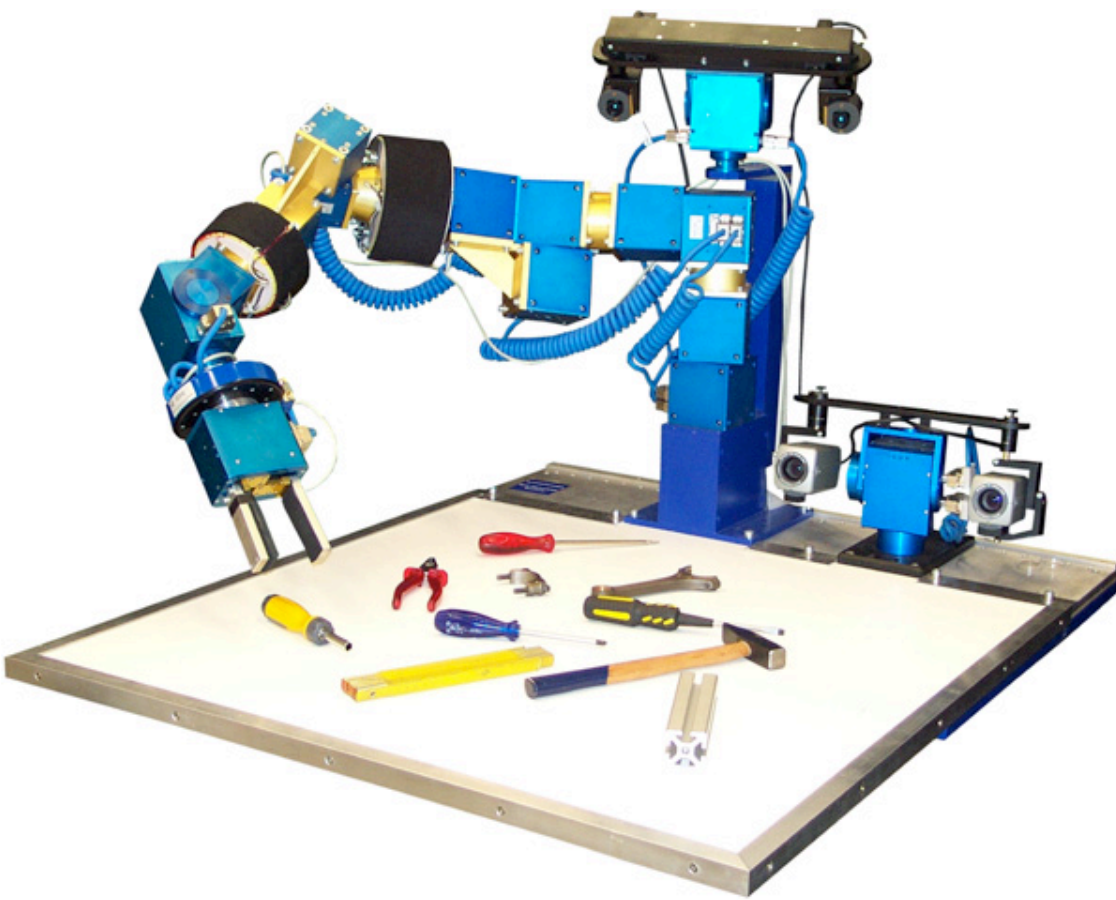
Robotic manipulation: overview and basic concepts

Gregor Schöner
gregor.schoener@ini.rub.de

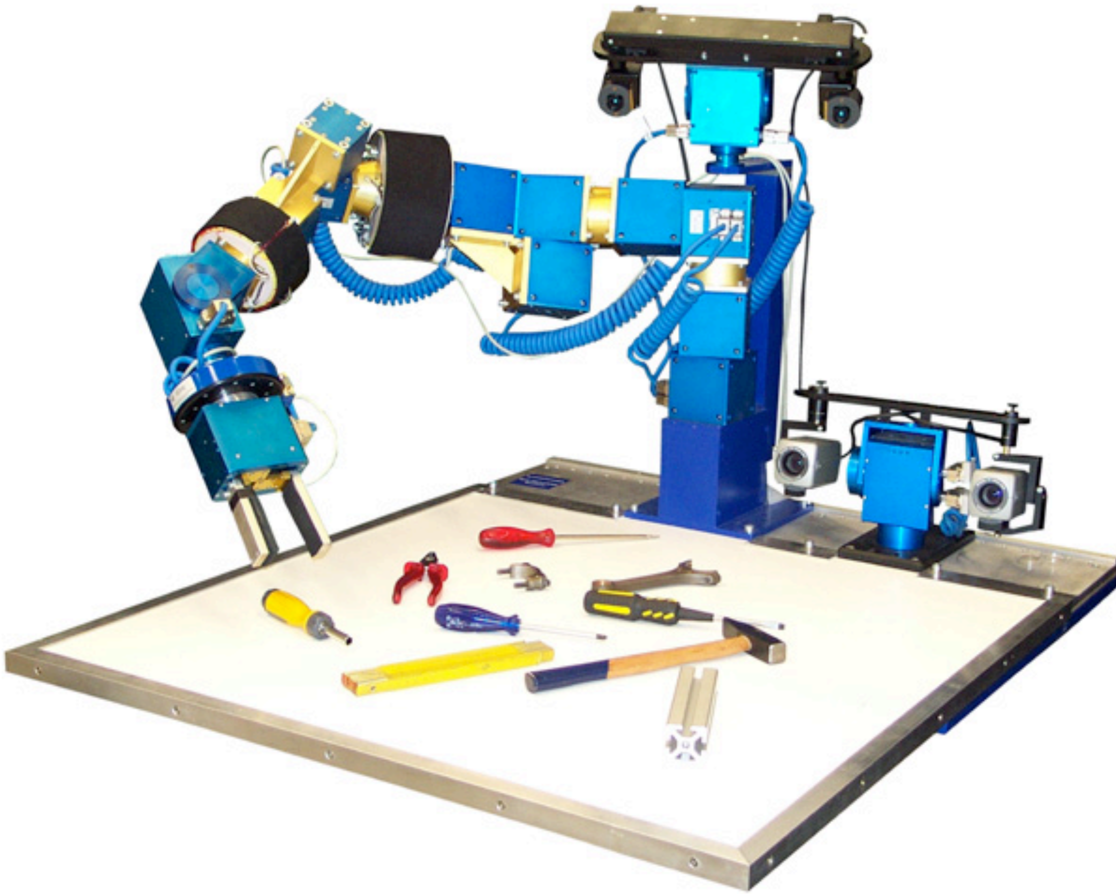
Movement to reach and grasp, lift, transport, manipulate

- involves a "manipulator", a robotic/human arm with a grasping mechanism/hand



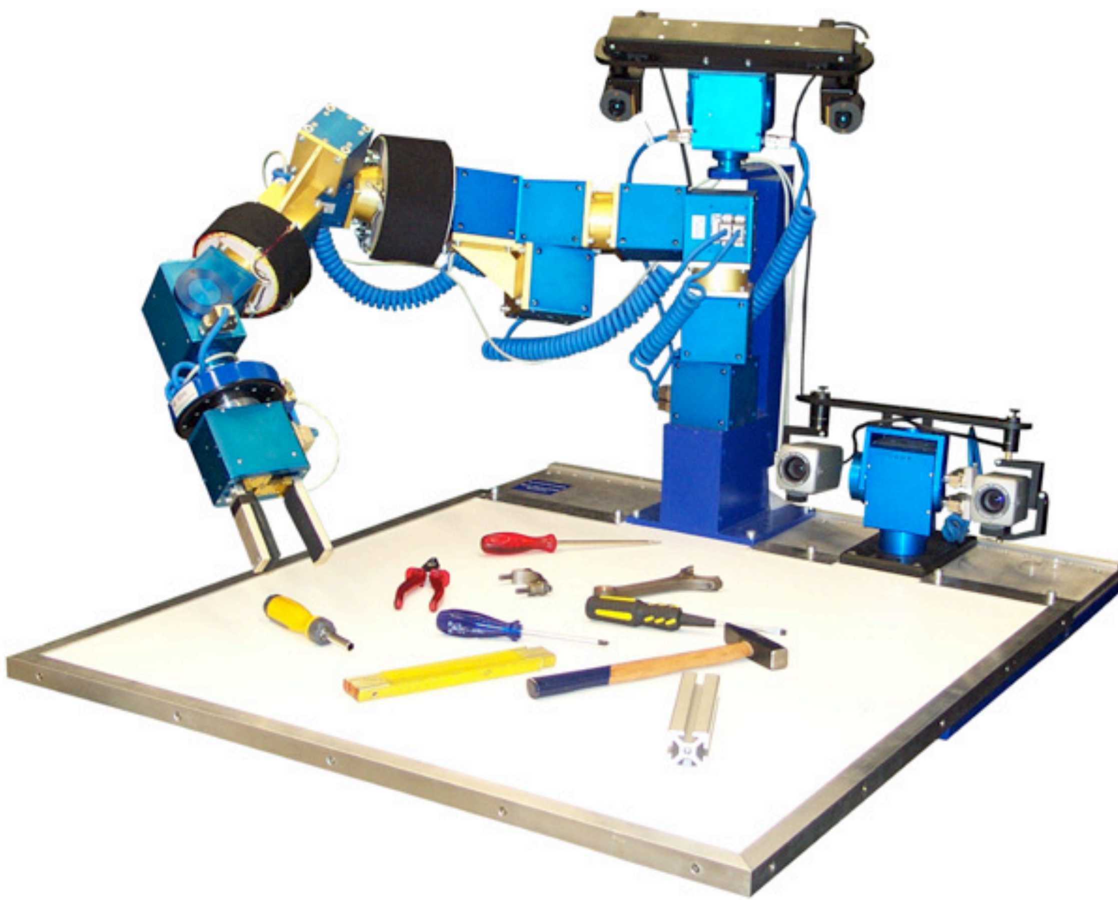
What is entailed in autonomously reaching for objects?

- Perception: recognizing and segmenting objects, estimating their pose
- Scene representation: registering the spatial array in the arms workspace for possible target objects, free space, and obstacles



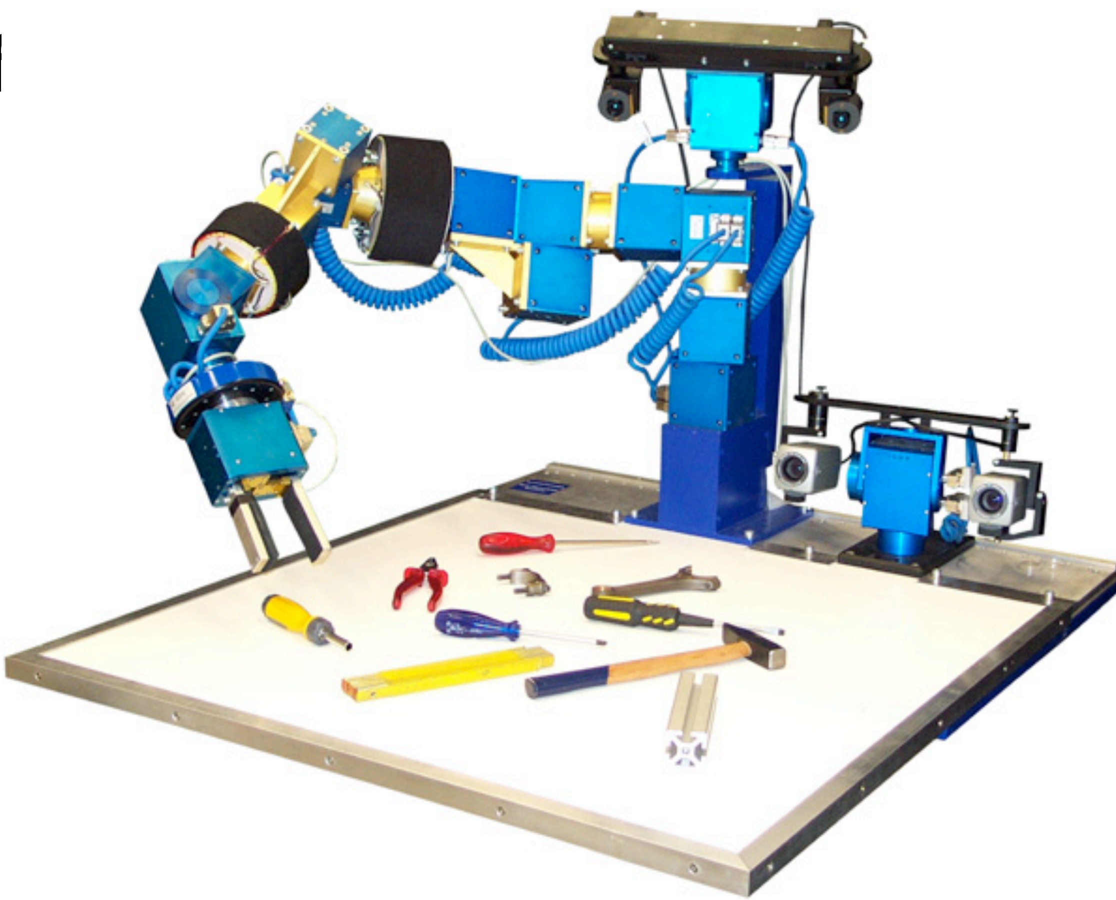
What is entailed in autonomously reaching for objects?

