ETH zürich

Institute of Robotics and
Intelligent Systems

Theory of Robotics and Mechatronics
Force Control and Haptics

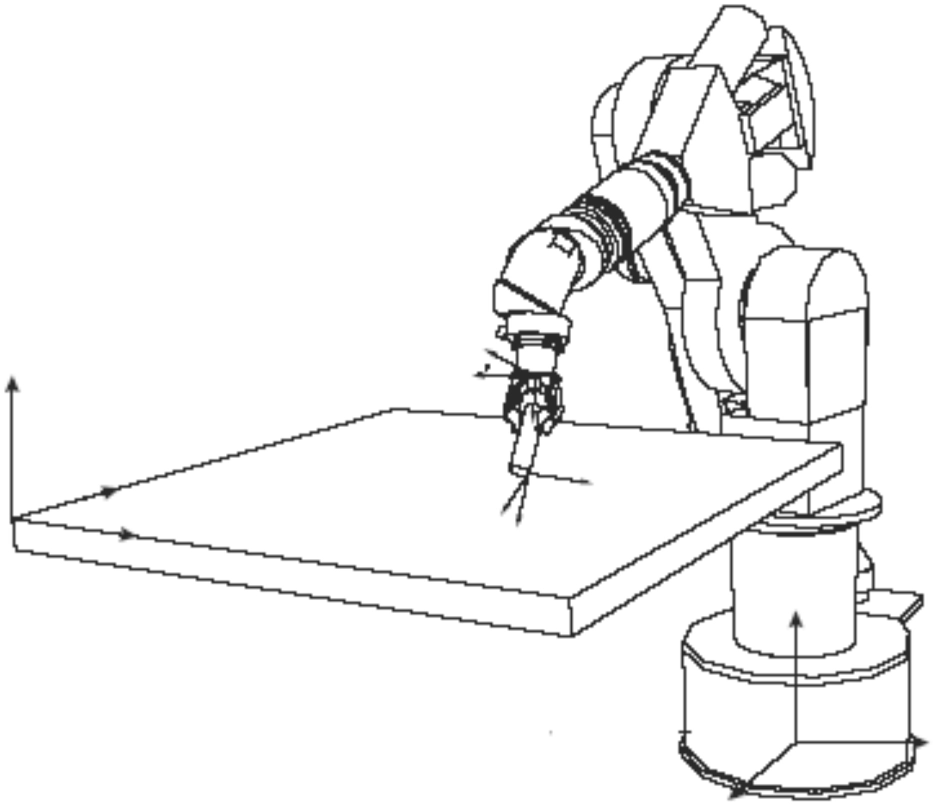
D MAVT

Agenda

1. Introduction to force control
2. Compliance frame
3. Control
4. Haptics

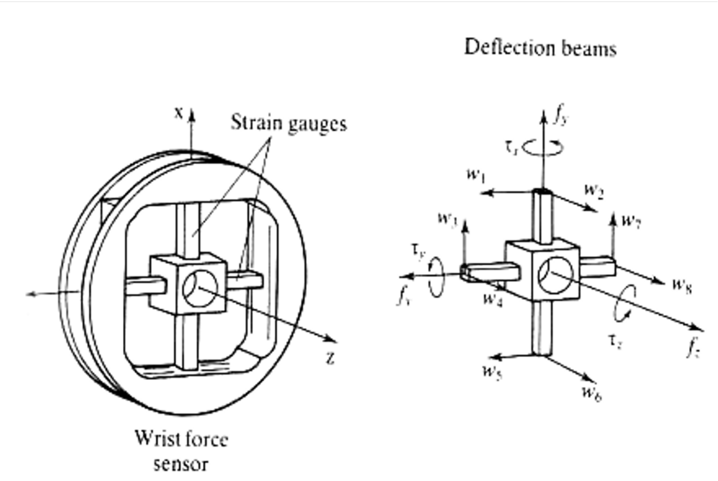
Introduction of force control

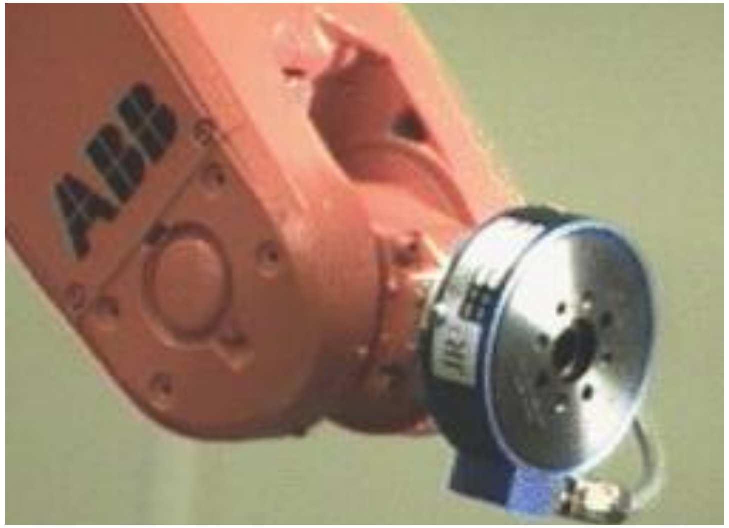
Contact tasks



- Mechanical part mating (assembly)
- Contour Tracking
- Machining

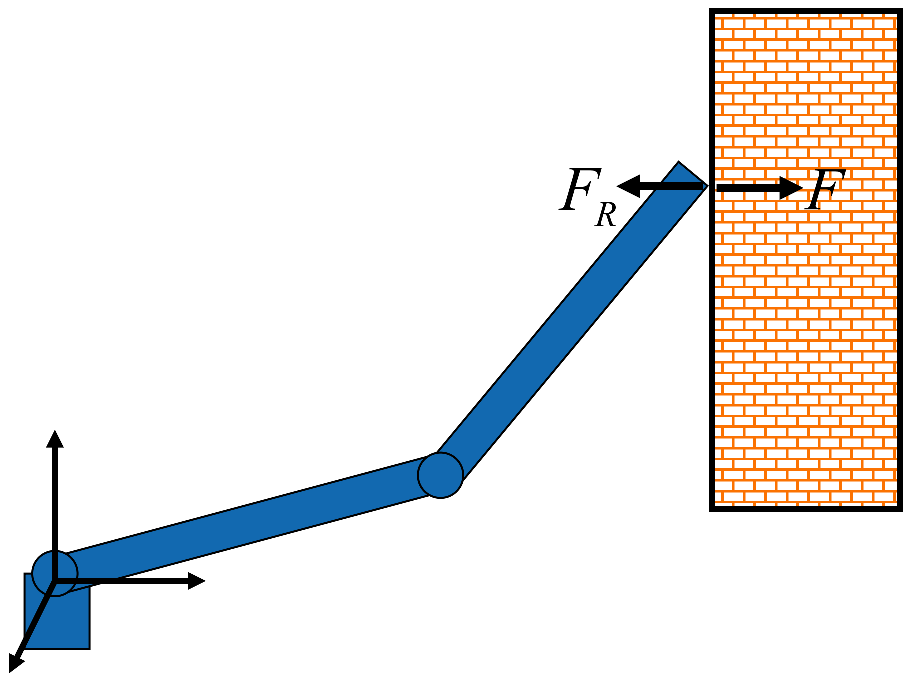
Force sensors





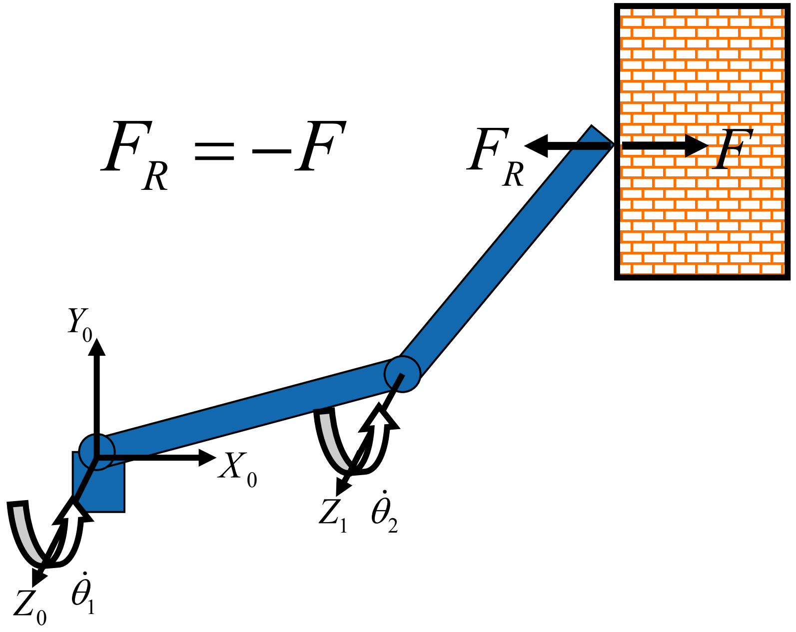
- Mostly at the wrist, sometimes at the joints and grippers (fingers)

Control of constrained motion



- The environment sets constraints on the geometric paths that must be followed by the end effector
- Trajectory control approach likely to fail due to:
  - Inaccuracy of robot and environment models
  - Corrective action of the position controller due to a trajectory error can easily create large forces, saturate the actuators and even crash the robot (or the constraint!)
- Must modify the control algorithm such that it respects the constraints

