INTRODUCTION TO THE ROBOT CONTROL

Andreja Rojko

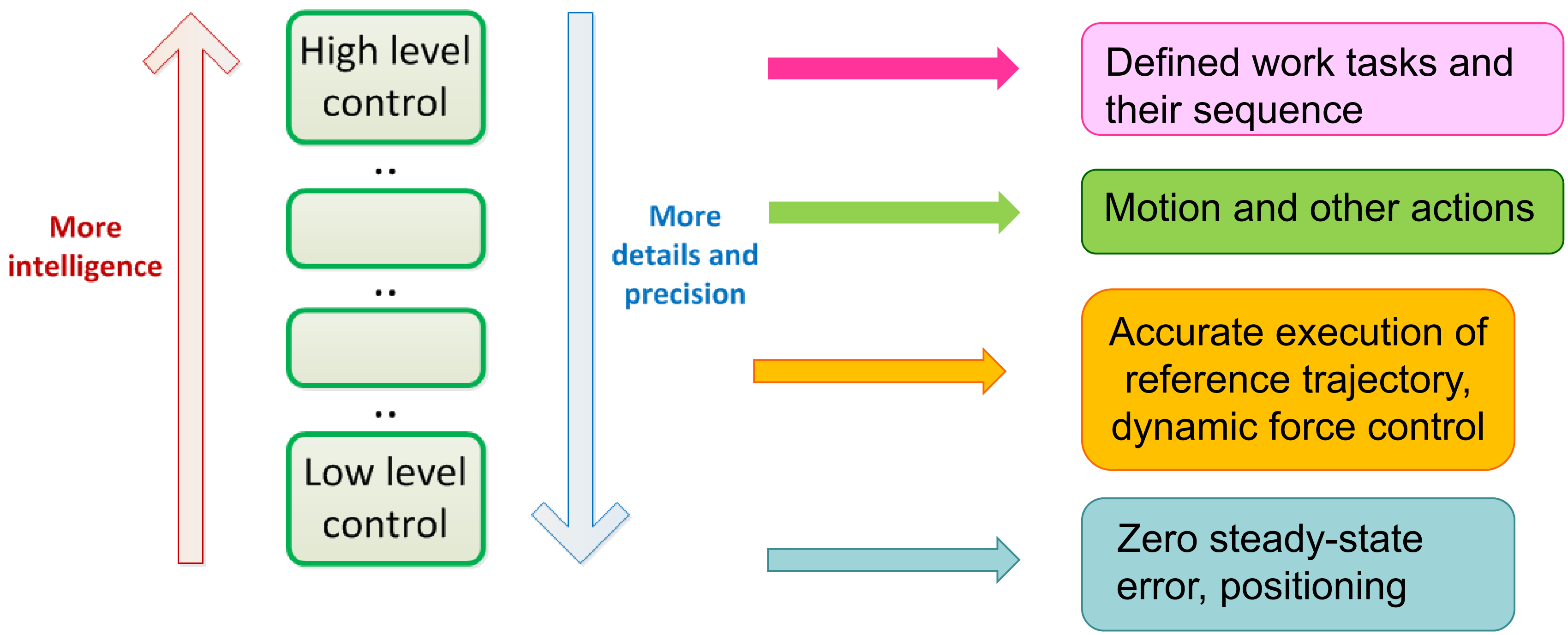
OUTLINE

- Introduction
- Robot control performance
- Control design process
- Robot control methods

