro-robotic system? It caters to the different parameters related to micro robotic systems. One of the parameters is related to mechanism design, signal processing, sensors and measurements, microprocessors, emotional controls, artificial intelligence, precision actuators, and information feedback. For all these parameters, these optomechatronic systems can cater to the requirements, and it can be appropriately used for integration.

Opto-Mechatronics System Design

- Opto-Mechatronic systems range from telescopes to microscopes, from wafer steppers to electron microscopes, from high-end 3D printers to gravitational wave observatories, systems that are dependent on cutting-edge mechanical engineering.
- To achieve a balanced design for such complex optical hardware, Opto Mechatronics is a discipline which combines mechatronics, design principle system engineering and optics.
- Optomechatronics is a field that investigates the integration of optica components and technology into mechatronic systems.
- The optical components in these systems are used as sensors to measur mechanical quantities such as surface structure and orientation.
- Optical sensors are used in a feedback loop as part of control systems fo mechatronic devices.
- Optomechatronics has applications in areas such as adaptive optics, automation, optofluidic, and thin-film technology

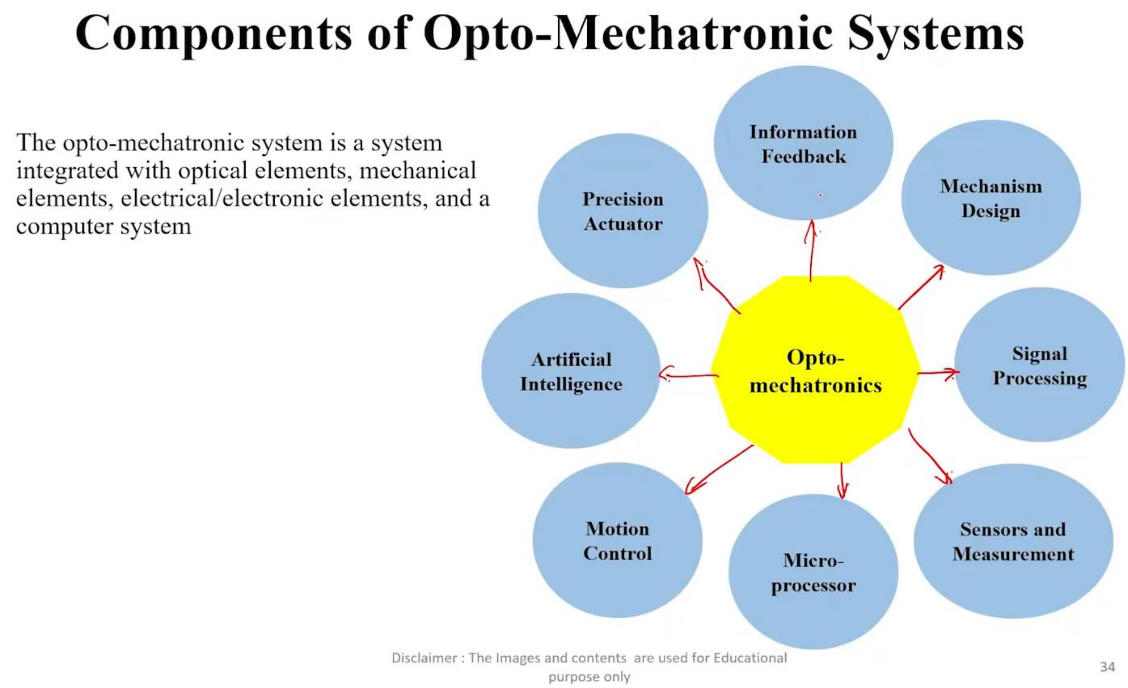


Now, when we try to see the function of this optomechatronic system, a number of fundamental functions can be generated by fusing an optical element with a mechatronic system. First, with reference to sensing, different techniques are being deployed, such as using an optical fiber sensor for pressure measurement, temperature measurement, displacement measurements, accelerations, three-dimensional imaging, optical motion capture, and confocal sensors. The optical scanning devices, which include a galvanometer, a resonance scanner, an acoustic optic scanner, a polygon mirror, a pan-tilt mechanism optical/visual scanning system, navigations and surveillance robot, and the image recognition system. These are some of the different functionalities that can be catered for under optical scanning.



Now, with reference to the motion control perspective point of view, we have the vision-guided machine robot; under the vision-guided machine robot, there is a weld seam tracker, a mobile robot, navigation, visual serving, and end effectors. Optical-based motion controls, such as inspection heads, auto focusing, and optical-based dead reckoning systems, can also be deployed. Now, with reference to optical actuator visual inspection, a hypersensitive light-driven device, visual inspection device: endoscopes, ersa scope. With reference to the inspection perspective point of view, we have the PCB pattern and the PCB solder joint inspection, a weld seam pattern. Three-dimensional shape reconstruction from a perspective point of view, X-ray tomography, X-ray radiography.

