UiO : Department of Technology Systems
University of Oslo

5. Actuators and Sensors

Kim Mathiassen

Lecture overview

cause to operate

- Joint actuating system
  - Power supply
  - Power amplifier
  - Servomotor
  - Transmission
- Drives
  - Electric drives
  - Transmission effects
- Proprioceptive sensors
  - Position transducers
  - Velocity transducers
- Exteroceptive sensors
  - Force sensors
  - Range sensors
  - Vision sensors

5.1 Joint Actuating System

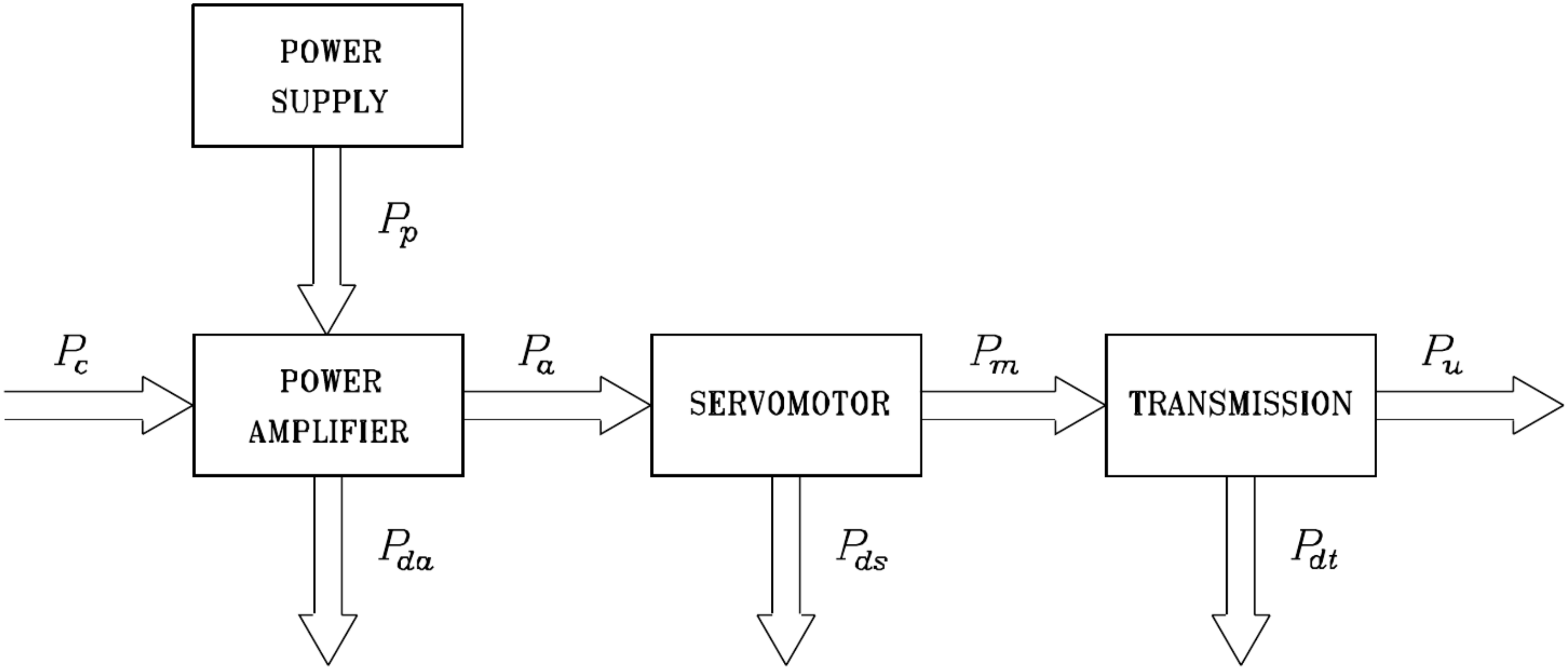


Fig. 5.1. Components of a joint actuating system

Transmissions

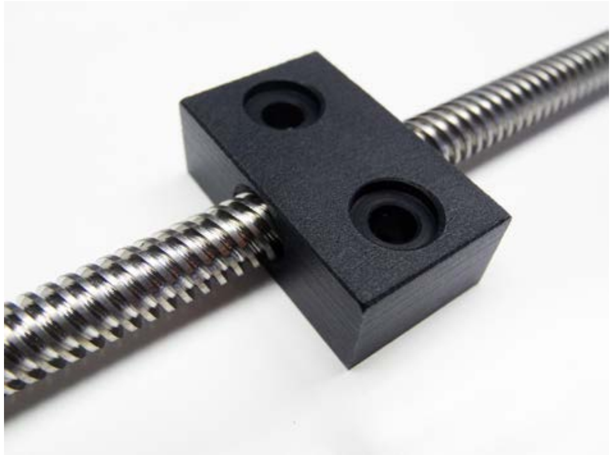
- Demand: low speed and high torque
- Servomotors: high speed and low torque
- Solution: Transmissions (gears)
- Side effect
  - Power lost due to friction
  - Backlash (dødgang)
  - Transmission elasticity

Transmissions

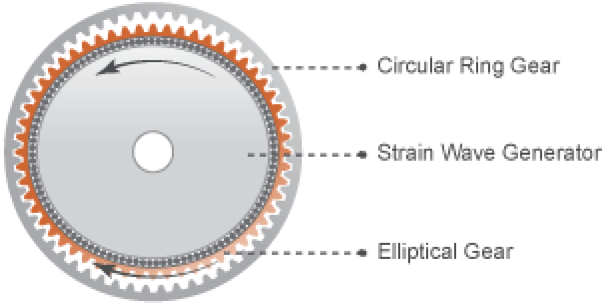
- Transforms the motor output in two ways
  - Quantitatively (velocity and torque)
- Qualitatively (rotation/translation)
- May have motors in the base of the robot, reduces weight
- Direct drive – Motor directly connected to the joint without transmission

Transmission types

Spur gears



Lead screws



Harmonic drive
(no backlash, high gear ratio)

