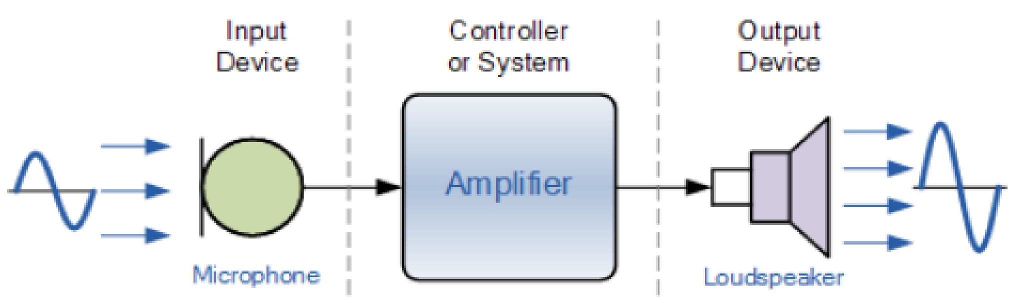
MODULE-2

IOT Sensing and Actuation

1 Introduction

- The basic science of sensing and actuation is based on the process of transduction.
- Transduction is the process of energy conversion from one form to another.
- A transducer is a physical means of enabling transduction.
- Transducers take energy in any form (for which it is designed)—electrical, mechanical, chemical, light, sound, and others—and convert it into another, which may be electrical, mechanical, chemical, light, sound, and others.
- Sensors and actuators are deemed as transducers.
- Example: Public Announcement System



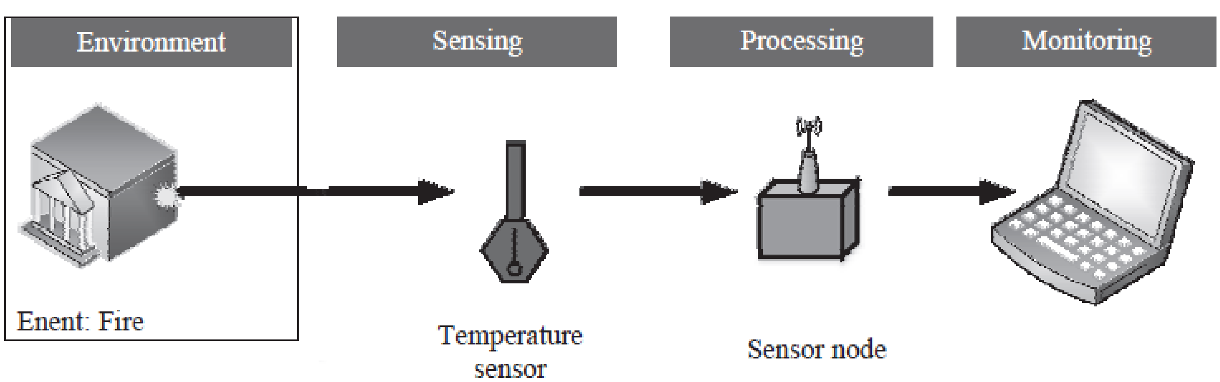
1.1 Sensors

- Sensors are devices that can measure, or quantify, or respond to the ambient changes in their environment or within the intended zone of their deployment.
- They generate responses to external stimuli or physical phenomenon through characterization of the input functions (which are these external stimuli) and their conversion into typically electrical signals.

- **For example**, heat is converted to electrical signals in a temperature sensor, or atmospheric pressure is converted to electrical signals in a barometer. sensor is only sensitive to the measured property only.
- It is insensitive to any other property besides what it is designed to detect. (e.g., a temperature sensor does not bother about light or pressure while sensing the temperature).
- a sensor does not influence the measured property (e.g., measuring the temperature does not reduce or increase the temperature).

