IoT Sensing and Actuation

Computing for Internet of Things

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Overview

Sensors, Actuators, and Transducers

- A major chunk of IoT applications involves sensing in one form or the other. Almost all the applications in IoT – be it consumer IoT, industrial IoT, or just plain hobby-based deployments of IoT solutions – sensing forms the first step.
- Incidentally, actuation forms the final step in the whole operation of IoT application deployment in a majority of scenarios.
- The basic science of sensing and actuation is based on the process of transduction.
- Transduction is the process of energy conversion of 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 any of the one among electrical, mechanical, chemical, light, sound, and others.

Transducers vs. Sensors vs. Actuators

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 a transducer.	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 sensor, Temperature sensors, Anemometers, Microphones, Accelerometers, Gas sensors, and others	Motors , Force heads, Pumps

Sensors

- Sensors are devices, which can measure, or quantify, or respond to the ambient changes in its environment or within the intended zone of their deployment.
- Sensors 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.
- A sensor is only sensitive to the measured property (e.g., a temperature sensor senses the ambient temperature of a room).
- IA sensor 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).

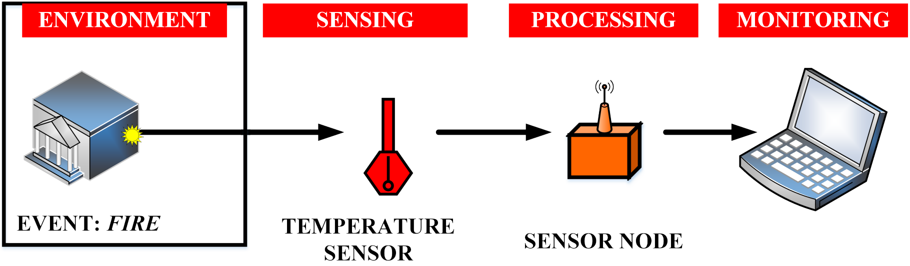


Figure: The outline of a simple sensing operation

Sensor Types

- **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:

Sensor Types based on Power Requirements

1. 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.
2. 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. For example, a thermistor's resistance can be detected by applying voltage difference across it or passing a current through it.

Sensor Types

- **Output**: The output of a sensor helps in deciding the additional components to be integrated with an IoT node or system. Typically, almost all modern-day processors are digital, to which digital sensors can be directly integrated. However, the integration of analog sensors to these digital processors or IoT nodes requires additional interfacing mechanisms such as analog to digital converters (ADC), voltage level converters, and others. Sensors are broadly divided into two types, depending on the type of output generated from these sensors, as follows:

Sensor Types based on Output

1. 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 can be used for measuring the temperature of a liquid (e.g., in household water heaters). These sensors continuously respond to changes in the temperature of the liquid.

Sensor Types based on Output

2 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 (non-continuous) values may be output as a single "bit" (serial transmission), eight of which combine to produce a single "byte" output (parallel transmission) in digital sensors.

Sensor Types

- **Measured property**: The property of the environment being measured by the sensor can be crucial in deciding the number of sensors in an IoT implementation. Some properties to be 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. Whereas some properties to be 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:

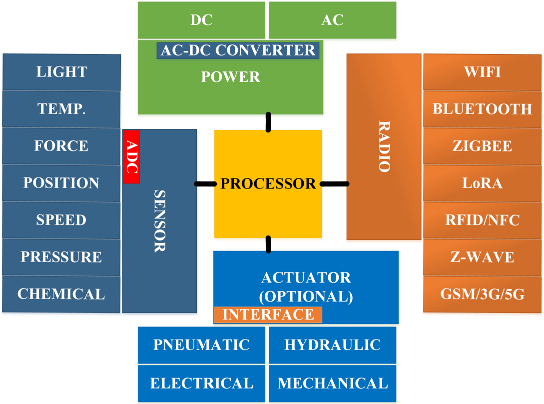
Sensor Types based on Measured Property

1 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. Examples of such measurable physical quantities include color, pressure, temperature, strain, and others. For example, a thermometer or thermocouple has the ability to detect changes in ambient or object temperatures (depending on the sensor's configuration). Factors such as changes in sensor orientation or direction do not affect these sensors (typically).

