Introduction to Robotics

Lecture 10

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Technical Aspects of Multimodal Systems

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Outline

Introduction

Spatial Description and Transformations

Forward Kinematics

Robot Description

Inverse Kinematics for Manipulators

Instantaneous Kinematics

Trajectory Generation 1

Trajectory Generation 2

Principles of Walking

Path Planning

Task/Manipulation Planning

Dynamics

Robot Control

- Introduction

Outline (cont.)

Dynamics – Recapitulation

- **Forward dynamics:**
  - *Input*: joint forces / torques;
  - *Output*: kinematics;
  - *Application*: Simulation of a robot model.
- **Inverse Dynamics**:
  - *Input*: desired trajectory of a manipulator;
  - *Output*: required joint forces / torques;
  - *Application*: model-based control of a robot.

$$\tau(t) \rightarrow \text{direct dynamics} \rightarrow \mathbf{q}(t), (\dot{\mathbf{q}}(t), \ddot{\mathbf{q}}(t))$$

$$\mathbf{q}(t) \rightarrow \text{inverse dynamics} \rightarrow \tau(t)$$

Dynamics – Recapitulation

General inverse dynamic equations of a manipulator:

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta)$$

Forward dynamic equations of a manipulator:

$$\begin{aligned}
\ddot{\Theta} &= M^{-1}(\Theta)(\tau - V(\Theta, \dot{\Theta}) - G(\Theta)) \\
\dot{\Theta} &= \int \ddot{\Theta} dt \\
\Theta &= \int \dot{\Theta} dt
\end{aligned}$$

Unlike kinematics, the inverse dynamics is easier to solve than forward dynamics.

Dynamics – Recapitulation

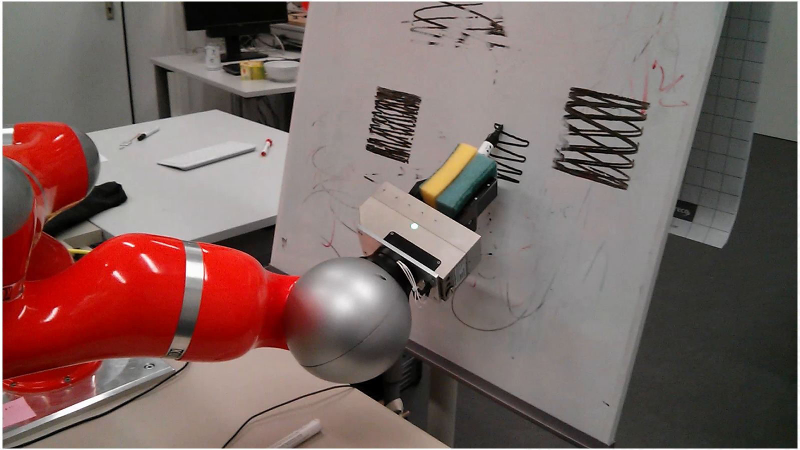
Two methods for calculation:

- Analytical methods
  - based on Lagrangian equations

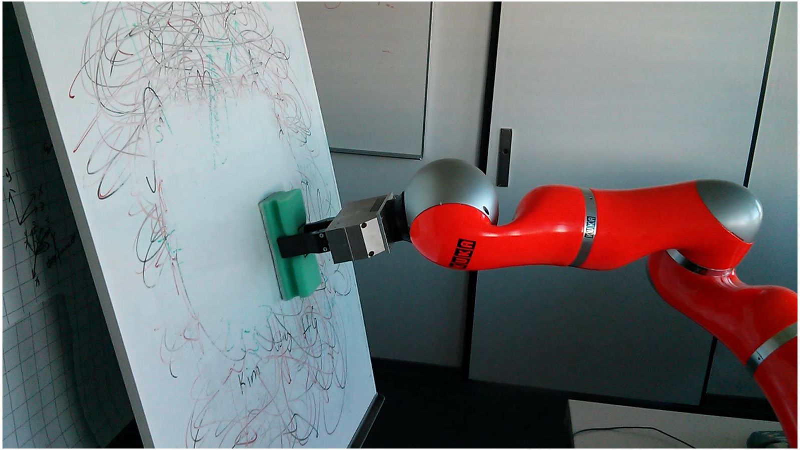
$$L(q_i, \dot{q}_i) = K(q_i, \dot{q}_i) - P(q_i)$$

- Synthetic methods:
  - based on the Newton-Euler equations

Drawing task



Wiping task



Definition

Controller

- Influences one or more physical variables
  - meet a control variable
  - reduce disturbances
- Compares actual value to reference value
  - minimize control deviation