- Sequentially organizing actions (“serial order”) and planning
- Selecting a relevant object or location in the scene



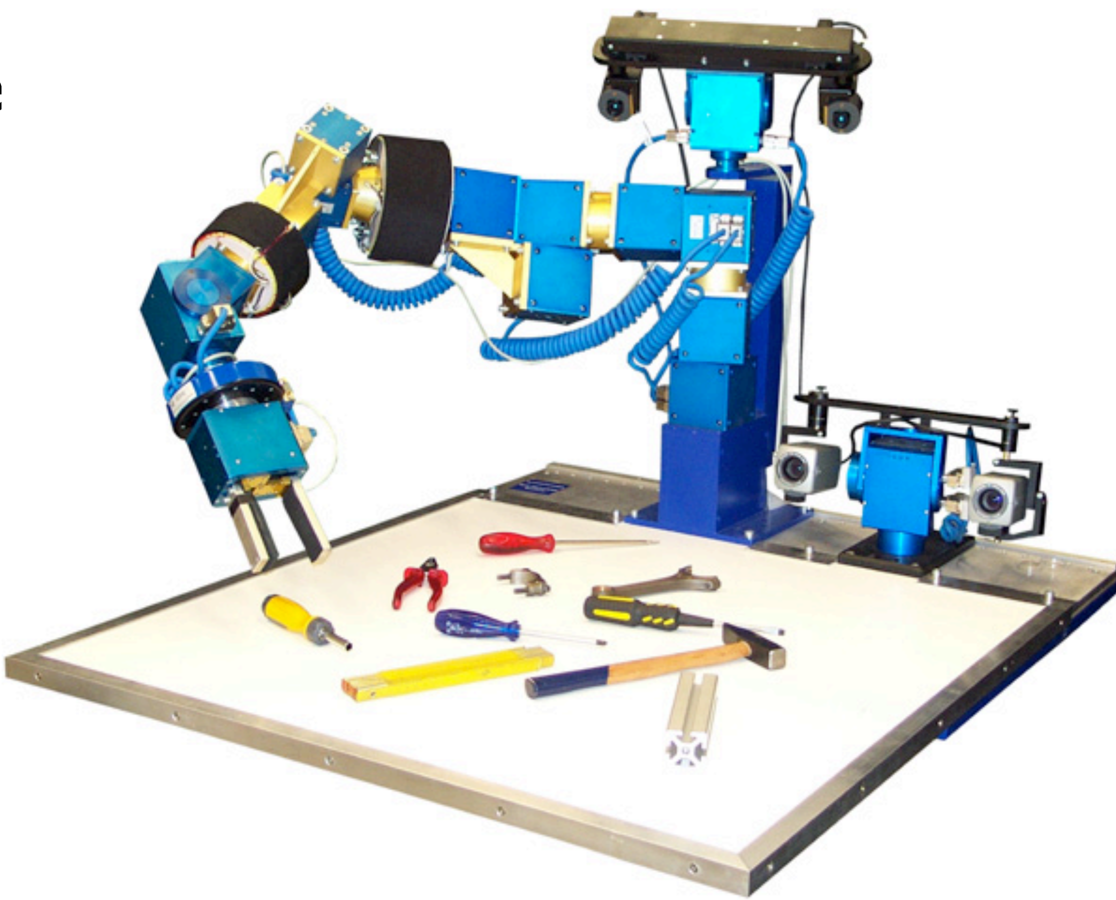
What is entailed in autonomously reaching for objects?

- Extracting parameters of an individual movement segment based on initial posture of arm and target state



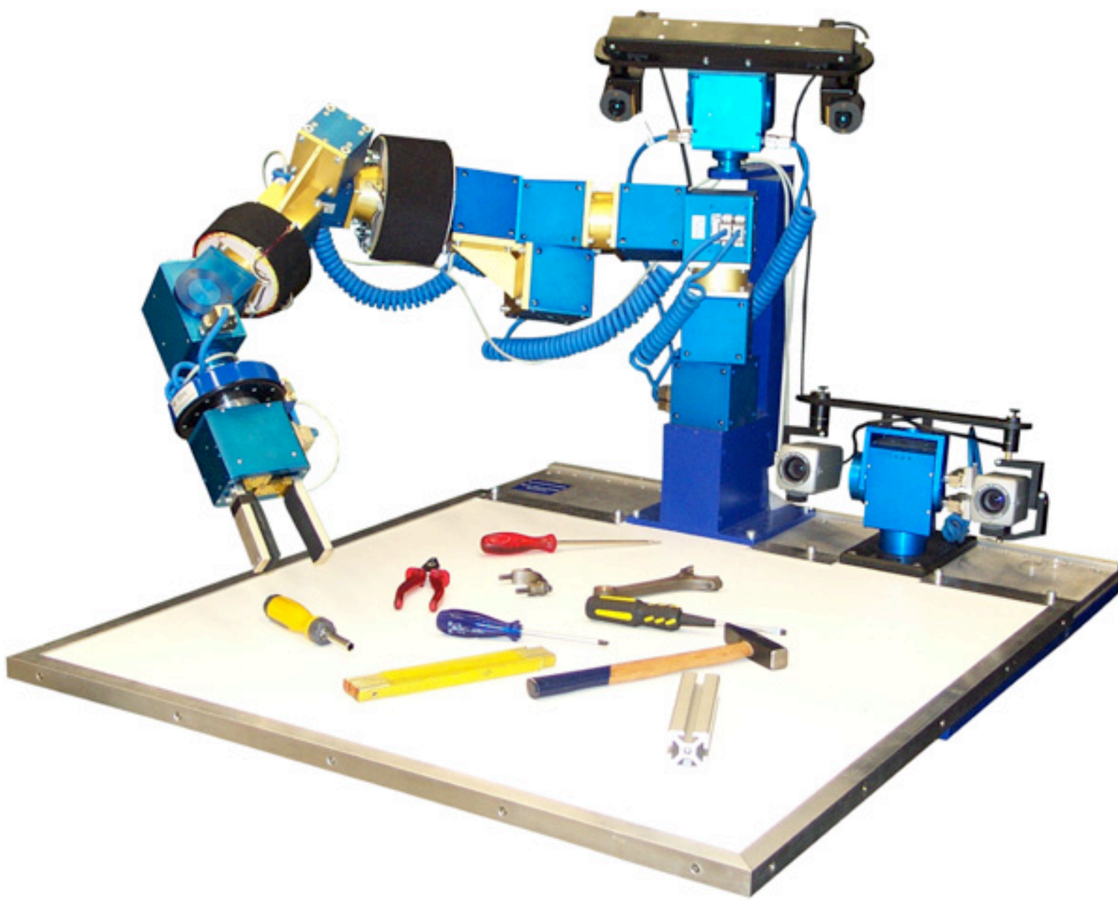
What is entailed in autonomously reaching for objects?

- Generating a time course for the degrees of freedom of the arm and hand that moves the arm from its initial posture to a state in which the target object is grasped
- Coordinating timed movement



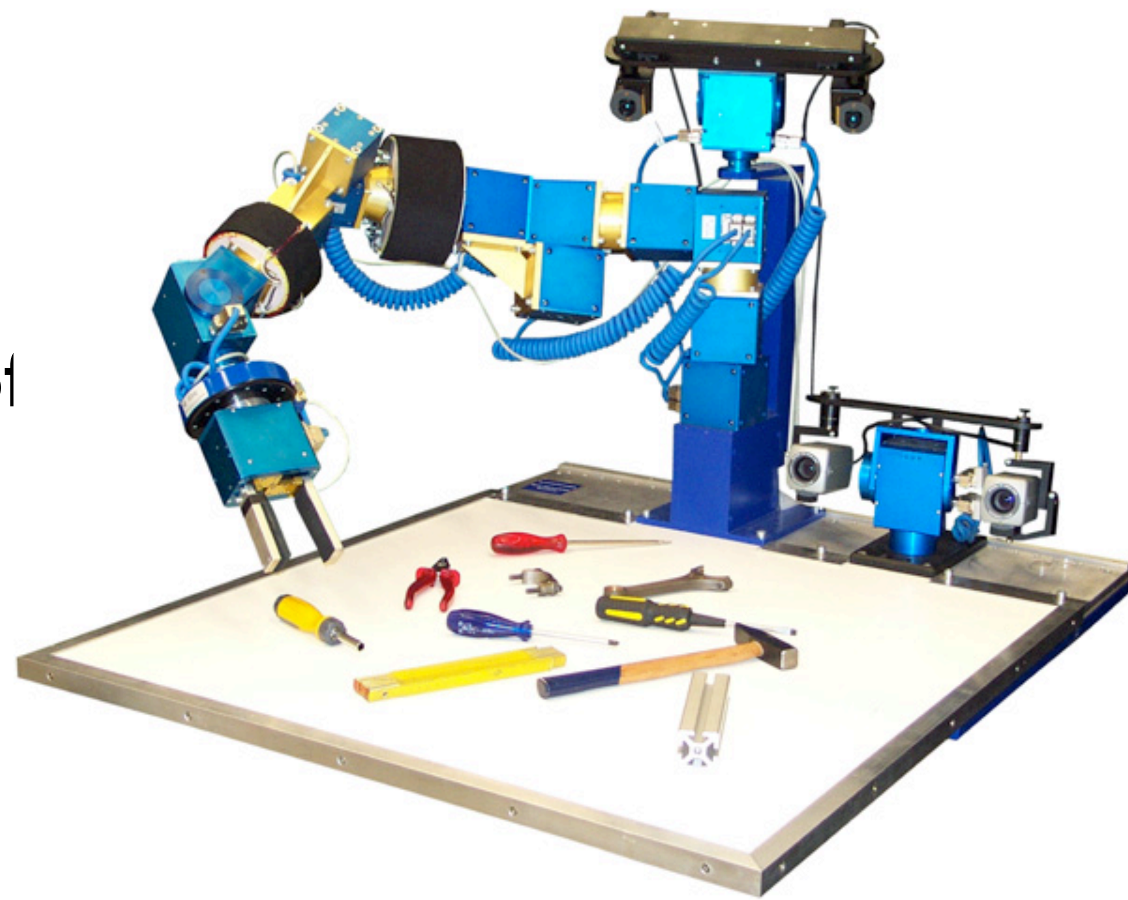
What is entailed in autonomously reaching for objects?

- Controlling the arm: translating the desired time course into control signals to the actuators/ muscles that move the arm
- potentially update these signals based on feedback



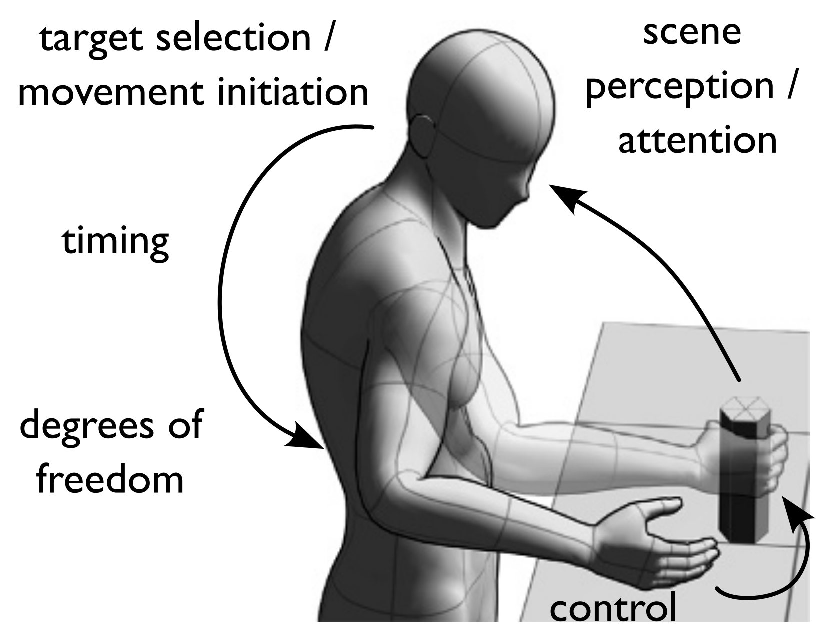
What is entailed in autonomously reaching for objects?

- Detect termination of the movement
- Transition to the next element in a sequence of movements…



Object-directed action by humans/neural processes

- scene perception, object perception
- movement planning
- movement organization
- trajectory formation
- control

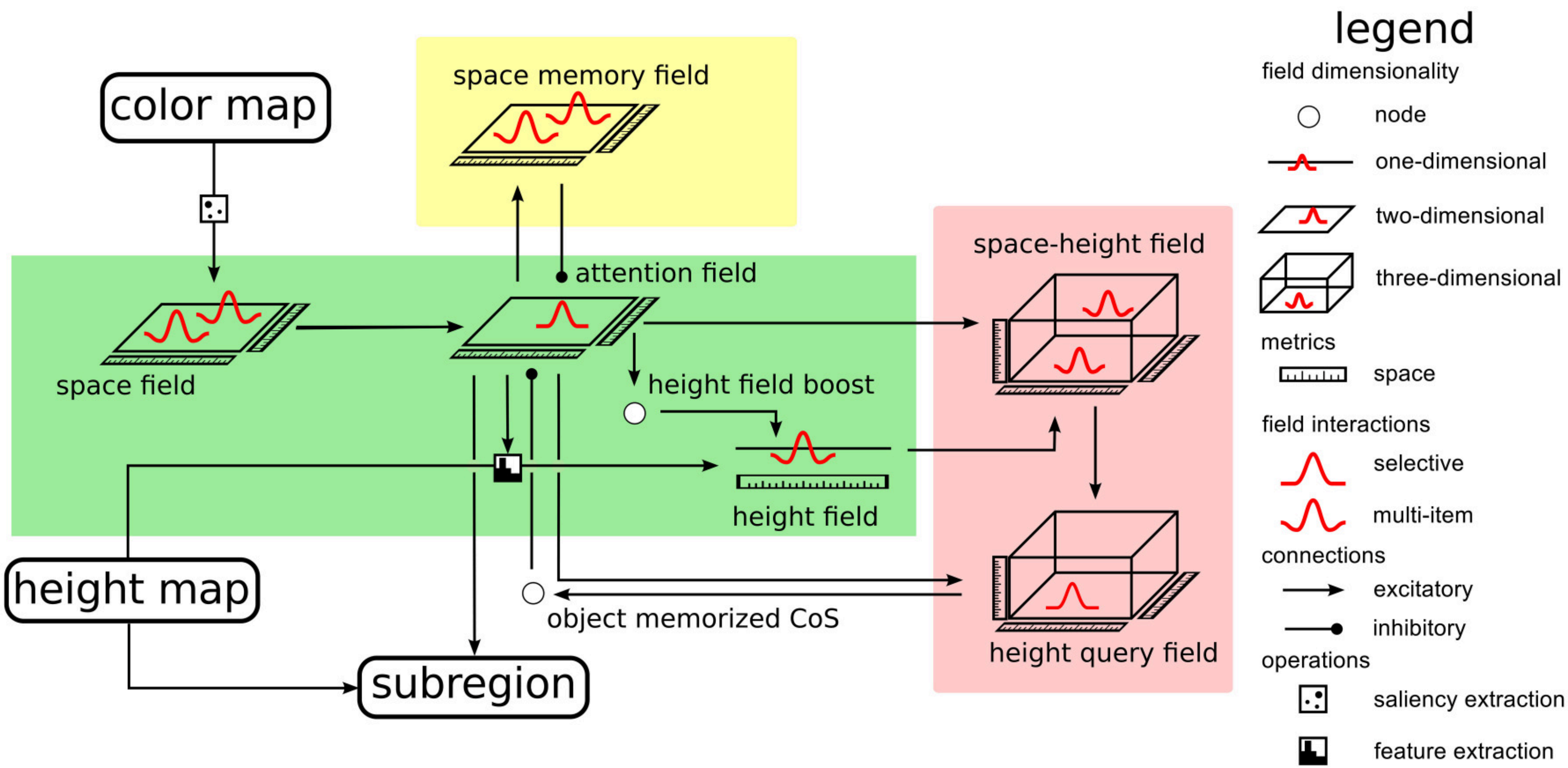


Perception

- attention, attentional selection
- recognition/classification
- estimation
- segmentation

