Introduction to Robotics (IN3140/IN4140)

Spring 2021

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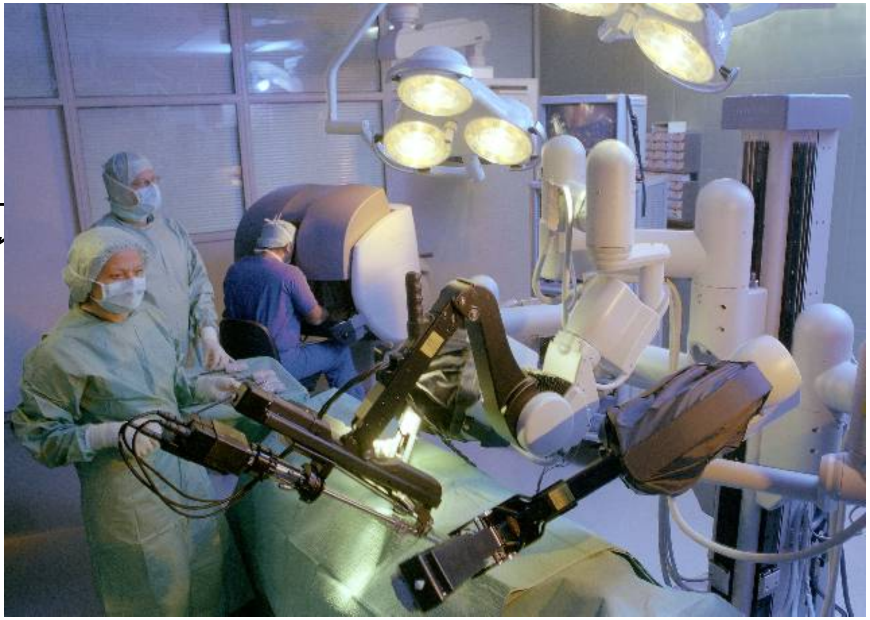


Personnel

Foreleser:

Ole Jakob Elle

Assistenter:

Farzan Majeed Noori (PhD student – ROBIN)

Abbas Tariverdi (ROS-support)

Gruppelærere og rettere:

Artem Chernyshov, Tony Nguyen og Kristian Roa Gran

Litteratur

- **Lærebok (pensum):**

M. Spong, S. Hutchinson, and M. Vidyasagar, “Robot Modeling and Control”, Wiley

- **Notater på enkelte emner kan komme i tillegg**

- **Støttelitteratur:**

John Craig, ”Introduction to Robotics”, Wesley

Teaching - time and place (IN3140 - spring 2021)

Undervisning - tid og sted (IN3140/IN4140 **- vår 2021)**

Forelesninger

Torsdag kl. 14:15 -16:00, Aud. Simula, Ole-Johan Dahls hus

Gruppetimer

Gruppe 1

Fredag kl. 10:15 -12:00, Digitalt på Zoom

Gruppe 2

Onsdag kl. 10:15 -12:00, Digitalt på Zoom

5 Compulsory assignments (Obliger): Handouts date and deadlines for 2021 will come later (link from course page to new plan)

Assignment 1, handed out during lecture of week 4, deadline night before lecture of week 10.

Assignment 2, handed out during lecture of week 10, deadline night before lecture of week 12.

Assignment 3, handed out during lecture of week 12, deadline night before lecture of week 15.

Assignment 4, handed out during lecture of week 14, deadline night before lecture of week 19.

Assignment 5 (Project). Handed out during lecture of week 8. Deadline for delivery and presentation is May 10th.

Eksamensordning

Hjemmeeksamen.

Utlevering av oppgaven: 11. juni kl. 09:00

Innleveringsfrist: 11. juni kl. 13:00

Sted: Inspera Digital innlevering

IN3140 – Introduction to Robotics

Fem obligatoriske øvinger, som bygger på hverande.

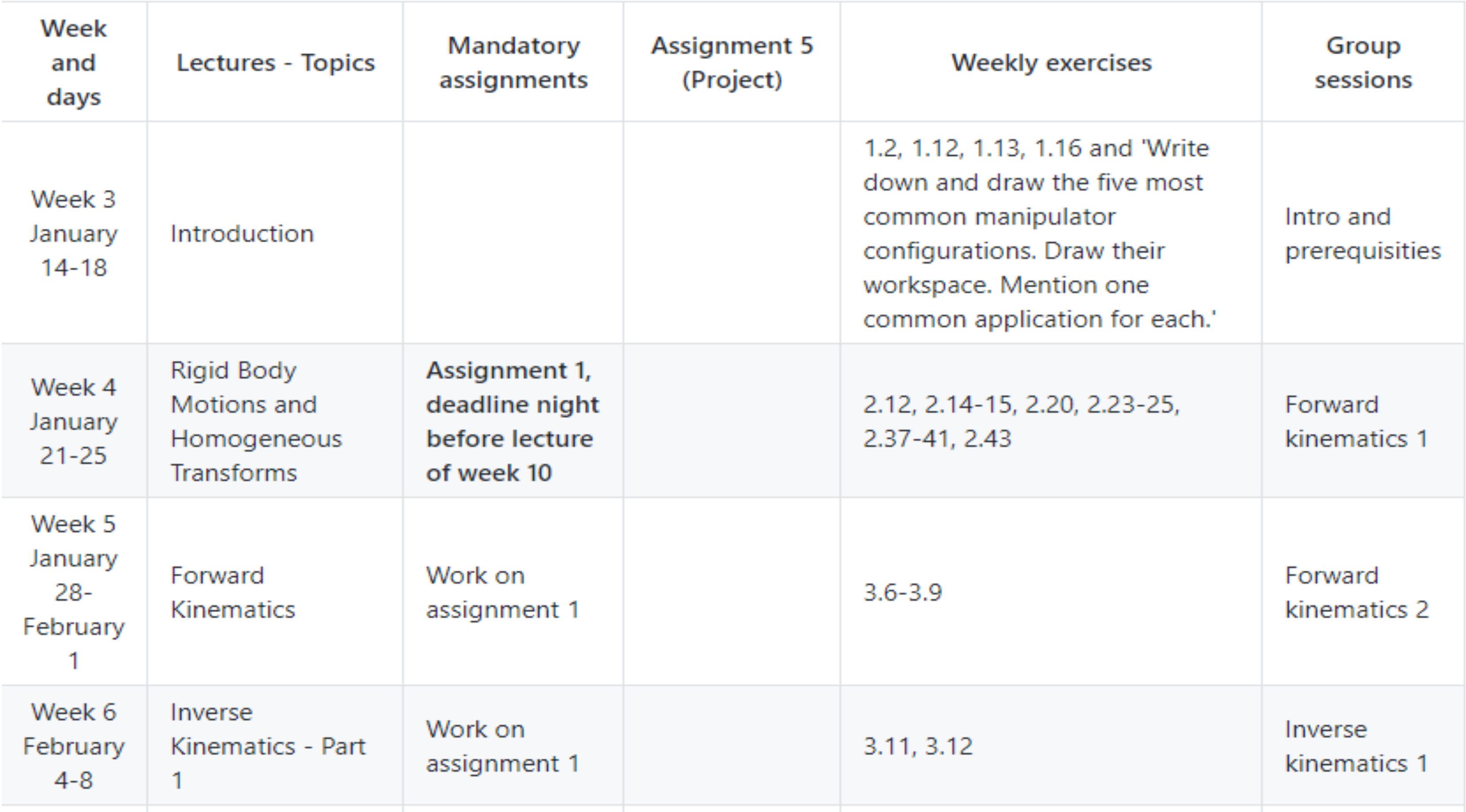
- 1,2: Kinematisk modellering : Sette opp kinematisk modell for en gitt robot og implementere dette i Python og ROS (Robot Operating System).
- 3: Utregning av dynamikk for en minirobot.
- 4: Implementering og styring av en minirobot: Benytte den implementerte kinematiske modellen, og dynamikken som grunnlag for å styre roboten.
- 5: En valgfri ros oppgave som strekker seg over hele semesteret. Vis visuelt, ved simulator/robot, valgfri deler av pensum.

Tema for øvingene

- Forover og inverskinematikk,
- ROS
- Hastighetskinematikk,
- Leddstyring,
- Dynamikk,
- Manipulering/bevegelsesstyring,
- Robot control – Reguleringsteknikk,

Forelesningsplan (blir oppdatert for 2021, ukesoppgaver fra hvert kapittel samme som vist i tabell under).

Første seks uker. Se github for hele planen.



Week and days	Lectures - Topics	Mandatory assignments	Assignment 5 (Project)	Weekly exercises	Group sessions
Week 3 January 14-18	Introduction			1.2, 1.12, 1.13, 1.16 and 'Write down and draw the five most common manipulator configurations. Draw their workspace. Mention one common application for each.'	Intro and prerequisities
Week 4 January 21-25	Rigid Body Motions and Homogeneous Transforms	**Assignment 1, deadline night before lecture of week 10**		2.12, 2.14-15, 2.20, 2.23-25, 2.37-41, 2.43	Forward kinematics 1
Week 5 January 28-February 1	Forward Kinematics	Work on assignment 1		3.6-3.9	Forward kinematics 2
Week 6 February 4-8	Inverse Kinematics - Part 1	Work on assignment 1		3.11, 3.12	Inverse kinematics 1

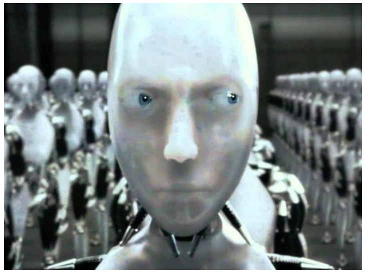
Introduction

Historical perspective

The acclaimed Czech playwright Karel Capek (1890-1938) made the first use of the word ‘robot’, from the Czech word for forced labor or serf.

The use of the word Robot was introduced into his play *R.U.R. (Rossum's Universal Robots)* which opened in Prague in January 1921. In R.U.R., Capek poses a paradise, where the machines initially bring so many benefits but in the end bring an equal amount of blight in the form of unemployment and social unrest.

Science fiction



Asimov, among others glorified the term ‘robotics’, particularly in *I, Robot*, and early films such as *Metropolis* (1927) paired robots with a dystopic society

Formal definition (Robot Institute of America):

"A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks".