Development of Control Engineering - Timeline

1788	J. Watt: engine speed governor
1877	J. Routh: differential equation for the description of control processes
1885	A. Hurwitz: stability studies
1932	A. Nyquist: frequency response analysis
1940	W. Oppelt: frequency response analysis, Control Engineering becomes an independent discipline
1945	H. Bode: discipline new methods for frequency response analysis
1950	N. Wiener: statistical methods
1956	L. Pontrjagin: optimal control theory, maximum principle
1957	R. Bellmann: dynamic programming
1960	direct digital control
1965	L. Zadeh: Fuzzy-Logic
1972	Microcomputer use
1975	Control systems for automation
1980	Digital device technology
1985	Fuzzy-controller for industrial use
1995	Artificial neuronal networks for industrial use

Control Problem

Given: dynamic system (to be controlled)

- Model describing dynamic system (e.g. Jacobian)
- Input variables – control variables
  - measured values (sensor data)
- Output variables – controlled variables
  - system input (force/torque data)

Problem

- Keep control variable values constant and / or
- Follow a reference value and / or
- Minimize the influence of disturbances

Control Problem (cont.)

Sought: controller (for dynamic system)

- Implement hardware or software controller
- Alter controlled-variables (output)
- Based on control variables (input)
- Solve the problem

Example: Cruise Control

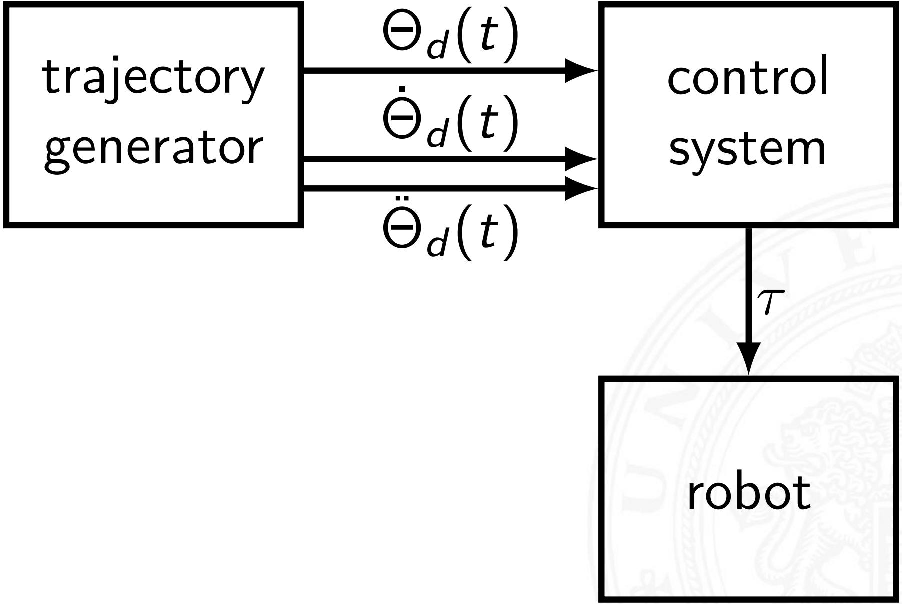
Input

- Speed over ground
- Relative speed to traffic
- Distance to car in front
- Distance to car behind
- Weather conditions
- Relative position in road lane
- ...