Timing belt and chains

Servomotors

- Pneumatic
  - Using pressurized gass as energy source
  - Hard to control accuratly because of compression errors
  - Not widely employed
- Hydraulic
  - Actuation based compressed fluid
- Electric
  - Actuation based on electric power

Electric vs. hydraulic servomotors

Electric (high speed, low torque)

- Widespread availability of power supply
- Low cost and wide range of products
- High power conversion efficiency
- Easy maintenance
- No pollution in working environment
- Burnout problems in static situations
- Special protection when working in flammable environments

Hydraulic (high torque, low speed)

- Need for hydraulic power station
- High cost, low product range, difficult to miniaturize
- Low power conversion efficiency
- Need for operational maintenance
- Possible oil leakage
- No burnout problems
- Are inherently safe in harmful environments
- Self lubricant, and disposes of heat
- Excellent power to weight ratios

Power amplifiers

adjust

- Modulate the power from the power supply according to the control signal
- For electric motors one use
  - Transistor amplifiers using pulse-width modulation (PWM)
  - DC-to-DC converters (choppers)
  - DC-to-AC converters (inverters)
- For hydraulic motors one control the flow rate of compressed fluid to the motor.
- The flow rate is controlled by a servovalve

Power supply

- Electric servomotors use transformers (AC to DC)
- Hydraulic servomotors use a pump to compress the fluid and a reservoir to store energy
- Power supply for hydraulic servomotors are complex

Example robots: WAM

- «Mechanical transmissions based on advanced, patented high-speed cable transmissions and patented zero-backlash, low-friction, cabled differentials”
- Inherently backdrivable
- Joint torque measurments
- 7 DoF

Example robot: UR5

- Collaborative robot
- Servos in the joints
- 6 DoF
- Brush-less DC motors with harmonic drives