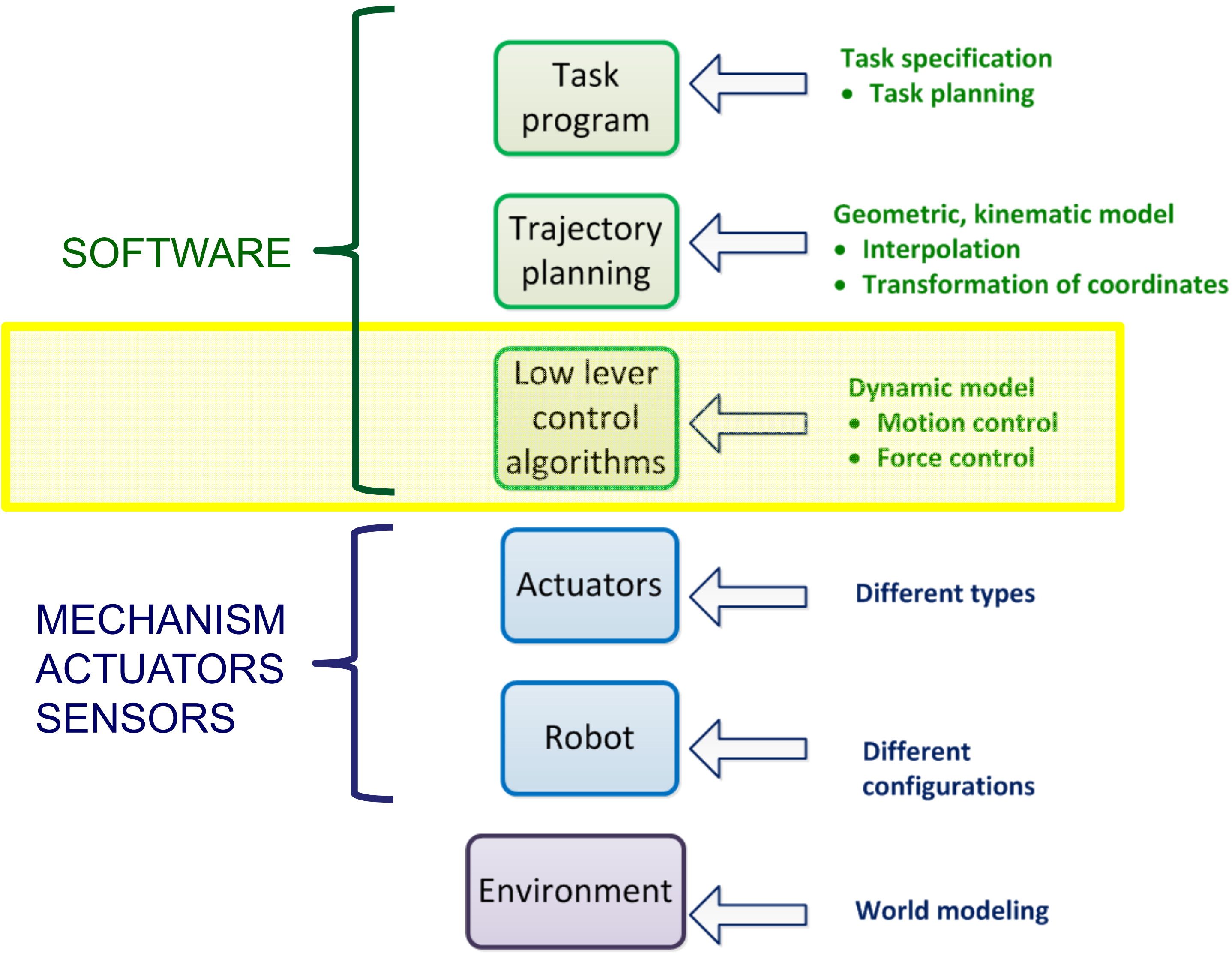
Introduction

What is ‘robot control’?

Definition of ‘Robot control’ depends on the level of problem definition.



Introduction



Introduction

- The need to produce something requires the ability to move something with a very high level of accuracy!

Robot control problem can be described as issuing the reference to joint actuators (joint torque) with the goal that the robot end-effector:

- o follows planned trajectory or keeps desired steady state position and/or,
- o exerts a reference force to the environment.

