Universität Bremen

Institute for Artificial Intelligence

Faculty 03

Mathematics &

Computer Science

Robot Programming with ROS

5. Sensors

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16th Nov. 2023

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Overview

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Learning Goals

- Understand the importance of sensors in autonomous mobile robotics & their working principles
- Distinguish the advantages & disadvantages of sensors
- Carry out basic analysis of sensor data

I. Basics of Sensors

Lecture Contents

1. Motivation — Why sensing in autonomous mobile robotics?
2. Definition — What is sensing? sensor?
3. Principle — How to sense?
4. Perception Vs Sensing — What sensing is not

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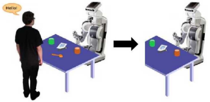
1. Motivation — Why sensing in autonomous mobile robots?

- Robots use knowledge about the world to purposefully act on it
- There is no prior complete knowledge of the world
- The world dynamics & constituents are not fully known
- Therefore, no pre-planning possible

Unexpected wheel slip



Unexpected spoon disapearance

Unexpected obstacle (wind)

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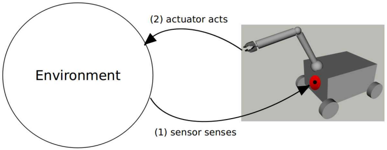
2. Definition — What is sensing? sensor?

Sensor is a device that senses the world, i.e.

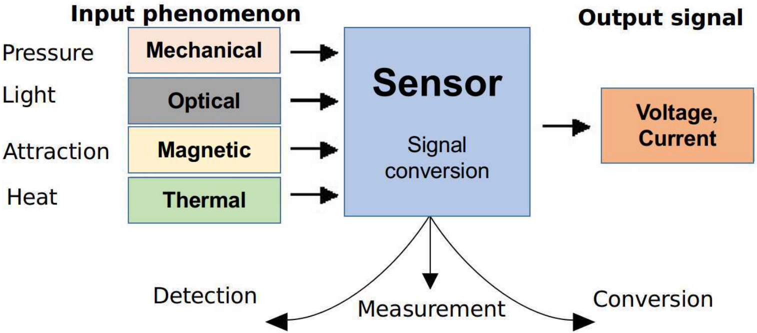
- detects a physical phenomenon (e.g. obstacle, light) in the world
- measures a physical quantity related to the phenomenon (e.g. distance, temperature, intensity)
- converts (transduces) the measurement into a suitable signal for processing (e.g. electrical, optical for electronic computers)



Environmental awareness through sensors

3. Principle — How to sense? (I)

Sensing occurs in three steps: detection, measurement, conversion



General working principle of sensors

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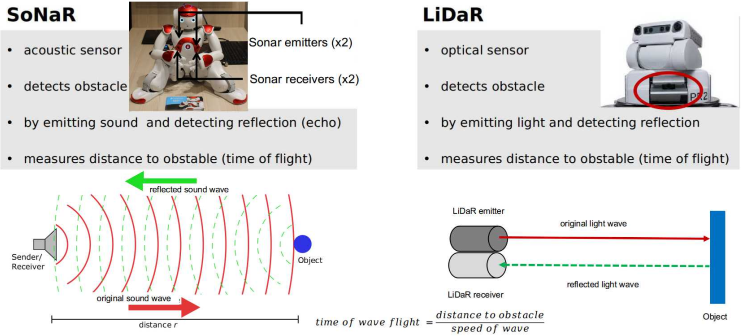
3. Principle — How to sense? (II)

