Microrobotics

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Week- 06

Lecture No- 26

**Micro Sensors and Micro Transducers - Module 01**

In today's lecture, we will discuss micro sensors and micro transducers. This is a part of module 4 in the course on micro robotics. As far as the module content is concerned, the objective of this module is segregated into six sub-modules; first, we'll be discussing the fundamentals of microsensors and micro transducers. There is more emphasis on opto-mechatronic system design, specifically on optical-based displacement sensors, sensors based on light intensity modulations, and interferometers, which are being efficiently used for micro-sensing related applications, and then we will also discuss optical fiber sensors. These micro sensors are miniaturized sensors that detect physical, chemical, or biological signals at a micro or nano scale. They convert these signals into electrical output for further processing.

Introduction to Microsensors and Micro-transducers

- Microsensors are miniaturized sensors that detect physical, chemical, or biological signals at a micro or nanoscale.
- They convert these signals into electrical outputs for further processing.
- A micro transducer is a device that converts one form of energy into another at a micro-scale.
- It plays a crucial role in microsensors by transforming detected signals into readable outputs.
- The small size, high accuracy, and sensitivity allows them to be integrated into compact electronic systems where a minor physical, chemical, or biological change is converted into measurable signals.
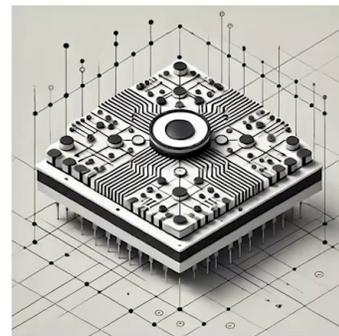
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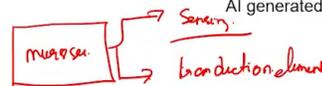
In other words, a micro transducer is a device that converts one form of energy into another at a microscale. It plays a crucial role in microsensors by transforming the detected signal into a readable output. So the small size, high accuracy, and sensitivity allow them to be

integrated into a compact electronic system where a minor physical, chemical, or biological change is converted into a measurable signal. In the case of a microsensor, if we consider this a microsensor, it has two different components.

One is the sensing element, and the other is the transaction element. The sensing element will be in touch with the parameter, and then it sends the impact or the influence that occurs on these parameters; appropriately, the signal is fed into the transduction element. The main function of transduction is to convert one form of energy into another form so that we can analyze, sense, or obtain signal data about the parameter we are trying to measure. Now, let us discuss the history of this micro sensor development. In the 1960s, there was the first effort at adapting a microfabrication technique to the creation of miniature silicon sensors.

History of Micro Sensor Development

- In 1960s the first efforts at adapting microfabrication techniques to the creation of miniature silicon sensors.
- After temperature and pressure sensors, optical detector arrays were probably the first such devices to find their way into production,
- And today, these devices are among the largest chips fabricated by the semiconductor industry.

- Hence, early research in microsensors started with the miniaturization of mechanical and electrical components using semiconductor fabrication techniques such as photolithography, thin-film deposition, and etching.
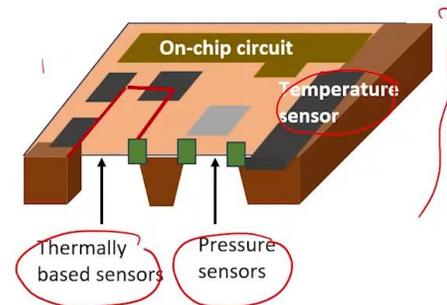

Structure and top view of a monolithic mass flow sensor containing transducers for gas flow rate, direction, type, pressure and temperature