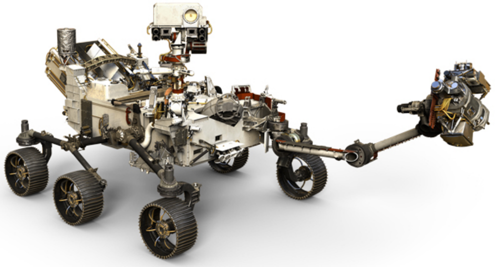
Robots in everyday use and popular culture

- Chances are, something you eat, wear, or was made by a robot
- 100s of movies; Terminator, Chappie, Iron Man, Transformers

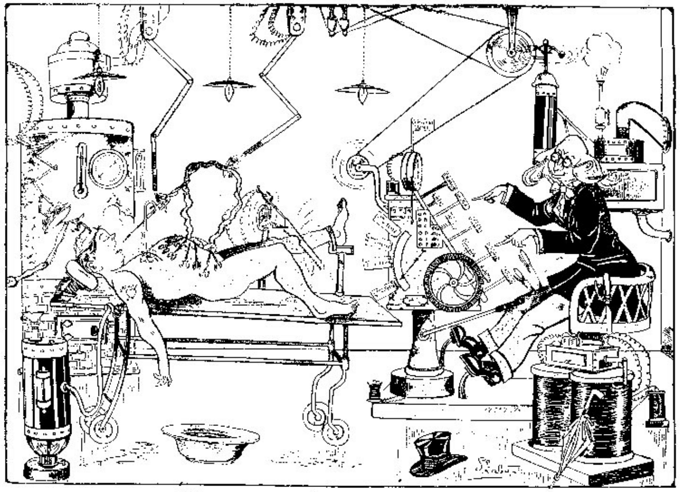
Common applications

- Industrial
  - Robotic assembly
- Commercial/Social
  - Household chores
  - Toys
  - Educational

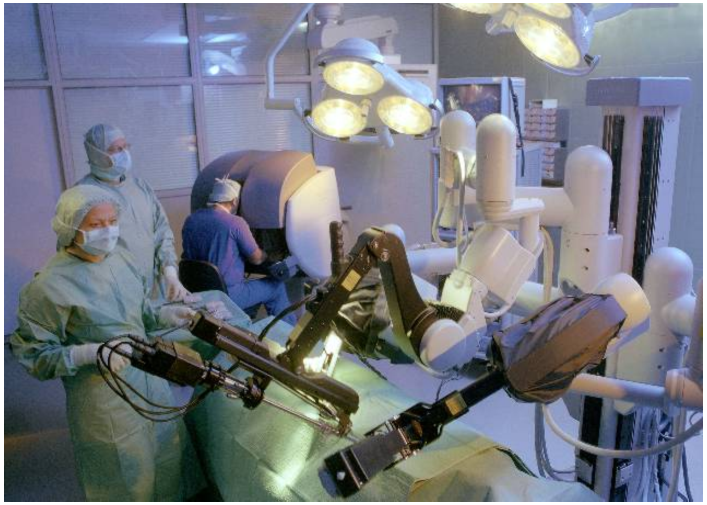
- Military
- Planetary Exploration
  - Mars rover



- Undersea exploration
- Medical
  - Robot-assisted surgery



UNE SALLE D'OPÉRATIONS EN L'AN 2000



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Oslo University Hospital

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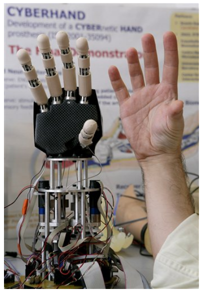
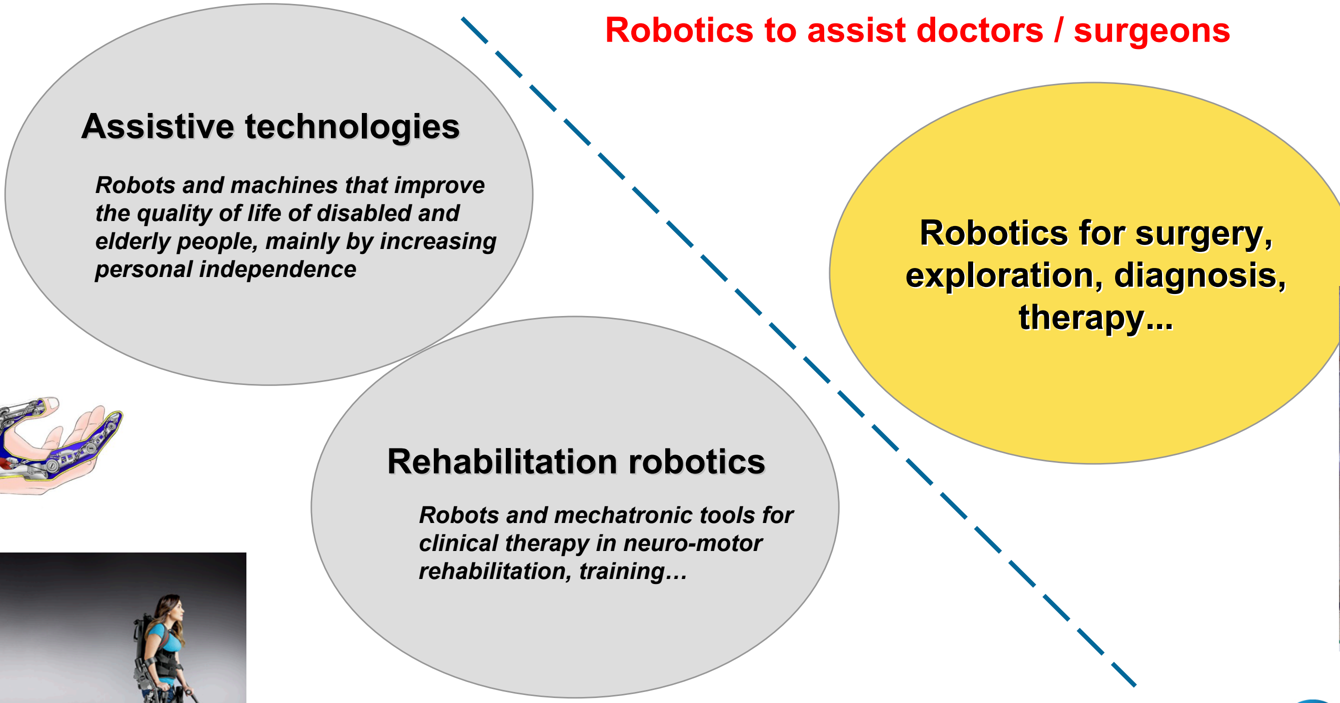
HELSE SØR-ØST

3rd SSSR, E. Dombre, Introduction to Surgical Robotics (4)

Medical Robotics





Robotics to assist doctors / surgeons

Assistive technologies

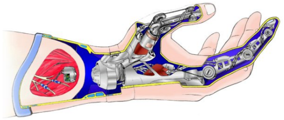
Robots and machines that improve the quality of life of disabled and elderly people, mainly by increasing personal independence

Robotics for surgery, exploration, diagnosis, therapy…

Rehabilitation robotics

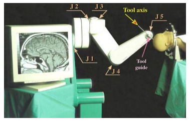
Robots and mechatronic tools for clinical therapy in neuro-motor rehabilitation, training…

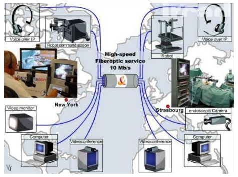
Robotics to assist people



*3rd SSSR, E. Dombre, Introduction to Surgical Robotics

Medical Robotics Timeline





1993:
(MIS)
AESOP 1000
FDA
clearance

1997:
(Neurosurgery)
NeuroMate
FDA clearance

1997:
(MIS)
EndoAssist
FDA clearance

1999:
(MIS)
daVinci
CE marking

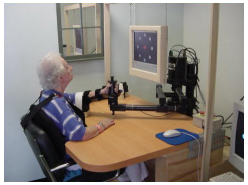
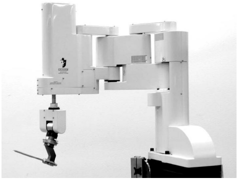
2001:
(MIS)
Operation
Lindbergh

2001:
(Rehabilitation)
Lokomat
CE marking

2003:
(MIS)
LapMan
FDA
clearance

2004:
(Neurosurgery
)
PathFinder
FDA
clearance

| 1990 | 1995 | 2000 | 2005






1994:
(Rehabilitation)
InMotion

1996:
(Orthopedics)
Robodoc
CE marking

1998:
(Assistance)
Care-O-Bot

1998:
(MIS)
ZEUS
CE marking

2000:
(Assistance)
Guido

2002:
(Rehabilitation)
AutoAmbulator
FDA clearance

2002:
(Orthopedics)
Acrobot

2004:
(Rehabilitation)
Paro

2004:
(Orthopedics
SpineAssist
FDA clearance

2006:
(Rehabilitation)
REO Therapy

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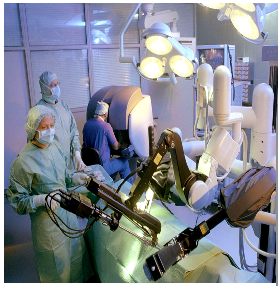
Surgical Robots – degree of autonomy



Da Vinci
(Intuitive
Surgical)

Acrobot
Sculptor
(Acrobot)

AESOP
(computer

Pathfinder
(Prosurgics)

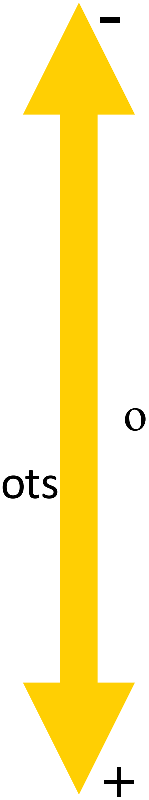
Auxiliary robots

Telesurgical robots

Synergetic Robots

Image-guided surgical robots

Autonomous Robots



Degree
of Autonomy

Automate biopsy (EU:I-SU

Industrial robot - Milling

Robots examples (from ABB)

https://www.youtube.com/watch?v=C5R-FSRBUbE

https://www.youtube.com/watch?v=ZPeaW9x31iw

Innslag på NRK – nett (vår 2015):

http://www.nrk.no/magasin/robotlegene-kommer_-1.12358595

Software/system er lisensiert av MEKTRON fra OUS-IVS og IFI-UIO (Nov 2014)

