Sensors are used to acquire knowledge about the environment as well as the internal state of the robot as illustrated in figure 1. Sensors are used for feedback control and external interaction with the world. They are designed to convert energy from one form to another form (the output is usually electrical energy) from which data is interpreted. Sensors have the opposite role of actuators as shown in figure 2, they are input transducers while actuators are output transducers. Animals and humans use sensors for every day activities where signals captured by the sensory system are sent to the brain where they are processed and interpreted.

**Human senses**
- Smell
- Touch
- Taste
- Hearing
- Vision

Robots may have additional sensors that humans do not have such as radioactivity sensors for example.

**A. Choice of sensors**

Different factors influence the choice of the sensor, such as:
- Cost
- Size and weight
- Type of the output

It is important to use the right sensor for the right application.

**B. Classification of sensors**

There are different ways to classify sensors.
- **Proprioceptive vs. Exteroceptive**
  - Proprioceptive sensors: measure quantities internal to the system such as the motor speed and the battery charging state.
  - Exteroceptive sensors: acquire information about the robot’s environment such as the location of the obstacles.

- **Analog vs digital sensors:**
  - The output of the sensor could be analog or digital. Analog sensors need A/D converter when connected to the microcontroller.

- **Active vs. passive:**
  - Passive sensors measure ambient environment energy entering the system. Example: microphone, camera, battery sensor.
  - Active sensors emit energy into the environment, and then measure the environment response. Example: laser range finders.
  - Usually active sensors have superior performance, they are able to create a more controlled environment.
  - Drawbacks of active sensors: signals emitted from other sources may influence the readings.

**C. Sensor characteristics**

- **Dynamic range:**
  - The dynamic range refers the spread between lower
and upper limits of the sensor measurements. Can be calculated in dB. Example: a sensor can measure current values from $1mA$ to $20mA$. The dynamic range is:

$$10\log_{10}(20/1)dB$$

(1)

- **Repeatability:**
The ability of a sensor to repeat a measurement when put back in the same environment.

- **Resolution:**
  Refers to the minimum difference between two values that can be detected. For a digital device of $n$ bits, the resolution is given by

$$\text{Resolution} = \frac{\text{full range}}{2^n}$$

(2)

**Example**

An encoder converts angular position to a digital or analog code. Find the resolution of an absolute encoder with 4 bits.

**Solution**

With 4 bits, an encoder can report angular position up to 16 levels, that is $2^4$.

$$\text{Resolution} = \frac{360}{16} = 22.5^0$$

(3)

- **Linearity:**
  If $x$ and $y$ are the inputs of the sensor, $f(x)$ and $f(y)$ are the outputs corresponding to $x$ and $y$, respectively, linearity implies that for any values of $a$ and $b$, we have:

$$f(ax + by) = af(x) + bf(y)$$

(4)

This means if you plot the input versus the output, you have a straight line.

- **Frequency:**
  Number of measurements per second

- **Sensitivity:**
  Amount in the input that will change the output, formally:

$$\frac{\text{output change}}{\text{input change}}$$

(5)

- **Error:**
  The difference between the measured and the true values

$$\text{Error} = m - v$$

(6)

where $m$ is measured and $v$ is true value

- **Accuracy:**
  The accuracy is defined in terms of the error as follows

$$\text{Accuracy} = 1 - \frac{|\text{error}|}{v}$$

(7)

When the error decreases, accuracy increases. The true value refers to the theoretical value.

- **Systematic errors:**
  Errors caused by factors that can be modeled mathematically such as poor calibration. These errors are deterministic, thus predictable.

**D. Sensors for Mobile Robots**

Robotics sensors can be grouped into different categories:

- **Inertial sensors**
  - Accelerometer
  - Gyroscope
  - Compass
  - Inclinometer: mainly measures angles of slope.

