Introduction to Robotics (INF3480/INF4380)

Spring 2018

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Personnel

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Gruppelærere:

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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 (INF3480 - spring 2018)

Undervisning - tid og sted (INF3480/INF4380 - vår 2018)

Forelesninger

Torsdag kl. 12:15 -14:00, KN Lille Auditorium, Ole-Johan Dahls hus
Undervisningsplan ligger på nettet, se timeplan

Ole Jakob Elle

Gruppetimer

Gruppe 1

Tirsdag kl. 10:15 -12:00, Sem.rom Pascal, Ole-Johan Dahls hus

Gruppe 2

Mandag kl. 10:15 -12:00, Sem.rom Pascal, Ole-Johan Dahls hus

Three Compulsory exercises (Obliger):

Exercise 1: Handed out 01.02, Deadline 22.02

Exercise 2: Handed out 01.03, Deadline 22.03

Exercise 3: Handed out 05.04, Deadline 03.05?

The last lecture will be held 24th of May.

Discussion forum – Slack: https://inf34804380robotics.herokuapp.com

INF3480 – Introduction to Robotics

- Tre obligatoriske øvinger

  1,2: Kinematisk modellering : Sette opp kinematisk modell for en gitt robot og implementere dette i MatLab/Python.

  3: Implementering og styring av en minirobot : Benytte den implementerte kinematiske modellen, og dynamikken som grunnlag for å styre roboten.

- Tema for øvingene
  - Forover og inverskinematikk
  - Hastighetskinematikk
  - Leddstyring
  - Dynamikk
  - (Manipulering/bevegelsesstyring)
  - Robot control – Reguleringsteknikk

Forelesningsplan

Forelesningsplan (tentativ):

18.01.18	Forelesning 1:	Introduction
25.01.18	Forelesning 2:	Rigid Body Motions and Homgenus Tranforms
01.02.18	Forelesning 3:	Forward Kinematics
08.02.18	Forelesning 4:	Inverse Kinematics
15.02.18	Forelesning 5:	Inverse Kinematics
22.02.18	Forelesning 6:	Jacobian
01.03.18	Forelesning 7:	Jacobian
08.03.18	Forelesning 8:	Dynamics
15.03.18	Forelesning 9:	Dynamics
22.03.18	Forelesning 10:	Control Theory
05.04.18	Forelesning 11:	Control Theory
12.04.18	Forelesning 12:	Robot Operating System (ROS)
19.04.18	Forelesning 13:	Robot Operating System (ROS)
26.04.18	Forelesning 14:	Evolutionary Robotics & Tour @ Robin
03.05.18	Forelesning 15:	Guest Lecture
24.05.18	Forelesning 16:	Revision