Perception

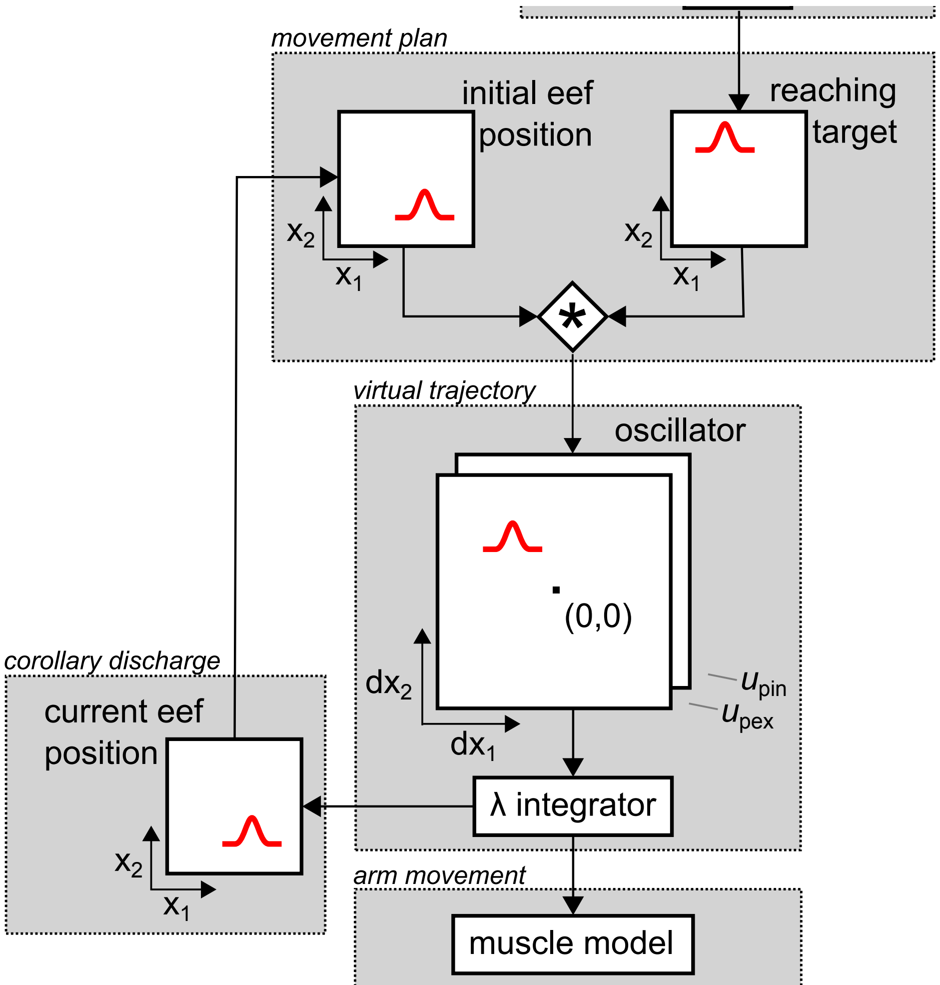
- attentional selection => pose



[Knips et al, Frontiers Neurorobotics 2017]

Movement planning

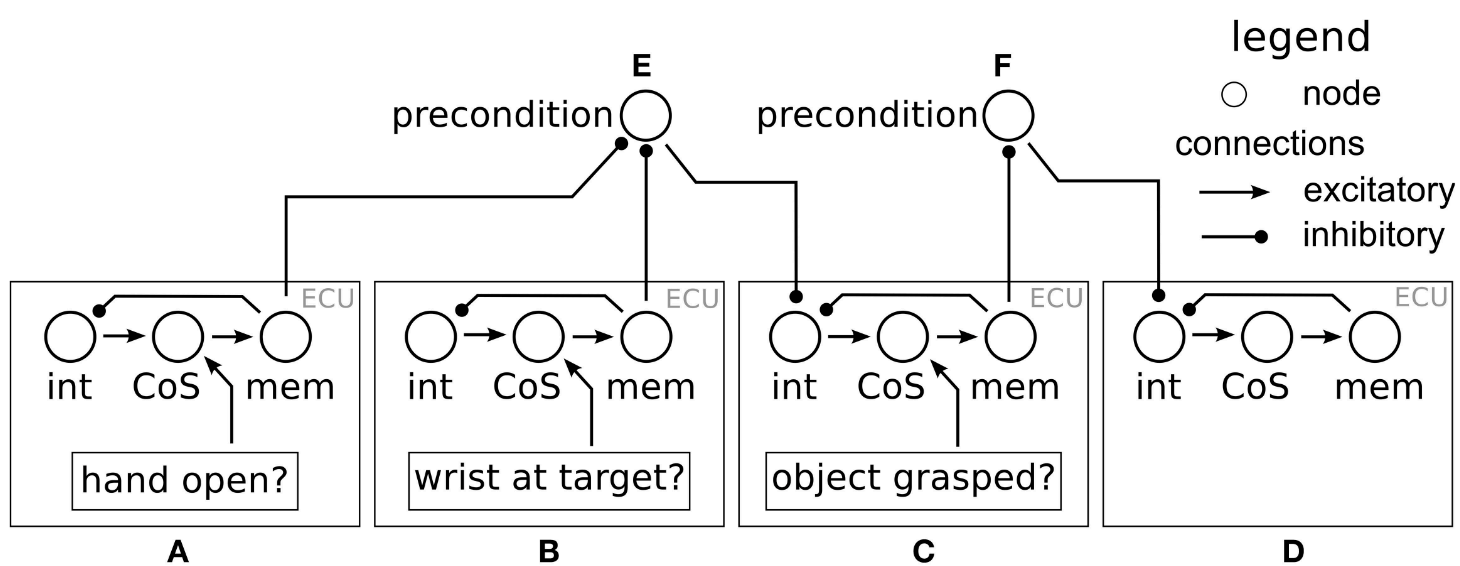
- planning sequence of movements toward goal
- extracting movement parameters for each movement



[Schöner, Tekülve, Zibner, 2019]

Movement organization

- initiation and termination of each movement
- serial/parallel activation of different movement "primitives"



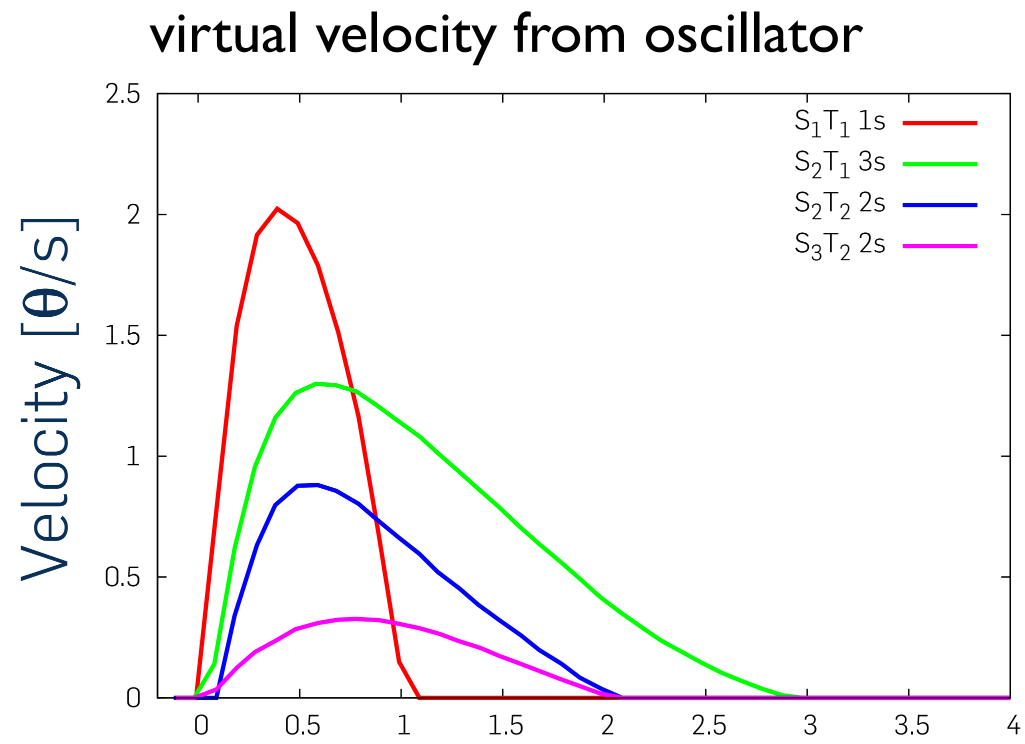
[Knips et al, Frontiers Neurorobotics 2017]

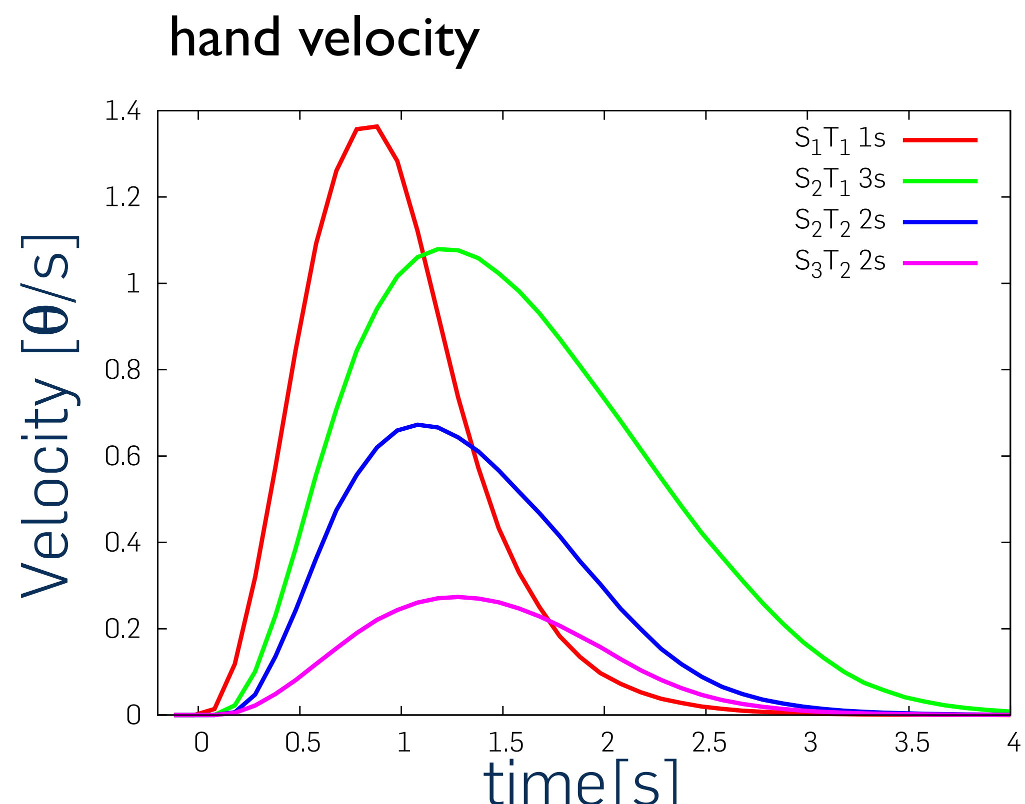
Trajectory formation

- generating end-effector velocity reference command
- here: from a field of neural oscillators

=> lecture on timing and coordination

[Zibner, Tekülve, Schöner, ICDL 2015; Schöner, Tekülve, Zibner, 2019]]





Control

- bringing about the physical movement…

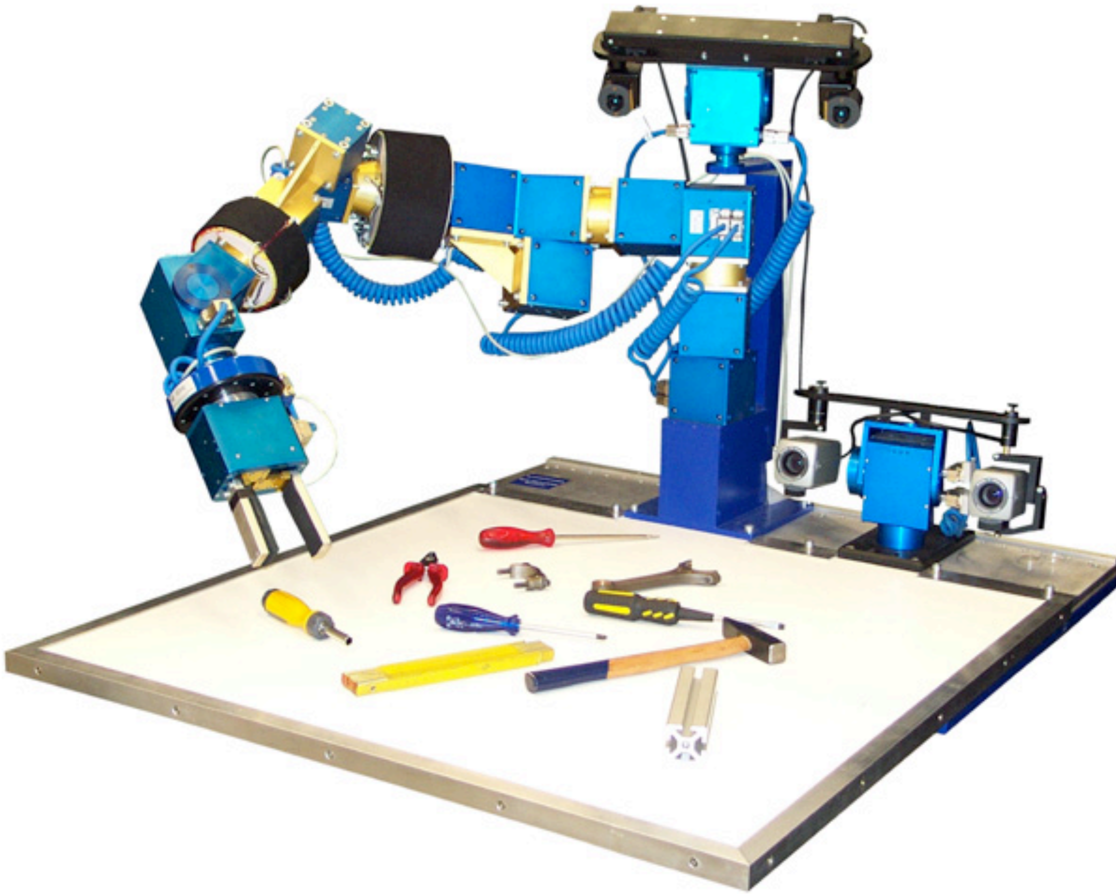
=> lecture on control

Basic concepts for robotic arms

- task vs control level: degree of freedom problem
- rigid body motion
- kinematics vs kinetics
- kinematic chain
- manipulator kinematics
- redundant manipulator kinematics

