A force/torque compliant robot

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Terminology, compliant actuator

- A stiff (non-compliant) actuator is able to move to a specific position/orientation or to track a predefined trajectory and stay to it regardless to external forces within a prescribed limits.
- A compliant actuator allows deviation from its own equilibrium position/orientation depending on the applied external force. The actuator in the equilibrium position generates no force/torque.
- With respect to variable stiff actuators other terms are also used: adjustable compliance, variable compliance, adjustable stiffness, controllable stiffness, variable (mechanical) impedance meaning informally both the compliance and the damping factor.
- More precisely, the mechanical impedance expresses resistance of a mechanical structure to harmonic forces (analogy to electrical impedance).

Motivation

- Manipulation tasks need to handle a physical contact between a robot and the environment.
- Pure motion control is inadequate because of unavoidable modeling errors and uncertainties.
- Force/torque feedback and force control is the needed tool.
- Force/torque feedback is necessary when robots cooperate with humans for safety reasons.

Actuator, gripper
stiff, passive compliant, active compliant

Stiff actuator, a gripper

- No energy can be stored.
- No shocks can be absorbed.
- Holds also for controllers with limited bandwidth.

Passive compliant actuator

- Implemented in a manipulation structure, servo or gripper.
- Contains an elastic element, e.g. a spring, enabling to store energy.

Active compliant actuator

- uses the controller to mimic the spring.
- Control system measures contact forces using Either 6 DoF sensor at the arm tip or 1 DoF force/torque sensor in each joint and reacts to these inputs.
- Active can be meant in a broader sense (e.g. vision, proximity feedback).
- The advantage of the active compliance is that the controller can make the compliance online adaptable.

Compliant motion in a broader sense

- Vision feedback
- Proximity feedback
- Force feedback
- etc.

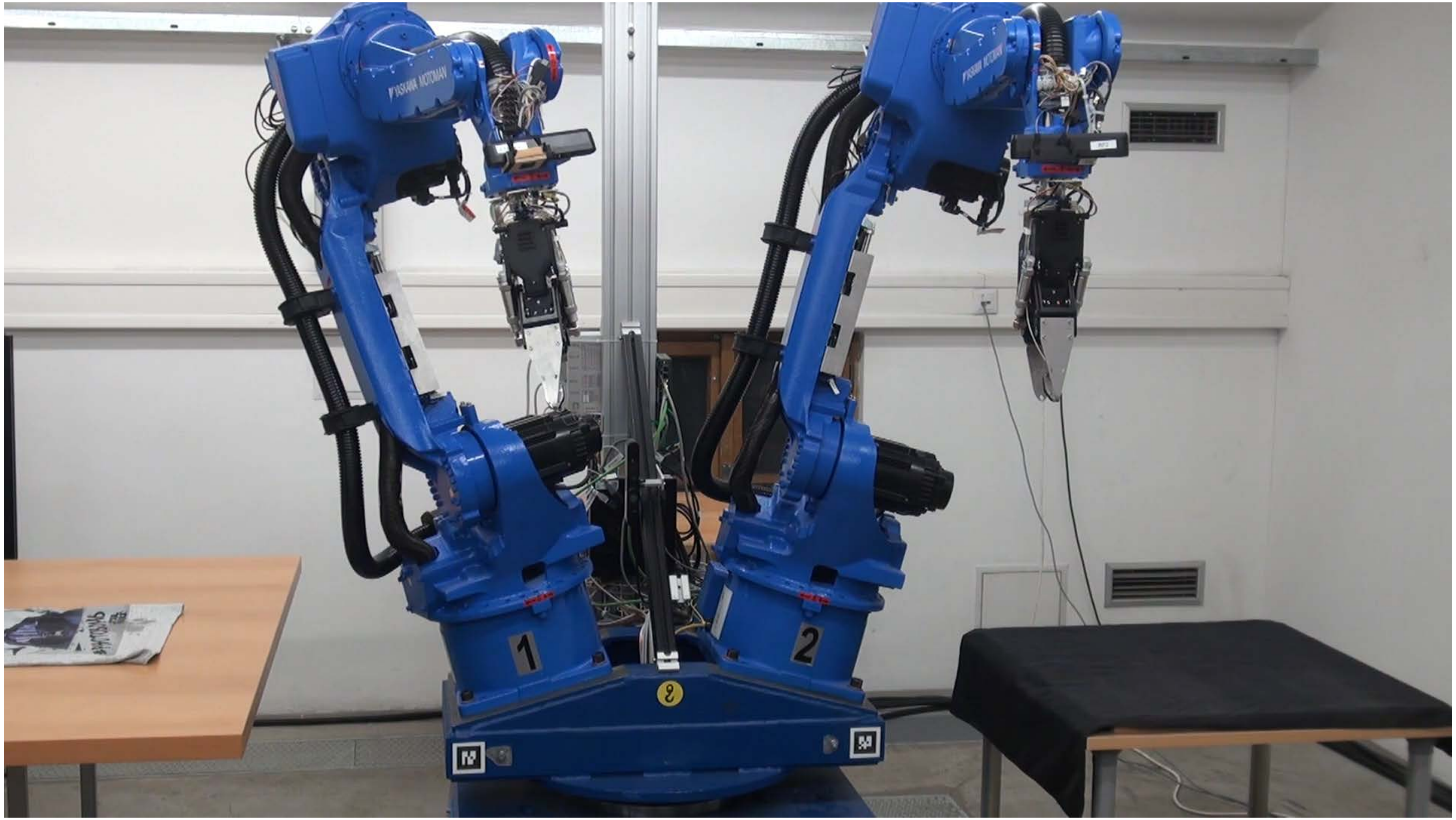
In this lecture, we deal with the force/torque compliant motion.

