Transducers For Instrumentation

Prof. Ankur Gupta
Centre for Applied Research in Electronics (CARE)
Indian Institute of Technology, Delhi

Lecture - 01

Introduction to the Course

Hello, welcome to the course Transducers and Instrumentation. Today's outline is that we will discuss the introduction to transducers, Transduction principles, and the classification of transducers. So, the transducer is a device that converts one form of energy into a corresponding signal. So, the incoming energy can be of any form. Let us say it is a mechanical, a thermal, it is a electromagnetic, optical, and chemical. The input form of energy can be anything and Transducer generates the equivalent output signal. This transducer take the form of a sensor or an actuator. So, basically transducer depending upon the application it takes the form of sensors or an actuator.

So, mostly we deal with the sensors because the sensor is a device That converts a physical parameter to an electrical output. So, the input form of energy can be anything, it can be mechanical, optical, chemical it can be anything, but the output what it generates is a electrical signal that is called a sensor. And why we are more interested in the sensor is because the electrical signals are easy to process. We have electronics, we have computers, we have ah so many microcontrollers etc. Where we can easily process these electrical signals and generate the meaningful data. So, when we say transducers most of the time we are dealing with the sensors Means the input can be anything, it is an environmental parameter, but the output is an electrical signal. The sensor is thermometer for example, we have a thermometer we are talking about here the digital thermometer which measures the the temperature of environment and gives the reading in the form of electrical output. Which can be a digital display it gives the temperature on the display like 100 degree Fahrenheit, 102 degree Fahrenheit depending upon the upon the parameter. So, the sensor is a device which converts physical parameter into a electrical signal.

It is a device that detects or measures a signal or stimuli from the outside environment and acquires information from the real world. What we live in the real world and most of the parameters are analogue in nature and this sensor sense those parameters and generate an equivalent electrical output. So, this is sensor the next part is the actuator. So, the actuator is kind of dual of sensor. Actuator converts an electrical signal into a physical output. So, the actuator accepts a electrical signal generated by some electronic circuit or electrical circuit and it generates a physical output in the form of rotation, in the form of pressure or in the form of temperature it can be anything. For example, a heater. So, heater is what it accepts electrical signal when we power it up from our socket the

electrical signal or electrical power comes in and it generates a thermal output. The temperature of heater goes up or goes down depending upon the signal. So, heater is an example of actuator where it converts an electrical signal into a physical output.

This is a device that generates a signal or a stimulus. So, in pictorial view you can see we have a real world which is analogue in nature and the sensor accepts the these physical parameters. For example, temperature it can be pressure, it can be a chemical output. So, the sensor accept these environmental parameters and convert that into a electrical signal which is further processed by the system an electrical system or an electronic system. The actuator does a positive of that it accepts these electrical signals and convert that into a physical parameter. For example, the heater we considered here which converts this electrical signal into temperature. So, all together this is called transducer and depending upon the application what we are applying here we call them as a sensor or a actuator and the combined both of the them combinedly called transducers.

So, in this course, we will mostly talk about the sensors because sensors are important because it converts all the physical parameters into electrical signal and as we discussed electrical signals are easy to process using our computer or electronics. So, now we discuss various transduction principles. So, the sensors we make they use multiple physical properties of of materials and convert and use those properties to convert out electrical to convert physical parameters into electrical signals. So, various transduction principles are based on the input and output for example, the input is mechanical and the output can be a mechanical or it can be a thermal, it can be electrical, it can be magnetic, it can be radiant and it can be chemical and and others as well. So, input can be mechanical and output can be anything or we change the input the input let us say we talk about the thermal input and we convert that into mechanical or thermal electrical.

So, these sensors use various properties which convert this thermal input to magnetic output or mechanical output. Similarly, we have electrical input coming in and we can convert it into mechanical. So, that time it takes the form of actuator where we take the electrical and convert it into mechanical. So, this row is kind of actuator where the input is electrical and the output is mechanical or thermal or magnetic or other forms. However, if the output is electrical and the input is anything else then this is sensor. So, this row corresponds to sensor where we have output in the form of electrical. So, let us discuss all these transduction principles in little more detail. We have here an acoustic sensor which is mechanical to mechanical. So, in this diagram we are converting a mechanical energy into a corresponding mechanical signal. So, you can see a diaphragm here which is connected to this pressure bellows and here the pressure port is there. So, what actually it is happening here we have this diaphragm which is very sensitive to pressure change. So, any pressure change here let us say the pressure is increasing this diaphragm will be pushed down which will be detected by this pressure bellows. If this

diaphragm goes down this pressure bellows will be squeezed or they will be compressed.

