JC3504 Robot Technology

Lecture 6: Sensing and Actuation

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Outline

Actuators

- Electric motors
- Hydraulic and pneumatic actuators

Sensors

- Measuring robot joint configuration
- Measuring ego-motion
- Measuring force
- Measuring distance

Actuators

Devices that allow to turn energy into rotation and translation. We generally call such devices actuators.

Electric Motors

Due to the dominance of rolling robots, the electric motor is among the most popular actuators.

The physics of the electrical motor (except for the stepper motor) requires it to revolve at very high speeds (multiple thousand rotations per minute). Therefore, electric motors are almost always used in conjunction with so-called reduction gears tasked with reducing their rotational speed and increasing their torque, i.e. the rotational force that the motor exerts to rotate about its axis.

AC Motors

In an AC motor, an electromagnetic coil is usually paired with a permanent magnet.

In order for this simple motor to not get stuck in its new configuration, we will need to swap the direction of the rotor’s magnetic field. This happens by itself when using so-called alternating current, or AC. AC is commonly used in the power-grid, where the direction of current changes with a frequency of 50 or 60 Hz.

The speed of an AC motor is constant depending on the frequency of the AC, whereas its maximum torque is given by its current.

AC Motors

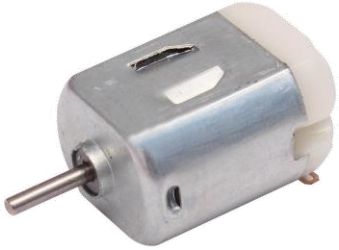
<Video: 06 - Induction Motor animation - The Rotating Magnetic Field RMF.mp4>

DC Motors

DC motor generates the desired switch in directionality by a so-called commutator . This allows running the motor with what is known as direct current, or DC, in which the direction of current does not change.

DC a motor can turn at arbitrary speeds and will become faster and faster, only limited by friction and torque applied to its shaft. Its speed depends on the voltage that is applied, whereas its torque is limited by the maximum current that is provided.

DC motors are widely used in robotics, but suffer from low efficiency due to the friction of the brushes and their wear-and-tear.



DC Motors

<Video: 06 - Standard Brushed DC Motor.mp4>

Stepper Motor

Driving Methods: Stepper motors are driven by digital pulses supplied by a controller, with the rotation direction, speed, and position controlled by the pulse sequence and duration.

For example, a stepper motor that turns 3.6 degrees per step will require 100 pulses for a complete revolution.

Brushless DC Motor

As the alternating current patterns are generated by electronics, the stepper motor does not require brushes to communicate.

Brushless motors require complex controllers. Because the current commutation time depends on the position of the rotor, brushless DC motors use small changes in current that result from the dynamo effect in the currently unused coils, to measure the current position of the rotor within the stator.

Due to the absence of friction, brushless DC motors are far more efficient than their brushed counterparts and can provide equivalent speed and torque at a smaller form factor and lower weight.

Servo Motor

Servo Motor is a motor specially designed for precise control of angle, position, speed and acceleration.

Servo systems usually include servo motors, drives or controllers, and feedback devices.

The actual output of the motor is monitored through feedback devices (such as encoders) and compared with expected commands to achieve high-precision control.

Servo motors can be either alternating current (AC) or direct current (DC) types. The main difference lies in the power supply method and control strategy.

Hydraulic and Pneumatic Actuators

Another popular class of actuators, in particular for legged robots, are linear actuators, that might exist in electric, pneumatic, or hydraulic form.

Hydraulic Actuators

Hydraulic actuators, mostly in the form of pistons, are well-known from construction machines and other heavy equipment.

The smallest available hydraulic actuators are orders of magnitude larger (in the order of tens of centimetres) than the smallest DC motors (in the order of millimetres).

However, they are relevant for larger bipedal and quadrupedal platforms, where they are often used in conjunction with electric motors.

Pneumatic Actuator and Soft Robotics

Pneumatic systems are lightweight and available in much smaller form factors than hydraulic systems. For example, solenoid valves can be as small as a few millimetres, allowing to construct intricate mechanisms such as realistically-sized robotic fish or robotic hands.

Pneumatic actuators can be designed in arbitrary form factors, allowing the designer to turn air pressure into almost any desired bending or torsional movement.

From a kinematic perspective, an ideal, fully soft robot can be modelled as a platform with an infinite number of mechanical degrees of freedom!

