64-424
Intelligent Robotics

https://tams.informatik.uni-hamburg.de/
lectures/2019ws/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 2019/2020

Outline

Overview

- Today we will have a look on how to sense rotation and motion
- First we will talk about sensors which are necessary for this
- Then we will see how we can use them to know where a robot is

Outline

1. Rotation / Motion
    - Encoder
    - Resolver
    - Potentiometer
    - Hall Sensor
    - IMU
    - Odometry

Optical encoder

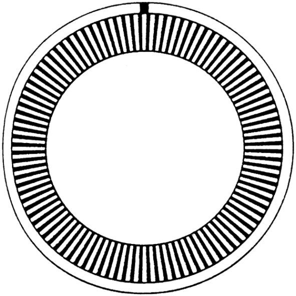
Use of an optical encoder is a well established approach to measurement of angular or linear motion

- 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

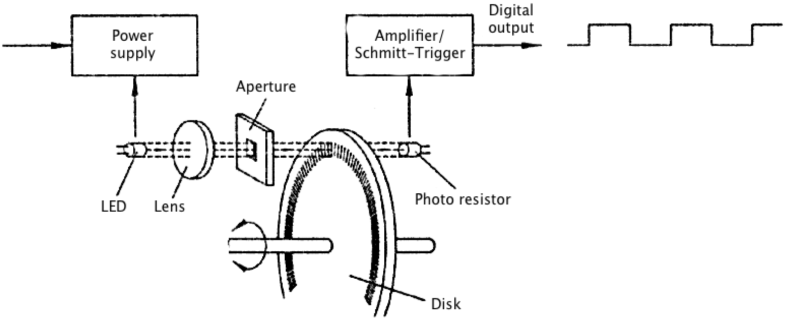
Incremental encoder

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



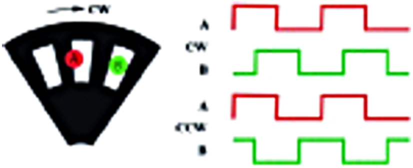
Incremental encoder (cont.)

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



Dual channel incremental encoder

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

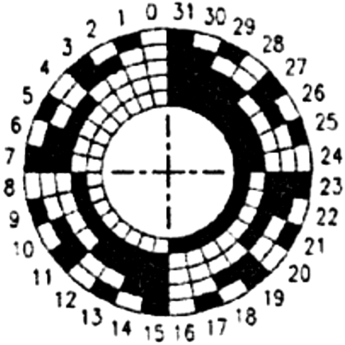


- Quadrature encoder: Separation of A and B by 90°
- Clockwise (CW) rotation → signal A leads
- Counter-clockwise (CCW) rotation → signal B leads

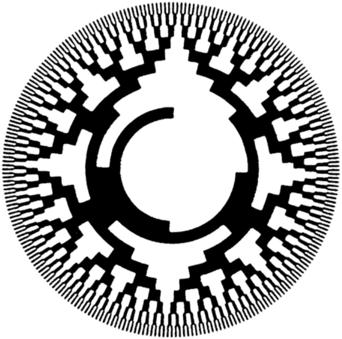
Absolute encoder

- In contrast to an incremental encoder, an absolute encoder provides absolute angles as its output signal
- Advantages:
  - Less errors due to slippage or jumps
  - Initial position not necessary to get current position
- 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.)

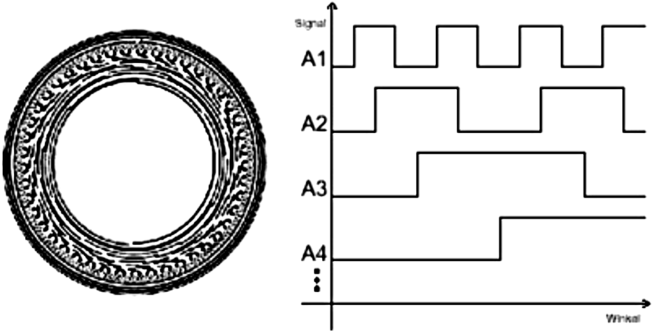


5 bit = 32 steps (11.25°)



