Robots in contact

From task demonstration to execution in contact part 2

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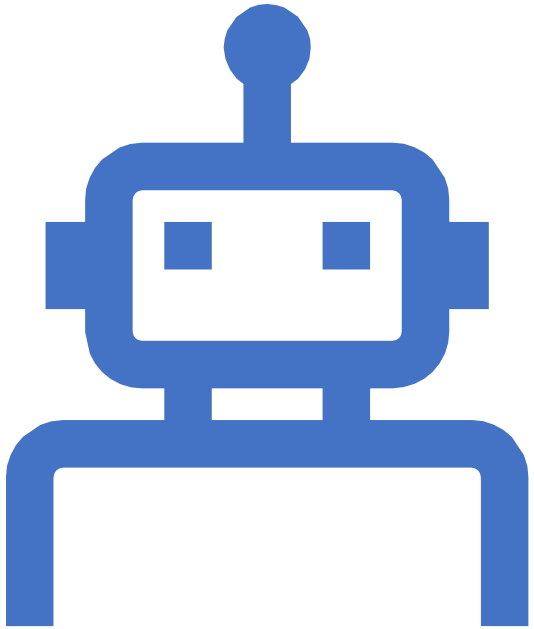
Based on M. Mihelj, T. Bajd. et al. Robtics – second edition, Springer, 2018

Siciliano, Bruno, and Oussama Khatib, eds. *Springer handbook of robotics*. Springer, 2016.



Agenda

- Robot control – recap (position and velocity control, Jacobians, etc.),
- Robot control in contact:
  - Force control – simple (PD),
  - Hybrid position/force control,
  - Impedance control,
  - Admittance control.
- Coupling force control with demonstrated data.
- Executions in contact.

Robot control

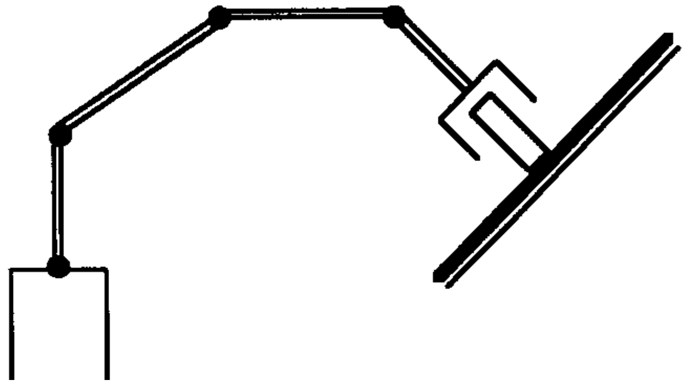
Terminology

- **Kinematics** – the study of motions of particles, bodies and systems of bodies in terms of position (and orientation), translation (and rotation), but without considering forces (and torques) causing the motions. The bodies are considered to be rigid.
- **Dynamics** – the study of motions of particles, bodies and systems of bodies in terms of mass (resp. inertia), force (and torque) or energies. The bodies can be rigid or deformable.
- **Kinematic system** – a system of rigid bodies (called **links**) designed to move in a given form by the introduction of moveable **joints** which connect the links.
- **Serial kinematic / Kinematic chain** – a kinematic system where each link is connected by joints to only one or two other links (without forming a circle). An important parameter is the **number of joints**.
- **Serial robot** – a serial kinematic, where some or all joints can be programmed, actuated and controlled to move the links in a defined way. (If not all joints can be actuated, the robot is called **underactuated**).

Terminology

- **Tool Center Point (TCP)** – the definition of a central coordinate system for each tool, which has to be controlled and moved to execute the actual manipulation, e.g. the center between the jaws of a gripper.
- **Forward kinematics** - Specifying the joint values to accomplish a robot move to a new configuration in space. These may not be simple as it seems because secondary joints such as four-bar linkages, ball screws, etc. may be required to accomplish this motion.
- **Inverse kinematics** - Solving a mathematical model of the robot kinematics to determine the necessary joint values to move the tool to a desired target (frame) in space. This is accomplished by frame representation whereby a coordinate system (xyz axes) is attached to the tool on the robot and a target frame is attached to the part or operating point in the workcell. The inverse kinematics determine the joint values required to align the tool coordinate system with the target triad.
- **Manipulator Jacobian:** The time derivative of the kinematics equations yields the Jacobian of the robot, which relates the joint rates to the linear and angular velocity of the end-effector. The Jacobian also provides a relationship between joint torques and the resultant force and torque applied by the end-effector.

Kinematics Loop



- With ***direct kinematics (DK)*** we compute the task space poses (DOFs) based on joint angles.

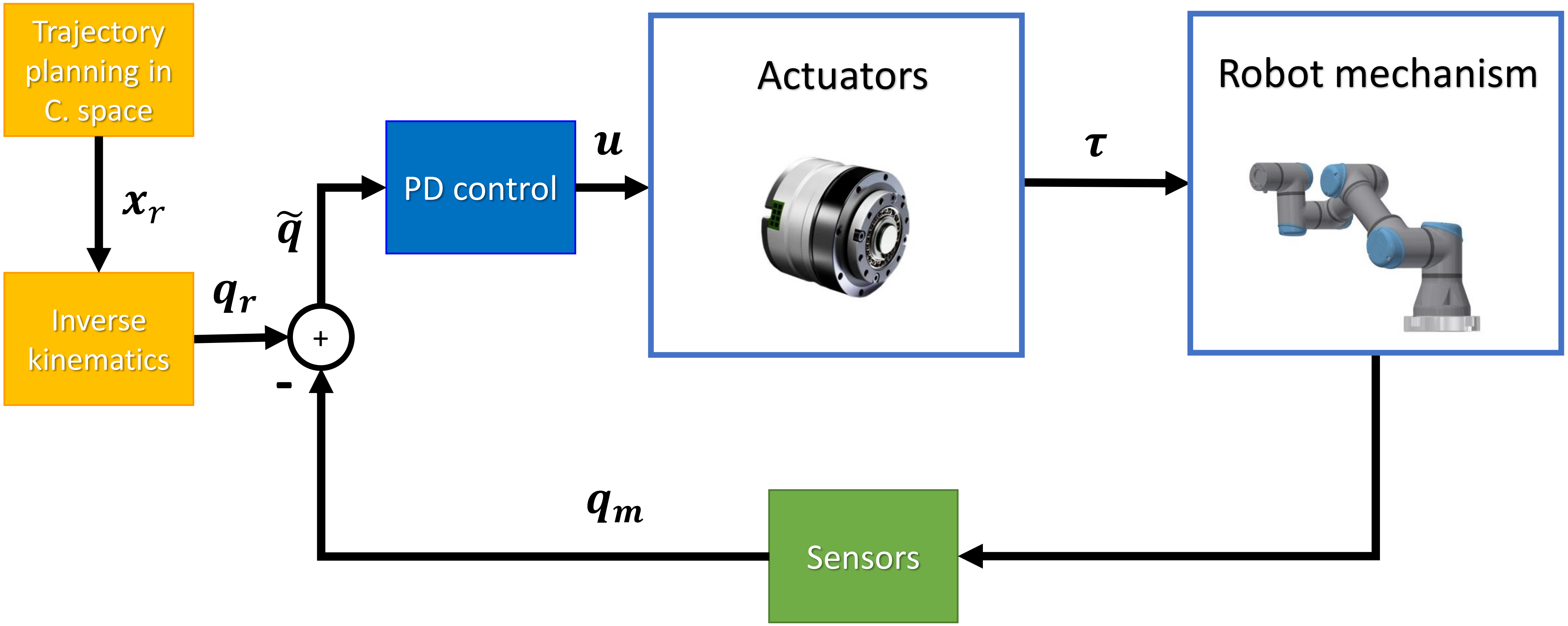
$$T_{task} = f(q(\theta)),$$

- The goal of ***inverse kinematics (IK)*** is to compute the vector of joint DOFs that will cause the end effector to reach some desired goal state,
- In other words, it is the inverse of the forward kinematics problem,