Parameters	Transducers	Sensors	Actuators
Definition	Converts energy from one form to another	Converts various forms of energy into electrical signals	Converts electrical signals into various forms of energy, typically mechanical energy
Domain	Can be used to represent a sensor as well as an actuator	It is an input transducer	It is an output transducer
Function	Can work as a sensor or an actuator but not simultaneously	Used for quantifying environmental stimuli into signals	Used for converting signals into proportional mechanical or electrical outputs
Examples	Any sensor or actuator	Humidity sensors, Temperature sensors, Anemometers(measures flow velocity), Manometers(measures fluid pressure), Accelerometers(measures the acceleration of a body), Gas sensors(measures concentration of specific gas or gases) and others	Motors(convert electrical energy to rotary motion), Force heads(which impose a force), Pumps(which convert rotary motion of shafts into either a pressure or a fluid velocity)

Simple outline of a sensing task:



1.2 The various sensors can be classified based on:

- 1) power requirements,
- 2) sensor output, and
- 3) property to be measured.

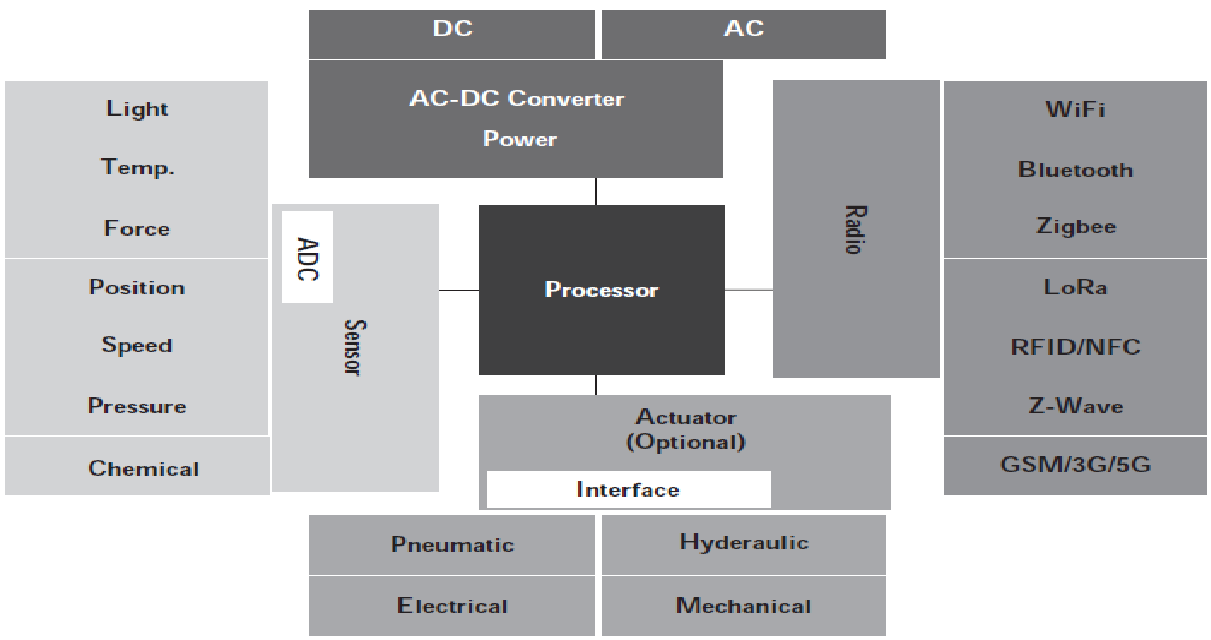
Power Requirements:

- The way sensors operate decides the power requirements that must be provided for an IoT implementation.
- Some sensors need to be provided with separate power sources for them to function, whereas some sensors do not require any power sources.
- **Depending on the requirements of power, sensors can be of two types.**
- **1. Active   2. Passive**
- **Active**:
- Active sensors do not require an external circuitry or mechanism to provide it with power. It directly responds to the external stimuli from its ambient environment and converts it into an output signal.
- For example, a photodiode converts light into electrical impulses.
- **Passive:**
- Passive sensors require an external mechanism to power them up. The sensed properties are modulated with the sensor's inherent characteristics to generate patterns in the output of the sensor.
- Example: Thermistor.
- **Sensor Output**:
- The output of a sensor helps in deciding the additional components to be integrated with an IoT node or system.
- Digital sensors can be directly integrated to the processors.
- Sensors are broadly divided into two types, depending on the type of output generated from these sensors, as follows.
- **1) Analog**