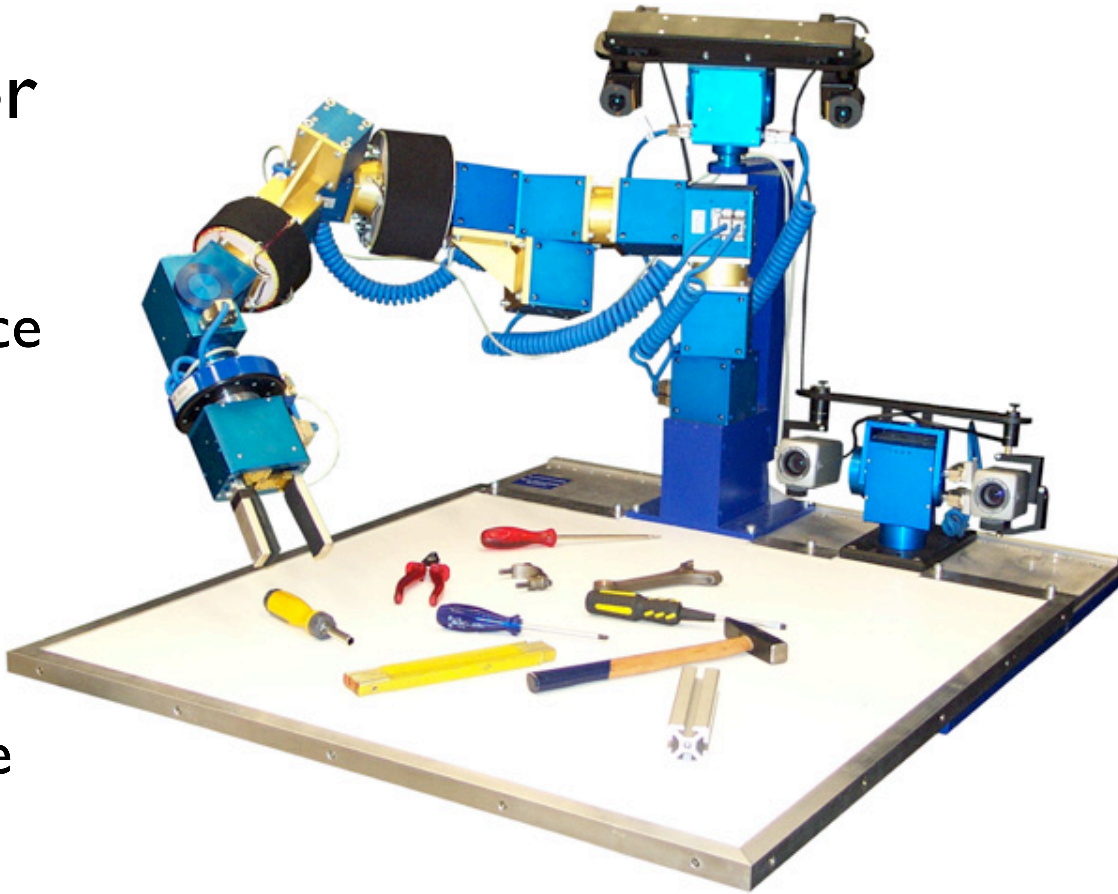
Levels of movement planning/control: Degree of freedom problem

- Perception, planning, organization, and timing are about the task level
- but control is at the level of the manipulator's actuators…



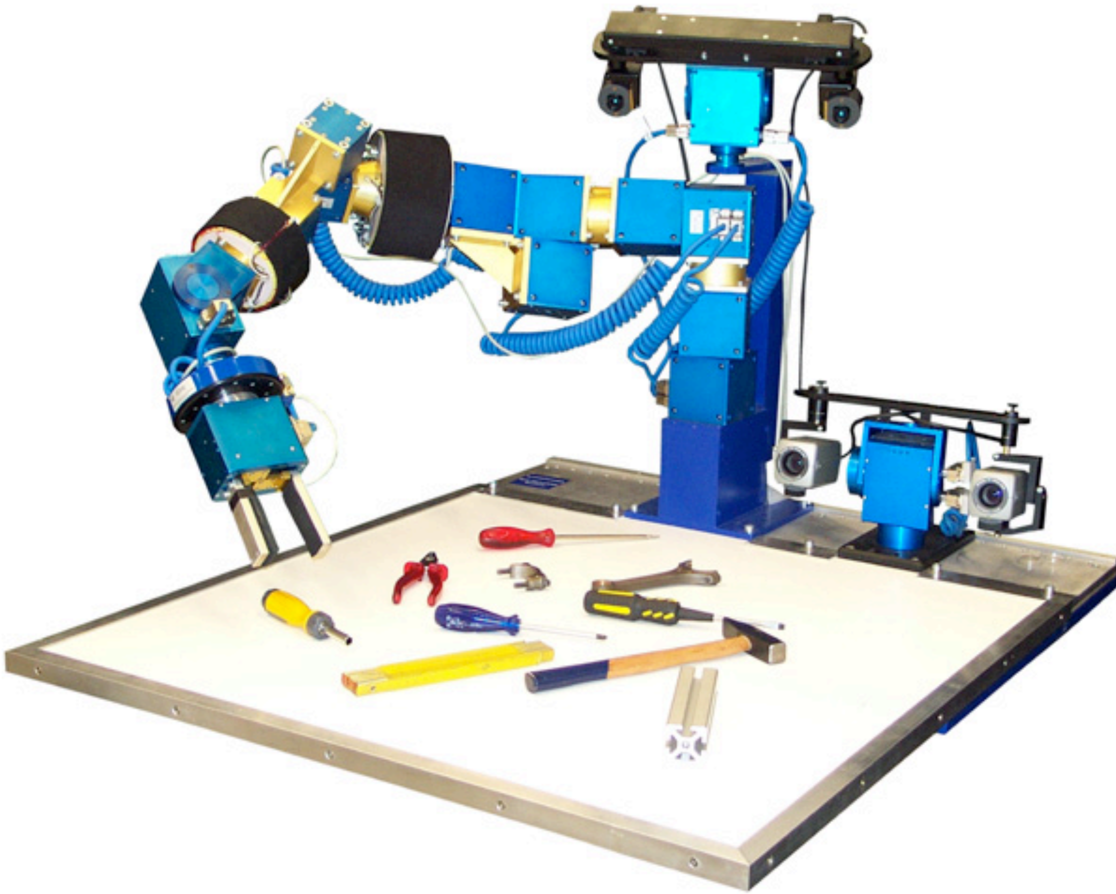
Task level

- target state at task level
  - 3D position of gripper/hand and 3D orientation of gripper/hand
- other task constraints for other task variables
  - e.g. closes point on arm surface to an obstacle
- timing at task level
  - e.g. for catching, hand at the right position at the right time



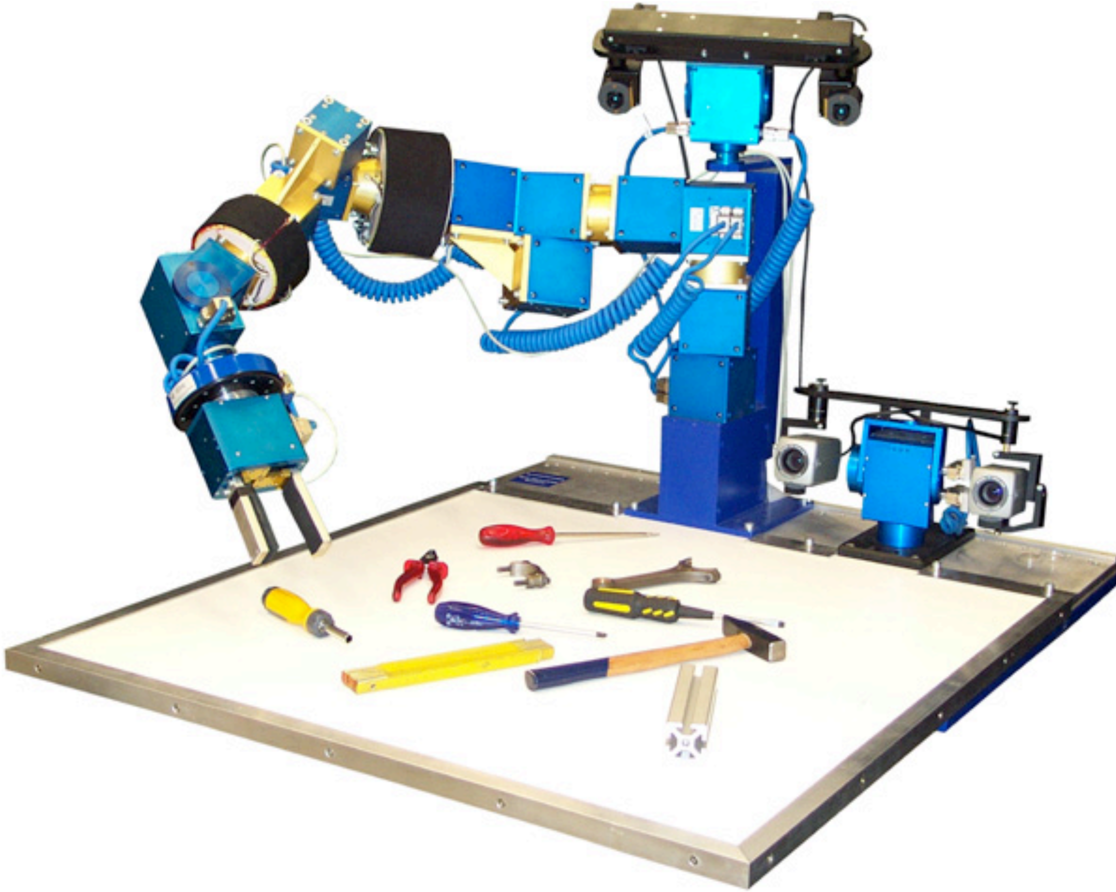
Control level

- mechanical degrees of freedom…
  - e.g. joint angles
- at which actuation takes place
  - motors
  - spring pre-load/muscle activation levels



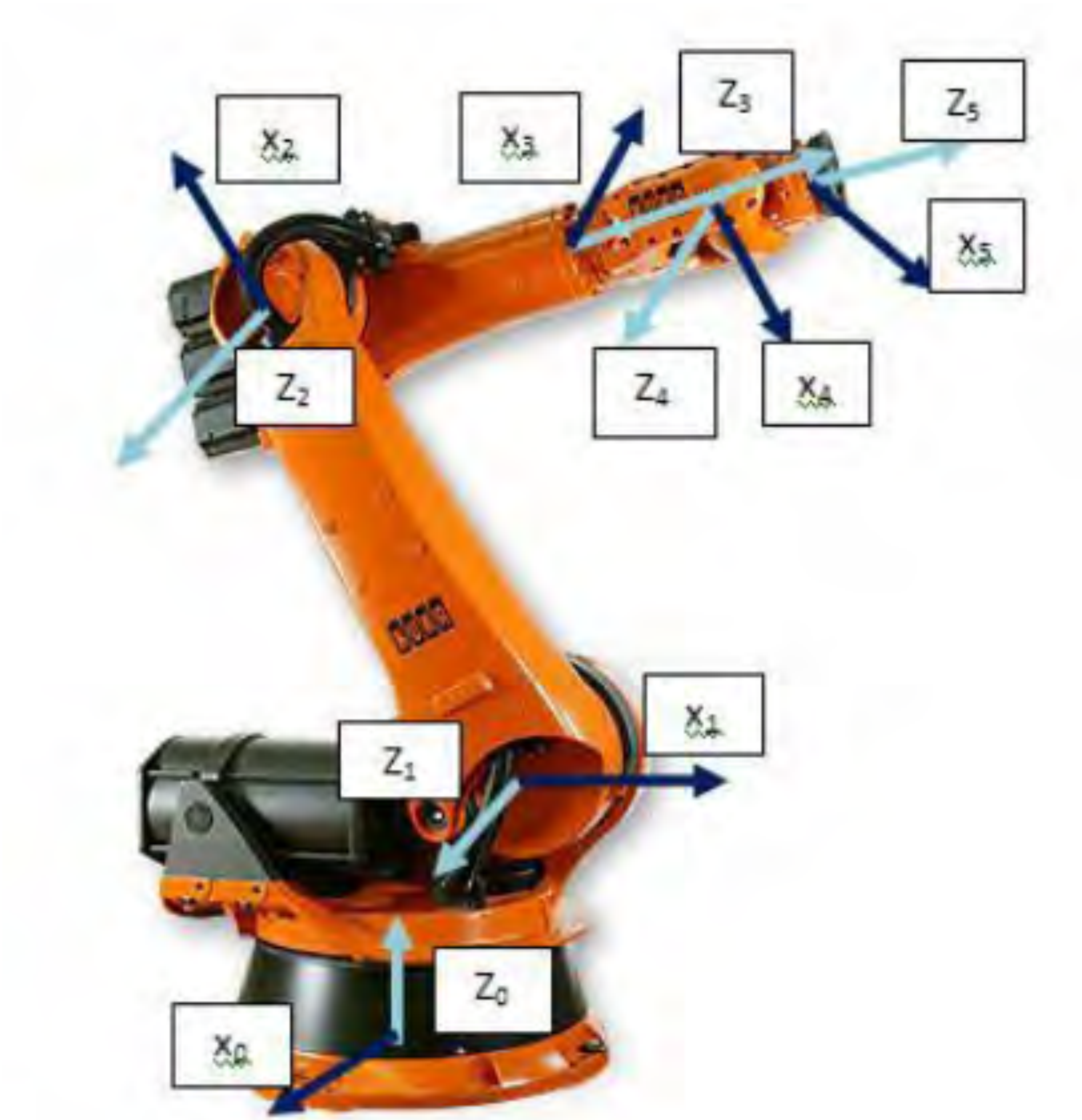
Redundancy

- when there are more variables at the control than the task level
  - e.g. 10 joints for human-like arm vs 3+3 coordinates for hand position and orientation
- => depends on the task!
- that gap between task and control level is the “degree of freedom problem”