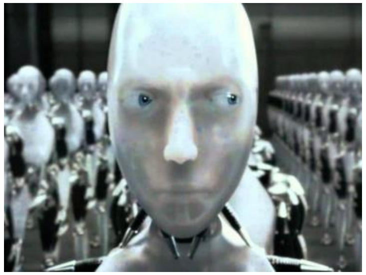
Introduction

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

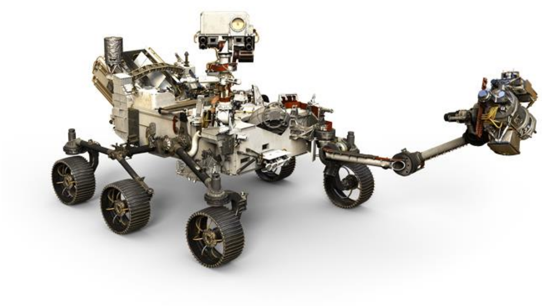
Commercial/Social

- Household chores
- Toys
- Educational

Military

Planetary Exploration

- Mars rover



Undersea exploration

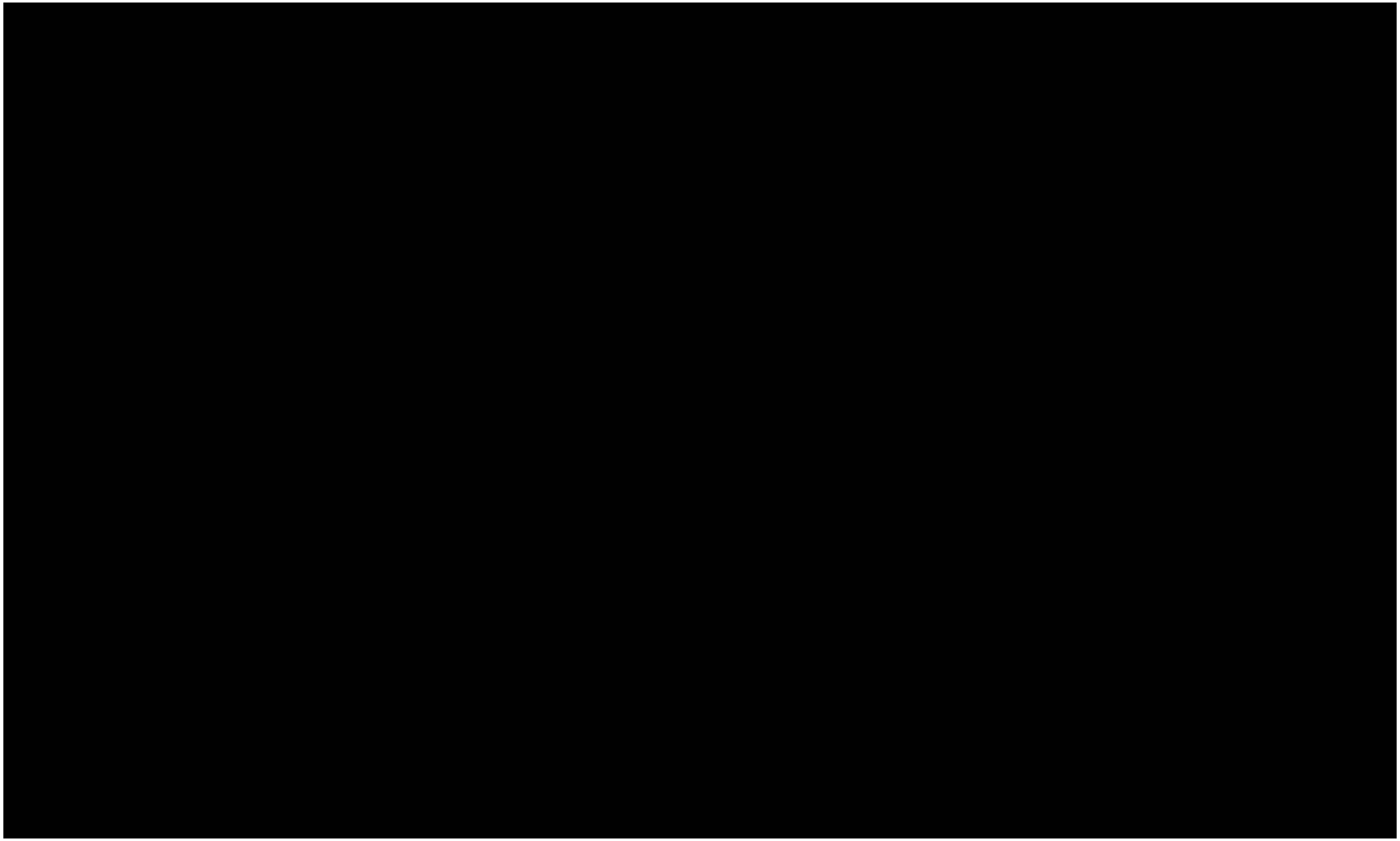
Medical

- Robot-assisted surgery

Industrial robot - Milling

RIKSHOSPITALET HELSE SØR-ØST

MR-kompatibel Neuro-robot



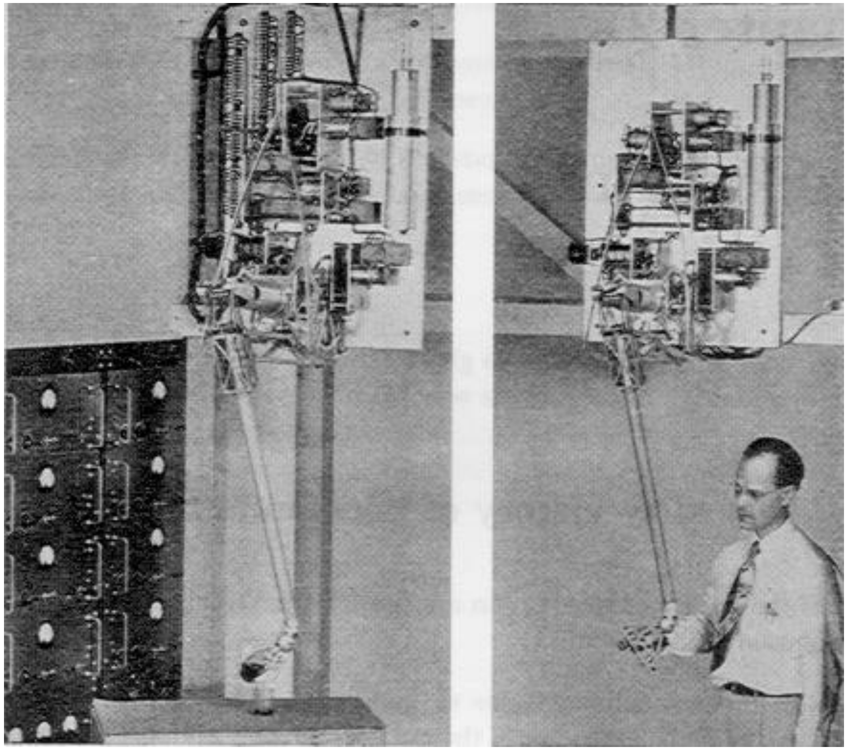
Robots and Telemanipulators – rough categorization

- 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

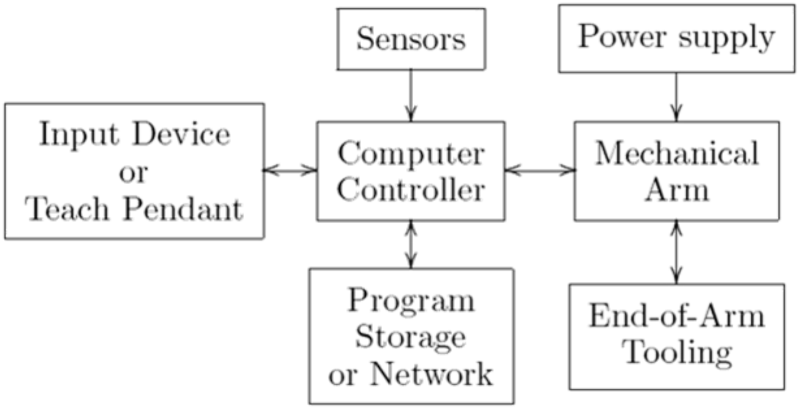
- Remote controlled from an operator control unit
- Autonomous and semi-autonomous features
- Flexible
- Force feedback

