Sensors and Sensing
Range Sensing

Todor Stoyanov

Centre for Applied Autonomous Sensor Systems
Örebro University
Sweden

Outline

Range Sensing

- A range sensor is any device that can estimate the distance between itself and a (set of) point(s) in the environment.
- Range sensors are usually active devices, which emit a signal and then measure a property of the reflected signal to estimate distance.
- Passive devices (such as cameras) can potentially be used for range sensing, using triangulation methods.
- Range sensors can also be classified as 1D, 2D or 3D:
  - 1D: measure distance along a single line of sight (a ray)
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Outline

Sonars

- Sonars are ultra-sonic time of flight sensors.
- The sonar is made up of a transceiver and a receiver.
- The transceiver sends short pulses of high-frequency sound waves.
- The receiver records reflected waves of the same frequency.
- The distance to the reflecting object is then obtained as:

$$d = \frac{vt}{2}$$

where v is the speed of propagation and t is the roundtrip time.

Figure: Seneca UTR4016

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Sonar Beam Models

- Sonars are wide-beam sensors and are generally assumed to cover a conic FOV
- The actual beam pattern depends on the device and usually exhibits side lobes.

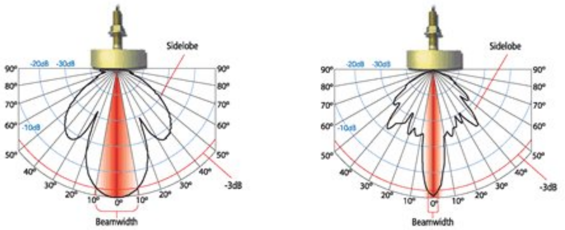

Figure: Typical sonar beam patterns, image courtesy of http://www.raymarine.com/

Infrared Proximity Sensors

- Infrared proximity sensors use an infrared LED to shine a beam into the environment.
- The time delay between sending and receiving a pulse of light, as well as the brightness of the reflected signal are typically used in range measurement.
- The intensity of the reflected light i is inversely proportional to the square of distance traveled
- ... however, the material of the object absorbs different amount of light
- Intensity is usually used to filter unreliable measurements, i.e. low intensity = low reliability

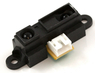

Figure: SHARP GP2Y0A21YK

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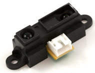

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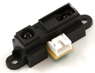

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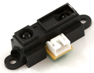

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Laser Range Finders

- A laser range finder (LRF) or laser scanner usually refers to a 2D laser-based range sensor.
- A laser beam is a concentrated stream of light of a particular wavelength.
- LRFs use laser beams instead of LED light, resulting in longer range measurements.
- Typically a single laser emitting device is coupled with an optical system to obtain a 2D range measurement.

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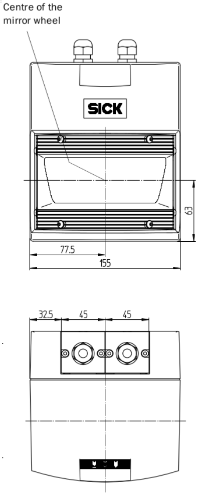
Time-of-flight Laser

- Time of flight lasers operate by sending pulses of laser beams.
- A rotating mirror sweeps the beam in a plane



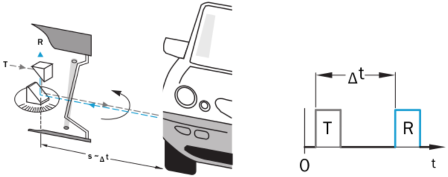
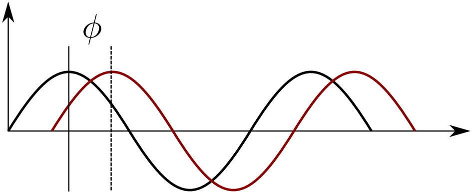


Figure: SICK LMS 200 operational principle (images courtesy of SICK manual)

Phase-shift Range Measurement

- Phase-shift can also be used for range measurement in LRFs
- The transmitter circuit sends modulated light with frequency f



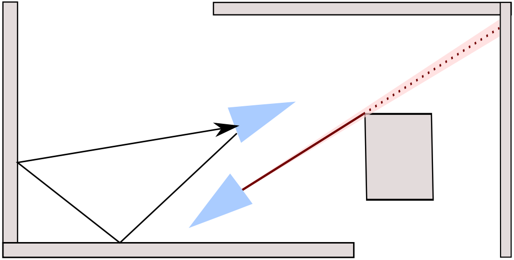
- The range to the reflected object can be recovered using:

$$d = \frac{\phi c}{4\pi f} \tag{1}$$

- The phase shift measurement induces an ambiguity of:

$$R_a = \frac{c}{2f} \tag{2}$$

Error Characterization for Range Sensors



- Typical modes of errors for range sensors: multiple reflections, mixed measurements, material reflectivity.
- Error characterization aims at empirically measuring the reliability of sensors to determine the types of errors that occur.