Robot control performance

What to consider when designing the controller and evaluating robot control performance:

- o Operating conditions
- o Type of the task
- o Error definition space

Robot control performance

Operating conditions:

To consider when designing controller and evaluating robot control performance:

- Operating conditions
- Type of the task
- Error definition space

Ideal/nominal operating conditions

- Conditions as predefined by the producer (environment, load).
- No faults, no unplanned collisions and heavy disturbances.

Model based controllers, sometimes even linear controllers can be implemented.

Perturbed operating conditions

- Changing environment, disturbances.
- Parametric uncertainties.
- Structural uncertainties.

Nonlinear, robust, adaptive control, soft computing controllers, estimators and observers.

Robot control performance

To consider when designing controller and evaluating robot control performance:

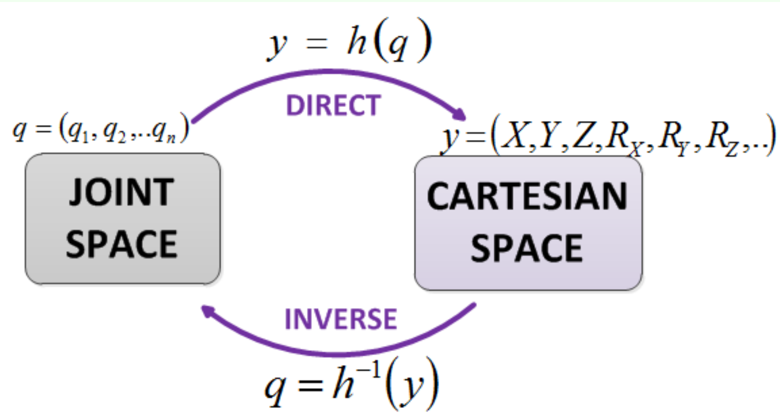
- Operating conditions
- Type of the task
- Error definition space

Types of the tasks:

- Free motion
  - Regulation (positioning, set-point control)
  - Trajectory tracking
- Contact Motion
  - Force control

Error definition space:

- Joint space
- Cartesian space



Robot control performance

How the robot control performance is evaluated?

For ideal/normal operation conditions:

- o Repeatability and accuracy
- o Requested time to execute the task (velocity/speed, cycle time)
- o Energy needs
- o ..

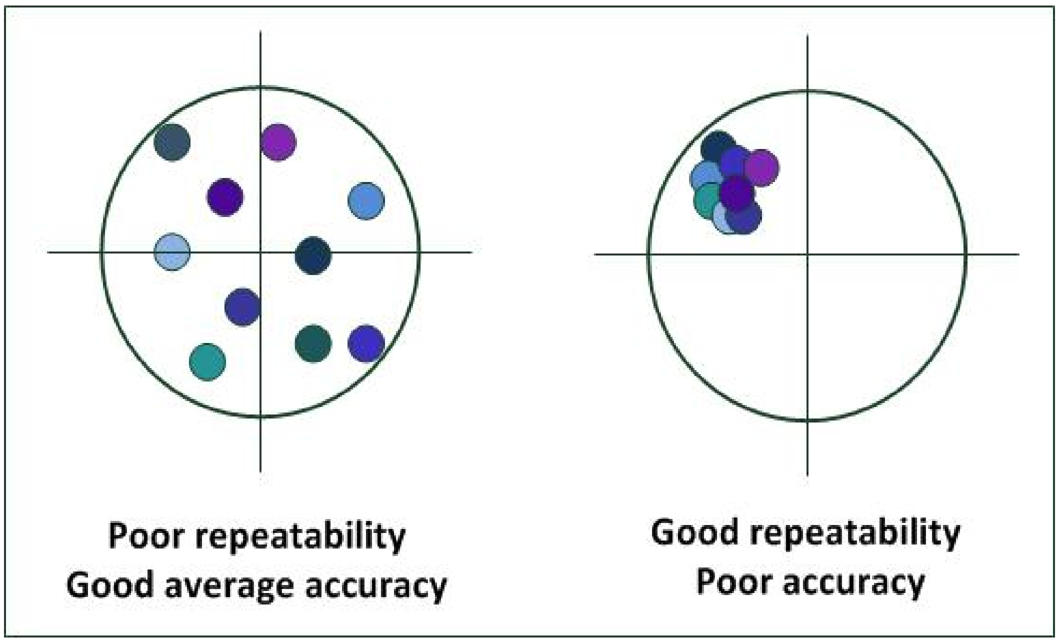
For perturbed operation conditions:

- o Above + robustness (disturbance rejection)

Robot control performance

Accuracy is the nearness of a measurement to the standard calibrated value. Good accuracy is expensive!