- **2) Digital**
- **Analog:**
- Analog sensors generate an output signal or voltage, which is proportional (linearly or non-linearly) to the quantity being measured and is continuous in time and amplitude.
- Physical quantities such as temperature, speed, pressure, displacement, strain, and others are all continuous and categorized as analog quantities.
- For example, a thermometer or a thermocouple
- **Digital:**
- These sensors generate the output of discrete time digital representation (time, or amplitude, or both) of a quantity being measured, in the form of output signals or voltages.
- Typically, binary output signals in the form of a logic 1 or a logic 0 for ON or OFF, respectively are associated with digital sensors.
- The generated discrete values may be output as a single "bit"eight of which combine to produce a single "byte"
- **Measured Property:**
- Measured by the sensors can be crucial in deciding the number of sensors in an IoT implementation.
- Measured do not show high spatial variations and can be quantified only based on temporal variations in the measured property, such as ambient temperature, atmospheric pressure, and others.
- Measured show high spatial as well as temporal variations such as sound, image, and others.
- Depending on the properties to be measured, sensors can be of two types.
- **1) Scalar**
- **2) Vector**
- **Scalar:**
- Scalar sensors produce an output proportional to the magnitude of the quantity being measured.
- The output is in the form of a signal or voltage.

- Scalar physical quantities are those where only the magnitude of the signal is sufficient for describing or characterizing the phenomenon and information generation
- Factors such as changes in sensor orientation or direction do not affect these sensors
- Example: Thermometer and Thermistor
- **Vector:**
- Vector sensors are affected by the magnitude as well as the direction and/or orientation of the property they are measuring.
- Physical quantities such as velocity and images that require additional information besides their magnitude for completely categorizing a physical phenomenon are categorized as vector quantities
- **For example**, an electronic gyroscope, which is commonly found in all modern aircraft, is used for detecting the changes in orientation of the gyroscope with respect to the Earth's orientation along all three axes.

1.3 The functional blocks of a typical sensor node in IoT



(a) Camera sensor (b) Color sensor (c) Compass and barometer (d) Current sensor (e) Digital temperature and humidity sensor

(f) Flame sensor (g) Gas sensor (h) Infrared sensor (i) Rainfall sensor (j) Ultrasonic distance measurement sensor

1.3 Sensor Characteristics

Sensors can be characterized by their ability to sense the phenomenon based on the following three fundamental properties.

- Sensor Resolution
- Sensor Accuracy
- Sensor Precision

Sensor Resolution:

- The smallest change in the measurable quantity that a sensor can detect is referred to as the resolution of a sensor.
- For digital sensors, the smallest change in the digital output that the sensor is capable of quantifying is its sensor resolution.
- The more the resolution of a sensor, the more accurate is the precision.
- A sensor’s accuracy does not depend upon its resolution.
- **[For example**, a temperature sensor A can detect up to 0:5 C changes in temperature; whereas another sensor B can detect up to 0:25 C changes in temperature. Therefore, the resolution of sensor B is higher than the resolution of sensor A.]

Sensor Accuracy:

- The accuracy of a sensor is the ability of that sensor to measure the environment of a system as close to its true measure as possible.
- For example, a weight sensor detects the weight of a 100 kg mass as 99.98 kg. that means this sensor is 99:98% accurate, with an error rate of +or-0.02%.

Sensor Precision:

- The principle of repeatability governs the precision of a sensor. Only if, upon multiple repetitions, the sensor is found to have the same error rate, can it be deemed as highly precise.
- For example, consider if the same weight sensor described earlier reports measurements of 98.28 kg, 100.34 kg, and 101.11 kg upon three repeat measurements for a mass of actual weight of 100 kg.
- The sensor precision is not deemed high because of significant variations in the temporal measurements for the same object under the same conditions.

1.5 Sensorial Deviations

- Most of the sensing in IoT is **non-critical**, where minor deviations in sensorial outputs seldom change the nature of the undertaken tasks. Critical applications of IoT, such as healthcare, industrial process monitoring, and others, do require sensors with high-quality measurement capabilities.
- As the quality of the measurement obtained from a sensor is dependent on a large number of factors, there are a few primary considerations that must be incorporated during the sensing of critical systems.
- Beyond its designed **maximum and minimum capacity** for measurement, the sensor output is truncated to its maximum or minimum value, which is also the sensor's limits.
- The measurement ranges between a sensor's characterized minimum and maximum values is also referred to as the full-scale range of that sensor.