Mektron skal ta dette produktet ut I markedet sommeren 2017

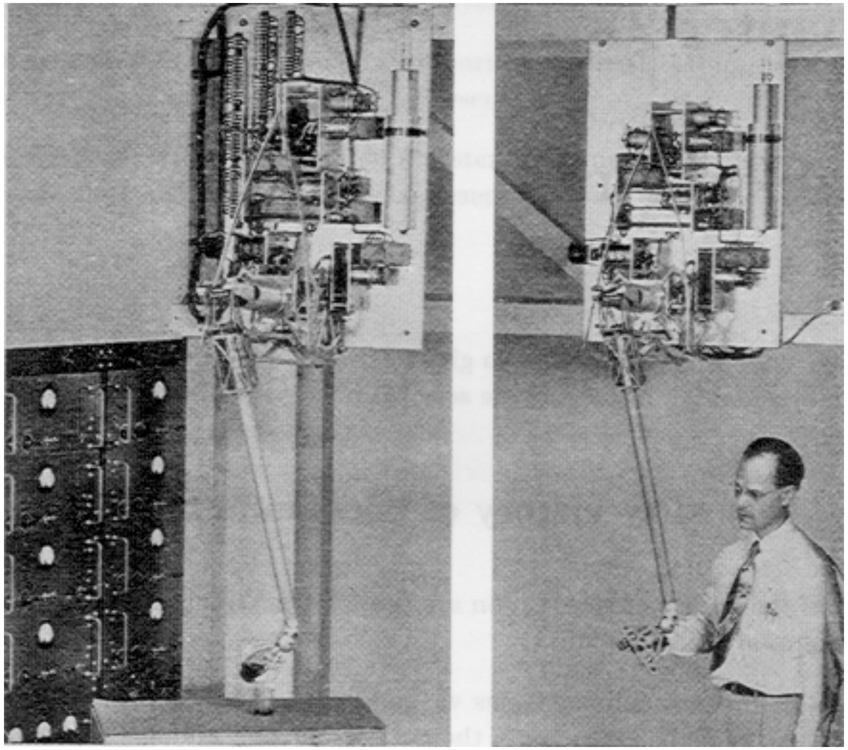
Robots and Telemanipulators – rough categorization

- Industrial robots (Automatic machines)
- Sensor controlled adaptive robots (Autonomous)
- Remote controlled manipulators (Telemanipulators)
- Hybride systems (Semi-autonomous manipulators)
- Micro/Nano-robots

Robots

- Automatic task execution with pre-programmed trajectory
- Accurate and fast
- Sensor control (e.g. Vision and contact sensors)
- Used for repetitive or heavy tasks in hostile environment

Telemanipulator



- The first mechanical master-slave manipulator was developed in 1948 by a group at Argome National Laboratory, USA, led by Ray Goertz (1).
- The same group was the first to develop a bilateral electrical system in 1954 (2).

Underwater Manipulators

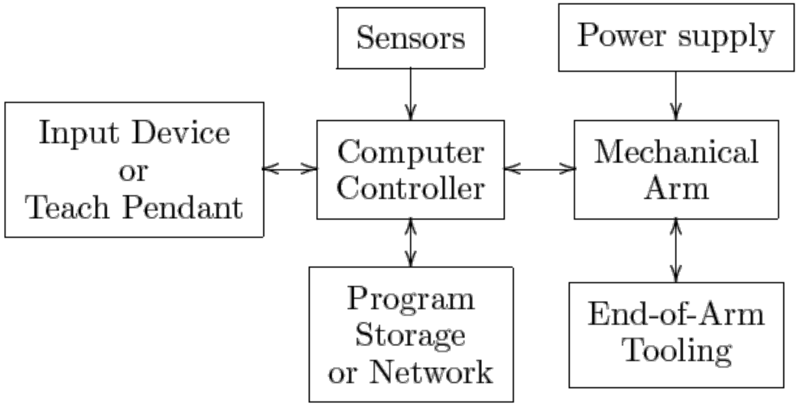
- Remote controlled from an operator control unit
- Autonomous and semi-autonomous features
- Flexible
- Force feedback

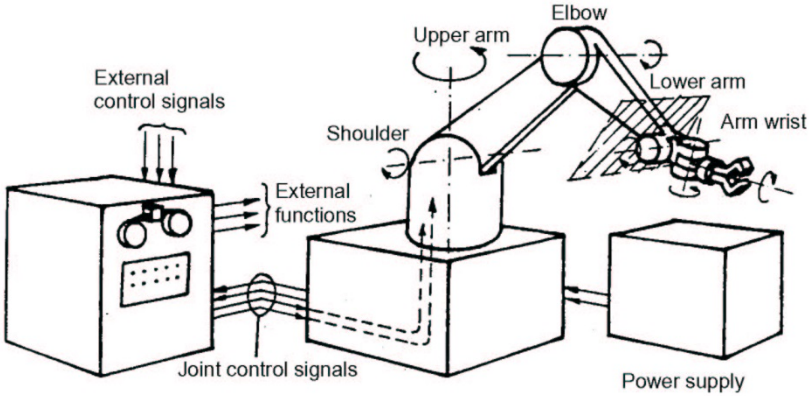
Industrial robots

High precision and repetitive tasks

Pick and place, painting, welding etc

Hazardous environments

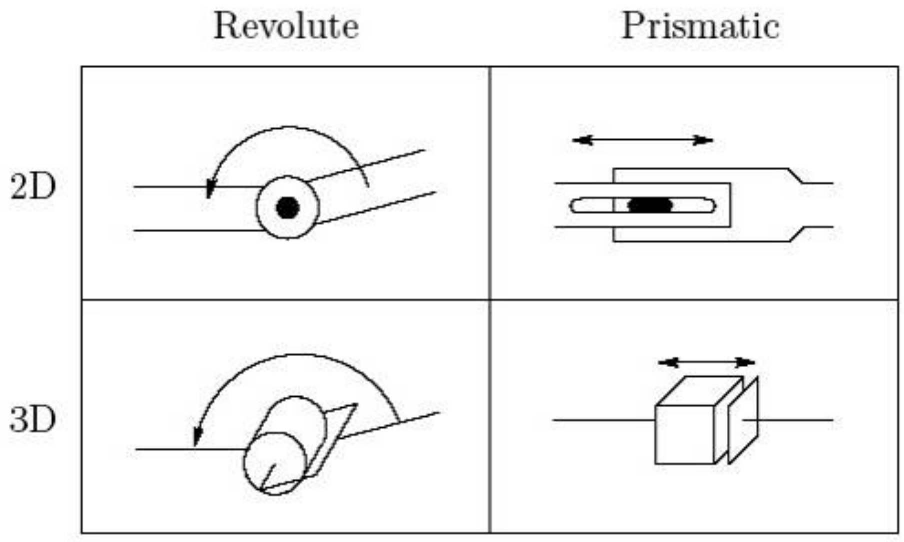


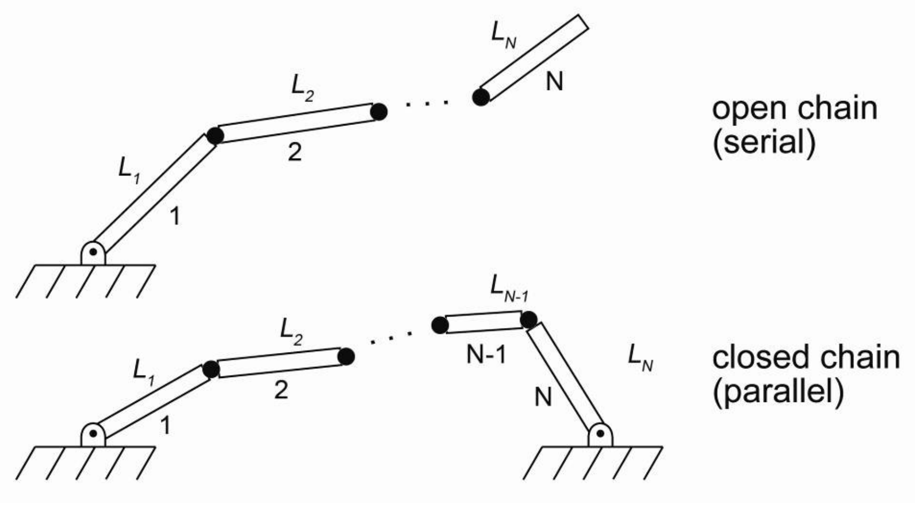


Representations

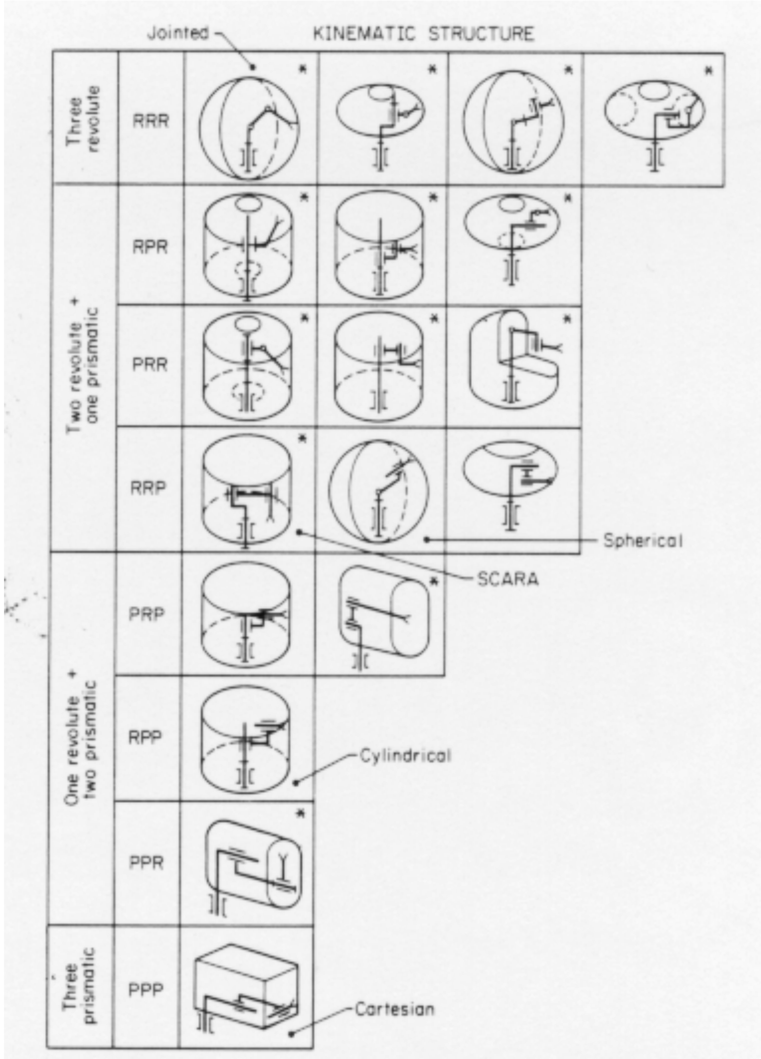
For the majority of this class, we will consider robotic manipulators as open or closed chains of links and joints

Two types of joints: revolute (θ) and prismatic (d)





Arm configurations



The most frequent arm configurations are :

- Open kinematic chains :
    - Jointed articulated or anthropomorphic (human-like arms) (RRR)
    - Spherical (RRP)
    - Scara (RRP)
    - Cylindrical (RPP)
    - Cartesian (PPP)
    - Multi-joined (RRRRRR…..) , Redundant configurations
- Closed kinematic chains

Definitions

End-effector/Tool

Device that is in direct contact with the environment. Usually very task-specific

Configuration

Complete specification of every point on a manipulator

set of all possible configurations is the *configuration space*

For rigid links, it is sufficient to specify the configuration space by the joint angles, $q = \begin{bmatrix} q_1 & q_2 & \ldots & q_n \end{bmatrix}^T$

