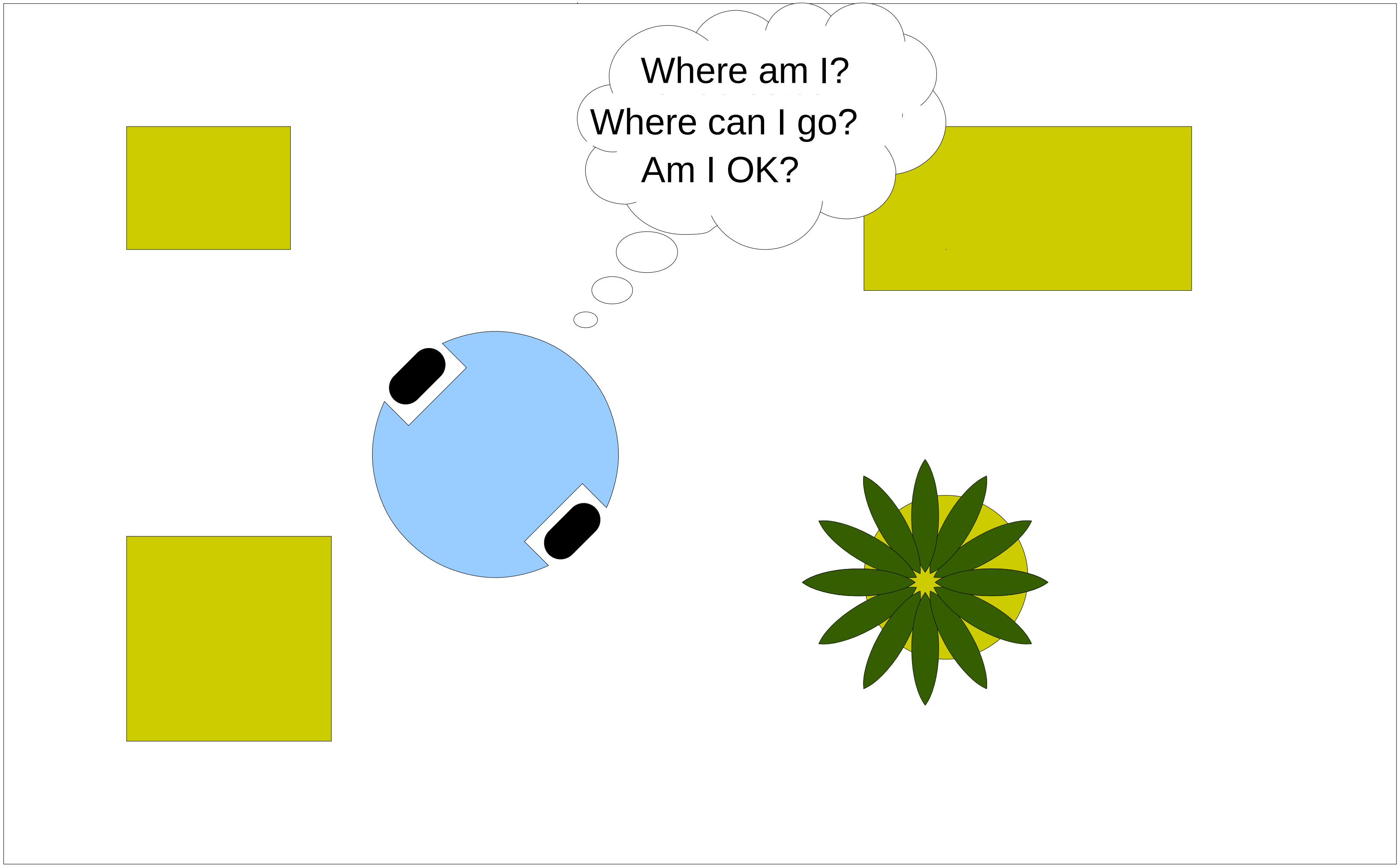
sensors

Robótica Móvel e Inteligente / Mobile and Inteligent Robotics
Mestrado Integrado em Engenharia de Computadores e Telemática

Academic year 2022/23

Departamento de Electrónica, Telecomunicações e Informática
Universidade de Aveiro

existencial problems in a robot's life



sensorial information

- Self perception (“How am I doing?”)
  - Posture
  - Batteries, ...
- Location (“Where am I?”)
  - Position
  - Orientation
- Environment perception (“Where can I go to?”)
  - obstacles
  - maps: constructing and location
  - targets (application level)