1.sensitivity error.

- Under real conditions, the sensitivity of a sensor may differ from the value specified for that sensor leading to sensitivity error. This deviation is mostly attributed to sensor fabrication errors and its calibration.

2.offset error or bias:

- If the output of a sensor differs from the actual value to be measured by a constant, the sensor is said to have an offset error or bias.
- **Example, while** measuring an actual temperature of 0 C, a temperature sensor outputs 1.1 C every time. In this case, the sensor is said to have an offset error or bias of 1.1 C.

3. Non-linearity:

- If a sensor’s transfer function (TF) deviates from a straight line transfer function, it is referred to as its non-linearity.
- The amount a sensor’s actual output differs from the ideal TF behavior over the full range of the sensor quantifies its behavior. It is denoted as the percentage of the sensor’s full range.

4.Drift:

If the output signal of a sensor changes slowly and independently of the measured property

- Physical changes in the sensor or its material may result in long-term drift, which can span over months or years.
- Noise is a temporally varying random deviation of signals.

5.Hysteresis error:

if a sensor’s output varies/deviates due to deviations in the sensor’s previous input values.

- The present output of the sensor depends on the past input values provided to the sensor.
- One way to check for hysteresis error is to check how the sensor’s output changes when we first increase, then decrease the input values to the sensor over its full range.
- It is generally denoted as a positive and negative percentage variation of the full-range of that sensor.

6.Quantization Error:

- If the digital output of a sensor is an approximation of the measured property
- Defined as the difference between the actual analog signal and its closest digital approximation during the sampling stage of the analog to digital conversion.

7. Dynamic errors:

- Caused due to mishandling of sampling frequencies can give rise to aliasing errors.
- Aliasing leads to different signals of varying frequencies to be represented as a single signal in case the sampling frequency is not correctly chosen, resulting in the input signal becoming a multiple of the sampling rate.

1.6 Sensing Types

Sensing can be broadly divided into four different categories based on the nature of the environment being sensed and the physical sensors being used to do so

1) Scalar sensing,

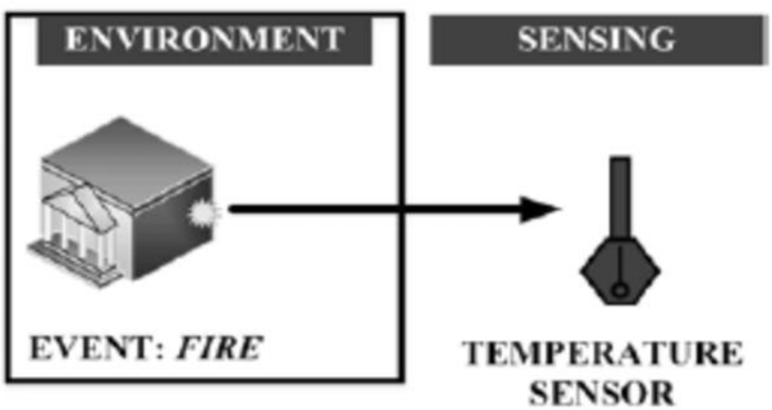
2) Multimedia sensing

3) Hybrid sensing

4) Virtual sensing

1. Scalar sensing

- Encompasses the sensing of features that can be quantified simply by measuring changes in the amplitude of the measured values with respect to time.
- Quantities such as ambient temperature, current, atmospheric pressure, rainfall, light, humidity, flux, and others are considered as scalar values as they normally do not have a directional or spatial property assigned with them.

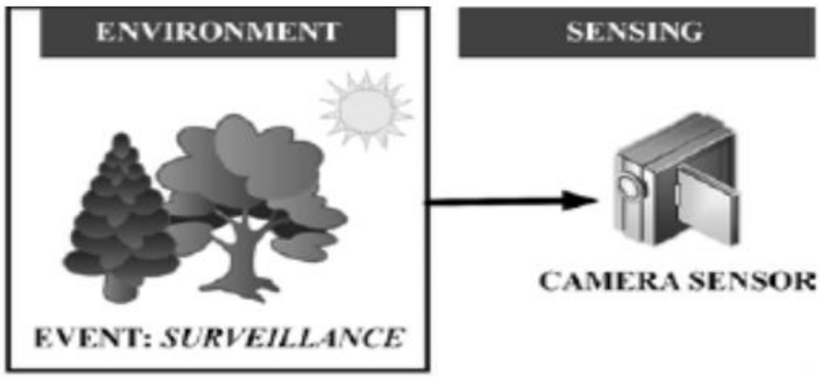


(a) Scalar sensing

2. Multimedia sensing

- Encompasses the sensing of features that have a spatial variance property associated with the property of temporal variance.
- Are used for capturing the changes in amplitude of a quantifiable property concerning space (spatial) as well as time (temporal).