With reference to laser-based material processing, there is a wide variety of techniques including laser cutting, laser drilling, laser welding, laser grooving, laser hardening, laser-based lithography, and stereolithography. These laser-based lithography and stereolithography have been evidently used in the case of microfabrication-related techniques. Then, with reference to optical pattern recognition, a target recognition system, a target tracking system, and a vision-based navigation system can be efficiently deployed. With reference to remote monitoring control and internet-based sensing control, remote monitoring diagnostics and remote visual feedback control can be deployed. Now, overall, if we try to look into an optomechatronic system in robotics, the system includes various mechatronic components in a mobile robot that navigates in a task environment.



In any mobile robot navigation, the optical visual perception unit displays a crucial role because it provides environmental information for navigation. The robot can autonomously perceive models and maps of the environment through which it navigates to carry out certain tasks. It can sense a three-dimensional shape, the dimensions of the object, construct a map of the environment, and recognize the object within the environment. This autonomous task execution is performed by an optical visual sensor, an optical scanning system, a robot controller, and a multifunctional software system. So, in all these cases, if you keenly observe two different elements, two different components will actively participate.

So one component is the light source, and the other component is the detector. Now, when we need to look into the fundamentals of the usage of a light source and the detector, let us consider that we have an object in place. So there is a light; this is a light source from which light is made to fall on the object. We get a reflection coming from the object, and it is captured by a detector or a camera. Now, this is one way in which we are trying to capture the overall features of the component.

In another way, what we can do is introduce a concept called shadowgraphy. Shadowgraphy is highly helpful for understanding the overall boundary of a component, and it is also useful for visualization. So in this aspect, whenever we try to capture a complete feature, camera-based systems can be deployed. When we try to talk about a shadow graphic, we can capture the overall background images using a shadow graphic technique. Now, if we try to take a closer view of this optomechatronic system, as I have discussed, we have a component, a light source, and a detector, which is nothing but an image acquiring system.

A light source that is used for illumination is the plane at which the image is acquired. If the image is acquired over here, we call it a shadow. If the image is acquired here, we can consider it a complete image that is coming from the reflection. So if we try to keenly observe some of the key parameters used for obtaining constructive images, one of them is the type of light source we are using. Second is the angle of illumination.

Functions of Opto-Mechatronics Systems

A number of fundamental functions can be generated by fusing optical elements with mechatronics elements.

Functionality	Illustrative Techniques/System
Sensing	Optical-fiber-based sensor: pressure, temperature, displacement, acceleration Optical/sensor: three-dimensional imaging, optical motion capture, confocal sensor
Optical scanning	Optical scanning device: galvanometer, resonant scanner, acoustics-optic scanner, polygon mirror, pan-tilt mechanism Optical/visual scanning system: navigation/ surveillance robot, image recognition system
Motion control	Vision-guided machine/robot: weld seam tracker, mobile robot, navigation, visual serving endeffectors Optical-based motion control: inspection head, auto focusing, optical-based dead reckoning
Optical actuator Visual inspection	Hyper-sensitive light-driven device, Visual inspection Devices: endoscope, Ersa scope Inspection: PCB pattern/PCB solder joint inspection, weld seam pattern
Three-dimensional shape reconstruction	X-ray tomography, x-ray radiography
Laser material processing	Laser cutting, laser drilling, laser welding, laser grooving, laser hardening, laser lithography, stereo lithography
Optical pattern recognition	Target recognition, target tracking, vision-based navigation
Remote monitoring/ control	Internet-based sensing/control, remote monitoring/diagnosis, remote visual feedback control

Third is the type of image-acquisition system. Fourth is image processing. So ideally, when we try to talk about the light source, there are different types of light sources that exist. One is a kind of monochromatic light source where we have lasers, LEDs, etc., and then we have a visible source in which multiple wavelengths interact.

Similarly, when we try to talk about the illumination angle, with reference to the illumination angle from a perspective point of view, it might either be an image acquisition or a shadow. So as far as image acquisition is concerned, if we need to have complete details of the features, we can go for image acquisition. In the case of a shadow, the shadow is mainly meant for visualizing the structures; for example, if I want to visualize the rate at which a micro robot moves. So there exactly the shadowgraphy plays a vital role. Now, when we talk about the image acquisition system, we have the detectors and the types of cameras.