Depending upon that when this pressure port you will get a pressure difference. So, this is kind of converting mechanical energy into a mechanical energy. This is one example of transduction principle where we are converting mechanical to mechanical itself. The next is thermal to mechanical we have we are converting thermal energy into mechanical energy. So, the example of this is thermal flow meter. What we are doing here this is this is the actual photo of the of the of the transducer and the working principle is here where we have a heating element which is shown in red here this is your heating element which is generating heat and this will be uniformly distributed. This will be initially uniformly distributed. However, if there is some gas flowing in this region gas or liquid flow in this region this heat signature will be something like this shown in this yellow curve because the incoming gas flow is at different temperature it can be colder than this temperature.

So, this because of this heat flow the thermal profile of this heating element will be similar to this colored waveform as shown here. So, because of this different color profile we can measure how much gas is flowing into the instrument. If the gas is low the the gas flow is low the profile will be very uniform and if the gas flow is very high this profile will be further deviated from from left side. So, this is an example of thermal to mechanical converter. Next is mechanical to electrical conversion. So, mechanical to electrical means we have a mechanical energy and we are generating corresponding electrical signal. So, this is actually a sensor. Here the example is acoustic sensors. Acoustic sensors we have these pressure change at the input and convert it into mechanical output into electrical output. So, this is a acoustic sensor which is generated by some some company. So, this acoustic sensor if this has a kind of a diaphragm at the input if the pressure changes then there is a Op-Amp circuitry connected to it and that Op-Amp circuit will convert this pressure change into a corresponding electrical output. So, this is acoustic sensor this is one commercially available acoustic sensor.

Another example is this delay line sensor. What this delay line sensor does this is made on a piezoelectric substrate. Piezoelectric substrate we will discuss in more detail in ah further lectures, but piezoelectric substrate generates corresponding electrical signal from an incoming mechanical signal. So, this piezoelectric substrate is there and on top of this substrate we make these in IDT structures or inter digital electrodes IDT's we call it this is these are like a comb structure where we have port where terminal number 1 and 2 and we apply signal on on these IDT structure. These IDT structures generate equivalent mechanical output from this electrical signal which travels into this delay line sensor from left to right and at the output on the right side these IDT's pick up this signal and convert back into an electrical signal which is further processed by electronic circuits.

So, this is the basic working principle of delay line sensors where we are converting

electrical to mechanical and then mechanical to electrical and based on the material we put here this IDT structures does sensing. All these sensors all these mechanism we will discuss later this is just the introduction. Next is thermal to mechanical and the very good example is our normal thermometer or the mercury thermometer. So, thermal to mechanical energy conversion is there where this thermometer is exposed to the temperature and there is a mercury inside the metal mercury is there which takes this thermal energy from ambient and because of the thermal expansion of of metal because of the temperature there is a change in the level of mercury. So, if we have a low temperature the temperature is less you see the level is less and if temperature goes high this mercury or some other material there is a elongation. So, this is a physical change in the material which is mechanical in nature and this mechanical output is produced by the thermal input the temperature. So, this is thermal to mechanical conversion this is one type of transduction principle.

Similarly, we have thermal to electrical conversion where we can convert this thermal energy into a electrical output and again this is a sensor because the output is electrical in nature. The example of thermal to electrical is thermocouples. These thermocouples are pair of metals where we have metal 1 or we can write type A and we have type B.