- **Visual sensors:** Camera

- **Satellite-based sensors (global):** GPS

- **Contact sensors:** Bumpers and whiskers

- **Proximity sensors and range finders:**
  - Sonar (time of flight (ToF))
- Radar (phase and frequency)
- Laser range-finders (triangulation, ToF, phase)
- Infrared (intensity)

**Position sensors**

Position sensors are used to measure displacement, rotary and linear. In many situations, the position information is used for velocity calculation.

- Encoders are electromechanical devices that convert the angular position or motion of a shaft or axle into an analog or digital quantity. A rotary encoder measures the rotation of a shaft or axle. Rotary encoders are used for example to measure the angle of a robotic arm, or how far a mobile robot have moved by measuring the rotations of its wheels.
  
  A linear encoder is similar to a rotary encoder, but measures position in a straight line, rather than rotation. There are two types of encoders: absolute and incremental.

- Potentiometers: They are used to convert position information into a variable voltage. Potentiometers can be rotary or linear. They are generally used as internal feedback sensors in order to record the position of joints and links.

**Working principle of encoders**

A typical encoder uses optical sensor(s), a moving mechanical component, and a special reflector to provide a series of electrical pulses to the microcontroller.

**Incremental Encoders**: An incremental rotary encoder provides cyclical outputs when the shaft is rotated. The arcs of clear and opaque sections are all equal and repeating. Each arc indicates an angle of revolution. The accuracy increases with the number of divisions. For example, if the wheel is divided into two potions, the resolution is $180^\circ$, if the wheel is divided into 16 positions, the resolution is $22.5^\circ$. Typical incremental encoders can have 512 to 1024 arcs in them. This type of encoder does not directly indicate the value of the actual position.

**Absolute Encoders**: There are multiple rows of arcs: The first one has only one clear and one opaque arc (one on, one off), the next row would have 4 sections, and the next one would have 8. Each row must have its own light source and light sensor. Each sensor sends out a signal, the position is obtained by combining information from all rows.

Figure 5 illustrates incremental and absolute encoders.

**Touch and tactile sensors**

Touch sensors are devices that send a signal when a physical contact has been made. A micro-switch is the simplest touch sensors. Force sensors provide more information: they scan measure how strong is the touching force. Whiskers and bumpers are simple touch sensors, where a mechanical contact leads to

- closing/opening of a switch
- change in resistance of some element
- change in capacitance of some element

Touch sensors are simple, cheap, and have binary output.

**Tactile sensors**: A tactile sensor is a collection of touch sensors. Tactile sensors provide additional information about the object such as the shape, size, and material type. In general a number of touch sensors are arranged in an array or matrix to form a tactile sensor.

**Proximity sensors**

A proximity sensor is used to determine that an object is close to another object before contact is made.

- Magnetic proximity sensors: they are active when they are close to a magnet.
- Optical proximity sensors: they use a light source (called an emitter) and a receiver, the receiver senses the presence or absence of light.
- Ultrasonic proximity: the ultrasonic emitter emits frequent bursts of high frequency sound waves (200 khz range).
Unlike proximity sensors, range finders are used to:

- Find larger distances
- Map surface of an object

Various common methods are used for range detection:

- Time of flight TOF or lapsed time.
- Triangulation
- Phase and frequency

Most proximity and ranger finders are based on sound, such as ultrasonic sensors or light such as infrared and laser.

**Triangulation and trilateration**

Triangulation and trilateration can be used to construct inexpensive but highly effective navigation systems. Three or more active transmitters mounted at known locations in the environment are used. In triangulation, the robot register the angles at which it sees the transmitters, from which the robot to determines its location. In trilateration, the robot uses distances only. Trilateration is discussed in the GPS section.

**Sniff Sensors**

Sniff sensors are similar to smoke sensors. They are sensitive to particular gases and send a signal when they detect those gases. There are many applications of sniff sensors such as explosive detection.

**SONAR SENSING**

Sonar or ultrasonic sensing uses propagation of acoustic energy where acoustic pulses and their echoes are used to measure the range to an object. Ultrasonic uses frequency higher than audible frequency (frequencies between $20Hz$ and $20KHz$). PING for example uses pulses at $40KHz$.

