64-424
Intelligent Robotics

https://tams.informatik.uni-hamburg.de/
lectures/2018ws/vorlesung/ir

Marc Bestmann / Michael Görner / Jianwei Zhang

University of Hamburg
Faculty of Mathematics, Informatics and Natural Sciences
Department of Informatics
Technical Aspects of Multimodal Systems

Winterterm 2018/2019

Outline

1. Rotation / Motion

Outline

1. Rotation / Motion
    - Encoder
    - Resolver
    - IMU
    - Odometry

Optical encoder

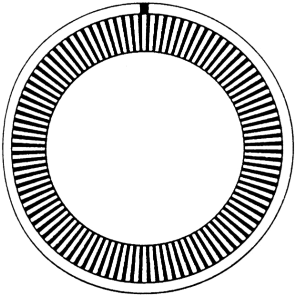
Use of an optical encoder is a well established approach to measurement of angular or linear motion

- The main component is a mask with transparent and opaque areas
- A ray of light cast onto the mask is registered by a photodiode located on the opposite side

- The mask pattern is usually manufactured as a disk or a strip
- **Disk:** Measurement of angular motion (rotation)
- **Strip:** Measurement of linear motion (translation)
- Measurement with respect to time yields angular/linear velocity

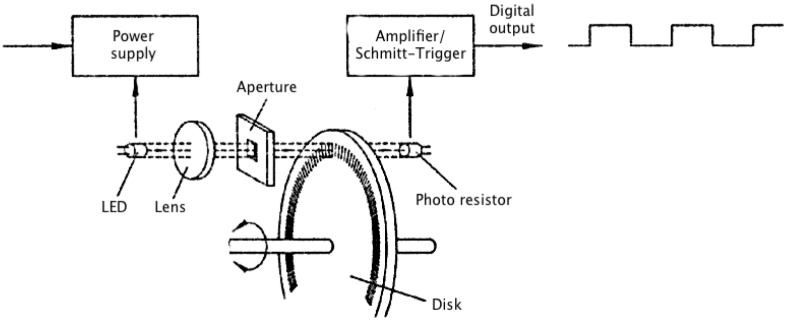
Incremental encoder

- The mask of an incremental encoder consists of equidistant, transparent and opaque areas equal in size



Incremental encoder (cont.)

- A simple (single channel) incremental encoder requires only a single LED [1] and photodiode in order to register motion

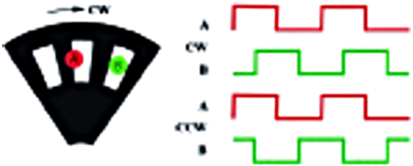


---

[1] Usually within the spectral range of 820nm to 960nm

Dual channel incremental encoder

- Using two LEDs and photodiodes (channels A and B) the direction of angular/linear motion can be determined



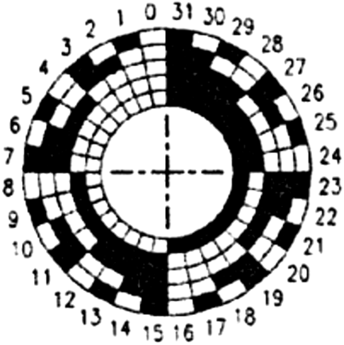
- Quadrature encoder: Separation of A and B by 90°
- Clockwise (CW) rotation → signal A leads
- Counter-clockwise (CCW) rotation → signal B leads

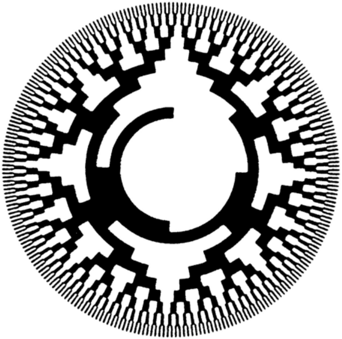
Absolute encoder

- In contrast to an incremental encoder, an absolute encoder provides absolute angles as its output signal

- Absolute encoder uses disk/strip with a binary-encoded pattern
- Several LEDs and photodiodes are used to scan the disk/strip
- One unique binary code is allocated to each resolution step
- Resolution directly affects the measurement accuracy

Absolute encoder (cont.)