After temperature and pressure sensors, optical detector arrays were probably the first such devices to find their way into production, and today, these devices are among the largest chips fabricated by the semiconductor industry. Hence, earlier research in microsensors started with the miniaturization of mechanical and electrical components using semiconductor fabrication techniques such as photolithography, thin film deposition, and etching. In this particular sensor, this is a structure and top view of a monolithic mass flow sensor containing a transducer for gas flow rate, direction, type, and it can measure pressure and temperature. In this particular case, we have a thermally based sensor that is integrated, a pressure sensor that is integrated, as well as a temperature sensor that is integrated. All these sensors are well integrated into a single packaging system so that it becomes a kind of single unit for appropriate applications or functional devices.
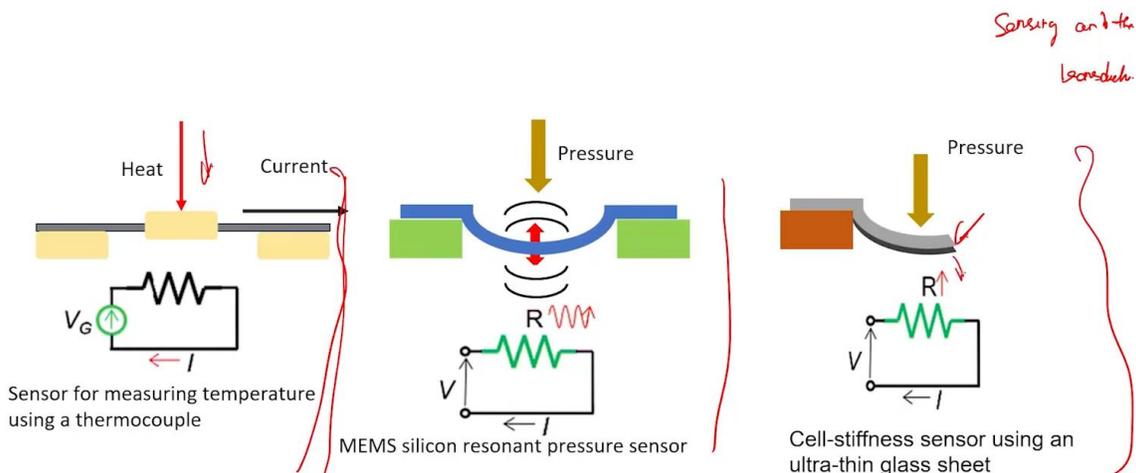
History

- Microsensor are part of the wider class of microelectromechanical system (MEMS) devices.
- Typical sizes of microsensors range from 10 um to 5 mm.
- The defining feature of any MEMS device is an element with some sort of mechanical functionality integrated with microelectronics.
- Microsensors can be regarded as miniature transducers, since they convert energy in the form of a measured mechanical signal into energy in electrical form.
- Therefore, MEMS-based microsensors have significantly evolved in terms of accuracy, miniaturization, and power efficiency.
- An early example of a MEMS device is the resonant-gate transistor, an adaptation of the MOSFET developed by Robert A. Wickstrom in1965.
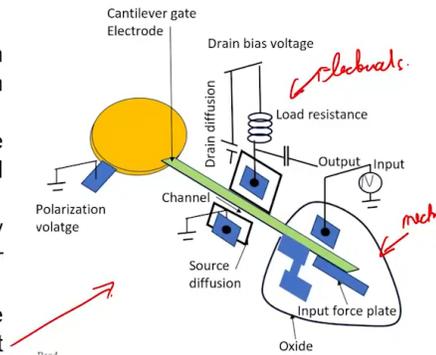
Circuit connection of RGT

Now in this particular talk, we will be discussing the concept of sensing elements, the different types of sensing elements that exist with reference to micro robotic applications, and how the sensing elements impact different functional behaviors. Now, when we try to look into a closer view of these micro sensors, micro sensors are a part of a wider class of micro mechanical system devices. Typically, the micro sensors range from 10 microns to 5 mm. The defining feature of any MEMS device is an element with some sort of mechanical function integrated with microelectronics. These micro sensors can be generated as miniature transducers since they convert energy in the form of a measured mechanical signal into energy in electrical form.