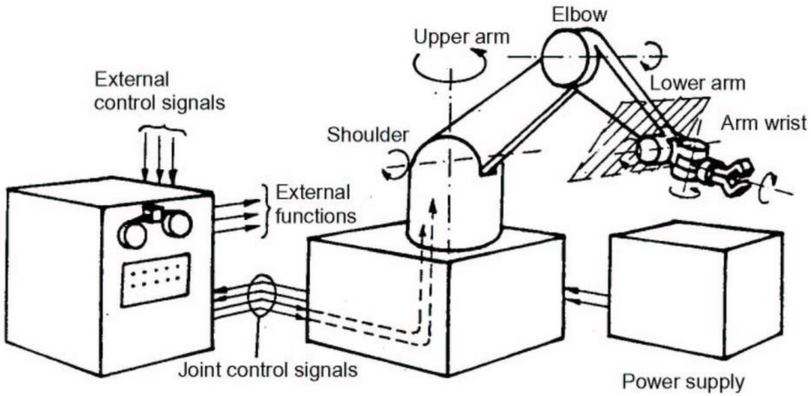
Industrial robots

High precision and repetitive tasks

- Pick and place, painting, welding etc

Hazardous environments

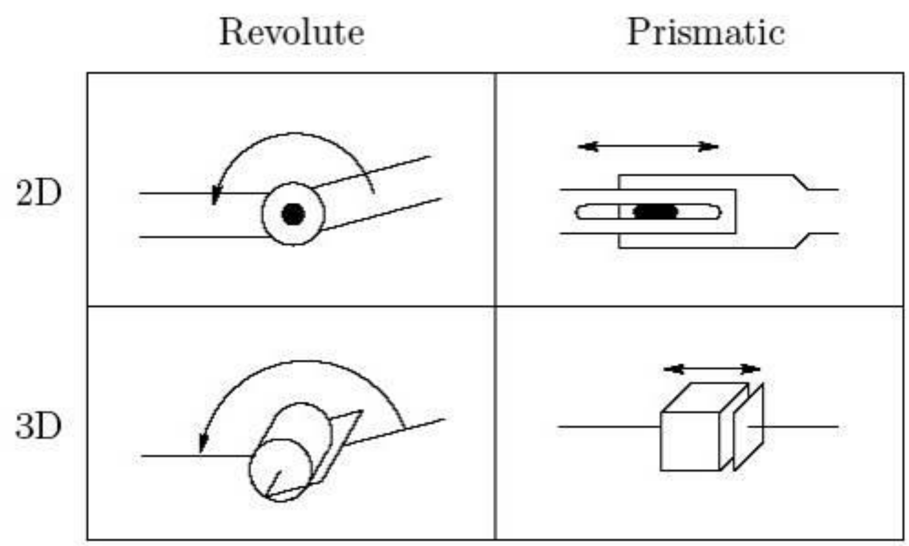


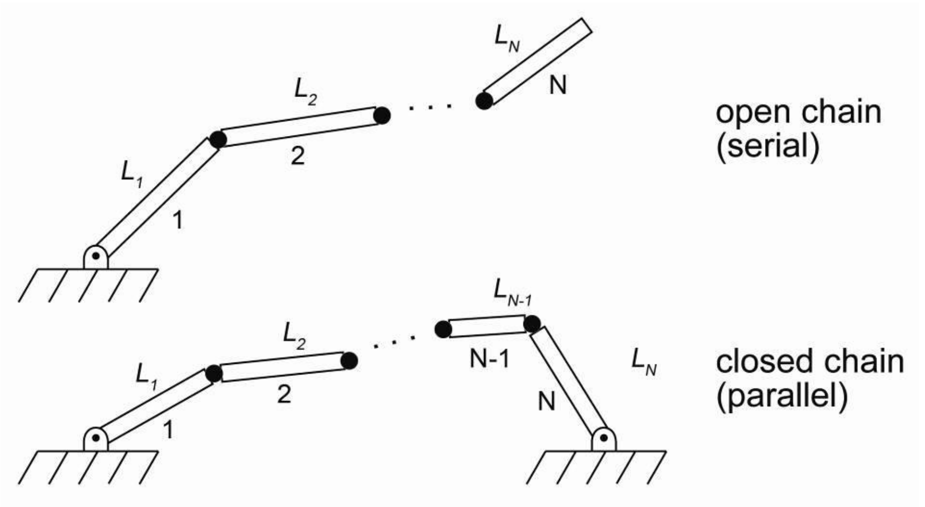


Representations

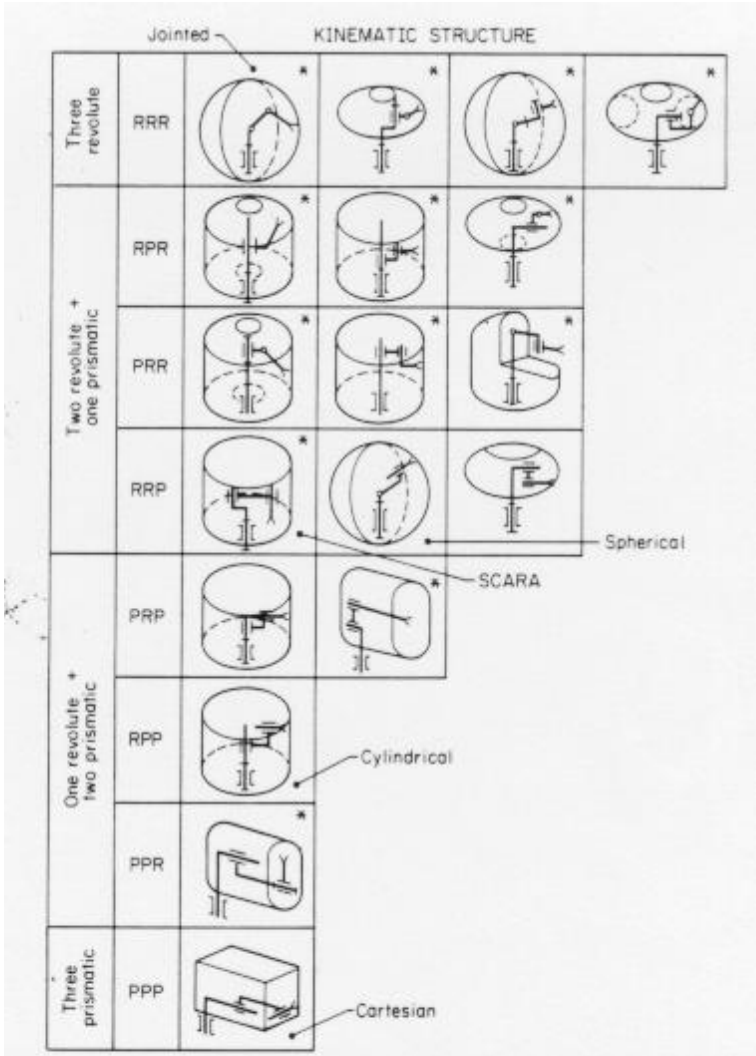
For the majority of this class, we will consider robotic manipulators as open or closed chains of links and joints

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, $q = [q_1 \quad q_2 \quad \dots \quad q_n]^T$

State space

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

Work space

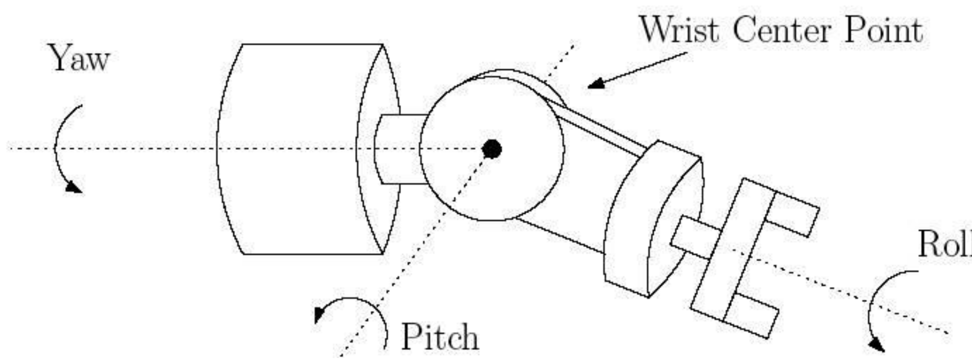
The reachable space the tool can achieve