- Quantities such as images, direction, flow, speed, acceleration, sound, force, mass, energy, and momentum have both directions as well as a magnitude.
- These quantities follow the vector law of addition and hence are designated as vector quantities.
- They might have different values in different directions for the same working condition at the same time.
- The sensors used for measuring these quantities are known as vector sensors.



(b) Multimedia sensing

3) Hybrid sensing

- The act of using scalar as well as multimedia sensing at the same time is referred to as hybrid sensing.
- Many a time, there is a need to measure certain vector as well as scalar properties of an environment at the same time.
- Under these conditions, a range of various sensors are employed (from the collection of scalar as well as multimedia sensors) to measure the various properties of that environment at any instant of time, and temporally map the collected information to generate new information
- Example, in an agricultural field, it is required to measure the soil conditions at regular intervals of time to determine plant health. Sensors such as soil moisture and soil temperature are deployed underground to estimate the soil's water retention capacity and the moisture being held by the soil at any instant of time
- This setup only determines whether the plant is getting enough water or not.
- There may be a host of other factors besides water availability, which may affect a plant's health.
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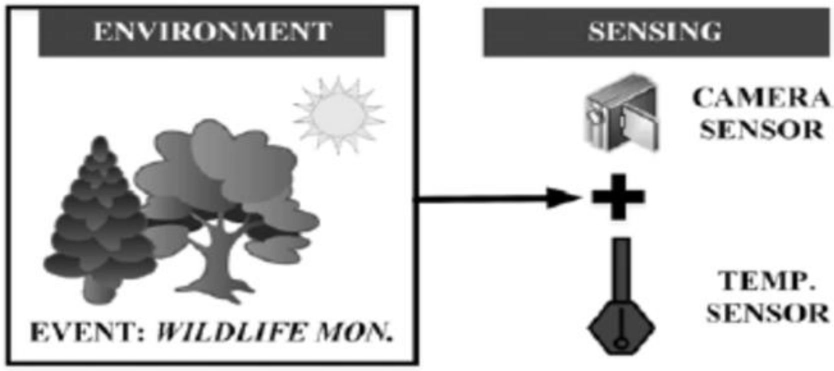

(c) Hybrid sensing

- The additional inclusion of a camera sensor with the plant may be able to determine the actual condition of a plant by additionally determining the color of leaves.
- The aggregate information from soil moisture, soil temperature, and the camera sensor will be able to collectively determine a plant's health at any instant of time.
- **Other common examples** of hybrid sensing include smart parking systems, traffic management systems, and others. Figure 5.4(c) shows an example of hybrid sensing, where a camera and a temperature sensor are collectively used to detect and confirm forest fires during wildlife monitoring.

4) Virtual sensing

- Many a time, there is a need for very dense and large-scale deployment of sensor nodes spread over a large area for monitoring of parameters. One such domain is agriculture.
- Here, often, the parameters being measured, such as soil moisture, soil temperature, and water level, do not show significant spatial variations.
- Hence, if sensors are deployed in the fields of farmer **A**, it is highly likely that the measurements from his sensors will be able to provide almost concise measurements of his neighbor **B**'s fields; this is especially true of fields which are immediately surrounding **A**'s fields.
- Exploiting this property, if the data from A's field is digitized using an IoT infrastructure and this system advises him regarding the appropriate watering, fertilizer, and pesticide regimen for his crops, this advisory can also be used by B for maintaining his crops. In short, A 's sensors are being used for actual measurement of parameters; whereas virtual data (which does not have actual physical sensors but uses extrapolation-based measurements) is being used for advising B.
- This is the virtual sensing paradigm.
- The event E2 does not have a dedicated sensor for monitoring it; however, through the superposition of readings from sensors S1 and S3, the presence of fire in E2 is inferred.