Ultrasonic sensors are popular in robotics. Their popularity is due to the following:

- Low cost
- Light weight
- Low power consumption
- Low computational effort

Ultrasonic sensors are used for different purposes including

- Obstacle avoidance
- Sonar mapping: perform rotational scan (360 for example) to construct a map of the environment.
- Object recognition: a sequence of sonar maps is processed using data fusion algorithms.

Ultrasonic sensors use the time of flight to determine the range:

$$r_o = \frac{v_s t_o}{2}$$  \hspace{1cm} (9)

where

- $v_s$ is the speed of sound, approximately $343$ m/s at standard temperature and pressure.
- $r_o$ is the object range
- Division by 2: round trip

**E. Problems with sonar sensors:**

- Smooth surfaces at oblique incidence do not produce detectable echoes.
- The echo from probing pulse 1 occurs after pulse 2 is emitted. Sonar measures the ToF of the most recent probing pulse and ends up with:

$$ToF = \text{echo of pulse } 1 - \text{emission time of pulse } 2.$$  \hspace{1cm} (10)

- Some materials absorb sound energy (such as foam). Fail to produce a reflection that is sufficiently strong to be sensed by the receiver.
- Environmental ultrasonic sounds from pumps and motors affect ultrasonic readings because of the noise they induce.
F. Sonar beam pattern

The beam pattern describes the direction pattern of the energy. The beam pattern is shown in figure 10 and can be approximated by a cone.

Two factors affect the sonar beam: the radius $a$ of the sensor (assuming the sensor has a circular shape) and the frequency of the waveform. Sonar emitter is usually modeled as a circular surface of radius $a$. The frequency $f$ is related to the wavelength $\lambda$ as follows:

$$\lambda = \frac{v}{f}$$  \hspace{1cm} (11)

and

$$\theta_0 = \arcsin\left(0.61\frac{\lambda}{a}\right)$$  \hspace{1cm} (12)

where $\theta_0$ is the cone angle.

G. Example

Calculate $\theta_0$ for the PING sensor: We know that $f = 40{\text{KHz}}$.
If $a = 1cm$, then $\theta_0 = 30$ approximately.

Speed of sound

The speed of sound varies with
• temperature
• pressure
• humidity

The speed of sound is given by

$$v_s = 20.05\sqrt{T_c + 273.16}\text{m/s}$$  \hspace{1cm} (13)

at sea level pressure in dry air. In general the speed of sound in air is

$$v_s = \sqrt{\gamma RT_K}$$  \hspace{1cm} (14)

where $\gamma$ is ratio of specific heat, $R$ is the gas constant and $T_K$ is the temperature in Kelvin.

Some properties

• Sonar measurements are affected by the motion of the sonar sensor or the target.
• The ultrasonic wave typically has frequency between 40 and 180 KHz and it is usually generated by a piezo or electrostatic transducer.
• Ultrasonic sensors used in robotics have typical range 2 cm to 5m. For PING for example, the range is from 2cm to 3m.

QTI Line Sensor

QTI sensor uses an infrared (IR) reflective sensor to determine the reflectivity of the surface. When the QTI sensor is over a dark surface, the reflectivity is very low; when the QTI is over a light surface, the reflectivity is very high and will cause a different reading from the sensor. The QRD1113/14 reflective sensor consists of an infrared emitting diode and an NPN silicon phototransistor mounted side by side in a black plastic housing as shown in figure 11. The on axis
radiation of the emitter and the on-axis response of the detector are both perpendicular to the face of the QRD1113/14. The phototransistor responds to radiation emitted from the diode only when a reflective object or surface is in the field of view of the detector.