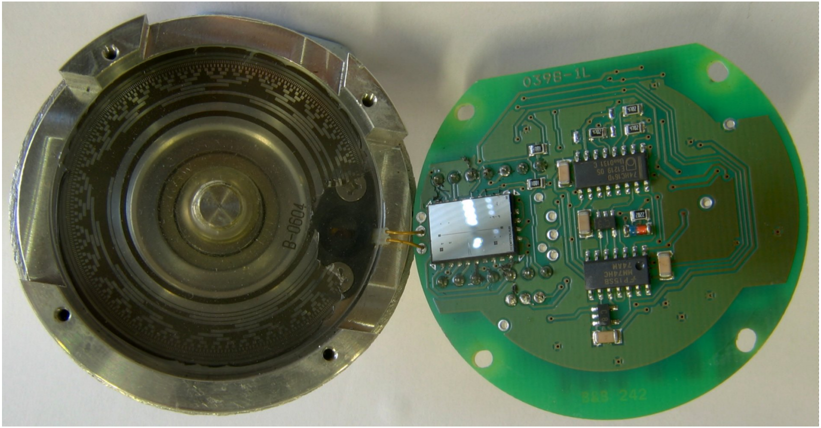
10 bit = 1024 steps (≈ 0.35°)

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

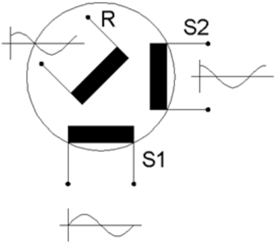
Absolute vs. Incremental

- 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:

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

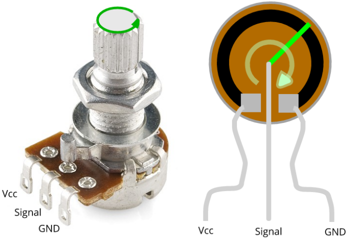
Comparison

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

Potentiometer

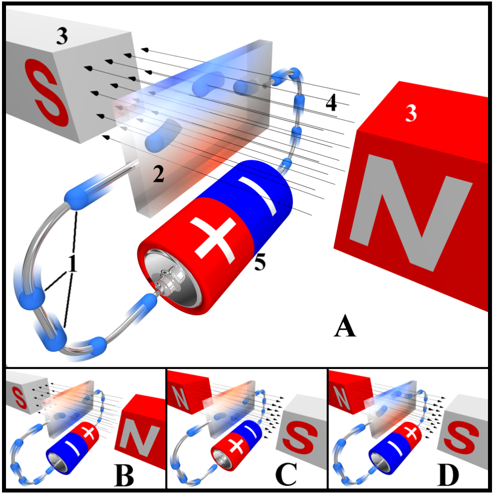
- A potentiometer gives a resistance value in relation to its absolute position
- Often used in user interfaces but also in (cheap) servo motors
- Has (comparably) high wear due direct contact of the material
- 360 degree turn not possible



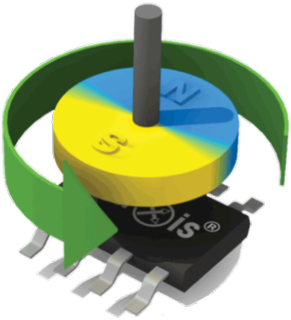
Hall Effect

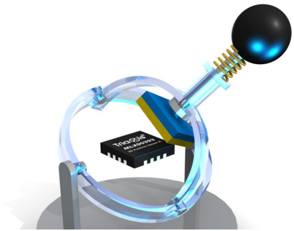
- Lorentz force is acting on charges in a magnetic field
- This results in an voltage difference orthogonal to the current
- This is called Hall effect / Hall voltage