Degree of freedom problem

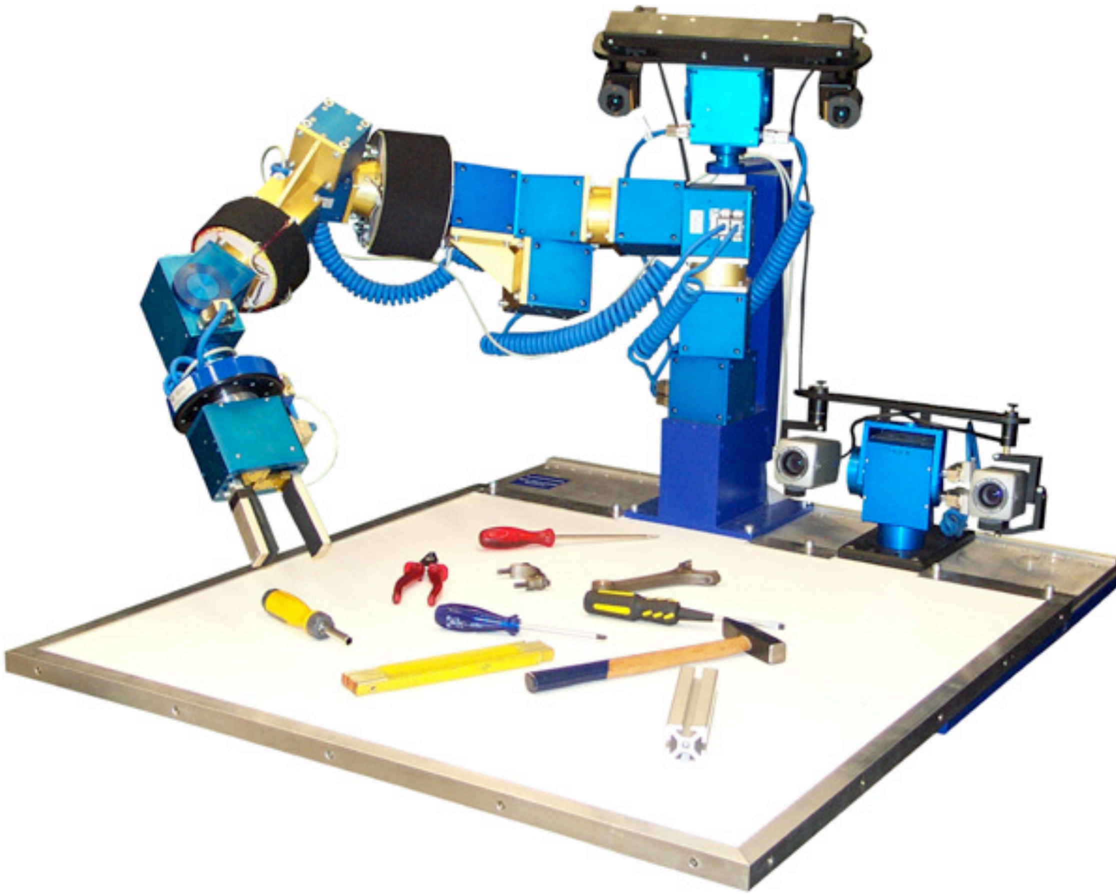
- many conventional robot arms are not redundant for end-effector task
  - most commonly: 3+3 hand/ gripper task variables and 6actuated joints



[Kuka KR16KS: Dahari, Tan 2012]]

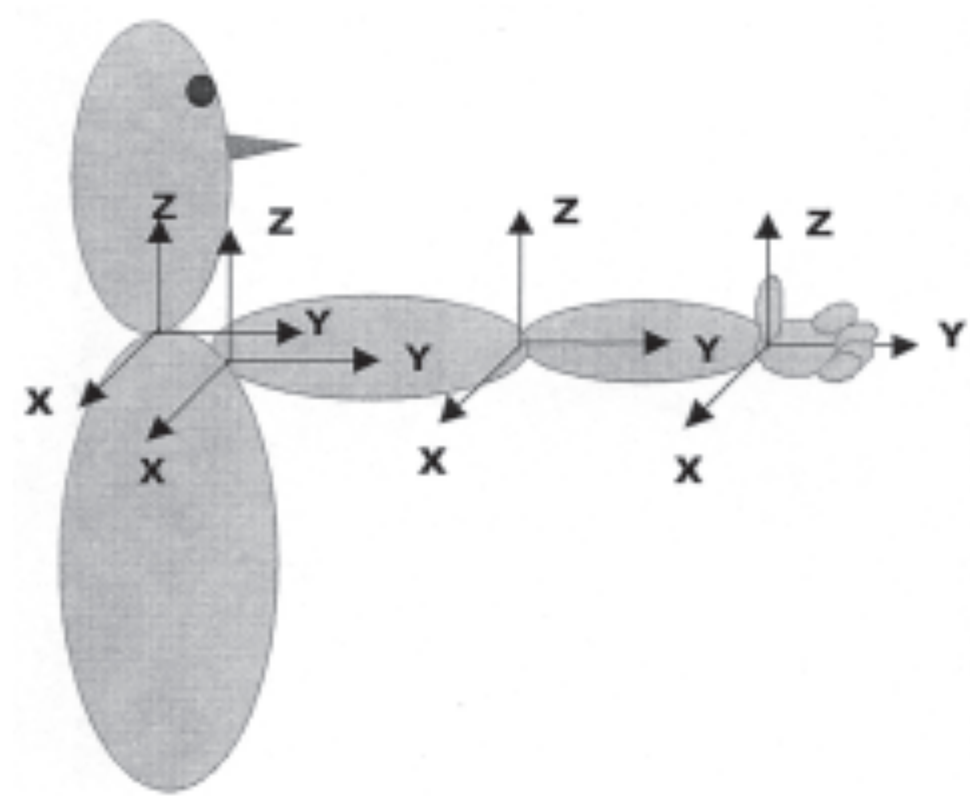
Degree of freedom problem

- but: some manipulators are redundant for some tasks
- which gives them added flexibility across tasks
- or enables them to deal with multiple tasks at the same time



Degree of freedom problem

- The human motor system is redundant for many tasks
- e.g. upper extremity for reaching/pointing
- > 10 Dof
- ca. 40 muscles
- 3-6 hand pose task variables



[Tseng, Scholz, Schöner, 2002]

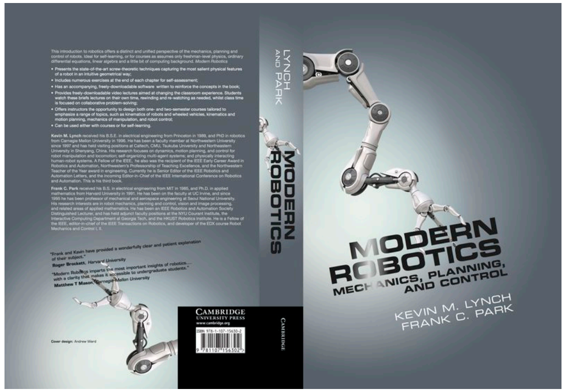
Basic concepts

- task vs control level: degree of freedom problem
- rigid body motion
- kinematics vs kinetics
- kinematic chain
- manipulator kinematics
- redundant manipulator kinematics

conventional robotics

- Murray, Li, Sastry: A Mathematical Introduction to Robotic Manipulation, CRC Press, Boca Raton FL USA 1994
    - a pdf is made available by the authors
    - quite an advanced text
- Lynch, Park: Modern robitics— mechanics, planning, and control. Cambridge Univ. Press, 2017
    - pre-print version available online from others
    - a more tutorial text

MODERN ROBOTICS
MECHANICS, PLANNING, AND CONTROI

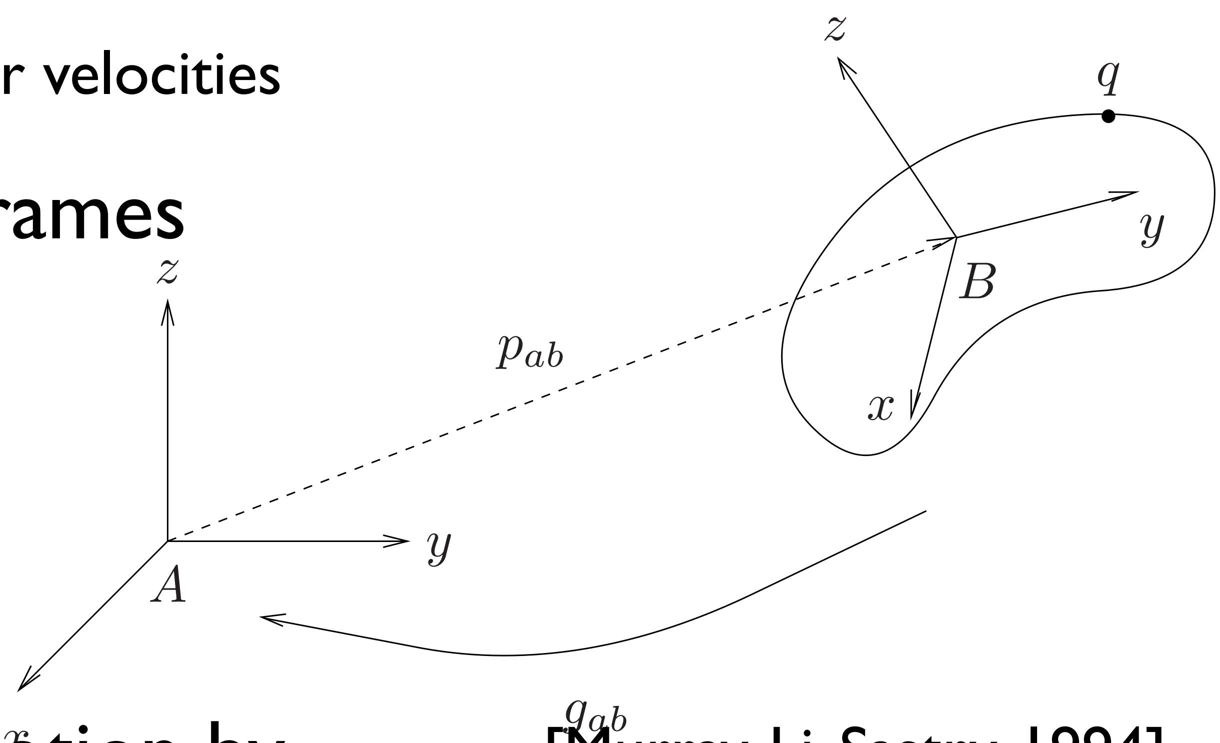


Kevin M. Lynch and Frank C. Park

[Murray, Li, Sastry, 1994]

Rigid body motion

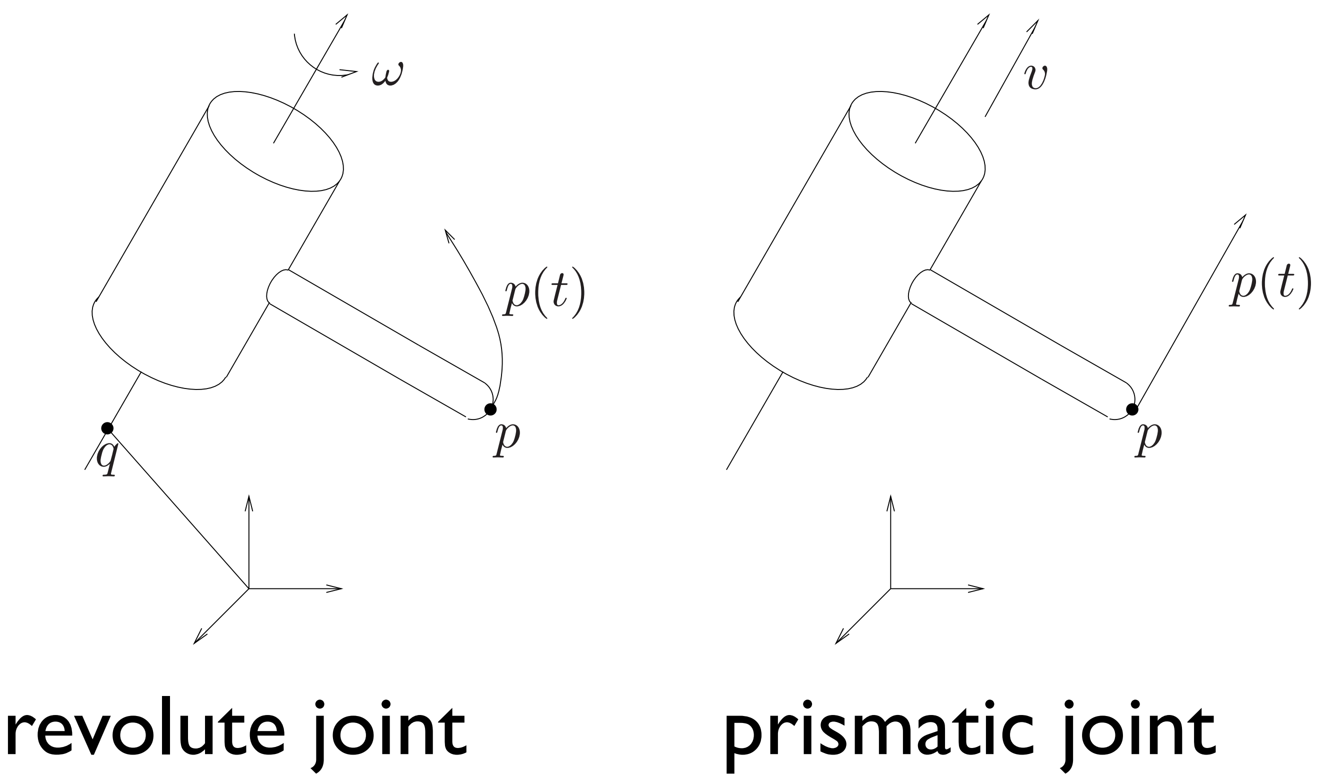
- a rigid body performs motion in 6D
  - three positions, three orientations
  - three linear, three angular velocities
- SE(3) transforming frames



- description of such motion by [Murray, Li, Sastry, 1994]
  - the position vector
  - a representation of rotation (Euler angles, Rotation matrix, generator of Lie group)

Rigid body motion

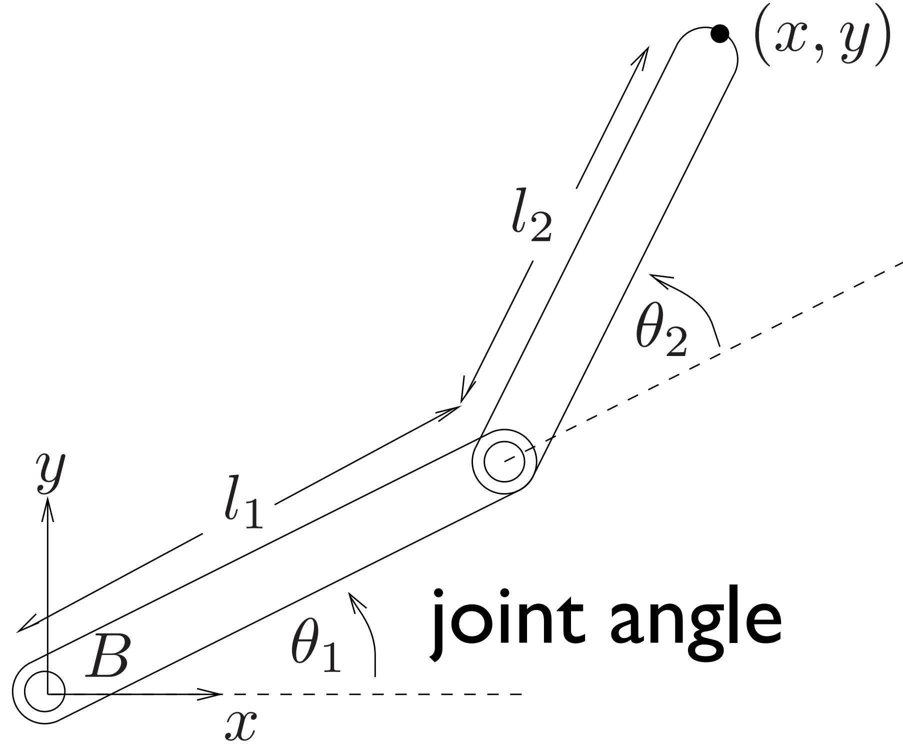
- constraints… revolute, prismatic, spherical.. joints
- reduce the number of degrees of freedom
- holonomic: can be formalized by reducing the number of variables