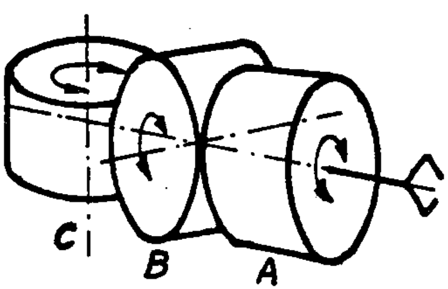
Reachable workspace

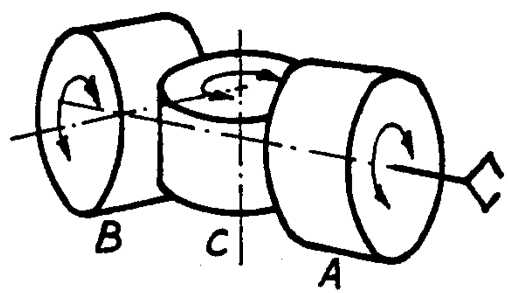
Dextrous workspace

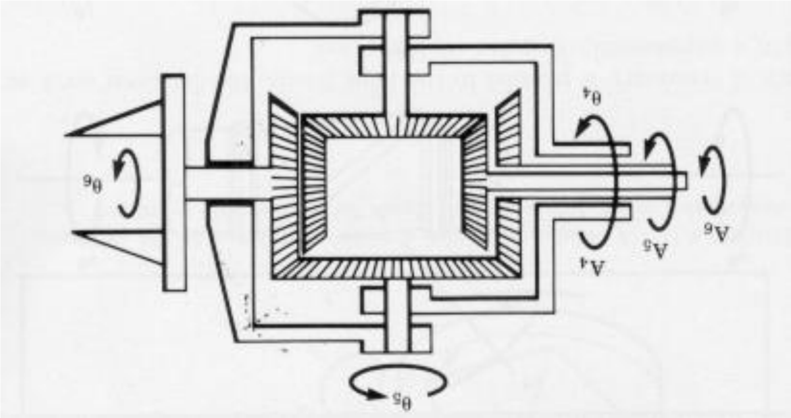
Common configurations: wrists

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





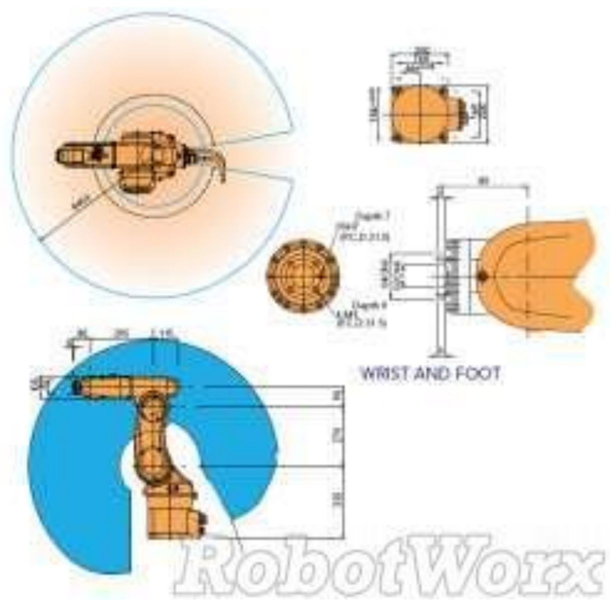




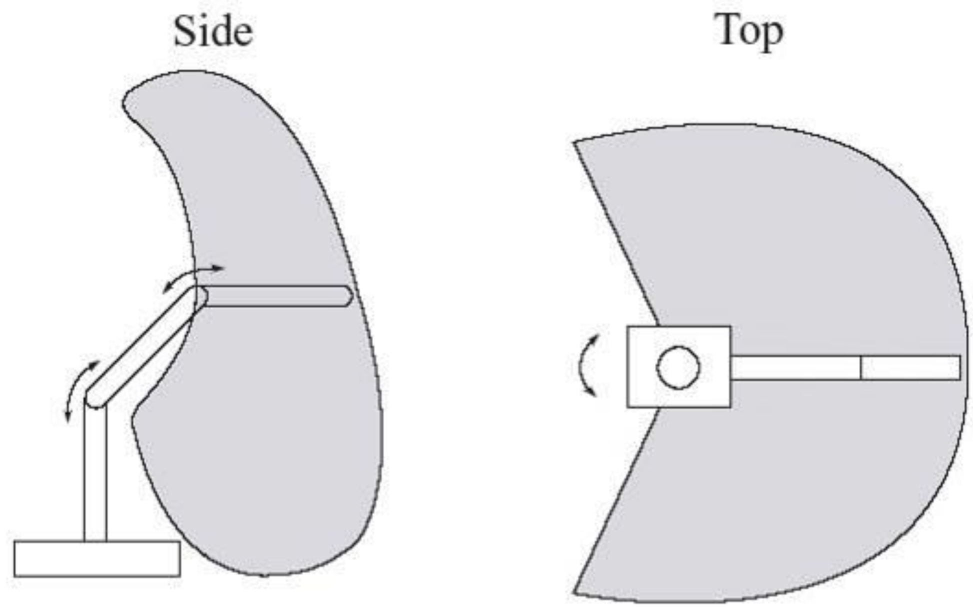
Common configurations: elbow manipulator

Anthropomorphic arm: ABB IRB14000 or KUKA

Very similar to the lab arm NACHI (RRR)

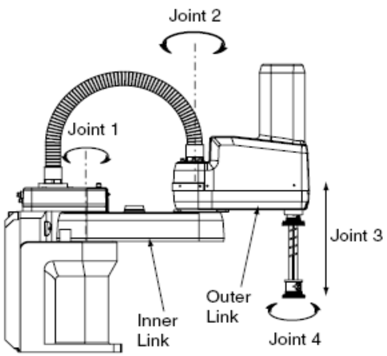


Workspace: elbow manipulator



Common configurations: SCARA (RRP)

Adept Cobra s600/s800 Robot
User's Guide



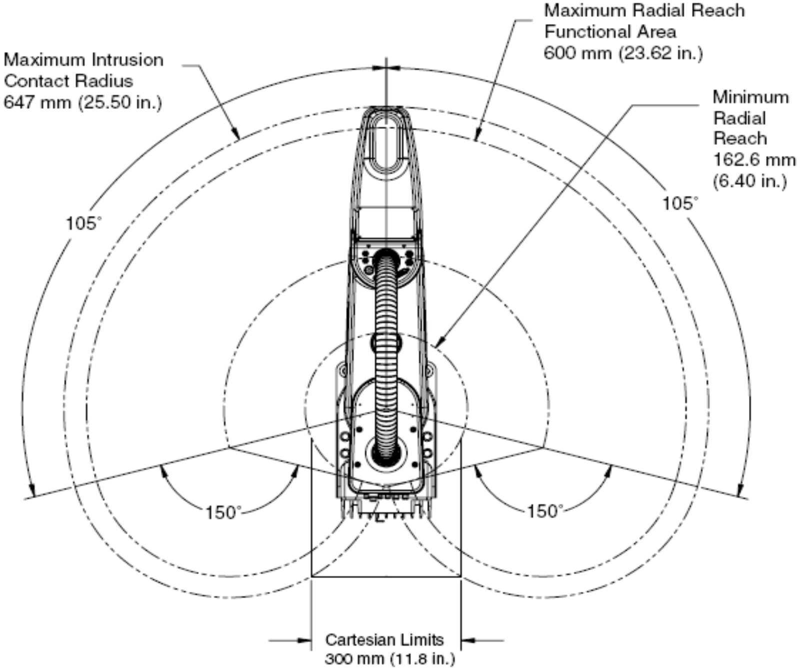


Figure 8-7. Adept Cobra s600 Robot Working Envelope

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)