There are a wide variety of cameras that exist; for example, if we focus on the visible spectrum, CCD cameras are available. Whereas when we focus more on the thermal images or the thermal signatures, IR cameras are available. Thermal images are available. If we are more focused on some kind of images related to topography, then we can also use a kind of hyperspectral imaging system that is available. Now, when we try to capture this image, it is captured in pixels.

So ideally, when these images are captured, these pixels comprise the photodiodes. So what happens is when the image gets captured on this particular matrix, the photodiodes get illuminated, and based on the illumination of the photodiodes, the images are processed. There are different stages of image processing that are being deployed. Like we might have heard about binary images. This binary image ideally comprises ones and zeros, which is nothing but either black or white.

Wherever the light falls and the photodiode gets excited, it is considered white, or in certain cases, wherever the photodiode doesn't get excited, it becomes black; it can also be a vice versa phenomenon based on our requirements or based on the functionality. Now, this binary image can be appropriately converted into the form of a greyscale image. So in the case of a grayscale image, it has shades of gray ranging from white to complete black. It is in the range of 0 to 255. Zero to 256 different shades will be deployed, and based on the different shades, we can appropriately see the overall features we are working on.

Now, these grayscales can be appropriately converted into color images, where these shades of gray are appropriately converted into RGB. So, appropriate intensity mappings are done with reference to these RGBs and through this intensity mapping. So, we get a kind of image that we are looking for. During the capture, once we get it in the form of a binary, the transformation of the binary is converted into gray and then from gray to color, so that there are different steps involved, including image reconstruction, edge detection, image thresholding, and image restoration, etc. These are the different steps that are involved in it.

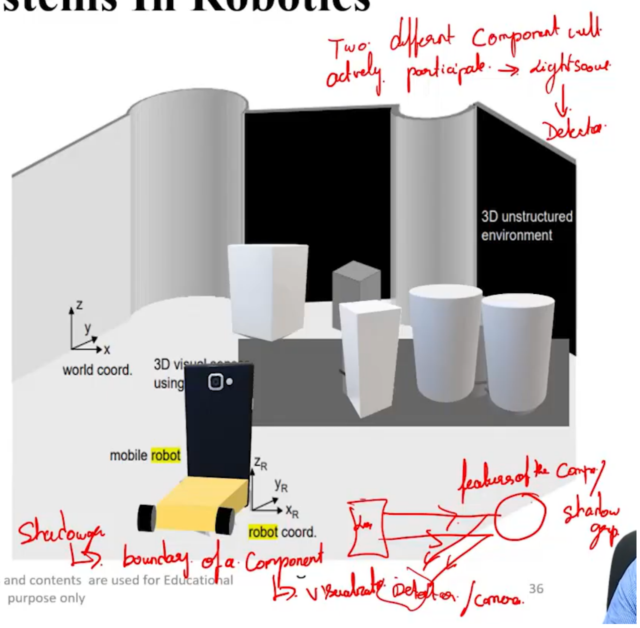
So we won't go in detail into those particular process. However, we will look into some of the fundamentals of how images are captured, how optomechatronic systems are designed in such a way that they are used for image acquisition, and how these image acquisitions are deployed for different sensing-related applications. Now let us take an example of a simple micro-optomechatronic system. So in this micro optomechatronic system, this is a kind of tube arrangement. So this is a kind of small micro robots that are equipped with a piezoelectric actuator coupled with a camera, and there is a tubing, a camera lid arrangement, and a moving guide, which is nothing but a kind of propulsion that exhibits, and then there is a data transmitter device that persists over here.

Now what happens in this is that piezoelectric actuators are deployed in this particular tubing structure, and by giving appropriate propulsion to the system, the movement of the piezoelectric actuators is monitored and appropriately captured. Now, when we try to observe the movement of these piezoelectric actuators, we see that they are precisely used for controlling the focusing optics or the camera. So, the inspection or measurement of a very small closed area is often very difficult due to the dimensional problems of sensing and actuating units. So micro-sizing of such machines or systems can be achieved with the aid of inherent optical sensing. So, a micro machine that inspects the inner surface of tubes in complex piping systems such as power plants is shown in the figure.

So, the machine consists mainly of a micro CCD camera, which is a kind of 10 mm in diameter for visual inspection, a piezoelectric driving actuator, and a microwave-based energy supply and data transmission device. So it can travel straight and in a curved metal tube with a minimum diameter of close to 10 microns or 10 mm, which is the overall size of the systems. So these kind of systems are mainly meant for certain amount of inspections. It has the capability for data transmission; it can either be a wired-based or a wireless-based system. Thus, data is appropriately transferred and captured.