[Murray, Li, Sastry, 1994]

Rigid body motion

- in a in a kinematic chain, the degrees of freedom of each rigid segment is reduced
- for revolute or prismatic joints to a single(!) degree of freedom captured



joint angle

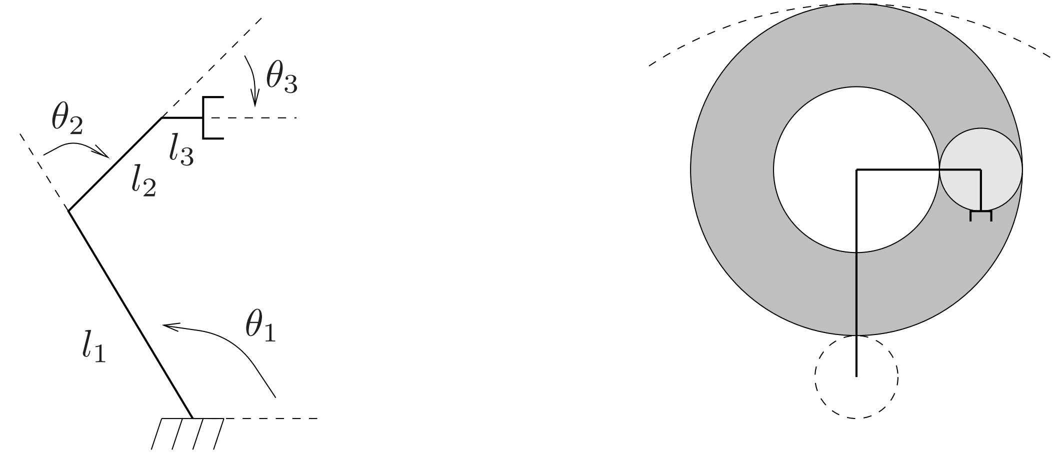
[Murray, Li, Sastry, 1994]

Kinematics vs Kinetics

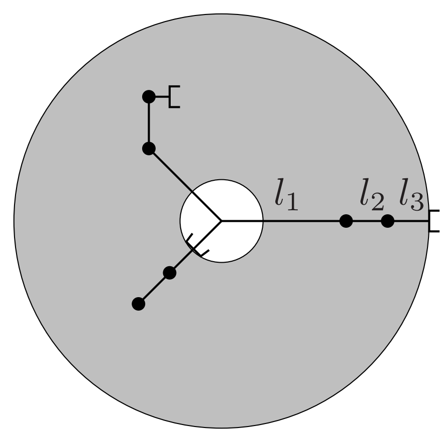
- kinematics: the description of the possible spatial (and velocity space) configurations of an arm taking into account the constraints
  - treated now
- kinetics: the dynamic equations of motion of an arm taking into account the constraints, gravity, and actuators mounted on the joints
  - (later in the lecture series)

Kinematic chain

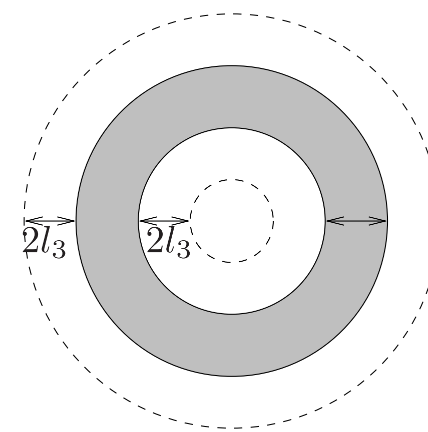
- notion of work space



(a) (b)



reachable space

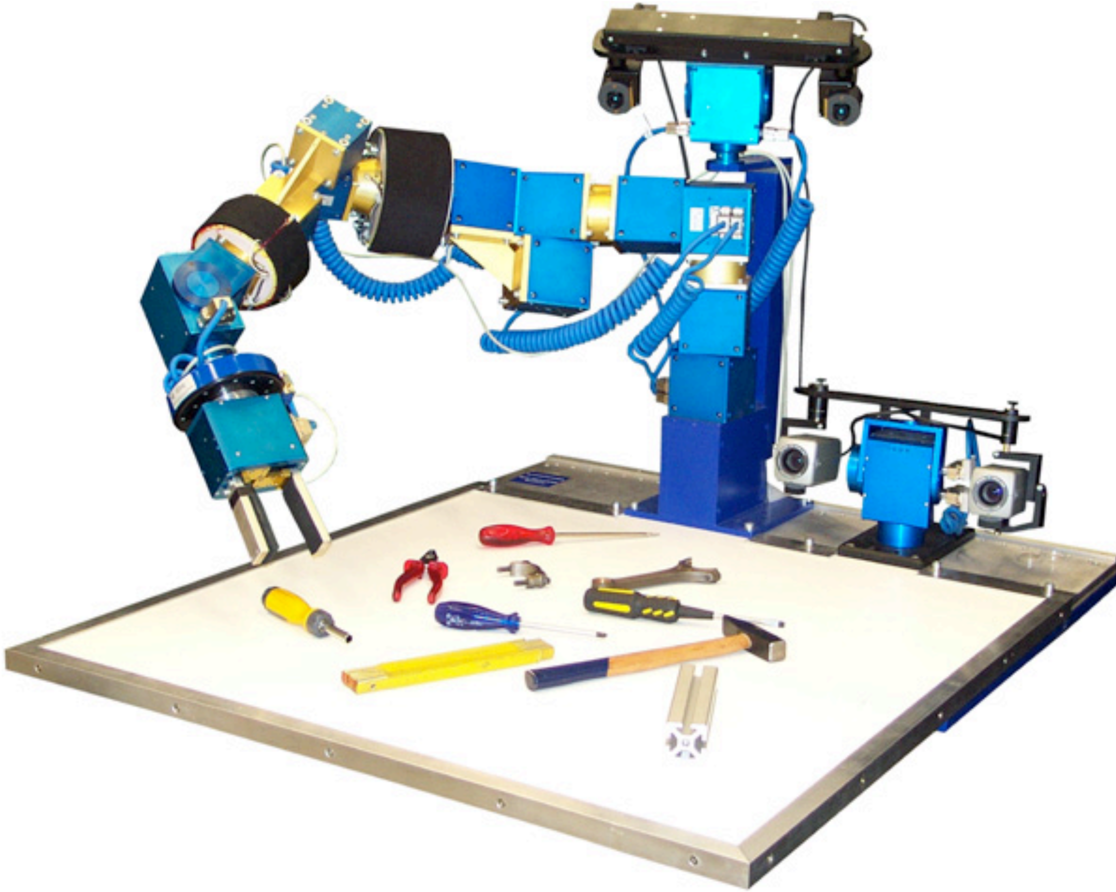


dexterous space: reachable with arbitrary orientation

[Murray, Li, Sastry, 1994]

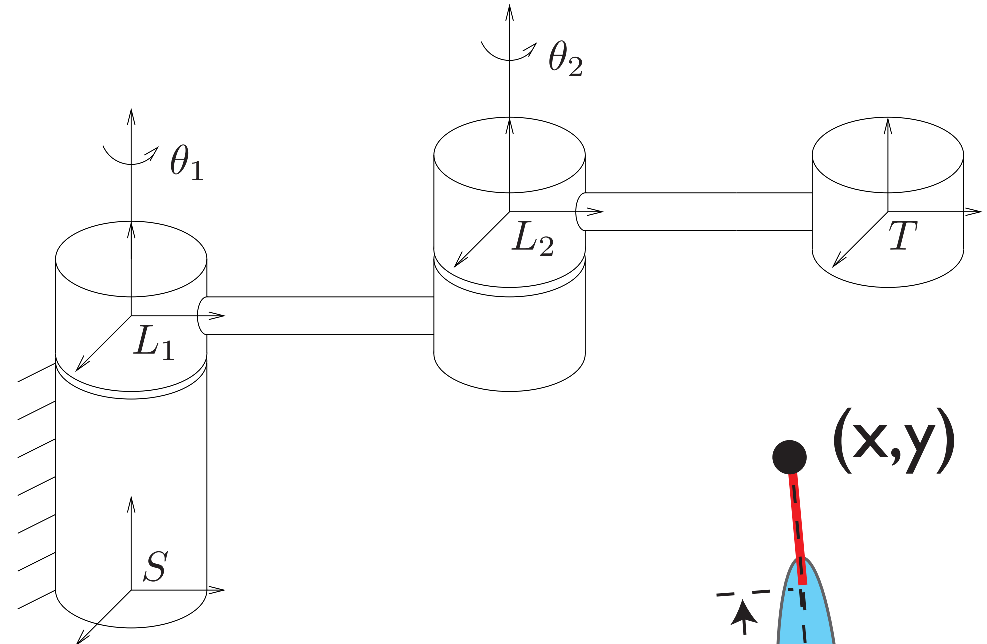
Manipulator kinematics

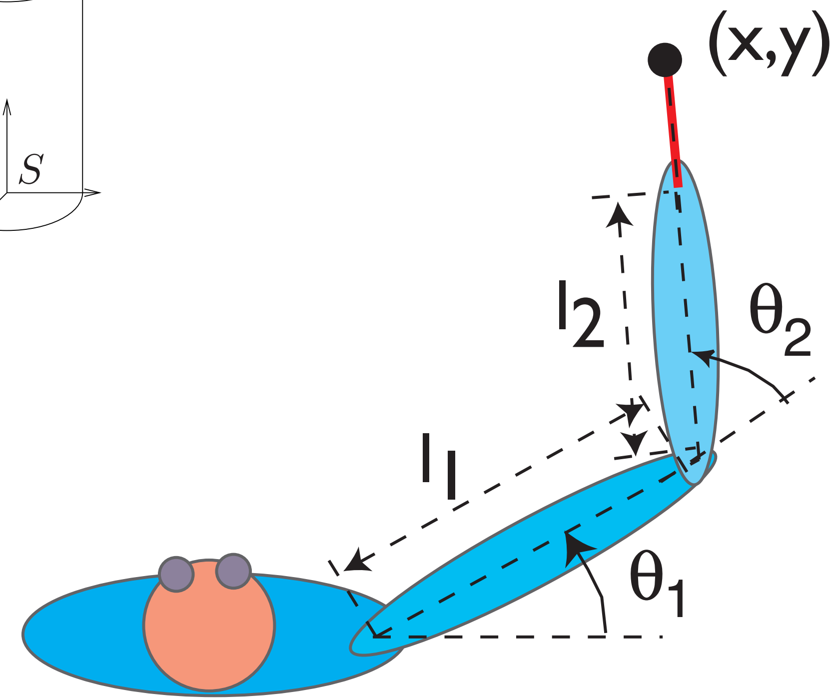
- end-effector
  - e.g. with 3 translational and 3 rotational degrees of freedom
- configuration space
  - e.g. 7 actuated joint angles



Forward kinematics

[Murray, Li, Sastry1994]





- where is the hand, given the joint angles..

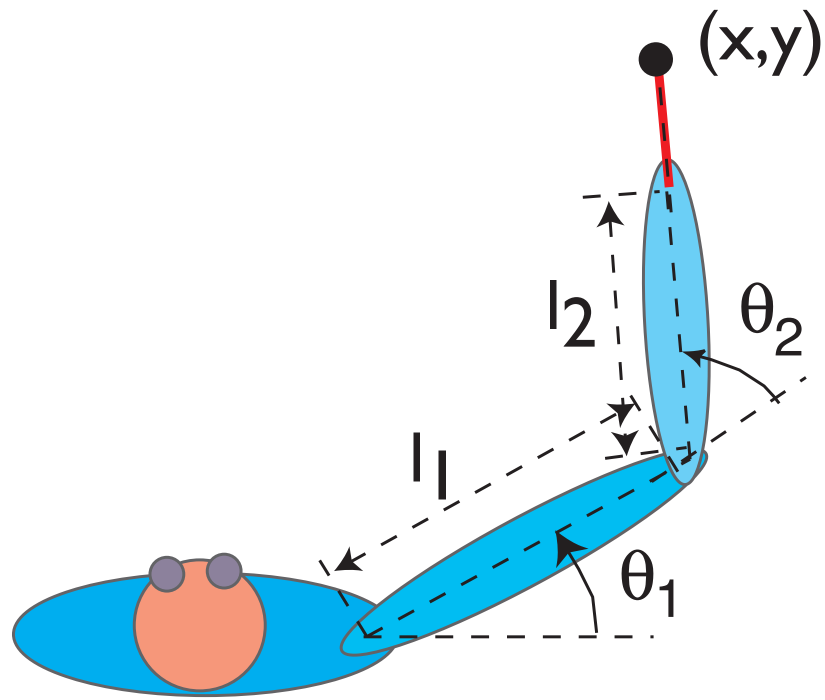
$$\mathbf{x} = \mathbf{f}(\theta)$$

$$x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2)$$

$$y = l_1 \sin(\theta_1) + l_2 \sin(\theta_1 + \theta_2)$$

Differential forward kinematics

- where is the hand moving, given the joint angles and velocities



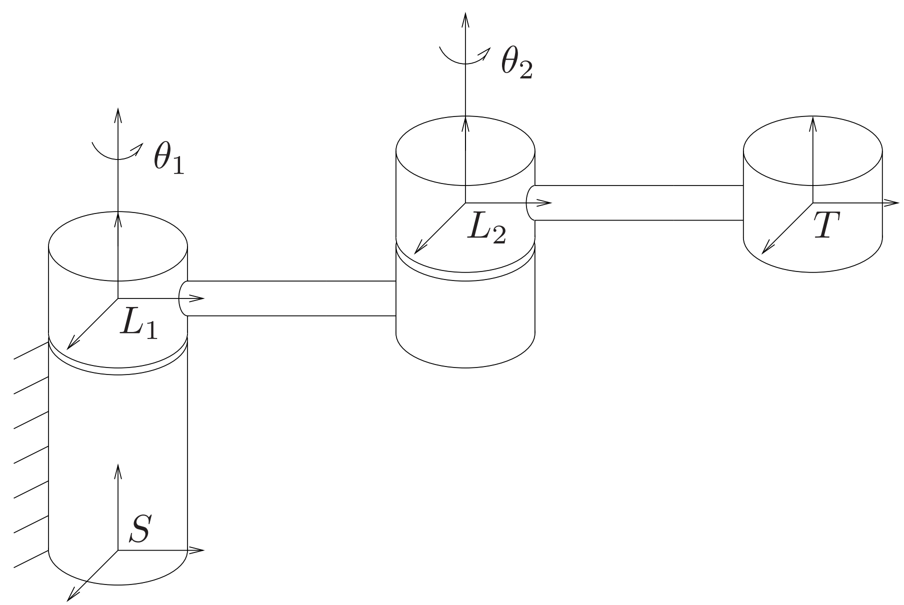
$$\dot{\mathbf{x}} = \mathbf{J}(\theta)\dot{\theta}$$

$$\dot{x} = -\,l_1 \sin(\theta_1)\dot{\theta}_1 - l_2 \sin(\theta_1 + \theta_2)\dot{\theta}_1 - l_2 \sin(\theta_1 + \theta_2)\dot{\theta}_2$$

$$\dot{y} = l_1 \cos(\theta_1)\dot{\theta}_1 + l_2 \cos(\theta_1 + \theta_2)\dot{\theta}_1 + l_2 \cos(\theta_1 + \theta_2)\dot{\theta}_2$$