Sensor Types based on Measured Property

2 Vector: Vector sensors are affected by the magnitude as well as the direction and/or orientation of the property they are measuring. Physical quantities, which require additional information besides their magnitude for completely categorizing a physical phenomenon, are categorized as vector quantities. Measuring such quantities such as velocity, image and are undertaken using vector sensors. 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.

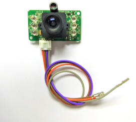
IoT Sensor Node



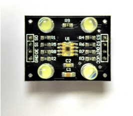
IoT Sensor Node

- A sensor node is made up of a combination of sensor/sensors, a processor unit, a radio unit, and a power unit.
- Sensor nodes are capable of sensing the environment they are set to measure and communicate the information to other sensor nodes or a remote server.
- Typically, a sensor node should have low-power requirements and be wireless. This enables them to be deployed in a vast range of scenarios and environments, without the constant need for changing their power sources or managing wires.
- The wireless nature of sensor nodes would also allow them to be freely relocatable and be deployed in large quantities without bothering about managing wires.

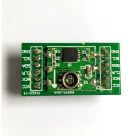
Some Sensor Types



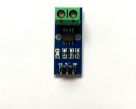
(a) Camera



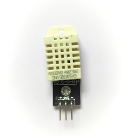
(b) Color



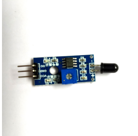
(c) Compass and Barometer



(d) Current

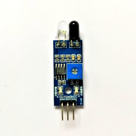


(e) Digital Temperature and Humidity

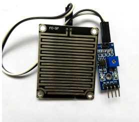


(f) Flame

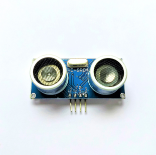
(g) Gas



(h) Infrared



(i) Rainfall



(j) Ultrasonic distance measurement

Sensor Characteristics

- All sensors can be defined by their ability to measure or capture a certain phenomenon and report them as output signals to various other systems.
- Within the same sensor type and class, the sensors themselves can be characterized by their ability to sense the phenomenon based on three fundamental properties - Resolution, Accuracy, and Precision

Sensor Characteristics: 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 is 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^oC changes in temperature, whereas another sensor **B** can detect up to 0.25^oC changes in temperature. Therefore, the resolution of sensor **B** is higher than the resolution of sensor **A**.

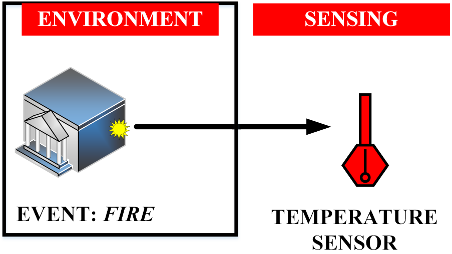
Sensor Characteristics: Sensor Accuracy

- 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 $100Kg$ mass as $99.98Kg$.
- We can say that this sensor is 99.98% accurate, with an error-rate of $\pm 0.02\%$.

Sensor Characteristics: Sensor Precision

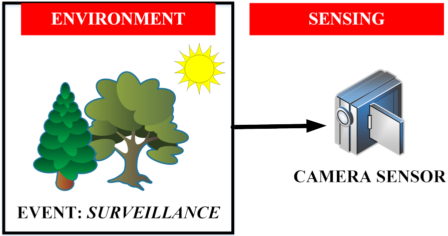
- The principle of repeatability governs the precision of a sensor. If, upon multiple repetitions, the sensor is found to have the same error-rate, then only it can be deemed as highly precise.
- Example: The weight sensor reports measurements of $98.28Kg$, $100.34Kg$, and $101.11Kg$ upon three repeat measurements for a mass of actual weight of $100Kg$.
- The sensor precision is not deemed high because of significant variations in temporal measurements for the same object under the same conditions.