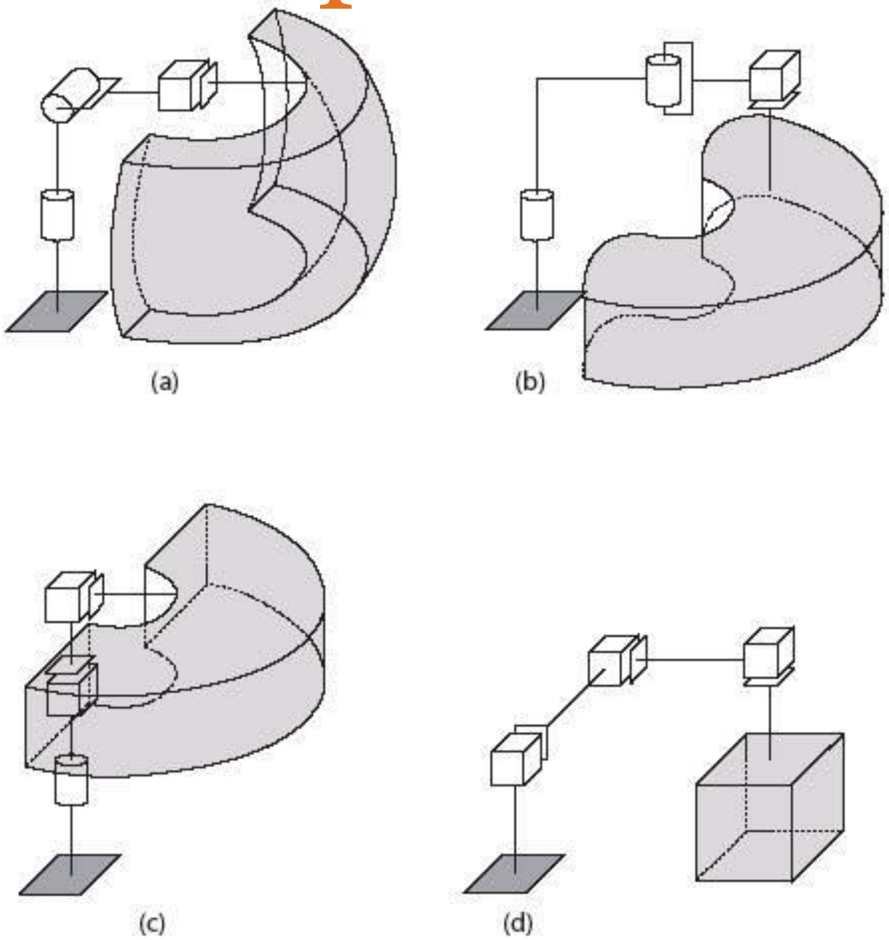
Workspace comparison

(a) spherical

(b) SCARA

(c) cylindrical

(d) Cartesian



Parallel manipulators

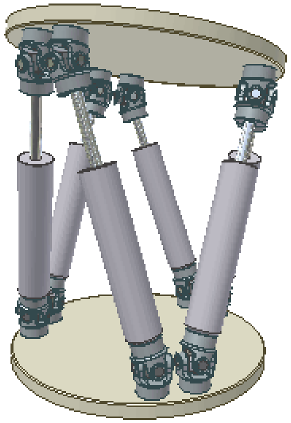
some of the links will form a closed chain with ground

Advantages:

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

Disadvantages:

Generally less motion, kinematics can be challenging

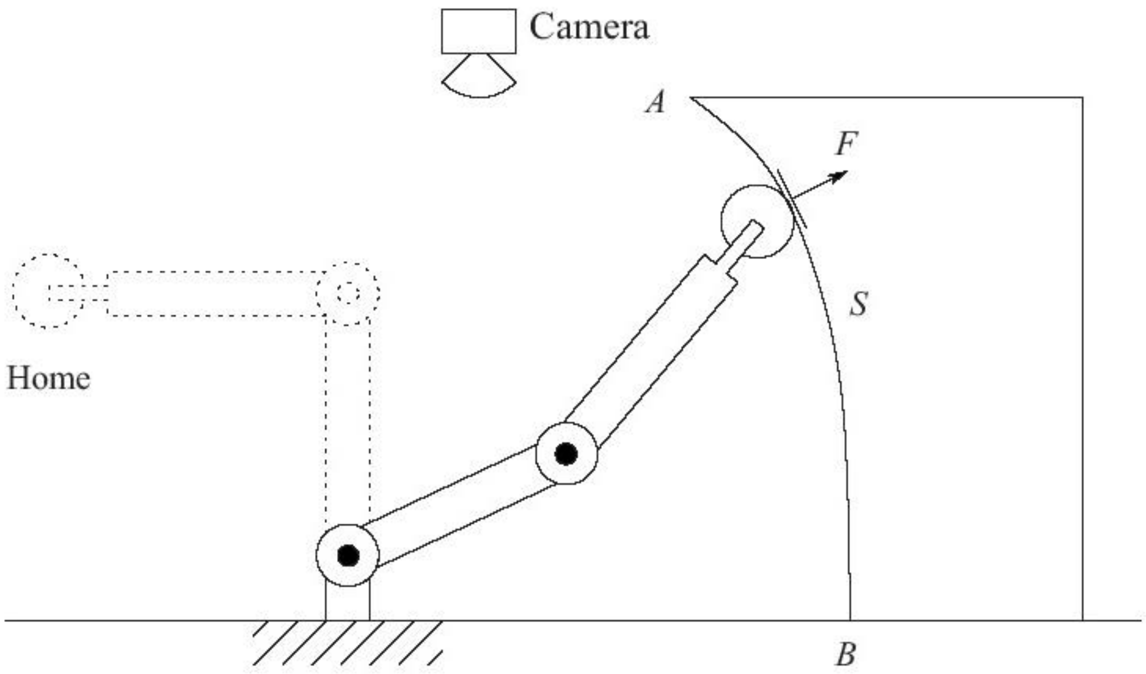


6DOF Stewart platform

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

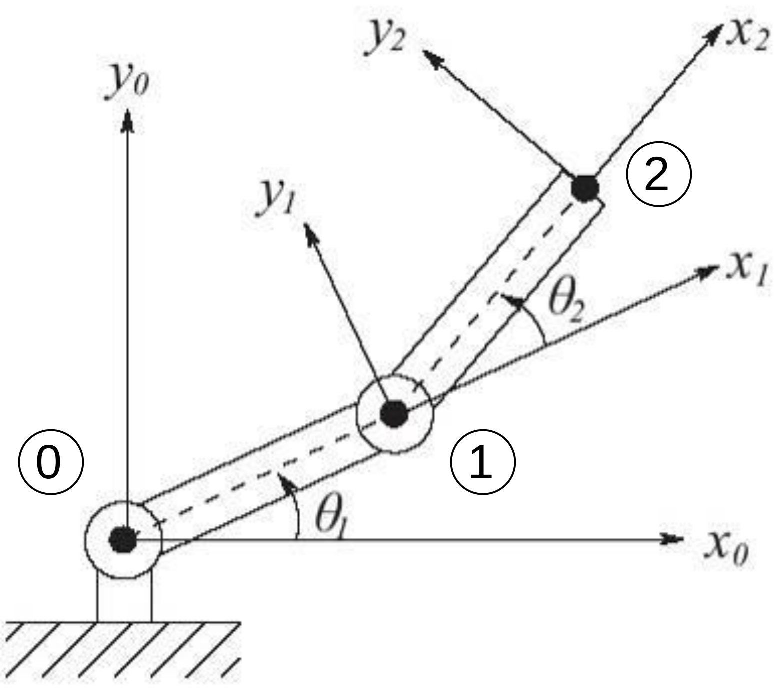
Three coordinate frames: ⓪ ① ②

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:

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

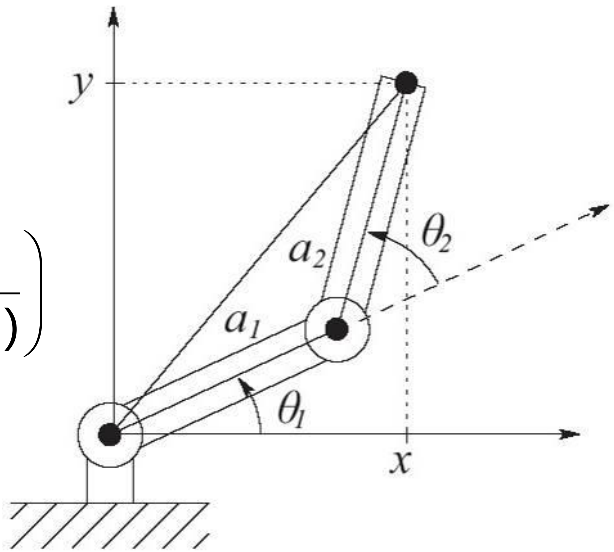
$$R_2^0 = \begin{bmatrix} \hat{x}_2 \cdot \hat{x}_0 & \hat{y}_2 \cdot \hat{x}_0 \\ \hat{x}_2 \cdot \hat{y}_0 & \hat{y}_2 \cdot \hat{y}_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \end{bmatrix}$$