State space

Current configuration (joint positions q) and velocities $\dot{q}$

Work space

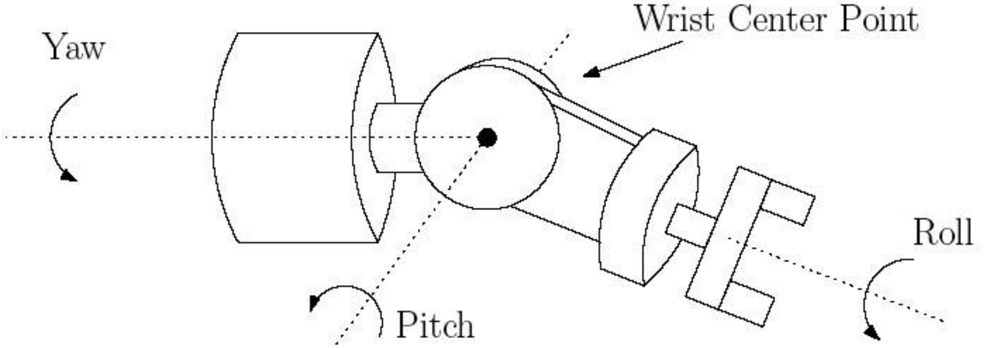
The reachable space the tool can achieve

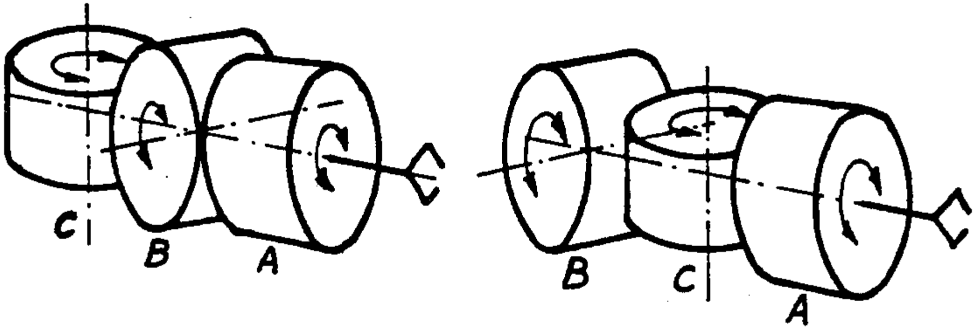
Reachable workspace

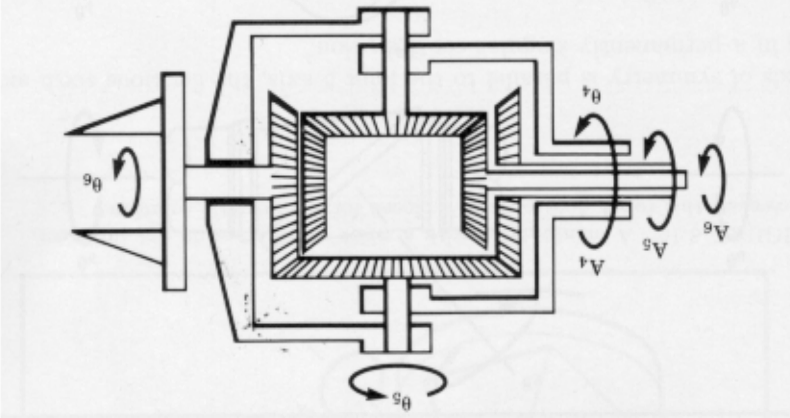
Dextrous workspace

Common configurations: wrists

Many manipulators will be a sequential chain of links and joints forming the ‘arm’ with multiple DOFs concentrated at the ‘wrist’



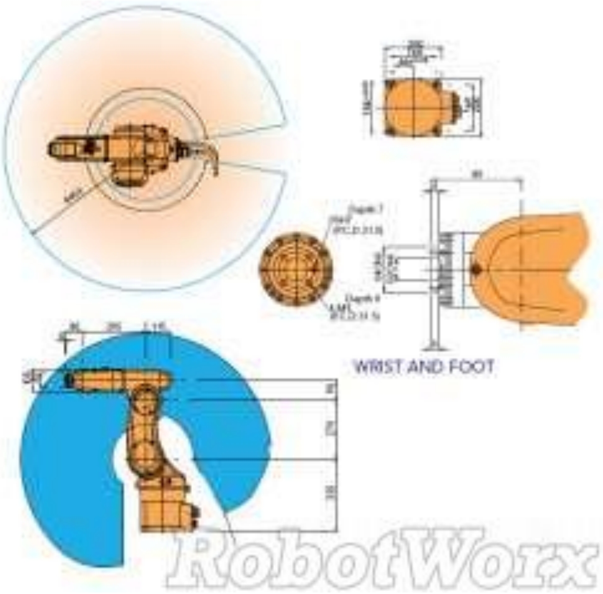




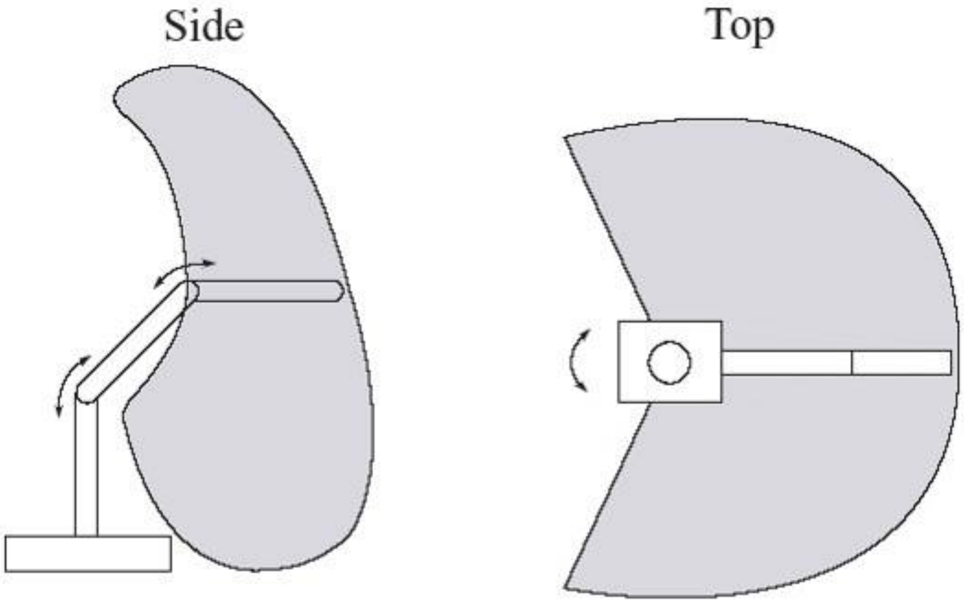
Common configurations: elbow manipulator

Anthropomorphic arm: ABB IRB14000 or KUKA

Very similar to the lab arm NACHI (RRR)

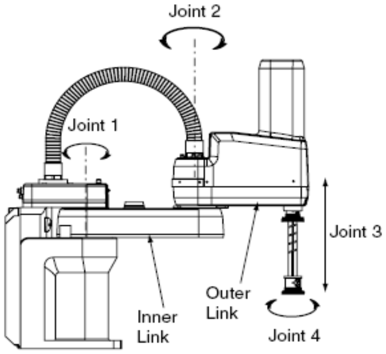


Workspace: elbow manipulator



Common configurations: SCARA (RRP)

Adept Cobra
s600/s800 Robot
User's Guide



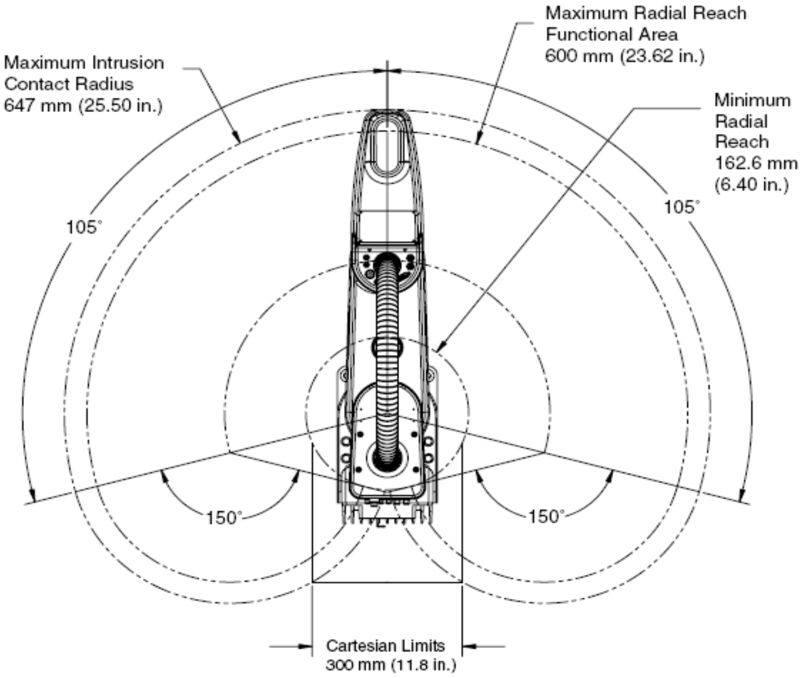


Figure 8-7. Adept Cobra s600 Robot Working Envelope

Common configurations: cylindrical robot (RPP)

workspace forms a cylinder

Seiko RT3300 Robot

Common configurations: Cartesian robot (PPP)

Increased structural rigidity, higher precision

Pick and place operations

Epson Chartesian robot (EZ-modules)