Repeatability is the nearness of successive samples to each other. It captures the overall uncertainty in positioning ability and the measurement of this positioning!



Goal of deterministic machine design = produce as repeatable a machine as is possible. In deterministic machine all errors can be predicted with enough modeling.

Robot control performance

Additional comments to the robot repeatability

- Most producers give this specification without telling how it was measured (no description of external device for measurement, number of measured points, number of locations within work space considered, number of joint used in the movements, payload). (1, 2)
- It can be measured as uni-directional (in which the same point is approached repeatably from the same direction) and bi-directional (in which the point is approached from two directions).
- Short and long-term repeatability.

Robot control performance

- Connected term is **resolution**. It can be:
  - o mechanical resolution which is the minimum usable mechanical displacement,
  - o electrical resolution which is the least significant digit of the displacement sensor. With analog sensors (mechanical resolution to 1nm) A/D conversion defines the resolution.
- Accuracy and repeatability cannot be better than resolution.

Robot control performance

- Errors caused by bad choice/implementation of lower level control are also called **dynamic errors**.
- Dynamic errors are caused by non-modeled dynamics, and are especially important at the mechanisms with pronounced coupling and non-linear dynamics, low gear ratio or no gears (direct drive robots). Friction and joint elasticity as especially problematic (SDA10). These errors affect trajectory tracking accuracy.

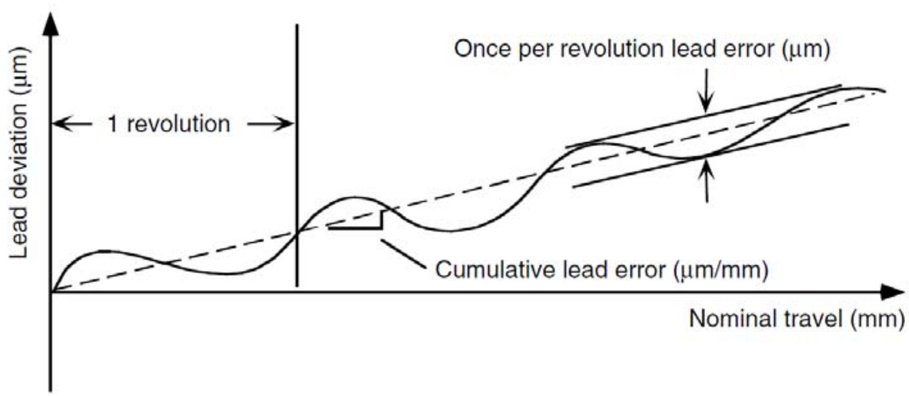
However sometimes the control performance is insufficient because of other errors so it is important to be aware of them.

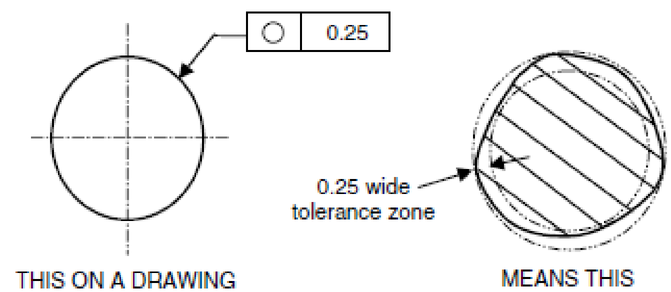
->OTHER SOURCES OF ERRORS

Robot control performance

OTHER SOURCES OF ERRORS

- **Geometric errors** are caused by the manufacturing inaccuracies of the robot. They can be translational, rotational, orthogonality and parallelism errors and are usually not considered (kinematics is calculated according to the technical plan). The worst kind are orthogonality and parallelism errors; Abbe errors, sine error. Cumulative error.