Static force/torque relationship

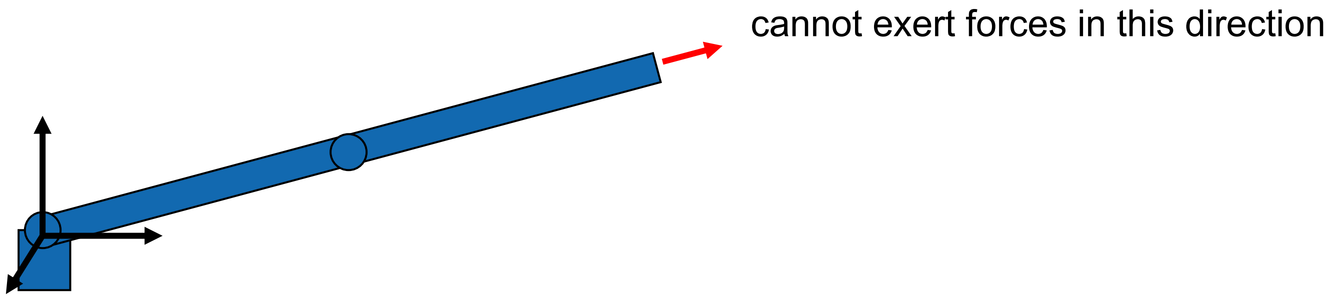


$$\tau^0 = J^T F_R^0$$

$$F_R = \begin{bmatrix} F_x \\ F_y \\ F_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \qquad \tau = \begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \end{bmatrix}$$

- Goal: map reaction force to joint torques

Impact of singularities on forces



- Singularities also have a significance in terms of forces that can be (actively) generated by the robot

Stiffness and compliance

Stiffness

- Proportionality constant k that relates a static displacement to the force due to this displacement

Compliance

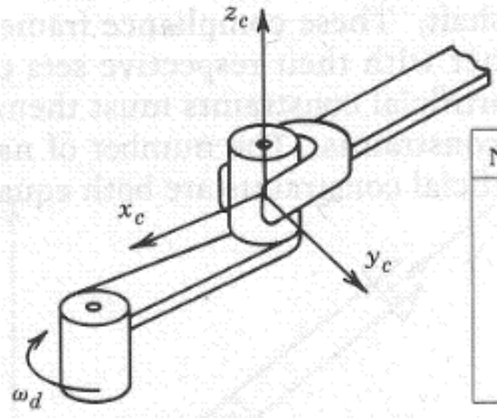
- Inverse of stiffness
- Passive compliance: Non-actuated (i.e., internal) tendency of a body displaced due to external forces
  Example: compression of a spring
- Active compliance: Controlled compliance in response to an external force
  Example: keeping the contact force at a certain limit
  (i.e., actively giving in)

$$F = k \, \Delta X$$

We cannot describe (control) force and displacement independently!

Compliance frame

Compliance frame (a.k.a. constraint frame)

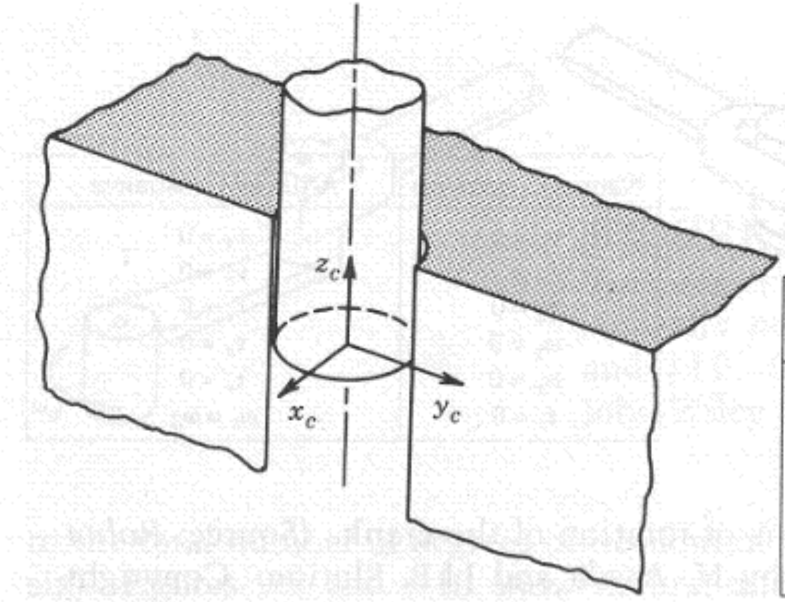


Natural Constraints	Artificial Constraints
$v_x = 0$	$f_x = 0$
$f_y = 0$	$v_y = 0$
$v_z = 0$	$f_z = 0$
$\omega_x = 0$	$\tau_x = 0$
$\omega_y = 0$	$\tau_y = 0$
$\tau_z = 0$	$\omega_z = \omega_d$

- A time-varying coordinate frame called the compliance frame is defined to describe the contact task
- The compliance frame decomposes the task so that either a pure position command or a pure force command can be specified

- We define natural and artificial constraints in the compliance frame:
  - **Natural constraints** are what the environment imposes on the robot
  - **Artificial constraints** are how we want the robot to act
  - The total number of constraints is equal to the degrees of freedom of the task space (usually six)
  - Constraints come in pairs: one natural, the other artificial
    v: velocity / f: force, ω: angular velocity / τ: torque)