KUKA

ABB
ROBOTICS

5.2 DRIVES

Electric drives

- *Electrical balance of armature*

$$V_a = (R_a + sL_a)I_a + V_g$$
$$V_g = k_v \Omega_m$$

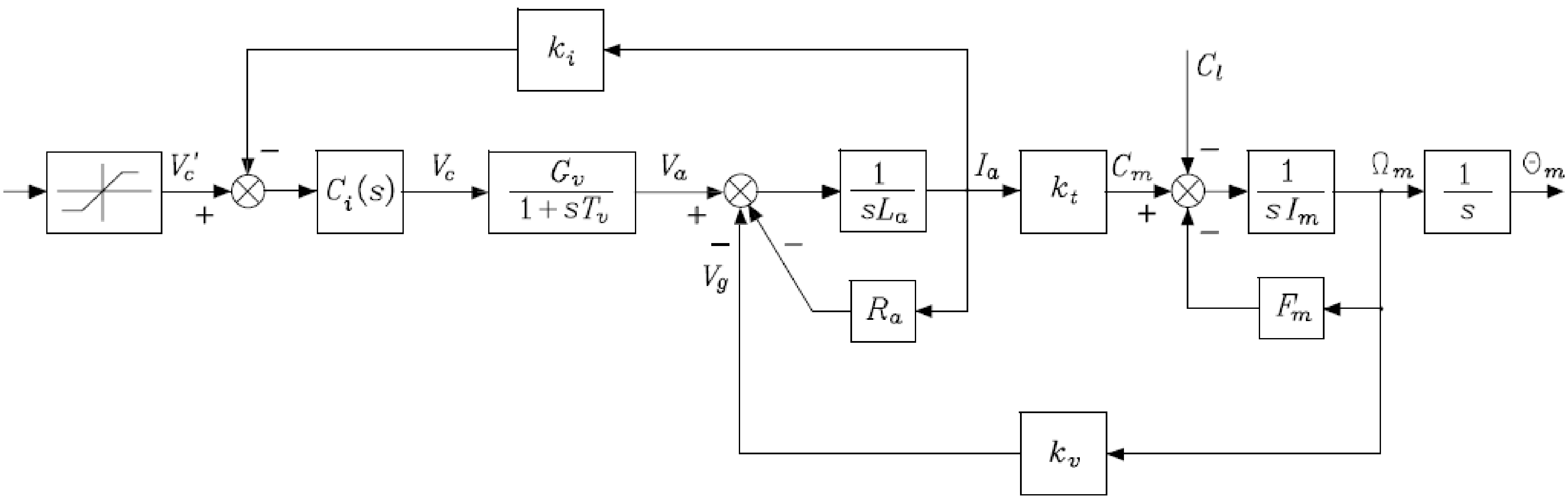
- *Mechanical balance*

$$C_m = (sI_m + F_m)\Omega_m + C_l$$
$$C_m = k_t I_a$$

- *Power amplifier*

$$\frac{V_a}{V_c} = \frac{G_v}{1 + sT_v}$$

Block scheme of an electric drive



Velocity- and torque-controlled generators

- *Steady-state approximations*

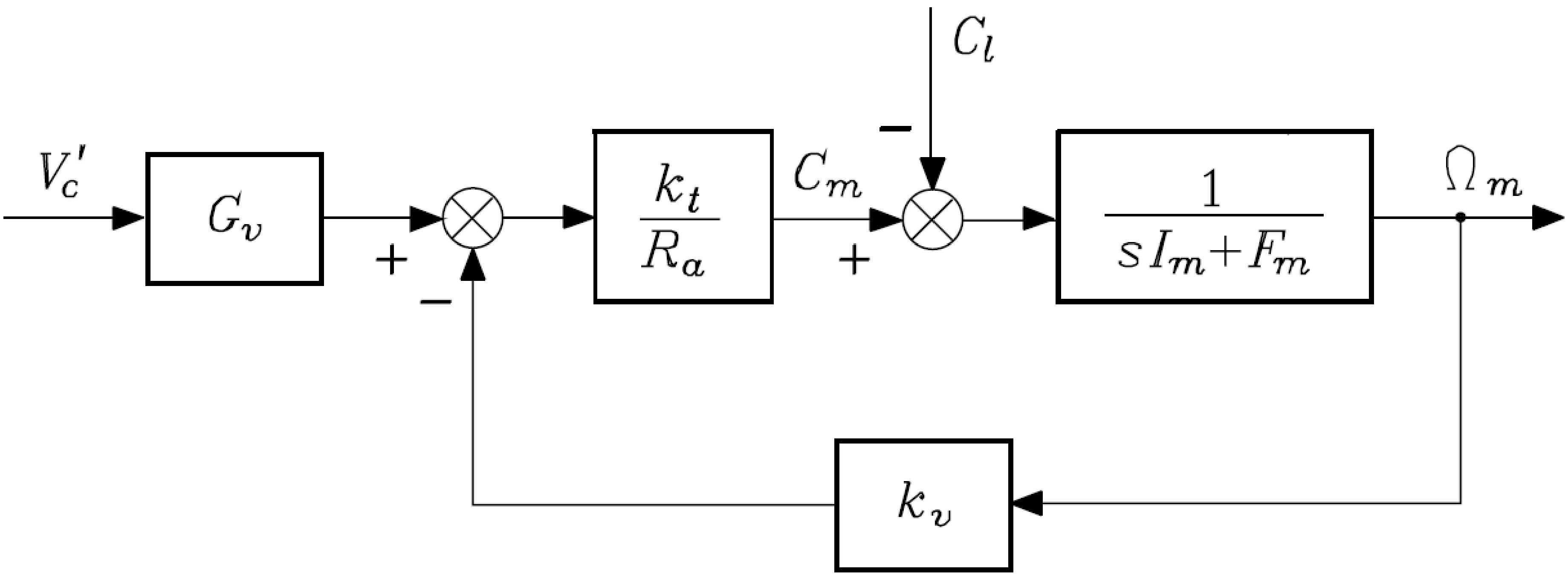
- *Velocity*

$$\omega_m \approx \frac{G_v}{k_v} v_c'$$

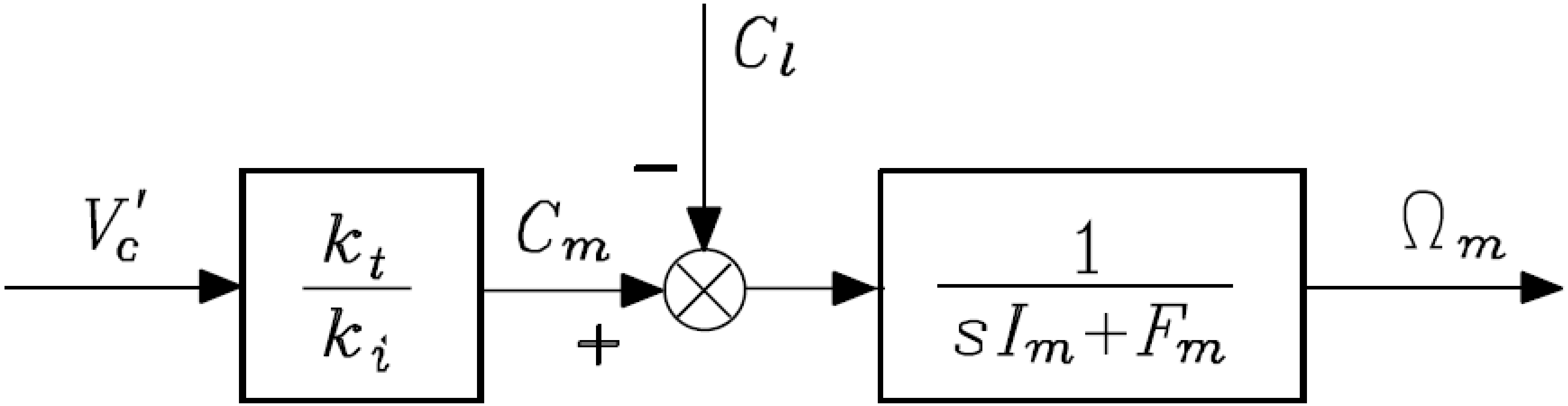
- *Torque*

$$c_m \approx \frac{k_t}{k_i} \left(v_c' - \frac{k_v}{G_v} \omega_m \right)$$

Reduced-order velocity generator



Reduced-order torque generator



Generator transfer functions

- Velocity

$$\Omega_m = \frac{\frac{1}{k_v}}{1 + s\frac{R_a I_m}{k_v k_t}} G_v V_c' - \frac{\frac{R_a}{k_v k_t}}{1 + s\frac{R_a I_m}{k_v k_t}} C_l \qquad (5.9)$$

- Torque

$$\Omega_m = \frac{\frac{k_t}{k_i F_m}}{1 + s\frac{I_m}{F_m}} V_c' - \frac{\frac{1}{F_m}}{1 + s\frac{I_m}{F_m}} C_l \qquad (5.10)$$