Requirements for the compliance motion

What is needed?

- 6 degrees of freedom sensor measuring 3 forces / 3 torques
- Adequate programming and control techniques

Compliant motion, motivating example



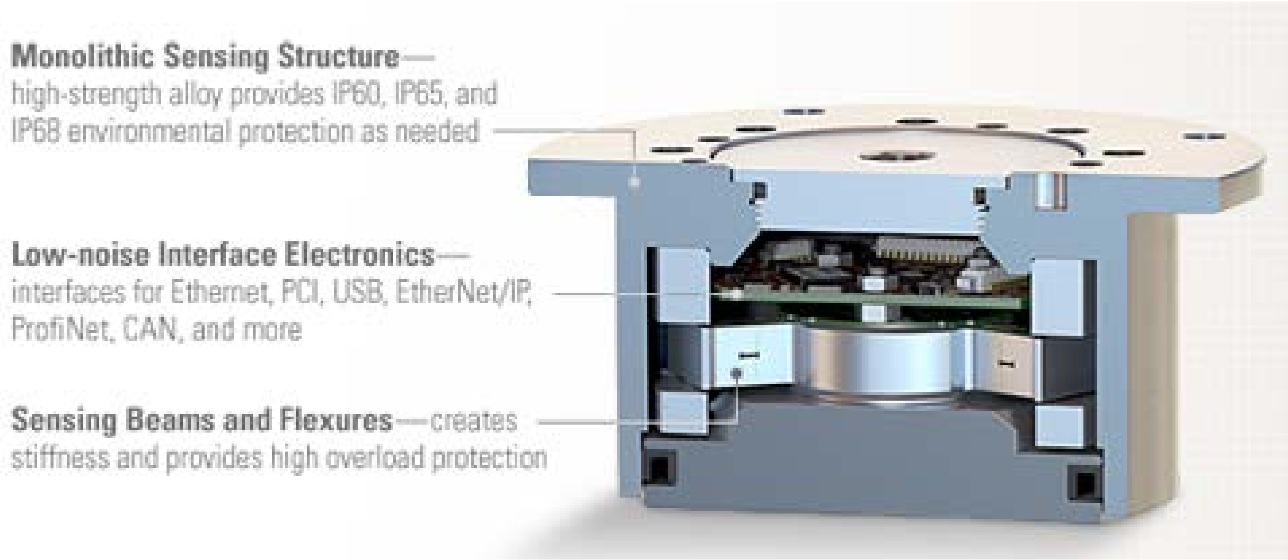
Two 6-DoF force/torque sensors between the gripper and robot arm