- Example of virtual sensing. Two temperature sensors S1 and S3 monitor three nearby events E1, E2, and E3 (fires).
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(d) Virtual sensing

1.7 Sensing Considerations

- The choice of sensors in an IoT sensor node is critical and can either make or break the feasibility of an IoT deployment.
- The following major factors influence the choice of sensors in IoT-based sensing solutions:
- 1) sensing range,
- 2) accuracy and precision
- 3)energy, and
- 4) device size.

1. **Sensing Range**:

- The sensing range of a sensor node defines the detection fidelity of that node.
- Typical approaches to optimize the sensing range in deployments include fixed k-coverage and dynamic k-coverage.
- A lifelong fixed k-coverage tends to usher in redundancy as it requires a large number of sensor nodes, the sensing range of some of which may also overlap.
- In contrast, dynamic kcoverage incorporates mobile sensor nodes post detection of an event, which, however, is a costly solution and may not be deployable in all operational areas and terrains .
- Additionally, the sensing range of a sensor may also be used to signify the upper and lower bounds of a sensor’s measurement range.

- For example, a proximity sensor has a typical sensing range of a couple of meters. In contrast, a camera has a sensing range varying between tens of meters to hundreds of meters.
- As the complexity of the sensor and its sensing range goes up, its cost significantly increases.

2. **Accuracy and Precision**:

- The accuracy and precision of measurements provided by a sensor are critical in deciding the operations of specific functional processes.
- Typically, off-the-shelf consumer sensors are low on requirements and often very cheap. their performance is limited to regular application domains.
- For example, a standard temperature sensor can be easily integrated with conventional components for hobby projects and day-to-day applications, but it is not suitable for industrial processes. Regular temperature sensors have a very low-temperature sensing range, as well as relatively low accuracy and precision.
- The use of these sensors in industrial applications, where a precision of up to 3–4 decimal places is required, cannot be facilitated by these sensors.
- Industrial sensors are typically very sophisticated, and as a result, very costly. These industrial sensors have very high accuracy and precision score, even under harsh operating conditions.

3. **Energy**

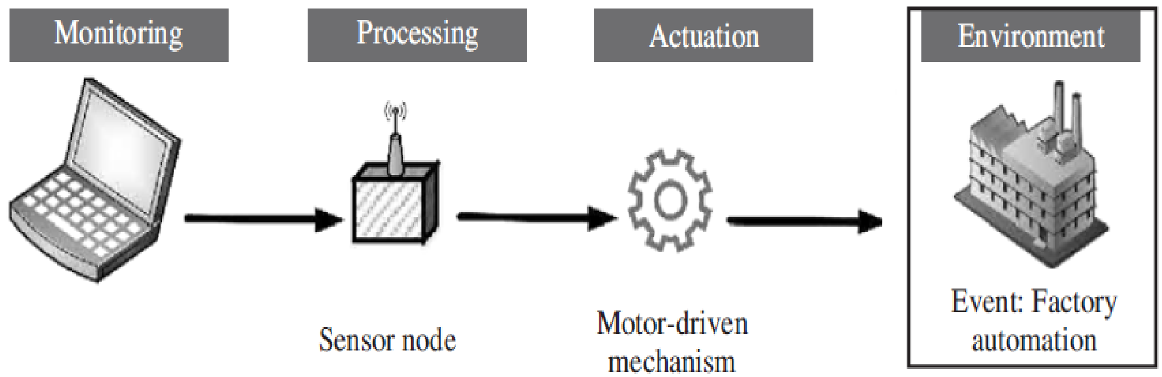
- The energy consumed by a sensing solution is crucial to determine the lifetime of that solution and the estimated cost of its deployment.
- If the sensor or the sensor node is so energy inefficient that it requires replenishment of its energy sources quite frequently, the effort in maintaining the solution and its cost goes up; whereas its deployment feasibility goes down.
- Consider a scenario where sensor nodes are deployed on the top of glaciers.
- Once deployed, access to these nodes is not possible.
- If the energy requirements of the sensor nodes are too high, such a deployment will not last long, and the solution will be highly infeasible as charging or changing of the energy sources of these sensor nodes is not an option.