Output

- Throttle
- Brakes
- Steering

Control System of a Robot



trajectory generator

$\Theta_d(t)$

$\dot{\Theta}_d(t)$

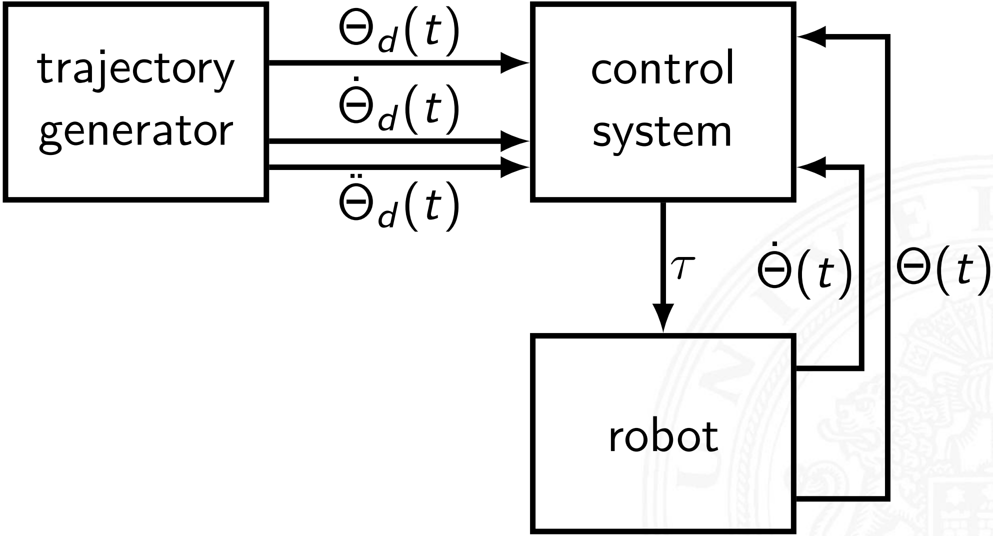
$\ddot{\Theta}_d(t)$

control system

τ

robot

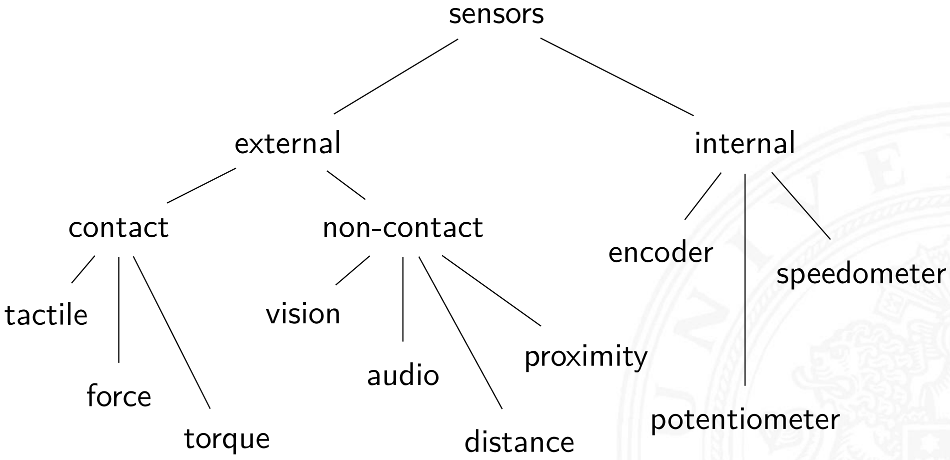
Control System of a Robot (cont.)



Control System of a Robot (cont.)

- Target values
    - $\Theta_d(t)$
    - $\dot{\Theta}_d(t)$
    - $\ddot{\Theta}_d(t)$
- Magnitude of error
    - $E = \Theta_d - \Theta, \dot{E} = \dot{\Theta}_d - \dot{\Theta}$
- Output (Control) value
    - $\Theta(t)$
    - $\dot{\Theta}(t)$
- Controlled value
    - τ

Sensor Classification Hierarchy



sensors

external

internal

contact

non-contact

tactile

force

torque

vision

audio

distance

proximity

encoder

potentiometer

speedometer

Internal Sensors of Robots

- Placed inside the robot
- Monitor the internal state of the robot
  - e.g. position and velocity of a joint

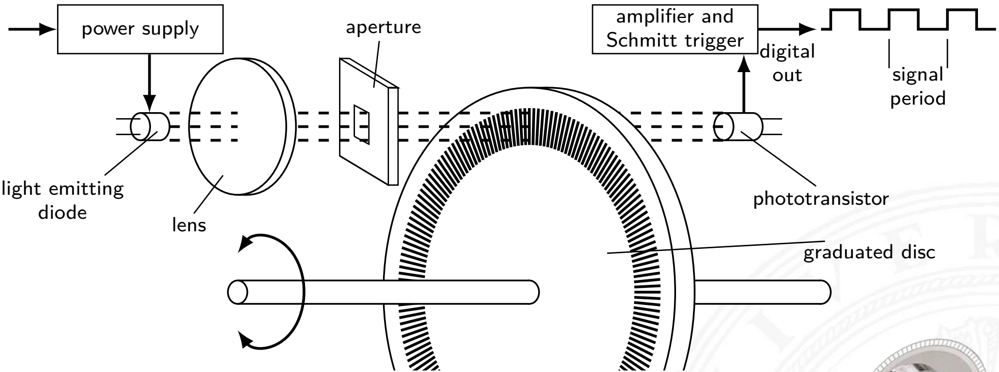
Position measurement systems

- Potentiometer
- Incremental/absolute encoder
- Resolver

Velocity measurement systems

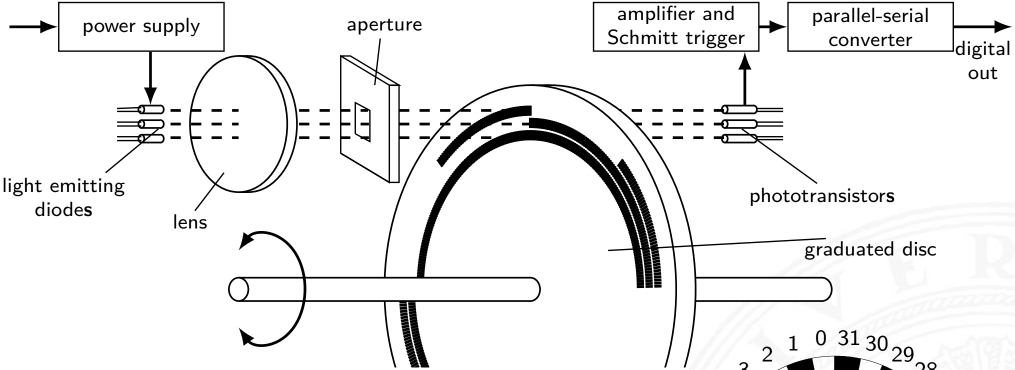
- Speedometers
- Calculate from position change over time