Inverse kinematics

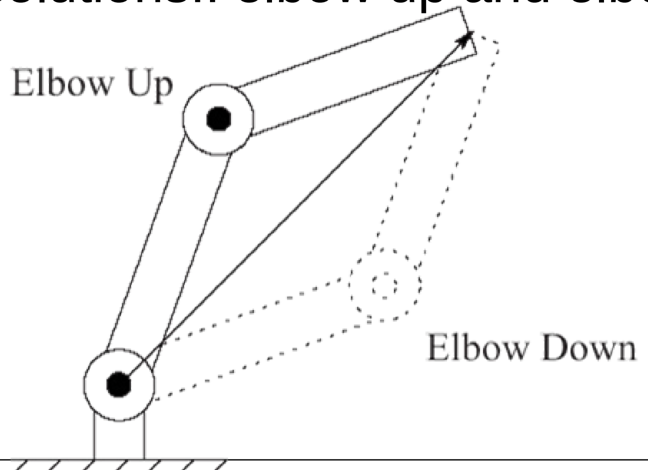
Find the joint angles for a desired tool position

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

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



Two solutions!: elbow up and elbow down



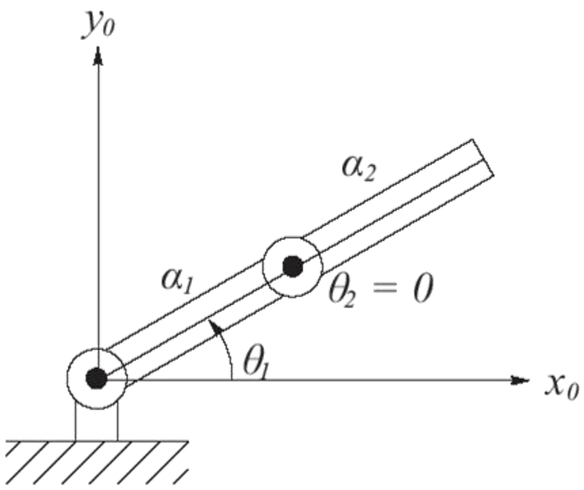
Velocity kinematics: the Jacobian

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:

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

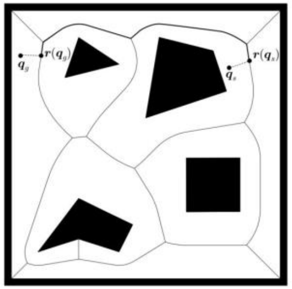
$$= \frac{1}{a_1 a_2 \sin(\theta_2)} \begin{bmatrix} a_2 \cos(\theta_1+\theta_2) & a_2 \sin(\theta_1+\theta_2) \\ -a_1 \cos(\theta_1) - a_2 \cos(\theta_1+\theta_2) & -a_1 \sin(\theta_1) - a_1 \sin(\theta_1+\theta_2) \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

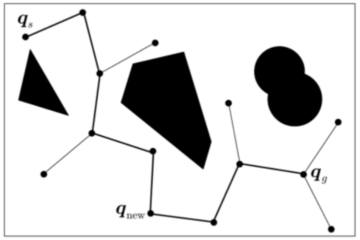
This inverse does not exist when $\theta_2 = 0$ or π, called singular configuration or singularity

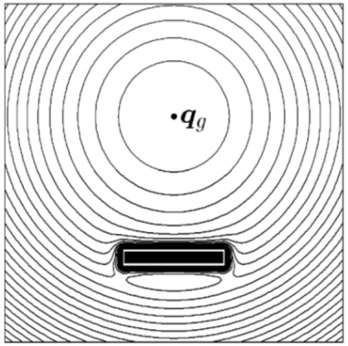
Path planning

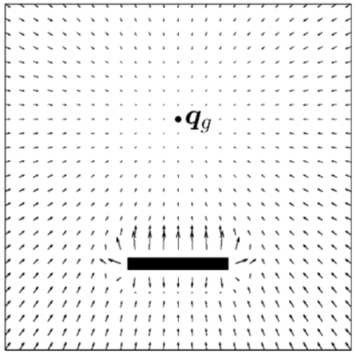
In general, move tool from position A to position B while avoiding singularities and collisions