Micro sensing and transduction element

Sensor for measuring temperature using a thermocouple

MEMS silicon resonant pressure sensor

Cell-stiffness sensor using an ultra-thin glass sheet

Therefore, MEMS-based micro sensors have significantly evolved in terms of accuracy, miniaturization, and power efficiency. Now let us take an early example of a MEMS

device: the Resonant Gate Transistor and the adoption of the MOSFET developed by Robert A. Wickstorm in 1965. Now the reason for bringing this particular example is that on a small scale we find a mechanical system. We can observe an electrical system that is being integrated over here.

Any kind of complex system can be connected appropriately in such a way that we can integrate the system for developing micro devices or micro robots based on the application. In this particular case, a force plate is a kind of cantilever that is being established. The overall characteristics of the cantilever are sensed using a type of source diffusion with a bias voltage that is available here. Now, as far as the main particular aspect of the micro-sensing perspective is concerned, the sensing element and the transduction element are essential. In this particular case, let us consider this a simple system.

In this system, there is a kind of resistor that is used, and then there is a thermocouple that is available. Now, when heat is made to incident on a thermocouple, the thermocouple appropriately converts it into a current; this is what is known as the Seebeck effect. Now, in this particular case, the heat that is being generated and the thermocouple that is directly used for sensing are considered as a sensing element. The conversion of this heat into an appropriate voltage or potential difference is what we call a transduction element. Let us take the example of the second case; in this particular case, it is a MEMS silicon resonant pressure sensor.

Working principle of Microsensor

- Microsensors operate on the fundamental principle of converting a physical change or stimulus into an electrical signal, facilitating the detection and measurement of specific parameters in a miniaturized form.
- These sensors are crucial components in various fields due to their ability to detect and respond to changes in their environment at a microscopic scale.
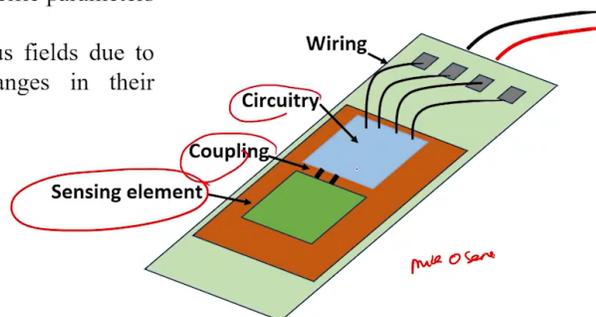
In this MEMS silicon resonant pressure sensor, we have a diaphragm in place, and then there is a pressure exerted on it; the pressure is connected to the resistance R and the current I here. So what happens is when the pressure is incident on it, this diaphragm will try to move back and forth. From the movement of the diaphragm, we can see a change in the resistance. Ideally, the diaphragm acts as a kind of sensing element, converting the pressure

induced on it into an appropriate signal, which you refer to as a transduction element. Let us take an example of this third system, which is called a self-stiffness sensor using an ultra-thin glass sheet, where there is a kind of cantilever that exists and then a pressure is exerted on it.

When we try to induce pressure, there is going to be a deflection, and the deflection is measured using a type of transduction element that is available here. The pressure is measured using a kind of cantilever, and the change in pressure is measured with the help of this transduction element. Now, when we see the overall workings of these micro sensors, let us take a simple example. These micro sensors operate on the fundamental principle of converting a physical change of stimulus into an electrical signal, facilitating the detection and measurement of specific parameters in a miniaturized form. These sensors are crucial components in various fields due to their ability to detect and respond to changes in their environment at a macroscopic scale.

If you try to see the overall components which are aligned in a microsensor, one is the sensing element, as I discussed earlier; then there is a coupling circuitry that takes care of the complete signal conditioning, etc., and finally, a kind of contact is established, which is mainly meant for some kind of power distribution, etc. This is a kind of skeletal structure of a microsensor, or I would say that this is a kind of template that is used basically for microsensor fabrication. Now, when we try to narrow down our micro sensors from a robotic application perspective, in particular for micro-robotic applications, they can be considered under five main categories. One is a radiation-based micro-sensor, a thermal micro-sensor, a magnetic micro-sensor, a mechanical micro-sensor, and a chemical micro-sensor.