$$\mathrm{q}(\theta) = f^{-1}(T_{task}).$$

Position control

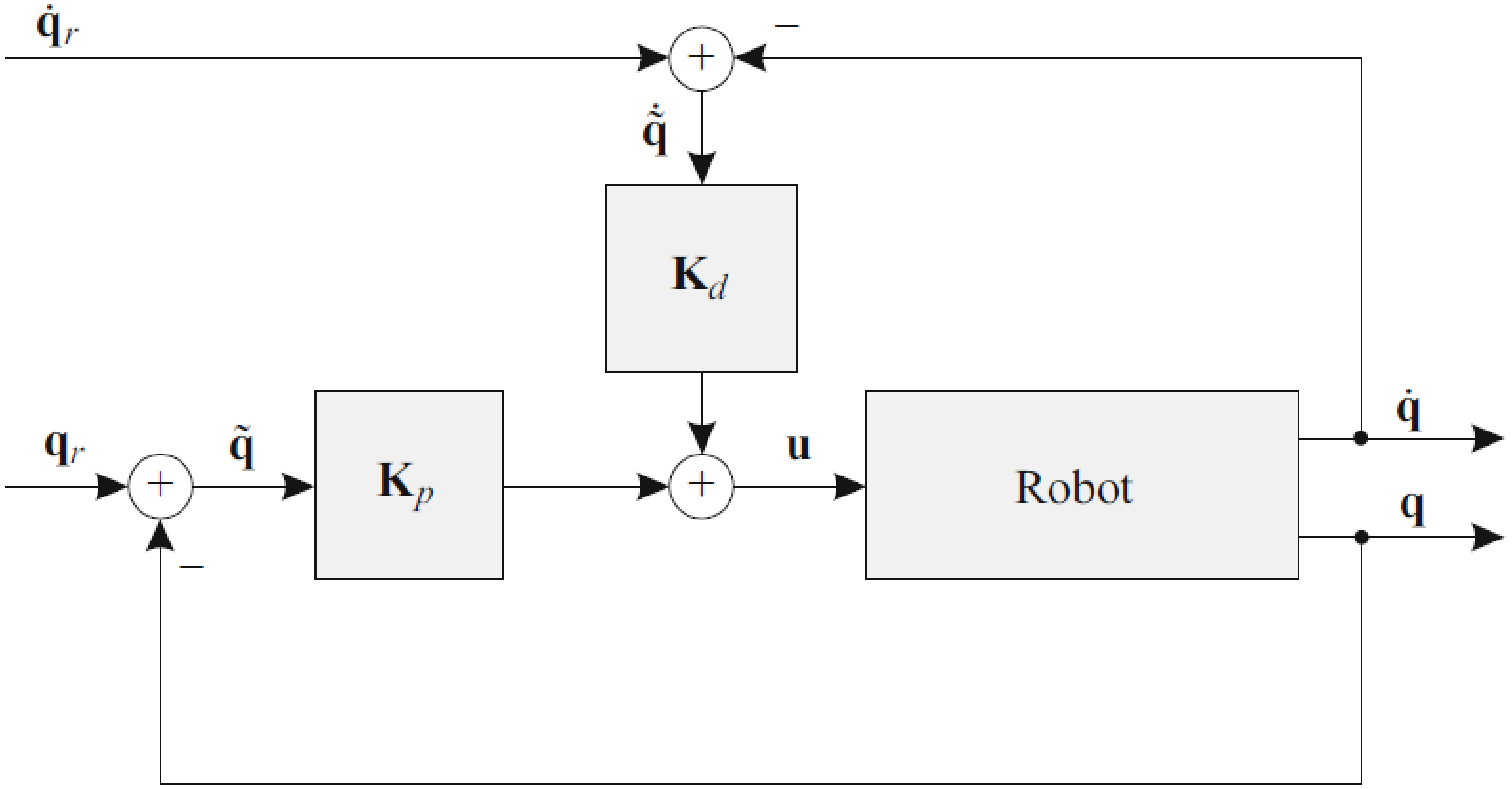
Position control



Position control

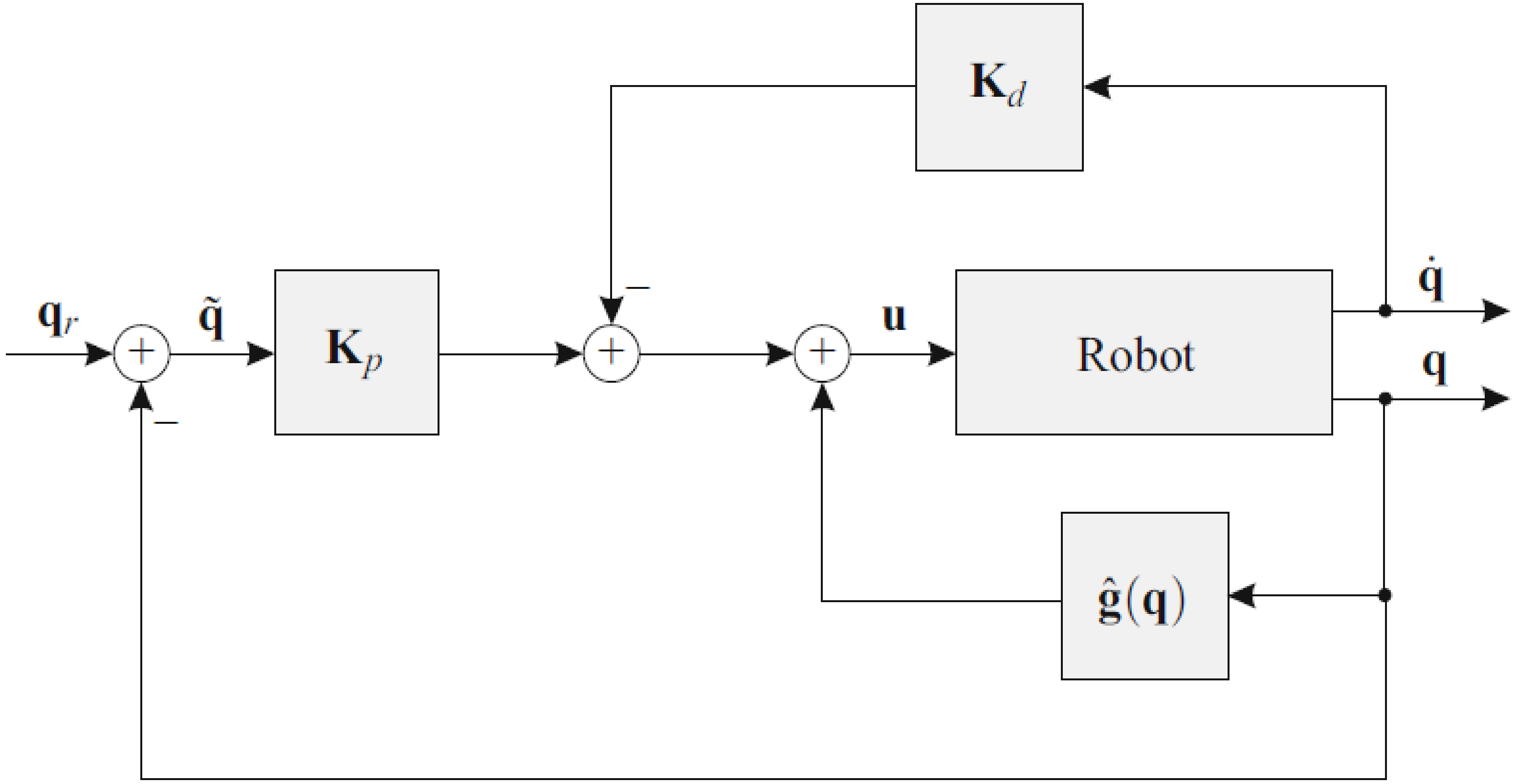
- Position control is also know as stiff control or high gain control.
- The manipulator is able to follow the stet points – with high accuracy.
- Normally implemented with PD control normally implemented on the positional level with joint position measurement in the feedback loop.
- For a normal industrial robot, position control is implemented in the controller, therefore we just send the set points to the controller.
- The dynamic parameters of the robot are normally not given by the manufacturer, but they can be estimated ☺ with proper procedures.

Position – velocity control



Position control with gravity compensation

- Friction dynamics is compensated in the control strategy enabling to control the robot in free-drive mode.