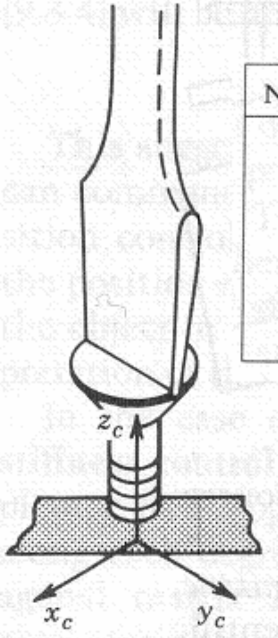
Peg in hole



Natural Constraints	Artificial Constraints
$v_x = 0$	$f_x = 0$
$v_y = 0$	$f_y = 0$
$f_z = 0$	$v_z = v_d$
$\omega_x = 0$	$\tau_x = 0$
$\omega_y = 0$	$\tau_y = 0$
$\tau_z = 0$	$\omega_z = 0$

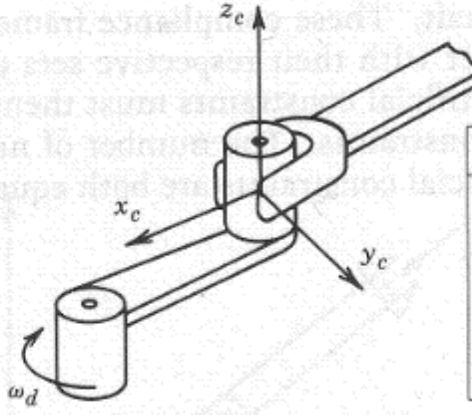
- We would like to have a large stiffness along artificial velocity constraint directions and a smaller stiffness along the natural velocity constrained directions

Screwdriver



Natural Constraints	Artificial Constraints
$v_x = 0$	$f_x = 0$
$v_y = 0$	$v_y = 0$
$f_z = 0$	$v_z = p\,\omega_d$
$\omega_x = 0$	$\tau_x = 0$
$\omega_y = 0$	$\tau_y = 0$
$\tau_z = 0$	$\omega_z = \omega_d$

Choice of frame



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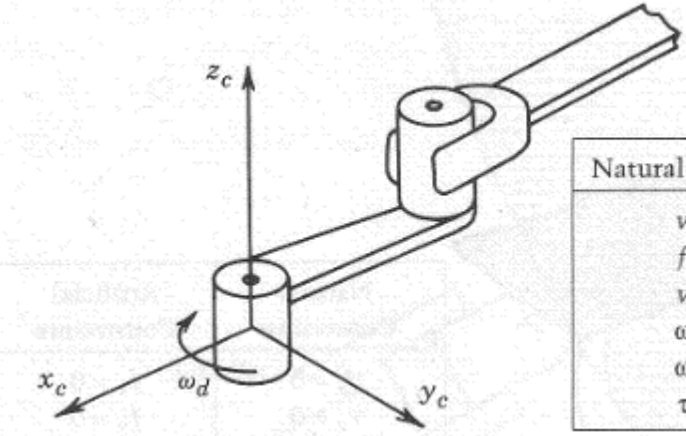
$\tau_z = 0$	$\omega_z = \omega_d$