Let us go one by one through the different types of micro-sensors and their usage, applications, and design for different functional characteristics. Now, let us discuss the radiation microsensor. These radiation microsensors are used to detect radiation with different energies or wavelengths such as x-rays, gamma rays, ultraviolet radiation, and infrared radiation. Example: a photoconductive microsensor. The figure basically explains the principle of operation of a photoconductive microsensor, which depends on creating a conduction process as a result of the energy gained by the electron from the incident radiation.

Radiation Microsensors

- Radiation microsensors are used to detect radiations with different energies or wavelengths (such as x-rays, gamma rays, ultraviolet radiations, and infrared radiations)
- Example: Photoconductive Microsensors
- The figure shows the principle of operation of photoconductive microsensors which depend on creating a conduction process as a result of the energy gained by electrons from the incident radiation.
- Specifically, such microsensor depends on inducing voltage across a semiconductor junction when subjected to the radiation.
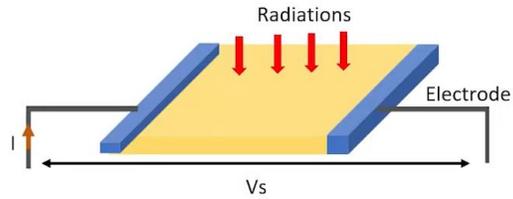- These types of microsensors have an output resistance of about 100 Ω - I M Ω

Fig. Photoconductive device

Especially such micro sensors depend on inducing voltage across a semiconductor junction when subjected to radiation. These types of micro sensors have an output resistance in the range of 100 ohms to 1 megaohm. The thermal microsensors are used to sense thermal quantities such as temperature, heat flow, and thermal conductivity. When we try to talk about thermocouples, the thermocouple works on the principle of the Seebeck effect. The Seebeck effect uses two different junctions; one is called a hot junction and the other is called a cold junction.

Thermal Microsensors

- Thermal microsensors are used to sense thermal quantities, such as temperature, heat flow, and thermal conductivity.

- Example: Platinum resistive temperature microsensors that depend on measuring the temperature by determining the change in the material resistance. They have a linear dependency of temperature

- Micro thermocouple microsensors: Depends on Seebeck Effect. They use materials that have different thermoelectric power. Figure shows the basic configuration of a micro thermocouple sensor.
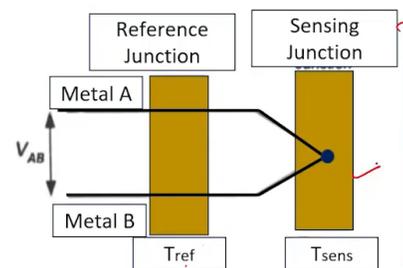

Figure: Basic configuration of Micro-thermocouple sensor

The difference between this hot junction and cold junction is a kind of potential difference that is exhibited here. So let us take an example of a platinum resistive temperature micro sensor that depends on measuring the temperature by determining the change in material resistance. They have a linear dependency on temperature, and as far as these micro

thermocouple sensors are concerned, they depend on the Seebeck effect. They use materials that have different thermoelectric powers. Here in this particular figure, it shows the basic configuration of a micro thermocouple sensor where two metal junctions are kept, and then there is a reference junction and a sensing junction.

From the reference junction, the deviation that is observed is being sensed by the sensing junction. That's how the thermal micro sensors can be easily integrated into the filter. Now, let us talk about the magnetic microsensor. These magnetic microsensors are used to detect and measure the magnetic flux density. For example, we might have heard about this term called magnetogalvanic.

Magnetic Microsensors

- Magnetic Microsensor used to detect and measure magnetic flux density.
- Example: Magnetogalvanic Microsensors that depend on the magnetogalvanic effect. In which a voltage is induced across a slab of a material that is proportional to the applied magnetic flux density in a perpendicular direction to a current passing through the slab. The schematic diagram of the Hall plate microsensor is illustrated in figure.
- Another example is Magnetoresistive Microsensors that depend on the proportional variation of the material resistance with the applied magnetic flux density.