Opto-Mechatronic Systems In Robotics

- A system that includes various mechatronic components is a mobile robot which navigating in a task environment.
- In any mobile robot navigation, the optical/visual perception unit plays a crucial role because it provides the environment information for navigation.
- As shown in figure, the robot can autonomously perceive, model, and map the environment through which it navigates to carry out certain tasks.
- In other words, it can sense three-dimensional shapes and the dimensions of objects, construct a map of the environment, and recognize the objects within the environment.
- This autonomous task execution is performed by an optical/visual sensor, an optical scanning system, a robot controller, and a multifunctional software system



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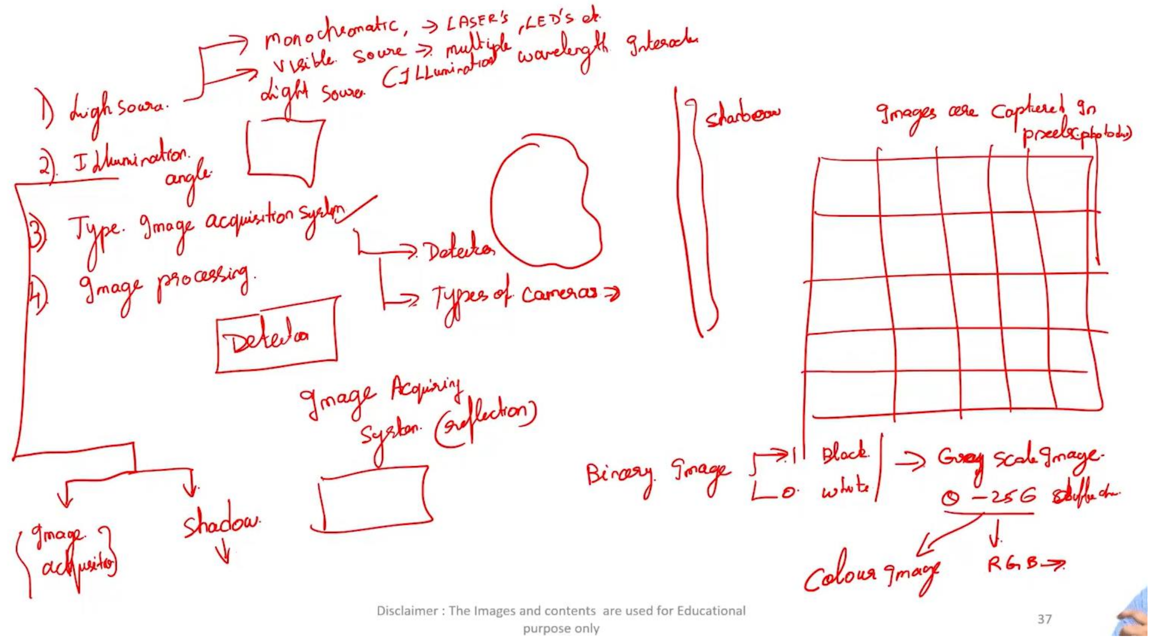
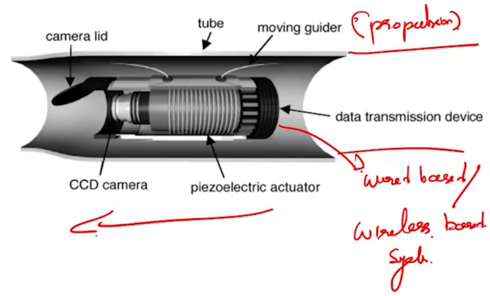
Now, when we try to classify the overall configuration of these MEMS-based optical sensors, these MEMS optoelectromechanical systems or optical microelectromechanical systems combine optical components with microelectromechanical system technology. The micro-level mechanical elements with micro-level motion manipulate the optical signal through actuation provided by electronic structures in a system called MOEMS. So as far as this MOEMS is concerned, it is well connected with an electronic system; it is also well connected with the collaborative impact from electronics to mechanical and optical systems. Ideally, there are different types of MEMS-based optical sensors that are being deployed for various functional applications. One that includes a kind of Mach-Zehnder interferometer.



Then there is a kind of micro cantilever that exists and optical tweezers that are used for micro-manipulation-related applications. So, we have a fiber Bragg grating; these fiber Bragg gratings are highly sensitive gratings that are used for different sensing-related applications. Then there are ring resonators; the main function of these ring resonators is to sense as well as to generate high-frequency systems. From an application perspective, these optomechatronic systems are widely used in optical communication, LiDAR systems, and optical measurement and inspection systems. Ideally, it is most suitable for biomedical imaging and surgery-related systems.