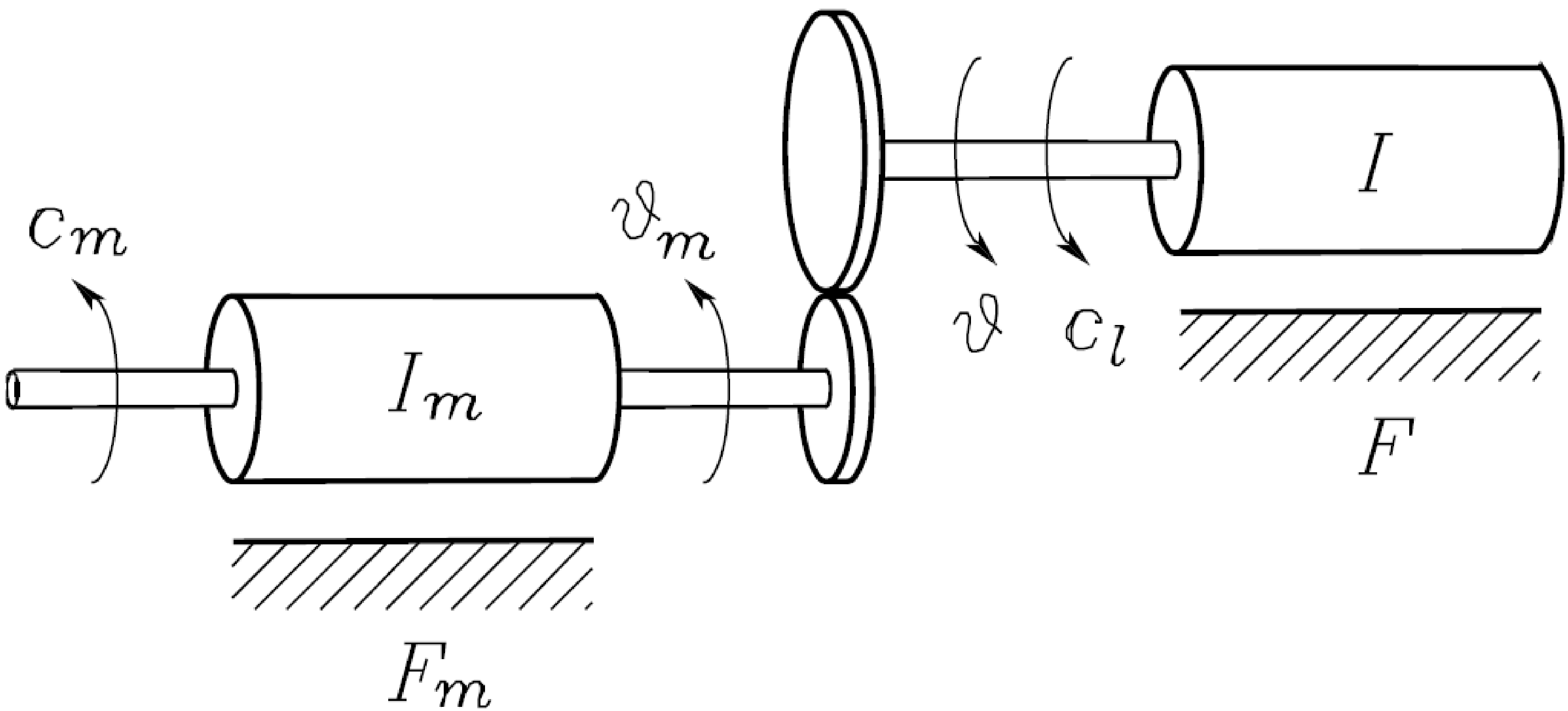
General generator function

- Blackboard

Velocity vs. Torque generators

- Velocity generator have better rejection of disturbance torques
  - Gain $(R_a/k_v k_t \ll 1/F_m)$
  - Time constant $(R_a I_m/k_v k_t \ll I_m/F_m)$
- In the velocity generator G_v contributes to the velocity, but not in the torque generator case
- Velocity generator are best for independent joint control, as it offers high disturbance rejection
- Torque generators are best for centralized control, as the torque can be controlled almost linearly with respect to the control voltage

Transmission effects



Transmission effects

- Gear reduction ratio

$$k_r = \frac{r}{r_m} = \frac{\vartheta_m}{\vartheta} = \frac{\omega_m}{\omega}$$

- Combined mechanical balance

$$c_m = I_{eq}\dot{\omega}_m + F_{eq}\omega_m + \frac{c_l}{k_r}$$

- Combined inertia moment and viscous friction

$$I_{eq} = \left(I_m + \frac{I}{k_r^2}\right) \qquad F_{eq} = \left(F_m + \frac{F}{k_r^2}\right)$$