Optical Incremental Encoders

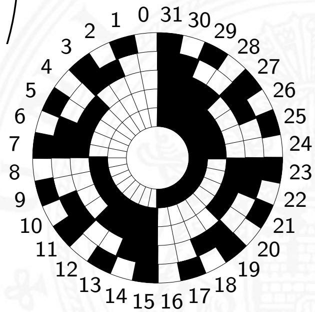


- An optical encoder reads the lines
- The disc is mounted to the shaft of the joint motor
  - PUMA-560: 1:1 ratio; .0001 rad/bit accuracy
- one special line is marked as the “zero-position”

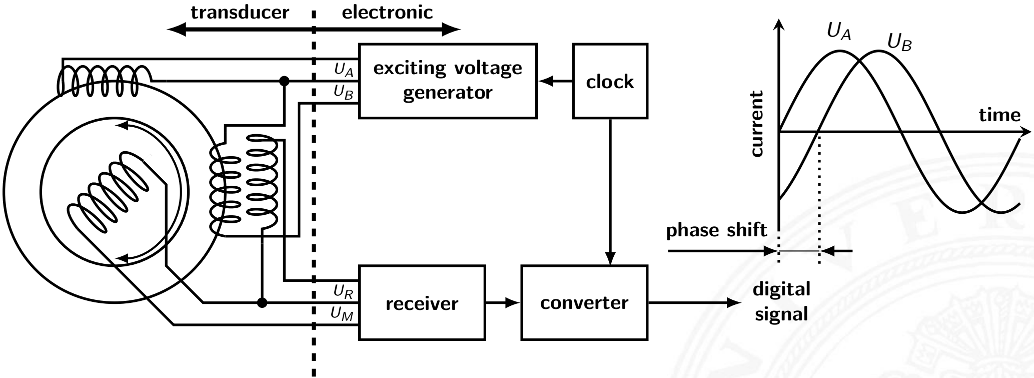
Optical Absolute Encoder



- multiple LEDs and phototransistors
- e.g. 5 bit dual code gives 32 angular positions and 11.25° resolution
- parallel-serial converter required
- absolute positioning and direction encoding



Resolver

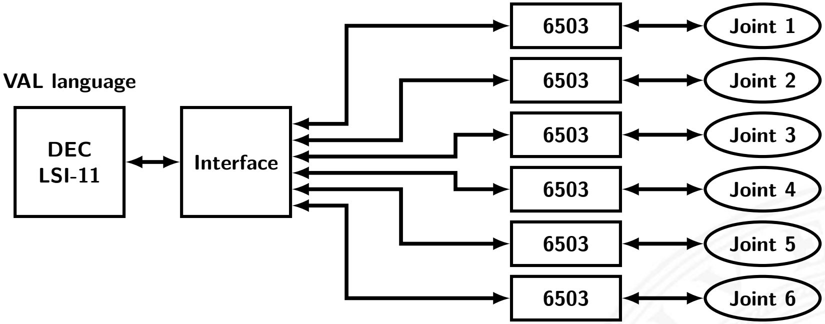


- analog rotation encoding
- phase shift between U_A and U_B determines rotation
- precision depending on digital converter

Encoder vs Resolver

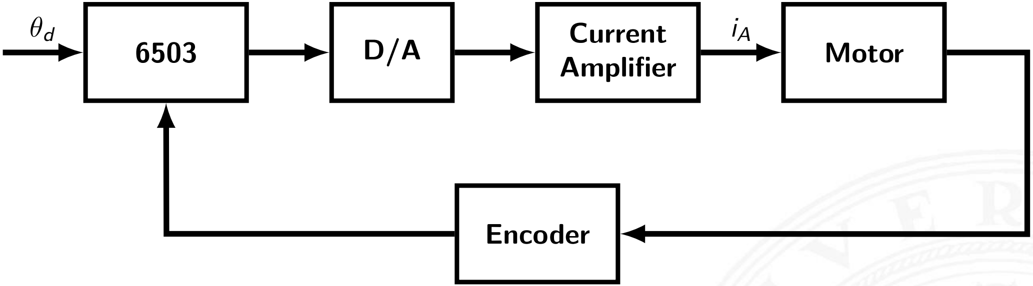
- Encoder:
  - higher accuracy
  - simplicity of integration, and update
  - suitable for applications with high acceleration and deceleration rates
- Resolver:
  - lack of sensitive optics
  - resistant to electrical disturbances
  - complexity of integrating a resolver into a system
  - suitable for extremely harsh applications, such as military and aerospace equipment

Control System Architecture of PUMA-Robot



- two-level hierachical structure of control system
- *DEC LSI-11* sends joint values at 35.7 Hz (28 ms)
    - trajectory
- Distance of actual value to goal value is interpolated
    - using 8,16,**32** or 64 increments

Control System Architecture of PUMA-Robot (cont.)