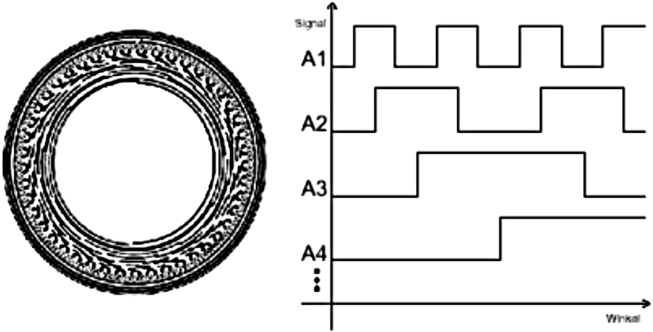




5 bit = 32 steps (11.25°)

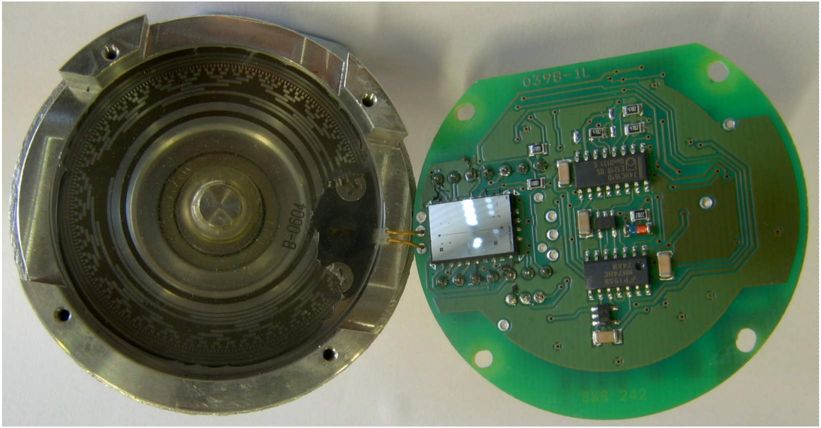
10 bit = 1024 steps (≈ 0.35°)

Absolute encoder (cont.)



- Gray-coded position results in exactly one signal change per tick
- Useful to allow measurement during tick-transition

Absolute encoder (cont.)



Comparison

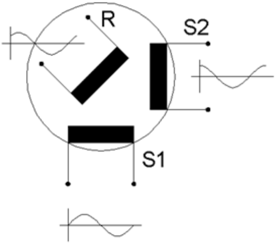
Absolute vs. Incremental

- Absolute encoders are used within systems that require absolute precision and cannot afford re-calibration procedures
  - Robotic manipulators
  - Positioning systems
- Incremental encoders have a lower price point
- They are often used in applications that are insensitive to small amounts of inaccuracy, do not require calibration and are mostly used to measure linear motion
  - Drive system of a mobile robot
  - Some input devices

Resolver

- A resolver is another widely used sensor device to measure angular motion
- Based on electromagnetic induction
- The most common type is the brushless transmitter resolver

- The brushless transmitter resolver consists of:
  - A reference winding (rotor) (R)
  - Two secondary windings *SIN* (S1) and *COS* (S2) at 90° to each other



Resolver (cont.)

- The reference winding (R) is powered with an alternating voltage V_R using a rotary transformer
- The field of the reference winding induces voltages into the secondary windings:

$$V_{S1} = V_R \sin(\theta)$$

$$V_{S2} = V_R \cos(\theta)$$

- All signals (input and output) are of the same frequency
- For a static rotor angle θ the output signals are sine waves with constant amplitudes

Resolver (cont.)

- The resolver delivers data about the rotor angle θ through relative amplitudes of the output at the secondary windings:

$$\frac{V_{S1}}{V_{S2}} = \frac{\sin(\theta)}{\cos(\theta)} = \tan(\theta)$$

- At any given time the value of θ corresponds to the ratio of V_{S1}/V_{S2}, regardless of speed or acceleration
- With the above the rotor angle θ is given by:

$$\theta = \text{arctan2}(V_{S1}, V_{S2})$$

Comparison

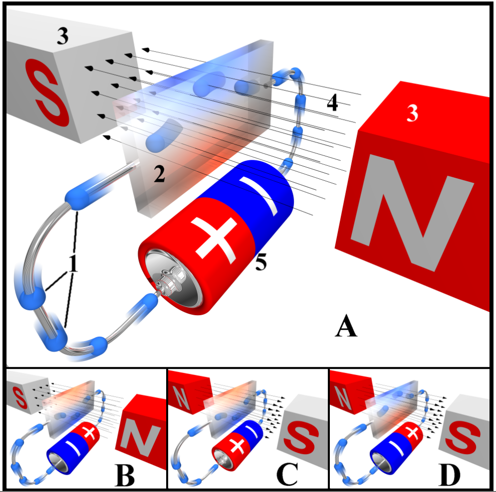
Resolvers vs. Optical encoders

- Resolvers are particularly reliable under demanding conditions
    - The brushless type exhibits virtually no wear
    - The output signal does not drift
    - The effect of extreme temperature conditions is negligible
- However, current resolvers and optical encoders are mostly equal on:
    - Resolution
    - Accuracy
    - Dynamic response