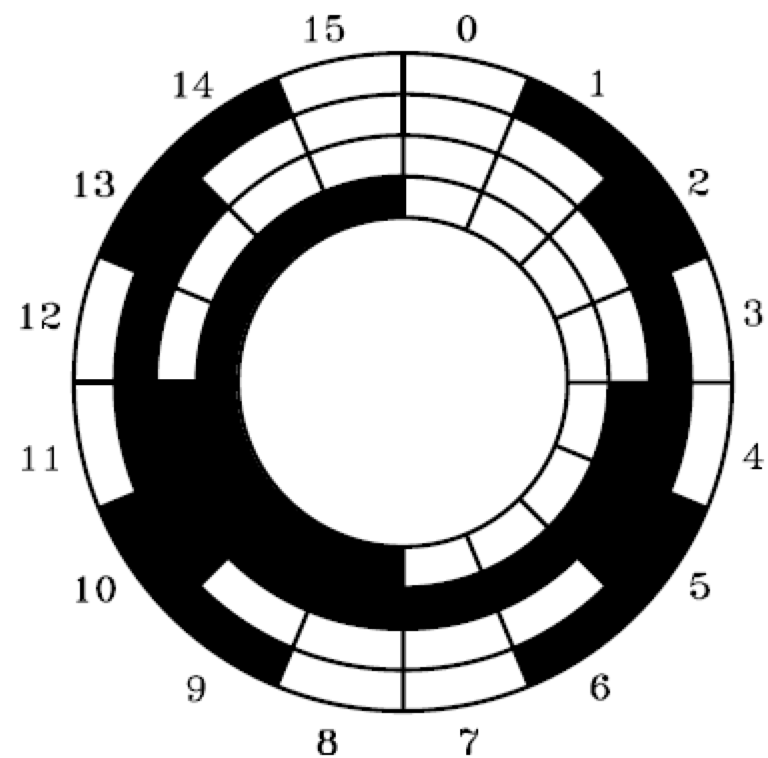
5.3 Proprioceptive sensors

- Measuring the internal state of the robot

- Joint positions
- Joint velocities
- Joint torques

Position transducers

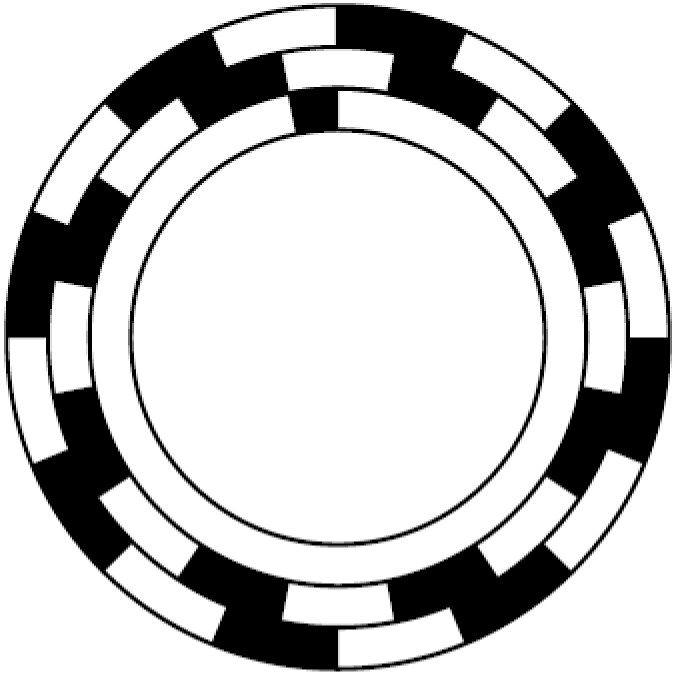
- Encoder
  - Absolute
  - Incremental
- Light is emitted through a disk en detected on the other side
- Absolute encoders use gray coding



Absolute encode

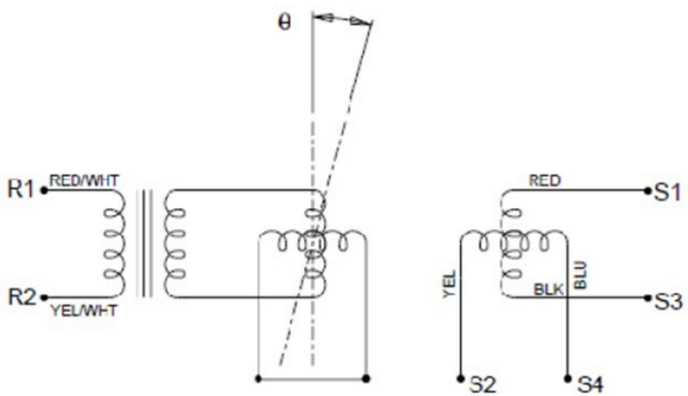
Incremental encoder

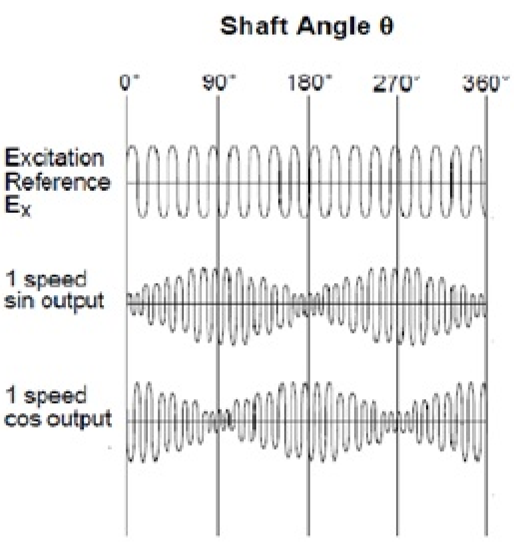
- Have a wider use than absolute encoders
- Simpler and cheaper
- Can determine the rotation sign by using two tracks
- A third track may be used to define an absolute mechanical zero
- Absolute position is stored electronically



Resolvers

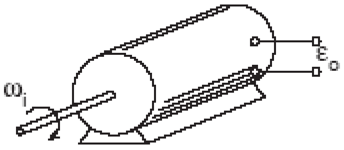
- Compact and robust transducer
- Based on the principle of mutual induction of the electric circuits
- A sinusoidal signal fed to the induction coil on the rotor
- The generated field generated a voltage in the two perpendicular stator coils

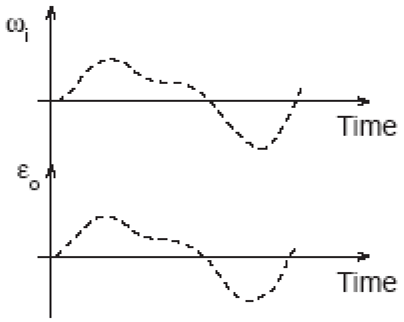




Velocity transducers

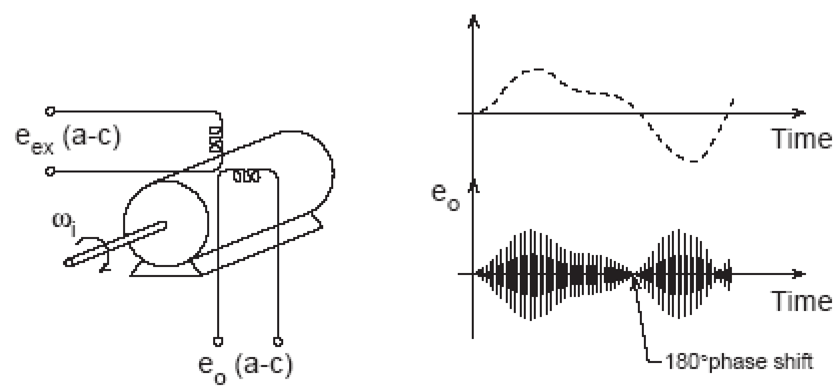
- DC tachometer
  - A magnetic field is provided by a permanent magnet
  - Since the flux is constant, when the rotot rotates the output voltage is proportional to the angular speed
  - A drawback is speed dependent ripple on the output voltage





AC tachometer

- Has two windings in the stator
- One is fed a constant magnitude sinusoidal voltage
- A voltage is induced in the other winding that has
  - Same frequency
  - Magnitude proportional with angular velocity
  - Opposite phase



