SENSORS

M.Sc. Mihaela Popescu
Robotics Innovation Center
DFKI Bremen

Prof. Dr. Dr. h.c. Frank Kirchner
Arbeitsgruppe Robotik, Universität Bremen
`https://robotik.dfki-bremen.de/`
`robotik@dfki.de`

2nd November, 2022 – Bremen, Deutschland

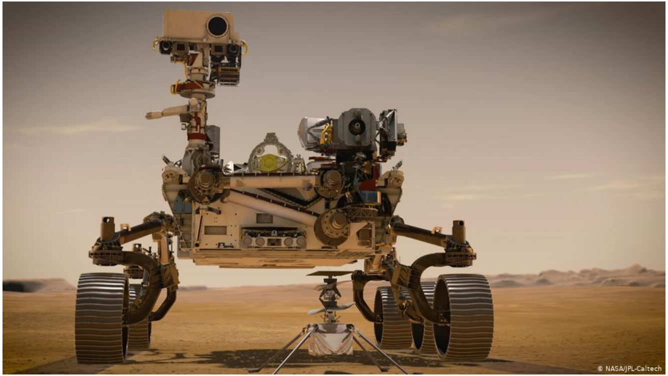
Introduction to Robot Design Lab

Contents

1. Robot Scenario
2. Introduction to Sensors
3. Robot vs. Human Sensing
4. Sensor Types
5. Challenges
6. Conclusion

Robot Scenario

Robot Scenario: How far can robots reach?



© NASA/JPL-Caltech

NASA's Perseverance rover has landed on Mars on Feb. 18, 2021 to seek signs of ancient life.

Robot Scenario

Robots for Space Exploration

Think from a NASA engineer's perspective:

1. How would you design the sensor suit of Perseverance?
2. What would you consider for ensuring long term autonomy?

Introduction to Sensors

Introduction to Sensors

What are sensors?

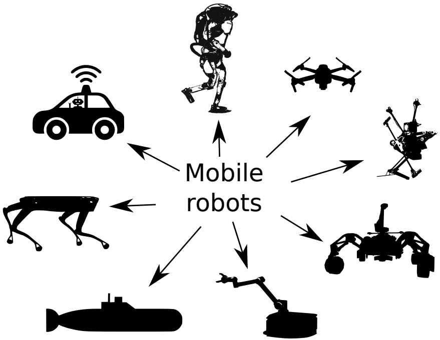
Sensors are physical devices that provide information about the world.

Measuring devices that humans use.

Introduction to Sensors

Perception in Mobile Robots

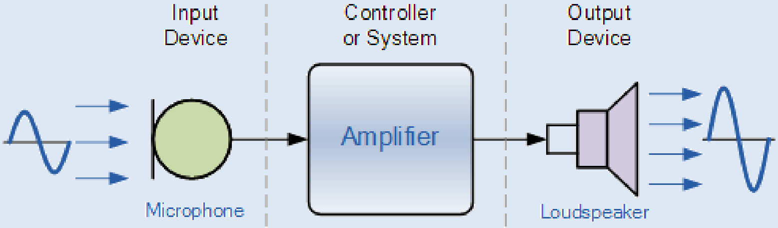
- Autonomous mobile robots rely on sensors to perceive their internal and external environment.



Introduction to Sensors

Link between Sensors and Actuators

- **Sensors**: sense the environment and convert its state into electrical signals.
- **Actuators**: convert electrical signals into actions as requested by the controller.



Source: `https://www.electronics-tutorials.ws/io/io_1.html`

Introduction to Sensors

Role of Perception

- Perceiving the environmental state accurately is crucial for robot **long-term autonomy** and successful **achievement of goals** (e.g. to navigate without hitting obstacles, to avoid internal damage due to overuse).

Role of Perception

- Perceiving the environmental state accurately is crucial for robot **long-term autonomy** and successful **achievement of goals** (e.g. to navigate without hitting obstacles, to avoid internal damage due to overuse).
- Why is this hard?
  - Dynamic environment.
  - Only partial information about the world is available.
  - Sensors have limited range and provide noisy measurements.
  - Large quantity of information to be perceived and processed.