So, we have two types of metals the wires made of these two different metals they are joined together and we make two junction one we put at the reference level or generally we call cold junction and the other junction is our sensing arm or sensing junction which is used to measure the temperature. This thermocouple senses the temperature at the sensing node with reference to the cold junction or the reference junction we call it cold junction as well as the reference junction. So, this temperature measurement is always relative to the reference junction and depending upon the temperature difference between these two junctions there is a electrical potential build up between these two nodes node 1 and node 2 which you can measure using normal multimeter or some other electrical instruments. So, this is thermocouple is an example of thermal to electrical conversion in say is a thermocouple sensor and this is the actual photograph which is available in the open market. Another transduction principle is thermal to optical where we are converting this thermal energy into a corresponding output or into a corresponding optical signal.

We have this kind of arrangement where if optical fiber is going through all this liquid and this liquid is at different temperature. If the light is passing through a optical fiber and the temperature is changed. So, multiple properties of these optical waves actually changes, and we will see that in optical sensors that these change in the optical properties can be detected using your analog interferometer or various other instruments. So, this is a thermal to optical converter. This is one form of transduction. Another transduction is electrical to mechanical where we are converting electrical signal into a mechanical

signal. So, here the input is electrical, and output is mechanical or it can be anything. So, here we are talking about the actuator because the actuator takes input as a electrical signal.

So, one example of this kind of actuator is piezoelectric sensors where we have some materials which show piezoelectricity. Piezoelectricity is when these special materials are exposed to some mechanical input. For example, you change the size of these material by applying pressure. They generate equivalent output voltage and reversibly if you apply electrical output electrical input to them then there is a mechanical change in the in the size of these materials. So, for example, we have piezoelectric material here which is here. For example, one piezoelectric material is SiO_2 or we say quartz. When we apply a electrical signal across this then there is a physical change. This is expanding in this direction or compressing. So, this physical change is corresponding to how much signal we apply at the electrical signal we apply across this quartz crystal. This is called piezoelectric effect and corresponding sensor is piezoelectric sensor and this is the actual sensor this is how it is seen in the market. Another transduction principle is electrical to thermal where we are converting electrical energy into thermal energy.

One example we have already seen which is our heater in a normal filament where we apply electrical power or electrical signal and correspondingly heat is generated. The other example is this Peltier sensors. These Peltier sensors they are made up made up of thermo thermocouples we have two different metals. When we apply a electrical signal between these two terminals this is positive this is negative. When we apply electrical signal across this depending upon the material we choose in both the metals one side of the this plate becomes hot and other side of this Peltier effect Peltier kit becomes cold. So, this is called Peltier effect and this is the Peltier kit we generally use for temperature measurement or temperature control also because the effect is reciprocal.

So, this Peltier kit converts this electrical signal into a thermal output. The next transduction principle is electrical to electrical where we have an input signal as a electrical signal and the output is also generated in the form of electrical signal. Example is some charge controller device where we are controlling the charge very much used in solar panels where we the solar panels are generating electrical charge from the from the sunlight and this electrical charge is again controlled by these devices. These are charge control devices and example this is the example of electrical-to-electrical transduction. Example 2 electrical which is again one another important transduction principle because the output is electrical it means it is a sensor the input is magnetic, but the output is in the electrical form.

One example is hall sensors. Hall sensor is it can measure the current flow in current flow in the circuit as well as it can measure the magnetic field applied across the sensor. So, the basic structure of this hall sensor is we have a conductive medium where the

current can pass we apply a potential difference across it from a DC supply and simultaneously we apply this magnetic field. This is the magnetic field which is the input to this sensor. Depending upon this magnetic field these charge carriers will feel a Lorentz force they will the positive side will go for example, this side and the magnetic and the negative side will go to the other side. If they accumulate positive on one side and negative on the other side essentially there is a potential build up across it and this potential difference is depending upon the applied magnetic field.

If we have high magnetic field applied then the hall voltage will be higher. So, this is example of magnetic to electrical conversion. Another example is chemical to electrical where we are converting chemical measurement to an electrical output this is again a sensor. So, here we have this IDT like structure we have two electrodes this is let us say one this is two this is a comb like structure we have this first comb and this is the second and this is a IDT structure or call it inter digitated electrodes and these electrodes we dip into the liquid or the chemical and depending upon the conductivity of chemical the resistance between this electrode and this electrode changes because the liquid is filled in between. So, depending upon the conductivity of that solution electrolyte solution that conductivity we measure or we can measure the resistance which is proportional to the conductivity of the electrolyte.