Micro Opto-Mechatronics systems

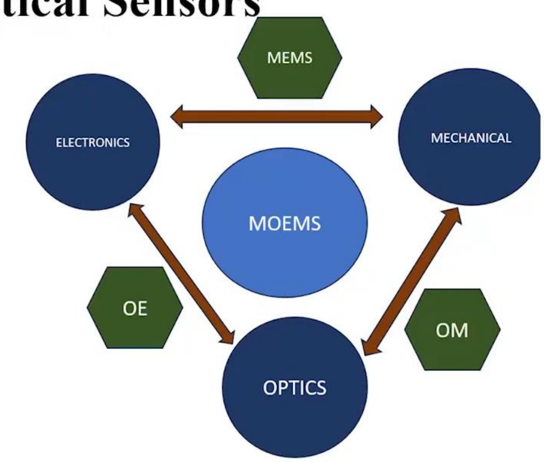
- Inspection or measurement of very small closed areas is often very difficult due to the dimension problem of the sensing and actuating units.
- Micro sizing of such machines or systems can be achieved with the aid of inherent optical sensing.
- A micromachine that inspects the inner surface of tubes in complex piping systems such as power plants is shown in Figure.
- The machine consists mainly of a micro-CCD camera (10 mm in diameter) for visual inspection, a piezoelectric driving actuator, and microwave-based energy supply and data transmission devices. It can travel in a straight and curved metal tube with a minimum diameter of 10 mm

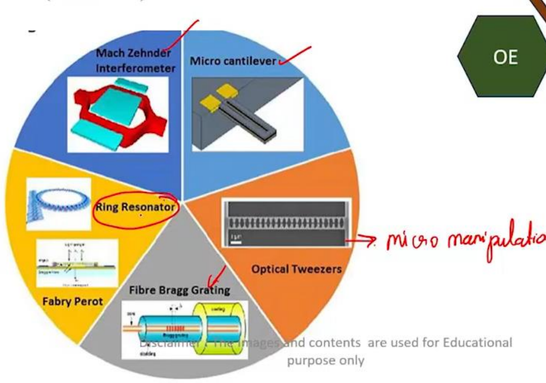


A larger number of applications are for laser material processing systems. In fact, we had discussed microfabrication. So, in the case of laser-based microfabrication for laser-based patterning or for laser-based micro 3D printing, establishing the complete manipulation unit, such an optomechanical system plays a vital role. Then we have an optical sensor automation that exhibits manipulation, actuation, and sensing. Then there is a kind of robotic vision and AI-assisted imaging that will cater to the complete image acquisition, image processing, and image restoration activities, and it also has the capability to compare with reference to the reference image and provide appropriate requirements or make appropriate decisions for different activities.