Introduction to Sensors

Role of Perception

- Perceiving the environmental state accurately is crucial for robot **long-term autonomy** and successful **achievement of goals** (e.g. to navigate without hitting obstacles, to avoid internal damage due to overuse).
- Why is this hard?
    - Dynamic environment.
    - Only partial information about the world is available.
    - Sensors have limited range and provide noisy measurements.
    - Large quantity of information to be perceived and processed.
- Sensors do not provide **state** directly (e.g. robot position) → raw measurements need to be processed first.

Introduction to Sensors

Perception Design

- Generally it is not a good idea to separate:
    - What the robot senses.
    - How it senses it.
    - How it processes it.
    - How it uses it.

Introduction to Sensors

Perception Design

- Generally it is not a good idea to separate:
    - What the robot senses.
    - How it senses it.
    - How it processes it.
    - How it uses it.
- Think of it as a single complete design:
    - The **task** the robot has to perform.
    - The best suited **sensors** for the task.
    - The best suited **mechanical design** that would allow the robot to get the necessary sensory information for the task (e.g. body shape, sensors placement).

Introduction to Sensors

Use of Sensors Data

1. What was the world like when the sensory reading was taken?
    - Deals with **representation and reconstruction** of the world.
2. Given a sensory reading, what should the robot do?
    - Deals with **actions** in the world.

Introduction to Sensors

Levels of Sensor Data Processing

There are 3 different levels at which sensor data can be processed.
Let's have a look at the examples below:

- Find out if a switch is opened or closed.
  - Measure voltage going through the circuit. → **electronics**
- Use a Doppler Velocity Log to compute water flow.
  - Separate signal from noise, measure frequency. → **signal processing**
- Use a camera.
  - Recognize objects in the image. → **data interpretation**

Introduction to Sensors

Levels of Sensor Data Processing

- Combination of all levels: use a microphone to recognize voice.
  - Acquire signal. → **electronics**
  - Separate signal from noise. → **signal processing**
  - Apply AI-algorithm to recognize voice. → **data interpretation**

Using A Priori Knowledge of the World

Perceptual processing can benefit if prior knowledge about the world is available.

1. Expectation-based perception *(what to look for)*.
    - Prior knowledge of the world constrains the interpretation of sensor data.

Using A Priori Knowledge of the World

Perceptual processing can benefit if prior knowledge about the world is available.

1. Expectation-based perception *(what to look for)*.
    - Prior knowledge of the world constrains the interpretation of sensor data.
2. Focus of attention methods *(where to look for it)*.
    - Prior knowledge can constrain where things may appear.

Introduction to Sensors

Using A Priori Knowledge of the World

Perceptual processing can benefit if prior knowledge about the world is available.

1. Expectation-based perception *(what to look for)*.
    - Prior knowledge of the world constrains the interpretation of sensor data.
2. Focus of attention methods *(where to look for it)*.
    - Prior knowledge can constrain where things may appear.
3. Perceptual classes *(how to look for it)*.
    - Prior knowledge constrains which types of sensing modalities are needed.

Robot vs. Human Sensing

Robot vs. Human Sensing

Neuroscientific Evidence

- Humans process information from multiple sensory modalities (vision, touch, hearing, smell, taste) using separate regions in the brain.
- Vision itself uses multiple brain regions:
  - Two main vision streams:
    - “what” (object recognition).
    - “where” (position information).
  - Pattern, color, movement, intensity, orientation.

Robot vs. Human Sensing

What can we learn from biology?

- Evolved sensors have specific geometric and mechanical properties.
- Biology uses clever designs to maximize the sensor's perceptual properties, range and accuracy.
- Examples in nature:
  - Flies → complex facetted eyes.
  - Birds → polarized light sensors.
  - Bugs → horizon line sensors.
  - Humans → complicated auditory systems.

Robot vs. Human Sensing

Physical Property	**Sensor**	**Human organ**
contact	switch	skin
sound	microphone	ears
light	photocell, camera	eyes
smell (taste)	chemical	nose
temperature	thermal, infrared	skin
distance	laser scanner, ultrasonic, infrared	eyes, ears

Remark: The sensors in blue are available on the Turtebot 3 robot.

Robot vs. Human Sensing

Physical Property	**Sensor**	**Human organ**
rotation	encoders, potentiometers	ears, eyes (balance)
altitude	altimeter	eyes (imprecise)
pressure	pressure gauges	ears (imprecise)
acceleration	accelerometers	eyes, ears, (stomach)
inclination	inclinometers, gyroscopes	eyes, ears
magnetism	compass, hall sensor	-

Remark: The sensors in blue are available on the Turtebot 3 robot.