Challenges in mobile robotics

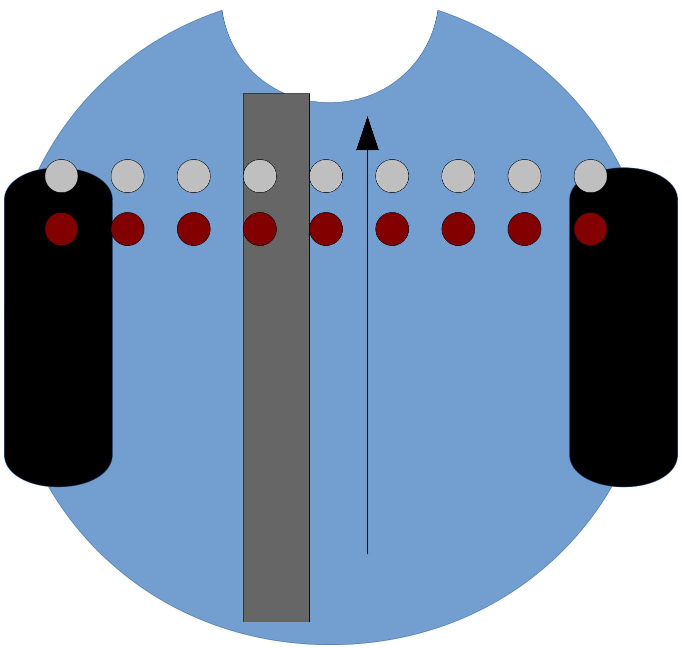
Navigate :: follow fixed path

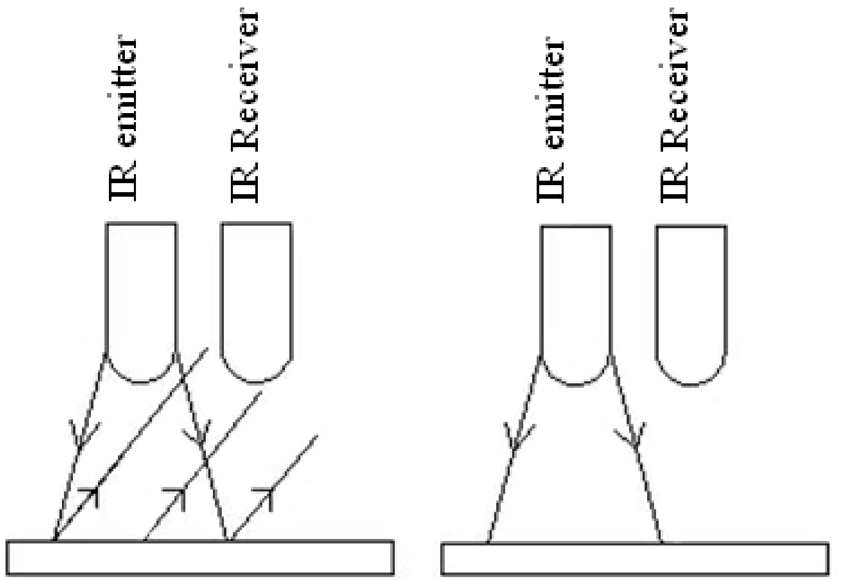
Line sensors: magnetic

https://www.roboteq.com/all-products/magnetic-guide-sensors

Line sensors :: optic

- Reflection on a object
- Detection depends on the object colour

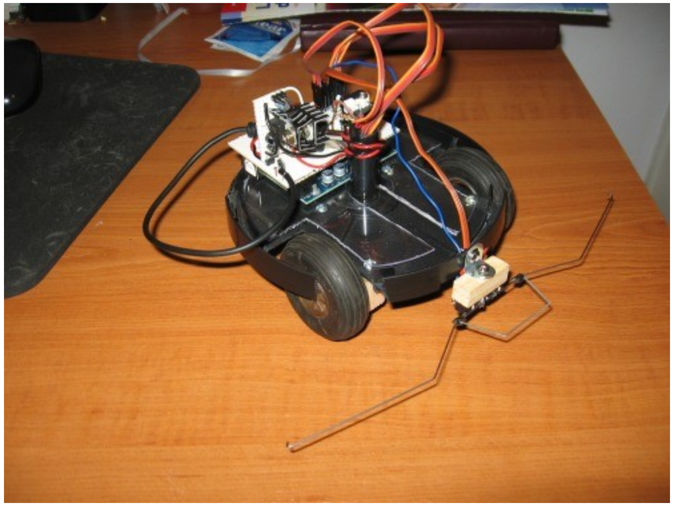




Navigate :: react to surroundings

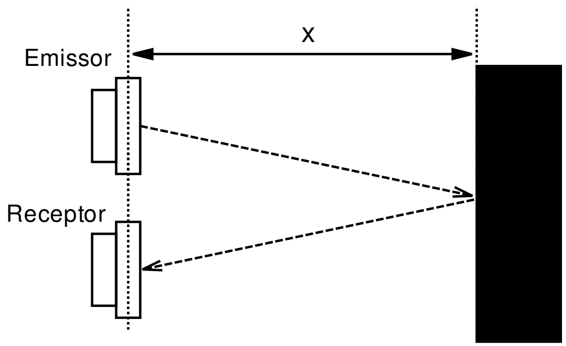
contact sensors

- **mechanically actuated switch**
  - whisker
  - bumper



ultra-sound

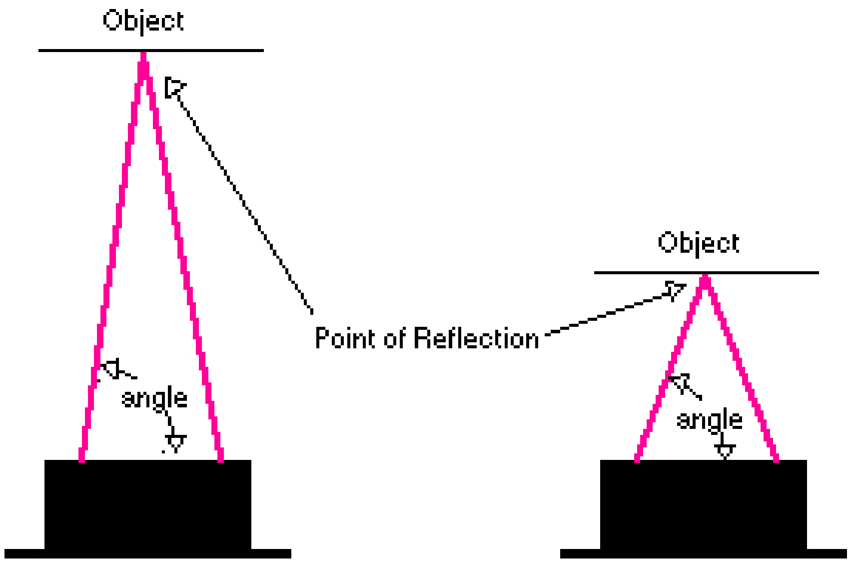
- Detection based on the reflection by an object



$$x = \frac{1}{2} \cdot c \cdot t_{\mathrm{echo}}$$

infra-red

- Sharp sensor
  - Distance information

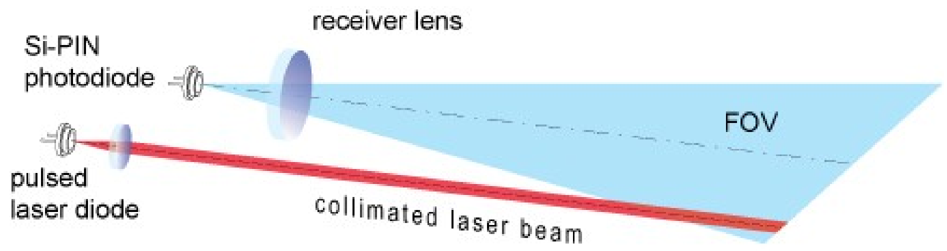


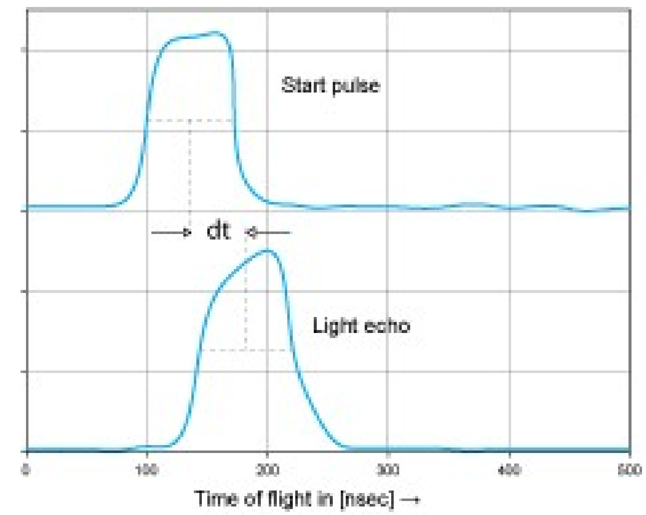
Robotic challenges

Navigate :: follow a path in a map

Laser range finder

- Laser scans the space ahead or around the robot
- Measuring obstacle distance
  - Limited to the bean working plan
  - Sometimes used with beam oscillation (⊥ to the plan of beam)





Laser range finder

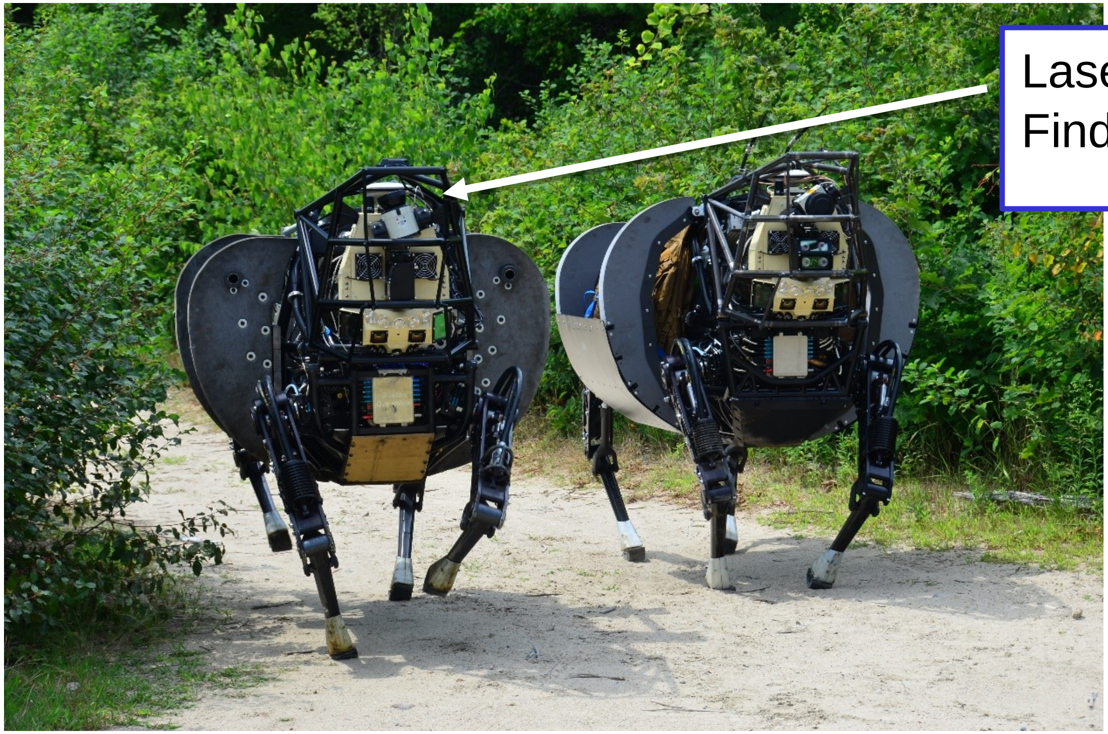
- Image of Sick’s LRF software application

Mapa of IEETA's building level 0,
obtained by LRF scanning

LS3 – Legged Squad Support System

- The LS3 (Legged Squad Support System) is an example of a robot using LRF.
  - For example, in the YouTube video, at 1:17 you can clearly see the LFR oscillating to create a 3D perception of space ahead.

    http://youtu.be/R7ezXBEBE6U?t=1m17s

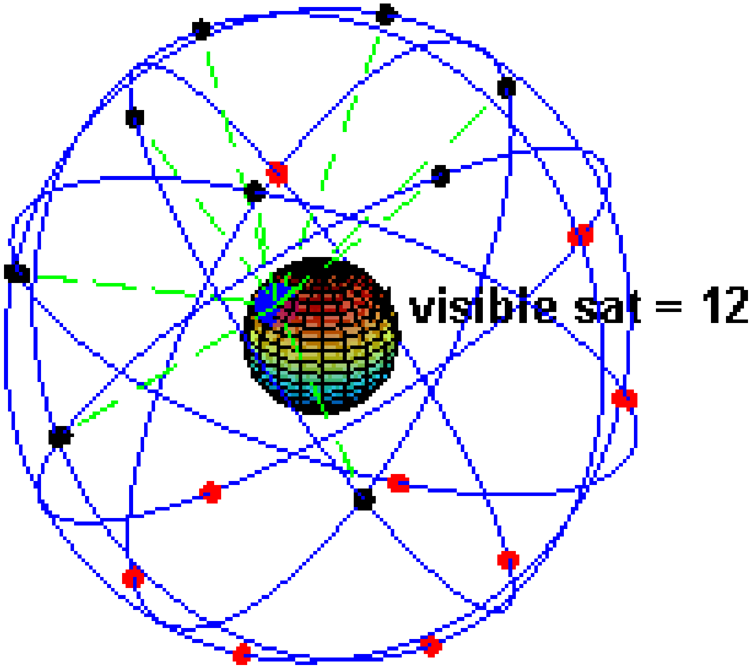


Laser Range Finder

position

GPS

- Absolute positioning (error in the order of m)
- Relative positioning (error in the order of cm for short time intervals)
- Requires line of sight to a minimum number of satellites → outdoor use
- Start time



error sources in GPS

Ionospheric effects	± 5 meters
Shifts in the satellite orbits	± 2.5 meter
Clock errors of the satellites' clocks	± 2 meter
Multipath effect	± 1 meter
Tropospheric effects	± 0.5 meter
Calculation and rounding errors	± 1 meter

http://www.kowoma.de/en/gps/errors.htm

mobile phone location

- Based on mobile phone location services
  - e.g.: multilateration with cell tower signals