Natural Constraints	Artificial Constraints
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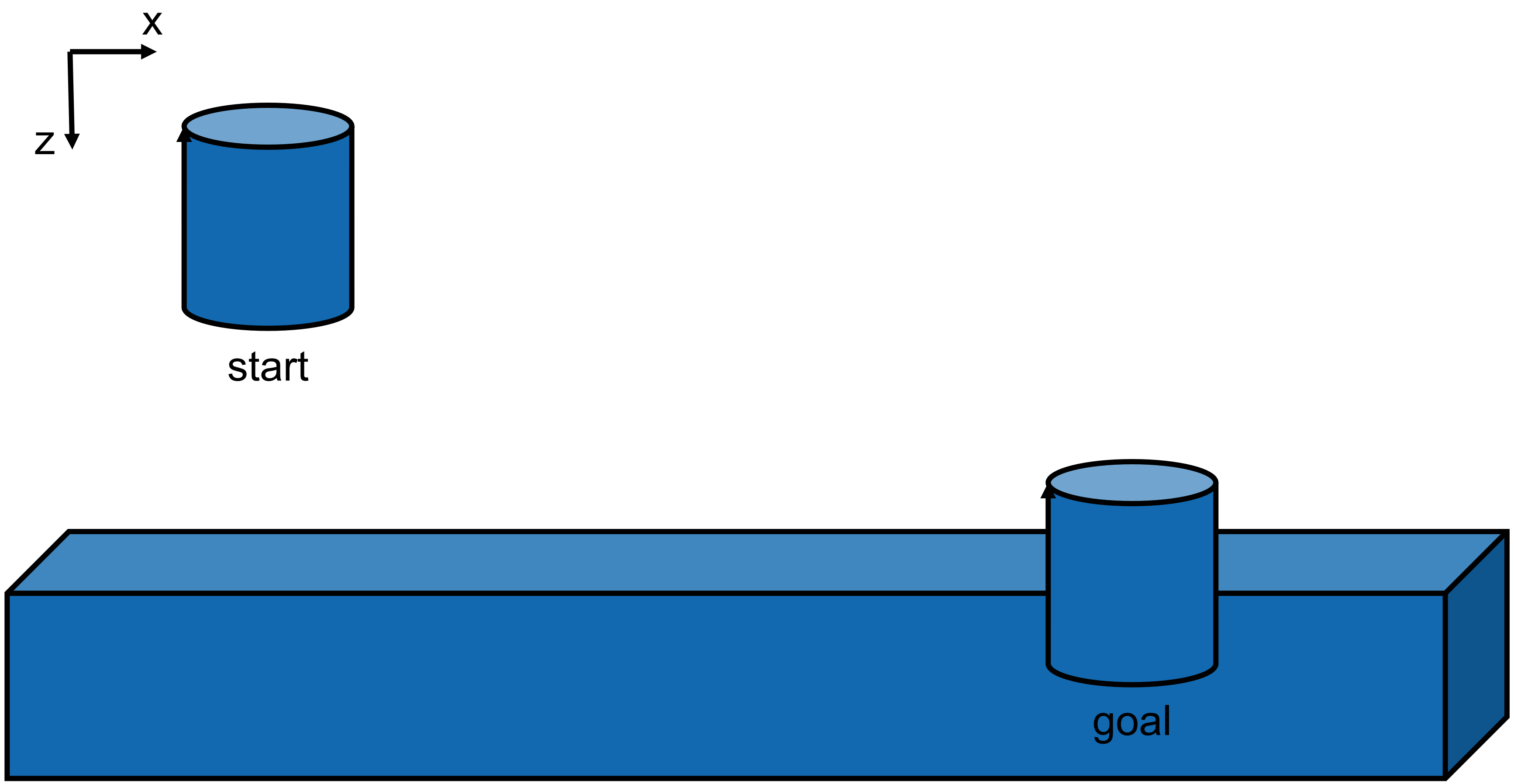
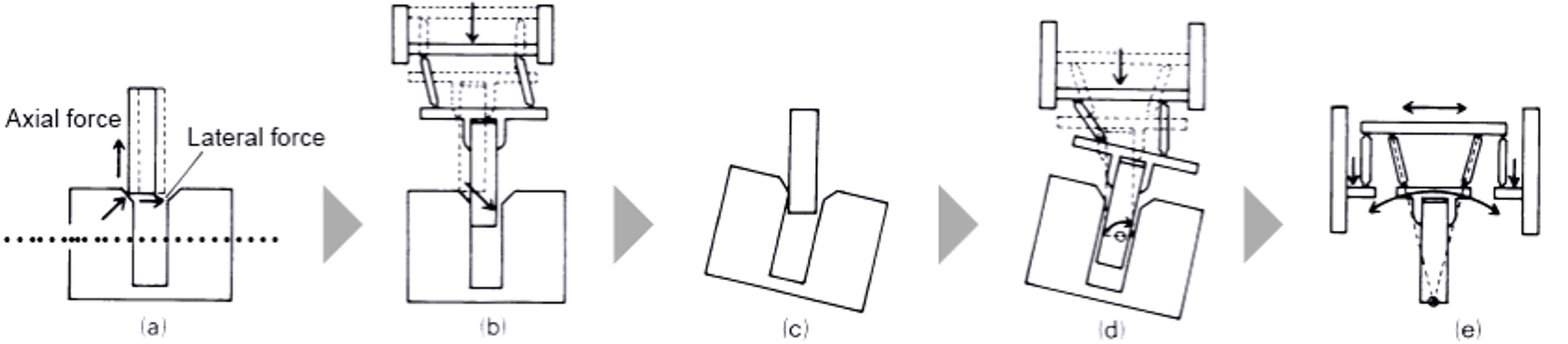
Exercise: peg in hole

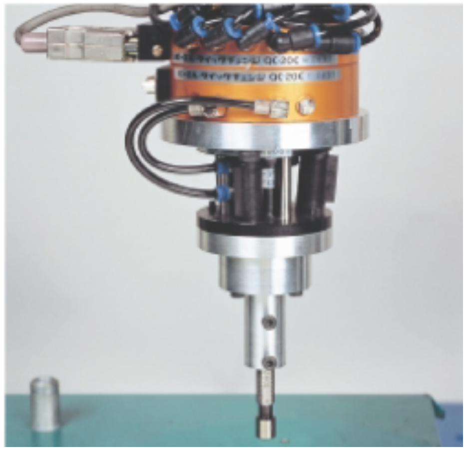


Control

Passive compliance



- Center of compliance is the point on the tool where a force at that point creates a pure translation and a moment creates a pure rotation about that point
- Remote Center Compliance (RCC) devices place the center of compliance at the tip of the tool with variable different stiffness along different directions of the compliance frame
- High stiffness for translations along the vertical axis