Sensor Types

Sensor Types

1. Interaction with the environment:
    - **Active** sensors - generate stimuli to perceive the environment.
    - **Passive** sensors - react to stimuli from the environment.

Sensor Types

1. Interaction with the environment:
    - **Active** sensors - generate stimuli to perceive the environment.
    - **Passive** sensors - react to stimuli from the environment.
2. Measurement representation:
    - **Digital** sensors - return discrete output (e.g. binary 0 and 1).
    - **Analogue** sensors - return a continuous output signal.

Sensor Types

3. Measured system:

- **Interoceptive** sensors - measure internal robot data (e.g. motor voltage and current, battery state, temperature).
- **Proprioceptive** sensors - measure robot state in the environment (e.g. linear and angular position, velocity and acceleration, forces and torques).
- **Exteroceptive** sensors - measure the environment directly (e.g. proximity sensors, camera, pressure).

Sensor Types

Sensor Characteristics

- **Range**: the maximum and minimum values that can be measured by the sensor.
- **Sampling Rate**: the average number of samples measured in one second (sampling frequency).
- **Resolution**: the smallest change that can be detected.
- **Accuracy**: the maximum difference between the true value and the measured value.
- **Quantization Error**: the difference between the analog signal and the closest available digital value.

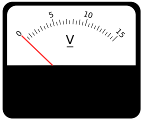
Interoceptive Sensors

Interoceptive Sensors

quantities that describe the internal robot state
(monitor hardware well-functioning)

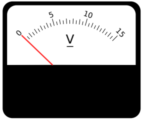
Interoceptive Sensors

- Battery voltage.

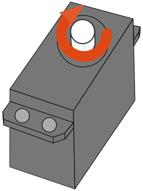


Interoceptive Sensors

- Battery voltage.

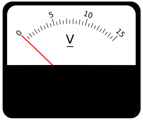


- Motor rotation.

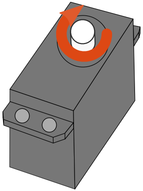


Interoceptive Sensors

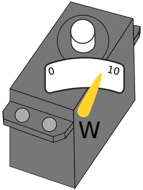
- Battery voltage.



- Motor rotation.

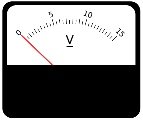


- Power consumption.

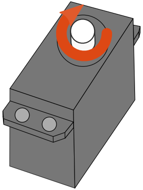


Interoceptive Sensors

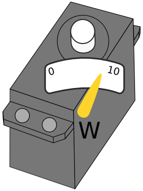
- Battery voltage.



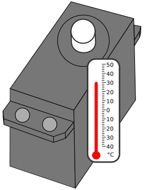
- Motor rotation.



- Power consumption.



- Temperature of motors and electronics.



Proprioceptive Sensors

Proprioceptive Sensors

stimuli within the body that describe the robot state in the environment [1]
(latin for “one’s own” or “individual”)

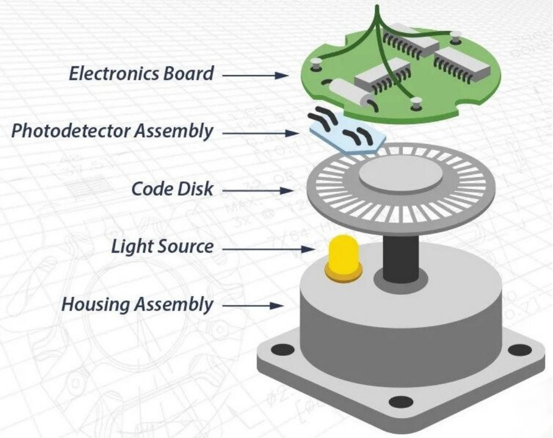
---

[1] According to the American Heritage Science Dictionary, proprioception is
“The unconscious perception of movement and spatial orientation arising from stimuli within the body.”