Robot control performance

OTHER SOURCES OF ERRORS

- **Thermal errors** are caused by the heating due to internal or external sources. Deformation of the robot components is due to either differences in thermal expansion coefficients or non-uniform temperature distributions. Can be caused by:
  - o environmental temperature,
  - o by heating caused by drives and electronics.
- They could be also considered as geometric errors.
- Example, thermal factor of iron is $1.17 \cdot 10^5 mK^{-1}$, change of temperature for $10°C$ causes change of length 0.117mm.

Robot control performance

OTHER SOURCES OF ERRORS

- **System errors** are caused by
  - bad calibration,
  - non-accurate sensors,
  - backlash,
  - poorly tuned servos (factory tuned for no-load or nominal load conditions).
- The system errors can be usually eliminated. However it is hard to identify them, respectively distinguish them between other errors.

Robot control performance

How the performance of industrial robots is specified by the manufacturers?

- Provided in the robot specifications sheet.
- The robot characteristics, which have to be provided by the manufacturer in the robot specifications, are defined by standard ISO 9946. In this way the buyer can compare different robots.

Robot control performance

- Although the manufacturers provide the same characteristics the methods for measuring them are not standardised and may differ. Therefore the specifications can only serve only for a rough comparison of similar robots. For exact data additional testing needs to be executed.

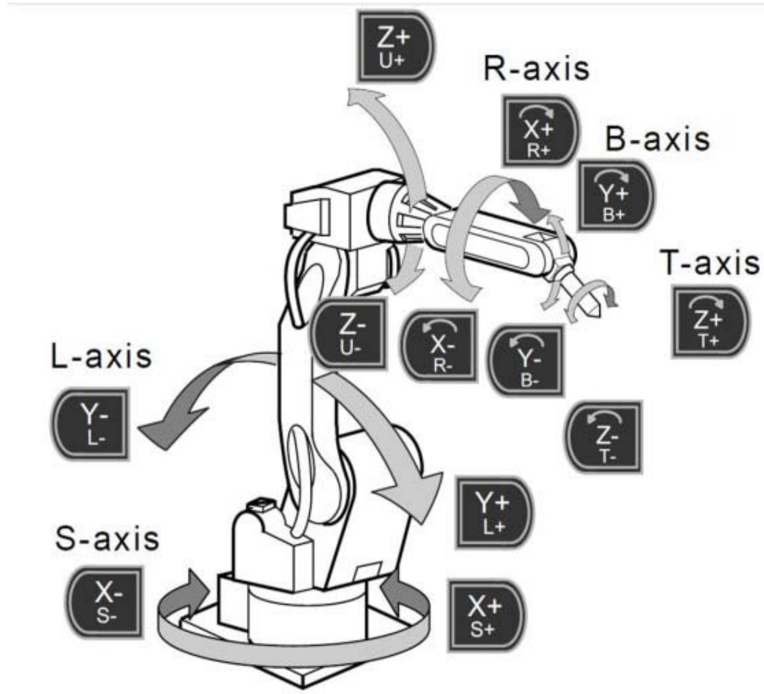
- Following characteristics have to be provided for the industrial robots in the specification:
  - o workspace;
  - o payload;
  - o maximum velocity;
  - o position repeatability.