Two ubiquitous sensors: SoNaR & LiDaR



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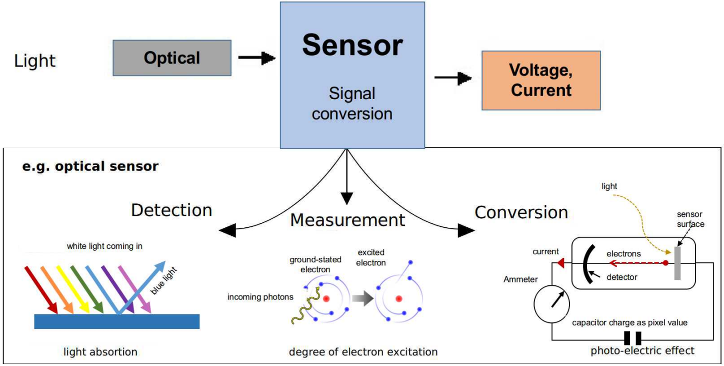
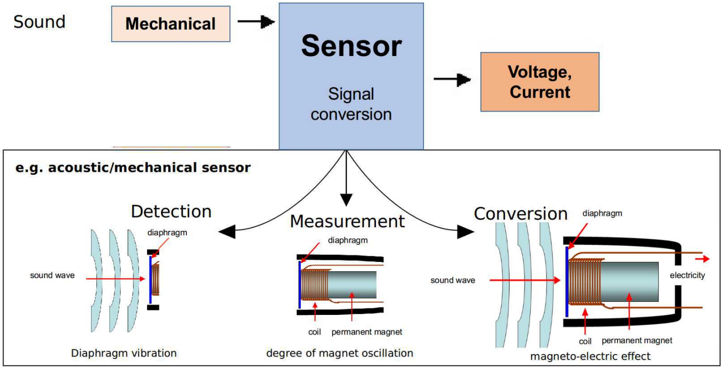
3. Principle — How to sense? (III)

LiDaR (Laser) — Light Detection and Ranging



3. Principle — How to sense? (IV)

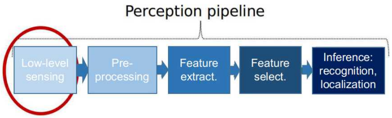
SoNaR — Sound Navigation and Ranging



4. Perception Vs Sensing — What sensing is not

- Sensing is just the earliest step in the measurement of the world state
- Sensing is mainly about collecting raw data about the world state (e.g. camera shows green area, but what is it?)
- The full measurement of the world state is known as perception
- Perception = Sensing + Data Interpretation (e.g. green area is mug)

Sensor detects green, but what is it?



Sensing as earliest step of perception

Lecture Summary

In this chapter, we learned about the roles of sensors in autonomous mobile robots and their working principles. This involved:

- Explaining the importance of sensors in autonomous mobile robots
- Defining sensors
- Presenting the general working principle of sensors
- Identifying and describing two ubiquitous sensors in autonomous mobile robots (LiDaR and SoNaR)
- Presenting detailed working principle of sensors through LiDaR and SoNaR

Thank you for your attention

Literature

1. "CHAPTER 1: INTRODUCTION TO SENSORS." National Research Council. 1995. Expanding the Vision of Sensor Materials. Washington, DC: The National Academies Press. doi: 10.17226/4782
2. https://www.researchgate.net/publication/301166370_Sensing_and_Sensor_Fundamentals
3. http://www.psych.purdue.edu/~willia55/120/6.S-PMM.pdf
4. Correll N., Introduction to Autonomous Robots: Kinematics, Perception, Localization and Planning, Magellan Scientific, 2016

Overview

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Lecture Contents

1. Proprioceptive Vs Exteroceptive
2. Active Vs Passive
3. Contact Vs Non-Contact
4. Optical, Mechanical, Acoustic, Electrical

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Motivation

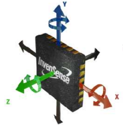
Different types of sensors w.r.t. functions, inputs, outputs & interactions with the world

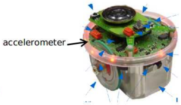
Images: *(Kenghagho's Master Thesis, 2019)*

1. Proprioceptive Vs Exteroceptive (I)

Proprioceptive sensors measure mechanics-related internal states of the robot

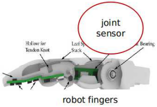
- Inertial sensors (e.g. accelerometer)
  (acceleration, rotation, speed, position)





- Force-Torque sensors
  (torque, force)

- Joint angle sensors (e.g. rotary encoder)
  (joint anglular position)



Images: *(https://industrial.panasonic.com/ww/products/sensors/sensors/6dof-inertial-sensor)*; *(Bélanger-Barrette's Blog, 2020)*; *(CONRAD)*

1. Proprioceptive Vs Exteroceptive (II)

Exteroceptive sensors measure external states of the robot (surroundings)