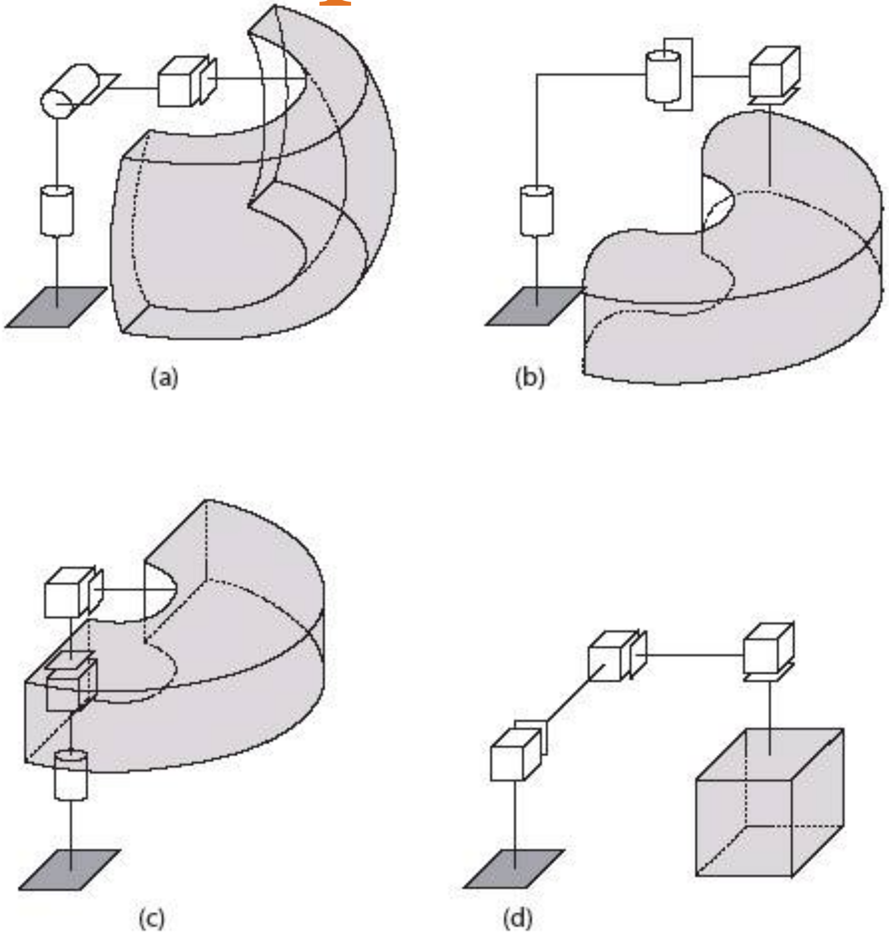
Workspace comparison

(a) spherical

(b) SCARA

(c) cylindrical

(d) Cartesian



Parallel manipulators

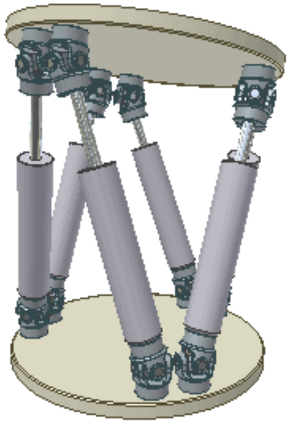
some of the links will form a closed chain with ground

Advantages:

Motors can be proximal: less powerful, higher bandwidth, easier to control

Disadvantages:

Generally less motion, kinematics can be challenging

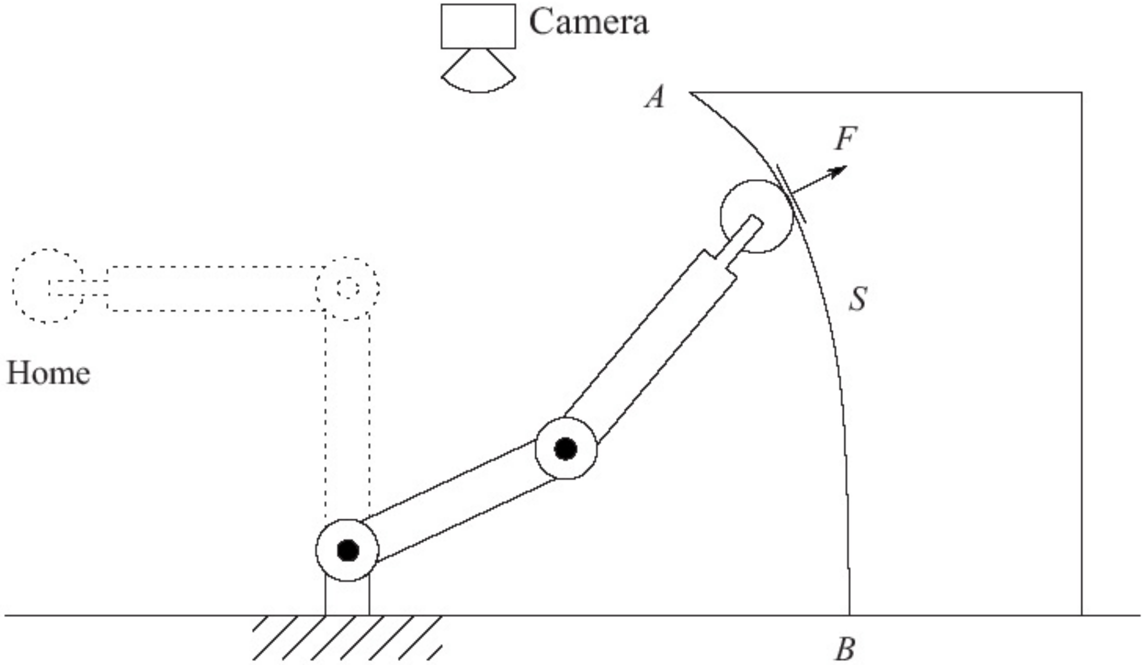


6DOF Stewart platform

ABB IRB940 Tricept

Simple example: control of a 2DOF planar manipulator

Move from ‘home’ position and follow the path AB with a constant contact force *F* all using visual feedback



Coordinate frames & forward kinematics

Three coordinate frames: ⓪ ① ②

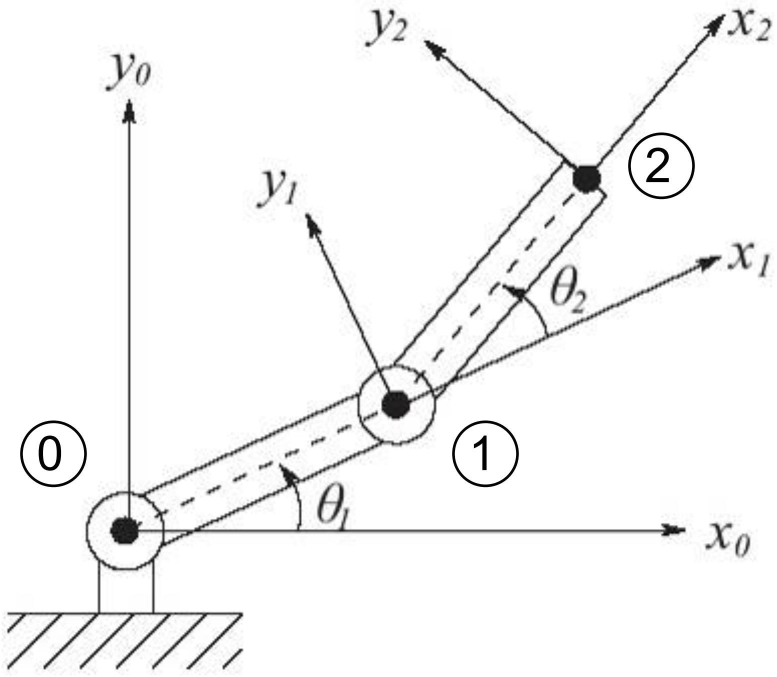
Positions:

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} a_1\cos(\theta_1) \\ a_1\sin(\theta_1) \end{bmatrix}$$

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_1\cos(\theta_1) + a_2\cos(\theta_1+\theta_2) \\ a_1\sin(\theta_1) + a_2\sin(\theta_1+\theta_2) \end{bmatrix} \equiv \begin{bmatrix} x \\ y \end{bmatrix}_t$$

$$\hat{x}_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \hat{y}_0 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Orientation of the tool frame:

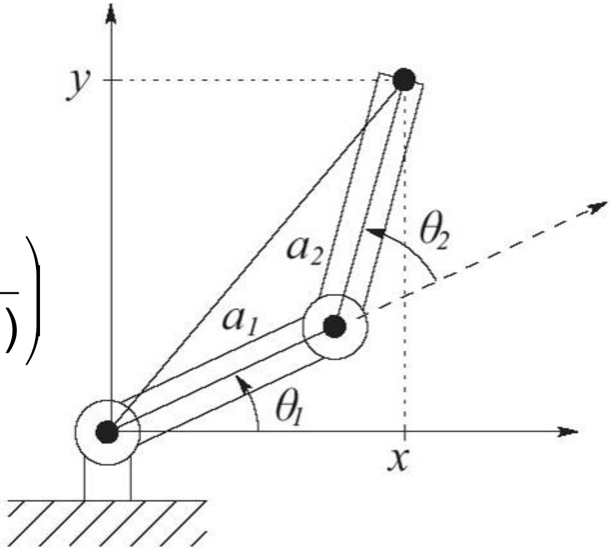


$$\hat{x}_2 = \begin{bmatrix} \cos(\theta_1+\theta_2) \\ \sin(\theta_1+\theta_2) \end{bmatrix}, \hat{y}_2 = \begin{bmatrix} -\sin(\theta_1+\theta_2) \\ \cos(\theta_1+\theta_2) \end{bmatrix}$$

$$R_2^0 = \begin{bmatrix} \hat{x}_2\cdot\hat{x}_0 & \hat{y}_2\cdot\hat{x}_0 \\ \hat{x}_2\cdot\hat{y}_0 & \hat{y}_2\cdot\hat{y}_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) \end{bmatrix}$$

Inverse kinematics

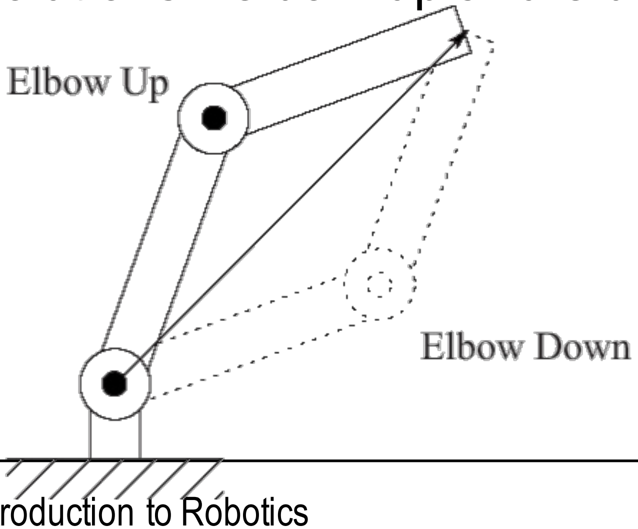
Find the joint angles for a desired tool position



$$\cos(\theta_2) = \frac{x_t^2 + y_t^2 - a_1^2 - a_2^2}{2a_1a_2} \equiv D \Rightarrow \sin(\theta_2) = \pm\sqrt{1-D^2}$$

$$\theta_2 = \tan^{-1}\left(\pm\frac{\sqrt{1-D^2}}{D}\right) \quad \theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{a_2\sin(\theta_2)}{a_1 + a_2\cos(\theta_2)}\right)$$