As air is orders of magnitudes more compressible than a liquid, pneumatic systems are not well suited to translate large forces.

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Pneumatic Actuator and Soft Robotics

<Video: 06 - Rochu Soft Gripper Applications 60s.mp4>

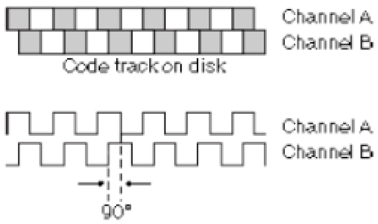
Sensors

Robotic sensors provide the necessary data for a robot to make decisions and control itself.

Measuring Robot Joint Configuration

The most common encoder in robotics is the quadrature encoder, which is an optical encoder. It relies on a pattern rotating with the motor and an optical sensor that can register black/white transitions.

A single sensor would be sufficient to detect rotational position and speed, but it does not allow to determine the direction of motion. Quadrature encoders therefore have two sensors, A and B, that register an interleaving pattern with a distance of a quarter phase. If A leads B, the disk is rotating in a clockwise direction. If B leads A, then the disk is rotating in a counter-clockwise direction.



Measuring Robot Joint Configuration

Modern robots typically use brushless motors or stepper motors. Since the commutation of the motor is controlled by the program each time, the controller is very clear about the motor's speed, direction, and displacement. So, no sensor is required.

For fields that require high repeatability precision, a common method is to use an inductive sensor placed near a metallic target, such as a gear with teeth passing by the sensor face.

Alternatively, people take high-speed photographs of the moving parts and compare each two consecutive pictures, (which is also the principle behind laser mice).

Measuring Egocentric Motion

Measuring ego-motion allows the robot to detect whether it is currently moving or even accelerating (such as falling), which is particularly important for robots that are only dynamically stable such as walking humanoids or quadrotors.

Motion can be estimated by relying on the principle of inertia. A moving mass does not lose its kinetic energy -- if there is no friction. Likewise, a resting mass will resist acceleration. Both effects are due to inertia and can be exploited to measure acceleration and speed.

Accelerometers

An accelerometer can be thought of as a mass on a dampened spring. Considering a vertical spring with a mass attached to it, we can measure the acting force $F = kx$ (Hooke's law) by measuring the displacement x that the mass has exerted on the spring.

In practice, these spring/mass systems are realized using microelectromechanical devices (MEMS). Accelerometer chips can be very small.

As gravity provides a constant acceleration vector, accelerometers are very good at estimating the pose of an object with respect to gravity (i.e. roll and pitch).