4. Device Size:

- Modern-day IoT applications have a wide penetration in all domains of life.
- Most of the applications of IoT require sensing solutions which are so small that they do not hinder any of the regular activities that were possible before the sensor node deployment was carried out.
- Larger the size of a sensor node, larger is the obstruction caused by it, higher is the cost and energy requirements, and lesser is its demand for the bulk of the IoT applications.
- Consider a simple human activity detector. If the detection unit is too large to be carried or too bulky to cause hindrance to regular normal movements, the demand for this solution would be low.
- It is because of this that the onset of wearables took off so strongly. The wearable sensors are highly energy-efficient, small in size, and almost part of the wearer's regular wardrobe.

1.8 Actuators

- An actuator can be considered as a machine or system's component that can affect the movement or control the said mechanism or the system.
- Control systems affect changes to the environment or property they are controlling through actuators.
- The system activates the actuator through a control signal, which may be digital or analog.
- It elicits a response from the actuator, which is in the form of some form of mechanical motion.
- The control system of an actuator can be a mechanical or electronic system, a software-based system (e.g., an autonomous car control system), a human, or any other input.
- A remote user sends commands to a processor.
- The processor instructs a motor controlled robotic arm to perform the commanded tasks accordingly.
- The processor is primarily responsible for converting the human commands into sequential machine-language command sequences, which enables the robot to move.
- The robotic arm finally moves the designated boxes, which was its assigned task.



1.9 Actuator Types

- Hydraulic
- Pneumatic
- Electrical
- Thermal/magnetic
- Mechanical
- Soft
- Shape memory polymers

Hydraulic Actuators

- A hydraulic actuator works on the principle of compression and decompression of fluids.
- These actuators facilitate mechanical tasks such as lifting loads through the use of hydraulic power derived from fluids in cylinders or fluid motors.
- The mechanical motion applied to a hydraulic actuator is converted to either linear, rotary, or oscillatory motion.
- The almost incompressible property of liquids is used in hydraulic actuators for exerting significant force.
- These hydraulic actuators are also considered as stiff systems. The actuator’s limited acceleration restricts its usage.

Pneumatic Actuators

- A pneumatic actuator works on the principle of compression and decompression of gases.
- These actuators use a vacuum or compressed air at high pressure and convert it into either linear or rotary motion.
- Pneumatic rack and pinion actuators are commonly used for valve controls of water pipes.
- Pneumatic actuators are considered as compliant systems.
- The actuators using pneumatic energy for their operation are typically characterized by the quick response to starting and stopping signals.

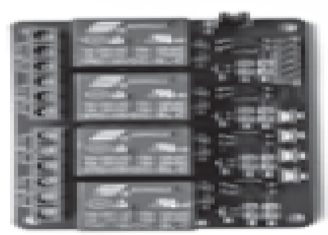
- Small pressure changes can be used for generating large forces through these actuators.
- Pneumatic brakes are an example of this type of actuator which is so responsive that they can convert small pressure changes applied by drives to generate the massive force required to stop or slow down a moving vehicle.
- Pneumatic actuators are responsible for converting pressure into force.
- The power source in the pneumatic actuator does not need to be stored in reserve for its operation.

Electric Actuators

- Typically, electric motors are used to power an electric actuator by generating mechanical torque.
- This generated torque is translated into the motion of a motor's shaft or for switching (as in relays).
- For example, actuating equipment's such as solenoid valves control the flow of water in pipes in response to electrical signals.

- This class of actuators is considered one of the cheapest, cleanest and speedy actuator types available.

(a) Brushless DC motor (b) Brushless DC motor (c) Stepper motor (d) Geared stepper motor (e) DC motor



(f) Relay array

Thermal or Magnetic Actuators

- The use of thermal or magnetic energy is used for powering this class of actuators.
- These actuators have a very high power density and are typically compact, lightweight, and economical.
- One classic example of thermal actuators is shape memory materials (SMMs) such as shape memory alloys (SMAs).
- These actuators do not require electricity for actuation. They are not affected by vibration and can work with liquid or gases. Magnetic shape memory alloys (MSMAs) are a type of magnetic actuators.