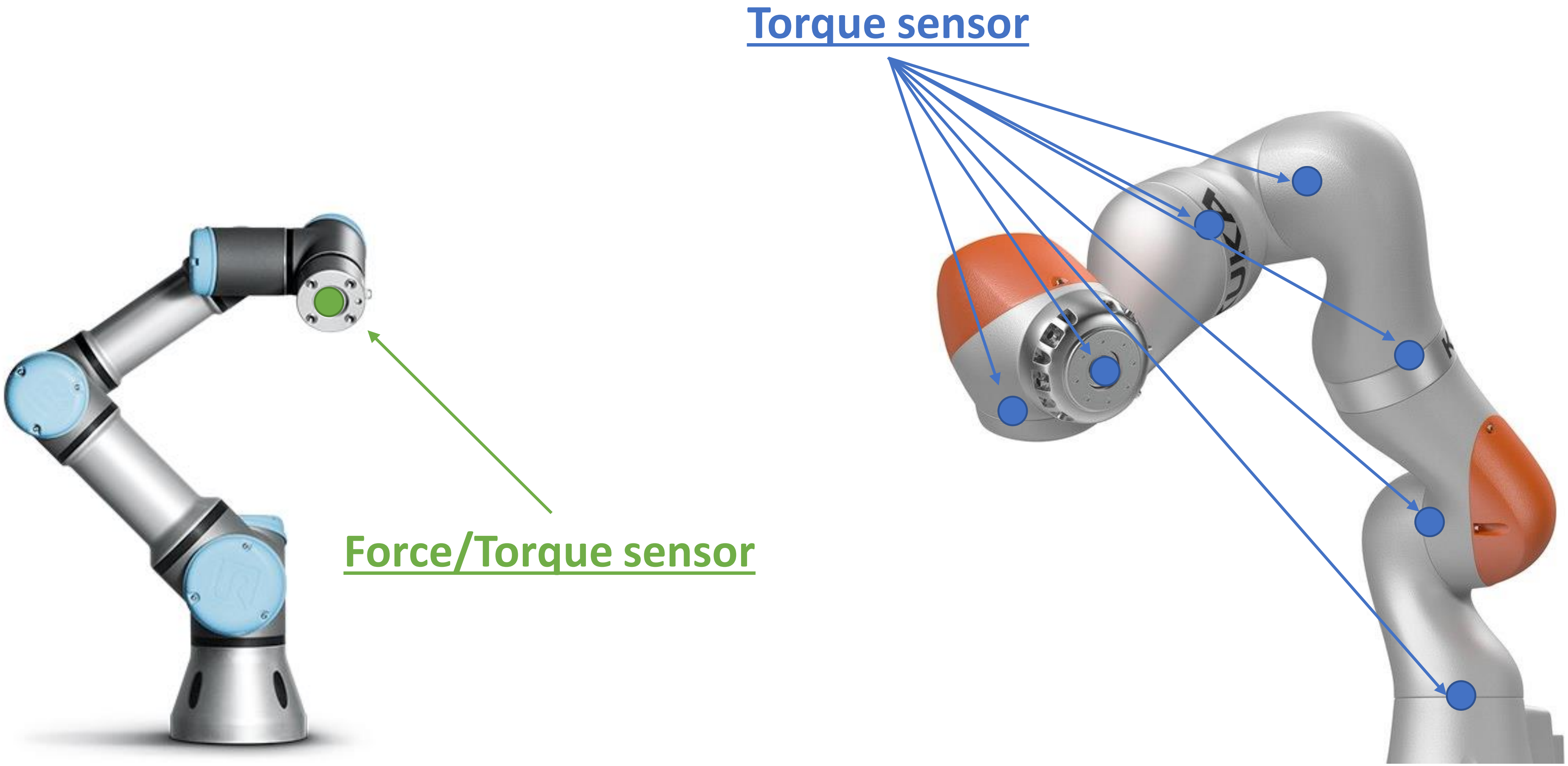


Position control limitation

- Can not adapt to unforeseen changes in the robot workspace,
- If a robot encounters an obstacle in its path of operation, the controller will increase the motor torque,
- The robot is fully stiff – risk of damages or injuries,
- Bad results when executing tasks, where the manipulator need to maintain constant contact wit the environment.

Measuring force data

Two types of robots



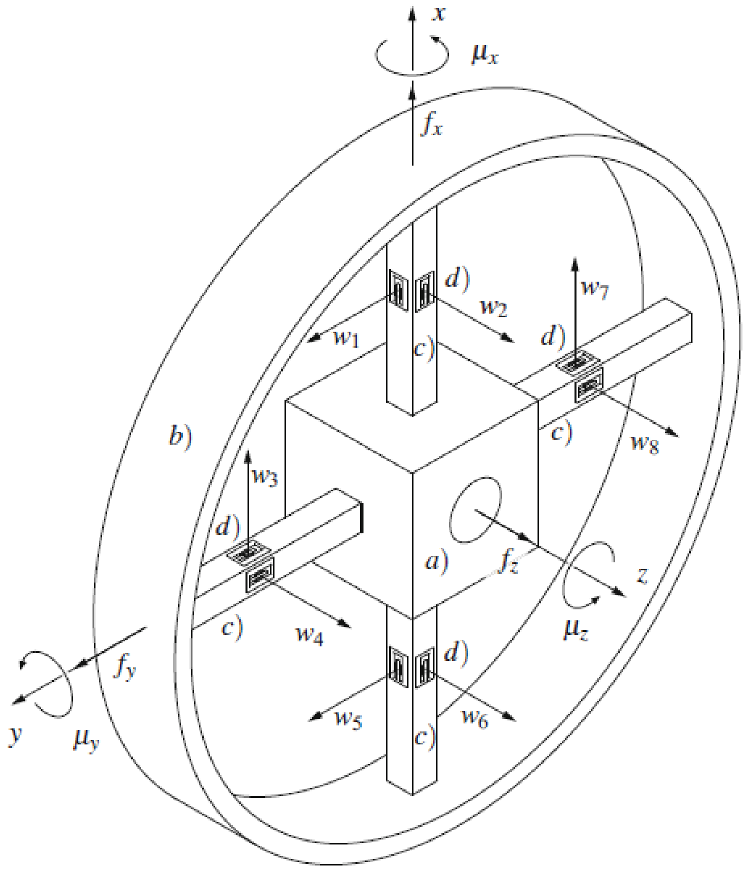
Force measurements

- In principal we distinguish 2 methods:
  - Force measurement with a force/torque sensor,
  - Torque measurement with a dedicated sensor mounted in the joint of the robot.

https://www.automationmag.com/7586-ati-develops-axia80-force-torque-sensor/

http://sensortransducer-com.sell.everychina.com/p-108800750-robot-joint-torque-measurement-transducer-robot-arm-torque-sensor.html

Force/torque sensor

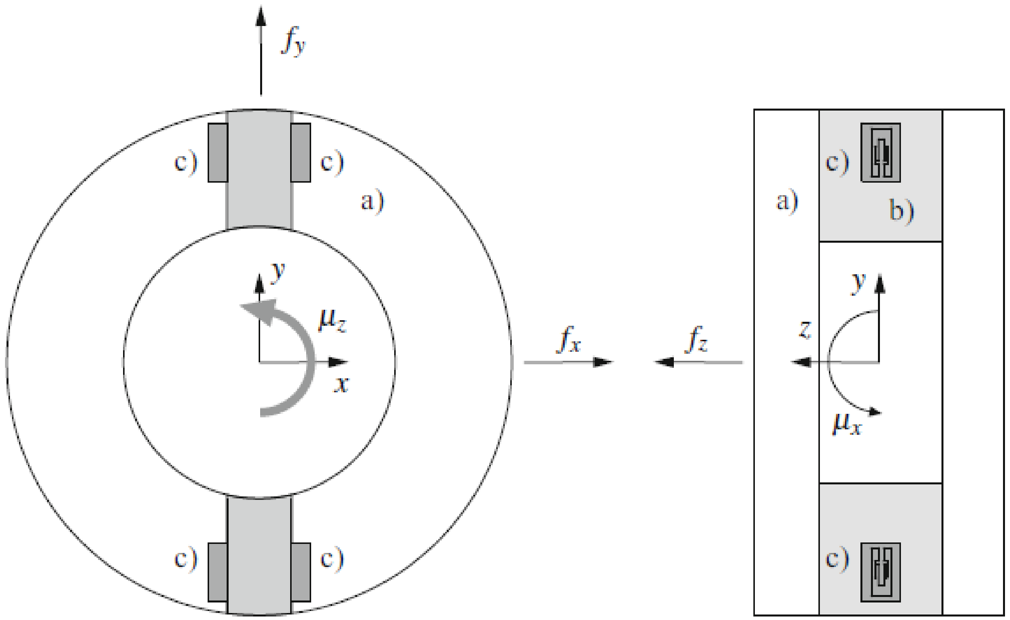


- Integrated system for measuring torques in all principal axis,
- deformations in the beams of the rigid structure are transformed to forces and torques.

$$F = [F_x, F_y, F_z], \qquad M = [M_x, M_y, M_z]$$

- generally, force torque sensors are mounted at the tool of the robot,
- the sensors are susceptive to drift, because of the temperature effects, therefore the measurements have to be temperature compensated accordingly.