Proprioceptive Sensors: Wheel Encoder

Optical Rotary Encoder

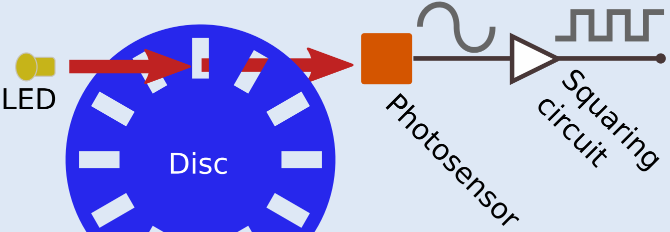
- The optical rotary encoder converts the angular position of the motor shaft to a digital code.
- Application: motor speed control.
- Remark: every wheel of the robot is actuated by a separate motor.



Source: `https://www.encoder.com/article-what-is-an-optical-encoder`

Proprioceptive Sensors: Wheel Encoder

Optical Rotary Encoder



Proprioceptive Sensors: Wheel Encoder

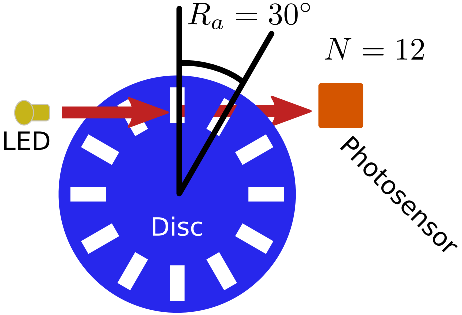
How can we compute the robot wheel displacement?

Distance Computation

- If we know the number of ticks N of the optical encoder disc, the radius r and the circumference $c = 2\pi r$ of the robot wheel, then we can compute:

$$R_a = \frac{2\pi}{N} \rightarrow \text{angular resolution}$$

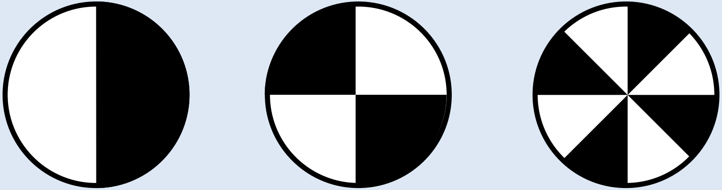
$$R_d = \frac{c}{N} \rightarrow \text{on-ground distance resolution}$$



Proprioceptive Sensors: Wheel Encoder

Color-Based Incremental Encoders

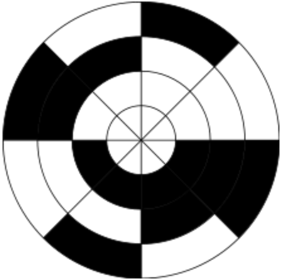
- Use a reflectance sensor to count the rotations.
- Black wedges absorb light, white reflect it and only reflections are counted.
- → Can be difficult due to wheel and gear slippage and backlash in gear trains.



Proprioceptive Sensors: Wheel Encoder

Color-Based Absolute Encoders

- Provides absolute angular position with 3-bit binary resolution (2^3 distinct positions).
- Black is '1' and white is '0'.
- Zero degrees is on the right-hand side, with angle increasing counterclockwise.

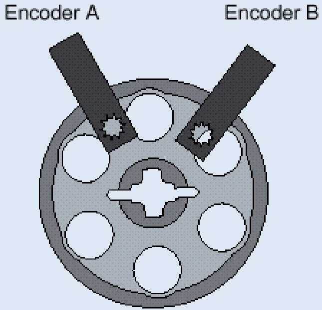


Standard binary encoding.
`http://www.drchrisbarnes.co.uk/A2.html`

Proprioceptive Sensors: Wheel Encoder

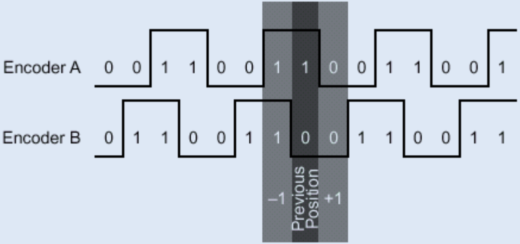
In which direction is the shaft moving?

- How to measure the direction of rotation:
  - Use two encoders (A and B) instead of one.
  - Align sensors to be 90 degrees out of phase.
  - Compare the outputs of both sensors at each time step with the previous time step.
  - Only one sensor changes state *(on/off)* at each time step, based on the direction of the shaft rotation → determines the direction of rotation.
  - Increment counter for the encoder that was *on*.