So, this is chemical to electrical sensor. So, we have discussed now multiple types of transduction principles where we apply a input and the output is generated in the form of electrical or other measurements, but we all considered where the input is only one, but some sensors for example, the hall sensors we just discussed it can have more than one one inputs. So, for example, in the hall sensor we have electrical and magnetic. So, this hall sensor can have two inputs electrical and magnetic. So, it is not possible to kind of classify all the sensors into a one definition. So, in the case of more than one input sometime it is the application aspects or the measurement type is given more important than input type because the input we have more than one.

So, for example, we have mechanical energy as the input and measurement can be length, area, volume, pressure, force, acceleration, torque these are all mechanical in nature. Another form of energy can be thermal where we have temperature, heat flow, entropy, state of matter all these measurements are there, but the essential the energy input is thermal in nature. We have electrical energy where we can measure charge, current, voltage, resistance and there are so many parameters we can measure, but the form of energy is electrical. We can have magnetic energy for example, the magnetic field intensity, flux density, permeability magnetic movements and so forth. Another form of energy is radiant where we can have radiation and the measurement can be intensity, phase, refractive index, reflectance, transmittance, absorbance, wavelength, polarization and so on.

Similarly, we can have even the chemical energy also as an input and the measurement can be the concentration, the composition of liquid, oxidation, reduction potential, reaction rate, pH is also chemical in nature and others. So, these are various measurements which we can measure, but the type of energy are different. Now we come to the classification of these transducers. So, it is difficult to classify all the sensors under one criteria because there are so many types of sensors some are mechanical input, some are electrical input, some are optical input. So, it is very difficult to classify all the sensors under a one criteria and that is why there are different criteria's are adopted worldwide for the classification of sensor.

One classification is based on the transduction principle which we will discuss there are multiple types of transduction principles. Second is the primary input quantity in means the measure and what it measures. The third is material and the technology used in the sensor. The fourth is applications based what application actually we are solving using this sensor or actuator and the property type the what is the property we are using in the sensor. So, these are basically few types of classification though all the sensors cannot be classified in these five as well we can have multiple classification criteria's as well, but we will we are going to discuss these five.

So, the first one is the transduction principle based on the type of transduction, type of conversion of energy from one type to another type depending upon the transduction principle we can have classification of these sensors. Transduction principles based on these physical, chemical or biological effects. So, transduction principle can be a physical type where we have thermo electric, photo electric, photo magnetic, magneto electric, electromagnetic, thermo elastic, electrostatic, thermo magnetic, thermo optic, photo electric and others. So, all these effects these are physical physical properties of materials. The other transduction principle is chemical in nature where we can have a chemical transformation the chemical used in the sensor it changes the property.

So, physical transformation, electrochemical process, spectroscopy and others these are all chemical type of transduction. We can have biological transduction as well where the compound we use in the sensor it changes its property when it when it binds with some biological components. So, here biochemical transformation is there physical transformation effect on test organs spectroscopy and others these are all biological in nature. So, these are transduction based principle we can classify the sensors. Other classification is the measure end base measure end is the input parameter which is coming from the real world we are measuring the temperature then the temperature is the measure end and we are converting into electrical signal.

So, classification can be based on the measure end measure end type. For example, we have a caustic sensor where the measure end can be a wave amplitude we can rather measure the phase, the polarization, the spectrum or the wave velocity and other

parameters. We can use any of the this measure end and the sensors will be the caustic sensors. Biological type where the stimuli is biological for example, the biomass type concentration state and others these are the all the measure ends we can use. If the stimuli is chemical then we can have multiple components for example, identities concentration states and others.

Stimuli can be electric where we can have multiple type of measure ends one is charge, the current flowing, the potential build up, voltage, electric field and in these we can have amplitude, phase, polarization, spectrum and conductivity, permittivity and various other parameters. If the stimuli is magnetic we have magnetic field again we can measure the amplitude, phase, polarization, spectrum, magnetic flux, permeability and other measure ends. If the stimuli is optical we can have wave amplitude, phase, polarization, spectrum, wave velocity, refractive index, emissivity, reflectivity, absorption others. We can have multiple types of measure end. If the stimuli is mechanical we can again have multiple measure ends position which can be linear as well as angular, acceleration, force, stress, pressure, strain, mass, density, movement, torque, speed, rate of mass, transport, shape, roughness these are all mechanical parameters and these can be used as a measure end.