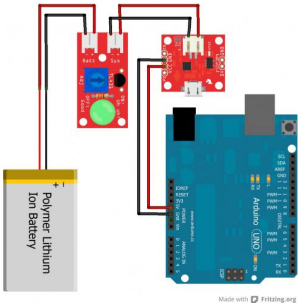
- Optical sensors (e.g. camera)
  (scene image, appearance)
- Accoustic sensors (e.g. microphone)
  (sound)
- Tactile sensors
  (pressure, texture, temperature)
- Proximity sensors (e.g. LiDaR, SoNaR)
  (depth, obstacle, distance)

Images: *(Evan-Amos); (CONRAD); (Hokuyo)*

1. Proprioceptive Vs Exteroceptive (III)

Interoceptive sensors measure feeling states of the robot (e.g. hunger, fear, hapiness, pains)

- still uncommon in robotics (embryonic research)
- Battery sensor (energy level)



Equilibrioceptive sensors measure the balance of the robot body

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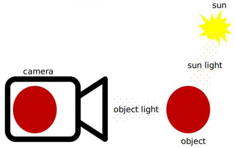
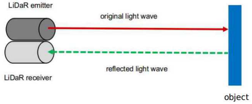
2. Passive Vs Active

Exteroceptive sensors can be classified either as active or passive

- Passive sensors only require energy from phenomena for detection (e.g. most camera)



- Active sensors emit energy towards phenomena and detect reflected energy (e.g. LiDaR)

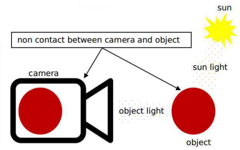


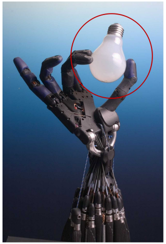
Images: *(GIS Geography)*; (https://steemit.com/technology/@rnjena/low-cost-solid-state-2d-lidar)

3. Contact Vs Non-Contact

Exteroceptive sensors can be classified either as contact or non-contact

- Non-contact sensors do not require any contact with energy sources for detection (e.g. most sensors)
- Contact sensors require contact with energy sources for detection (e.g. tactile sensors)



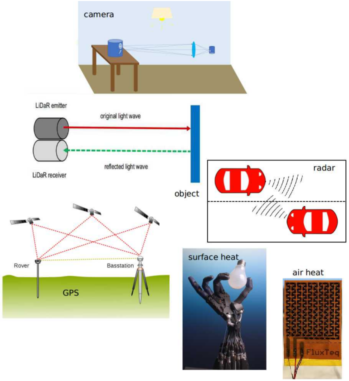


Images: (*https://medium.com/decodein/the-time-of-flight-camera-is-shaping-the-future-f47806aba135*); (Dsouza, 2016)

4. Optical, Mechanical, Acoustic, Electrical (I)

Optical sensors detect phenomena through electromagnetic energy (e.g. visible light, infrared, radiowaves, microwaves)

- Camera (visible light, appearance, depth loss)
- LiDaR (infrared, depth, indoor)
- RaDaR (radiowave, depth, outdoor)
- GPS (radiowave, 3D-position, outdoor)
- Temperature sensor (infrared, temperature)



Images: *(C.R. Nave, 2017); (Wikipedia RCraig09, 2009); (IAI Bremen, 2020); (G. Donald Allen, 2003); (ROMELa)*

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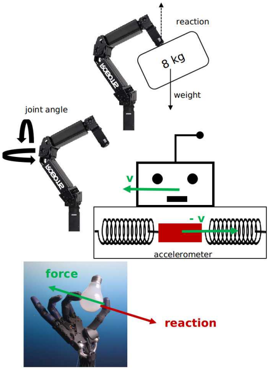
4. Optical, Mechanical, Acoustic, Electrical (II)

Mechanical sensors detect phenomena through mechanical energy

- Force-Torque sensor (force, torque)
- Rotary Encoder (joint angle)
- Inertial sensor (acceleration, rotation, speed)
- Tactile sensor (contact force/pressure)



Images: *(Universal Robots); (AKM); (IAI Bremen, 2020); (University of Southern California)*

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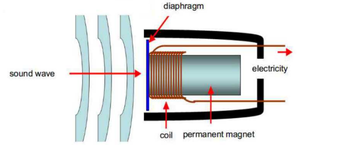
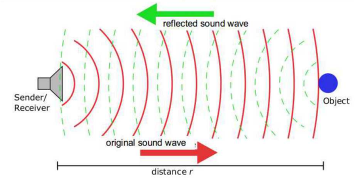
4. Optical, Mechanical, Acoustic, Electrical (III)