Error Characterization for Range Sensors

How can we experimentally quantify the noise in an LRF?

Proceedings of the 2002 IEEE
International Conference on Robotics & Automation
Washington, DC • May 2002

Characterization of a 2-D Laser Scanner for Mobile Robot Obstacle Negotiation

By
Cang Ye and Johann Borenstein*
The University of Michigan

We will look into this paper and the experimental methodology [1].

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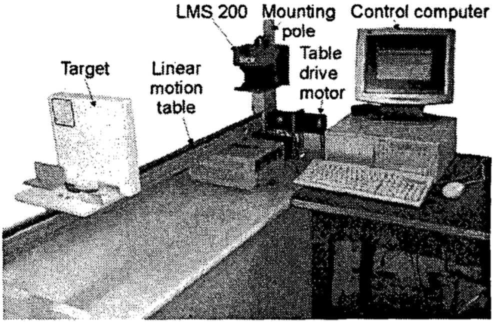

Figure: Experimental methodology

Error Characterization for Range Sensors

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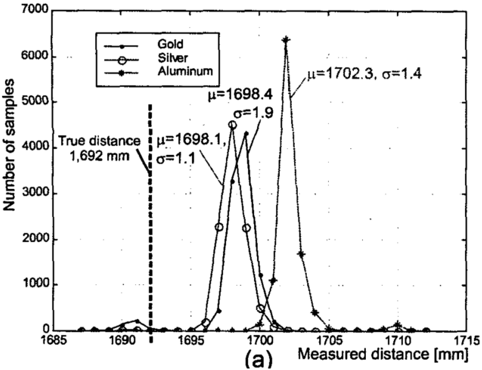

Figure: Material reflectivity

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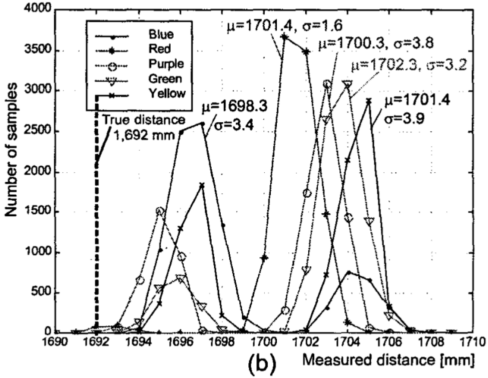

Figure: Material color

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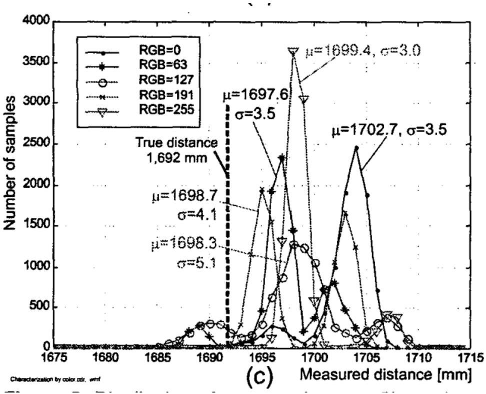

Figure: Color intensity

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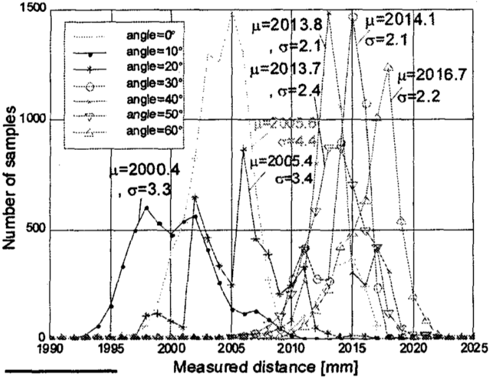

Figure 7: Distribution of ranges at various orientations.