Hall effect microsensor
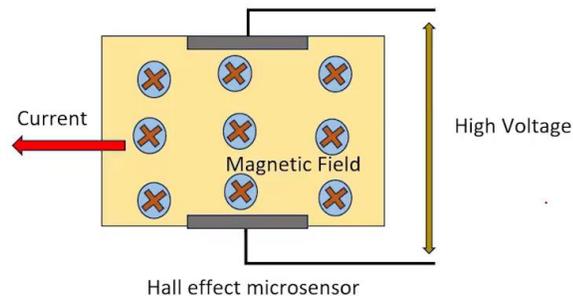
These magnetogalvanic microsensors depend upon the magnetogalvanic effect in which a voltage is induced across the slab of a material that is proportional to the applied magnetic flux density in a perpendicular direction to the current passing through the slab. Here, if you observe, this is a kind of Hall effect microsensor. In this Hall effect microsensor, what happens is that we are trying to apply a high voltage over here. With reference to the change in the magnetic field, the deflections were sensed. Another example of using a magnetic microsensor is called a magnetoresistive microsensor.

This magnetoresistive microsensor depends on the proportional variation of the material's resistance with the applied magnetic flux density. In fact, with reference to the magnetoresistive effect, we have discussed a lot in the magnetoresistive-based actuator. Almost it is the same kind of principle that is used for sensing-related applications. Now let us talk about a mechanical microsensor. On a larger scale, these systems are called hot wire anemometers.

Mechanical Microsensors

- They are considered the most important type of microsensors due to their wide range of application and variety in their mechanical measurand such as; flow rate, pressure, acceleration, and force.

- Example: Flow Microsensors are used to measure the flow rate of a gas or a liquid. They depend on monitoring the heat transferred per unit time from a resistive wire heater to a moving liquid at two points via microthermocouple temperature sensors as shown in figure.
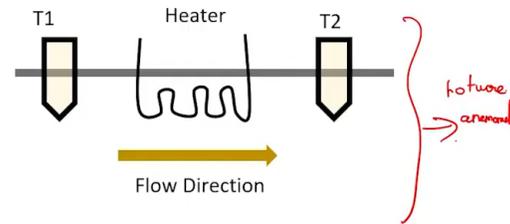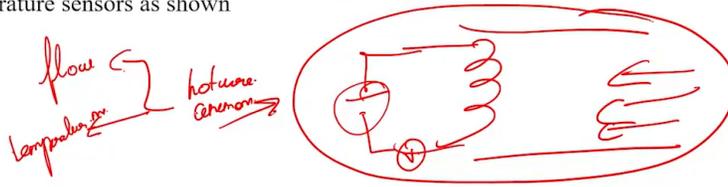
Figure: Operation of flow sensor

These systems are considered to be the most important type of micro sensor due to their wider range of applications and variety in their mechanical measurements such as flow rate, pressure, acceleration, and force. These micro sensors, specifically flow micro sensors, are used to measure the flow rate of a gas or a liquid. They depend on monitoring the heat transferred per unit time from a resistive wire heater to a moving liquid at two points via a micro thermocouple temperature sensor, as shown here. Let us consider a coil through which a flow is passing, connected to an electrical biasing. There is a voltmeter available over here, so what happens is when a current is passing through this coil and when there is a continuous convection of air passing through it, there will be a reduction in the heat; this reduction in heat will try to draw a greater amount of current from the potential difference region of the source.

Chemical Microsensors

- They are composed mainly of a chemically sensitive layer and a transducer.

- A physical change occurs in the sensitive layer while detecting a molecule of the sample gas. This change is detected and converted by the transducer to an electrical signal.

- Example: Conductimetric Microsensors that depend on changing the electrical resistance of a material when subjected to the target gas. This change is measured using special devices.