Two solutions!: elbow up and elbow down



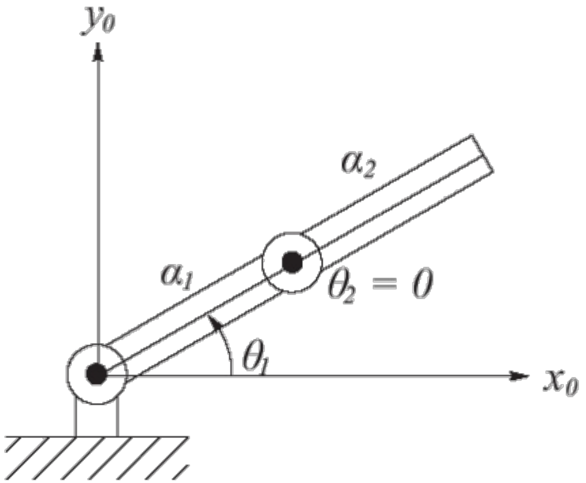
Velocity kinematics: the Jacobian

State space includes velocity

$$\begin{bmatrix}\dot{x}_2\\ \dot{y}_2\end{bmatrix} = \begin{bmatrix} -a_1\sin(\theta_1)\dot{\theta}_1 - a_2\sin(\theta_1+\theta_2)(\dot{\theta}_1+\dot{\theta}_2)\\ a_1\cos(\theta_1)\dot{\theta}_1 + a_2\cos(\theta_1+\theta_2)(\dot{\theta}_1+\dot{\theta}_2)\end{bmatrix}$$

$$= \begin{bmatrix} -a_1\sin(\theta_1) - a_2\sin(\theta_1+\theta_2) & -a_2\sin(\theta_1+\theta_2)\\ a_1\cos(\theta_1) + a_2\cos(\theta_1+\theta_2) & a_2\cos(\theta_1+\theta_2)\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\end{bmatrix}$$

$$= J\dot{\vec{q}}$$



Inverse of Jacobian gives the joint velocities:

$$\dot{\vec{q}} = J^{-1}\dot{\vec{x}}$$

$$= \frac{1}{a_1 a_2\sin(\theta_2)}\begin{bmatrix} a_2\cos(\theta_1+\theta_2) & a_2\sin(\theta_1+\theta_2)\\ -a_1\cos(\theta_1) - a_2\cos(\theta_1+\theta_2) & -a_1\sin(\theta_1) - a_1\sin(\theta_1+\theta_2)\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\end{bmatrix}$$

This inverse does not exist when θ_2 = 0 or π, called singular configuration or singularity

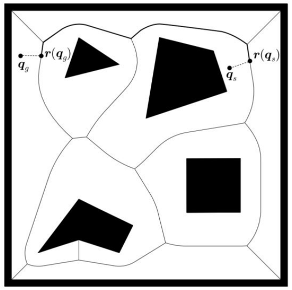
Path planning

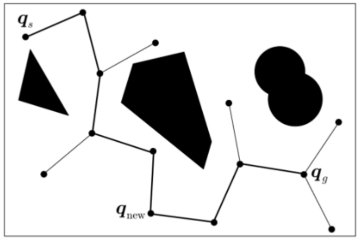
In general, move tool from position A to position B while avoiding singularities and collisions

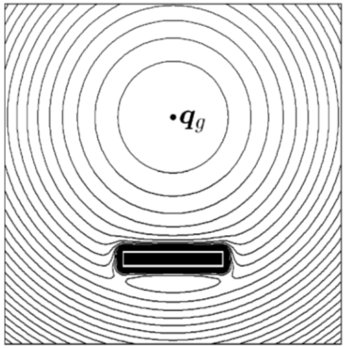
This generates a path in the work space which can be used to solve for joint angles as a function of time (usually polynomials)

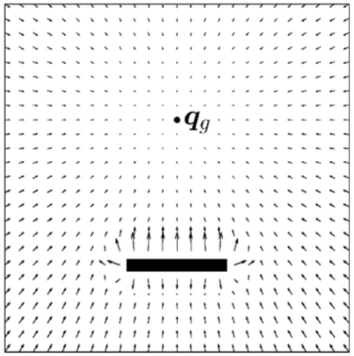
Many methods

Can apply to mobile agents or a manipulator configuration





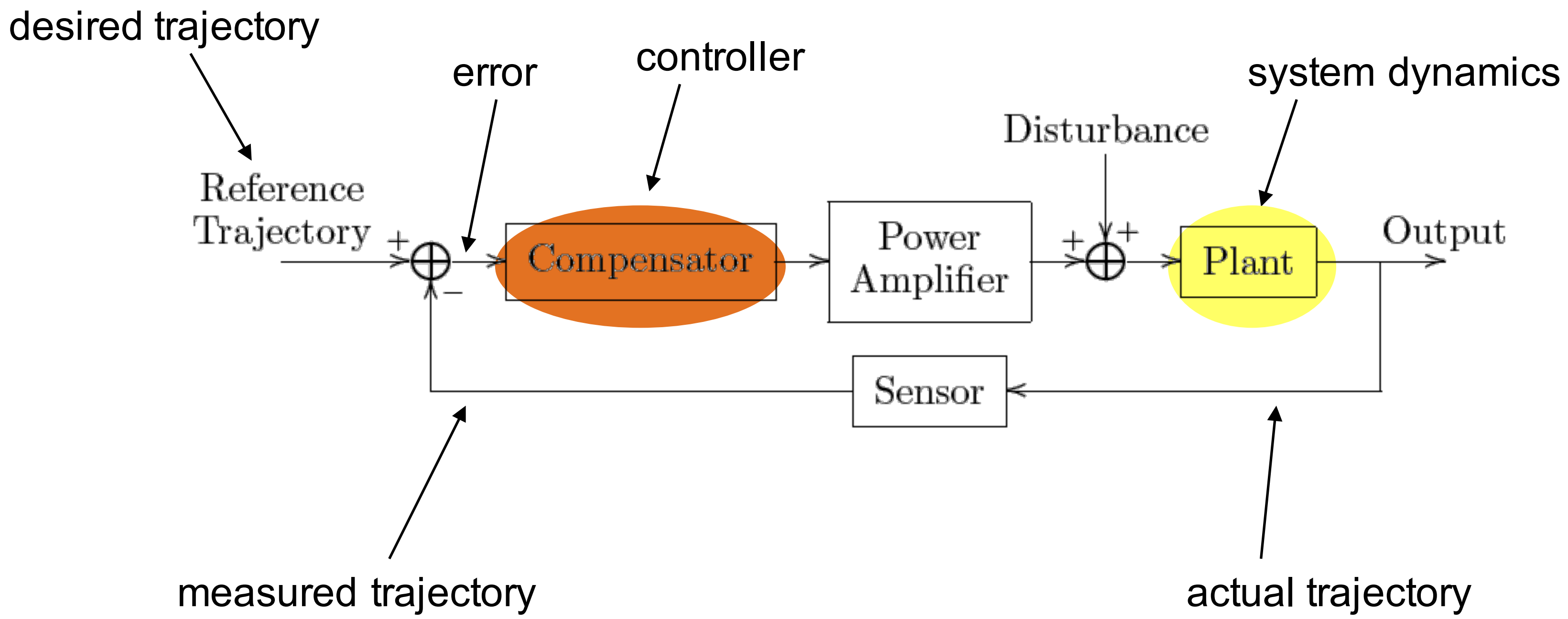




Joint control

Once a path is generated, we can create a desired tool path/velocity

Use inverse kinematics and Jacobian to create desired joint trajectories



Other control methods

Force control or impedance control (or a hybrid of both)

- Requires force/torque sensor on the end-effector

Visual servoing

- Using visual cues to attain local or global pose information

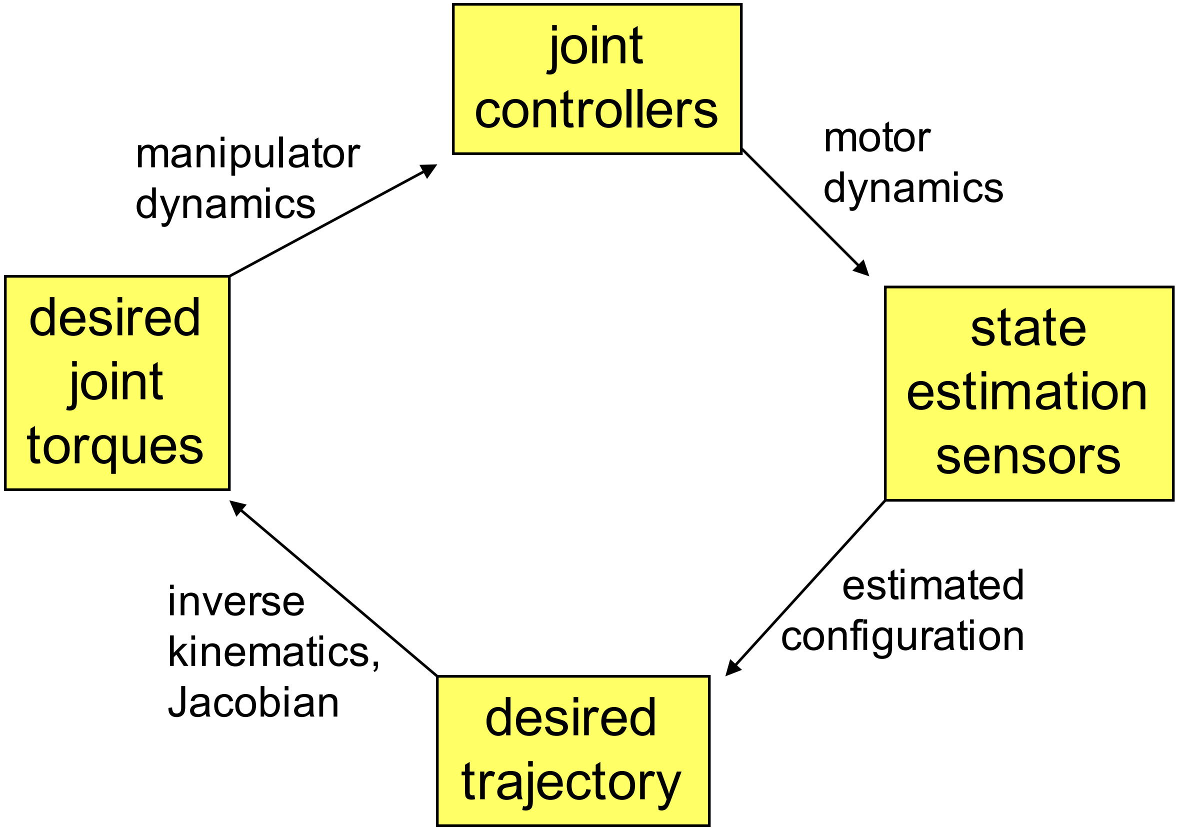
Common controller architectures:

- PID
- Adaptive

Challenges:

- nonlinearity

General multivariable control overview


joint controllers

motor dynamics

state estimation sensors

estimated configuration

desired trajectory

inverse kinematics, Jacobian

desired joint torques

manipulator dynamics

Industrial robot Kuka modofoed for medical use with x-ray (fluoroscopy)

Sensors and actuators

Sensors

- Motor encoders (internal)
- IMU - Inertial Measurement Unit
- Vision (external)
- Contact and force sensors