Joint torque sensor



- The senor is located at the every joint of the robot,
- deformation of mechanical structure due to joint torque is measured by strain gauges,
- with this method forces can be estimated on every point of robots structure,
- if the dynamic model of the robot is known, we can transform the measurements to end-effector forces

$$\boldsymbol{F} = \boldsymbol{J}^{-\boldsymbol{T}}(\boldsymbol{q})\boldsymbol{\tau}$$

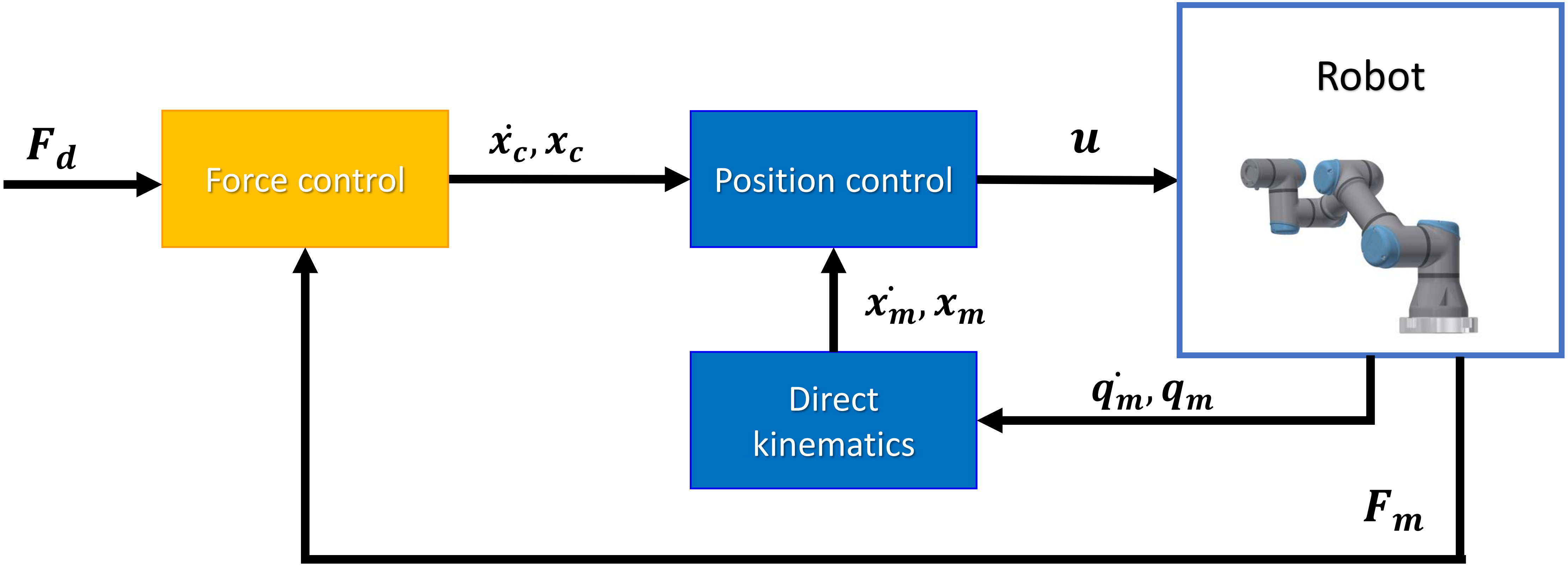
$\boldsymbol{\tau} = [M_1, .., M_N]$, N is the number of joints

Force control strategies

Common strategies

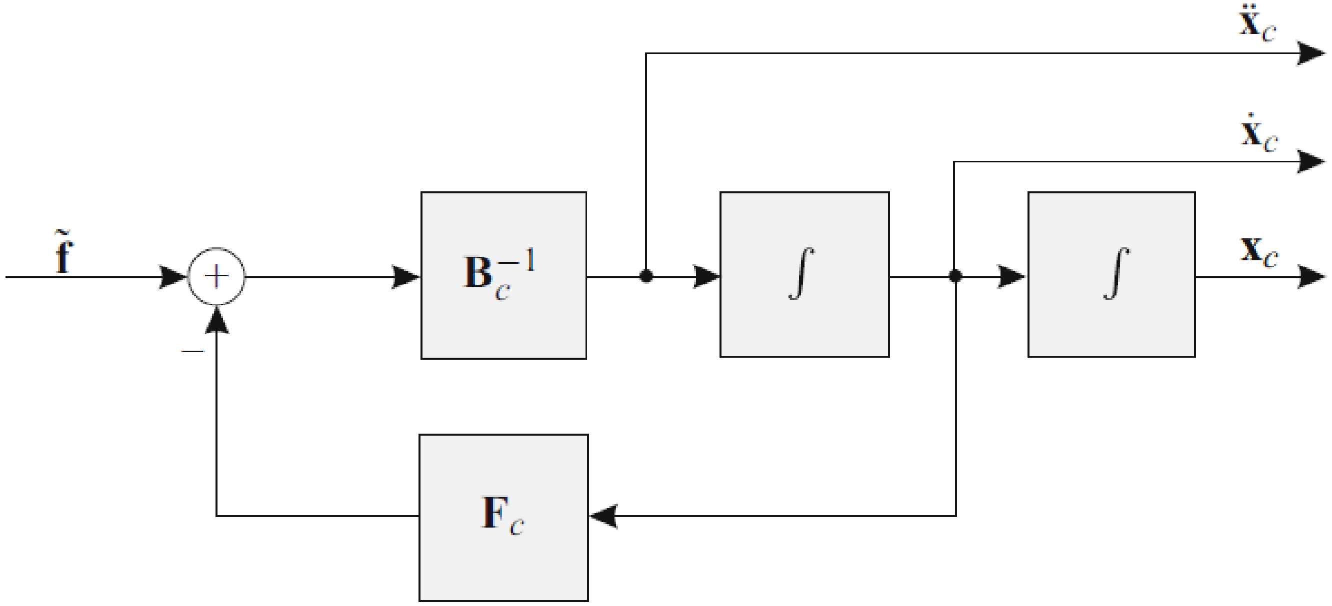
- **Direct force control**
  - PD control force control,
  - Parallel control,
  - Hybrid control,
- **Impedance control**
  - Passive,
  - Active,
  - Admittance control,
- **Couplings with feedforward trajectory control**

Force control



- The force control will be denoted as control of the end-effector pose,
- if we wish the robot to increase the force exerted on the environment, the robot end-effector must be displaced in the direction of the action of the force.