Implemented in 2013 by Vladimír Petrík

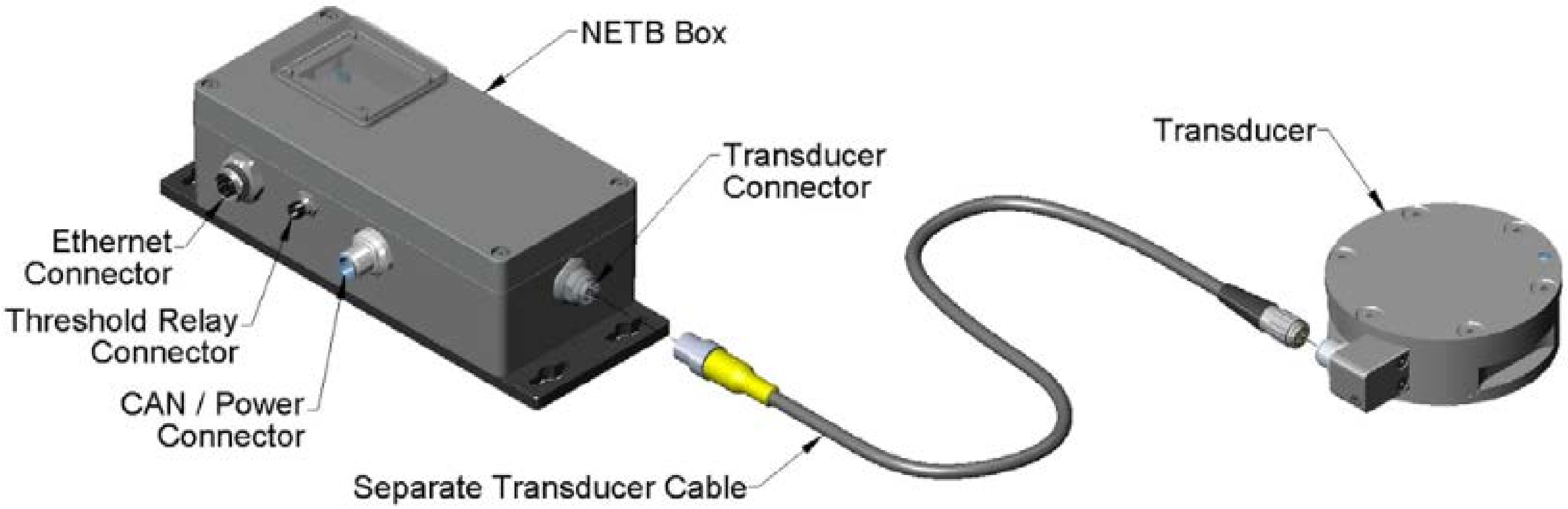
Force/torque sensor used at CTU

Project CloPeMa, 2 sensors ITI Mini45, EUR 6.150 each.

6 DOF Force/torque sensor



- Sampling 20 kHz
- Precision 2 %



Compliant motion

Contact forces/torques modify or generate the robot (endpoint) trajectory.

Task examples utilizing force/torque compliance:

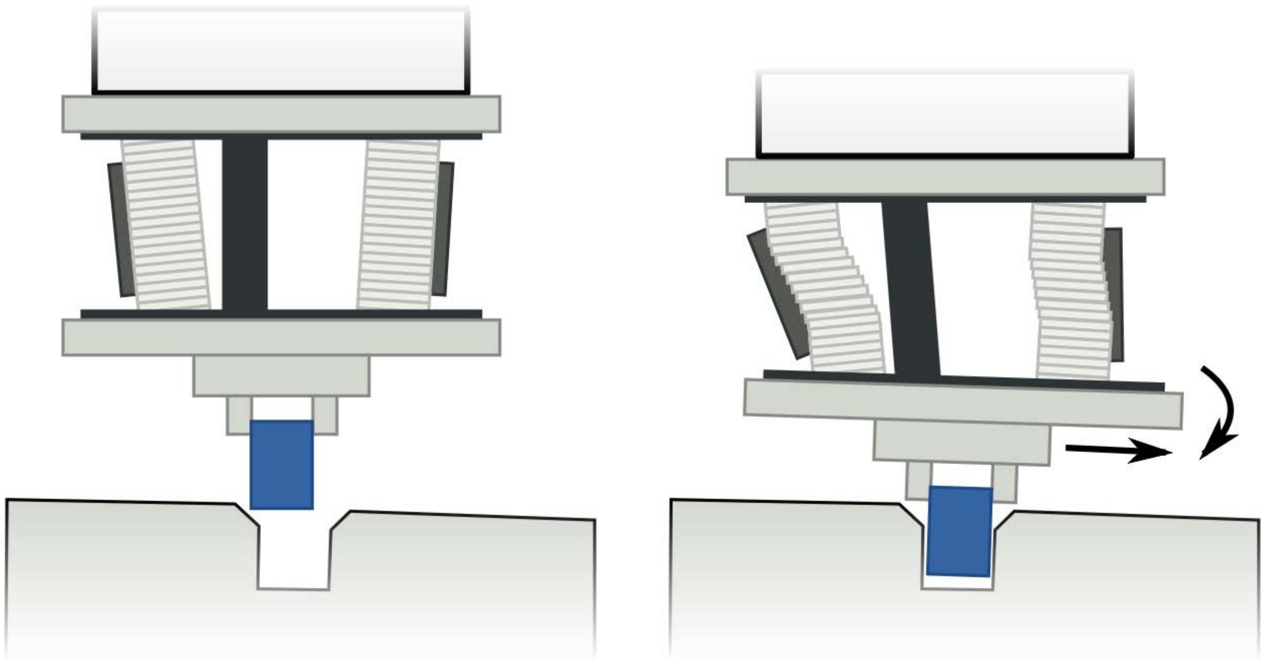
- Inserting a peg into a hole
- Placing an object on top of another one
- Driving a screw
- Opening a door
- Following a contour, e. g. grinding a curved surface while keeping the force normal to the surface constant