Formal approach to kinematics

- base frame S and tool frame T
- ask how any object represented in the tool frame is represented in the base frame => forward kinematics
- transformation from tool frame g_t to the base frame g_s is a function of the joint angles

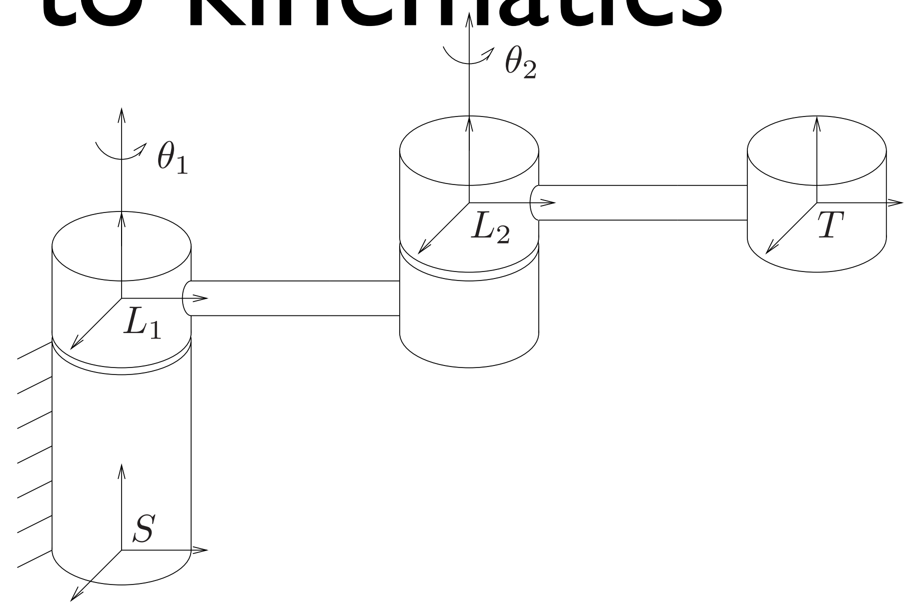


$$g_{st}(\theta_1, \theta_2) = g_{sl_1}(\theta_1) g_{l_1 l_2}(\theta_2) g_{l_2 t}.$$

[Murray, Li, Sastry, 1994]

Formal approach to kinematics

- product of exponentials



$$g_{st}(\theta_1, \theta_2) = g_{sl_1}(\theta_1) g_{l_1 l_2}(\theta_2) g_{l_2 t}.$$

$$g_{st}(\theta_1, \theta_2) = e^{\widehat{\xi}_1 \theta_1} g_{st}(\theta_2) = e^{\widehat{\xi}_1 \theta_1} e^{\widehat{\xi}_2 \theta_2} g_{st}(0),$$

$$e^{\widehat{\xi}_1 \theta_1} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\xi_i = \begin{bmatrix} -\omega_i \times q_i \\ \omega_i \end{bmatrix},$$

$$e^{\widehat{\xi}_2 \theta_2} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_1 \sin\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & l_1(1-\cos\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

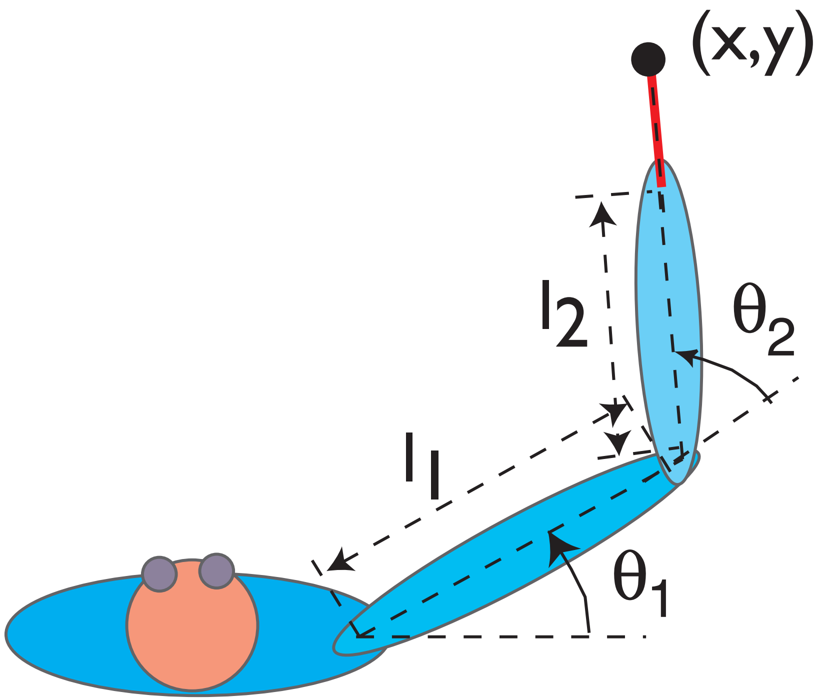
$$g_{st}(0) = \begin{bmatrix} I & \begin{pmatrix} 0 \\ l_1 + l_2 \\ l_0 \end{pmatrix} \\ 0 & 1 \end{bmatrix}.$$

[Murray, Li, Sastry, 1994]

Inverse kinematics

- what joint angles are needed to put the hand at a given location
- exact solution:

$$\theta = \mathbf{f}^{-1}(\mathbf{x})$$



Inverse kinematics

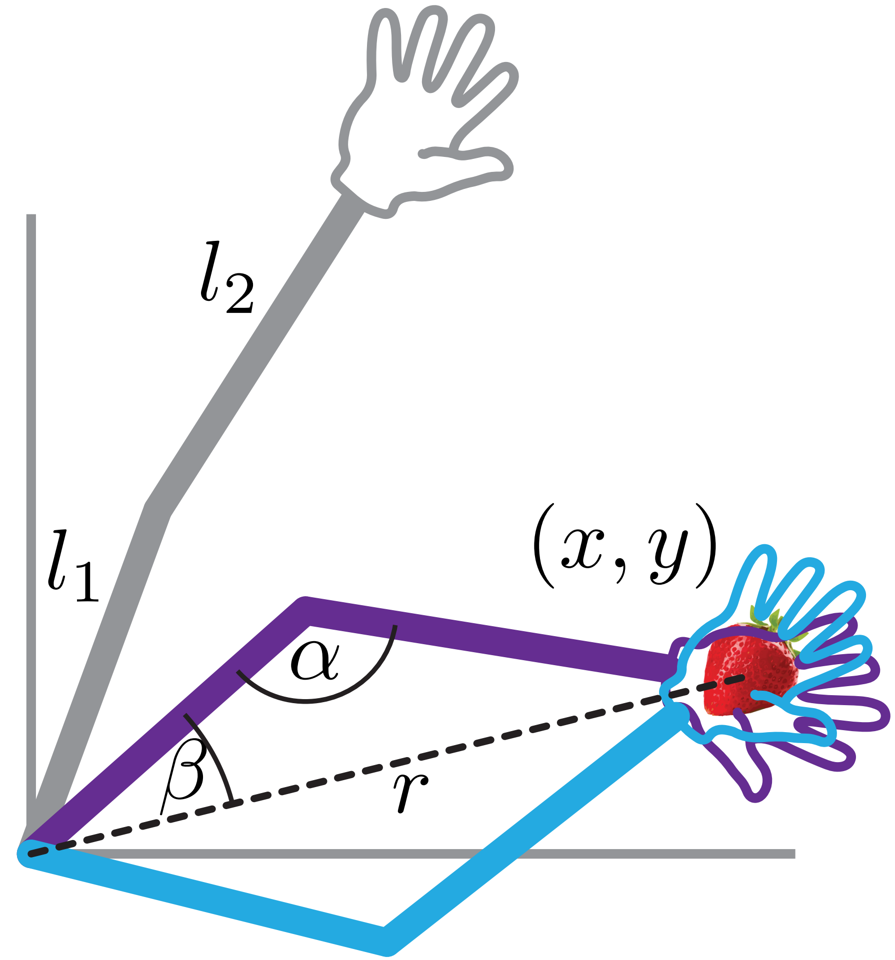
$$\theta_1 = \arctan_2(y, x) \pm \beta$$

$$\theta_2 = \pi \pm \alpha$$

$$\alpha = \cos^{-1}\left(\frac{l_1^2 + l_2^2 - r^2}{2 l_1 l_2}\right)$$

$$\beta = \cos^{-1}\left(\frac{r^2 + l_1^2 - l_2^2}{2 l_1 l_2}\right)$$

where $r^2 = x^2 + y^2$

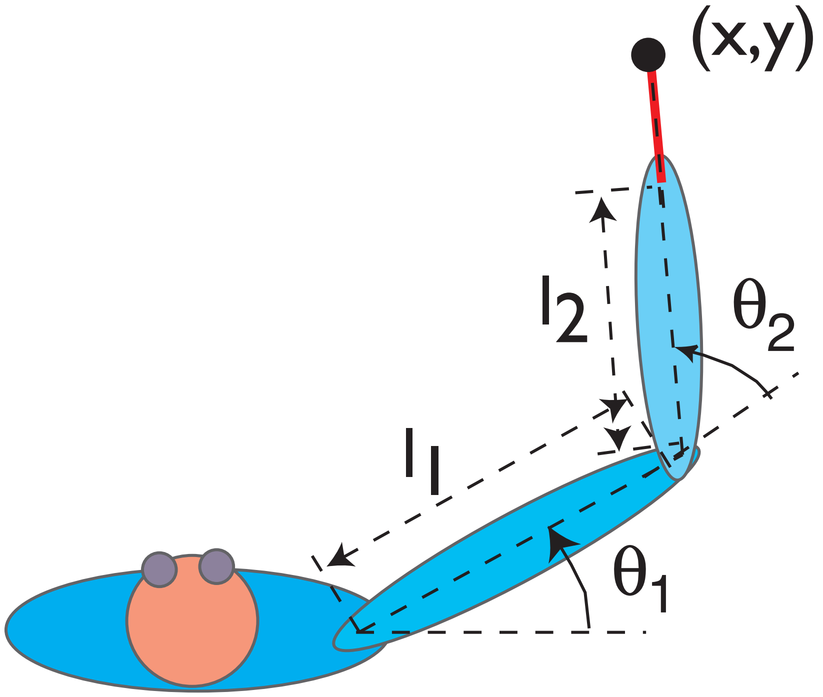


[thanks to Jean-Stéphane Jokeit]

- => multiple "leafs" of the inverse kinematics

Differential inverse kinematics

- which joint velocities to move the hand in a particular way

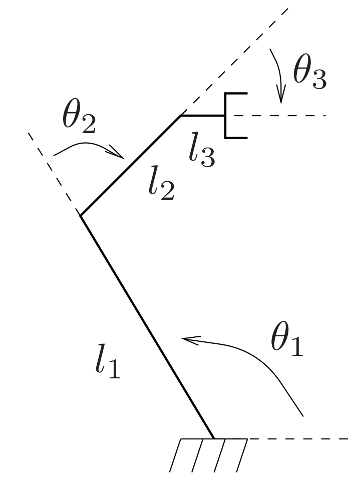


$$\dot{\theta} = \mathbf{J}^{-1}(\theta)\dot{\mathbf{x}}$$

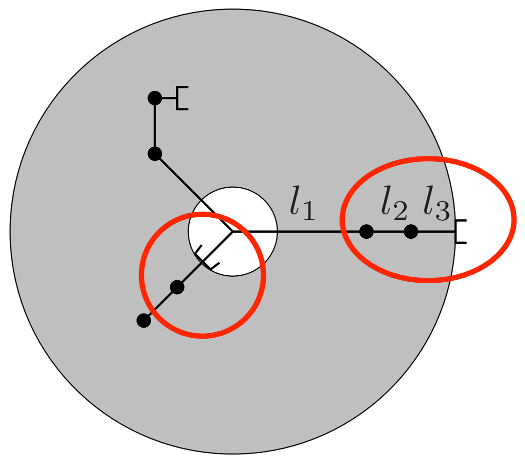
with the inverse, $\mathbf{J}^{-1}$, of $\mathbf{J}$, if it exists

Singularities

- where the Eigenvalue of the Jacobian becomes zero (real part)…
- so that movement in a particular direction is not possible…
- typically at extended postures or inverted postures
- at limit of workspace



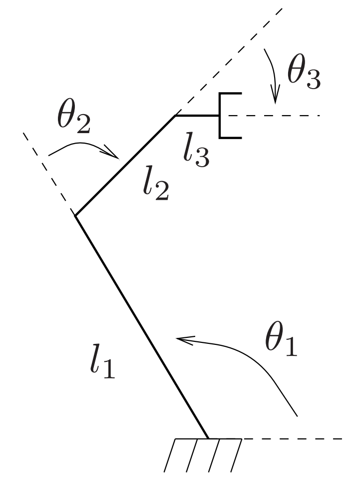
(a)



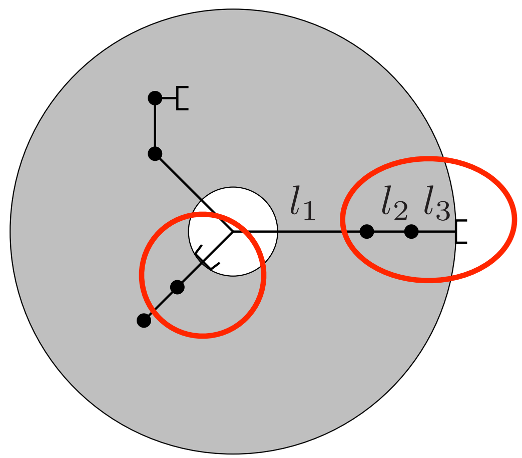
(c)

Singularities

- leading to non-invertability!
- and to sensitive dependence on parameters
- => avoid singularities in motor planning… major effort in robotics
- humans: joint angles prevent us from getting near singularities (for the most part)