- The Taguchi-type tin oxide gas microsensor and the silicon micromachined resistive gas sensor are examples of such devices. The schematic diagram of the silicon gas microsensor is illustrated in figure

- These types of microsensors have a thermal operating range from ambient temperature up to 500 ºC.
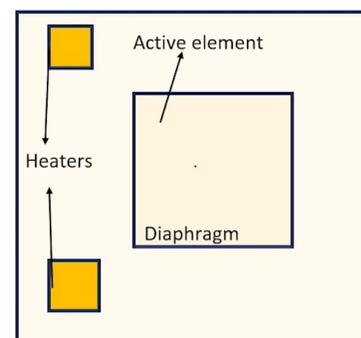
Figure: Silicon gas microsensor

From the amount of power drawn, we can estimate how much flow is passing through it and how much temperature reduction occurs in it. This particular process is called a hot wire anemometer. It is mainly meant for flow measurement, temperature measurement, etc. Almost this also works on a similar concept; the only thing is we are trying to scale it down to a lower scale so that it takes care of the flow direction. Now, we have the chemical microsensors; they are composed mainly of chemically sensitive materials and a transducer.

A physical change occurs in the sensitive layer while detecting a molecule of the sample gas. This change is detected and converted by the transducer to an electrical signal, for example, a conductive metric microsensor that depends on changing the electrical resistance of a material when subjected to the target gas. This change is measured using a special device, and Taguchi-type tin oxide gas micro sensors and silicon micromachined resistive gas micro sensors are examples of such devices. If we try to observe this, there is a kind of diaphragm and the silicon gas micro sensors are available here. This active element is a kind of diaphragm that will try to absorb substances that are highly chemically sensitive, and it will try to disperse the amount of heat that is liberated.

These types of micro sensors have a thermal operating range from ambient temperature up to 500 degrees Celsius. This is a kind of silicon-based gas micro sensor. Now, when we are trying to establish these microsensors or microtransducers, there is a need to identify the material based on the requirements. Now when we try to look into the materials, the materials which are commonly used for microsensors are silicon, which is considered to be a standard substrate material for IC fabrication and thus the most common substrate material in microfabrication. The use of silicon substrate material enables the configuration of transducers and circuitry, as seen in CMOS-based microsystems.

A single crystal silicon has excellent mechanical properties which enable the design of these mechanical structures. When we try to talk about glasses, they exhibit attractive dielectric and optical properties. Several micromachining techniques, such as isotropic wet etching and anisotropic dry etching, have been developed to structure glasses. Now, when we try to talk about ceramics, they have been extensively used as a substrate for hybrid microelectronics and are common in microelectronic packaging. The standard material is alumina, and other materials like BeO and AlN are used efficiently.

Polymers have been explored more and more as an inexpensive substrate material. A special process such as hot embossing, injection molding, laser machining, or stereolithography has been developed to structure the polymer even in the micrometer range. Now, let us see some of the key applications of these microsensors in microrobotic applications. One is a kind of precision manipulation; for instance, when we try to hold a particular component, especially in the case of micro-robotic applications, where we are talking about micro-manipulation. Such kinds of micro sensors are efficiently integrated

with the micro grippers so that the force is sensed and the inputs are appropriately provided to the system.

Microsensors in Robotics

- **Precision manipulation:** Microsensors integrated into robotic grippers can measure the force applied to an object, allowing for delicate handling of fragile items like surgical instruments or electronic components.

- **Obstacle detection and avoidance:** Tiny proximity sensors can detect obstacles very close to the robot, enabling navigation in tight spaces and preventing collisions with unexpected objects.

- **Environmental monitoring:** Microsensors can measure temperature, humidity, pressure, and air quality in a robot's surroundings, allowing for adaptive behavior based on environmental conditions.

- **Object identification and tracking:** Vision systems combined with microsensors can identify and track specific objects on a conveyor belt or in a workspace, facilitating precise manipulation and sorting.