Two kinds of compliance

1. Passive compliance
   Example

   Inserting a peg into a hole with the help of springs

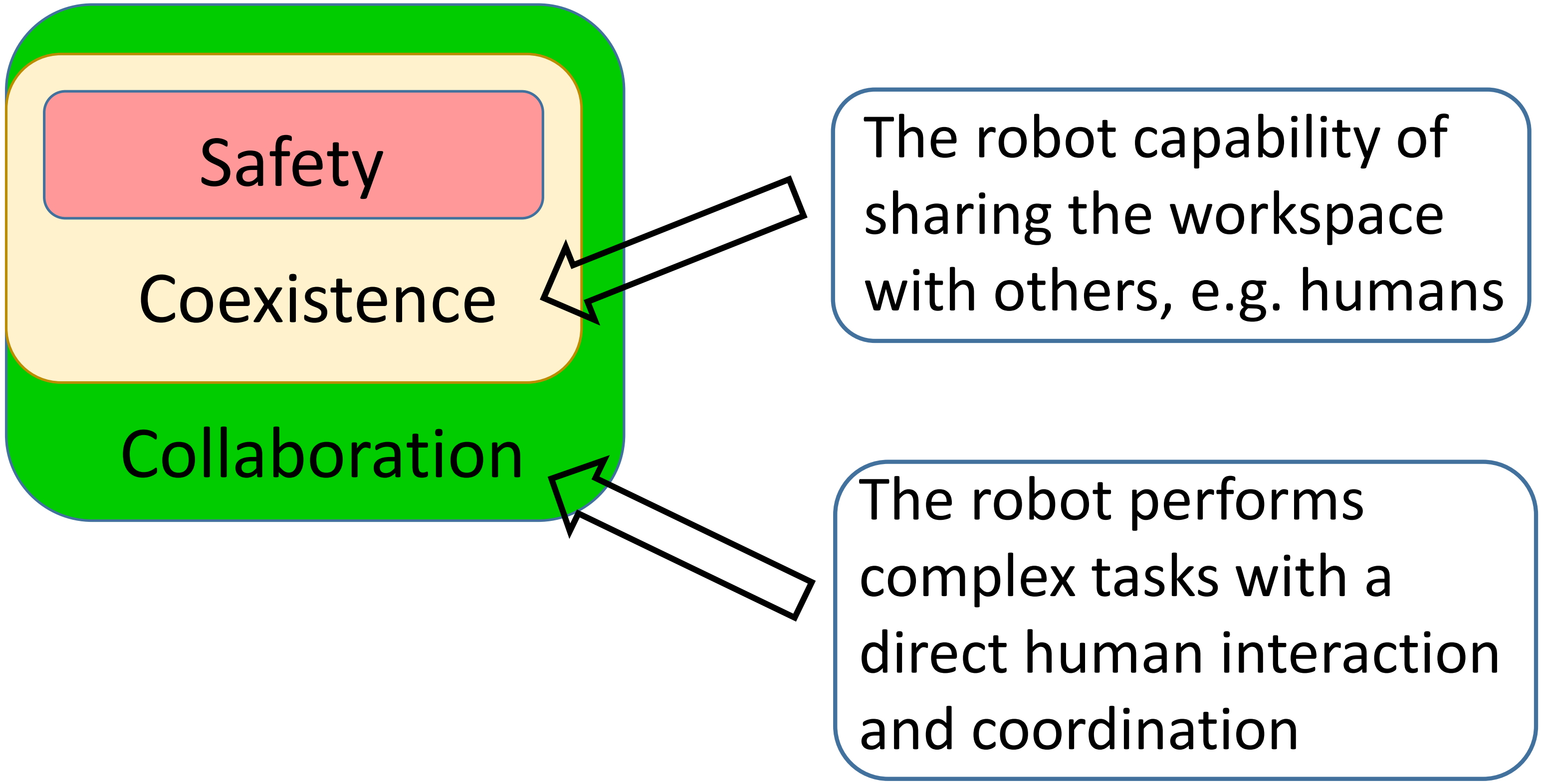
   Courtesy: Wikipedia



2. Active compliance
   - Measures contact forces
   - Reacts to these inputs

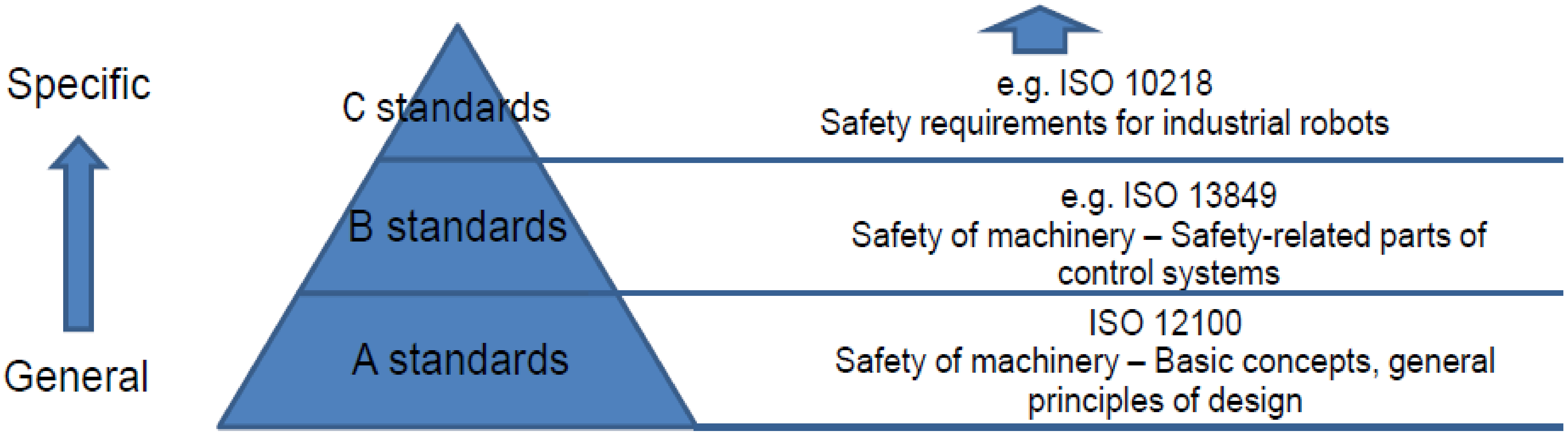
Human-robot collaboration, safety issues

- Force compliance is the enabling technology for robot-human collaboration in industry.
- Top-down hierarchy
  - Collision avoidance
  - Physical collision detection
  - Variable Stiffness Actuator
  - Lightweight and compliant robots



The collaboration is determined by the application and workspace, NOT the robot itself.