Proprioceptive Sensors: Wheel Encoder

Quadrature Shaft Encoding



Current State

Previous State	00	01	10	11
00	0	+1	–1	×
01	–1	0	×	+1
10	+1	×	0	–1
11	×	–1	+1	0

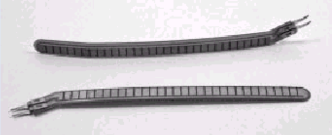
0 = no change
–1 = decrement count
+1 = increment count
× = illegal transition

“01” = encoder A is 0, encoder B is 1

Proprioceptive Sensors: Resistive Position Sensor

Resistive Position Sensors

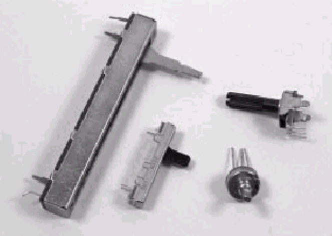
- Useful for **contact sensing** and **wall-tracking**.
- Electrically, the bend sensor is a simple resistance.
- The resistance of a material increases as it is bent.
- The bend sensor is less robust than a light sensor and requires strong protection at its base, near the electrical contacts.
- Unless the sensor is well-protected from direct forces, it will fail over time.



Proprioceptive Sensors: Potentiometer

Potentiometers

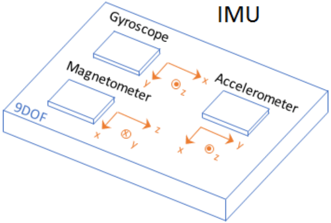
- Manually-controlled **variable resistor**, commonly used as volume/tone control.
- Designed as a movable tab along two ends.
- The resistance of the sensor can be adjusted by tuning the knob.
- Application: it can be mounted on the rotating shaft of a moving part of the robot to provide **angular position** measurement.



Proprioceptive Sensors: Inertial Measurement Unit

Inertial Measurement Unit (IMU)

- Measures robot velocity and acceleration.
- Components:
  - Gyroscope (3-axis angular velocities).
  - Accelerometer (3-axis linear accelerations).
  - Magnetometer (3-axis magnetic field).
- Used for robot localization.
- Integrated on the OpenCR board of the Turtlebot 3 robot.



IMU Components.

Exteroceptive Sensors

Exteroceptive Sensors

stimuli that come from outside the body
(environment representation)

Exteroceptive Sensors

Physical quantity	**Human**	**Robot**	**Range**
contact	skin	switch	proximity
sound	ears	microphone	near
distance	eyes, ears	laser scanner	mid-range
light	eyes	camera	far

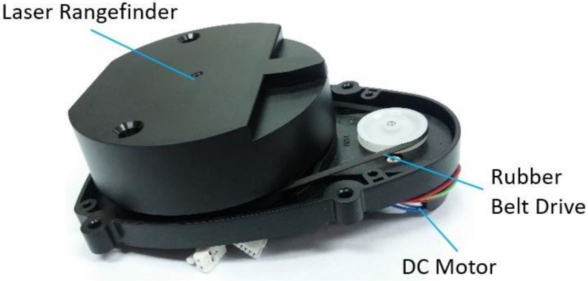
Note

This is not very strictly defined and depends on the scenario and the environment.

Exteroceptive Sensors: Laser Scanner

Laser Scanner

- Active sensor used to measure distances to obstacles.
- Also known as LiDAR: **L**i**ght** **D**etection **A**nd **R**anging sensor.



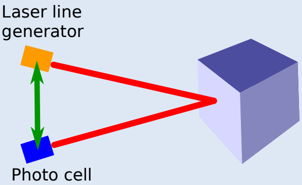
Laser Scanner LDS-01 mounted on Turtlebot 3.

Exteroceptive Sensors: Laser Scanner

1. Time-of-Flight (TOF) Method

- Send out one laser beam.
- Reflected beam gets detected by optical sensor.
- Calculate the distance d knowing the time of flight t_f of the beam and the speed of light c:

$$t_f = \frac{2 * d}{c}$$



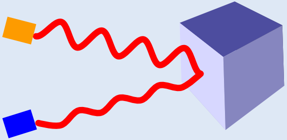
- Wide range but relatively slow (0.05 MHz).