Robot control performance

ROBOT SPECIFICATIONS

		HP6 Standard	HP6S Short (High-Speed)	HP6R Shelf-Mount
Structure		Vertical jointed-arm type	Vertical jointed-arm type	Vertical jointed-arm type
Controlled Axes		6	6	6
Payload		6 kg (13.2 lbs.)	6 kg (13.2 lbs.)	6 kg (13.2 lbs.)
Vertical Reach		2,403 mm (94.6")	1,597 mm (62.9")	2,456 mm (96.7")
Horizontal Reach		1,378 mm (54.25")	997 mm (39.3")	1,528 mm (60.2")
Repeatability		±0.08 mm (0.003")	±0.08 mm (0.003")	±0.08 mm (0.003")
Maximum Motion Range	S-Axis (Turning/Sweep)	±170°	±170°	+130°/-105°
	S-Axis (Wall Mount)	±30°	±30°	n/a
	L-Axis (Lower Arm)	+155°/-90°	+133°/-80°	+100°/-120°
	U-Axis (Upper Arm)	+250°/-175°	+165°/-130°	+300°/-115°
	R-Axis (Wrist Roll)	±180°	±180°	±180°
	B-Axis (Bend/Pitch/Yaw)	+225°/-45°	+225°/-45°	±135°
	T-Axis (Wrist Twist)	±360°	±360°	±360°
Maximum Speed	S-Axis	150°/s	180°/s	140°/s
	L-Axis	160°/s	220°/s	160°/s
	U-Axis	170°/s	220°/s	170°/s
	R-Axis	340°/s	340°/s	340°/s
	B-Axis	340°/s	340°/s	340°/s
	T-Axis	520°/s	520°/s	520°/s
Approximate Mass		130 kg (286.7 lbs.)	120 kg (264.6 lbs.)	140 kg (308.7 lbs.)
Brakes		All axes	All axes	All axes
Power Consumption		1.5 kVA	1.5 kVA	1.5 kVA
Allowable Moment	R-Axis	11.8 N • m	11.8 N • m	11.8 N • m
	B-Axis	9.8 N • m	9.8 N • m	9.8 N • m
	T-Axis	5.9 N • m	5.9 N • m	5.9 N • m
Allowable Moment o Inertia	R-Axis	0.24 kg • m^2	0.24 kg • m^2	0.24 kg • m^2
	B-Axis	0.17 kg • m^2	0.17 kg • m^2	0.17 kg • m^2
	T-Axis	0.06 kg • m^2	0.06 kg • m^2	0.06 kg • m^2
Internal User I/O Cable		16 conductors + ground	16 conductors + ground	16 conductors + ground
Internal User Air Line		PT 3/8" connector	PT 3/8" connector	PT 3/8" connector

- Motoman HP6



http://www.motoman.com/

Robot control performance

- When buying industrial robot all control issues are resolved and repeatability of the robot is sufficient for most industrial application (arc and spot welding, spray painting, grinding and polishing, material handling)
- What is the main reason why the industrial robot's applications design fails?
  - The requirements for cycle time are not met.
  - Problem: the manufacturers usually don't specify the maximum velocity of the robot end-effector, since it depends on too many factors. They provide the maximum velocity of each robot joint instead.

OUTLINE

- Introduction
- Robot control performance
- Control design process
- Robot control methods

Control design process

Design of the robot controller:

1. Design of the complete system either prior to, or in conjunction with the control design.
2. Modeling of the system and in some cases also modeling of the system’s interaction with environment.
   - kinematic and rigid-body dynamic modeling of the robot,
   - obtaining model parameters via direct measurements and/or identification,
   - verifying the correctness of the models and validating the estimated parameters,
   - estimating to what extent the rigid-body model covers the real robot dynamics,
   - if needed for high-performance control, the identification of the dynamics not covered by the derived model.

Control design process

Design of the robot controller:

3. Analysis of dynamic properties by simulation.
4. Control requirement specifications.
5. Controller choice and design including reconsideration of related components such as sensors, controller's hardware and sometimes actuator(s), gears.
6. Simulation, verification and control prototyping.
7. Implementation, tuning, verification.