Another stimuli is radiation where the radiation type can be a measure end what kind of radiation is there is infrared, it is ultraviolet, it is in the visible region. So, that can be a measure end type energy, intensity and other measure end type. If the stimuli is thermal we can have thermal flux, we can have specific heat, thermal conductivity and others. So, these are all classification based on the measure end type. So, we can have the material based sensor, material based classification where the sensor fabrication material is used for the classification.

So, where we can have basically two type one is the inorganic type and the second is the organic type. Inorganic type sensors are for example, the material used is a conductor just like a metal or it is a semiconductor for example, silicon based sensors or some biological substance these are all fall in inorganic type of material, inorganic type of sensors. The other sensor type is organic where we can have insulators, we can have liquid gas or plasma also these are also used as a sensor and other materials. So, this is basically the classification based on the material used for sensor fabrication. Some classification we can do based on the property type, the property we what we use for these transduction.

So, for example, we have these properties on x axis and the technology used on this y axis for example, flow we can measure and we can have differential pressure, positional displacement, vortex, thermal mass, electromagnetic, corollarys, electro ultrasonic, anemometer, open channel these are all for flowmetry. We can have level where we have mechanical, magnetic, differential pressure, thermal, displacement, vibrating rod, magnetostrictive, ultrasonic, radio frequency, capacitance type and microwave radar or

nuclear type. Another property is the temperature where we can have filled in systems or the RTDs, RTDs are we can have filled in systems, we can have RTDs, we can have thermistors, we can have ICs thermocouples, inductive, inductively coupled or radiation. Another property is the pressure where we can have elastic, liquid based, manometers, inductive LVDTs, piezoelectric, electronic fiber, optic, MEMS or vacuum. Proximity and displacement we have potentiometric inductive LVDTs, the capacitive, magnetic, photoelectric, magnetostrictive or ultrasonic.

Another property is acceleration where we can have accelerometers or gyroscopes, these are very much used nowadays as a MEMS device in all the smart electronics. We can have image for example, we can use CMOS, we can use CCDs or the charge coupled devices, we can have the acceleration. Another is gas and chemical where we can have chemical bead, electrochemical, thermal conductance, paramagnetic ionization, infrared and semiconductor. Another property is biosensors where we have electrochemical, light addressable potentiometer, LEP we call in short surface plasmon resonators or resonant mirrors and others as well for example, mass, force, load, humidity, moisture and viscosity. So, these are the property based classification we where we use the property of of sensing and we classify all these sensors and transducers based on this property type.

Apart from this we have multiple emerging type of technologies and then we called emerging sensors where all these because of the advancement of microelectronics area, we have multiple sensing technologies coming in. And some of the example is given here where we have these image sensor technology which is CMOS based. So, we have image sensors and they are fabricated using CMOS process and they use multiple type of technology actually the signal processing technologies are different. Based on that we can classify and they are used pretty much in traffic and security surveillance, blind spot detection as auto sensors for example, the robots in inside the robots we use them, video conferencing, consumer electronics, biometrics and PC imaging these are these sensors are very much used. Next we have these motion detectors or the motion detector technology I they use IR ultrasonic or microwave radars.

These are very much used in defense application for example, the obstruction detection, autos or the robots or even for example, the the detection of drones that is also part of radar engine, security detection, toilet surveillance, toilet activation, kiosk, videograms and simulations, light activation there are multiple applications where these sensors are widely used. The third is biosensors or the biosensor technology which is electrochemical in nature. These biosensors are very much used in water testing, food testing for example, in food testing we do contamination detection using these biosensors typically we can calculate how if the food is edible or not if these fruits which comes from outside outside the country we can judge the quality of those fruits and other edible products whether they are edible or they are not edible using these biosensors. Medical care device is

another very big area where we use these biosensors for example, the sugar test kit which is a biosensor where the drop of blood we put on the strip and it gives the sugar level inside the blood is widely used for a diabetic patient and this is a biosensor. There are multiple type of biosensors available in the market, sugar testing is one another one thing there can be some other sensors for example, the radiation sensor which has which is also a biosensor.