Safety standards



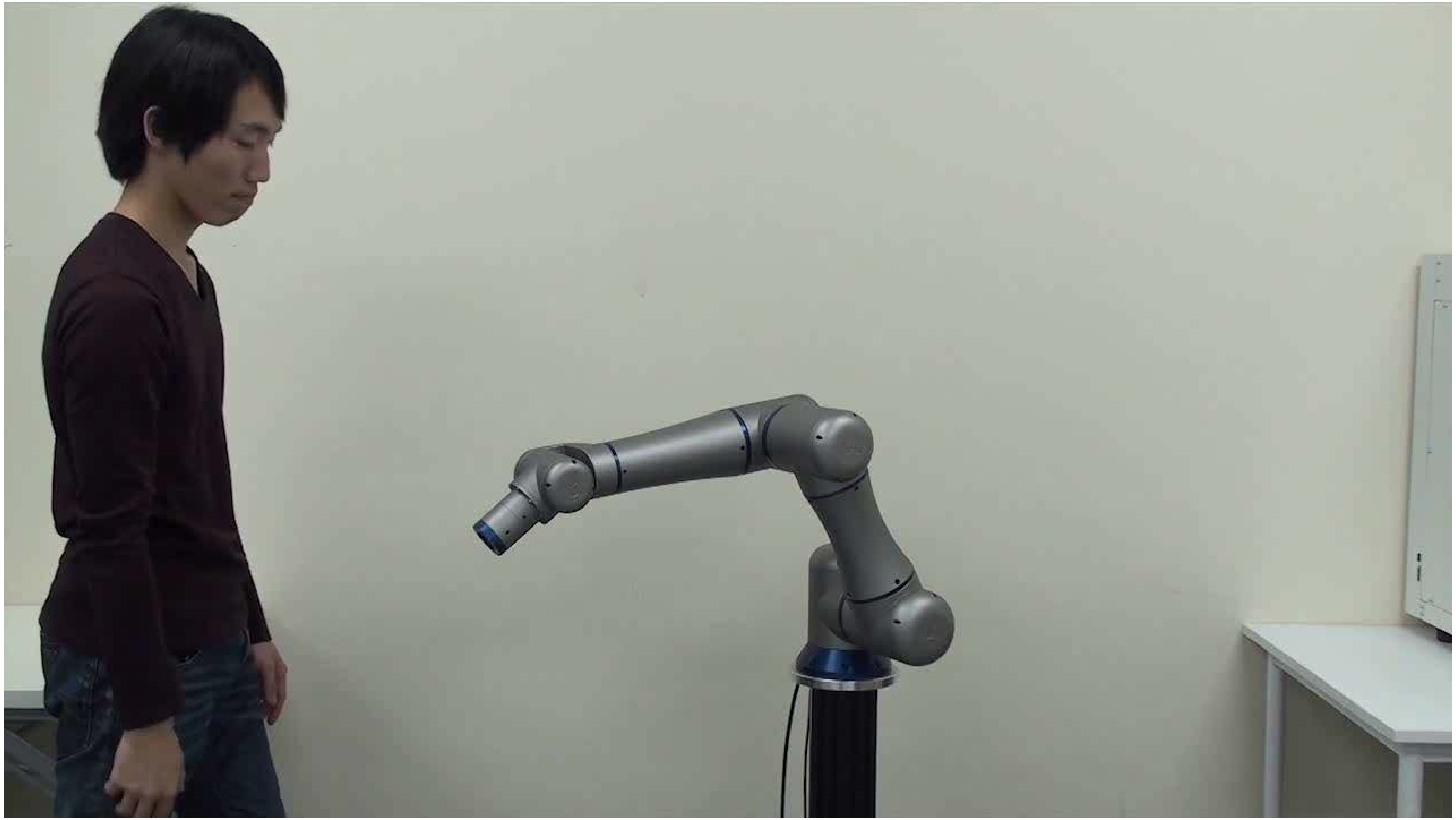
Needed skills

- Gravity compensation
- Controlled oscillation
  - Soft spring and soft damper
  - Hard spring and soft damper
  - Hard spring and hard damper
- Active compliance, demonstrated with a soft object, e.g. a ball
- Torque limit in a motion
  - Accidental collision without force control
  - Accidental collision with force control
- Bimanual coordinated task execution