Gyroscopes

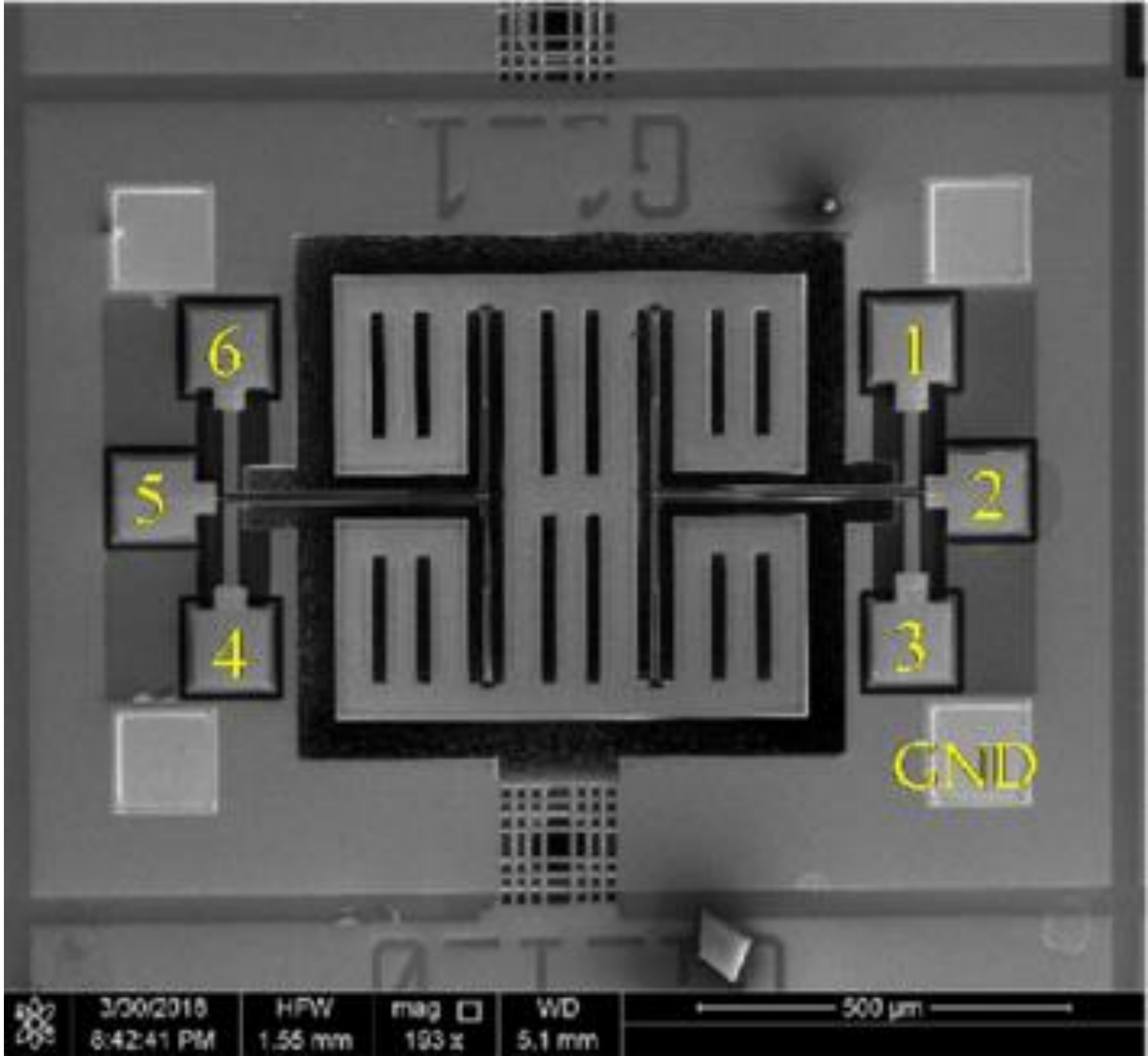
A gyroscope is an electro-mechanical device that can measure rotational speed, and in some configuration's orientation. It is complementary to the accelerometer that measures translational acceleration.

MEMS (Micro-Electro-Mechanical Systems) rate gyros are widely available and use different technology, as they rely on a mass suspended by springs. The mass is actively vibrating, making it subject to Coriolis forces when the sensor is rotated. Coriolis forces can be best understood by moving orthogonally to the direction of rotation on a vinyl disk player. In order to move in a straight line, you will not only need to move forwards, but also sideways. The necessary acceleration to change the speed of this sideways motion is counteracting the Coriolis force, which is both proportional to the lateral speed (the vibration of the mass in a MEMS sensor) and the rotational velocity, which the device wishes to measure.

MEMS Accelerometer & Gyroscope

<Video: 06 - How MEMS Accelerometer Gyroscope Magnetometer Work.mp4 >

MEMS Gyroscopes



Measuring Force

A six-axis force/torque sensor, also known as a 6-DOF (degrees of freedom) sensor captures the full range of motion and applied forces/torques in three-dimensional space.

It can measure

- forces in the X, Y, and Z directions (linear forces)
- torques around the X, Y, and Z axes (rotational forces)

These sensors are crucial in applications requiring precise control and measurement of force and torque, such as robotics, automation, and testing environments.