Mechanical Actuators

- In mechanical actuation, the rotary motion of the actuator is converted into linear motion to execute some movement.

- The use of gears, rails, pulleys, chains, and other devices are necessary for these actuators to operate.
- These actuators can be easily used in conjunction with pneumatic, hydraulic, or electrical actuators.
- They can also work in a standalone mode.
- The best example of a mechanical actuator is a rack and pinion mechanism.

(g) Hydroelectric generator (h) Hydroelectric generator (i) Solenoid-based flow valve (j) Solenoid-based flow valve

(k) DPDT switch (l) Push button switch

Soft Actuators

- Soft actuators (e.g., polymer-based) consists of elastomeric polymers that are used as embedded fixtures in flexible materials such as cloth, paper, fiber, particles, and others
- The conversion of molecular level microscopic changes into tangible macroscopic deformations is the primary working principle of this class of actuators.
- These actuators have a high stake in modern-day robotics.
- They are designed to handle fragile objects such as agricultural fruit harvesting, or performing precise operations like manipulating the internal organs during robot-assisted surgeries.

Shape Memory Polymers

- Shape memory polymers (SMP) are considered as smart materials that respond to some external stimulus by changing their shape, and then revert to their original shape once the affecting stimulus is removed [6].

- Features such as high strain recovery, biocompatibility, low density, and biodegradability characterize these materials.
- SMP-based actuators function similar to our muscles.
- Modern-day SMPs have been designed to respond to a wide range of stimuli such as pH changes, heat differentials, light intensity, and frequency changes, magnetic changes, and others.
- Photopolymer/light-activated polymers (LAP) are a particular type of SMP, which require light as a stimulus to operate. LAP-based actuators are characterized by their rapid response times.
- Using only the variation of light frequency or its intensity, LAPs can be controlled remotely without any physical contact.
- The development of LAPs whose shape can be changed by the application of a specific frequency of light have been reported.
- The polymer retains its shape after removal of the activating light.
- In order to change the polymer back to its original shape, a light stimulus of a different frequency has to be applied to the polymer

Actuator Characteristics

- A control mechanism is required after sensing and processing of the information obtained from the sensed environment.
- Actuators perform the physically heavier tasks in an IoT deployment; tasks which require moving or changing the orientation of physical objects, changing the state of objects, and other such activities.
- The correct choice of actuators is necessary for the long-term sustenance and continuity of operations, as well as for increasing the lifetime of the actuators themselves.
- A set of four characteristics can define all actuators:

    1. Weight
    2. Power Rating
    3. Torque to Weight Ratio
    4. Stiffness and Compliance

Weight

- The physical weight of actuators limits its application scope.
- Example, the use of heavier actuators is generally preferred for industrial applications and applications requiring no mobility of the IoT deployment.
- In contrast, lightweight actuators typically find common usage in portable systems in vehicles, drones, and home IoT applications.
- It is to be noted that this is not always true. Heavier actuators also have selective usage in mobile systems, for example, landing gears and engine motors in aircraft.

Power Rating

- The power rating defines the minimum and maximum operating power an actuator can safely withstand without damage to itself. Generally, it is indicated as the power-to-weight ratio for actuators.
- For example, smaller servo motors used in hobby projects typically have a maximum rating of 5 VDC, 500 mA, which is suitable for an operations-driven battery-based power source.
- Exceeding this limit might be detrimental to the performance of the actuator and may cause burnout of the motor.
- In contrast to this, servo motors in larger applications have a rating of 460 VAC, 2:5 A, which requires standalone power supply systems for operations.
- It is to be noted that actuators with still higher ratings are available and vary according to application requirements.

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Torque to Weight Ratio

- The ratio of torque to the weight of the moving part of an instrument/device is referred to as its torque/weight ratio.
- This indicates the sensitivity of the actuator.
- Higher is the weight of the moving part; lower will be its torque to weight ratio for a given power.

Stiffness and Compliance

- The resistance of a material against deformation is known as its stiffness, whereas compliance of a material is the opposite of stiffness.
- Stiffness can be directly related to the modulus of elasticity of that material.
- Stiff systems are considered more accurate than compliant systems as they have a faster response to the change in load applied to it.
- For example, hydraulic systems are considered as stiff and non-compliant, whereas pneumatic systems are considered as compliant.