- 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





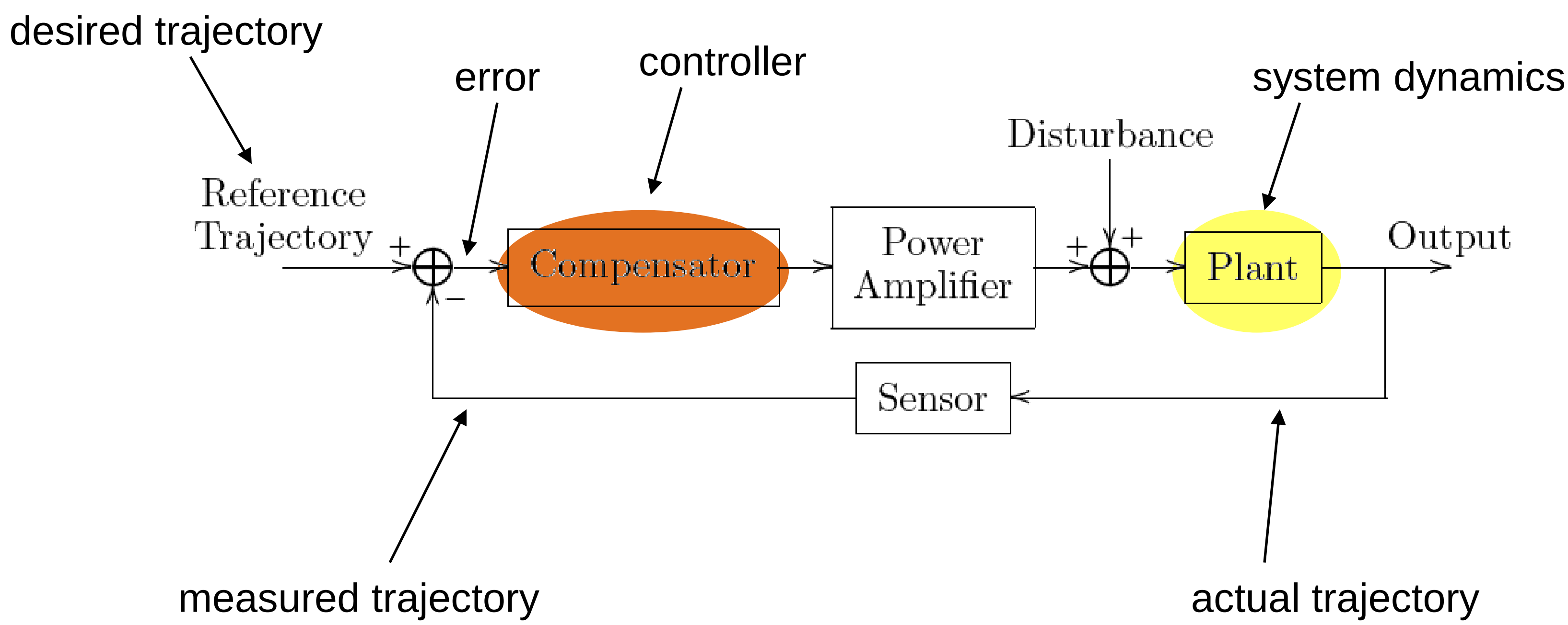




Joint control

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

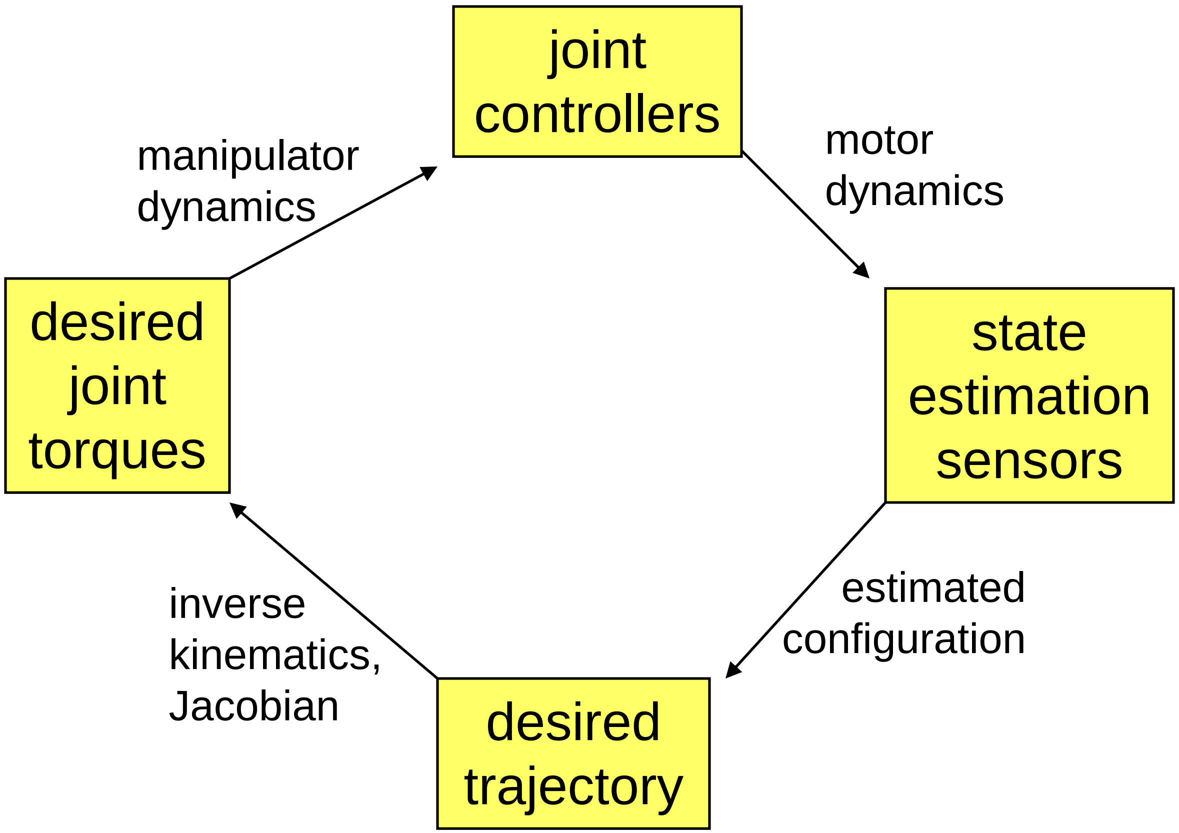
Common controller architectures:

- PID
- Adaptive

Challenges:

- nonlinearity

General multivariable control overview



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

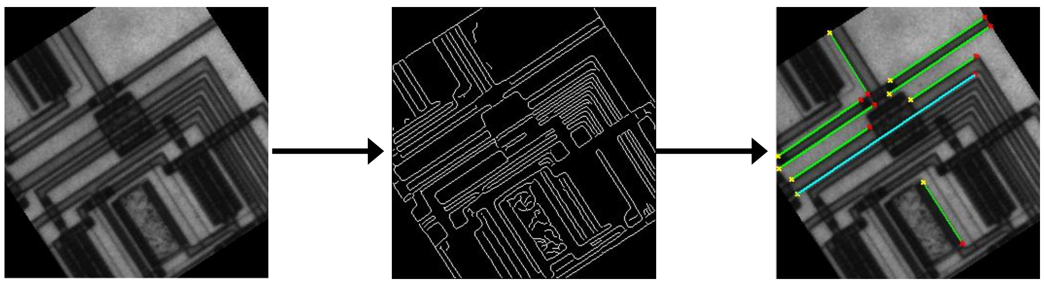
Basic quantities for both:

- Bandwidth
- Dynamic range
- sensitivity

Computer Vision

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

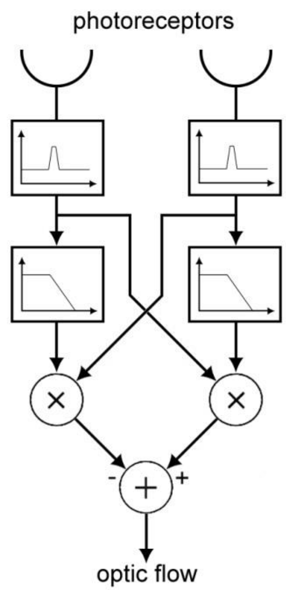
- Usually a statistical process
- Ex: finding lines using the Hough space



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

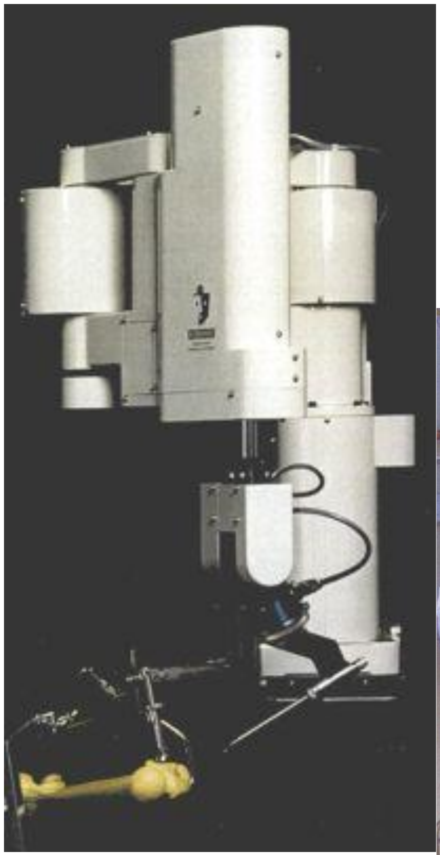
- At the present state of the art, robotic technology for surgical applications can broadly be divided into four main classes
  - Image-guided surgical robots (industrial robots)
  - Surgical telemanipulators (Remote controlled manipulators)
  - Assisting manipulators (Remote controlled manipulators)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