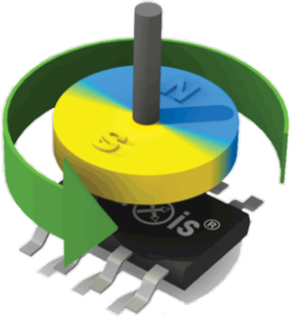
Hall Effect

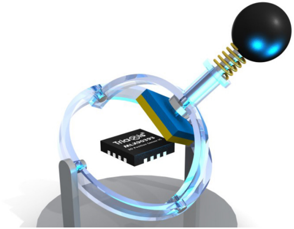
- Lorentz force is acting on charges in a magnetic field
- This results in an voltage difference orthogonal to the current
- This is called Hall effect / Hall voltage

Hall Effect



Hall Effect Sensor





Hall Effect Sensor

- Smaller than the other solutions
- Comparably cheap
- No AC current needed
- Can be influenced by strong magnetic fields

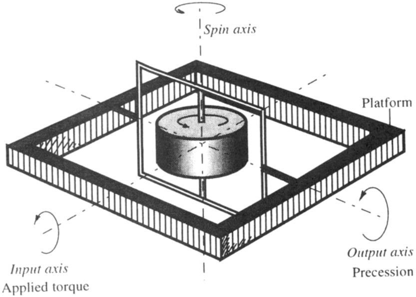
Gyroscope

- A gyroscope is a "direction keeper"
- An alternative to a magnetic compass
- Most commonly used sensor in navigation
- Used in outer space applications

- Categories:
  - Mechanical gyroscope
  - Semiconductor (MEMS) gyroscope
  - . . .

Mechanical gyroscope

- Solid disc rotating around an axis
- Rotation axis (spin axis) is located in a frame
- This frame can rotate around one (or two) axes



Mechanical gyroscope (cont.)

Two useful properties:

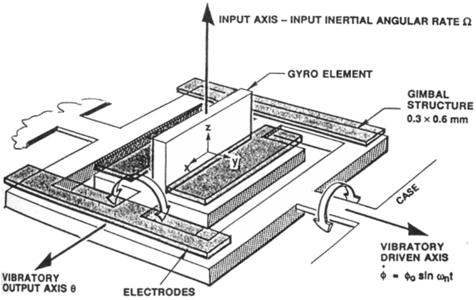
1. Spin axis of a free gyroscope stays fixed in relation to a global coordinate system
2. A gyroscope will deliver an output signal (torque) that is proportional to the angular velocity about an axis perpendicular to the spin axis

The second property is a phenomenon called precession

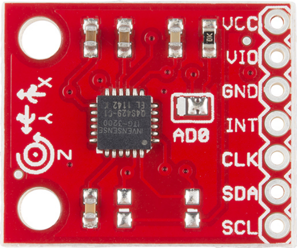
- "Precession is always in such a direction as to align the direction of rotation of the wheel with the direction of rotation of the applied torque"

Semiconductor gyroscope

- Micro-Electro-Mechanical System (MEMS) in silicone
- Manufactures using surface or bulk micromechanic processes
- Various implementations exist



Semiconductor gyroscope (cont.)



Accelerometer

- Relies on displacement of *inertial mass* w.r.t. framing
- Measures *proper* acceleration in one dimension
- This includes gravity as $9.81 \mathrm{m/s^2}$ pointing up

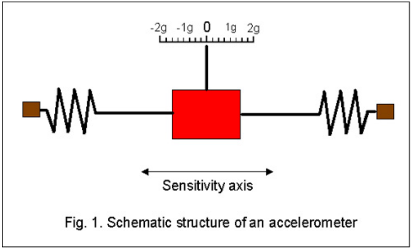


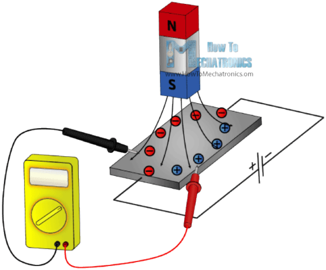
Fig. 1. Schematic structure of an accelerometer