- The joint control loop operates at 1143 Hz (0.875 ms)
- Encoders are used as position sensors
- No dedicated speedometer
  - velocity is calculated as the difference of joint positions over time

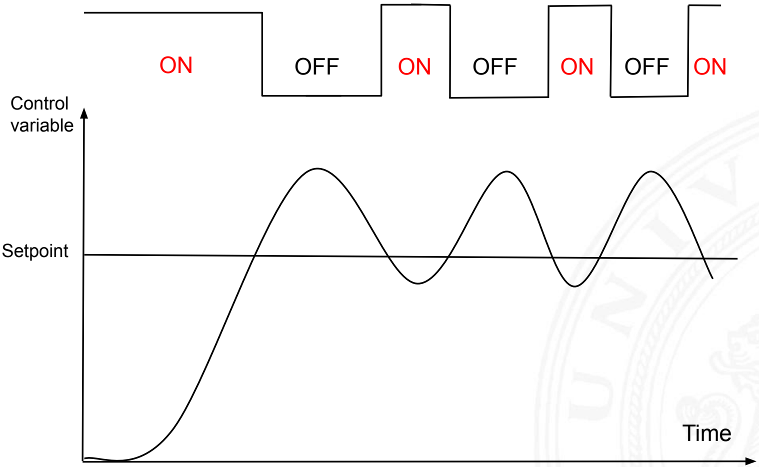
Introduction—PID controller

- more than half of the industrial controllers in use today are PID controllers or modified PID controllers
- many different types of tuning rules have been proposed in the literature
- Using these tuning rules, delicate and fine tuning of PID controllers can be made on-site

P	Proportional controller
I	Integral controller
D	Derivative controller

Bang Bang (On-off) controller

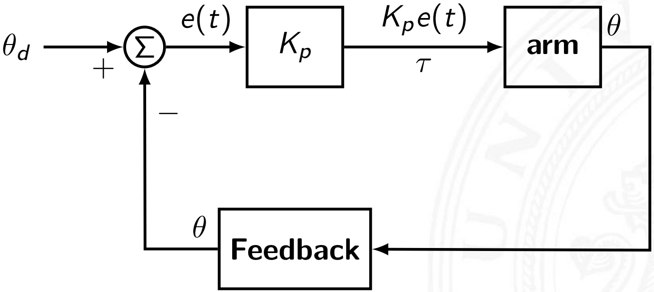
This is the simplest form of control.



Proportional control

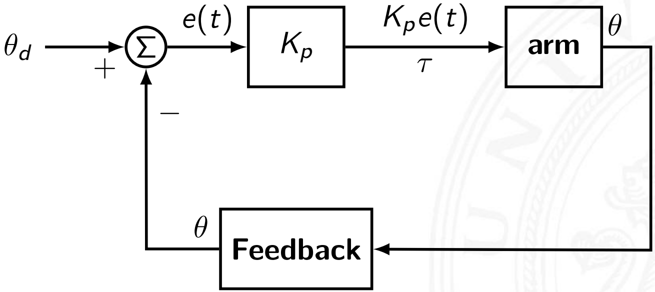
In proportional mode, there is a continuous linear relation between value of the controlled variable and position of the final control element.

- $e(t) = \theta_d - \theta$
- output of proportional controller is $\tau(t) = K_p e(t)$, K_p is proportional gain.



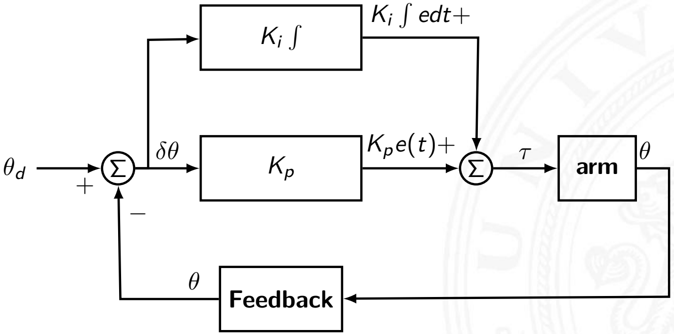
Proportional control (cont.)