**INERTIAL SENSORS**

Inertial sensors are used to determine the robot’s pose (such as position, orientation and inclination). Inertial sensors are usually proprioceptive. According to the general relativity theory, only force and angular velocity can be measured inside a isolated system. Therefore, inertial sensors provide estimate of the linear acceleration and the angular velocity. The linear velocity, orientation and position can be obtained using integration. Inertial measurements depend on the measurement carried out inside the system; therefore, they are not affected by the environment. The most popular inertial sensors are summarized below:

- **Compass**: measures the weak magnetic field of the earth.
- **Gyroscope**: an inertial sensor that is used to measure the rate of rotation independent of the coordinate frame.
- **Accelerometer**: can be used to measure all external forces acting on an object including gravity. Different mechanisms are used to translate forces into a readable signal. The most traditional mechanism is the mechanical accelerometer, which is essentially, a spring–mass–damper system. Most accelerometers do not handle jitter very well, which happens frequently in wheeled and especially in walking robots. As a result, some software corrections have to be made for signal filtering.
- **Inertial measurement unit (IMU)**: uses gyroscopes and accelerometers (and sometime magnetometers) to estimate the relative position, velocity and acceleration of a moving object widely used for ships and airplanes. First demonstrated in 1949 by CS Drapper, IMUs have become popular navigation tools widely used in ships and airplanes, and in robotics applications as well. In general IMU has three orthogonal accelerometers and three orthogonal gyroscopes. The integration process is shown in figure 12. An IMU system can estimate the 6 DOF pose ($x$, $y$, $z$) and orientation (roll, pitch and yaw) of a vehicle.

**GLOBAL POSITIONING SYSTEM:**

GPS is the most commonly used mechanism for location estimation and navigation. It provides a 3 dimensional position estimate in absolute coordinates (longitude, latitude and height co-ordinates) accurate to within a range of 20m to 1mm, as well as time and date (Universal Time Coordinates (UTC)), accurate to within a range of 60ns to 5ns. The GPS is based on 24 satellites + additional satellites. The satellites are organized into six orbital planes with four satellites in each. GPS is available anywhere on earth.

Originally, GPS was developed for military applications by the U.S. Department of Defense, but it was later open to civilian applications. The civilian signal SPS (Standard Positioning Service) can be used freely by the general public, whilst the military signal PPS (Precise Positioning Service)
can only be used by authorized government agencies. The first satellite was placed in orbit on 22nd February 1978.

- There are several global positioning systems in the world, when we talk about GPS we refer to the NAVSTAR (NAVigation System with Timing And Ranging) system in general. The other major systems are
  - GLONASS satellite system (Russia)
  - Galileo satellite system (EU)
- When people talk about “GPS”, they usually mean GPS receiver.
- There are at least 24 satellites orbiting the earth. The orbits are arranged so that at any time, anywhere on earth, at least four satellites are “visible” .
- The satellites have highly accurate atomic clocks (error is 1s in 300000 years).

GPS PSEUDO RANGE EQUATIONS

Signal transit time

How far are you from a flash of lightning? To calculate the distance you can use the signal transit time:

- Time the lightning is perceived is the start time
- Time the thunder is heard is the stop time

Distance = transit time × speed of sound \hspace{1cm} (15)

Figure 14 shows 4 satellites and a receiver (user). The coordinates of the GPS satellites are known in a global reference frame. To determine the global position, the GPS receiver uses signals from four different satellites. We have four signal transit times \( \Delta T_i \) \((i = 1, \ldots, 4)\). The range of the user from the satellite is denoted by \( R_i \), \( i = 1, \ldots, 4 \). This is the true range or the geometric range. The location of the satellites is known. The satellites clocks are synchronized, the time at which the satellites send the signal is known very precisely. However, the received clock is not synchronized, the receiver clock is slow or fast by \( \Delta T_0 \). A positive value of \( \Delta T_0 \) means the received clock is fast and a negative value means the receiver clock is slow. We do not know \( \Delta T_0 \). The pseudo range can be calculated using the following equation:

\[
PSR_i = c\Delta T_{measured,i} = c(\Delta T_i + \Delta T_0) = R_i + c\Delta T_0 \hspace{1cm} (16)
\]

where

- \( R_i \) is the range between satellite \( i \) and the receiver (user)
- \( c \) is the speed of light
- \( \Delta T_i \) is the signal transit time from the satellite to the user.
- \( \Delta T_0 \) is the difference between satellite clock and user clock. In other words the offset of the user clock.
- \( PSR_i \) is the pseudo range