Active compliance

- A position-controlled robot reacts to positioning errors by applying torques at the joints such that the positioning error is reduced
  - If the gain along a direction of motion is low, the robot effectively exhibits high compliance in that direction by generating only a small opposing force to correct a position error. By adjusting the gains of the controller we can make the robot behave as a 6 DOF spring with controlled stiffness in each direction.

$$\tau = K_P E + K_D \dot{E}$$

- The action of the desired 6 DOF spring can be formulated as:

$$F = K_{S,6\times6} \partial X \text{ (K is diagonal)}$$

- We translate this desired behavior in the task space into the joint space by:
  - This is the desired (steady-state) response of the actuators to small joint space errors such that the robot will behave as a 6 DOF spring with spring constant (matrix) K_S

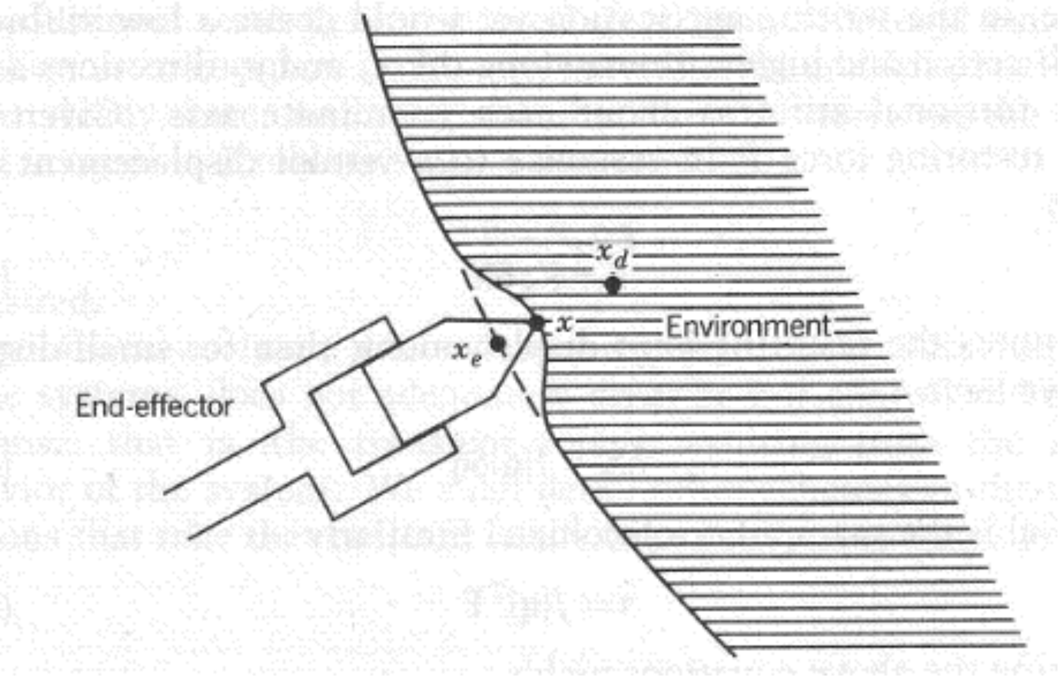
$$\tau = J^T F = J^T K_S \partial X, \; \partial X = J \partial \theta$$

$$\tau = J^T K_S J \partial \theta$$

- We then modify the control law as:

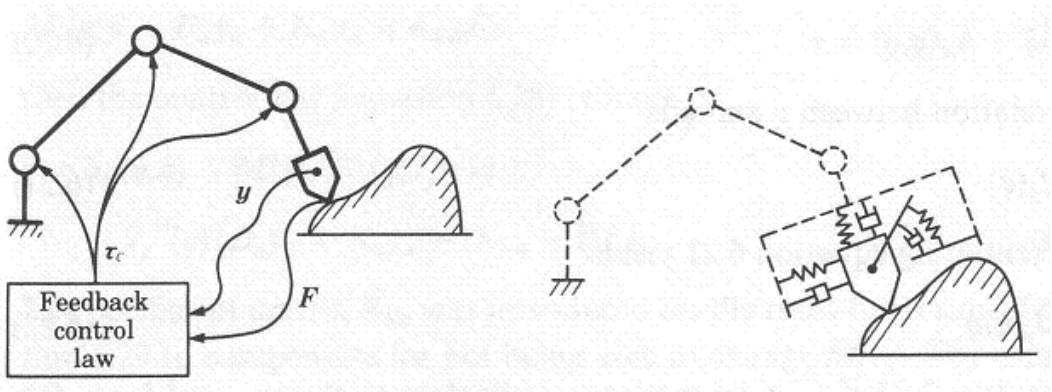
$$\tau = \underbrace{J^T K_S J}_{\text{joint space stiffness matrix}} E + K_D \dot{E}$$