- Using P control is simple, but often insufficient:
  - If K_p is small, the sensor reading will approach the setpoint slowly and never reach it
  - As the gain is increased the system responds faster to changes in set-point but becomes progressively underdamped and eventually unstable.
  - If K_p is large, the system may overshoot, oscillate (i.e. become unstable)



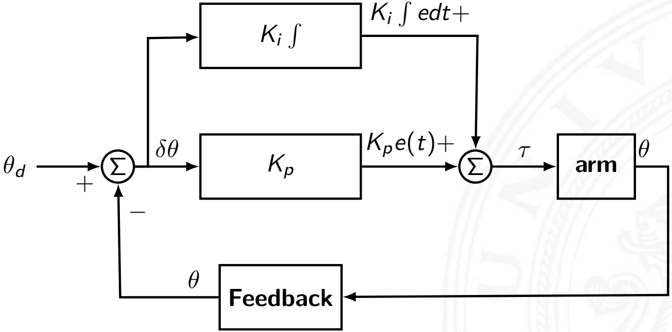
Proportional-Integral (PI) control

- $\tau(t) = K_p e(t) + K_i \int edt$
- The P term will take care of the large movement
- Integral signal is sum of all instantaneous errors
- The I term will take care of any steady-state error



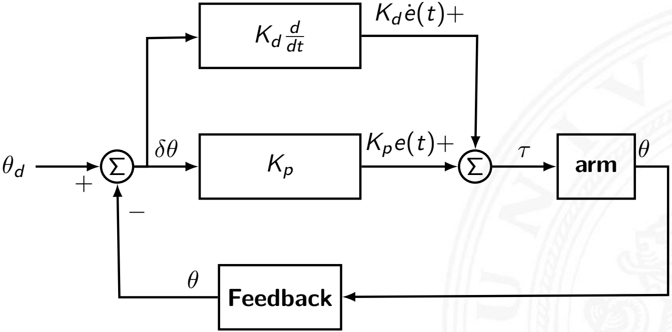
Proportional-Integral (PI) control (cont.)

- It eliminates steady-state error
- It can help with stability of the system, especially if K_p is large
- But, it responds relatively slowly to an error signal



Proportional-Derivative (PD) control

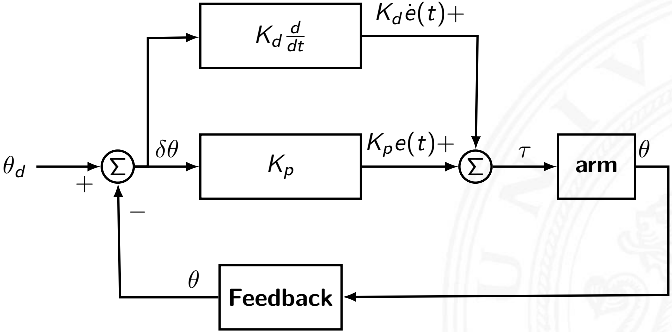
- $\tau(t) = K_p e(t) + K_d \dot{e}(t)$
- Differential term at time $n = K_d(e(n) - e(n-1)/\Delta t)$



Proportional-Derivative (PD) control (cont.)

The main advantages of the PD controllers are:

- The derivative term acts as "brake" to the system
- It can improve the system's tolerance to external disturbances



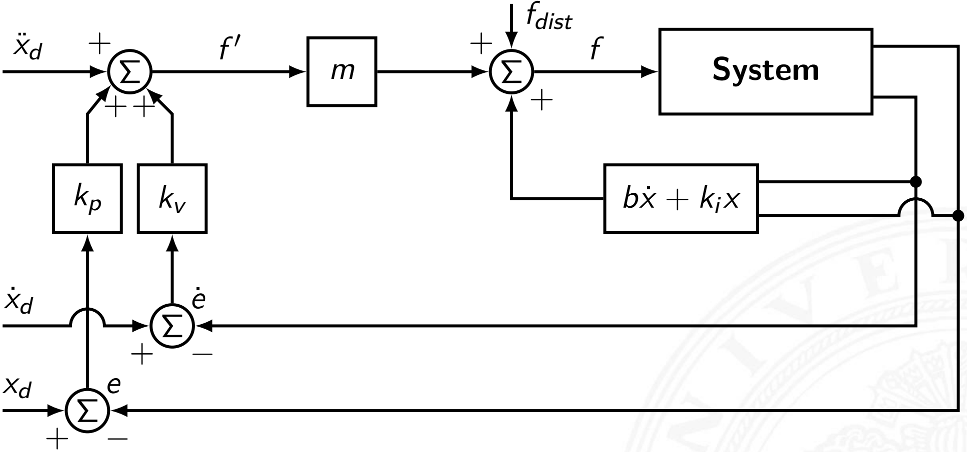
PID-Controller

- P Proportional controller: $\tau(t) = k_p \cdot e(t)$
  The amplification factor k_p defines the sensitivity.
- I Integral controller: $\tau(t) = k_i \cdot \int_{t_0}^{t} e(t')dt'$
  Long term errors will sum up.
- D Derivative controller: $\tau(t) = k_v \cdot \dot{e}(t)$
  This controller is sensitive to changes in the deviation.