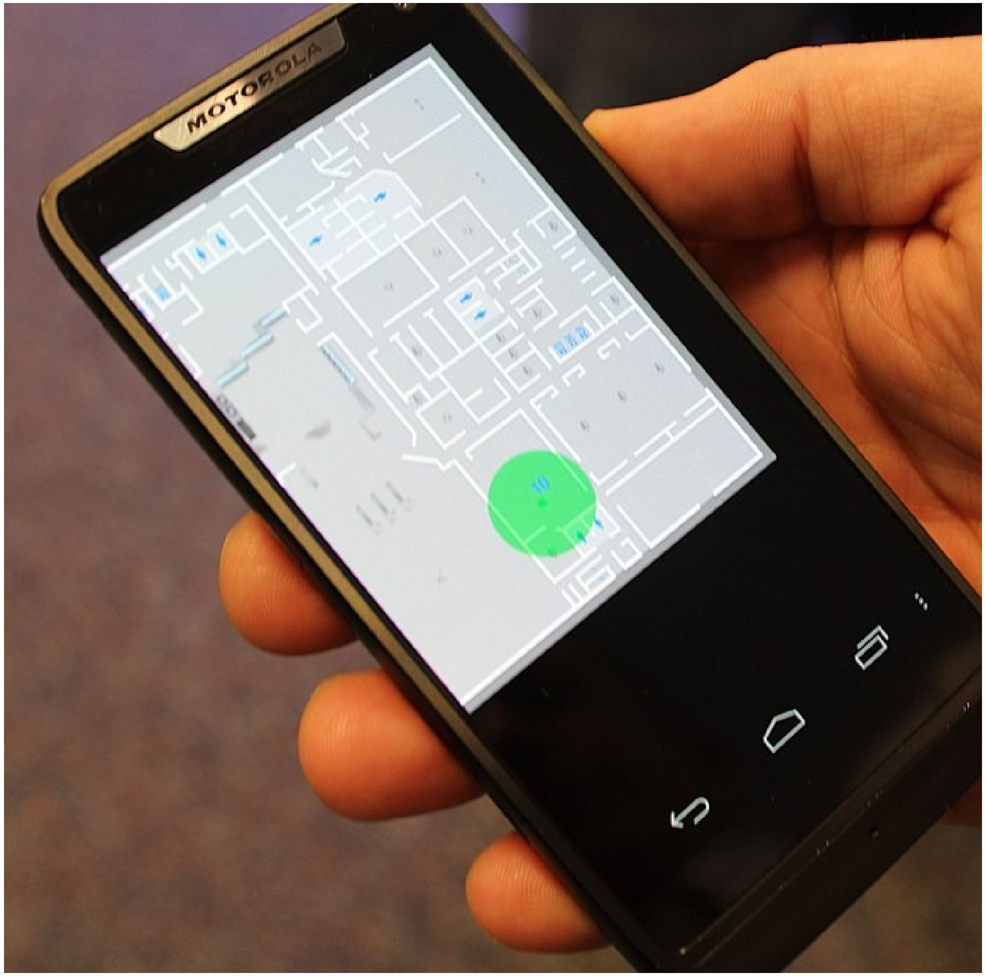


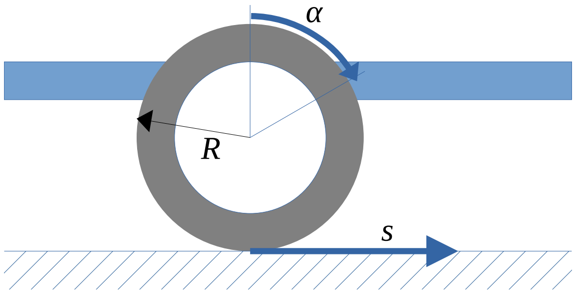
Photo by Intel Free Press - Indoor location services on mobile phone, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=71130241

Navigate :: sense myself

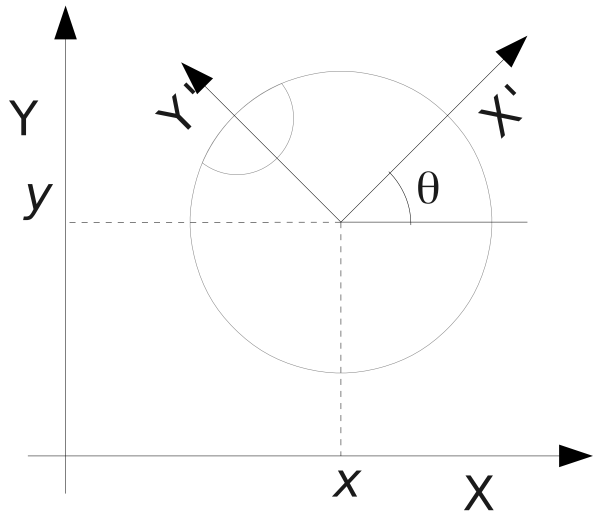
Position

- Odometry
  - def.: use of data from motion sensors to estimate change in position over time
  - relative position
  - Sources of error:
    - limited resolution (encoder)
    - model inaccuracies:
      - systematic → accumulates (error in slope)
        - error in wheel diameter
    - slippage
      - random, can reach significant values
  - Errors accumulate → unbounded !!

s

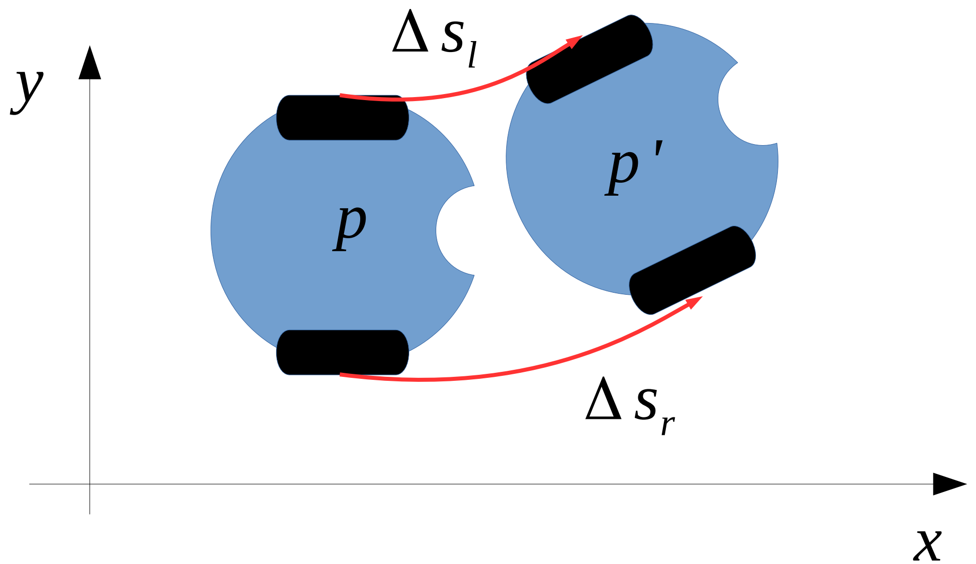


$$s = \alpha \times R$$

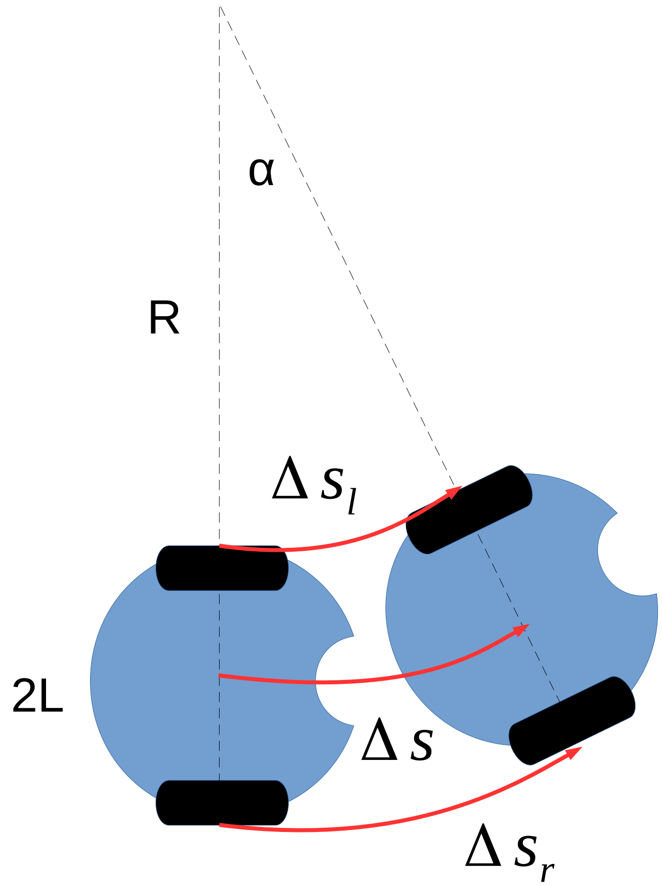


Robot location in the plane
Pose

$$p = \begin{bmatrix} x \\ y \\ \Theta \end{bmatrix}$$



$$\Delta s_l = R\alpha$$
$$\Delta s_r = (R+2L)\alpha$$
$$\Delta s = (R+L)\alpha$$
$$\Delta s = \frac{\Delta s_l + \Delta s_r}{2}$$