Exteroceptive Sensors: Laser Scanner

2. Phase-Shift (PS) Method

- Send out a constant beam of light with a fixed phase.
- Measure the phase of the returning laser beam.
- Calculate the distance d based on the signal phase shift $\Delta\phi$ and the modulation frequency F_0:

$$\Delta\phi = 2\pi * t_f * F_0, \text{where } t_f = \frac{2 * {\color{red}d}}{c}.$$

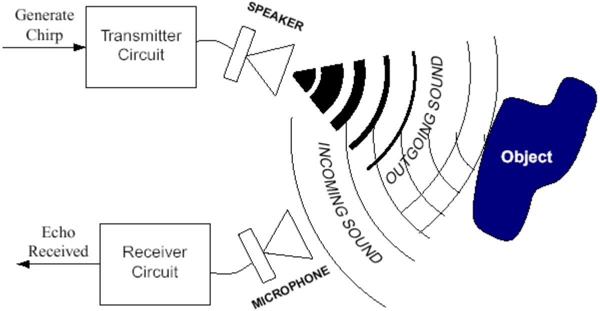


- Only up to $\sim$ 80 meters and less accurate but very fast (up to 1 MHz).

Exteroceptive Sensors: Sonar

Ultrasonic Distance Sensing

- **Sonar**: **so**und **na**vigation and **r**anging sensor.
- Based on the time-of-flight principle.



Exteroceptive Sensors: Sonar

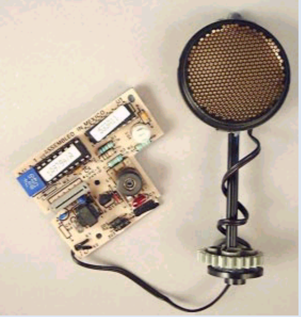
Sonar Time-of-Flight Principle

- The emitter sends a “chirp” of sound.
- If the sound encounters a barrier, it reflects back to the sensor.
- The reflection is detected by a receiver circuit, which is tuned to the frequency of the emitter.
- Distance to objects can be computed by measuring the elapsed time between the chirp and the echo.
- Sound travels at about 343 m/s.

Exteroceptive Sensors: Sonar

Sonar Sensor

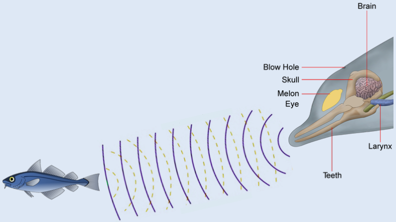
- The emitter is a membrane that transforms mechanical energy into a “ping” (inaudible sound wave).
- The receiver is a microphone tuned to the frequency of the emitted sound.
- Applications:
    - in underwater robotics.
    - in cameras to measure the distance from the camera to the subject for auto-focus system (polaroid ultrasonic sensor).



Exteroceptive Sensors: Sonar

Echolocation

- **Echolocation**: finding location using sonar.
- Some animals use echolocation:
  - Bats: finding prey, avoid obstacles, find mates, communication with other bats.
  - Dolphins/Whales: find small fish, swim through mazes.
- Natural sensors are much more complex than artificial ones.



Toothed Whale Echolocation.
Source:
`https://commons.wikimedia.org/wiki/File:Toothed_Whale_Echolocation.png`

Exteroceptive Sensors: Sonar

Specular Reflection

- Sound does not reflect directly and come right back.
- Factors to be considered:
    - **Specular Reflection:** the sound wave bounces off multiple sources before returning to the detector.
    - **Smoothness:** the smoother the surface the more likely is that the sound would bounce off.
    - **Angle of Incidence:** the smaller the incident angle of the sound wave the higher the probability that the sound will bounce off.

Exteroceptive Sensors: Infrared (IR) Sensor

Infrared (IR) Sensor

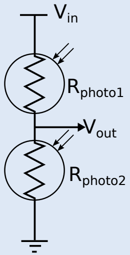
- The infrared (IR) sensor measures infrared radiation in the environment.
- IR radiation has higher wavelength than visible light hence it is invisible to the human eye.
- Heat is a source of infrared radiation.
- There are two types of infrared sensors:
    - Active: emit and detect infrared radiation **(proximity sensor)**.
    - Passive: detect infrared radiation **(motion detection)**.