---

[1] `http://rotoview.com/accelerometer_schematic.jpg`

Magnetometer

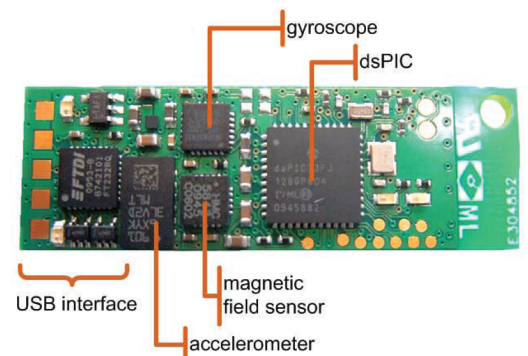
- Compass
- Measures orientation in magnetic field
- Most sensors are based on measuring the Hall effect
- Application in robotics is difficult due to electromagnetic fields



---

[1] `http://howtomechatronics.com`

Inertial Measurement Unit (IMU)



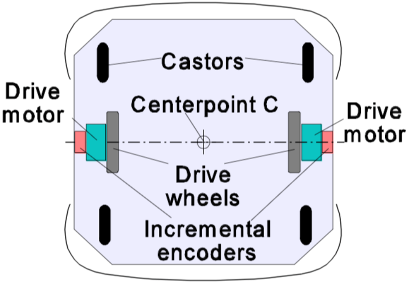
- In practice gyroscopes, accelerometers, and magnetometers are often combined in one device
- This yields a good estimate of the orientation of the device

---

[1] https://commons.wikimedia.org/wiki/File%3AETHOS_pcb.png

Encoder applications

- Most common use case: Combination with motors
- Used to measure:
  - Absolute/relative angle
  - Direction of the rotation
  - Angular/linear velocity
- Knowledge about connected transmission and wheels allows to determine the distance traveled



Localization of mobile robots

- In most cases, the motors used in mobile robotic systems are equipped with incremental encoders
- Using knowledge about the transmission and the wheel diameter and circumference, the location of the moving robot can be determined
- A global coordinate frame must be referenced for this purpose

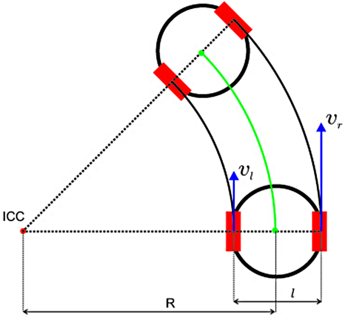
- This basic procedure for the localization of mobile robots is called dead-reckoning
- The relative position and orientation of the mobile robot is determined using the history of accumulated measurement values from the incremental encoders

Dead-reckoning

- The simplest case of dead-reckoning for mobile robots can be set up using a differential drive
- On a differential drive, the two wheels of a robot are located on a shared axis
- Wheel speeds can be controlled and adjusted separately
- The center of the robot is located in the middle of the link between the two wheels
- If wheel speeds are equal, the robot moves forward or backward
- If wheel speeds differ, the robot moves along a circular path

Dead-reckoning (cont.)

- The center of the circular path which the robot moves along is necessarily a point on the shared axis of the wheels
- This point is called the instantaneous center of curvature (ICC)
- Variation of the wheel speeds changes the location of the ICC



Dead-reckoning (cont.)

- Let ω be the angular velocity of the rotation of the robot around the instantaneous center of curvature
- Let ℓ be the distance (baseline) between the two wheels
- Let R be the distance between the center of the robot and the ICC

The velocities of the wheels (v_l and v_r) are given by:

$$\begin{aligned} v_l &= \omega \cdot (R - \ell/2) \\ v_r &= \omega \cdot (R + \ell/2) \end{aligned}$$

Dead-reckoning (cont.)

- ω, R, v_l and v_r are time-dependent terms

At each point in time ω and R can be calculated as follows:

$$\begin{aligned} \omega(t) &= \frac{v_r(t) - v_l(t)}{\ell} \\ R(t) &= \frac{l}{2} \cdot \frac{v_l(t) + v_r(t)}{v_r(t) - v_l(t)} \end{aligned}$$

Dead-reckoning (cont.)