Acoustic sensors detect phenomena through acoustic energy (e.g. infrasound, sound, ultrasound)

- Microphone (sound, indoor)
- SoNaR (infrasound, ultrasound, depth, outdoor)





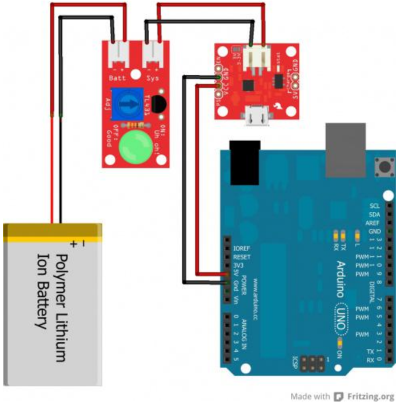
Images: *(PJ Aviation, 2020); (Vinoj Appukuttan, 2018)*

4. Optical, Mechanical, Acoustic, Electrical (IV)

Electrical sensors detect phenomena through electrical energy

- Battery sensor (energy level)

Images: *(Praveen Dehari, 2018)*



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Lecture Summary

In this chapter, we learned how to select a sensor for a given problem based on its function, the nature of its input, output and interaction with the world . This involved:

- Classifying sensors w.r.t. to functions, inputs, outputs & interaction mode with the world
- Identifying at least one common sensor per class and locating it on the robot
- Combining sensors to achieve more information

Thank you for your attention

Literature

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2. http://ijarse.com/images/fullpdf/160.pdf
3. http://www.cim.mcgill.ca/~yiannis/417/2013/LectureSlides/06-Sensors.pdf
4. http://robotics.sjtu.edu.cn/upload/course/5/files/Robot%20Sensors%20and%20Actuators-new.pdf

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Overview

Lecture Contents

1. Range
2. Accuracy
3. Sensitivity
4. Precision
5. Resolution
6. Latency
7. Hysteresis (Deviation)

Motivation

- Sensors detect, measure and convert energy into electrical energy
- However, they can be useless under circumstances despite functional capability
- Sensor characteristics inform about the expected quality of collected data

1. Range

Is the maximum and minimum value range over which a sensor works well

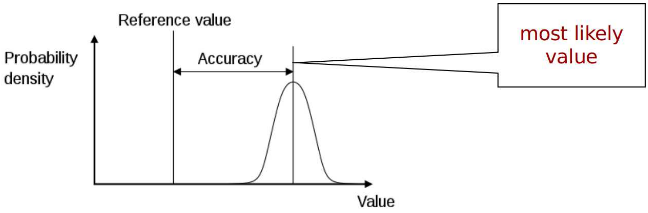
- SoNaR (HC-SR04): $2 \sim 400cm$
- LiDaR (UTM-30LX): $10 \sim 3000cm$

Images: *(Kuongshun Electronic); (Hokuyo)*

2. Accuracy

Is the degree of agreement between the measured (most likely) and "correct" value

- SoNaR (HC-SR04): $\pm 0.035cm/cm$
- LiDaR (UTM-30LX): $10 \sim 1000cm : \pm 3cm, 1000 \sim 3000cm : \pm 5cm$



Images: *(Wikipedia Pekaje, 2007); (IAI Bremen, 2020)*

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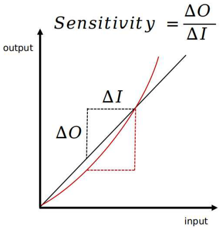
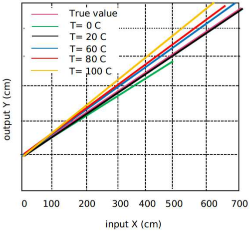
3. Sensitivity

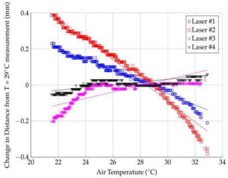
Is how much the sensor output changes when the input changes



(a) Sensitivity



(b) HC-SR04 Sensitivity



(c) Laser Sensitivity

Images: *(Cliodhna Ni Scanaill et al., 2013); (Abdusalam Al-Khwaji, 2016); (Matthew S. Kuester et al., 2018)*