Combined ⇒ PID-controller:

$$\tau(t) = k_p \cdot e(t) + k_v \cdot \dot{e}(t) + k_i \int_{t_0}^{t} e(t')dt'$$

Linear Control for Trajectory Tracking



$$f' = \ddot{x}_d + k_v\dot{e} + k_p e + k_i \int edt \qquad (47)$$

is called the principle of PID-control.

Summary: the characteristics of P, I, D controllers

	Rise time	Overshoot	Settling time	S-S error
Kp	decrease	increase	small change	decrease
Ki	decrease	increase	increase	eliminate
Kd	small change	decrease	decrease	small change

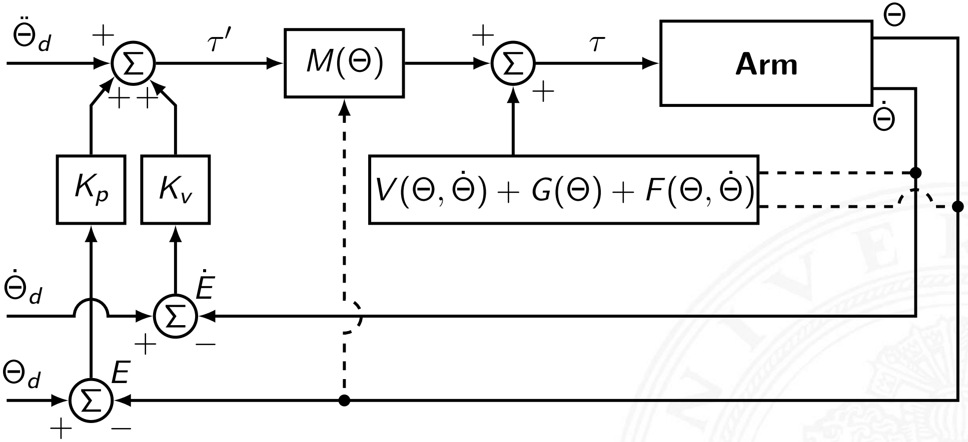
Further Resources

- PID Control with Python (simple-pid)
- PID Control with MATLAB and Simulink

Tips for designing a PID controller

1. Obtain an open-loop response and deternine what needs to be improved
2. Add a P control to improve the rise time
3. Add a D control to improve the overshoot
4. Add a I control to eliminate the steady-state error
5. Adjust each of K_p, K_d, K_i until you obtain a desrired overall response

Model-Based Control for Trajectory Tracking



The dynamic equation: $\tau = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta)$

where $M(\Theta)$ is the position-dependent $n \times n$-mass matrix of the manipulator, $V(\Theta,\dot{\Theta})$ is a $n \times 1$-vector of centripetal and Coriolis factors, and $G(\Theta)$ is a complex function of Θ, the position of all joints of the manipulator.

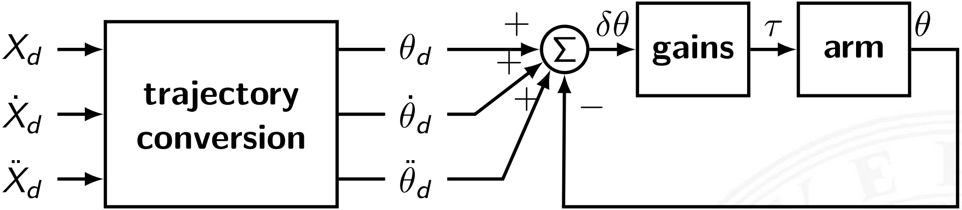
Classification of Robot Arm Controllers

As the problem of trajectory-tracking:

- Joint space: PID, plus model-based
- Cartesian space: joint-based
  - using kinematics or using inverse Jacobian calculation
- Adaptive: model-based adaptive control, self-tuning
  - controller (structure and parameter) adapts to the time-invariant or unknown system-behavior
  - basic control circle is superimposed by an adaptive system
  - process of adaption consists of three phases
    - identification
    - decision-process
    - modification
- Hybrid force and position control is also a popular research topic

Control in Cartesian Space – Method I

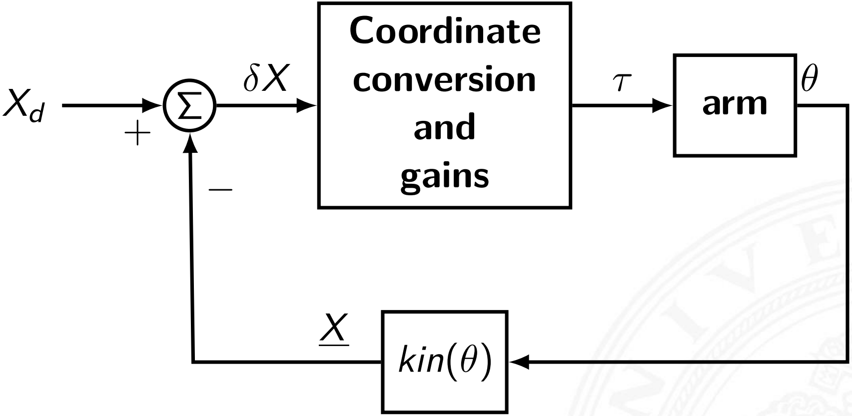
Joint-based control with Cartesian trajectory input