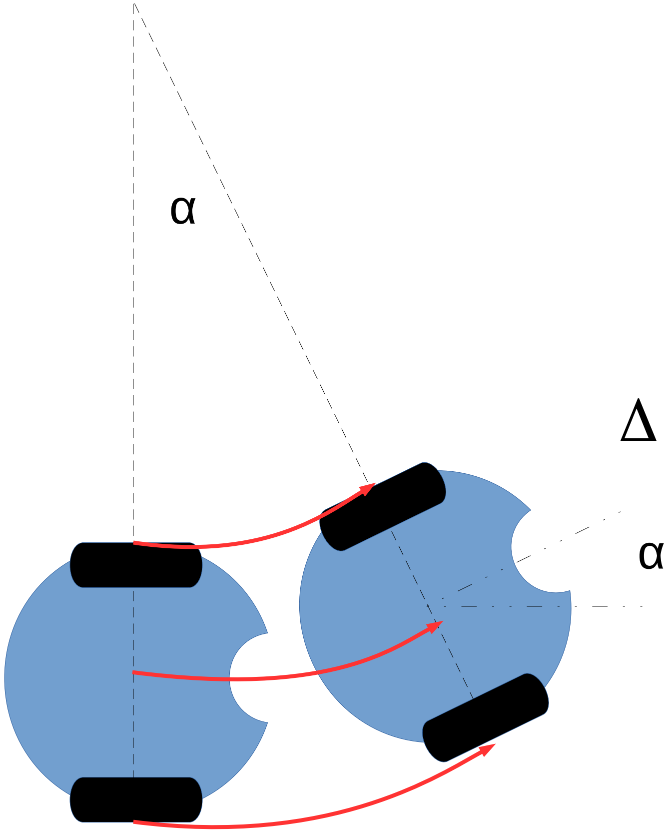


$$\Delta s_l = R\alpha$$

$$\Delta s_r = (R + 2L)\alpha$$

$$\frac{\Delta s_l}{R} = \frac{\Delta s_r}{R + 2L}$$

$$R = \frac{2L\Delta s_l}{\Delta s_r - \Delta s_l}$$



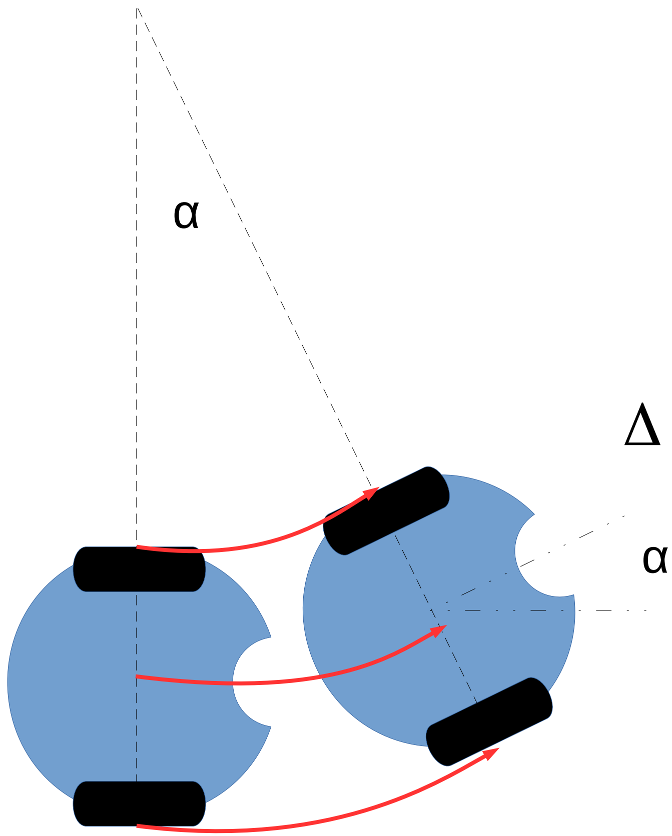
$$\Delta\Theta \simeq \alpha$$

$$\Delta S_l = R\alpha$$

$$R = \frac{2L\Delta S_l}{\Delta S_r - \Delta S_l}$$

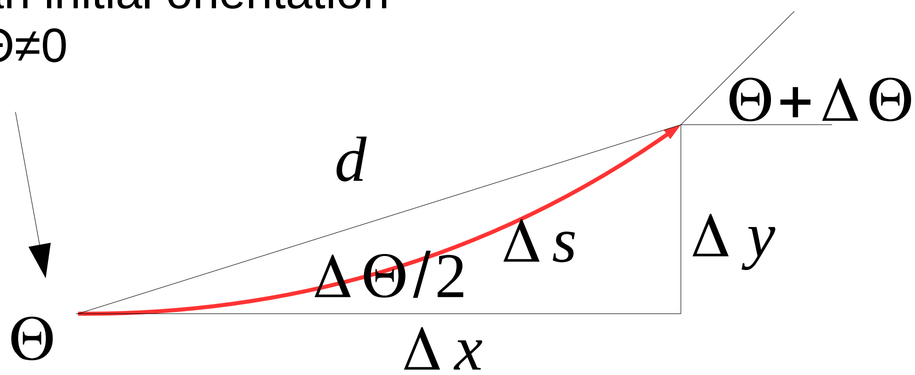
$$\begin{aligned} \alpha &= \Delta S_l / R \\ &= \frac{\Delta S_r - \Delta S_l}{2L} \end{aligned}$$

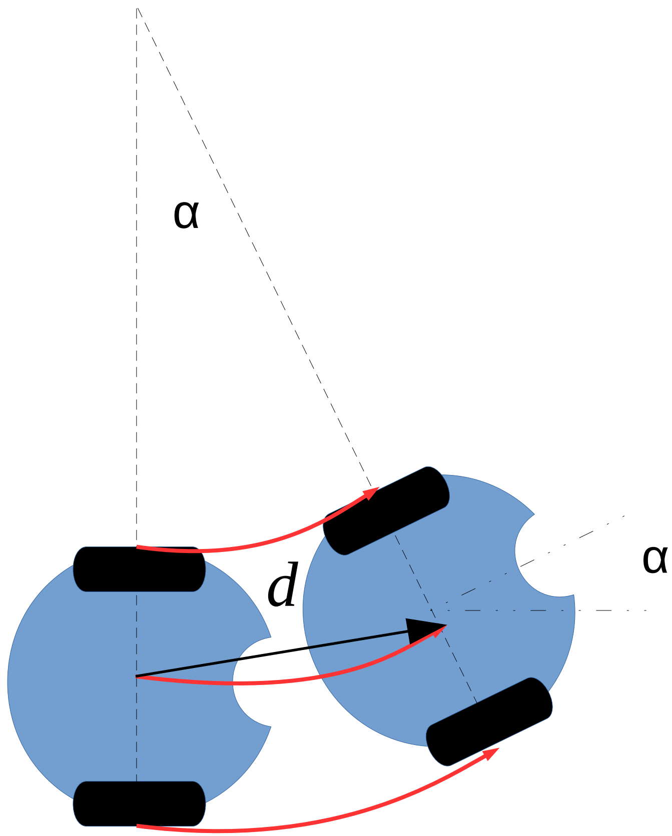
$$\Delta\Theta \simeq \frac{\Delta S_r - \Delta S_l}{2L}$$



$$\Delta\Theta \simeq \alpha$$

Robot may have
an initial orientation
$\Theta \neq 0$





Projection of *d* on the *x* and *y* axis

$$\Delta x = \Delta d \cos\left(\Theta + \Delta\Theta/2\right)$$
$$\Delta y = \Delta d \sin\left(\Theta + \Delta\Theta/2\right)$$

If Δs very small:

$$\Delta x = \Delta s \cos\left(\Theta + \Delta\Theta/2\right)$$
$$\Delta y = \Delta s \sin\left(\Theta + \Delta\Theta/2\right)$$