Compliance control



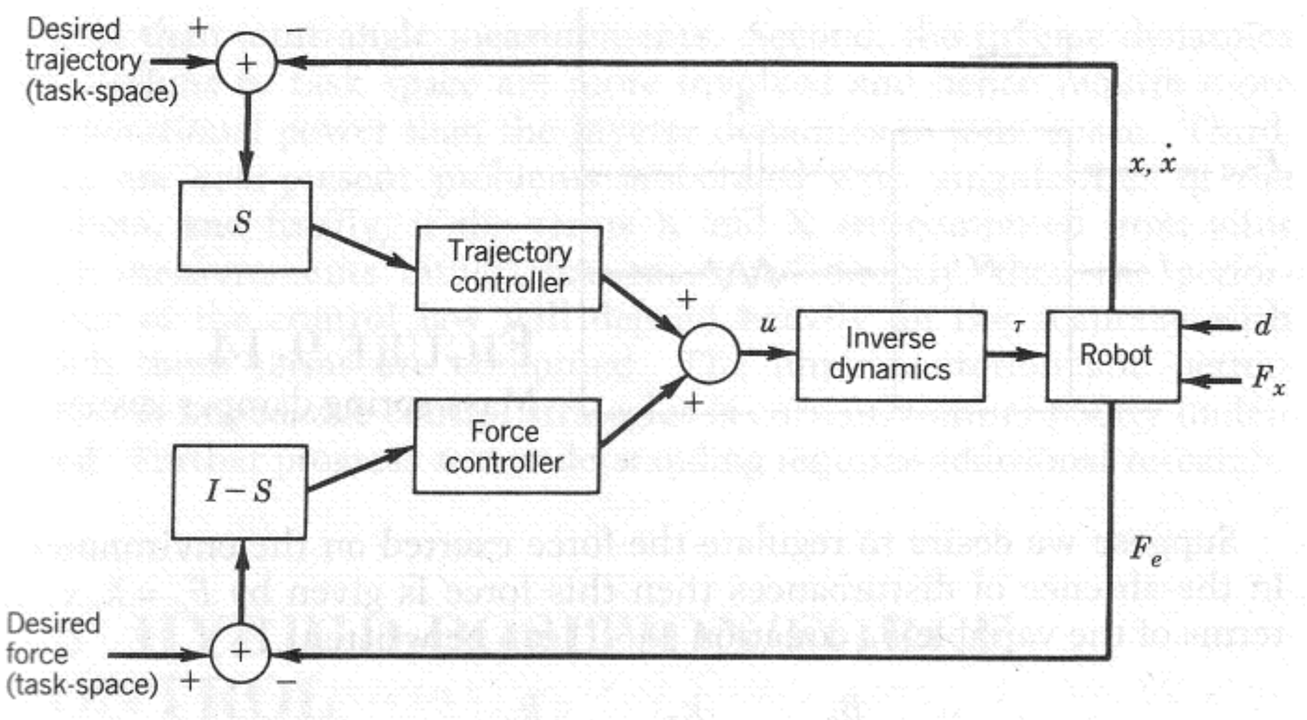
- We can now control the force by modifying the position reference such that the resulting position error will end in a desired force through the 6-DOF stiffness matrix
- Using a force sensor to measure the actual force, we can measure the error in the desired and actual forces and adjust the position reference in real-time
- This is a modified position control scheme to accommodate the constraints. Therefore, it can be applied with commercial robot (path) controllers by changing the desired path on the fly

Impedance control



- Impedance control is similar to compliance control, but the end effector is made to behave like a 6 DOF mass-spring-damper system
- Applied by modifying a task-space path control scheme such as inverse dynamics control
- Often used with robotic hands where the fingers must grasp with certain force. The fingers must be springy enough to deform and not damage the object while stiff enough to hold the object when subject to disturbances caused by contact with other objects, for example, in assembly

Hybrid position-force control

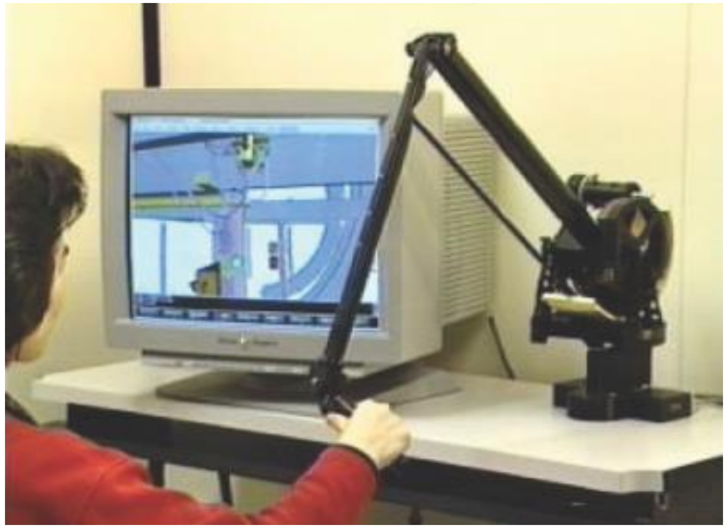


- Apply position control or force control along different degrees of freedom of the compliance frame

$$S = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ Selection matrix}$$

Haptics

Haptic interfaces



- Haptic interfaces are human-computer interfaces that provide tactile feedback to the user
- Force, temperature, vibration
- Games, user interfaces, training, teleoperation, …