- **Surface mapping:** Microsensors integrated into robotic arms can provide detailed surface topography information, allowing for precise path planning and adaptation to uneven terrains.
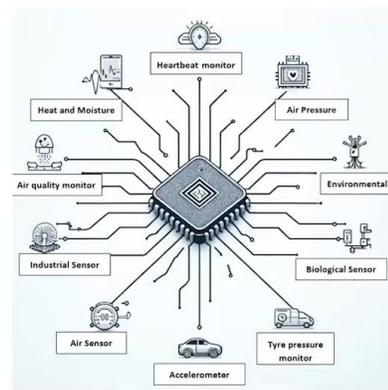

These micro sensors are integrated into a robotic gripper that can measure the force applied to an object, allowing for delicate handling of fragile items like surgical instruments or electronic components. Similarly, when we try to talk about obstacle detection and obstacle avoidance, it is basically in the case of AGVs, small micro robots, a swarm of micro robots, or micro drones, etc. A tiny proximity sensor can detect obstacles very close to the robot, enabling navigation in tight spaces and preventing collision with unexpected objects. Similarly, when we try to talk about environmental monitoring, micro sensors can measure temperature, humidity, pressure, and air quality in a robotic environment, allowing for adaptive behavior based on environmental conditions. So, ideally, you can integrate these micro sensors with a drone or a micro drone.

We have also discussed when we are discussing microelectronics and micro robotics; it was observed that micro robotics can be used for sensing pollutants in underwater conditions, etc. In those underwater conditions, when we try to integrate these kinds of microsensors, especially the environmental monitoring microsensors, along with the systems, so they can be used for sensing the pollutants individually, we can appropriately sense based on the type of pollutant. Next is a kind of object identification and tracking, so micro robotics integrated with a vision system combined with a micro sensor can identify and track specific objects on a conveyor belt or in a space, facilitating precise manipulation or sorting. In addition to this, when we have a camera-integrated micro-robotics system, it can be used for several biologically related applications. In fact, it can be used for some kinds of endoscopy-related applications, which are some of the key domains that will be opened up when we try to introduce an object identification and tracking system along with the micro robotic systems.

Micro transducers

A micro transducer is a device that converts one form of energy into another at a micro-scale. It plays a crucial role in microsensors by transforming detected signals into readable outputs. Such small devices can be used for a variety of purposes, including medical imaging, acoustic mapping, and biosensing.
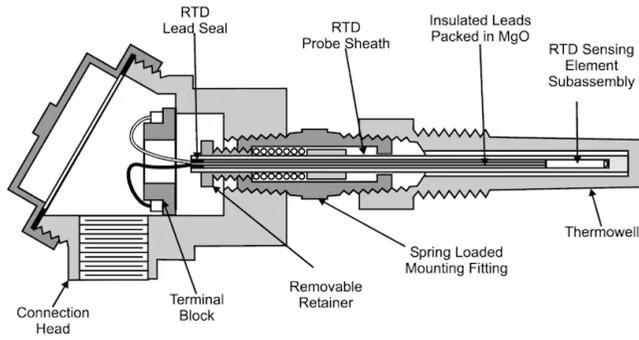
Resistance Temperature Detector

Then we have a kind of surface mapping, so as far as surface mapping is concerned, though the micro sensors integrated into a robotic arm can provide detailed surface topography information, allowing for precise path planning and adaptation to uneven terrains. Sometimes this can be efficiently used for mapping the overall surface roughness or manipulating the surface roughness based on the requirements or based on the characteristics. Now let us discuss microtransducers. A microtransducer is a device that converts one form of energy into another at a micro scale. So it plays a crucial role in microsensors by transforming the detected signal into a readable output.

Such a small device can be used for a variety of purposes, including medical imaging, acoustic mapping, and biosensing. Especially when we try to talk about these kinds of transducers, several challenges are observed when we are working on the microtransducers level. Some of the key challenges include signal conditioning, the energy requirements of the system, and the impact of the environment on these systems. These are some of the key challenges that microtransducers basically used to face. Now when we try to classify these microtransducers, the microtransducers for robotic applications can be considered under five main categories.

One is a kind of pressure transducer, the second is a kind of piezoelectric transducer, the third is a kind of capacitive transducer, an inductive transducer, and an ultrasonic transducer. Let us discuss the different types of transducers that are used for micro robotic applications in detail in the upcoming classes.