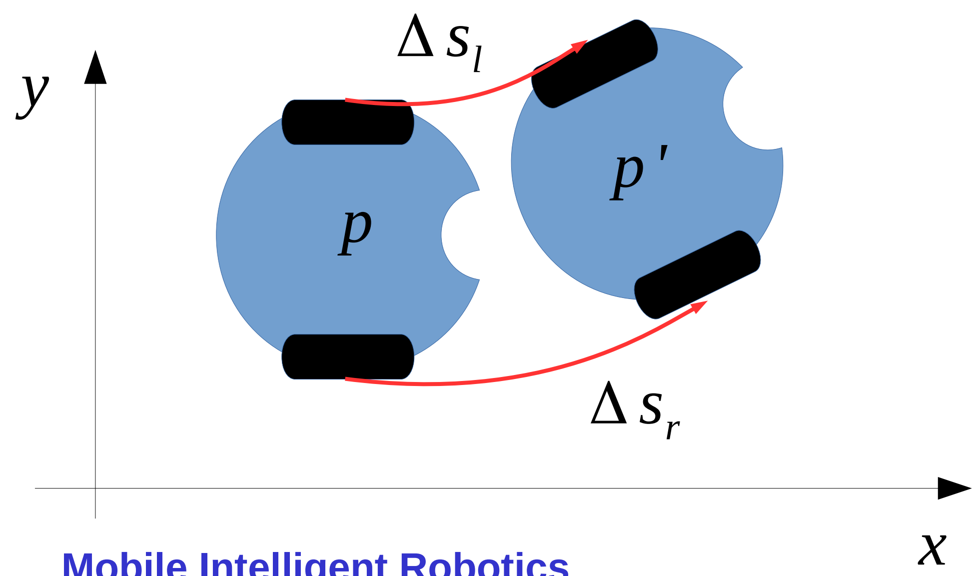
Initial pose:

$$p=\begin{bmatrix} x \\ y \\ \Theta \end{bmatrix}$$

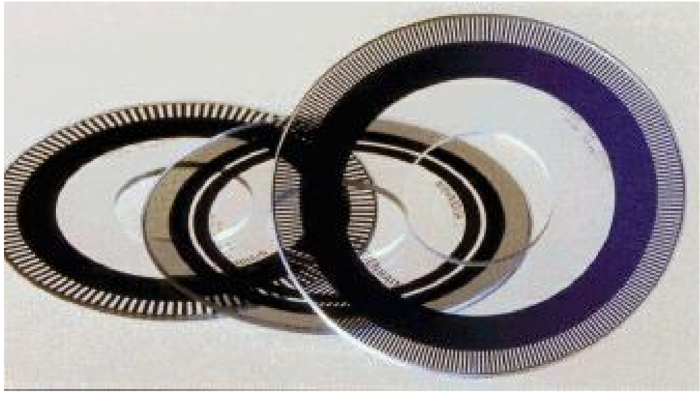
$$\Delta x=\Delta s\cos\left(\Theta+\Delta\Theta/2\right)$$
$$\Delta y=\Delta s\sin\left(\Theta+\Delta\Theta/2\right)$$
$$\Delta\Theta\simeq\frac{\Delta s_r-\Delta s_l}{2L}$$
$$\Delta s=\frac{\Delta s_l+\Delta s_r}{2}$$

Final pose (after displacement)

$$p'=\begin{bmatrix} x \\ y \\ \Theta \end{bmatrix}+\begin{bmatrix} \frac{\Delta s_l+\Delta s_r}{2}\cos\left(\Theta+\Delta\Theta/2\right) \\ \frac{\Delta s_l+\Delta s_r}{2}\sin\left(\Theta+\Delta\Theta/2\right) \\ \frac{\Delta s_r-\Delta s_l}{2L} \end{bmatrix}$$



optical encoder

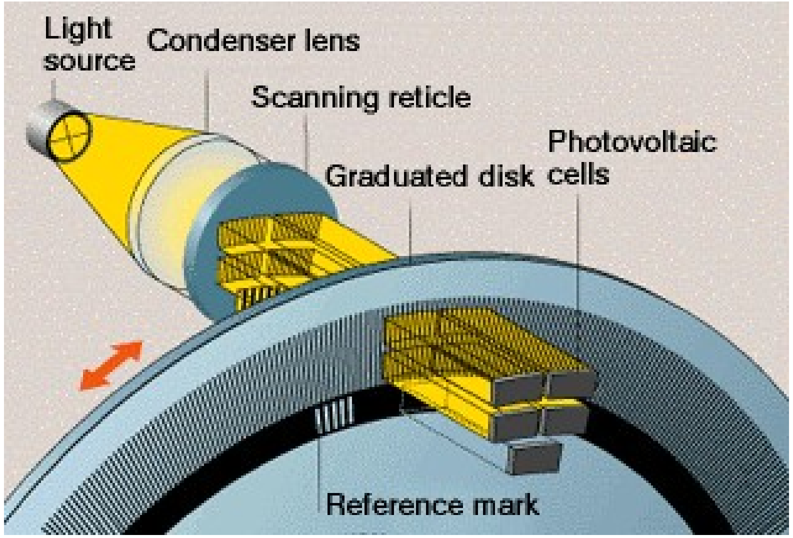


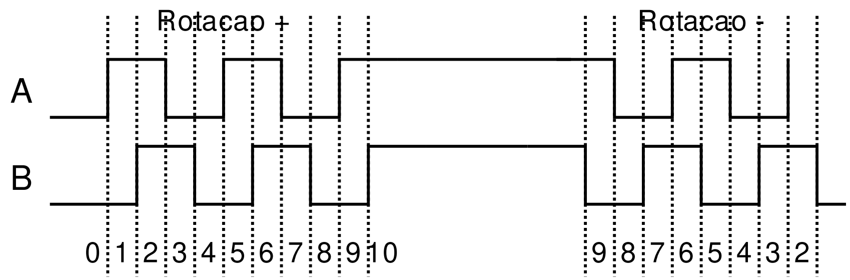
- Pulses generated by the interference of two patterns of stripes
- encoder characterized by p.p.r. (pulses per revolution)
- # of pulses proportional to displacement

$$\alpha = \frac{\text{count}}{\text{p.p.r.}} \cdot 2\pi$$

optical encoder

- Interference generates a varying signal with displacement
- This signal is converted to digital

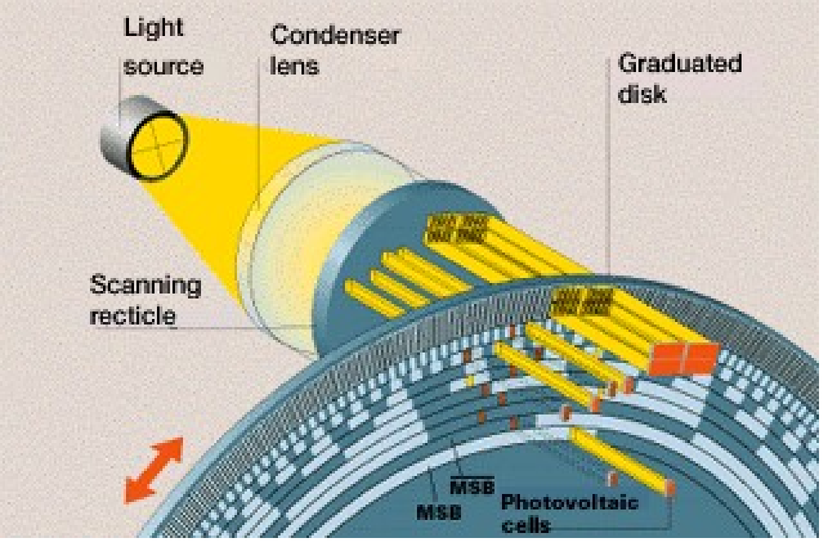


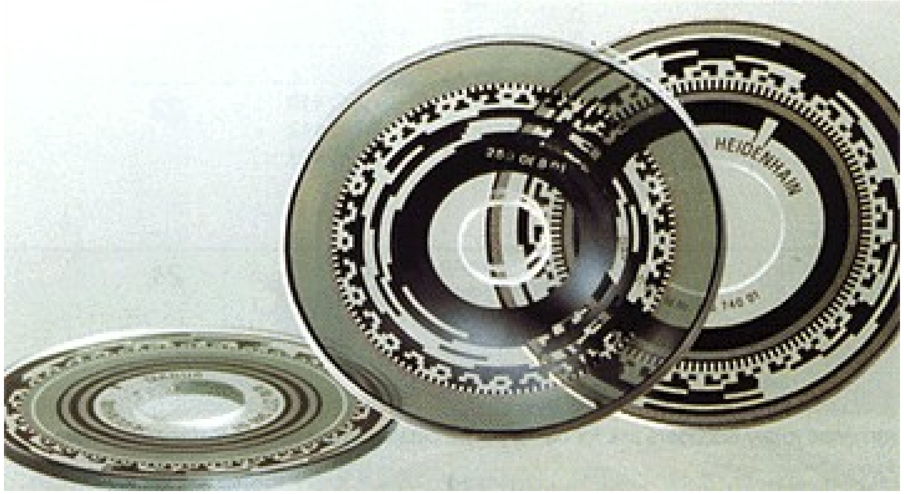


- Quadrature allows:
  - to detect the direction of movement
  - multiply encoder resolution by 4
    - 1 impulse = 4 counts

absolute encoder

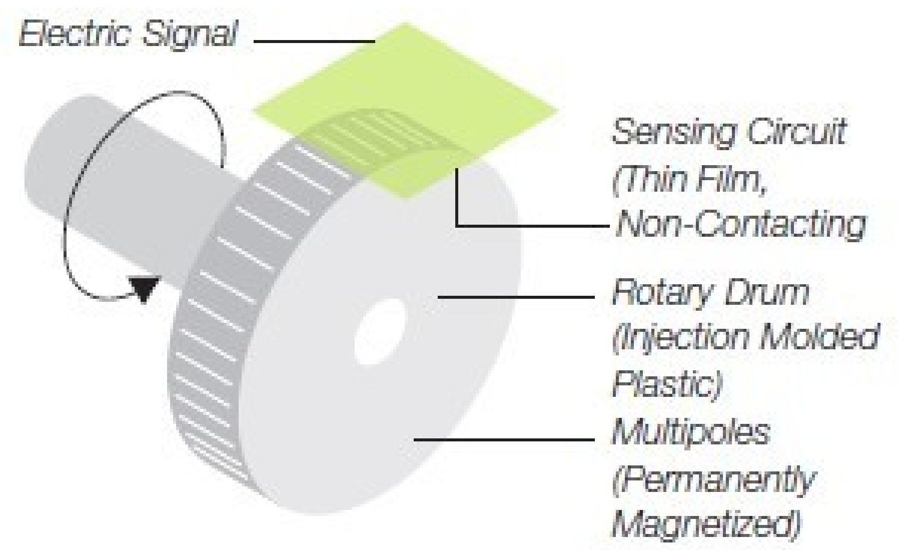
- optical disk with Gray code
- output is shaft position (angle) in binary code





magnetic encoder

- principle similar to optical incremental encoder
- small permanent magnets in the shaft drum
- sensing circuit detects passing magnets and measures rotation
- Pro: unaffected by dust, moisture, and extreme temperatures, and shock.