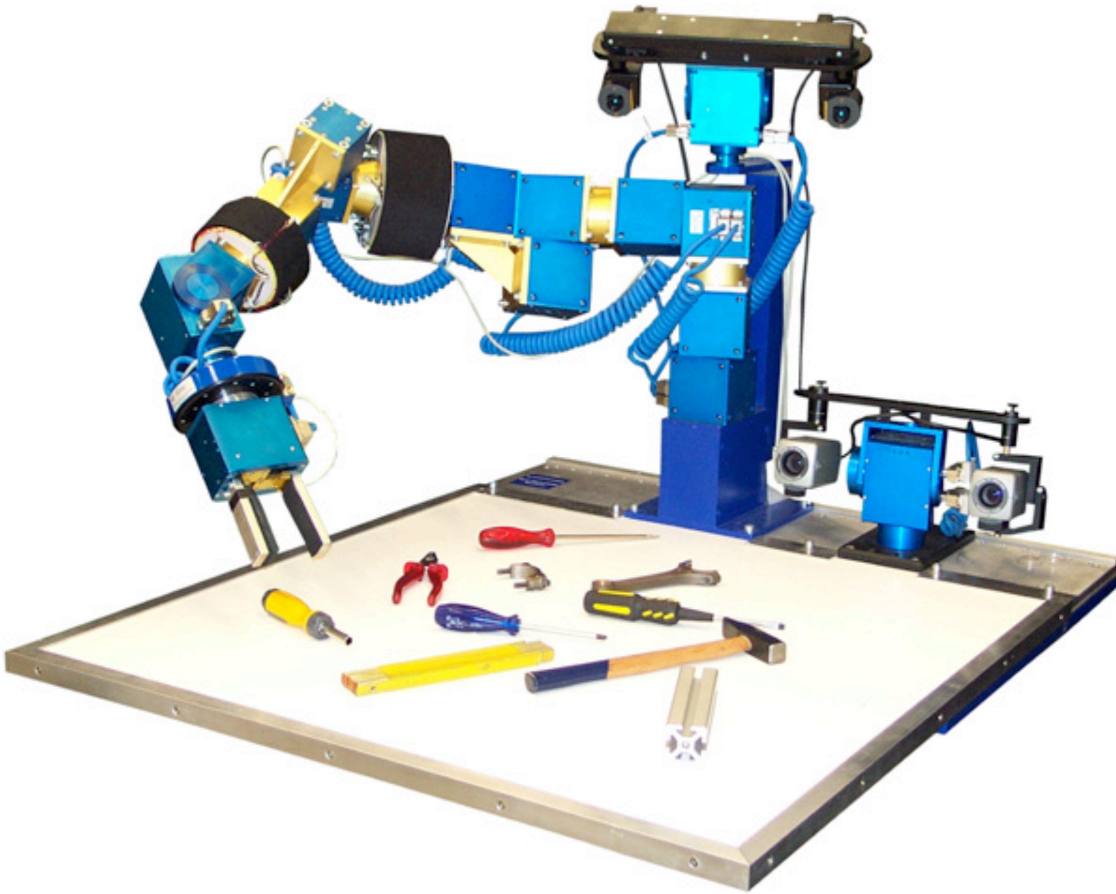
(a)



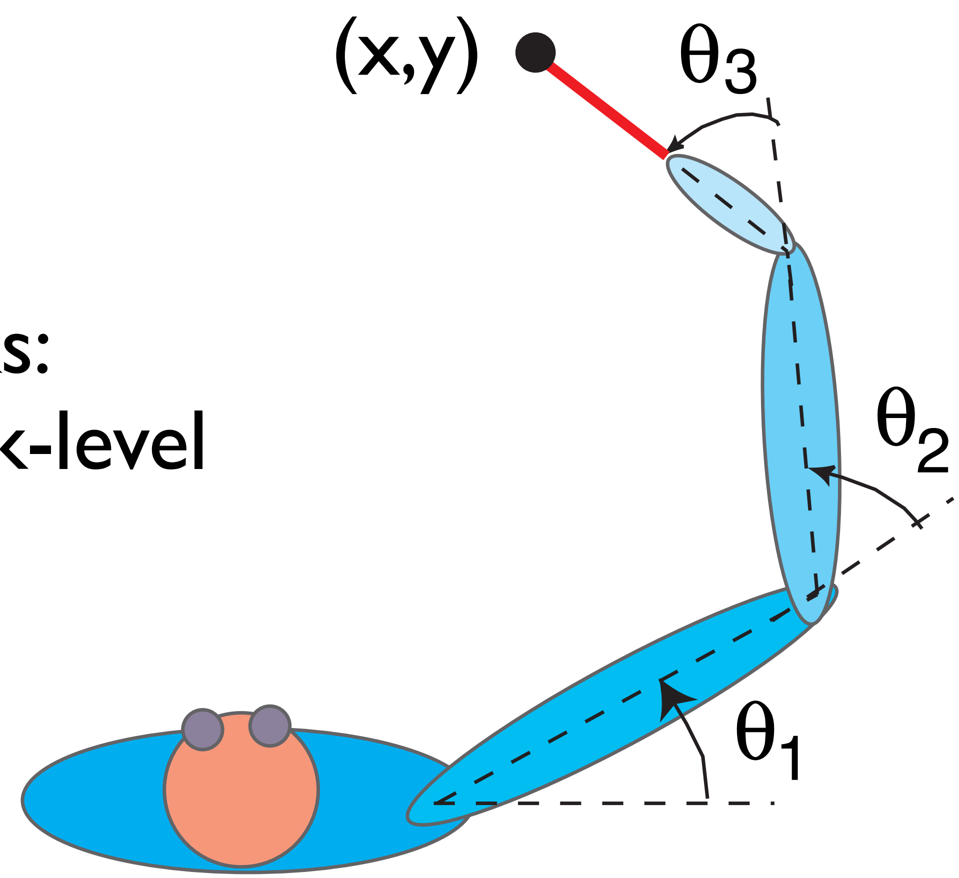
(c)

Summary arm kinematics

kinematic model	$\mathbf{x} = \mathbf{f}(\theta)$	$\dot{\mathbf{x}} = \mathbf{J}(\theta)\dot{\theta}$
inverse kinematic model	$\theta = \mathbf{f}^{-1}(\mathbf{x})$	$\dot{\theta} = \mathbf{J}^{-1}(\theta)\dot{\mathbf{x}}$



Redundant kinematics



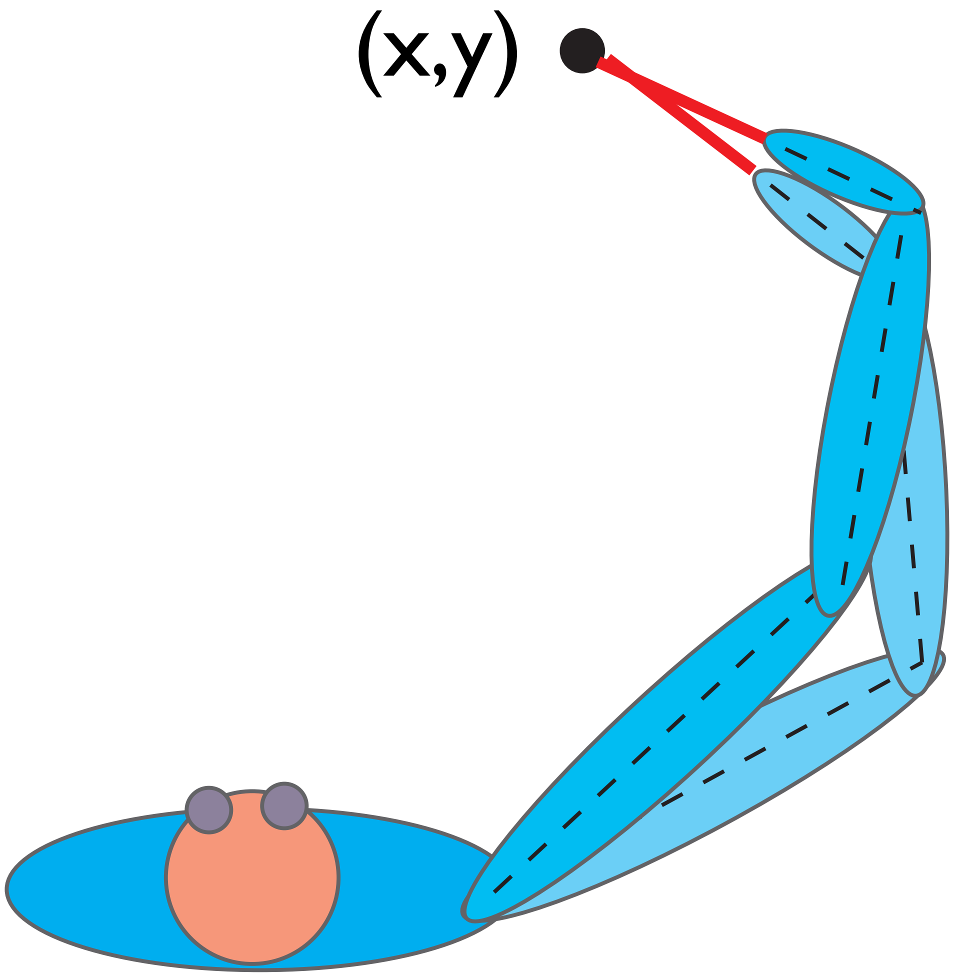
- redundant arms/tasks: more joints than task-level degrees of freedom

$$x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1+\theta_2) + l_3 \cos(\theta_1+\theta_2+\theta_3)$$

$$y = l_2 \sin(\theta_1) + l_2 \sin(\theta_1+\theta_2) + l_3 \sin(\theta_1+\theta_2+\theta_3)$$

Redundant kinematics

- => (continuously) many inverse solutions…



Redundant kinematics

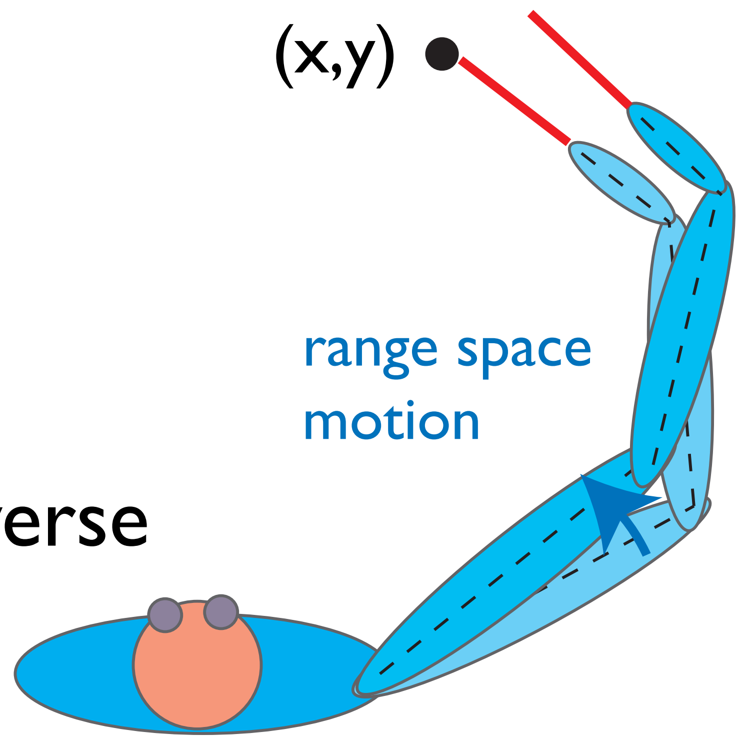
- use pseudo-inverses that minimize a functional (e.g., total joint velocity or total momentum)

$$\dot{\mathbf{x}} = \mathbf{J}(\theta)\dot{\theta}$$

$$\dot{\theta} = \mathbf{J}^{+}(\theta)\dot{\mathbf{x}}$$

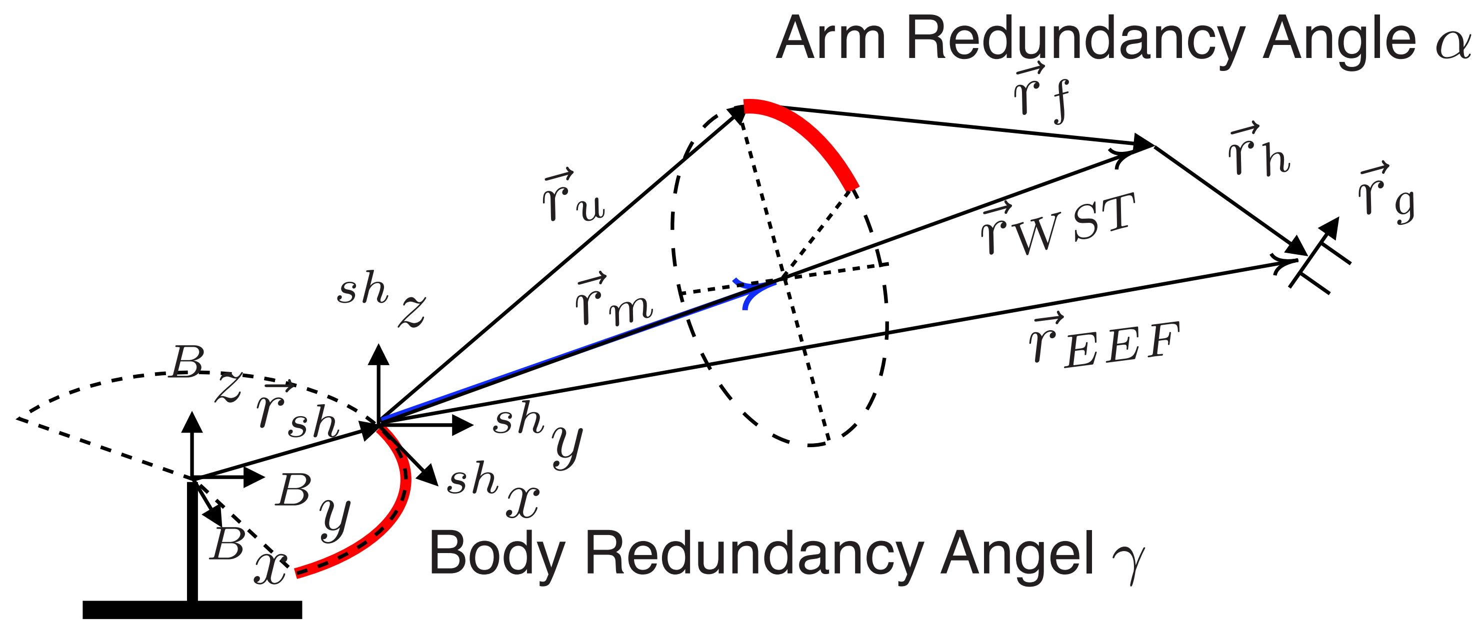
$$\mathbf{J}^{+}(\theta) = \mathbf{J}^{T}(\mathbf{J}\mathbf{J}^{T})^{-1}$$ pseudo-inverse

minimizes $\dot{\theta}^2$



Spaces for robotic motion planning

- or use extra degrees of freedom for additional tasks



[Iossifidis, Schöner, ICRA 2004]

Basic concepts

- degree of freedom problem
- rigid body motion
- kinematics vs kinetics
- kinematic chain
- manipulator kinematics
- redundant manipulator kinematics