5.4 Exteroceptive Sensors

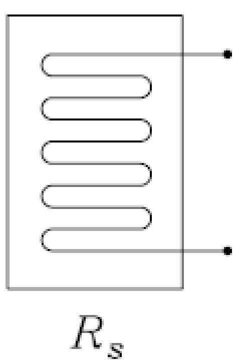
- Provide the robot with knowledge about the surrounding environmant

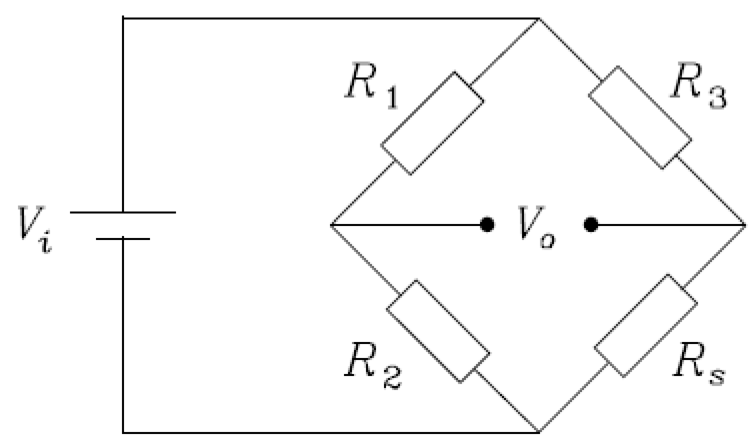
- Force sensors
- Tactile sensors
- Proximity sensors
- Range sensors
- Vision sensors

Force sensors

- Strain gauge
  - A wire where the resistance change under the action of stress
  - Measured by a Wheatstone bridge

a)





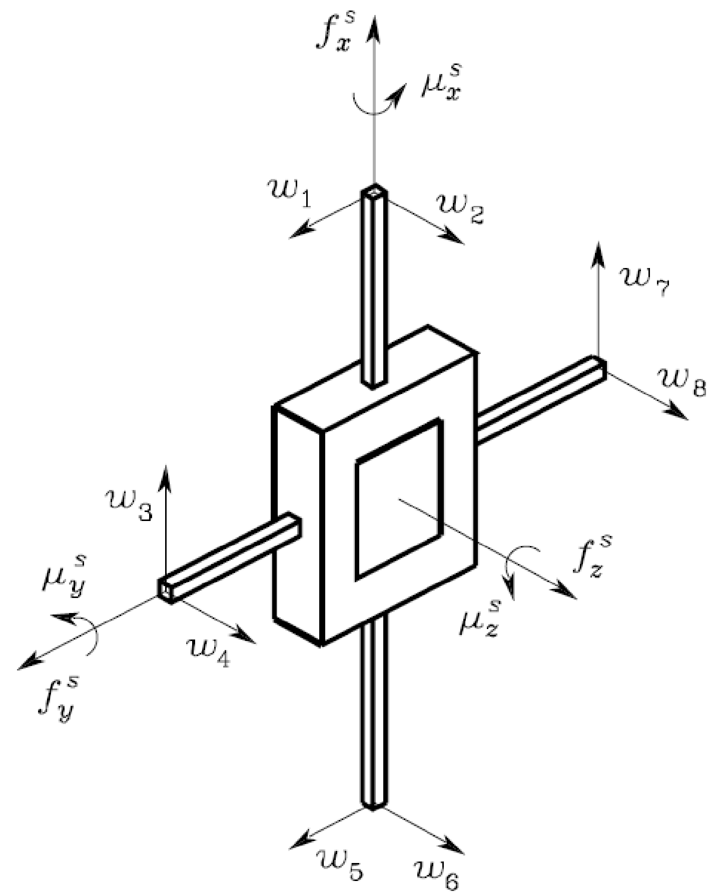
b)

Shaft torque sensor

- Motor torque may be found from the armature current
- If direct measurements is wanted we need to use a shaft torque sensor
- The sensor is mounted between the motor and joint
- Strain gauges is used to measure the torque
- The measured torque is that delivered by the servomotor to the joint
- This is not the same as the driving torque in the models
- Inertial and friction torque contributions are not measured

Wrist torce sensors

- Mounted at between the last joint and the end-effector
- Not possible to decouple deformations and force/torque measurements
- A calibration is needed to know the relationship between deformations and force/torque



Schematic representation of a Maltese-cross

Wrist force sensors

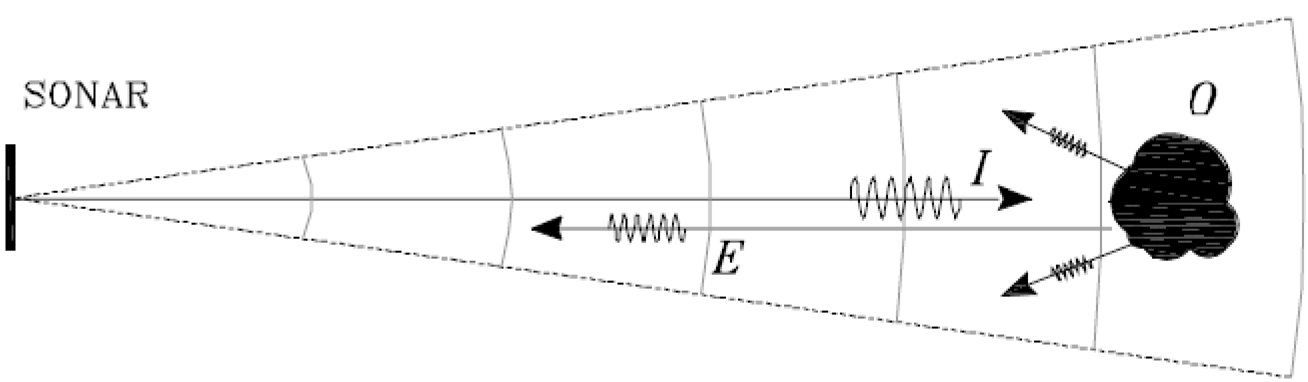
- Typically 6 DoF
- Sample bandwidth typically around 1 kHz
- Measurements from the sensor must be transformed to the end-effector frame

$$\begin{bmatrix} f_c^c \\ \mu_c^c \end{bmatrix} = \begin{bmatrix} R_s^c & O \\ S(r_{cs}^c)R_s^c & R_s^c \end{bmatrix} \begin{bmatrix} f_s^s \\ \mu_s^s \end{bmatrix} \quad (5.32)$$