Figure: Incidence angle

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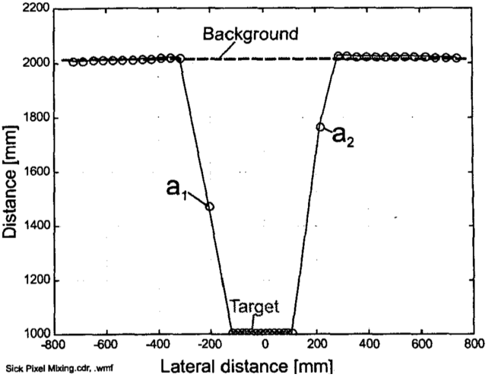
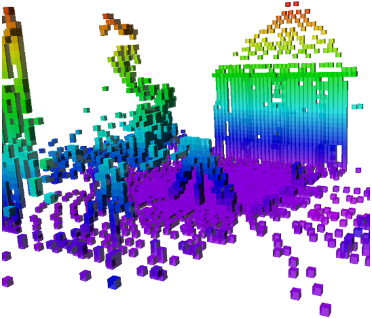


Figure: Mixed measurements

Outline

Occupancy Map Formulation

- An occupancy grid map is a sensor fusion approach to estimating a map of the environment, given noise corrupted range measurements.
- Each cell in an occupancy grid represents the probability that the space inside the cell is occupied.



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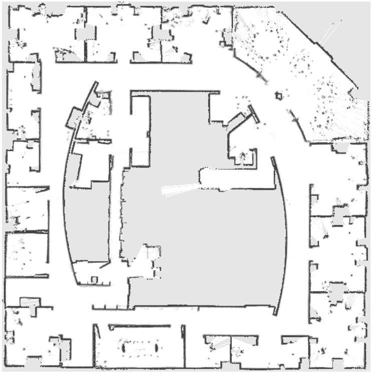

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Occupancy Map Formulation

- Formally, a map m consists of cells $m_{i,j}$ modeled as binary random variables, i.e. $m_{i,j} = \{1, 0\}$.
- The probability of a given cell i, j being occupied is:

$$p(m_{i,j}) = p(m_{i,j} = 1) = 1 - p(m_{i,j} = 0)$$

Occupancy Map Formulation

- The mapping problem is to estimate a map m, given range measurements $z_{1:t}$ taken at robot poses $x_{1:t}$:

$$p(m|z_{1:t}, x_{1:t})$$

- Assume $x_{1:t}$ is encoded in $z_{1:t}$. The probability of a cell $m_{i,j}$ is then formulated recursively as:

$$p(m_{i,j}|z_{1:t}) = \frac{p(z_t|m_{i,j})p(m_{i,j}|z_{1:t-1})}{p(z_t|z_{1:t-1})} \quad (3)$$

- Applying Bayes rule to $p(z_t|m_{i,j})$:

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Log-odds Formulation

- The above equations can be simplified by tracking the odds ratio, instead of probability:

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o(m_{i,j}|z_{1:t}) &= \frac{p(m_{i,j}|z_{1:t})}{1 - p(m_{i,j}|z_{1:t})} = \frac{p(m_{i,j}|z_{1:t})}{p(\bar{m}_{i,j}|z_{1:t})} && (5)\\
&= \frac{p(m_{i,j}|z_t)p(\bar{m}_{i,j})p(m_{i,j}|z_{1:t-1})}{p(\bar{m}_{i,j}|z_t)p(m_{i,j})p(\bar{m}_{i,j}|z_{1:t-1})} && (6)\\
&= o(m_{i,j}|z_t)\frac{p(\bar{m}_{i,j})}{p(m_{i,j})}o(m_{i,j}|z_{1:t-1}) && (7)
\end{aligned}
$$

- Assuming equal prior, i.e $p(m_{i,j}) = p(\bar{m}_{i,j}) = 0.5$ and taking $l(\cdot|\cdot) = \log(o(\cdot|\cdot))$:

$$l(m_{i,j}|z_{1:t}) = l(m_{i,j}|z_{1:t-1}) + l(m_{i,j}|z_t) \qquad (8)$$

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Assumptions

In the above derivation we made several assumptions:

- Independence of map: we assume that the occupancy of every cell $m_{i,j}$ is independent of the occupancy of any other cell in m.
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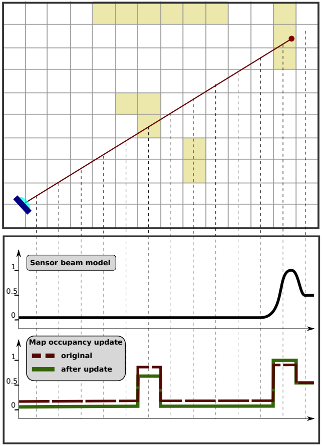
Forward and Inverse Sensor Models

- Updating the probabilities of occupancy of cells along the ray is done using a probabilistic laser beam model.
- A forward sensor model models the probability of observing a range measurement, given a certain map: $p(z_t|m)$.
- $l(m_{i,j}|z_t)$ in Eq.8 represents an inverse sensor model
- i.e., how likely is it that a cell $m_{i,j}$ is occupied, given a sensor measurement z_t