Hall Effect

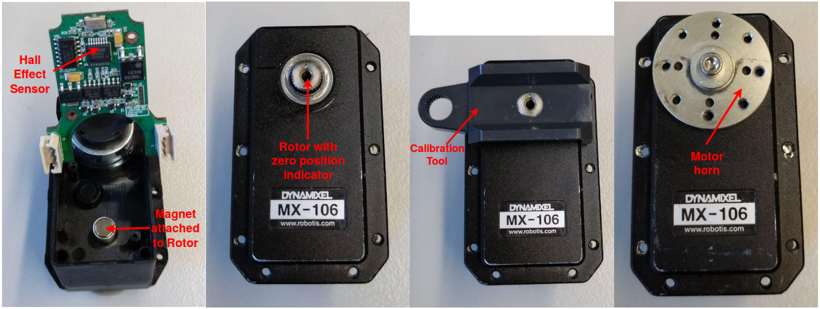


Hall Effect Sensor





Hall Effect Sensor



Jasper Güldenstein, Comparison of Measurement Systems for Kinematic Calibration of a Humanoid Robot

Hall Effect Sensor

Live demo

Hall Effect Sensor

- Smaller than the other solutions
- Comparably cheap
- No AC current needed
- Can be influenced by strong magnetic fields
- Most commonly used in modern robots

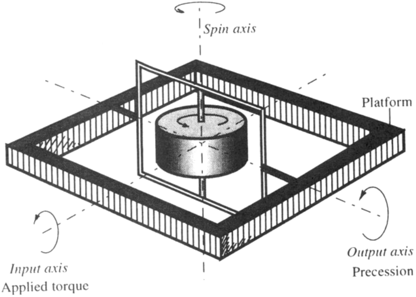
Gyroscope

- 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"

Mechanical Gyroscope

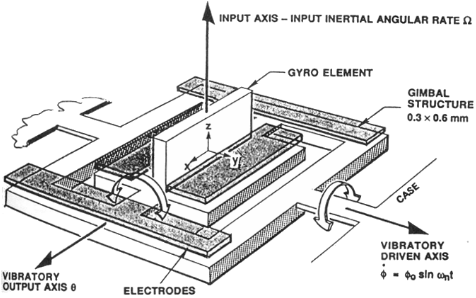
Video

Video2

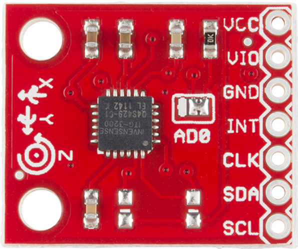
https://www.youtube.com/watch?v=xQb-N486mA4

Semiconductor gyroscope

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



Semiconductor gyroscope (cont.)



Semiconductor gyroscope (cont.)

Video
https://www.youtube.com/watch?v=eqZgxR6eRjo (1:30 - 1:47)

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

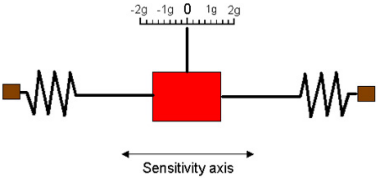
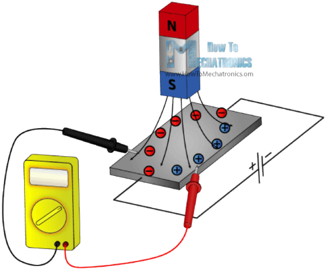


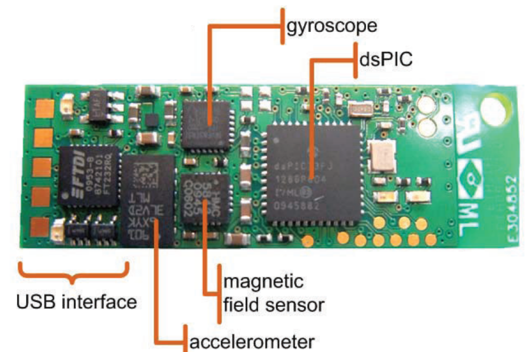
Fig. 1. Schematic structure of an accelerometer