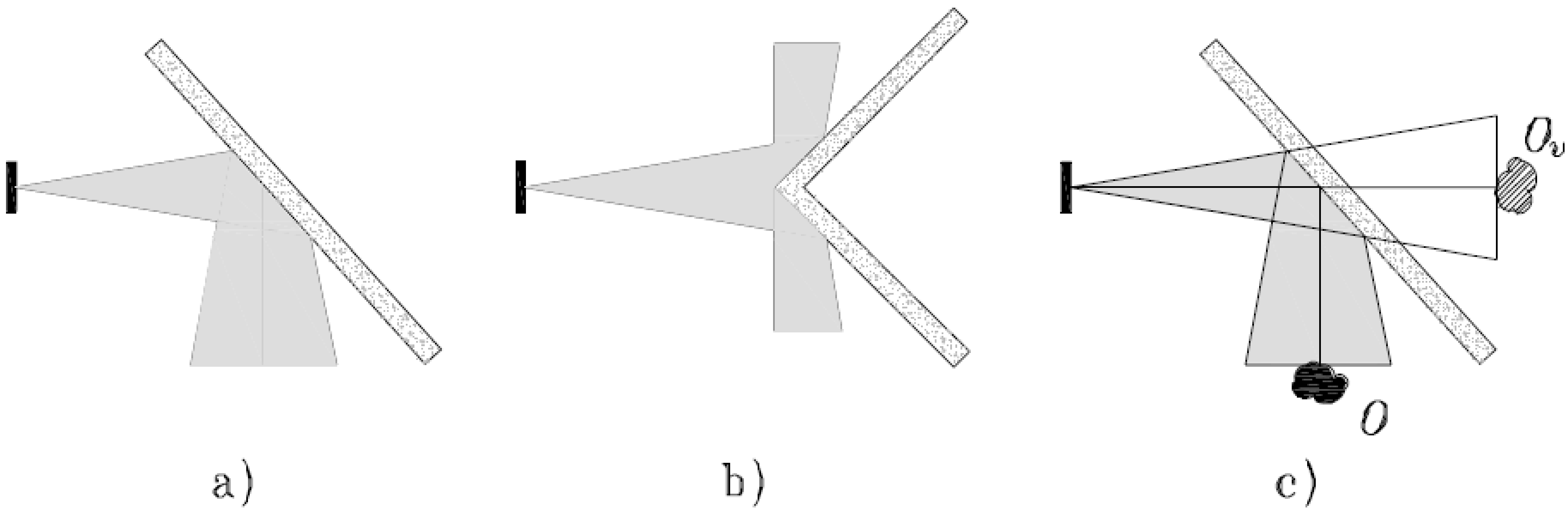
s – sensor frame

Range sensors

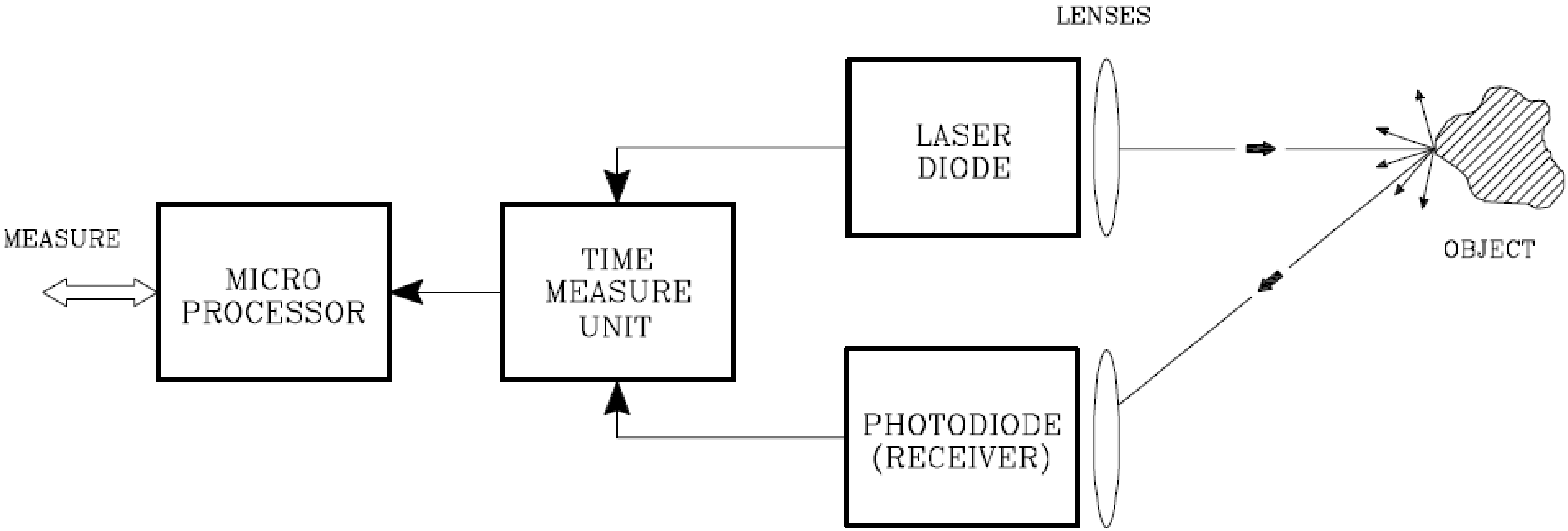
- Sonar
  - Use acustic pulses and echoes to measure distance
  - Time-of-flight
  - Widely used in underwater and mobile robotics
  - Low cost, light weight and low power consumption
- Use audible frequencies (20 Hz – 20 kHz) and ultrasound frequencies (20 kHz and above)
- Limits on angular and radial resolutions
- Limits on min/max range