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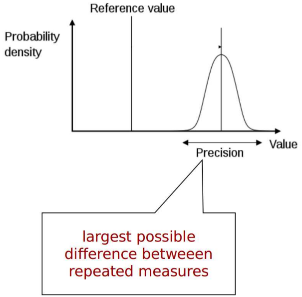
4. Precision / Repeatabilty / Stability

Is the difference between repeated measures

- SoNaR (HC-SR04): $0.1 \sim 0.5cm$
- LiDaR (UTM-30LX): $1 \sim 3cm$

Images: *(Wikipedia Pekaje, 2007); (IAI Bremen, 2020)*



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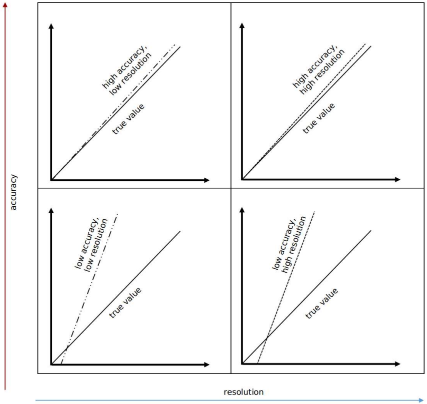
5. Resolution

Is the smallest detectable change in the phenomenon

- SoNaR (HC-SR04): $\approx 0.3cm$
- LiDaR (UTM-30LX): $\approx 0.1cm$

Images: *(Tim Shotter, 2012)*



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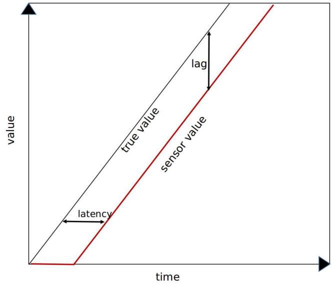
6. Latency

Is time required for a change in input to cause a change in output

- SoNaR (HC-SR04): $\approx 343 m/s$
- LiDaR (UTM-30LX): $\approx 3 \times 10^8 m/s$

Images: *(Monolithic Power Systems .Inc, 2020); (IAI Bremen, 2020)*



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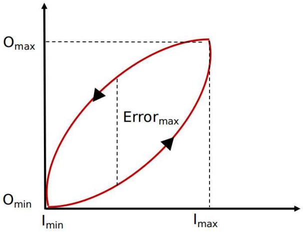
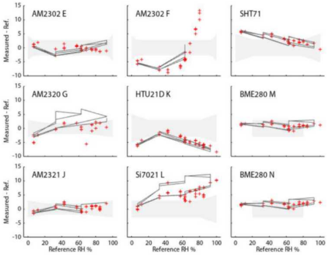
7. Hysteresis / Error / Deviation

Is the maximum difference in output at different points when measuring within the sensor's specified range with increasing and then with decreasing input



Sensor Hysteris



Hysteris comparision of Humidity sensors

Images: *(Michael J. McGrath et al., 2014)*; *(http://www.kandrsmith.org/RJS/Misc/Hygrometers/calib_many.html)*

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Lecture Summary

In this chapter, we learned how to select a sensor for a given problem based on its properties. This involved:

- Identifying and defining the key properties of sensors
- Illustrating these properties by comparing two ubiquitous sensors namely the LidaR and SoNaR sensors

Thank you for your attention

Literature

1. https://www.researchgate.net/publication/321625640_Sensor_Characteristics_Input_and_output_Characteristics
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3. https://www.philadelphia.edu.jo/academics/kaubaidy/uploads/Sensor-Lect2.pdf
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Overview

Lecture Contents

1. R(obot) O(perating) S(ystem) & Sensor Data
2. Sensor Noise
3. Sensor Model

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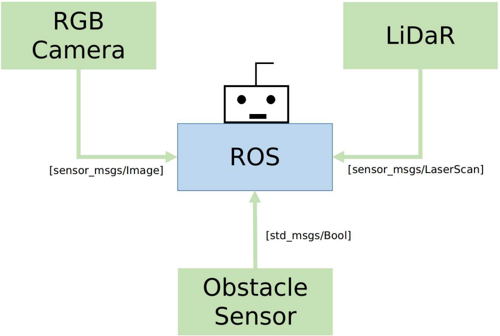
1. R(obot) O(perating) S(ystem) & Sensor Data (I)