U of Dortmund 2013, instructive video

Gravity compensation and external force following

Impedance control: soft spring, soft damper



Impedance control: hard spring, soft damper

Impedance control: hard spring, hard damper

Impedance control: torque limit in motion

Impedance control: robot touches human

Bimanual coordinated cucumber expelling

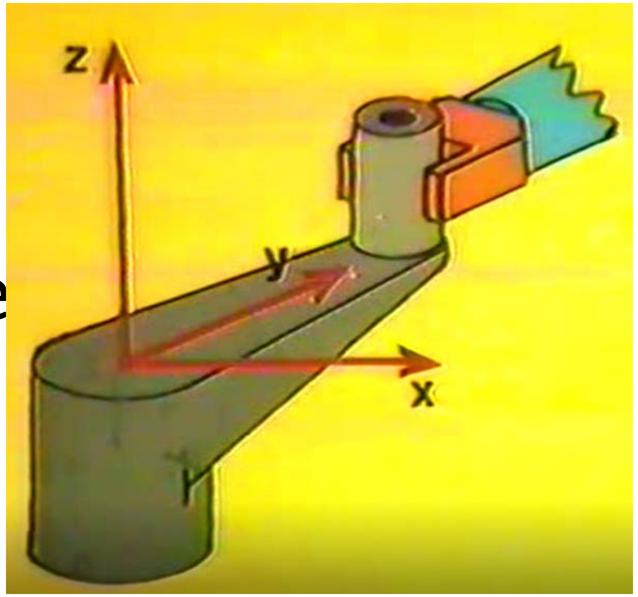
Constraint motion, drawing on a white board

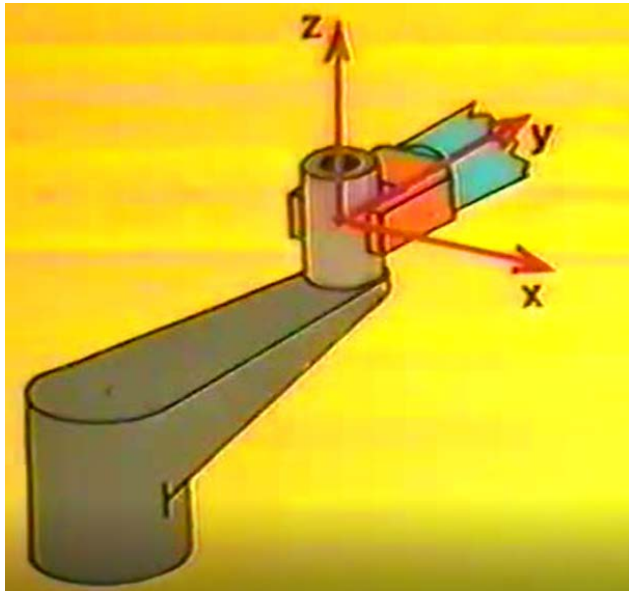
Industry: KUKA iiwa in Škoda Auto Vrchlabí

Task coordinate frame

For a force compliance task, a task coordinate frame exists, in which it can be expressed in terms of

- Velocity controlled directions
- Force controlled directions
- Tracking directions



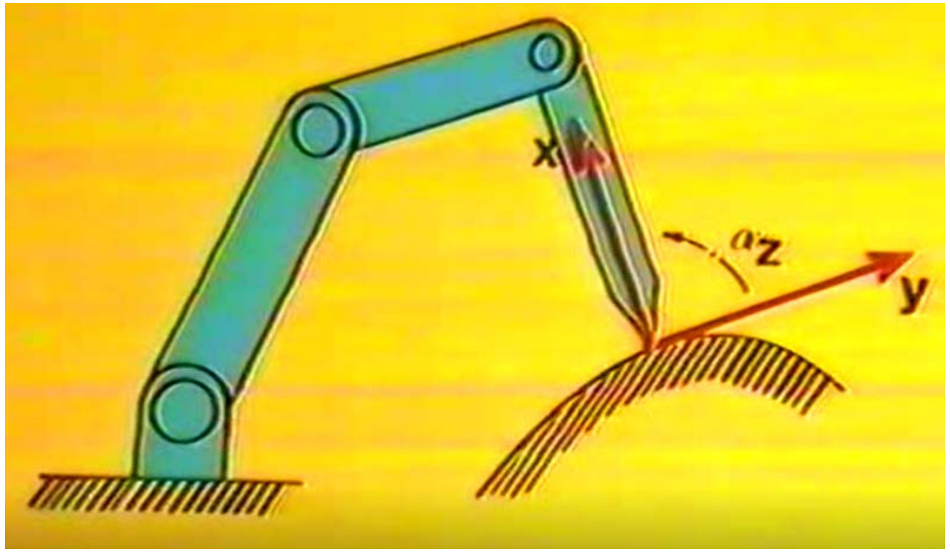


A crank rotation example

The task coordinate frame is not unique.