Motors/actuators

- Electromagnetic
- Pneumatic/hydraulic
- Electroactive
  - Electrostatic
  - Piezoelectric

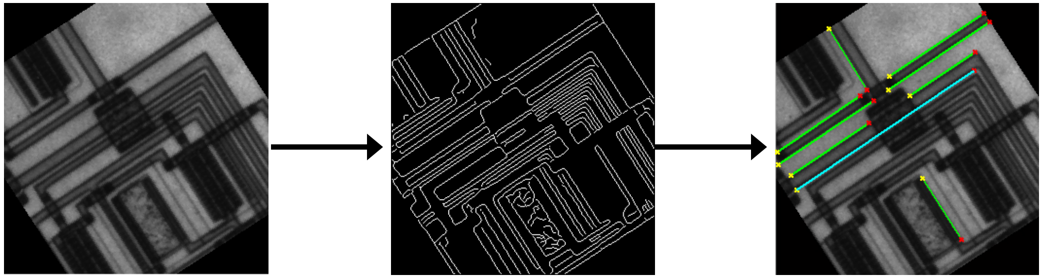
Basic quantities for both:

- Bandwidth
- Dynamic range
- sensitivity

Computer Vision

Simplest form: estimating the position and orientation of yourself or object in your environment using visual cues

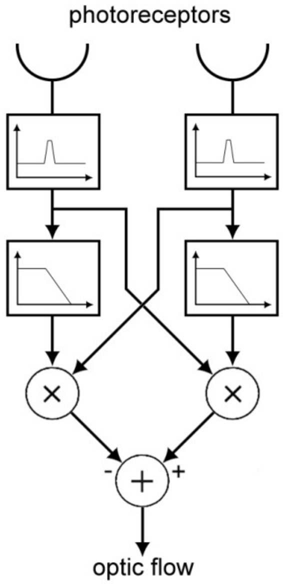
- Usually a statistical process
- Ex: finding lines using the Hough space



More complex: guessing what the object in your environment are

Biomimetic computer vision: how do animals accomplish these tasks:

- Obstacle avoidance
  - Optical flow?
- Object recognition
  - Template matching?



MEMS and Microrobotics

Difficult definition(s):

- Robotic systems with feature sizes < 1mm
- Robotic systems dominated by micro-scale physics

MEMS: Micro ElectroMechanical Systems

- Modified IC processes to use ‘silicon as a mechanical material’

Robotic surgery

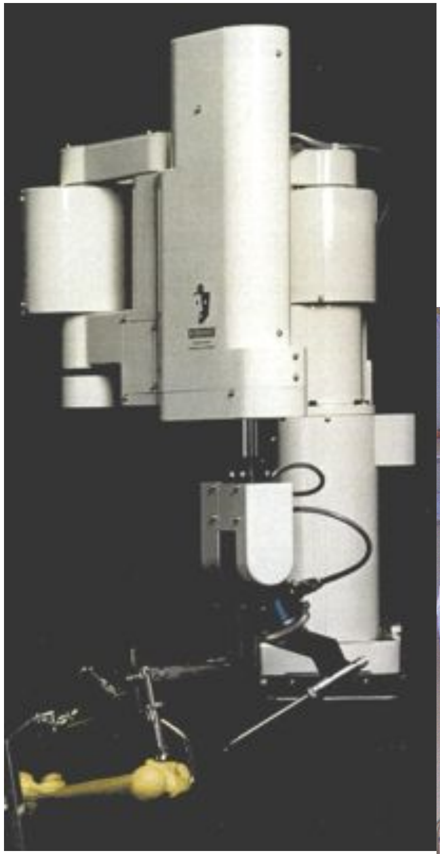
- At the present state of the art, robotic technology for surgical applications can broadly be divided into four main classes
  - Image-guided surgical robots (industrial robots)
  - Surgical telemanipulators (Remote controlled manipulators)
  - Assisting manipulators (Remote controlled manipulators)
  - Mikro-/nanorobots

Robotic surgery

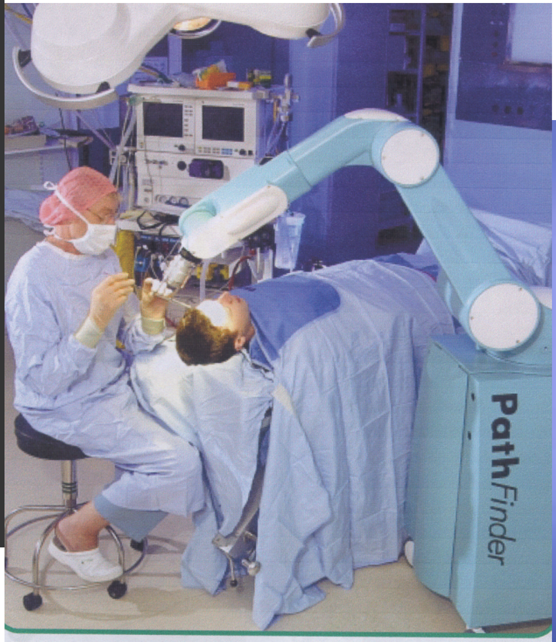
- Image guided with preprogrammed path
  - Caspar
  - Robodoc
  - NeuroMate
  - PathFinder from Armstrong HealthCare
- Remoteoperated- or Teleoperated manipulators
  - The Fraunhover Neuro robot
  - Da Vinci from Intuitive Surgical
  - Zeus Microsurgical system from ComputerMotion
  - Aesop from ComputerMotion
  - EndoAssist from Armstrong HealthCare

Image-guided robots

ROBODOC –
Integrated Surgical Systems Inc.



PathFinder –
Armstrong HealthCare Lmt.

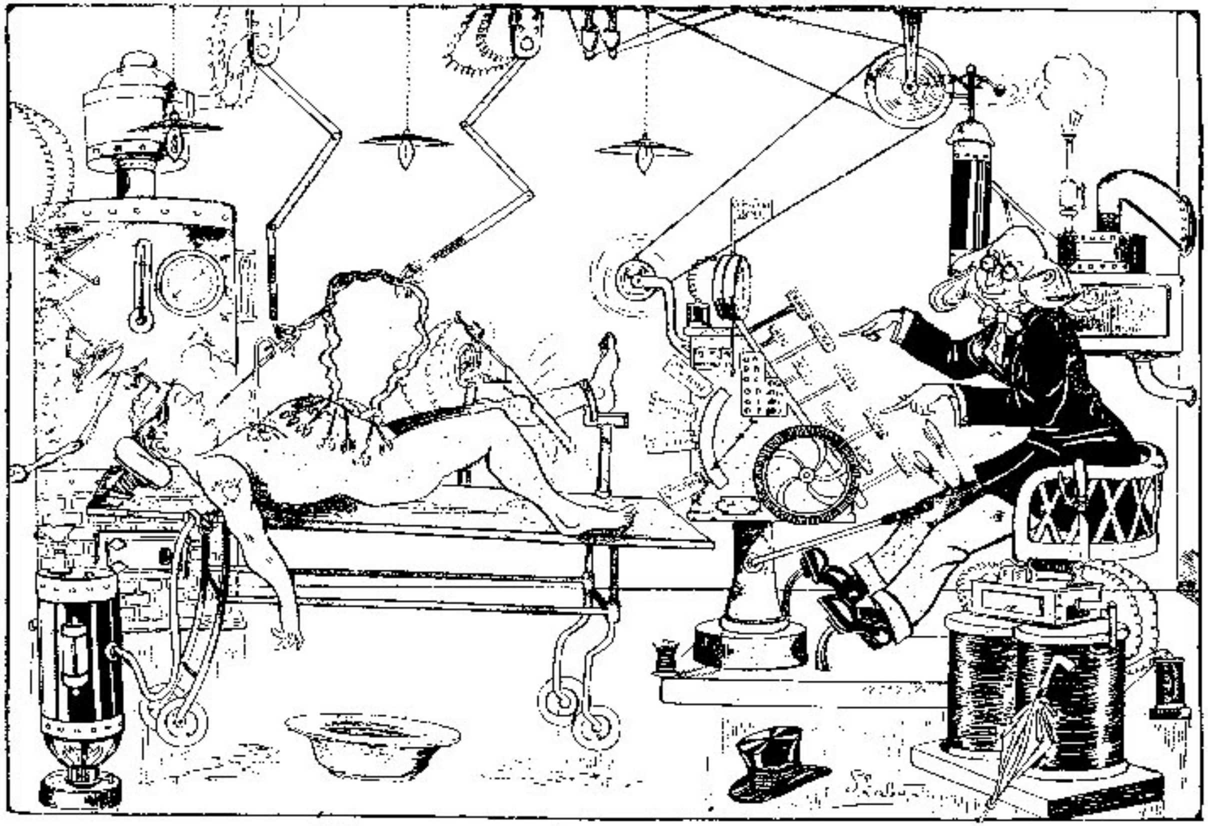


CASPAR - Maquet

Robotic surgery - Advantages

- High accuracy
- Automatic task execution
- Movement compensation
- Guide for tool positioning in 3D-environment using optical navigation or image guidance
- Automatic alignment of tool based on sensor information

A French comic drawing from 1914 showing how the artist envisioned the operating room of year 2000