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



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

IMU Application

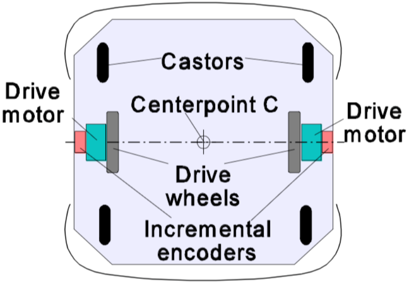
Video
https://www.youtube.com/watch?v=n_6p-1J551Y

IMU Application

Live demo

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

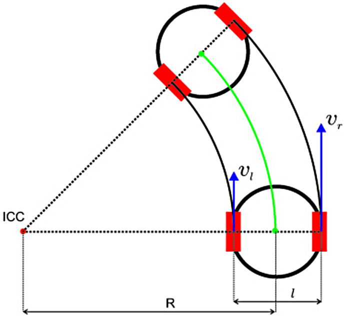
- This basic procedure for the localization of mobile robots is called dead-reckoning
- The relative position and orientation of the mobile robot is determined using the history of accumulated measurement values from the incremental encoders

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
- Cars work in a different way, but will not be discussed here

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

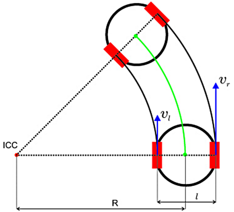


Dead-reckoning (cont.)

- 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:

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



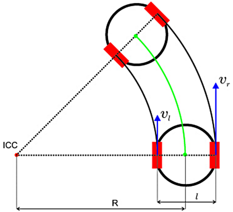
Dead-reckoning (cont.)

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

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

$$\omega(t) = \frac{v_r(t) - v_l(t)}{\ell}$$

$$R(t) = \frac{l}{2} \cdot \frac{v_l(t) + v_r(t)}{v_r(t) - v_l(t)}$$



Dead-reckoning (cont.)

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

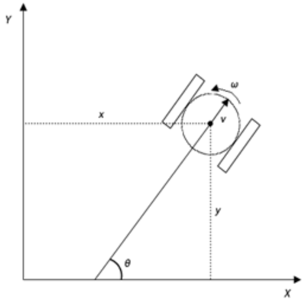
- Equation for the radius is not solvable
- Denominator equals zero
- Radius is effectively infinite
- Robot drives straight ahead

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

Video
https://www.youtube.com/results?search_query=robot-navigation-using-dead-reckoning-techniques

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

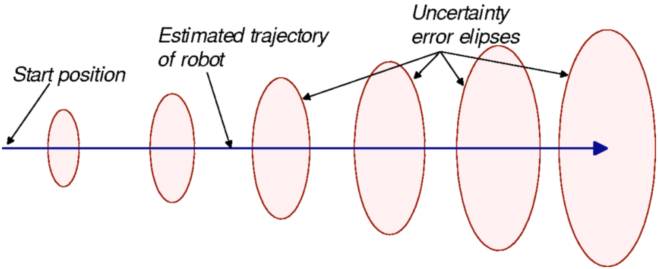
Odometry deviation (cont.)

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

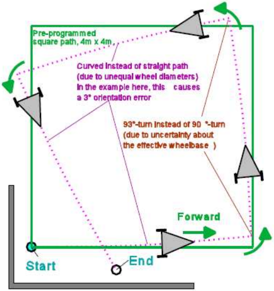
Odometry deviation (cont.)