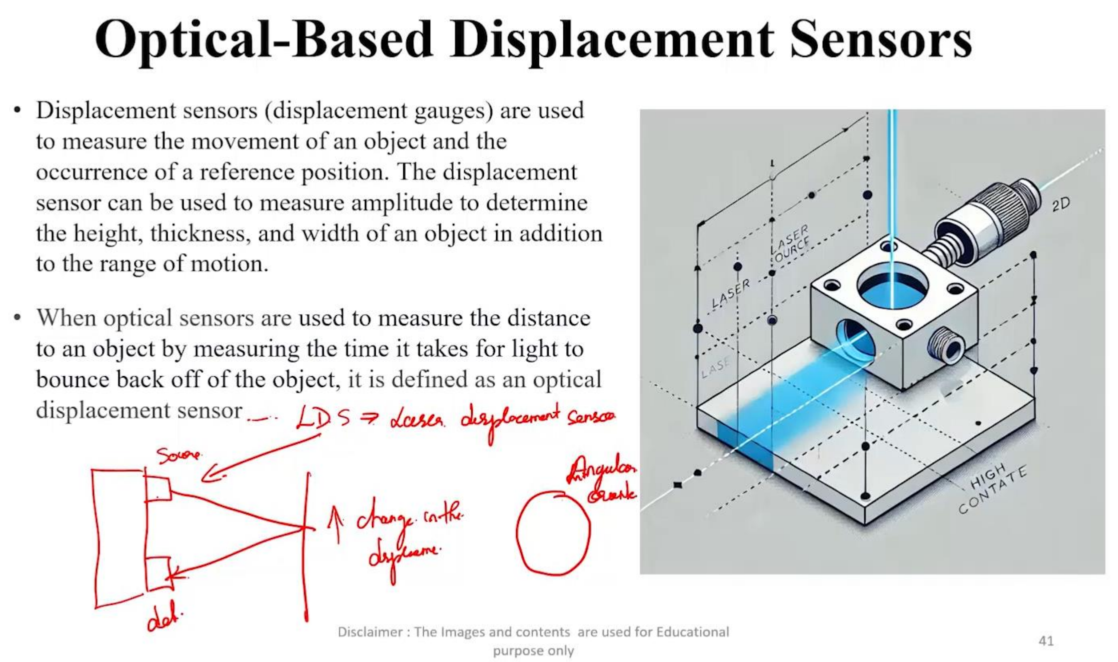
MEMS-Based Optical Sensors

Micro-opto electromechanical system or optical micro-electromechanical system combines optical components with micro electromechanical system technology. The micro-level mechanical elements with micro-level motion manipulate the optical signals by actuation provided by electronic structures in a system called micro-opto electromechanical system (MOEMS)



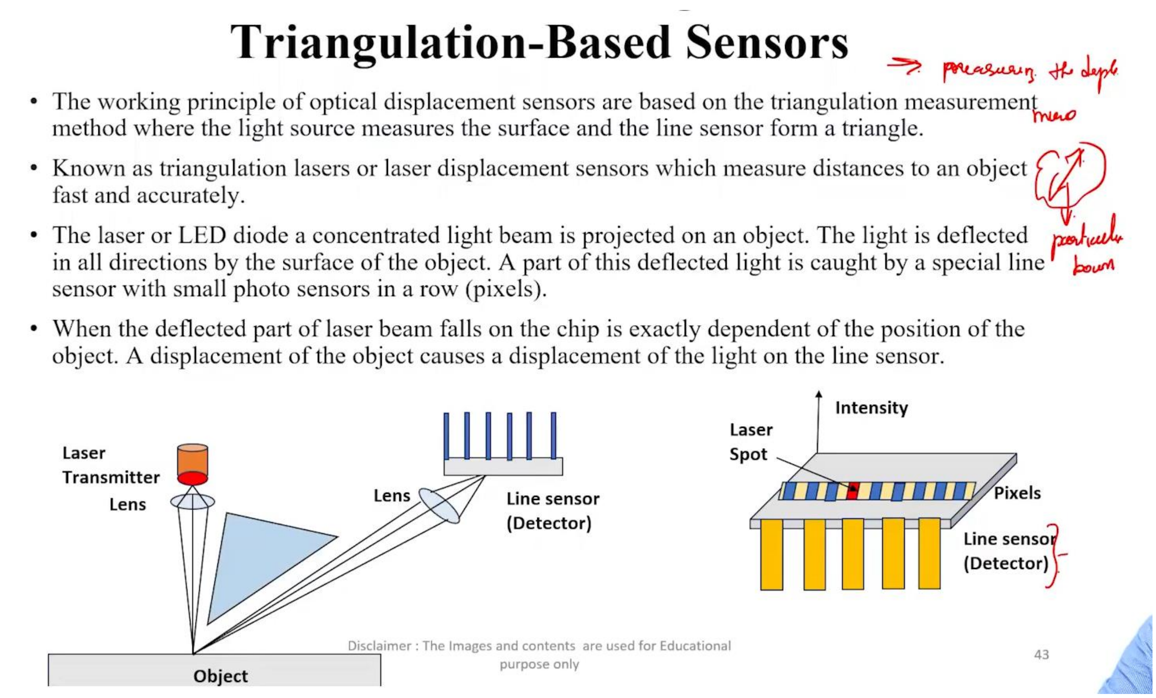


For instance, today we are talking about these autonomous robots, which are used for moving on a particular platform, and when there is an obstacle, appropriately based on the size of the obstacle, they try to take a boundary and move along the boundary for efficient path planning. Now let us discuss this optical-based displacement sensor. So as far as these optical-based displacement sensors are concerned, these displacement sensors are used to measure the movement of an object and the occurrence of a reference point. The displacement sensor can be used to measure the amplitude to determine the height, thickness, and width of the object, in addition to the range of the motion. When optical sensors are used to measure the distance to an object by measuring the time it takes for light to bounce back from the object, it is defined as an optical displacement sensor.



In an optical displacement sensor, when we try to consider a generic construction, there is a sensor named LDS, which is called a laser displacement sensor. This laser displacement sensor compresses a source and compresses a detector. So, from the source, light hits the surface and comes back to the detector. Now, for example, if I want to measure the change in the displacement, there is a kind of circular disc. In the circular disc, if I want to measure the linear and angular orientation, these kinds of LDS sensors can be deployed.