Sensing Types in IoT



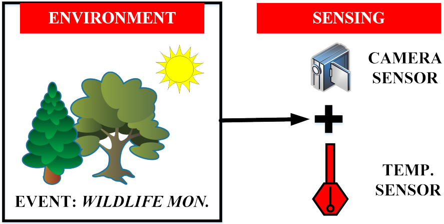
(k) Scalar sensing

Sensing Types in IoT



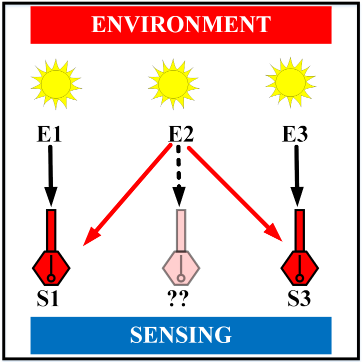
(I) Multimedia sensing

Sensing Types in IoT



(m) Hybrid sensing

Sensing Types in IoT



(n) Virtual sensing

Sensing Considerations: Sensing Range

1. The sensing range of a sensor node defines the detection fidelity of that node.
2. Typical approaches to optimize the sensing range in deployments include fixed k-coverage and dynamic k-coverage.
3. A lifelong fixed k-coverage tends to redundancy as it requires a large number of sensor nodes, the sensing range of some of which may also overlap.
4. In contrast, dynamic k-coverage 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.
5. The sensing range of a sensor may also be used to signify the upper and lower bounds of a sensor's measurement range.
6. 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.

Sensing Considerations: Accuracy and Precision

1. The accuracy and precision of measurements provided by a sensor are critical in deciding the operations of specific functional processes.
2. Typically, off-the-shelf consumer sensors are low on requirements and often very cheap. However, their performance is limited to regular application domains.
3. 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.
4. Regular temperature sensors have a very low-temperature sensing range, as well as relatively low accuracy and precision.
5. The use of these sensors in industrial applications, where the 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. However, these industrial sensors have very high accuracy and precision score, even under harsh operating conditions.

Sensing Considerations: Energy

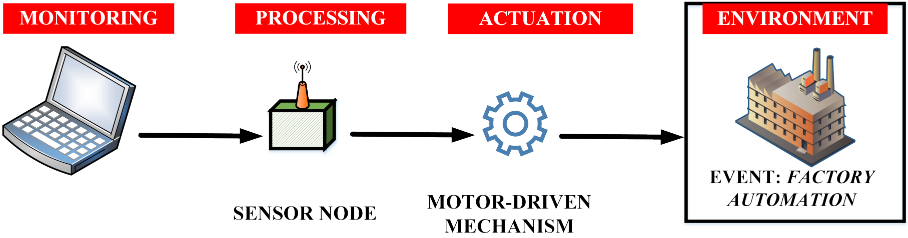
1. The energy consumed by a sensing solution is crucial to determine the lifetime of that solution and the estimated cost of its deployment.
2. In case, the sensor or the sensor node is so energy inefficient, that it requires replenishment of its energy sources quite frequently, the effort in maintaining the solution and its cost goes up, whereas its deployment feasibility goes down.
3. Consider a scenario where sensor nodes are deployed on the top of glaciers. Once deployed, access to these nodes is not possible.
4. 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.

Sensing Considerations: Device Size

1. Modern-day IoT applications have a wide penetration in all domains of life.
2. 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.
3. 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.
4. 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 feeble.
5. It is because of this, the onset of wearables took off so strongly.
6. The wearable sensors are highly energy-efficient, small in size, and almost part of the wearer's regular wardrobe.