ROS is a platform that supports the development & excecution of highly distributed robotic applications including the collection of data with sensors

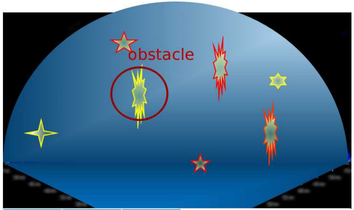
- Install ROS
- Connect sensors to machine
- Download ROS-compatible sensor softwares from GitHub
- Run software on computer to collect data



Images: *(Gaurav Gupta, 2019)*

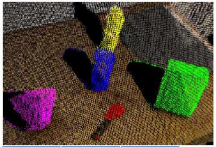
1. R(obot) O(perating) S(ystem) & Sensor Data (II)

Sensor data as streams of qualitative and quantitative values



0.75	0.00	0.15	...
0.18	0.78	0.69	...
0.29	0.35	0.57	...
0.17	0.42	0.60	...
...	...	...	...

(a) SoNaR image



0.49	0.37	0.53	...
0.12	0.38	0.29	...
0.09	0.49	0.33	...
0.21	0.54	0.69	...
...	...	...	...

(b) LiDaR image

Images: *(Yoav Zitun, 2017); (IAI Bremen, 2020)*

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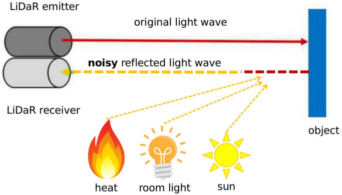
2. Sensor Noise (I)

- Sensor data are extremely noisy
- Sensor noise characterizes any undesirable (unwanted) quantity in data/signal
- Noise corrupts frequency, amplitude and phase of signal
- Noise usually presents random aspects

- Internal sources of noise:
  poor sensor characteristics, wrong parameriterization, failure ...
- External sources of noise:
  signal interferences, disturbances, absorption, ...



Sources of noise

Images: *(Abhilash Patel, 2020)*

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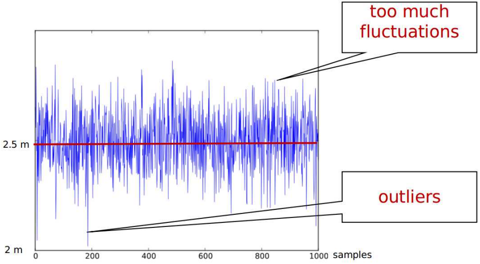
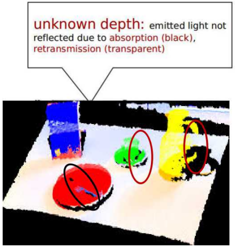
2. Sensor Noise (II)

Illustration of noise in sensor data



(a) SoNaR data, true value in red, measured value in blue



(b) LiDaR image with unknown values

Images: *(IAI Bremen, 2020); (Ching-Tang Hsieh, 2015)*

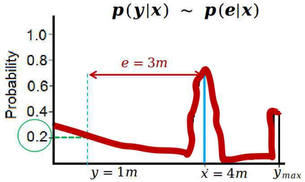
3. Sensor Model (I)

- Sensor modeling is a mathematical attempt to describe noise in sensor data
- General (additive) model: $y = f(x) + e(x)$, where
  - x, is the sensor input
  - y, is the sensor output
  - e, is the sensor error
  - f, is the sensor's ideal transduction function
- Sensor error e quasi-impossible to model analytically (random + unknown)
- e is modeled probabilistically through statistical inference

3. Sensor Model (II)

- Probability $p(e)$: how likely can error e occur in sensor output y?
- Probability $p(e|x)$: how likely can e occur in y given input signal x?
- Deduce $p(e)$ from $p(e|x)$: $p(e) = \sum_x p(e|x).p(x)$ (marginalization)
- Compute $p(e|x)$ or $p(e)$ through statistical inference, i.e.
  - sample sensor data y for sensor input x or various x
  - check how erroneous y
  - infer $p(e|x) \sim p(y|x)$ or $p(e)$

- e.g. how erroneous(e) is the measured distance (y) to an obstacle located at 4m (x) far from a LiDaR sensor?