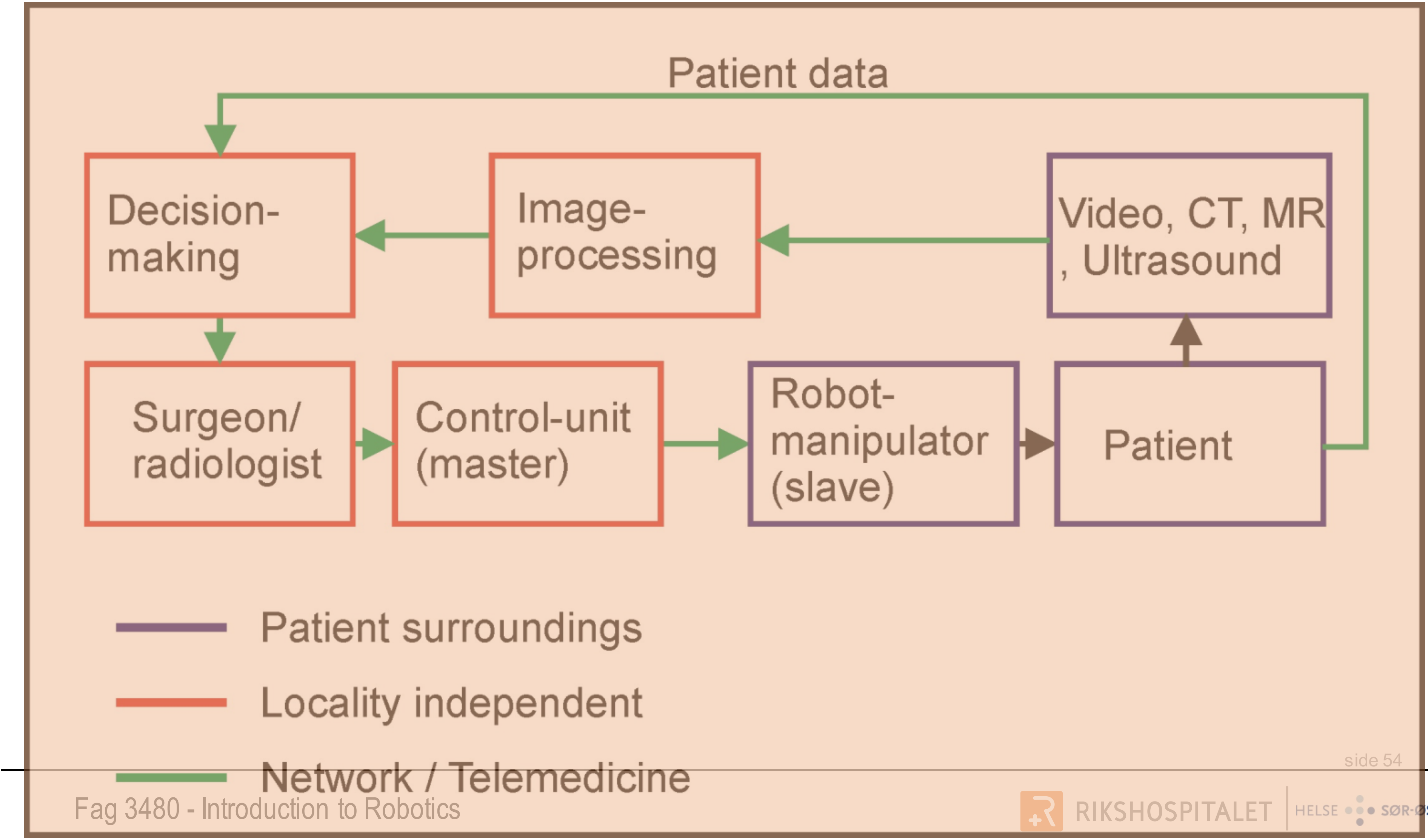
UNE SALLE D'OPÉRATIONS EN L'AN 2000

Surgical telemanipulators

Zeus-
ComputerMotion Inc.

DaVinci-
Intuitive Surgical Inc.

Control loop - Tele manipulation



Patient data

Decision-making

Image-processing

Video, CT, MR, Ultrasound

Surgeon/ radiologist

Control-unit (master)

Robot-manipulator (slave)

Patient

- 🟪 Patient surroundings
- 🟥 Locality independent
- 🟩 Network / Telemedicine

Tele-manipulation in surgery - Advantages

- Higher accuracy - Scaling of operator movements
- Elimination of tremor
- Improved dexterity - Computer controlled dexterity of instruments inside the body
- “Converts” keyhole surgery to open technique (instrument tip control)
- Improved Ergonomics

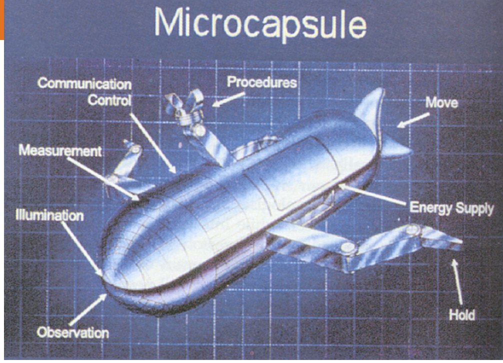
Surgical robotics

Minimally invasive surgery

- Minimize trauma to the patient
- Potentially increase surgeon’s capabilities
- Force feedback necessary, tactile feedback desirable

Future robots - Micro

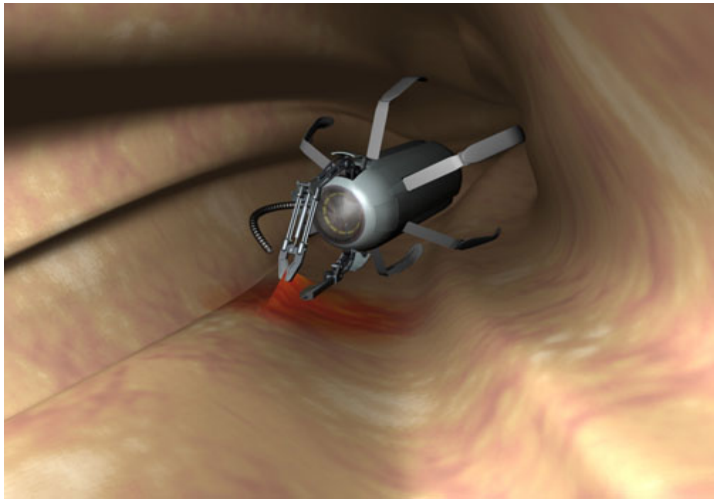
- Automated systems with artificial intelligence
- Miniatyrized telemanipulators
- Cross-linked with medical information

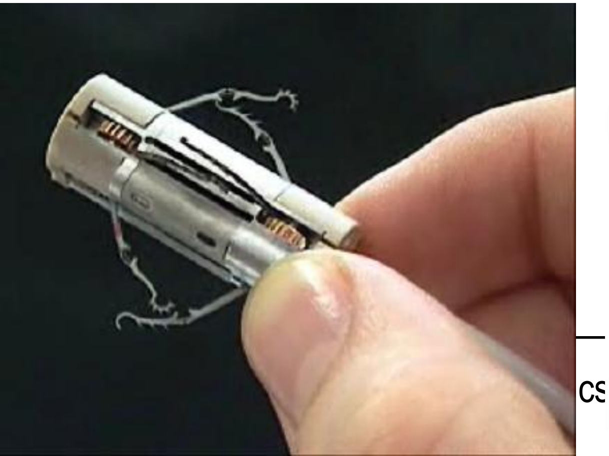


Olympus trawing board, 1997

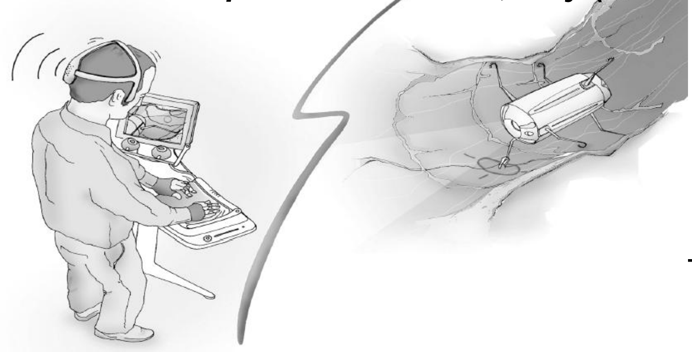
2001: Capsule endoscopy

VECTOR-Versatile Endoscopic Capsule for gastrointestinal TumOr Recognition





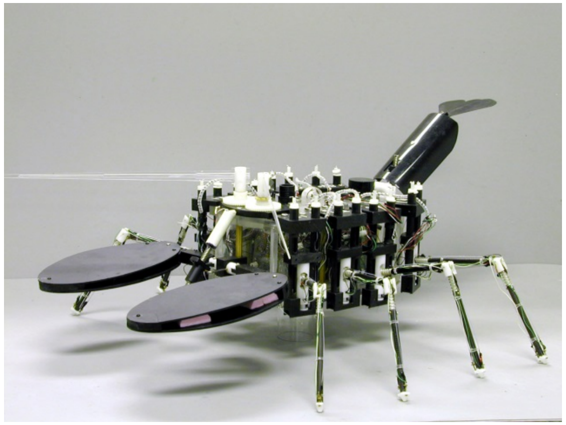
Tele-operated Endoscopic Capsule with Active Locomotion
Scuola Superiore Sant'Anna, Italy (research project)

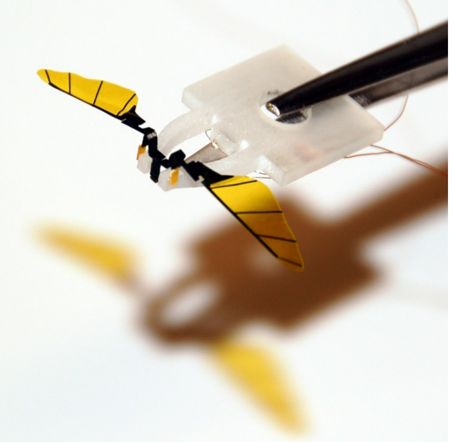


Biomimetic Robots

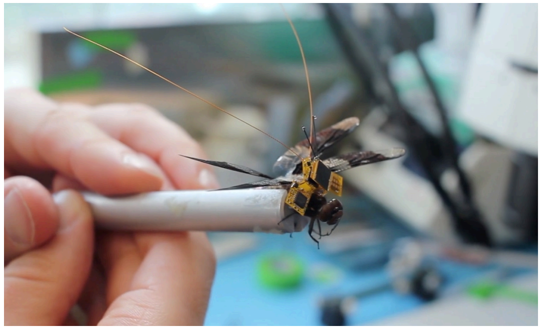
Using biological principles to reduce design space

Lobster robot from Northeastern University





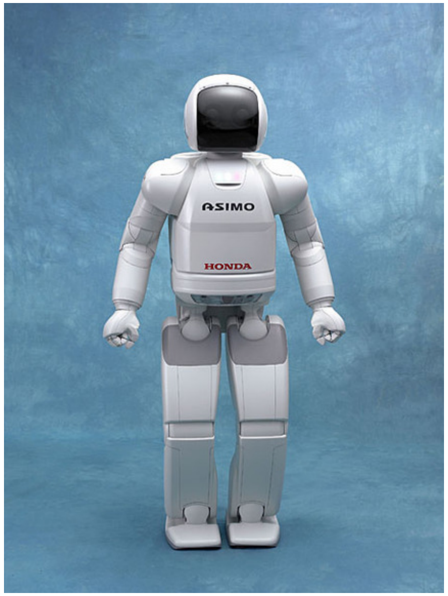
MFI; Harvard & Berkeley



Cyborg DragonflEye

Humanoid robots

For robots to efficiently interact with humans, should they be anthropomorphic to replicate humans natural movements.



Honda's entry into the humanoid robot race, ASIMO is an acronym that stands for Advanced Step in Innovative MObility. Honda claims that the robot's name is not a reference to noted science fiction writer Isaac Asimov, who also wrote about robotics. The current model is the result of decades of research that began in 1986. ASIMO's special abilities include the capacity to walk smoothly, run, climb stairs, communicate, and recognize people's voices and faces.

Different robots from ABB

Next classes...

Rotation matrices and Homogeneous transforms as the basis for forward and inverse kinematics

Come talk to me if you have questions or concerns!

RIKSHOSPITALET

Universitetssykehuset Rikshospitalet HF eies av Helse Sør-Øst RHF og består av Rikshospitalet, Radiumhospitalet, Epilepsisenteret-SSE og Spesialsykehuset for rehabilitering.

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