Force control

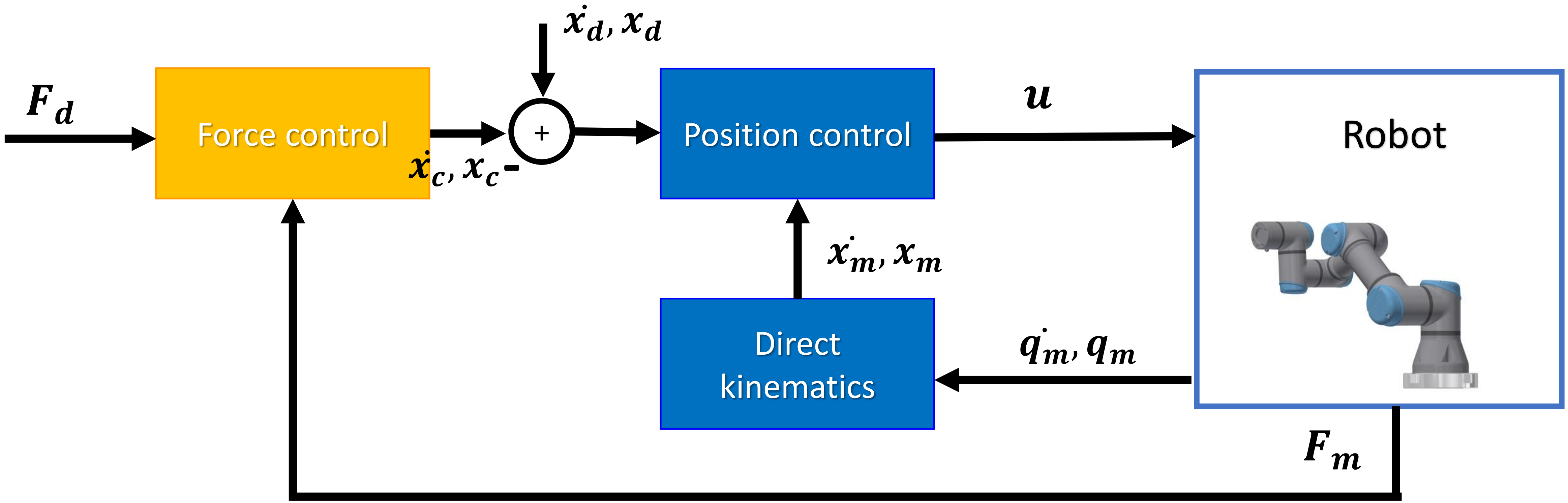


- Lets assume we have a constant desired force F_d and a feed of measured forces at the end-effector F_m. Then the force error e.g. control signal can be calculated as $\tilde{\boldsymbol{f}} = \boldsymbol{F}_d - \boldsymbol{F}_m$, which is coupled on the acceleration level.
- The end effector movement can be determined based on the force, mass and damping, from which we can calculate the control parameters for the position controller.

$$\tilde{\boldsymbol{f}} = \boldsymbol{B_c}\ddot{\boldsymbol{x}}_{\boldsymbol{c}} + \boldsymbol{F_c}\dot{\boldsymbol{x}} \text{ -> } \ddot{\boldsymbol{x}}_{\boldsymbol{c}} = \boldsymbol{B_c^{-1}}(\tilde{\boldsymbol{f}} - \boldsymbol{F_c}\dot{\boldsymbol{x}}_{\boldsymbol{c}})$$

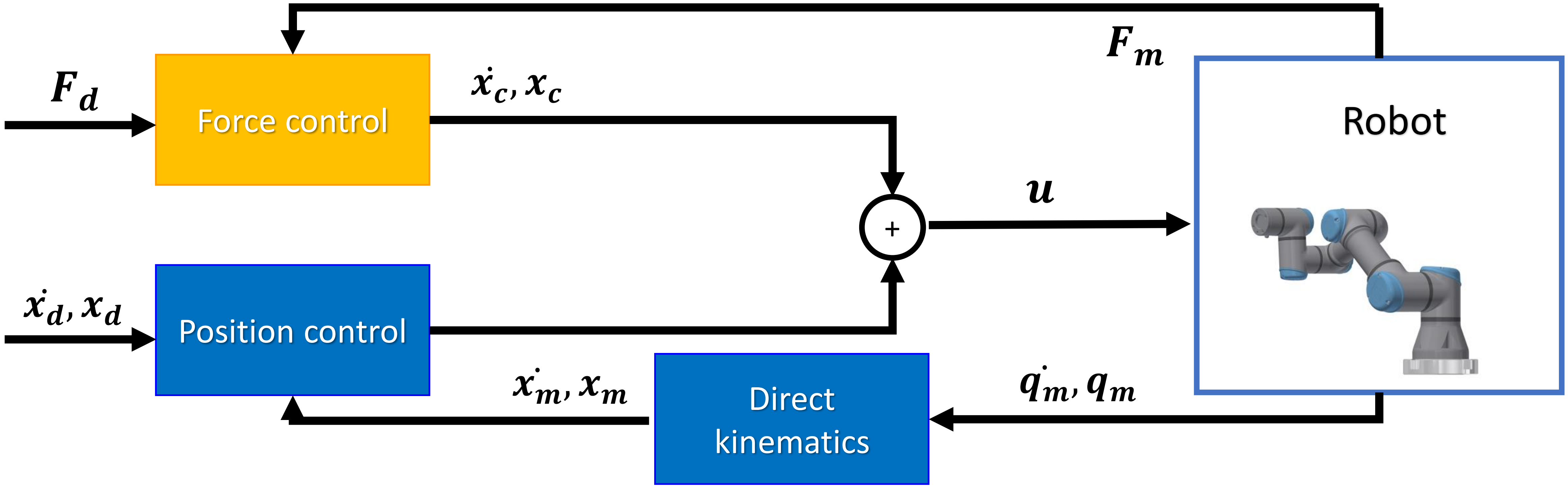
Parallel force control

- Can be also called cascade control,
- there is a tradeoff between the accuracy of force and position control,
- position control can be changed to velocity control, for a more dynamic response.

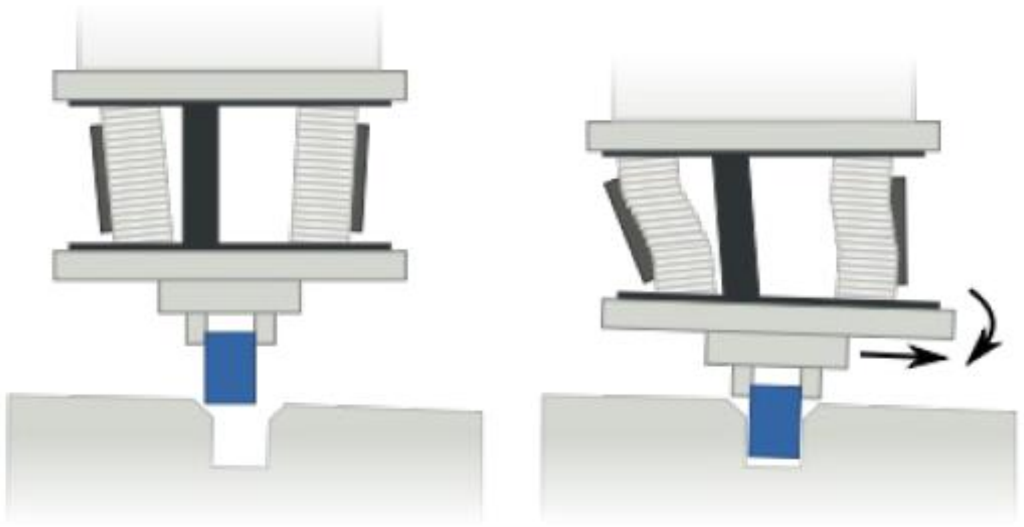


Hybrid force control

- Position or force control,
- can be used for constrained zones defined by position or force,
- switchable based on a force threshold.



Passive impedance control



- Specialized tools mounted between the robots TCP and the tool (gripper),
- Expensive and precise parts,
- No robot control needed – instant adaptation based on the mechanical structure,
- Stiffness – force of adaptation – is controlled bases on the material properties of the elastic parts.
- Also known as - remote center of compliance -.

Active impedance control

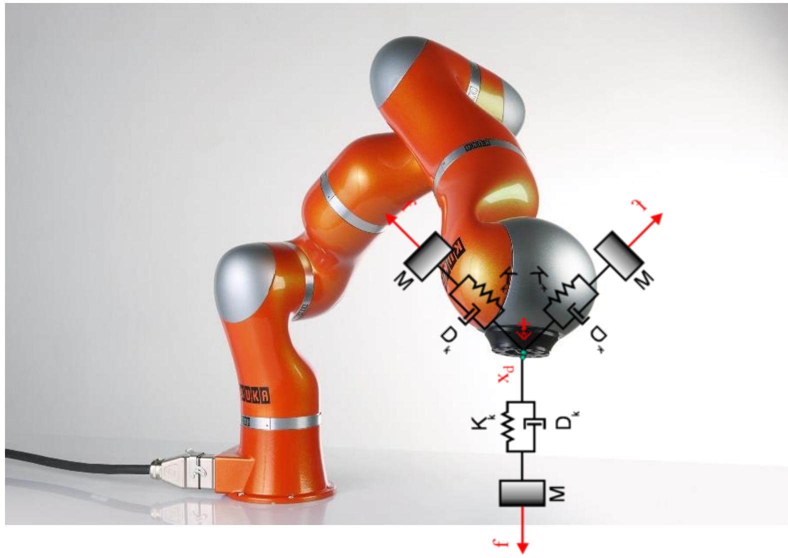
- In contact with the environment the behavior of the robot e.g. end effector, should be as dynamic as possible.
- To satisfy this condition we can relate the system to the behavior of a second order mechanical system second-order mechanical system with six degrees of freedom, characterized by a given mass, damping, and stiffness, known as mechanical impedance.
- Lets consider the following model of an rigid manipulator:

$$M(q)\ddot{x} + C(q,\dot{q})\dot{x} + F_g(q) = F_d - F_m$$

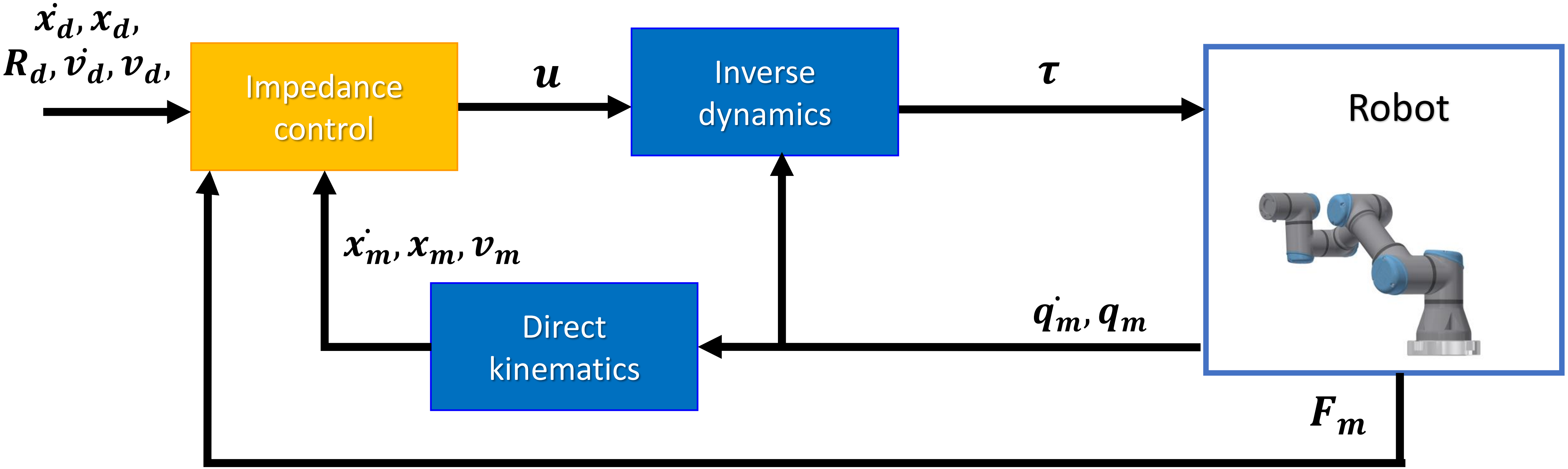
- For the rigid manipulator the impedance control law can be written as:

$$M(q)\ddot{x} + (C(q,\dot{q}) + D_I)\dot{x} + K_I x = F_m$$

where $M, D_I \; and \; K_I$ are the robot inertia, damping and stiffness $\mathbb{R}^{6x6}$, respectively (Villani and De Schutter et al., Hand book of robotics 2016, Shahriari, E et al. Adapting to contacts: Energy tanks and task energy for passivity-based dynamic movement primitives 2017).

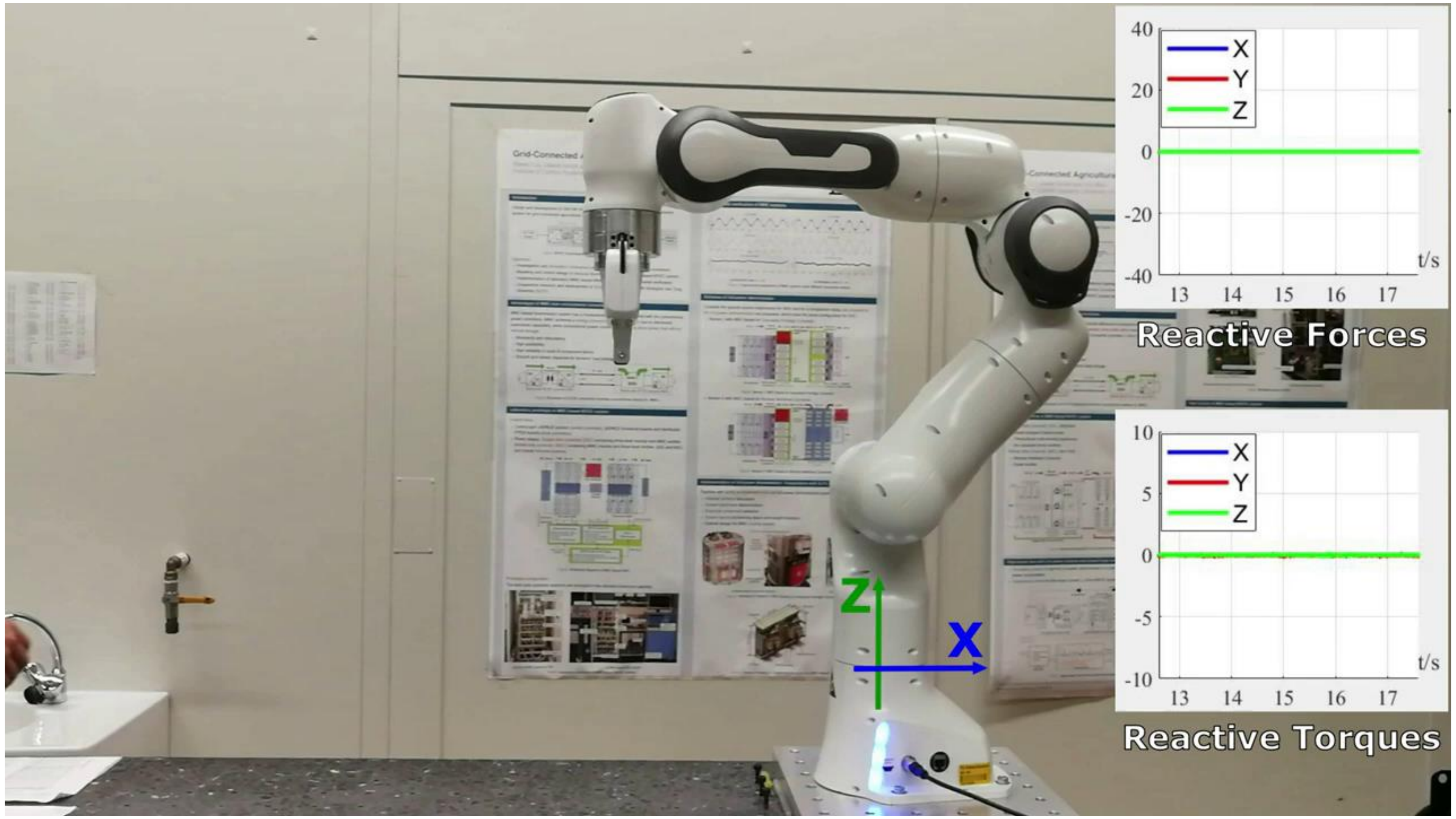


Admittance control



- The desired position of the end effector is controlled based on the measured force and the dynamics of the Impedance controller.
- The method can be implemented on torque control robots, where the dynamics of the robot are known.