A six-axis force/torque sensor

Six-axis Force/Torque Sensor

<Video: 06 - Epson Force Sensor.mp4>

Measuring Distance

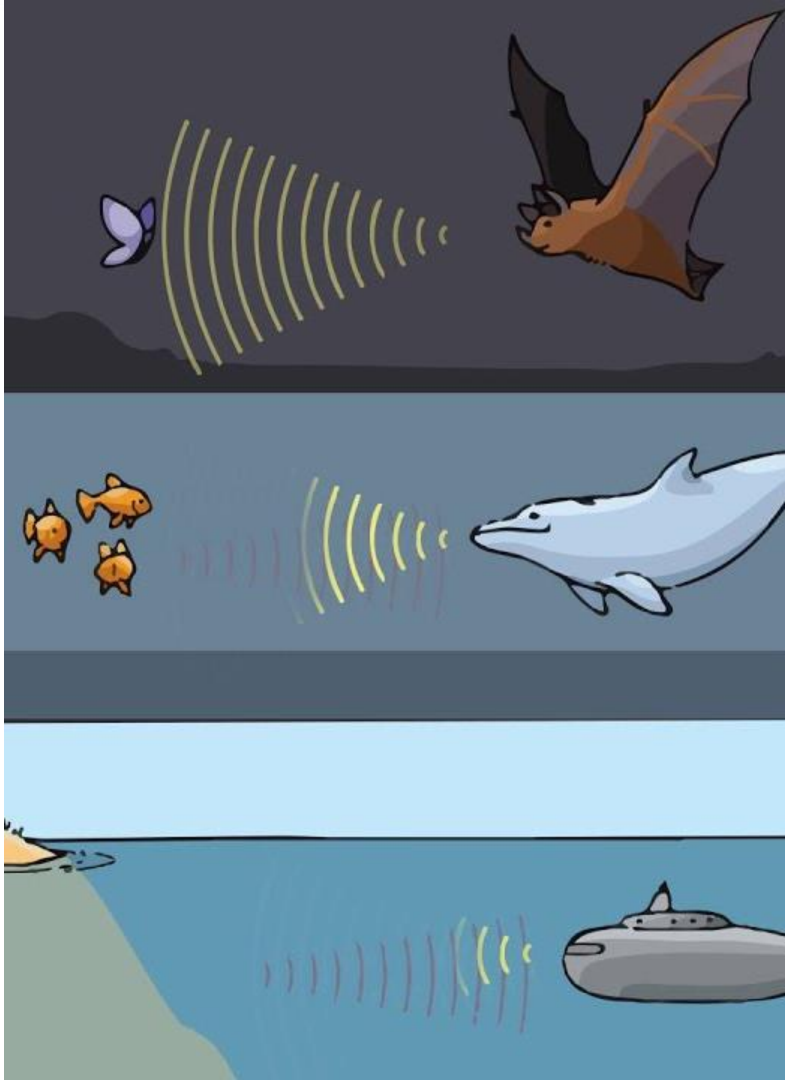
Robot distance sensors are devices used to measure the distance between a robot and surrounding objects. They play a crucial role in applications such as robot navigation, obstacle avoidance, positioning, and environmental perception. Based on their working principles and application requirements, distance sensors can be categorized into several types, including:

- Ultrasonic Sensors
- Infrared Sensors
- Laser Sensors (LIDAR)

Ultrasonic Sensors

These measure distance by emitting ultrasonic pulses and receiving the reflected waves.

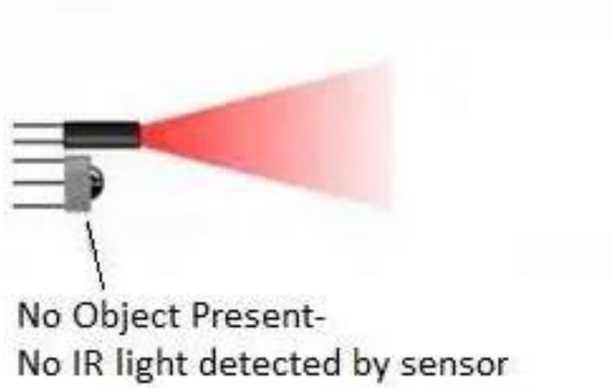
The principle is based on the time difference between the emission and reception of the ultrasonic pulses, calculating the distance using the speed of sound. Ultrasonic sensors work well in air and are commonly used for indoor robot obstacle avoidance and distance measurement.

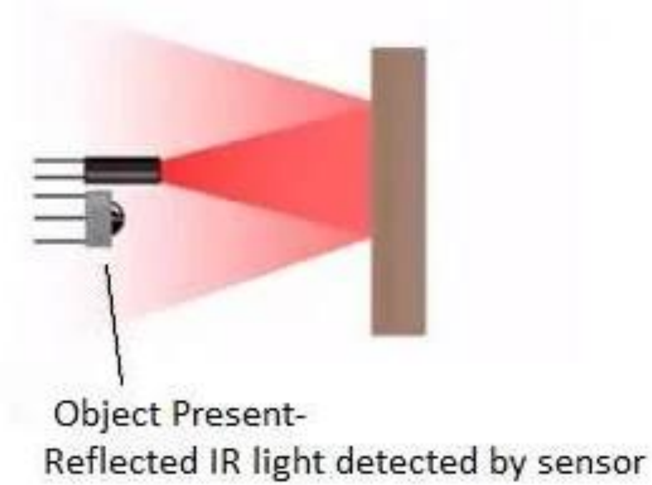


Infrared Sensors (Infrared ranging)

These measure distance by emitting infrared light and detecting the **intensity** of the reflected light.