If $v_l(t) = v_r(t)$:

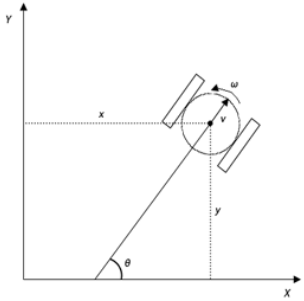
- Equation for the radius is not solvable
- Denominator equals zero
- Radius is effectively infinite
- Robot drives straight ahead

If $v_l(t) = -v_r(t)$:

- Numerator of the equation for the radius becomes zero
- The robot is turning on the spot

Forward kinematics

- While driving, the robot changes its position (x, y) and orientation (θ) in reference to a global or world coordinate system
- The triple (x, y, θ) representing position and orientation is called the pose of the robot
- The angle θ is the angle in relation to the x-axis of the global coordinate system



Forward kinematics (cont.)

- The calculation of the pose which is achieved at given wheel velocities $v_l(t)$ and $v_r(t)$ is called forward kinematics
- In this context the ICC is calculated as follows:

$$ICC = \begin{pmatrix} x - R \cdot \sin(\theta) \\ y + R \cdot \cos(\theta) \end{pmatrix}$$

Forward kinematics (cont.)

Knowing the ICC, the subsequent pose (x', y', θ') of the robot can be determined at the time of $t = t_0 + \delta t$

- If $v_r(t)$ and $v_l(t)$ remain constant

$$\begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} \cos(\omega \cdot \delta t) & -\sin(\omega \cdot \delta t) & 0 \\ \sin(\omega \cdot \delta t) & \cos(\omega \cdot \delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x - ICC_x \\ y - ICC_y \\ \theta \end{bmatrix} + \begin{bmatrix} ICC_x \\ ICC_y \\ \omega \cdot \delta t \end{bmatrix}$$

- Through integration the *pose* of the robot can be determined for any point in time t starting from (x_0, y_0, θ_0) at $t = 0$
- Wheel velocities $v_l(t)$ and $v_r(t)$ must be known

Forward kinematics (cont.)

- Use of incremental encoders allows for a simple calculation of wheel velocities v_l and v_r at any given time
- Carried out periodically (δt), integration turns into accumulation
- It is assumed that the speeds remain constant during δt

- **General issue:** Accumulation of measurement errors!

Odometry

- The process of calculating the pose of a robot based on knowledge about its own actions/motions is called odometry
- Errors in orientation exhibit a strong impact on the deviation of the estimated pose from the real one
- Nevertheless, odometry is used in all established mobile robot systems:
  - Odometry is combined with absolute pose measurements
  - Using landmarks for absolute pose determination, a precise odometry may help reducing the number of landmarks needed
  - Sometimes odometry is the only available source of data

Odometry deviation

Systematic errors caused by:

- Varying wheel diameters
- Actual baseline differs from expected distance
- Wheels are not on the same axis

- Finite resolution of the encoders
- Finite sampling rate of the encoders

- Varying floor friction

Odometry deviation (cont.)

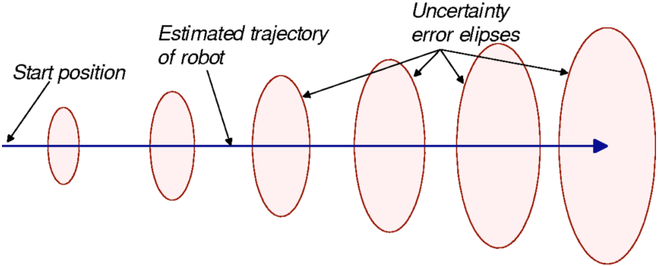
Random errors caused by:

- Uneven ground
- Unexpected objects on the ground

- Spinning wheels
  - Slippery ground
  - Excessive acceleration
  - Skidding (fast turning)
  - Internal/external forces
  - No contact with the ground

Odometry deviation (cont.)

- Only systematic errors are considered, since the upper bound of the effect of random errors is impossible to predict



Multi-sensory Odometry

Odometry can improve through multiple data sources:

- Wheel-based odometry provides superior linear estimates
- IMU (gyroscope) provides superior orientation estimates
- Camera-based Visual Flow provides good odometry in structured environments

"Gyrodometry"

- Compute linear part by wheel-based odometry, use IMU reading for orientation
- Better: Integrate multiple readings through Kalmanfilter

Literature list

[1] Jacob Fraden.
Handbook of Modern Sensors: Physics, Designs, and Applications, chapter 8, pages 327–352.
Springer New York, 4. edition, 2010.