- Cartesian trajectory is converted into joint space first
- joint space trajectory is sent to the controller
- trajectory controller sends joint targets to motor controllers
- motor controller sends torque data to motor
- sensors output joint state

Control in Cartesian Space – Method II

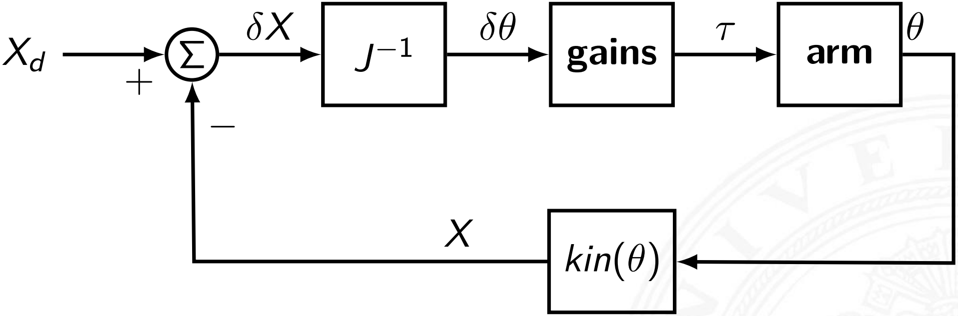
Cartesian control via calculation of kinematics



- controller operates in cartesian space
- joint space conversion within control cycle
- error values in cartesian space using FK

Control in Cartesian Space – Method III

Cartesian control via calculation of inverse Jacobian



- no explicit joint space conversion
- dynamic conversion using inverse Jacobian

Robot Control Improvements

Scientific Research

- model-based control
- adaptive control
- hybrid control

Industrial robotcs

- PID-control system with gravity compensation

$$\tau = \dot{\Theta}_d + K_v \dot{E} + K_p E + K_i \int E dt + \hat{G}(\Theta)$$

Hybrid Control of Force and Position

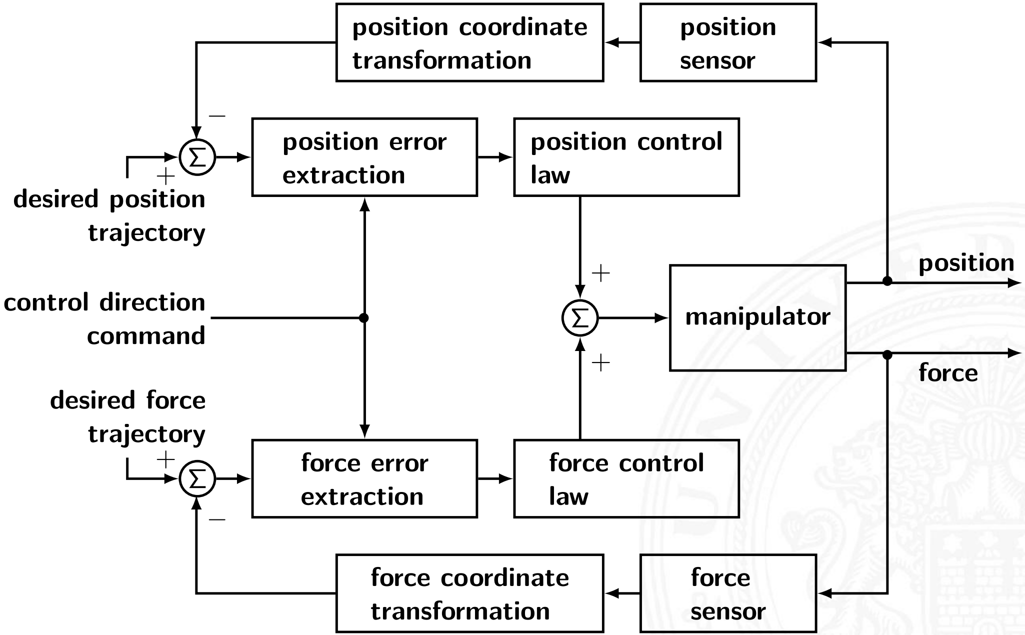
Motivation

Certain tasks require control of both: position and force of the end effector:

- assembly
- grinding
- opening/closing doors
- crank winding
- ...

An example shows two feedback loops for separate control of position and force

Hybrid Control of Force and Position (cont.)



Hybrid Force/Torque Control

Franke Emika Panda

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