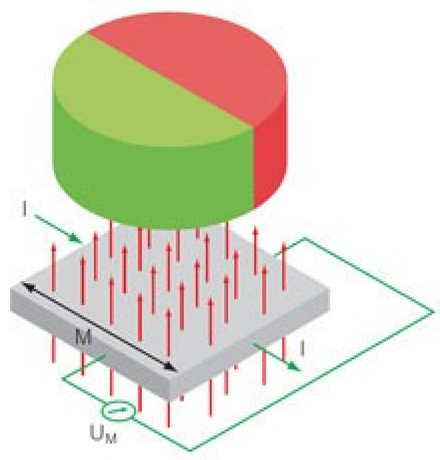


- bicycle computers work in a similar fashion

https://www.bicycle-guider.com/cycling-advice/best-bike-computers-buyers-guide/

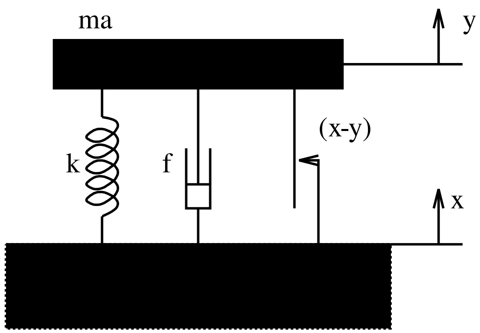
hall effect encoder

- Based on **Hall effect**
  - production of a voltage difference (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current
- A permanent magnet is attached to the shaft
- Orientation of magnetic field is detected by an array sensor



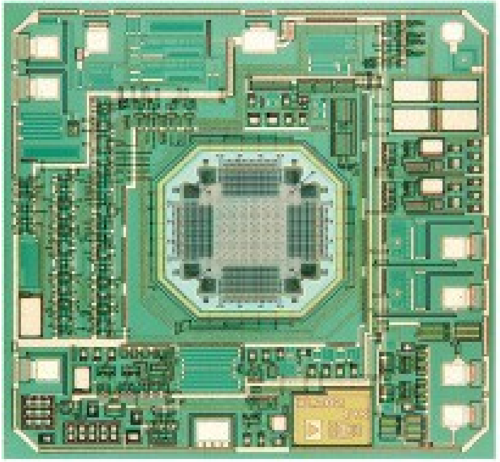
https://www.dynapar.com/Technology/Encoder_Basics/Magnetic_Encoder/

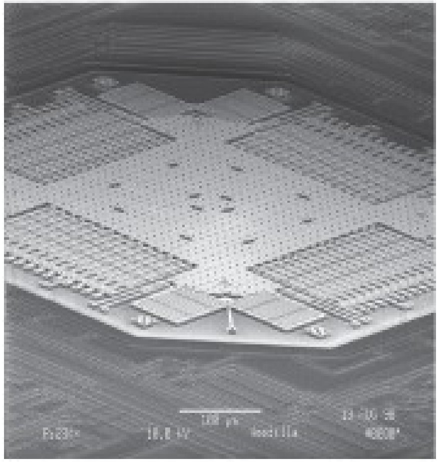
accelerometers



$$k(x-y)+f(\dot{x}-\dot{y})-m_a\ddot{y}=0$$

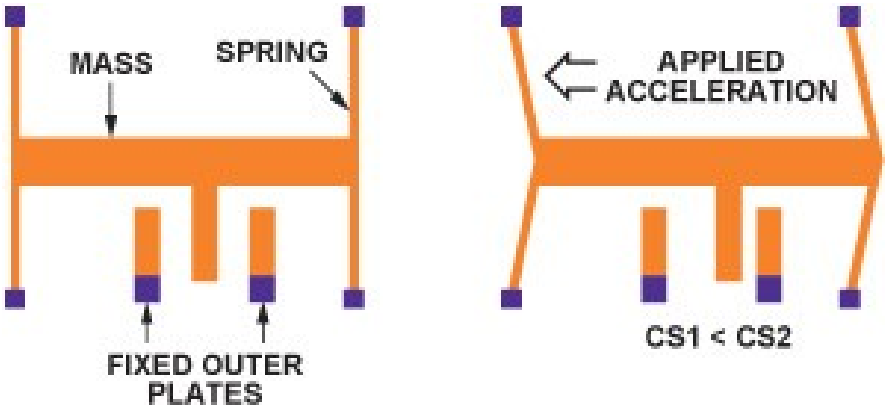
- inertial mass principle
- Ex.: ADXL... from Analog Devices
- MEMS: Micro-electromechanical Systems

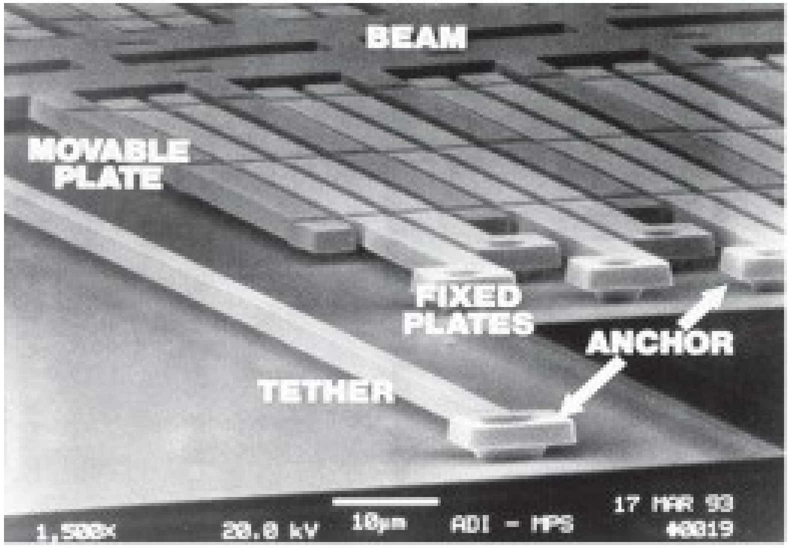




accelerometers

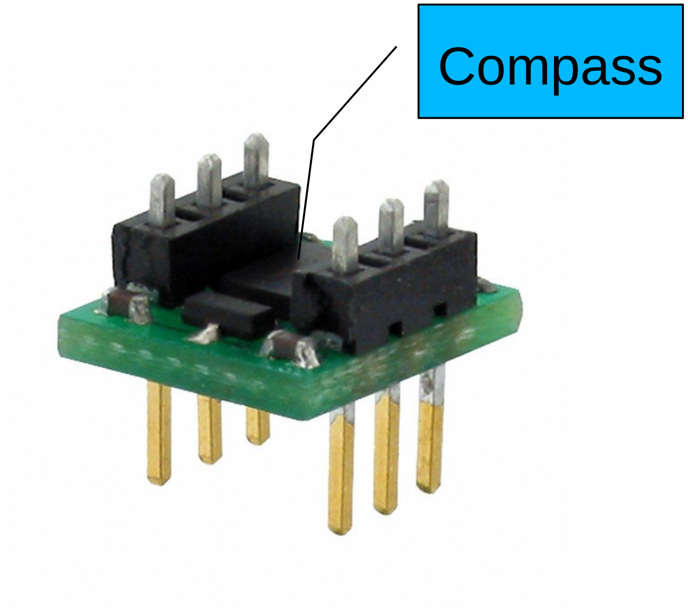
- Detection by changes on:
  - capacity
  - resistance