Pseudocolor image taken in long wavelength infrared light *(body temperature)* .

Exteroceptive Sensors: Photocell

Photocells

- Photocells/photoresistors are used for light detection.
- Light-dependent resistor that changes its resistive value (in ohms Ω) depending on the light on the surface.
- Photocells can measure:
  - Light intensity: how bright/dark it is.
  - Differential intensity: difference between photocells.
  - Break-beams: changes in intensity.



Differential Photocell Sensor

Exteroceptive Sensors: Photocell

Comparison: Photocell vs. Phototransistor

Photocells

- Easy to work with, electrically they are just resistors.
- Slow response time.
- Suitable for low frequency applications (e.g., detecting when an object is between two fingers of a robot gripper).

Reflective Optosensors (photodiode or phototransistor)

- Rapid response time.
- More sensitive to small levels of light, which allows the illumination source to be a simple LED element.

Exteroceptive Sensors: Camera

Camera

- Camera models biological eyes → human vision.
- Provides detailed information about the environment.
- Examples of applications in robotics:
  - object detection:
    - obstacles.
    - objects to manipulate.
    - goal or destination.
    - human and face recognition.
  - mapping and localization.
  - navigation.

Intel RealSense D435 Depth Camera.

Challenges

Challenges

Challenges in Robot Sensing

- measurement uncertainties
- deterministic and stochastic noise
- limited measurement frequency
- poor resolution
- loss of calibration over time
- sensor failures
- insufficient storage
- multimodal data ...

Challenges

Challenges in Robot Sensing

- measurement uncertainties
- deterministic and stochastic noise
- limited measurement frequency
- poor resolution
- loss of calibration over time
- sensor failures
- insufficient storage
- multimodal data ...

What can we do about it?

Minimize errors using **sensor fusion**.

Challenges

Sensor Fusion

- Combining multiple sensors to get better information about the world.
- Sensor fusion is a complex process:
  - Different modalities.
  - Contradictory information.
  - Different sampling rates (asynchronous perception).
- Methods: Kalman Filter, Particle Filter, Machine Learning, etc.

Challenges

Sensor Architectures for Long-Term Autonomy

- What does **long-term** mean?
- There are different definitions:
  - $max\left(\frac{mission\ time}{amount\ of\ \ human\ interactions}\right)$
  - $max\left(\frac{mission\ time}{cost}\right)$

Challenges

Sensor Architectures for Long-Term Autonomy

What does this mean for the sensors?

- Sensors have to be robust.
- The system has to detect sensing errors.
- Constant monitoring of the system and its environment.

Challenges

Sensor Architectures for Long-Term Autonomy

What does this mean for the sensors?

- Sensors have to be robust.
- The system has to detect sensing errors.
- Constant monitoring of the system and its environment.

What does this mean for sensor processing?

- Lots of sensors with different modalities.
- Increased demand of:
    - spatial resolution.
    - sensitivity.
    - sampling rate.
    - computing power.

Conclusion

Conclusion

Back to the initial questions!

1. How would you design the sensor suit of Perseverance?

Conclusion

Back to the initial questions!

1. How would you design the sensor suit of Perseverance?
    - Proprioceptive and interoceptive sensors to monitor the robot state.
    - Exteroceptive sensors to inspect the soil.
    - Multi-modal sensor system for a good knowledge of the environment.

Conclusion

Back to the initial questions!

2. What would you consider for ensuring long-term autonomy?

Conclusion

Back to the initial questions!

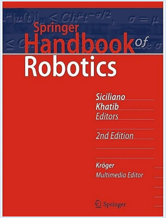
2. What would you consider for ensuring long-term autonomy?
    - More sensors to increase robustness (e.g. more cameras, different sensors to monitor the environment conditions).
    - Mechanisms to detect errors and sensor failures.
    - More computing power to cope with future changes in the mission plan.
    - Use a second robot (e.g. NASA's Ingenuity helicopter accompanies Perseverance rover on Mars).

References

Additional Literature

Springer Handbook of Robotics (English)

- Chapter 4.2: Sensors



Source: `https://link.springer.com/referencework/10.1007%2F978-3-540-30301-5`

Mobile Roboter (German)

- Chapter 2: Sensorik

Source: `https://link.springer.com/book/10.1007/978-3-642-01726-1`

Next: Robot Odometry