Example: tracking a unknown 2D contour

- Needed:
  - a desired velocity along a contour tangent
  - a desired force in the direction of contour normal
- The task is underspecified as the position and orientation of a contour is not know in advance.
- Ambiguity is solved by introducing a tracking direction.



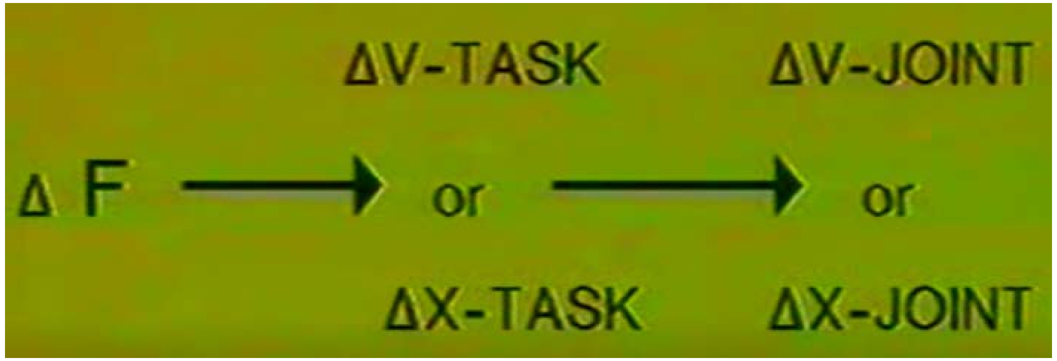
Task specification:

1. x: Force F [N]
2. y: velocity v [mm/s]
3. z: velocity 0 [mm/s]
4. αx: velocity 0 [mm/s]
5. αy: velocity 0 [mm/s]
6. αz: comes from tracking

Controlling compliant motion

Basic ideas:

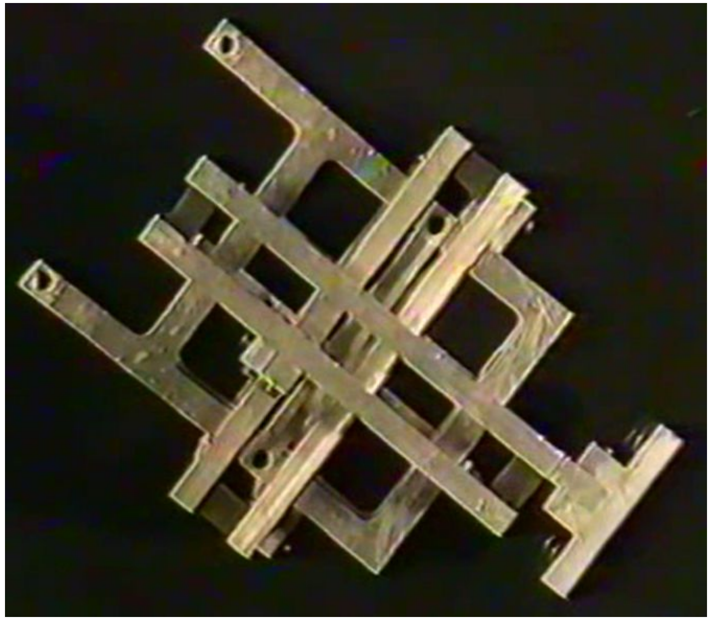
1. Robot as a close loop positioning device.
2. Close an external an servo loop around for this positioning system for every degree of freedom in the task frame.



- Force errors occurring in the task frame are transformed into velocity or position commands.
- These commands are transformed from the task frame to the joint space.

Passive compliance involved

- A passive compliance device is needed to avoid large limit cycles caused by the finite resolution of the positioning device (e.g. a robot).
- The exact value of this compliance is not critical.
- However, stiffness and position resolution determine the force resolution.



Force control, Schunk robot example

Types of compliance, examples