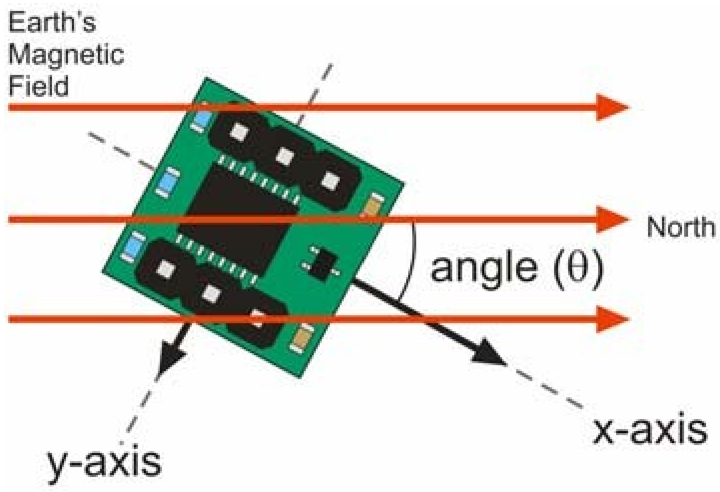




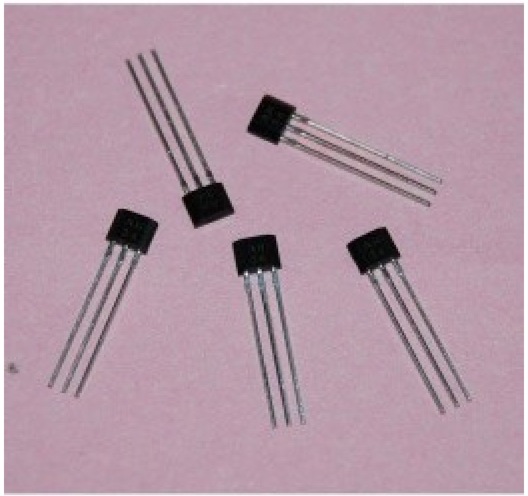
compass

- Ex.: HM55B (Hitachi)
  - Magnetic field detection in 2 axes, x e y
  - Trigonometry is used to compute angle with magnetic N





working principle



- **Hall effect**
  - voltage as a function of magnetic field

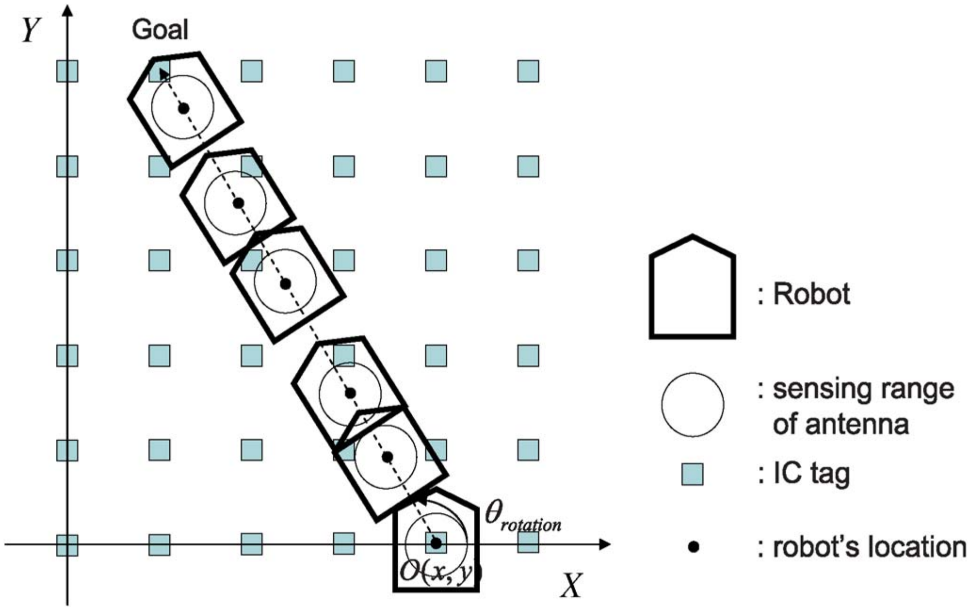
Gyroscopes

- Based on inertia principle
  - rotating disk
- Electronic devices based on mechanical oscillation
  - Foucault pendulum

Navigate :: use external references

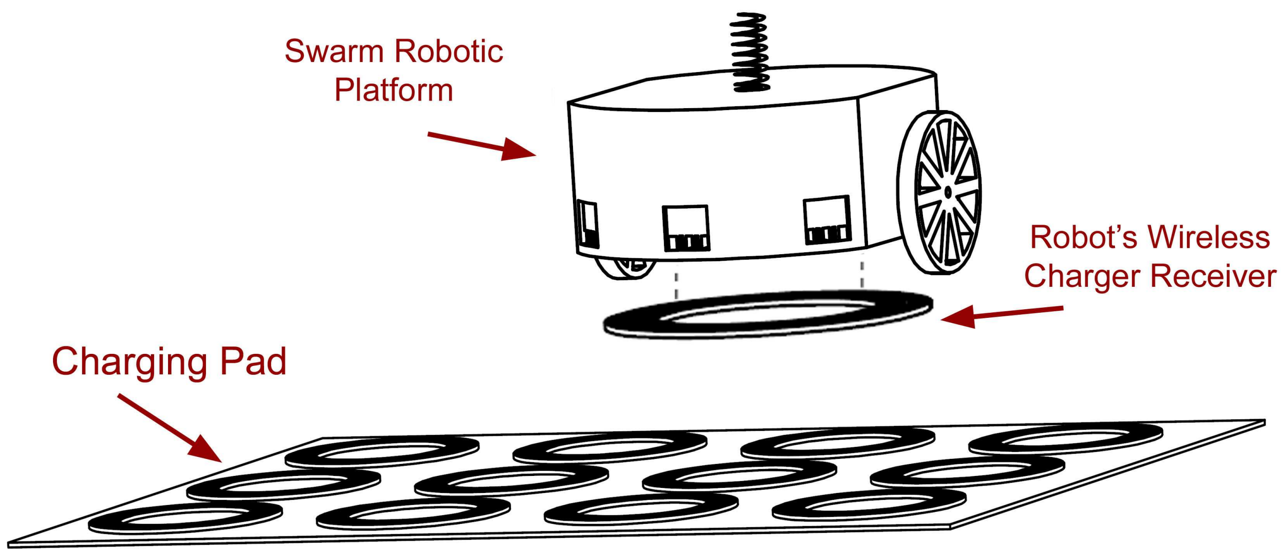
RFID location

- set of RFID tags installed in the floor
  - identifying the tag allows knowledge of position.



[1] Sunhong Park e Shuji Hashimoto, «Autonomous Mobile Robot Navigation Using Passive RFID in Indoor Environment», IEEE Transactions on Industrial Electronics, vol. 56, n. 7, Jul 2009.

Charging and location

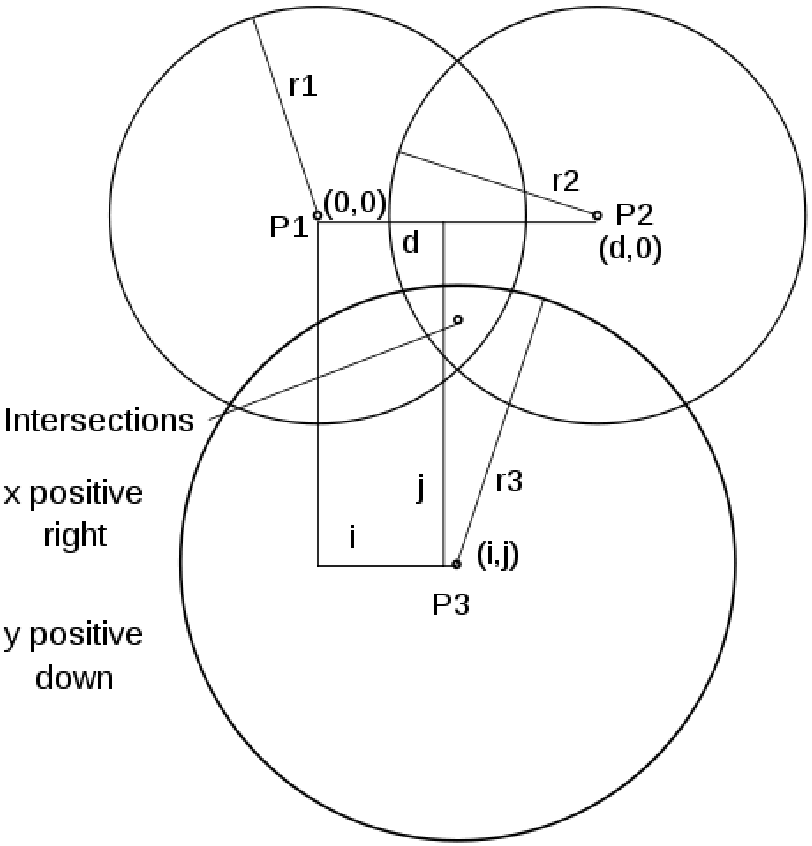


Coils in the floor can work for both:
- Charging (Dynamic Wireless Charging)
- Location

Li, Y., Zhong, L., & Lin, F. (2021). Predicting-Scheduling-Tracking: Charging Nodes With Non-Deterministic Mobility. Ieee Access, 9, 2213–2228. https://doi.org/10.1109/ACCESS.2020.3046857

trilateration

- computing position by measuring distance to 3 reference points
- TOF: ultra-sounds
- RSSI: radio signal
    - D. Hahnel, W. Burgard, D. Fox, K. Fishkin, e M. Philipose, «Mapping and localization with RFID technology», 2004, pp. 1015-1020 Vol.1.



$$
\begin{aligned}
d_1^2 &= (x - x_1)^2 + (y - y_1)^2 \\
&= x^2 - 2 x x_1 + x_1^2 + y^2 - 2 y y_1 + y_1^2 \\
d_2^2 &= x^2 - 2 x x_2 + x_2^2 + y^2 - 2 y y_2 + y_2^2 \\
&\dots \\
d_n^2 &= x^2 - 2 x x_n + x_n^2 + y^2 - 2 y y_n + y_n^2
\end{aligned}
$$