Images: *(IAI Bremen, 2020); (Ricardo Omar Chavez-Garcia, 2014)*

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16th Nov. 2023

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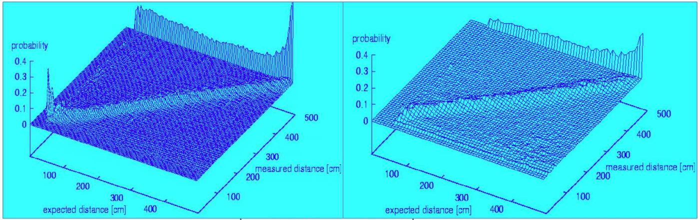
Mathematics & Computer Science

3. Sensor Model (III)

- Statistical inference of probabilistic function of noise $p(e)$ in SoNaR and LiDaR data
- $y^* = y - e^*$, is the denoised sensor output, e^* sampled w.r.t. $p(e)$



(a) LiDaR

probability density of noise:

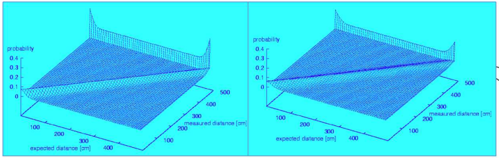
LiDaR is less noisy than SoNaR

(b) SoNaR

Images: *(IAI Bremen, 2020); (Lectures of Wolfram Burgard et al., University of Freiburg)*

3. Sensor Model (IV)

- Intuitively choose a parameterized probabilistic model for $p(e)$
  e.g. gaussian distribution, $p(e) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(e-\mu)^2}{2\sigma^2}}$
- Use collected data to estimate the parameters μ and σ
- Practical parameter estimation techniques
  e.g. gradient descent, genitic algorithms



(a) LiDaR (b) SoNaR

Approximations of probability densities of LiDaR and SoNaR noise

Images: *(IAI Bremen, 2020); (Lectures of Wolfram Burgard et al., University of Freiburg)*

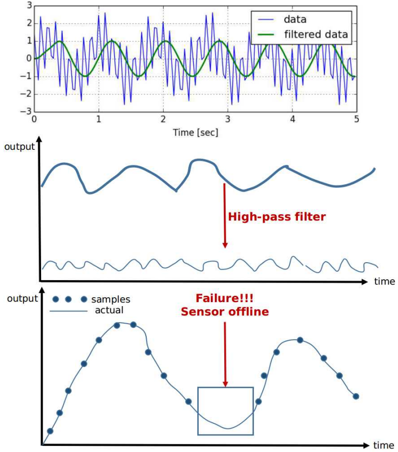
3. Sensor Model (V)

Other common denoising techniques

- Low Pass Filtering: filters out all high-frequencies from signal

- High Pass Filtering: filters out all low-frequencies from signal

- Interpolation: recovers missed measurements from neighbooring measurements



Images: *(Warren Weckesser, 2014); (NDT Resource Center); (Rafael Schultze-Kraft, 2017)*

Lecture Summary

In this chapter, we learned how to carry out basic analysis of sensor data. This involved:

- collecting data from the robot world with sensors
- criticizing the quality of sensor data
- explaining/justifying the quality of sensor data
- hypothesizing noise in sensor data

Thank you for your attention

Literature

1. http://wiki.ros.org/
2. http://people.fisica.uniroma2.it/~solare/en/wp-content/uploads/2018/12/Lez_12_Noises.pdf
3. https://www2.chemistry.msu.edu/courses/cem434/Chapter%205%20%20%20%20%20%20Signals%20and%20Noise.pdf
4. http://ais.informatik.uni-freiburg.de/teaching/ss11/robotics/slides/07-sensor-models.pdf

Overview

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16th Nov. 2023

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Assignment and dates

- Assignment 5:
  `https://github.com/artnie/rpwr-assignments`
- Grades: 8 points for this assignment
- Due: 22.11., 23:59 AM German time
- Next class: 23.11., 14:00

Nils Leusmann, Arthur Niedźwiecki, Stefan Eirich
16th Nov. 2023

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Evaluation

Thanks for your attention!

Special thanks to the IAI team for the content of this lecture!

`https://forms.gle/iZyKqLCxsrwBU3XZ6`