We can write for each satellite:

\[
R_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} \hspace{1cm} (17)
\]

and

\[
PSR_i = R_i + c\Delta T_0 \hspace{1cm} (18)
\]

Because we have four unknown variables: \((x_u, y_u, z_u)\) and \(\Delta T_0\), we need four independent variables to solve

\[
PSR_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + c\Delta T_0 \hspace{1cm} (19)
\]

from which we can solve for the position of the user.

LASER RANGE FINDERS

Laser stands for: Light Amplification by Stimulated Emission of Radiation. Light is an electromagnetic radiation but Laser has some different and interesting properties. Because of their properties, lasers are used in a wide variety of applications. Laser corresponds to intense beams of light which is monochromatic, coherent, and highly collimated. The wavelength of laser light is extremely pure (monochromatic, single color) when compared to other sources of light. Light from a laser typically has very low divergence. It can travel over great distances or can be focused to a very small spot with a brightness which exceeds that of the sun. Different techniques can be used to measure ranges using laser such as

- Time of flight (ToF): very similar to ultrasonic sensors. For lasers, electronics capable of resolving picoseconds are required, thus the circuitry is expensive. The ToF method is typically used for large distances such as hundreds of meters or many kilometers.
- Phase shift measurement: uses an intensity-modulated laser beam with a constant frequency and measures the phase difference between transmitted and received signals as shown in figure 15. The wavelength of the modulating signal is \( \lambda \) with

\[
\lambda = \frac{c}{f} \hspace{1cm} (20)
\]

The distance to the object is given by

\[
D = \frac{\lambda \theta}{4\pi} \hspace{1cm} (21)
\]

where \( \theta \) is the measured phase difference between the transmitted and the reflected light beams. Once angle \( \theta \) is measured, distance \( D \) is obtained using equation (21).
Distance measurement by the phase-shift technique is a good method to obtain a resolution of some millimeters in 1 to 20m ranges.

Example

Assume that the modulating signal has a wavelength of \( \lambda = 60\text{m} \) \((f = 5\text{MHz})\), what is the phase measurement for a range of:

- a range of 5m?
- a range of 35m?

Solution

In both cases we have

\[
\theta = 60^\circ
\]  \hspace{1cm} (22)

There is an ambiguity interval for \( \lambda \). It is possible to decrease the ambiguity interval by increasing \( \lambda \). For example, if \( \lambda = 120\text{m} \), \( D = 5\text{m} \) will be confused with \( D = 65\text{m} \).

A. Optical triangulation

This is another method used to determine range. Triangulation can be defined as follows: if the length of one side and two interior angles of a triangle are known, then the length of the two remaining sides and the other angle can be determined. An optical triangulation device shown in figure 16 has two components:

- Collimated light source: any focused light can be used, including laser.
- Camera: position sensitive device

An illustration of the sensor is shown in figure 16, where \( B \) is the base line and \( \alpha \) is the angle between the camera optical axis and the laser beam, and \( f \) is the focal length of the camera. These variables are properties of the system and are known. We want to determine the distance \( L \) to a target surface. The light sensor (laser) projects a pattern of light onto the object and \( p' \) is the position of point \( p \) in the pixel reference frame. The only unknown variables are \( \gamma, L \). When the projection of point \( p \) in the image frame is known, we can determine angle \( \gamma \) as follows:

\[
\gamma = \arctan \frac{u}{f} \hspace{1cm} (23)
\]

Using trigonometry, we can find:

\[
L = B \tan(\alpha + \gamma) \hspace{1cm} (24)
\]

Effect of the parameters

- Base line: Large value of \( B \) results in better resolution, but for small values of \( B \), the sensors is more compact.
- Focal length: Long focal length results in better accuracy but smaller field of view.