Subtracting the first equation from equations 2 to n:

$$
\begin{aligned}
d_2^2 - d_1^2 &= 2 x (x_1 - x_2) + x_2^2 - x_1^2 + 2 y (y_1 - y_2) + y_2^2 - y_1^2 \\
d_3^2 - d_1^2 &= 2 x (x_1 - x_3) + x_3^2 - x_1^2 + 2 y (y_1 - y_3) + y_3^2 - y_1^2 \\
&\dots \\
d_n^2 - d_1^2 &= 2 x (x_1 - x_n) + x_n^2 - x_1^2 + 2 y (y_1 - y_n) + y_n^2 - y_1^2
\end{aligned}
$$

$$
\begin{aligned}
2(x_1-x_2)x+2(y_1-y_2)y &= d_2^2-d_1^2+x_1^2-x_2^2+y_1^2-y_2^2\\
2(x_1-x_3)x+2(y_1-y_3)y &= d_3^2-d_1^2+x_1^2-x_3^2+y_1^2-y_3^2\\
&\dots\\
2(x_1-x_n)x+2(y_1-y_n)y &= d_n^2-d_1^2+x_1^2-x_n^2+y_1^2-y_n^2
\end{aligned}
$$

$$
\begin{bmatrix} 2(x_1-x_2) & 2(y_1-y_2)\\ 2(x_1-x_3) & 2(y_1-y_3)\\ \dots & \dots\\ 2(x_1-x_n) & 2(y_1-y_n) \end{bmatrix}
\begin{bmatrix} x\\ y \end{bmatrix} =
\begin{bmatrix} d_2^2-d_1^2+x_1^2-x_2^2+y_1^2-y_2^2\\ d_3^2-d_1^2+x_1^2-x_3^2+y_1^2-y_3^2\\ \dots\\ d_n^2-d_1^2+x_1^2-x_n^2+y_1^2-y_n^2 \end{bmatrix}
$$

$$A\,X = B$$

$$A = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) \\ \ldots & \ldots \\ 2(x_1 - x_n) & 2(y_1 - y_n) \end{bmatrix} \quad X = \begin{bmatrix} x \\ y \end{bmatrix}$$

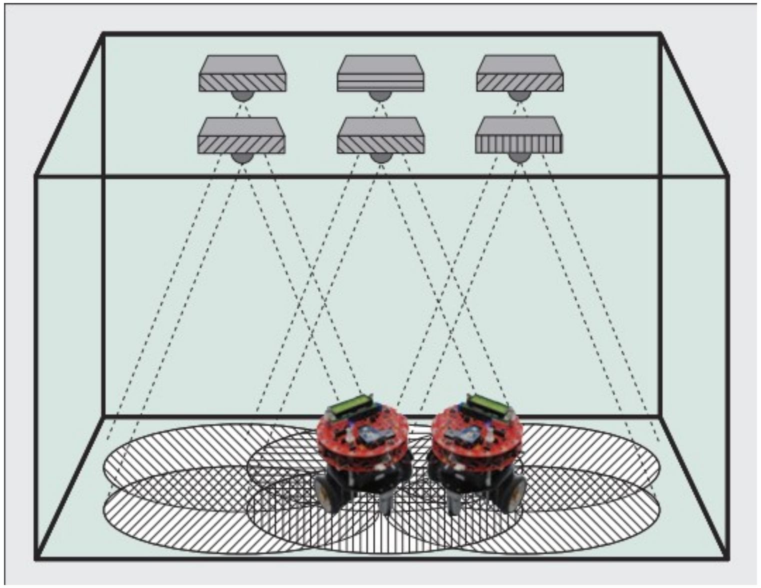
A least-square approximation can be found by using the Moore-Penrose pseudo-inverse:

$$X = (A^T \cdot A)^{-1} A^T B$$

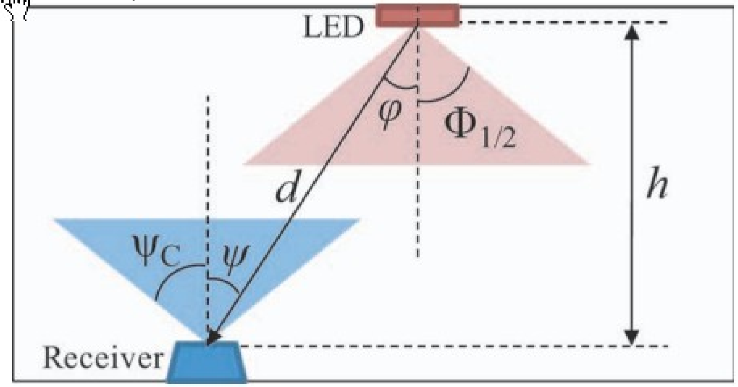
$$B = \begin{bmatrix} d_2^2 - d_1^2 + x_1^2 - x_2^2 + y_1^2 - y_2^2 \\ d_3^2 - d_1^2 + x_1^2 - x_3^2 + y_1^2 - y_3^2 \\ \ldots \\ d_n^2 - d_1^2 + x_1^2 - x_n^2 + y_1^2 - y_n^2 \end{bmatrix}$$

visible light positioning (VLP)

- Conditions
  - widespread use of LED for illumination
  - LEDs allow light modulation → VLC (visible light communication)
- VLC + AOA (Angle of Arrival) = VLP
  - AOA is not the only method



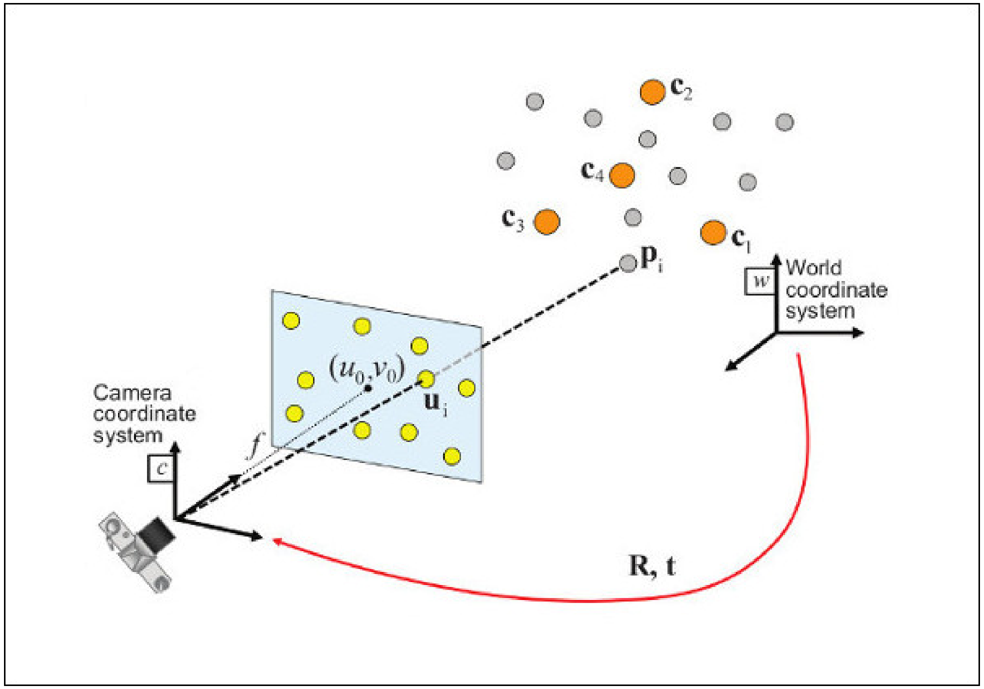
J. Armstrong, Y. Sekercioglu, e A. Neild, «Visible light positioning: a roadmap for international standardization», *Communications Magazine, IEEE*, vol. 51, n. 12, pp. 68–73, Dez. 2013.



S.-Y. Jung, S. Hann, S. Park, e C.-S. Park, «Optical wireless indoor positioning system using light emitting diode ceiling lights», *Microwave and Optical Technology Letters*, vol. 54, n. 7, pp. 1622–1626, 2012.

Visible Light Positioning

- Perspective-N-Point



$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \mathbf{A}\,\mathbf{\Pi}\,{}^{\mathbf{c}}\mathbf{T}_{\mathbf{w}} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

This matrix contains the camera (~robot) position coordinates in the world

visible light positioning (VLP)

sensor classification

- Proprioceptive / exteroceptive
  - Proprioceptive information internal to the robot.
    - Ex: motor speed, battery voltage, ...
  - Exteroceptive: external information to the robot
    - Ex .: distance to objects, light intensity
- Passive / Active
  - Passive: have no explicit source of energy; energy required comes from the measurement process itself
    - Ex temperature probes .:
  - Active: have internal power source, necessary for the measurement process; uses that energy to interact with the environment
    - Ex .: laser range finder

Classification	Sensor	PC/EC	A/P
Tactile Sensors	Switches	EC	P
	Optical barrier	EC	A
	Contactless proximity sensors	EC	A
Wheels and motors	Potentiometers	PC	P
	Synchros and resolvers	PC	A
	Optical encoders	PC	A
Orientation	Compass	EC	P
	Gyroscope	PC	P
	Inclinometer	EC	A/P
Localization	GPS	EC	A
	RF beacons	EC	A
	Reflected beams	EC	A
Ranging	Sensores ultrassons	EC	A
	Laser Range Finder	EC	A
	Optical triangulation	EC	A
Vision	CCD/CMOS cameras	EC	P

R. Siegwart e I. R. Nourbakhsh, *Introduction to autonomous mobile robots*. Cambridge Mass.: MIT Press, 2004.

Challenge

- Think of a mobile robot mission
- Devise the sensor structure required for that mission
  - What sensors will the robot need?