Introduction to Robotics

Lecture 9

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Technical Aspects of Multimodal Systems

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Outline

Outline (cont.)

Definitions

Controller

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

Definitions (cont.)

System

- Physical or technical construct
  - input signal – stimulus
  - output signal – response
- Transforms stimulus into response
- Symbolical illustration
  - block with marked signals
  - direction of signal effect expressed with arrows

Definitions (cont.)

Input and output variables

- Change over time
    - expressed as $u(t)$ and $v(t)$ (dynamic system)
- Infinite number of possible variables
    - for real-world dynamic technical systems (in principle)
- Description of system behaviour based on desired application
    - using the relevant variables

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

Development of Control Engineering - Timeline

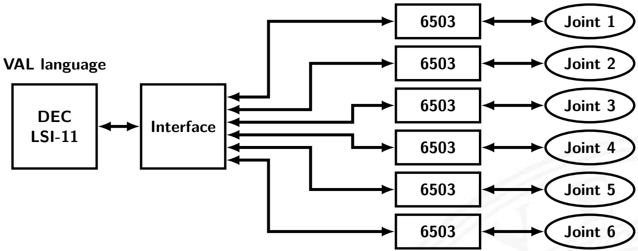
1788	J. Watt: engine speed governor
1877	J. Routh: differential equation for the description of control processes
1885	A. Hurwitz: stability studies
1932	A. Nyquist: frequency response analysis
1940	W. Oppelt: frequency response analysis, Control Engineering becomes an independent discipline
1945	H. 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

Classification of Robot Arm Controllers

As the problem of trajectory-tracking:

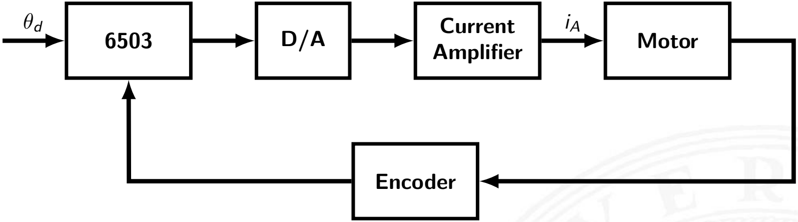
- Joint space: PID, plus model-based
- Cartesian space: joint-based
  - using kinematics or using inverse Jacobian calculation
- Adaptive: model-based adaptive control, self-tuning
  - controller (structure and parameter) adapts to the time-invariant or unknown system-behavior
  - basic control circle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

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
- Potentiometer are used for rough estimation (only PUMA-560)
- No dedicated speedometer
  - velocity is calculated as the difference of joint positions over time

Internal Sensors of Robots

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

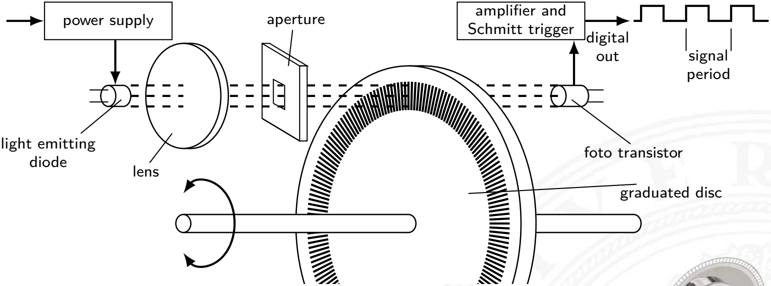
Position measurement systems

- Potentiometer
- Incremental/absolute encoder
- Resolver

Velocity measurement systems

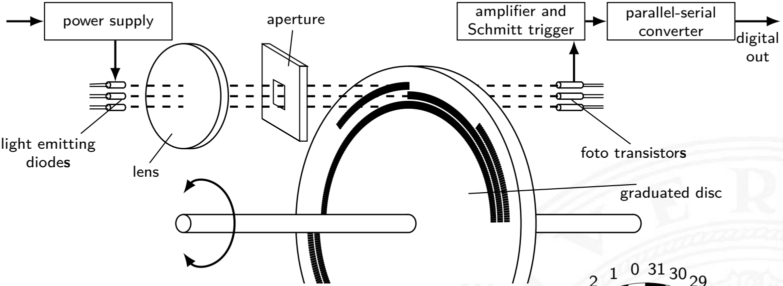
- Speedometers
- Calculate from position change over time

Optical Incremental Encoders

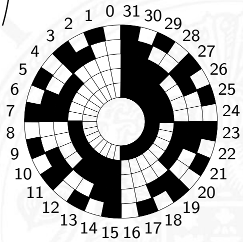


- An optical encoder reads the lines
- The disc is mounted to the shaft of the joint motor
  - PUMA-560: 1:1 ratio; .0001 rad/bit accuracy
- one special line is marked as the “zero-position”