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



Odometry Calibration

- Systematic errors can be reduced by calibration
- Random errors can't be solved by calibration
- Different calibration procedures are possible



David M. Bradley, Odometry: Calibration and Error Modeling

Multi-sensory Odometry

Odometry can improve through multiple data sources:

- Wheel-based odometry provides superior linear estimates
- IMU (gyroscope) provides superior orientation estimates
- Legged odometry provides equal linear and orientation estimates
  - Quality much lower for running
- Camera-based Visual Flow provides good odometry in structured environments

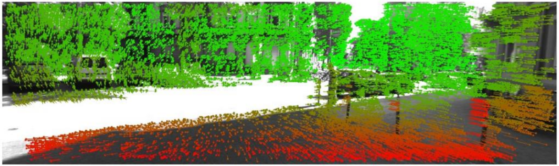
"Gyrodometry"

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

Visual Odometry

- Use of a (mono/stereo/RGB-D) cameras as motion sensor
- Take difference between two sequential images
- Compute movement that caused this difference
- Different approaches exist
    - Classical feature extraction
    - Learned neural networks
    - ...
- Accuracy bound by used image resolution
- Used resolution often bound by hardware, since visual odometry is expensive to compute

Visual Odometry



(a) Feature matching (2 frames, moving camera)

(b) Feature tracking (5 frames, static camera)

Geiger et al., "Stereoscan: Dense 3d reconstruction in real-time"

Visual Odometry

Video
https://www.youtube.com/watch?v=homos4vd_Zs

Visual Odometry

Different error sources are possible:

- Lighting conditions
- Feature less environment
- Repeating features
- Motion blur
- Rolling shutter effect
- Large parts of the visible environment move in relation to the robot (e.g. when there is a bus in the image)

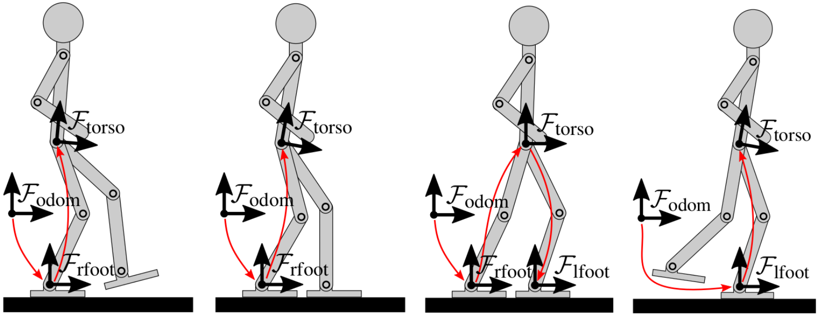
Lidar Odometry

- Similar to visual odometry
- Take "picture" with a laser distance sensor (see lecture "Distance Sensing")
- Compute difference and get motion
- Features are not visual but structural
- Less prone to light problems

Walking Odometry

- On robots with legs, we don't directly get their velocity from the motors
- We need to compute the transformation for each step and sum them up over time
- To compute the transformation of a step, we do forward kinematics through the legs
- We always have one frame on our support foot and a transformation from there to the torso

Walking Odometry



https://www.hrl.uni-bonn.de/teaching/ss19/lecture-humanoid-robotics/slides/hr07_particlefilter.pdf

Walking Odometry

Different error sources are possible:

- Angle of a joint is not correct
- Link length not correctly modeled
- Backlash in joints (depends on the servo)
- Due to multiple joints and links, we have often multiple error sources each step
- Small angular errors (joints), lead quickly to large absolute errors (step position)
- Slippage
- Uneven ground
- ...

Walking Odometry

Video
https://www.youtube.com/watch?v=9HT33KMtfLw

Drone Odometry

- Drones move in all 6 dimensions
- Odometry is therefore a bit more complicated to compute
- Using the rotator speeds to compute odometry is theoretical possible, but not often used
- Mostly "visual inertial odometry" is used, a combination of visual odometry and an IMU

Further Motion Measuring Possibilities

Thou the previously presented approaches are the most used ones, there are other possibilities

- Difference between two absolute positions (derivation is velocity)
  - Visual landmarks (e.g. April Tags)
  - Radio landmarks (e.g. GPS) (see lecture "Distance sensing")
  - Using various distance sensing methods
  - Better to use in combination with Bayes Filter (see lecture "State estimation")
- Doppler effect (not discussed in this lecture)