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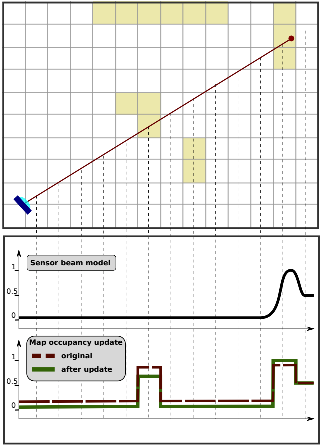

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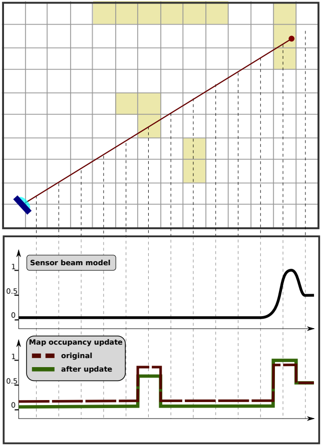

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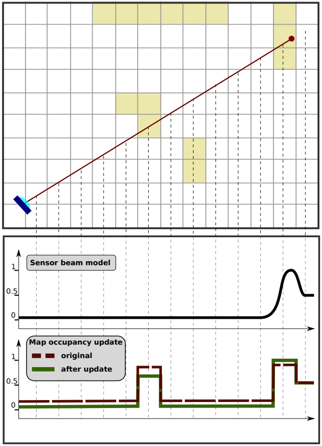
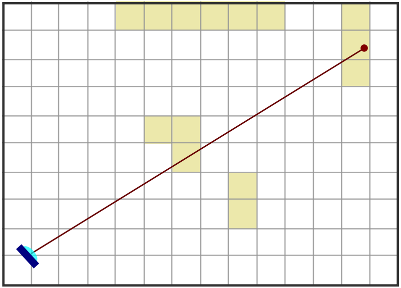
- $l(m_{i,j}|z_t)$ in Eq.8 represents an inverse sensor model
- i.e., how likely is it that a cell $m_{i,j}$ is occupied, given a sensor measurement z_t

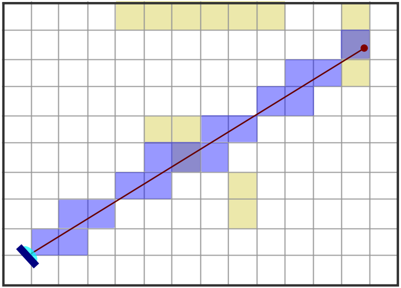


Ray-tracing



- In order to update map cells with new measurements efficiently, we need to detect all cells through which a laser beam passes
- This operation is known as ray tracing.
- Naive implementation: sample along the ray with a sufficiently small resolution
- ... or, process volume in parallel and project volumes into sensor frame

Ray-tracing



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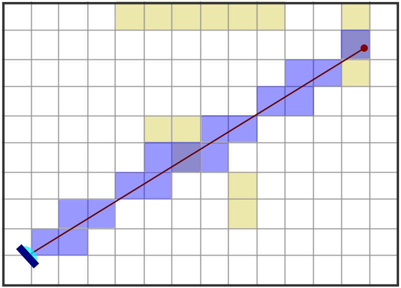

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Outline

1 Sonars and Infrared

2 Laser Range Finders

3 Occupancy Maps

4 Practice: Laser Scanners

Sample Questions

- True/False
  - a: The SICK LMS laser scanner measures time of flight of a laser beam using the phase shift method.
  - b: Occupancy grid maps treat each cell as an independent random variable.
  - c: Sonars are point range sensors.

Sample Questions

- Design/Derive
  - a: Formulate the log-odds update rule for a single cell $m_{i,j}$ in the map m, given a set of previous observations $z_{1:t-1}$ and a new observation z_t. (3 points)
  - b: You have a range scanner with 256 rays. Provide pseudo-code for initializing and updating an occupancy grid with your sensor readings. (3 points)
  - c: Draw an inverse sensor model and explain how you would use that in your map update procedure. (4 points)

Practice problem

- Download the bag file from `http://www.aass.oru.se/Research/mro/data/tutorials/mapping.bag`
- Clone the git repository: git clone https://github.com/tstoyanov/sensors_exercises.git
- Implement a simple occupancy mapping routine by following the comments.
- Test your code on the provided bag file

References

Cang Ye and Johann Borenstein.
Characterization of a 2d laser scanner for mobile robot obstacle negotiation.
In Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on, volume 3, pages 2512–2518. IEEE, 2002.

Sensors and Sensing
Range Sensing

Todor Stoyanov

Centre for Applied Autonomous Sensor Systems
Örebro University
Sweden