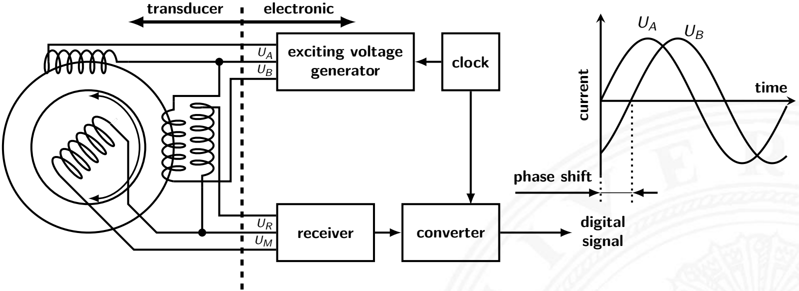
Optical Absolute Encoder



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

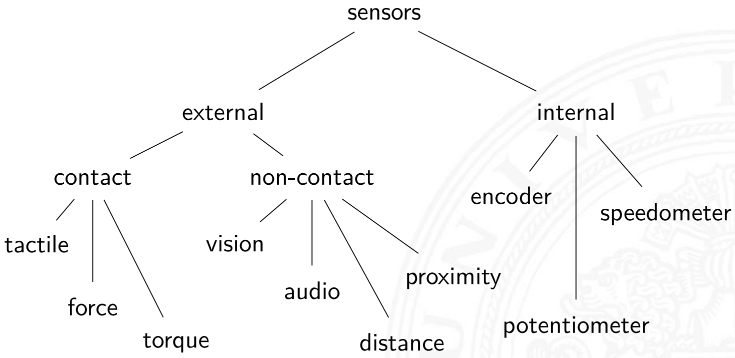


Resolver

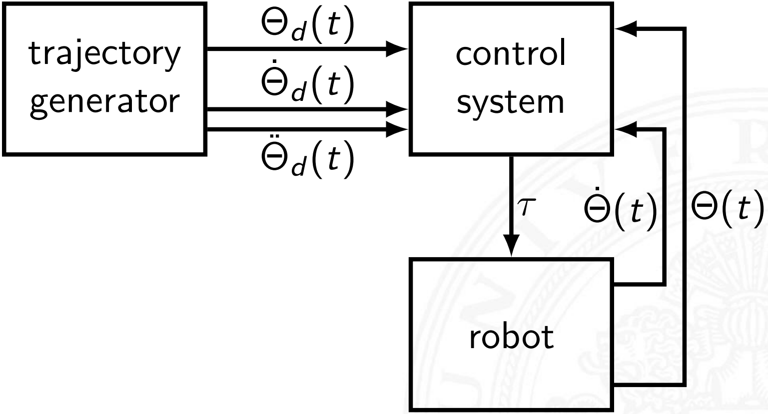


- analog rotation encoding
- phase shift between U_A and U_B determines rotation
- precision depending on digital converter

Sensor Classification Hierarchy



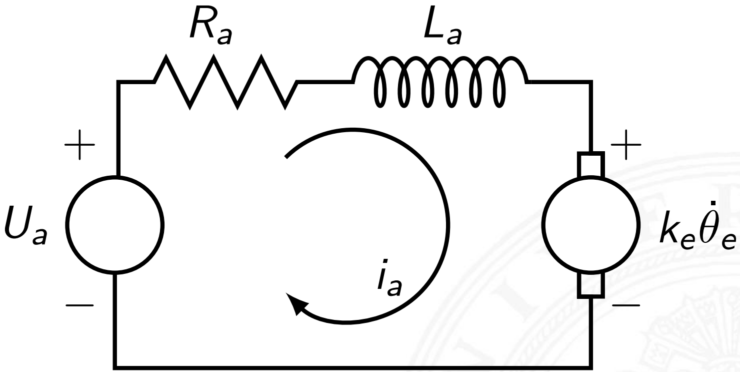
Control System of a Robot



Control System of a Robot (cont.)