Impedance control example



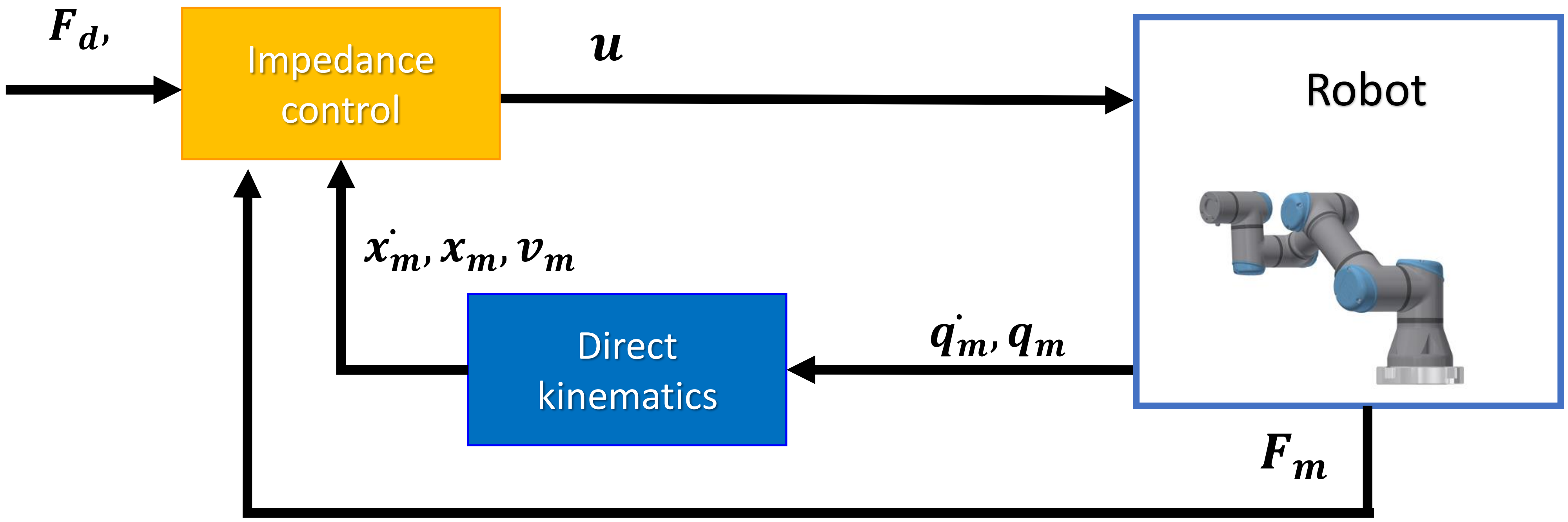
https://www.youtube.com/watch?v=XwiX2vv14Qs

Admittance control

- The main difference between admittance control and impedance control is:
  - With admittance control we control the motion of the manipulator after force is being measured.
  - With impedance control force exerted on the environment is being controlled after the motion or deviation from a set point is measured.
- Impedance controllers are usually implemented on stiff / industrial robots, equipped with an external force/torque sensor.
- The control low of the controller can be written as:

$$M_a \ddot{x}_a + D_a \dot{x}_a + K_a x_a = F_d - F_m$$

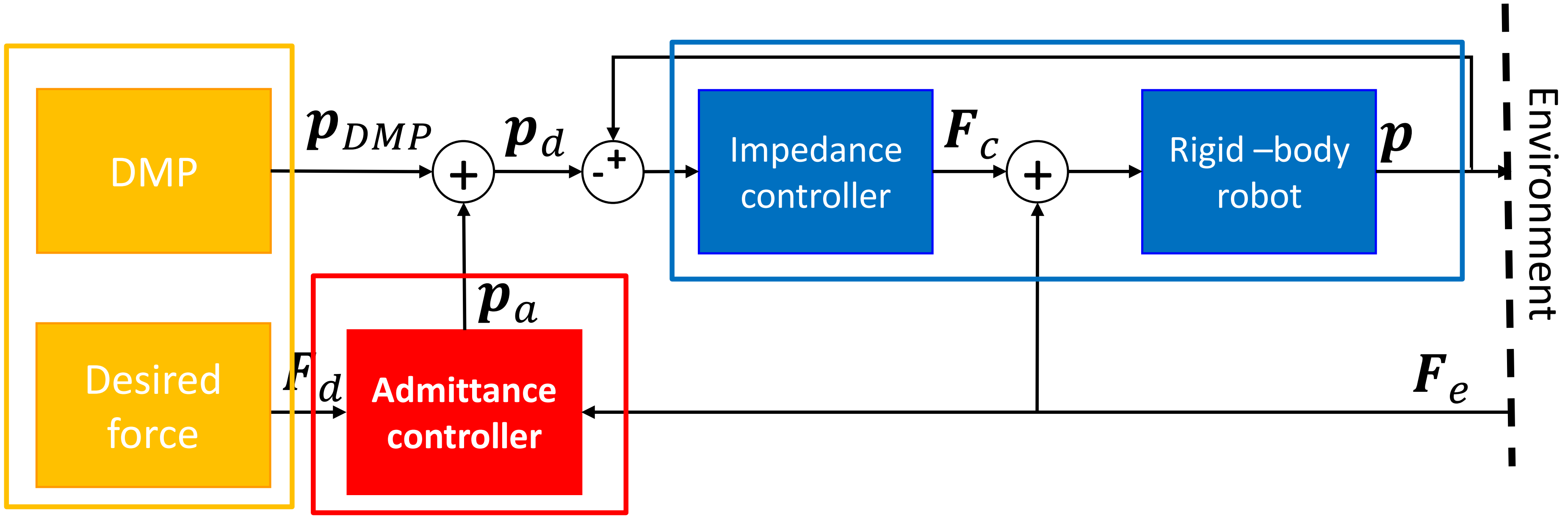
Admittance control



Admittance control example

https://www.youtube.com/watch?v=jGhFNMyVDSw

Coupling with feedforward trajectory control



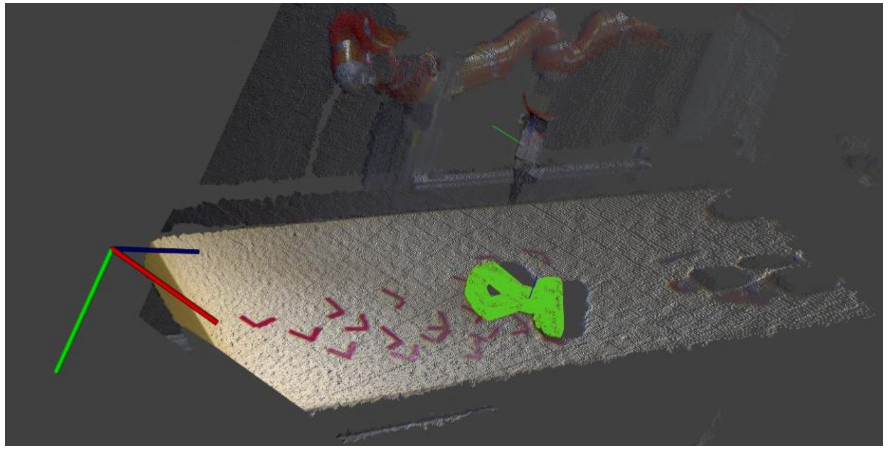
Feed forward trajectory

Force controller

Robot controller

Coupling the primitive with sensory input

- Model based object detection with external RGB-d sensor.
- The detected object displacement $(\Delta\boldsymbol{p}_v, \Delta\boldsymbol{q}_v)$is used for movement transformation.
- Execution with adaptation of the learned movement at new positions.
- Problems:
    - detection inaccuracy,
    - environmental influences,
    - robot to camera calibration.