The PHANToM

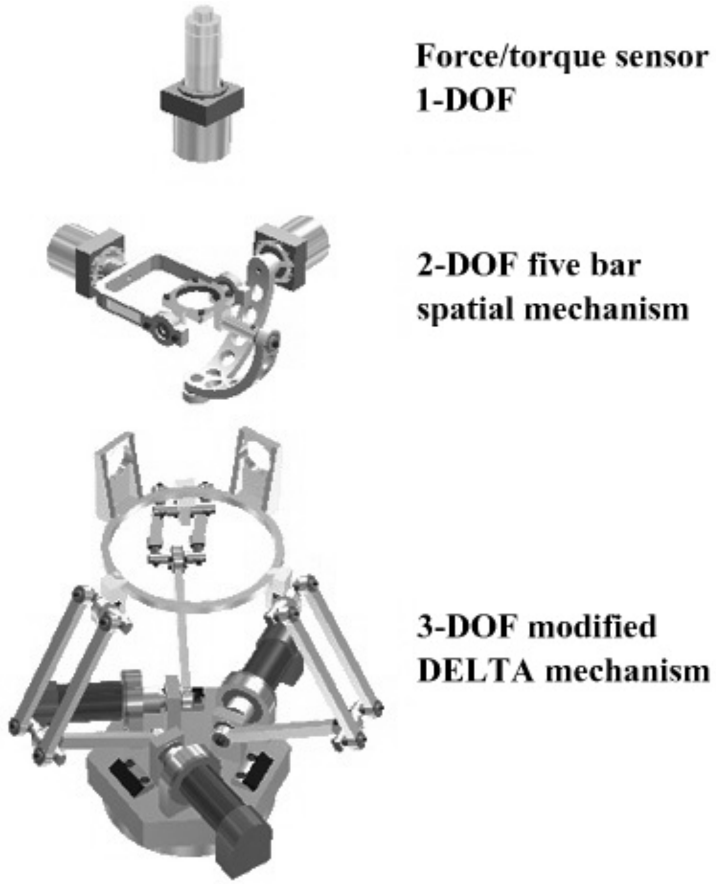
The PHANToM by SensAble is the most popular haptic interface

- The device has low inertia, low friction and is well balanced

These devices have limits to the stiffness that can be stably displayed

Parallel haptic interfaces


The DELTA Haptic Device

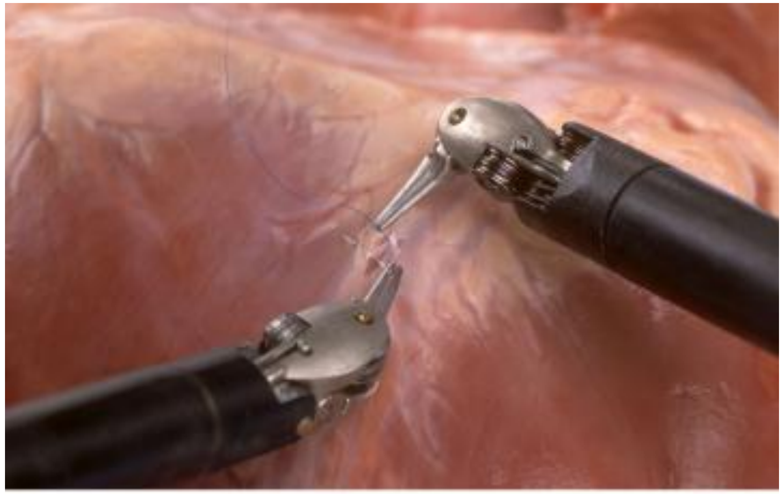


- Parallel devices increase our ability to generate stiff environments
- This comes at the cost of greatly reduced workspace

Admittance devices

- A haptic device can be made like a traditional industrial robot (non-back-drivable, strong) by attaching a force/torque sensor where the human user interfaces with the robot
- Very stiff environments are easy to generate: simply don't command any motion
- Displaying free motion becomes difficult to do stably

Haptics for teleoperation



- Haptic devices are used for interacting with virtual and real environments
- To interact with real environments, the haptic interface acts as a master device, and a remote robot acts as a slave device
- Force feedback has been shown to improve user performance in certain tasks
- Force feedback in commercial devices (like the da Vinci) is still an active area of research

Summary

Summary

- Force control allows contact tasks and adds adaptability to robots
- Singularities reduce the force the robot can exert
- The compliance frame is a time-varying coordinate frame used to decompose a task into a pure position or force command
- Haptics increase the immersion for the human user

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