So these LDS sensors are efficient enough that they can be deployed in any kind of system, and small-level LDS sensors are also available, which can be used for micro displacement or micro analysis. Now, let us discuss the different principles that are deployed for this typical optical displacement sensor. The optical displacement sensors are categorized based on their working principles as well as their applications. The main types of optical displacement sensors include the triangulation-based sensor, the interferometric displacement sensor, a confocal sensor, a time-of-flight sensor, and an optical encoder. There is also a particle sensor that works on the principle of shadowgraphy, which we will be discussing.



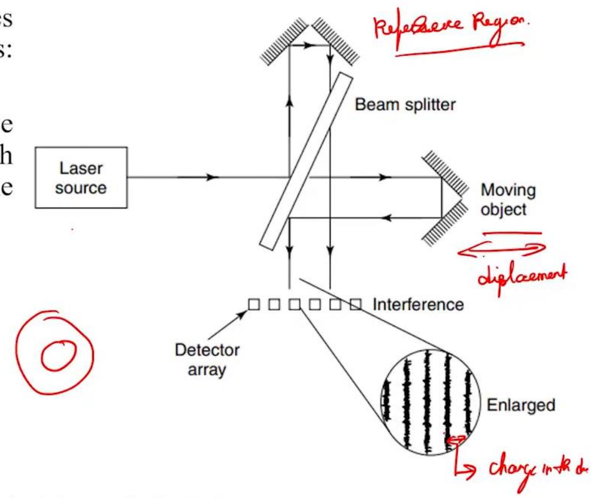
Now let us talk about the triangulation-based sensor. This triangulation-based sensor is concerned; let us consider that a laser transmitter lens is available here. This lens is used to focus the light on the object. Now the light that is focused on the object is reflected through the lens and hits the line sensor on the detector. So the working principle of the optical displacement sensors is based on the triangulation measurement method where the light source measures the surface and the line sensor forms a triangle.

These are known as a triangulation laser or laser displacement sensor, which measures distance to an object quickly and accurately. The laser or LED diode projects a concentrated light beam on an object. The light is deflected in all directions by the surface of the object. A part of the deflected light is caught by a special line sensor with small photo sensors in a row or pixel. When the deflector part of the laser beam falls on the chip, it is exactly dependent on the position of the object.

So a displacement of the object causes a displacement of the light on the line sensor. Ideally, this is a kind of laser spot that is being integrated onto the pixel, and these are a type of line sensor; this is a representation of a line sensor detector. Now these triangulation principles have a potential application towards analyzing the displacement of a micro robot within a particular boundary. Within this particular boundary, if we need to measure the displacement, such a triangulation-based system will be highly helpful. Now let us talk about the interferometer-based displacement sensor.

Interferometric Displacement Sensors

- Interferometric displacement sensors involves splitting a coherent light beam into two paths: a measurement beam and a reference beam.
- The difference in distance traveled by these beams creates a phase difference, which results in an interference pattern when the beams are recombined
- Example: Michelson interferometer



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This interferometer-based displacement sensor is quite an interesting technique where we split the beam of light into two and then use the superposition principle to create the interference. If we look into the overall configuration of this interference-based sensor, it has a laser source, a beam splitter, a moving object, and the interference is collected by a detector array. So what happens is from the laser source the laser beam is split and then it is made to pass through the beam splitter where the beam is split into two. This acts as a reference region, and this is the area or parameter that we need to measure. So ideally, we will be measuring the displacement over here.

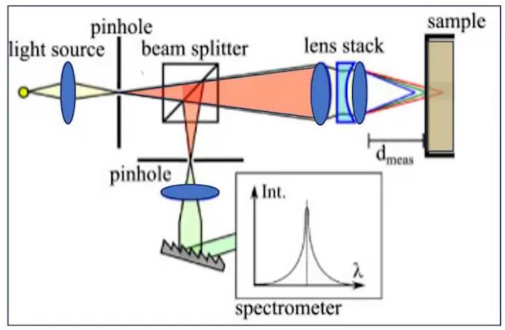
So since a laser source is used, it can be used for measuring the displacement on the micron order. So in this particular case, we have a reference region and then there is a moving object that is available. The laser beam is split into two. When the moving object moves back and forth, there is going to be a superimposed portion of the image. This superposition of this image will result in an interference that is observed over here.

So, the overall interference looks something like this. So here, there is a kind of alternative dark and bright fringe available in this interference pattern. So when we try to change the displacement of the moving object, the fringes will get enlarged appropriately, and based on the enlargement in the fringes, we can estimate the change in the alternative dark and bright fringes, so we can appropriately estimate the change in the displacement. So, since the overall interference change is going to be highly significant on a micron level. So, there is a need to integrate a detector array into the system.