Medical warfare or the agent detection this is also also a area where biosensors are widely used. Accelerometer technologies this the acceleration measurement and the technology we used here is the MEMS devices. MEMS is a short form of micro electro mechanical system, micro electro mechanical system. So, these are mechanical systems which are generally big in nature, but we fabricate these mechanical systems using CMOS process or fabrication process and the size is so small that we start calling them micro electro mechanical systems. These mechanical systems detects the mechanical input and convert that into an electrical output.

So, very good example of this is we have a gyroscope in inside the laptops or inside the mobile phones which detects the orientation of mobile phone. For example, we have mobile phone in the in the portrait mode then our screen becomes portrait if we rotate the mobile phone then the screen automatically changes the orientation. So, that is done using these MEMS devices because there is a hanging pendulum inside which detects in which direction we are putting our mobile based on that the screen is changed. This is one application of these MEMS devices. The vehicle dynamic system is also very important where we have these airbags in our cars and these airbags are connected to a pendulum inside it is a kind of pendulum it is a mechanical device is a very small inside.

So, we can call it as MEMS device. Whenever there is a accident or there is a collision this pendulum detects that jerk in the in the system and because of this this change in the mechanical system these airbags gets open and the passengers are saved. So, one example is airbag and these are also used in patient monitoring including pacemakers etcetera pacemakers are again life saving devices where these all emerging sensors are used. So, these are some classification based on the emerging technologies where these sensors are are fabricated in mass scale using fabrication technology CMOS based or other fabrication technologies. So, these are all the classifications. However, it is not possible to classify all that sensors in the world into these definitions and we can have some other classification as well which can be active or passive.

So, this another classification can be based upon the power or energy requirement of these sensors. So, for example, we have a sensor and this does not need any electricity or external bias or external power to convert the signal into electrical signal then this sensor is called a passive sensor because it does not need any extra power supply. If a sensor it needs any external power supply or some external energy to do the transduction to

convert the input into the output then this sensor is called the active sensor because this needs external power supply. So, some sensors they require power supply these are called active sensors. Active sensors means you have some electronic circuits inside which is detecting some change in the parameter and generating output.

So, all these electronic circuits they need some external power supply. So, these are all active sensors this is one classification where we need power supply. The passive sensors are something like your piezoelectric substance for example, your quartz or SiO_2 when we apply a physical change or we compress it this SiO_2 crystal compress it or expand it, it automatically generates a potential across it. This system does not need any external power supply we just press the system and it generates an equivalent electrical output and this concept is reciprocal. So, this kind of system does not need any external power supply and we call it a passive system or passive sensor.

Another example of active and passive sensor is the mercury thermometer. We have this old mercury thermometer where this mercury is filled in a glass tube and when we expose this whole tube to the temperature this thermometer when we let us say connect it to our body it takes the thermal energy from our body and because of this thermal energy that the mercury inside it changes its volume it expands when we heat up the things it expands. So, the mercury filled inside it expands inside that tube and we have multiple markings on that based on that expansion we can measure how much is the temperature. So, this thermometer the mercury filled thermometers they are passive in nature because we need not to have any external battery external power source or any other kind of input biasing to this thermometer this is passive thermometer. However, the new thermometers which we have nowadays they are digital in nature they show the number as a temperature reading. So, these thermometers they have some kind of thermocouples inside which measures the temperature but this electrical this signal generated by this thermocouple this is further processed using some electronic circuitry for example, this kind of electronic circuitry and this electronic circuitry gives its output on LCD or the screen we have in these thermal sensors or this thermometer.

This electronic circuit it uses external biasing or some external power source where some voltage is applied here let us say 5 volt typically and this circuit performs only when this voltage supply is there. So, all these thermometers we have digital thermometers they have a battery inside which is powering all these electronic circuit and based on that there is a sensing by these digital thermometer. So, these digital thermometers they are active sensors. So, we can classify based on these two properties as well where we say passive sensors where we do not need any power supply and we have an active sensors where we need an external power source to do the processing. So, we discussed multiple types of classification of transducers and we discussed the introduction to transducers.

Thank you.