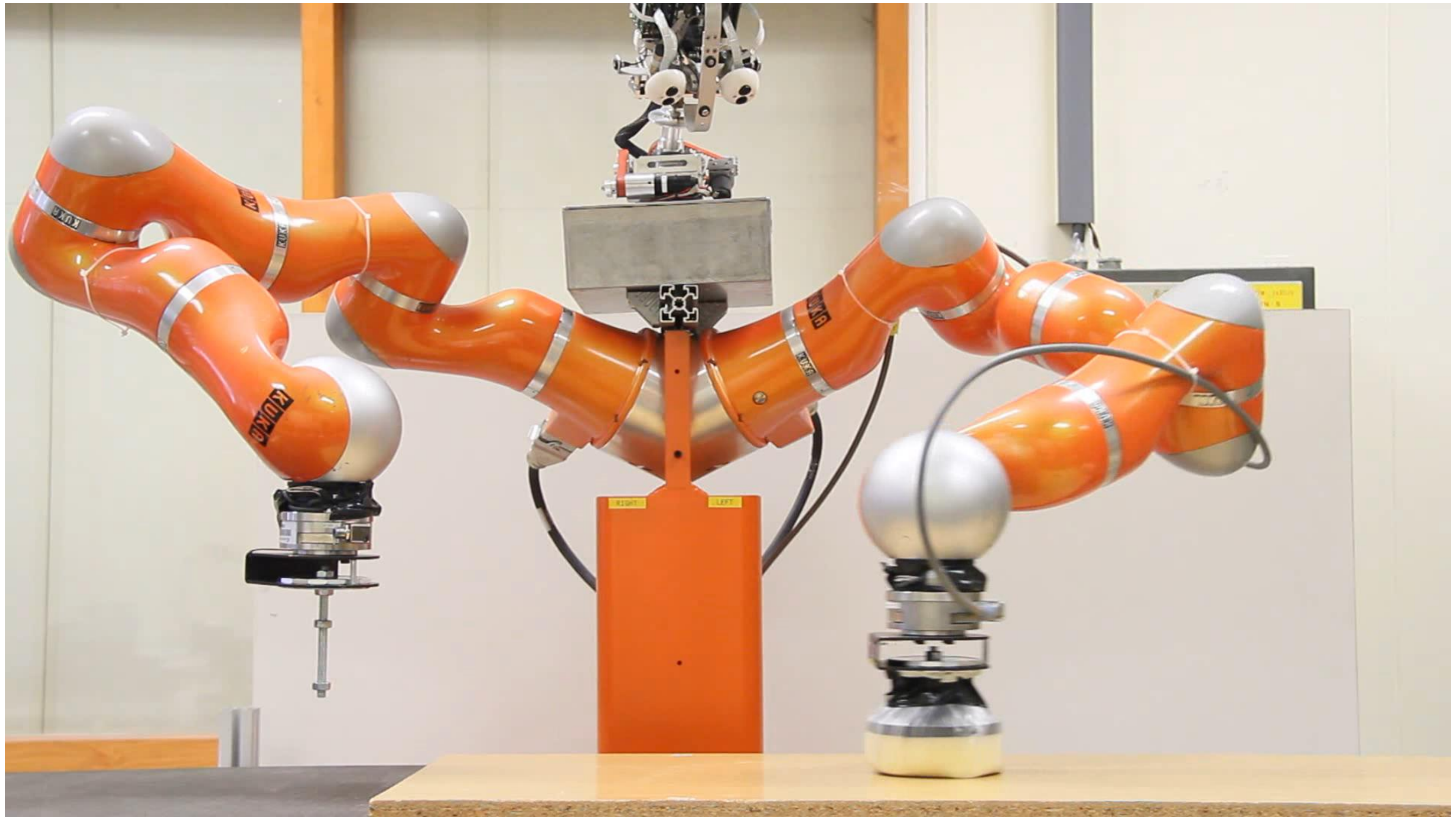


$$\boldsymbol{e}_p(s) = \boldsymbol{q}(s) * \left(\boldsymbol{F}_{ref} - \boldsymbol{F}_m\right) * \overline{\boldsymbol{q}}(s),$$
$$\boldsymbol{e}_q(s) = \boldsymbol{q}(s) * \left(\boldsymbol{M}_{ref} - \boldsymbol{M}_m\right) * \overline{\boldsymbol{q}}(s).$$

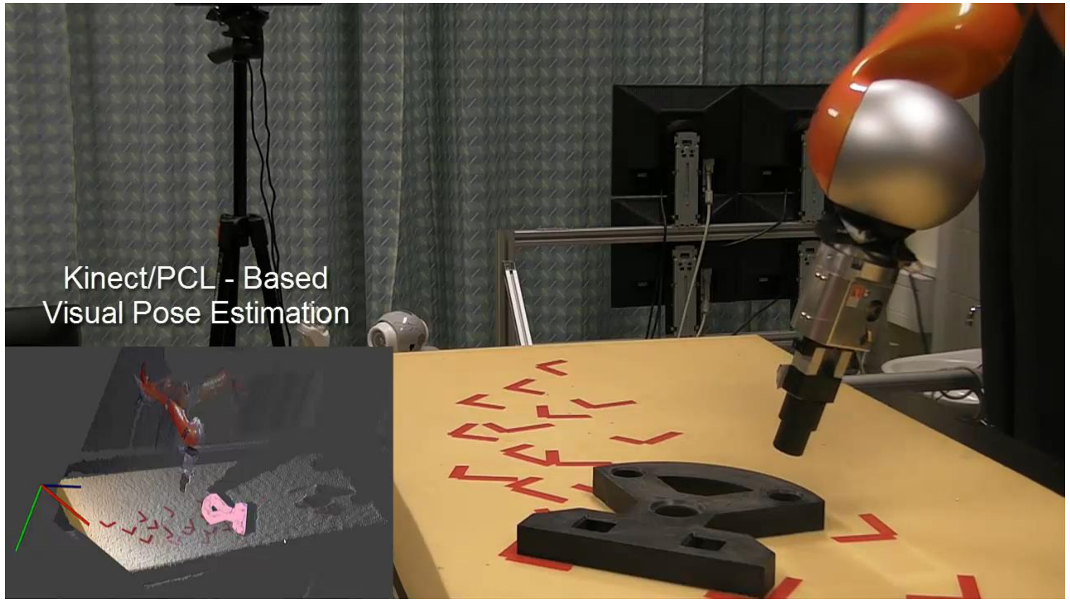
$$\boldsymbol{p}_r(s) = \boldsymbol{\varphi}_p(s) + \boldsymbol{K}_{S1}\boldsymbol{e}_p(s) + (\Delta\boldsymbol{q}_v * \boldsymbol{p}_{DMP}(s) * \overline{\Delta\boldsymbol{p}_v} + \Delta\boldsymbol{p}_v),$$

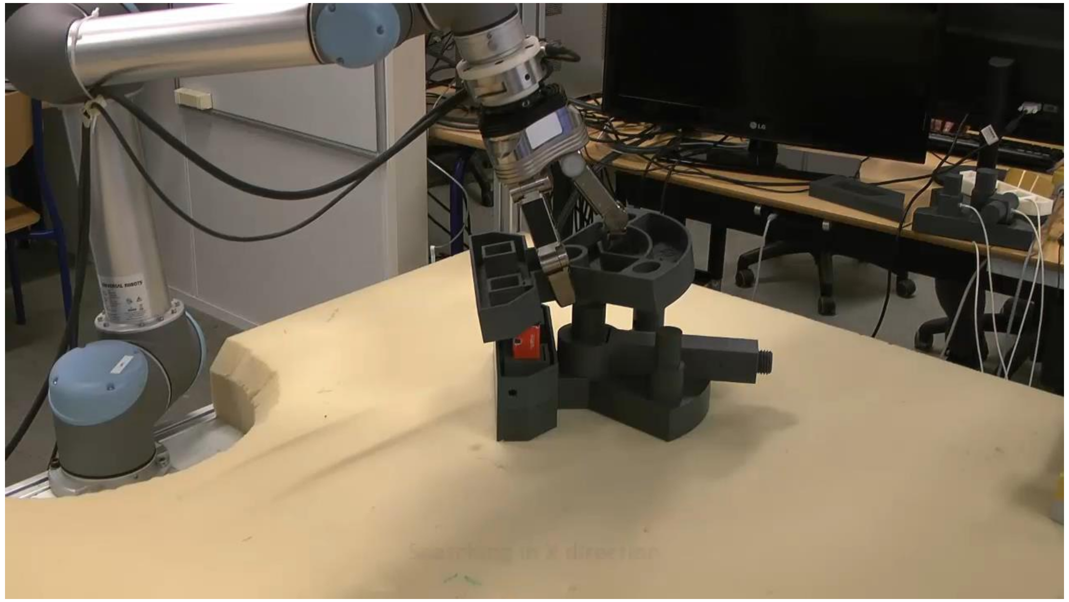
$$\boldsymbol{q}_r(s) = \exp\left(\frac{1}{2}\left(\boldsymbol{K}_{S2}\boldsymbol{e}_q(s) + \boldsymbol{\varphi}_q(s)\right)\right) * \Delta\boldsymbol{q}_v * \boldsymbol{q}_{DMP}(s),$$

Example implementations



Example implementations





- Demonstrated assembly with search strategy's.

Conclusion

Depending on the structure and available sensing of the manipulator, the correct force control strategy can be implemented.

Basic force control strategies can be simply used with modern collaborative robots, because they are already implemented in the controller preset library.

When implementing force control strategies special attention has to be given to a proper selection and evaluation of control parameters.

Force control in combination with position control can be used for various robot tasks in contact with the environment.