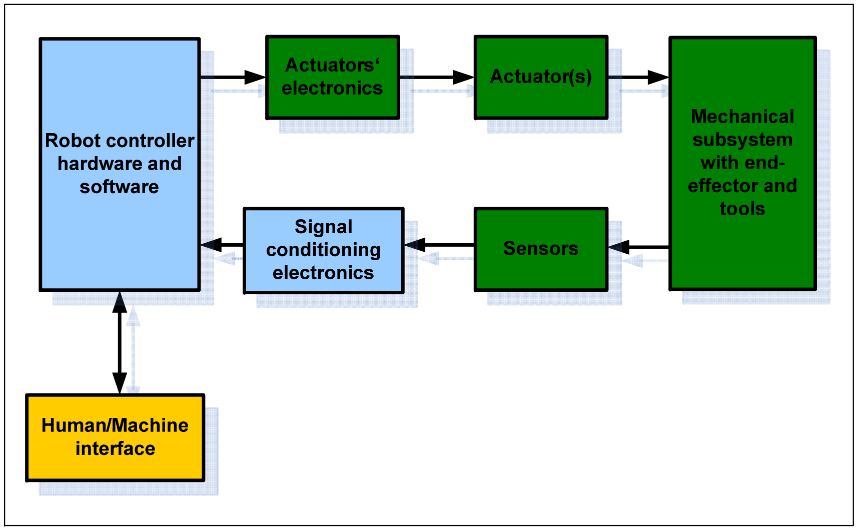
The order of the listed design steps is not fixed.

Control design process

Other issues to consider to improve performance of robot controller:

- Integration and interplay of control, mechanics, and electronics (modern precision-positioning systems are mechatronic in nature).
- Smart design can reduce control efforts (mechanics, thermal management, cable management, gears).
- Actuators with higher dynamic performance (e.g., direct drives).
- Introduction of feedback on all hierarchical levels.

The applications should justify the price.



OUTLINE

- Introduction
- Robot control performance
- Control design process
- Robot control methods

Robot control methods

Key issues in robot control

- Stability
  - o Stability, convergence
  - o Asymptotic stability
  - o Global asymptotic stability
- Robustness to uncertainties in the dynamics model
  - o In general dynamic models of robots are not exact (already mentioned parametric and structural uncertainties, changing load). However often bounds of uncertainties can be estimated.
- Robustness to external disturbances
  - o Vibrations, signal noise..

Robot control methods

- Feedback control
  - o Computed torque (CT): Model based, feedforward linearization and feedback linear controller. Not sensitive to smaller disturbances and parameters variations.
- Robust control
  - o Acceptable performance even in the presence of relatively large uncertainties. Sliding mode control.
- Adaptive control
  - o Adapting the control law/control parameters in ‘real-time’ according to unknown disturbances uncertainties and/or parameter variations.
- Force control
  - o Control of force exerted on the environment.

Robot control methods

- Soft computing (intelligent) control
  - o Belong under adaptive and in most cases also under robust control.
  - o Change of internal structure or parameters in ‘real-time’ = learning, artificial neural networks (can replace unknown model).
  - o Application of human operator fuzzy knowledge in the controller, fully logic systems (can replace not precisely known model).

Robot control methods

Few more control terms that will be used:

- Trajectory tracking: following the prescribed (reference, desired) trajectory: position, velocity, acceleration).
- Set-point control: reaching a goal configuration in either task or joint space irrespective of the trajectory. This is also called the stabilization problem. Set-point error = steady state error.
- Position/velocity control: compensates for model's parametric and structure uncertainties and suppresses disturbances.
- Force control: Controlling the force exerted by the manipulator onto an object in a single or multiple degrees of freedom. Can be reduced to position control if the stiffness of the manipulator and object are known, but it usually requires force sensing. Hybrid control will be addressed, e.g. controlling force along certain DOFs and position along other DOFs.

Final

- We will address the problem of torque regulation by developing different robot torque controllers.
- The output from the torque controller is reference torque/current for each robot drive.
- Current needs to be measured.
- The controllers will be built directly on dynamic models of the robots.
- High performance control of robot manipulator trough torque regulation is very complex task. The difficulty arises from the complexity of the robot dynamic model.