So, this detector array will completely record or completely measure the interference and appropriately it gives a readout to the system. So, as far as this interferometric dissipation sensor is concerned, this involves splitting a coherent light beam into two parts: a measurement beam and a reference beam. The difference in the distance traveled by this beam creates a phase difference that results in an interference pattern when the beams are combined. A good example of an interferometer that is widely used for different applications is the Michelson interferometer, which is used for vibration sensing, micro displacement sensing, pressure sensing, etc.

Confocal Sensors

- Confocal sensors are advanced optical instruments used for precise displacement, distance, and thickness measurements.
- They operate based on the confocal principle, which involves focusing light onto a target and detecting the reflected light through a pinhole or similar aperture
- A broadband light source is focused on a pinhole which is imaged on the sample surface.
- Due to the chromatic aberration, each wavelength is focused in a different image plane.
- The reflected light is directed towards a spectrometer via a beamsplitter.
- In this receiving light path, there is a second pinhole, which ensures that only light that was in focus on the sample surface passes to the spectrometer.
- The recorded spectrum exhibits a peak at the wavelength corresponding to the sample distance



The next important sensor is called a confocal sensor. So as far as these confocal sensors are concerned, these confocal sensors are advanced optical instruments which are used for precise displacement, distance, and thickness measurement. They operate based on the confocal principle, which involves focusing light onto a target and detecting the reflected light through a pinhole or similar aperture. So a broad light source is focused on a pinhole, which is imaged on the sample surface, as shown over here. So this is the overall construction of the pinhole.

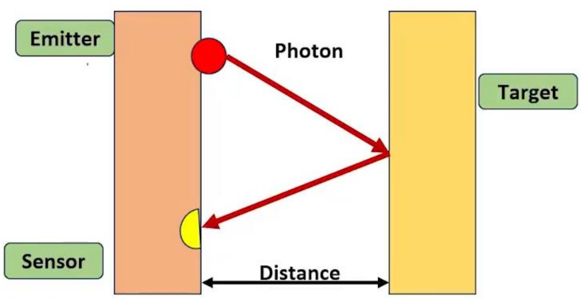
A confocal sensor. So, in the case of a confocal sensor, we have a light source; then there is a pinhole arrangement available here, followed by a beam splitter arrangement, a lens stack system, and the sample. So, the main function of this confocal sensor is to measure the displacement, distance, and thickness of this particular sample. So a light source is used. The light source is made to pass through the pinhole to remove the unnecessary elements to have a focused beam, and this focused beam is made to pass through the beam splitter. From the beam splitter, it is made to pass through the lens stack.

So within the lens tag, once it reaches the lens tag, it hits the sample, and the reflected beam is bounced back. So here there are two things. So in the case of a beam splitter, we will be getting one reference beam. And the other one will be the beam that will be getting it from the sample.

So these will be passed through a kind of spectrometer. So, using a spectrometer, we can analyze the overall characteristics of the sample. So ideally, due to chromatic aberration, each wavelength is focused in a different image plane. So, the reflected light is directed towards a spectrometer using a beam splitter. In this receiving light path, there is a second pinhole that ensures that only light that is in focus on the sample surface passes to the spectrometer. Now the recorded spectrum exhibits a peak at the wavelength corresponding to the sample distance.

Time-of-Flight (ToF) Sensors

Time-of-Flight (ToF) sensors measure the distance between the sensor and an object by calculating the time it takes for a signal, typically infrared light, to travel from the sensor to the object and back



$$\text{Measured Distance} = \frac{\text{Photon travel time}}{2} \times \text{Speed of Light}$$

The next configuration is called a time of flight configuration. So, as far as this time of flight configuration is concerned. So in this flight configuration, we have an emitter and a sensor. The photon hits the target and then reaches the sensor. So the distance between one plane and the target plane is considered to be a distance t. So the measured distance is the photon travel time multiplied by 2 into the speed of light.

So this time-of-flight sensor measures the distance between the sensor and an object by calculating the time it takes for a signal, typically in infrared light, to travel from the sensor to the object. So, this kind of time of flight measurement is effectively used for dynamic analysis. It gives a complete overview, so whenever a micro robot is moving or whenever there is a need for analyzing the micromanipulation in a micro robot, such kinds of time-of-flight sensors can be efficiently used to investigate the overall micromanipulation behavior in detail. So like that is the precision of this particular system is evident from the parameters including a photon travel time and the speed of light which is measured over here. Next, we will discuss the shadow projection sensor in the upcoming classes.