The closer an object is to the sensor, the greater the intensity of the reflected infrared light. Infrared sensors are suitable for short-range measurements and are commonly seen in robot obstacle detection and object recognition.





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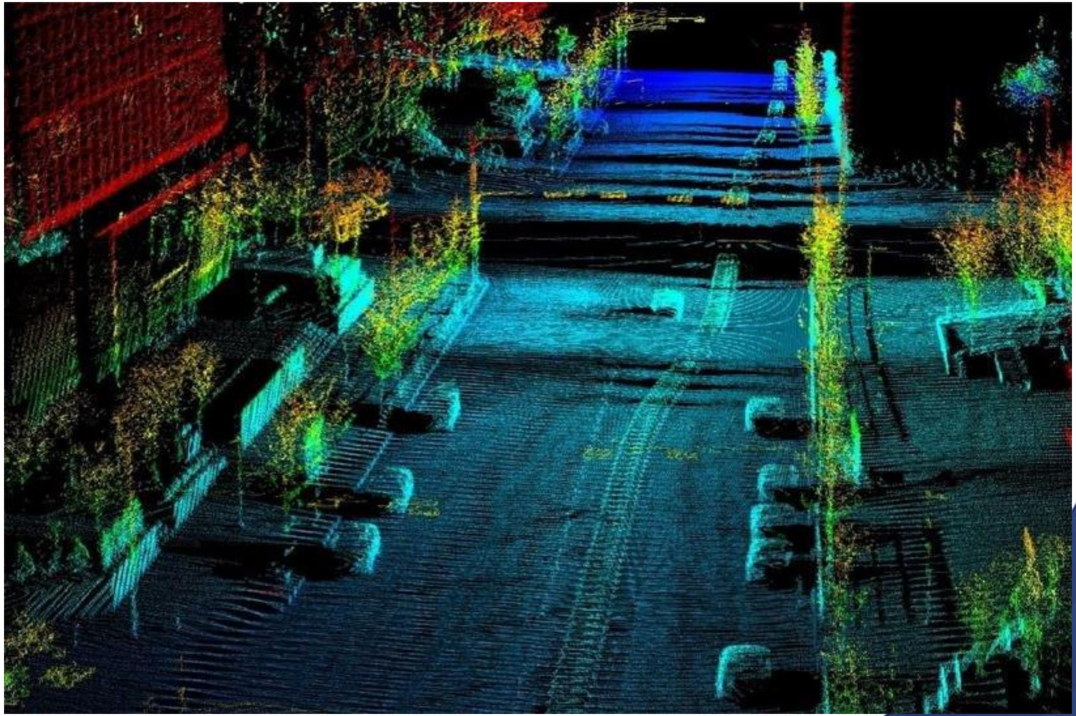
Laser Sensors (LIDAR)

LIDAR scans the environment with laser beams and measures distance based on the time or phase shift of the reflected laser light. LIDAR provides high-precision distance measurements and high-resolution environmental maps, making it ideal for autonomous vehicles, advanced robot navigation, and terrain mapping.



Sensors to Sense Global Pose

In order to reliably navigate in the environment, robots also need some notion of a world coordinate frame.

The most sophisticated of such systems is the Global Positioning System (GPS). GPS consists of a number of satellites in orbit that are equipped with knowledge about their precise location and have synchronized clocks. These satellites broadcast a radio signal that travels at the speed of light and is coded with its time of emission. GPS receivers can therefore calculate the distance to each satellite by comparing time of emission and time of arrival.

GPS measurements are neither precise nor accurate enough for robotics applications, and require to be combined with other sensors, such as IMUs.

Conclusion

- There exists an almost limitless repertoire of techniques to turn energy into motion, many of which have been explored to create robots, with the electric motor remaining the dominant actuator in small-scale robotic systems.
- What makes a good actuator is not only determined by its efficiency to the available energy source, but also by how far its position, velocity, and torque can be measured to enable accurate and precise control.
- Most of a robot's sensors either address the problem of determining the robot's pose or localizing and recognizing objects in its vicinity.
- Each sensor has advantages and drawbacks that are quantified in its range, precision, accuracy, and bandwidth. Therefore, robust solutions to a problem can only be achieved by combining multiple sensors with differing operation principles.