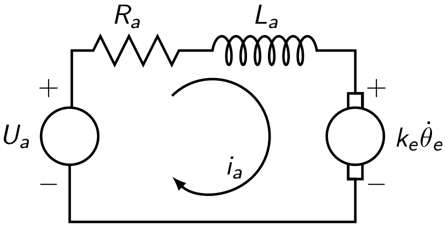
- Target values
  - $\Theta_d(t)$
  - $\dot{\Theta}_d(t)$
  - $\ddot{\Theta}_d(t)$
- Magnitude of error
  - $E = \Theta_d - \Theta, \dot{E} = \dot{\Theta}_d - \dot{\Theta}$
- Output (Control) value
  - $\Theta(t)$
  - $\dot{\Theta}(t)$
- Controlled value
  - τ

Simplified Circuit of a DC-Motor



U_a	input voltage of armature (motor) circuit
R_a	armature (motor) resistance
L_a	armature (coil) inductance
i_a	armature current (passing the motor)
k_e	exciter (motor) torque constant

Simplified Circuit of a DC-Motor (cont.)



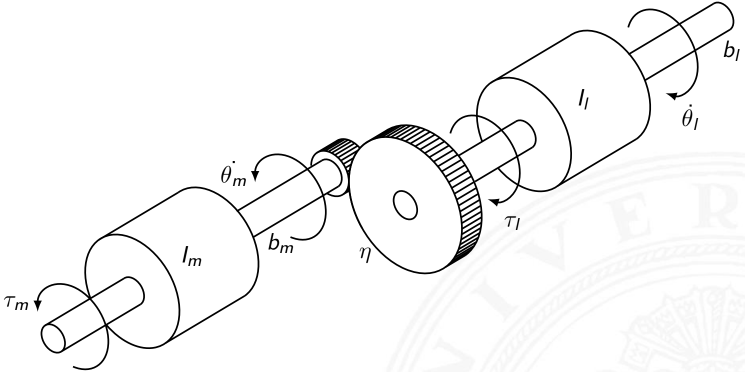
U_a	input voltage
R_a	armature resistance
L_a	armature inductance
i_a	armature current
k_e	exciter torque constant

The circuit can be described with the first order differential equation:

$$L_a\dot{i}_a + R_a i_a = U_a - k_e\dot{\theta}_e$$

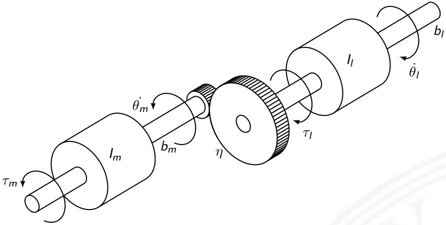
- Inductance relative to current change
- Resistance relative to absolute current
- Torque relative to rotation change

Connection Between Motor and a Joint



η	transmission ratio
$I_{m/l}$	inertia of motor/load
$\tau_{m/l}$	torque of motor/load
$\dot{\theta}_{m/l}$	rotation velocity of motor/load
$b_{m/l}$	friction factor

Connection Between Motor and a Joint (cont.)



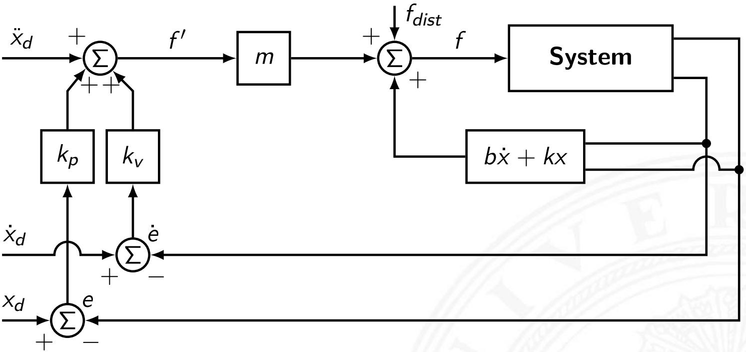
The motor torque formula is

$$\tau_m = (I_m + I_l/\eta^2)\ddot{\theta}_m + (b_m + b_l/\eta^2)\dot{\theta}_m$$

an the load torque is

$$\tau_l = (I_l + \eta^2 I_m)\ddot{\theta}_l + (b_l + \eta^2 b_m)\dot{\theta}_l$$

Linear Control for Trajectory Tracking



$$f' = \ddot{x}_d + k_v \dot{e} + k_p e + k_i \int e dt \tag{86}$$

is called the principle of PID-control.

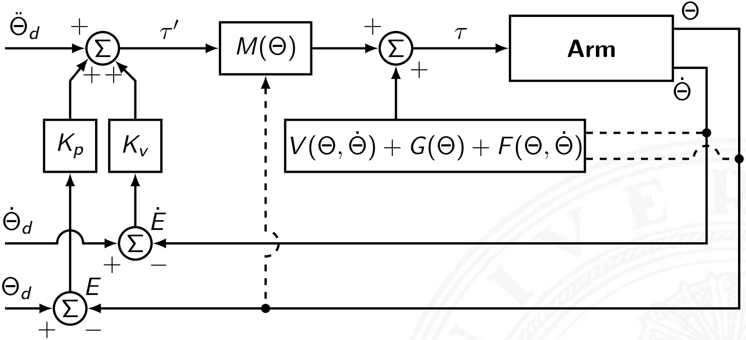
PID-Controller

- 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:

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

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.