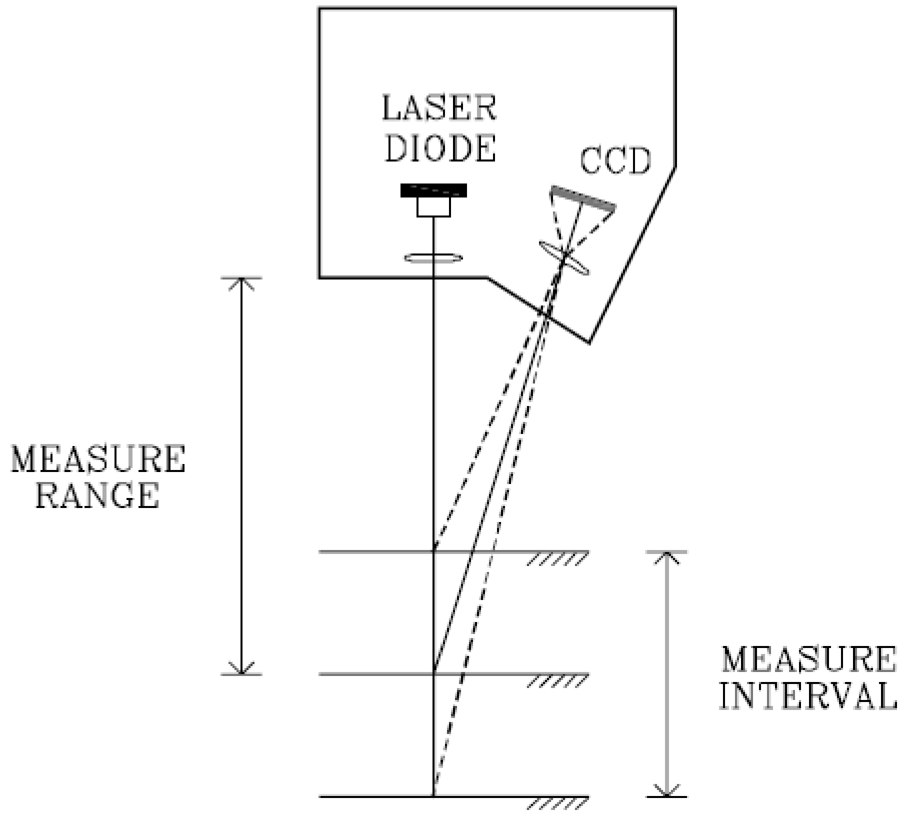
Sonars



Lasers (time-of-flight)

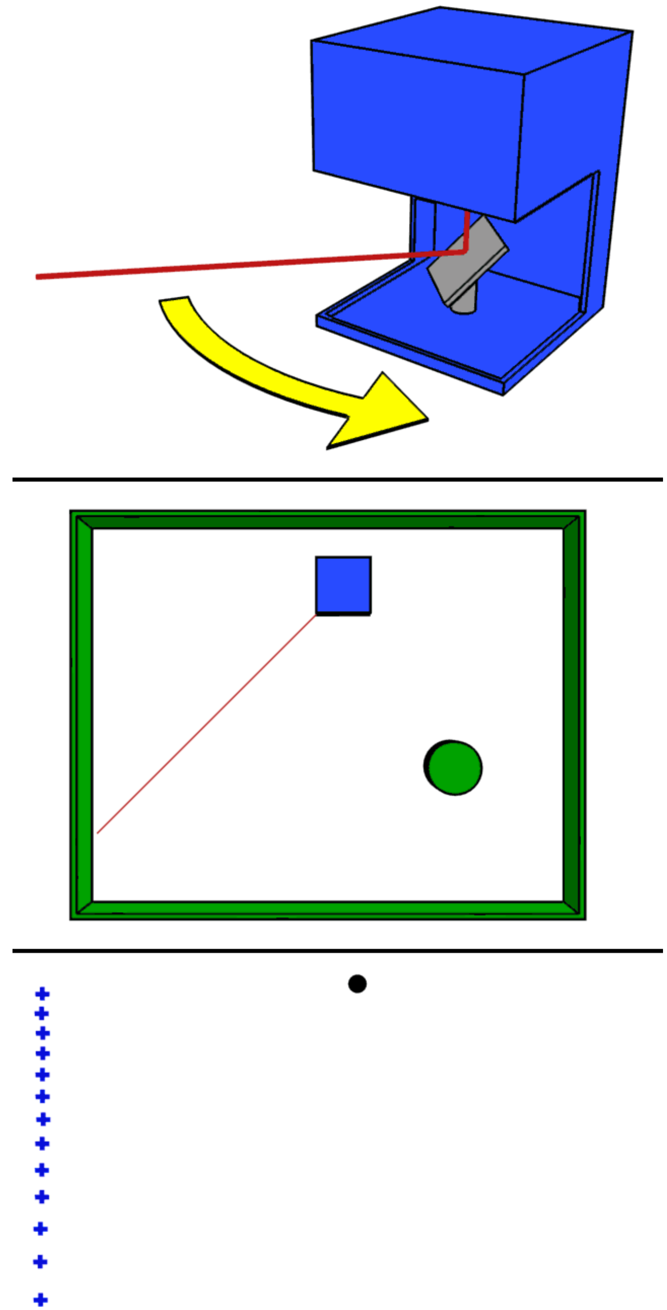


Lasers (triangulation)



LiDAR

- Light Detection And Ranging
- Using lasers to find a 3D representation of a target
- Widely used in self-driving cars
- Relatively expensive



1

Lidar

Vision sensors

- Light intensity is measured by a sensor to form an image
- Camare calibration of intrinsic camera parameters are needed to relate the image to the real world
- More in depth in visual servoing lecture