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 control system activates the actuator through a control signal, which may be digital or analog.
- The control system elicits a response from the actuator, which is in the 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.


MONITORING
PROCESSING
ACTUATION
ENVIRONMENT
SENSOR NODE
MOTOR-DRIVEN MECHANISM
EVENT: *FACTORY AUTOMATION*

Actuator Types

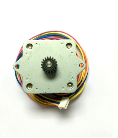
Broadly, actuators can be divided into seven classes

1. Hydraulic
2. Pneumatic
3. Electrical
4. Thermal/ Magnetic
5. Mechanical
6. Soft
7. Shape Memory Polymers.

Some Actuators

(o) Brushless DC motor

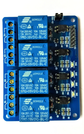
(p) Brushless DC motor



(q) Stepper motor

(r) Geared stepper motor

(s) DC motor



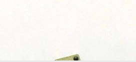
(t) Relay array

(u) Hydroelectric generator

(v) Hydroelectric generator

(w) Solenoid-based flow valve

(x) Solenoid-based flow valve



Hydraulic and Pneumatic Actuators

Hydraulic

1. These actuators use fluid pressure and to perform some mechanical activities
2. Typically, consists a cylinder or fluid motor

Pneumatic

1. The actuator, which use the compressed air for mechanical motion.
2. The mechanical motion may further control a system

Electric Actuators

1. Typically, electric motors are used to power an electric actuator by generating mechanical torque.
2. This generated torque is translated into the motion of a motor's shaft or for switching (as in relays).
3. For example, actuating equipments such as solenoid valves, control the flow of water in pipes in response to electrical signals.
4. This class of actuators is considered one of the cheapest, cleanest and speedy actuator types available.

Thermal or Magnetic Actuators

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

Mechanical Actuators

1. In mechanical actuation, the rotary motion of the actuator is converted into linear motion to execute some movement.
2. The use of gears, rails, pulleys, chains, and other devices are necessary for these actuators to operate.
3. These actuators can be easily used in conjunction with pneumatic, hydraulic, or electrical actuators.
4. They can work in a standalone mode also. The best example of a mechanical actuator is a rack and pinion mechanism.
5. For example, a hydroelectric generator convert the water-flow induced rotary motion of a turbine into electrical energy.

Soft Actuators

1. Soft actuators (e.g., polymer-based) consists of elastomeric polymers, which are used as embedded fixtures in flexible materials such as cloth, paper, fiber, particles, and others.
2. The conversion of molecular level microscopic changes into tangible macroscopic deformations is the primary working principle of this class of actuators.
3. These actuators have a high stake in modern-day robotics.
4. Use 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

1. Shape memory polymers (SMP) are considered as smart materials, which respond to some external stimulus by changing their shape, and then revert to their original shape once the affecting stimulus is removed.
2. Features such as high strain recovery, biocompatibility, low density, and biodegradability characterize these materials.
3. SMP-based actuators function similar to our muscles.
4. Modern-day SMPs have been designed, which respond to a wide range of stimuli such as pH changes, heat differentials, light intensity, and frequency changes, magnetic changes, and others.

Light Activated Polymers

1. Photopolymer/light-activated polymers (LAP) are a particular type of SMP, which require light as a stimulus to operate.
2. 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.
3. The development of LAPs have been reported, whose shape can be changed by the application of a specific frequency of light.
4. 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 them.

Actuator Characteristics

- The choice or selection of actuators is crucial in an IoT deployment, where 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, 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.

Actuator Characteristics: Weight

- The physical weight of actuators limits its application scope.
- For 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 used 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, e.g., landing gears and engine motors in aircraft.

Actuator Characteristics: Power Rating

- This helps in deciding the nature of the application with which an actuator can be associated.
- 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 5VDC, 500mA, which is suitable for operations-driven using a 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 460VAC, 2.5A, 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.

Actuator Characteristics: 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.

Actuator Characteristics: 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.

The End