Robot Control Improvements

Scientific Research

- model-based control
- adaptive control

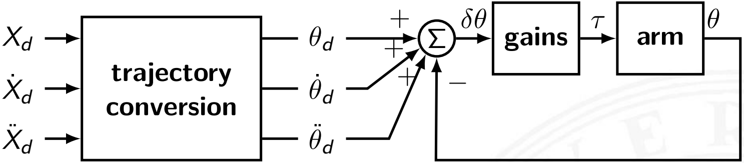
Industrial robotcs

- PID-control system with gravity compensation

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

Control in Cartesian Space – Method I

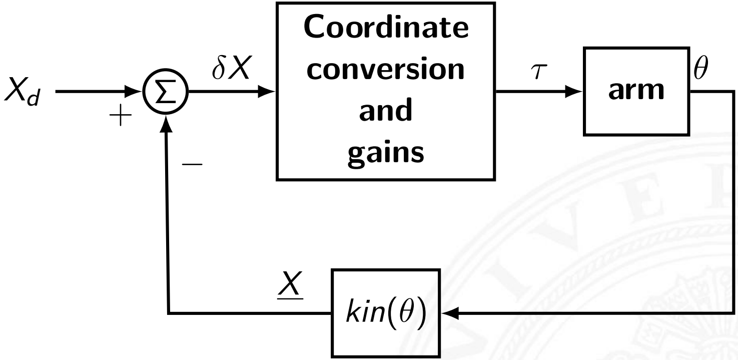
Joint-based control with Cartesian trajectory input



- 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

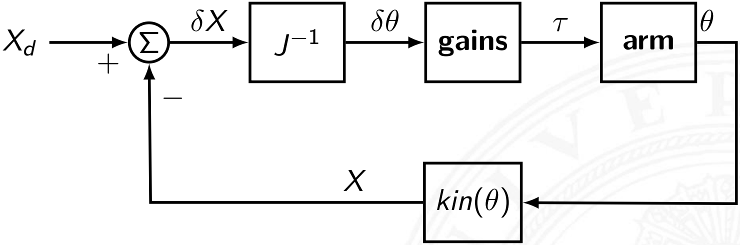
Cartesian control via calculation of kinematics



- 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

Hybrid Control of Force and Position

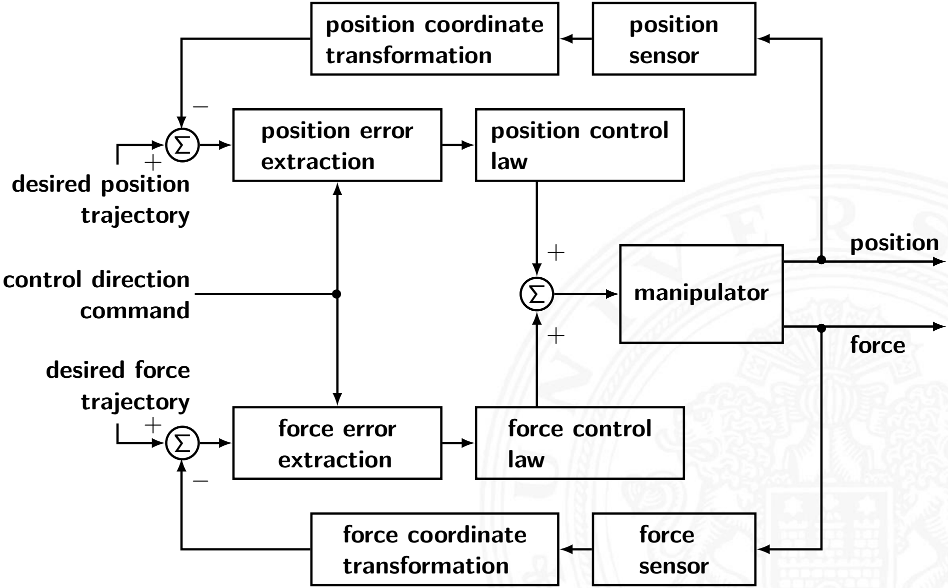
Motivation

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 seperate control of position and force

Hybrid Control of Force and Position (cont.)



Hybrid Force/Torque Control for safe HRI

DLR

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