Robotic surgery

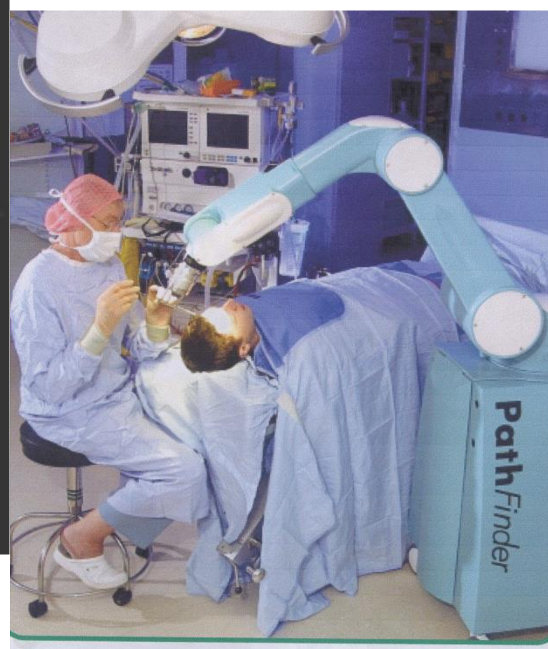
- Image guided with preprogrammed path
  - Caspar
  - Robodoc
  - NeuroMate
  - PathFinder from Armstrong HealthCare
- Remoteoperated- or Teleoperated manipulators
  - The Fraunhover Neuro robot
  - Da Vinci from Intuitive Surgical
  - Zeus Microsurgical system from ComputerMotion
  - Aesop from ComputerMotion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

Image-guided robots

ROBODOC –
Integrated Surgical Systems Inc.



PathFinder –
Armstrong HealthCare Lmt.

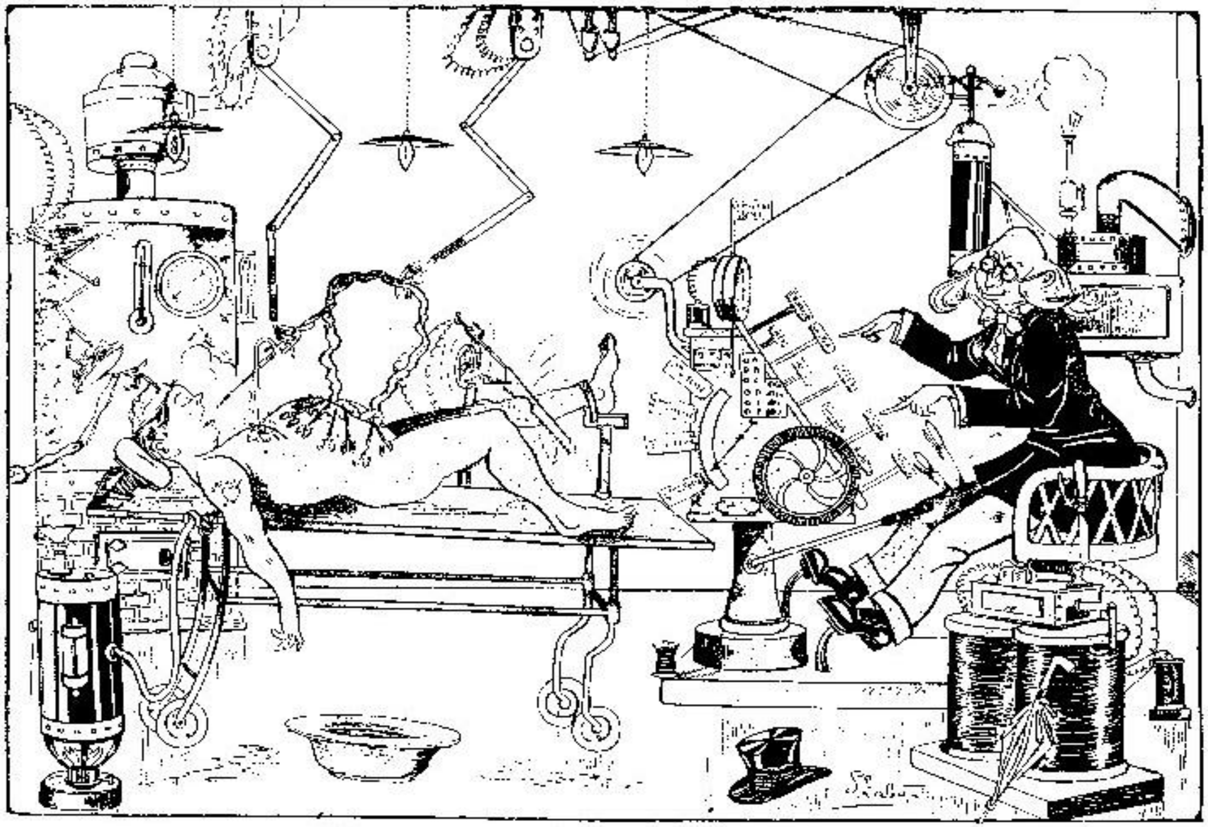


CASPAR - Maquet

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

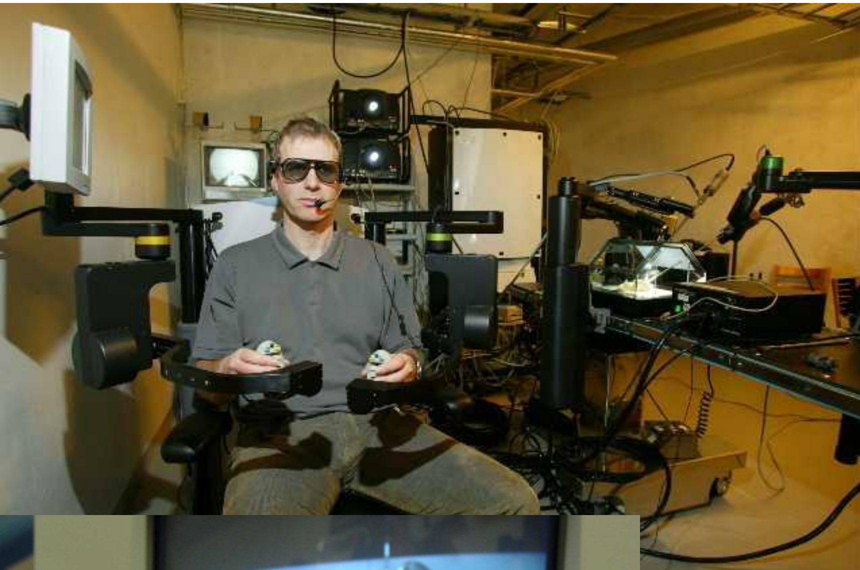
A French comic drawing from 1914 showing how the artist envisioned the operating room of year 2000



UNE SALLE D'OPÉRATIONS EN L'AN 2000

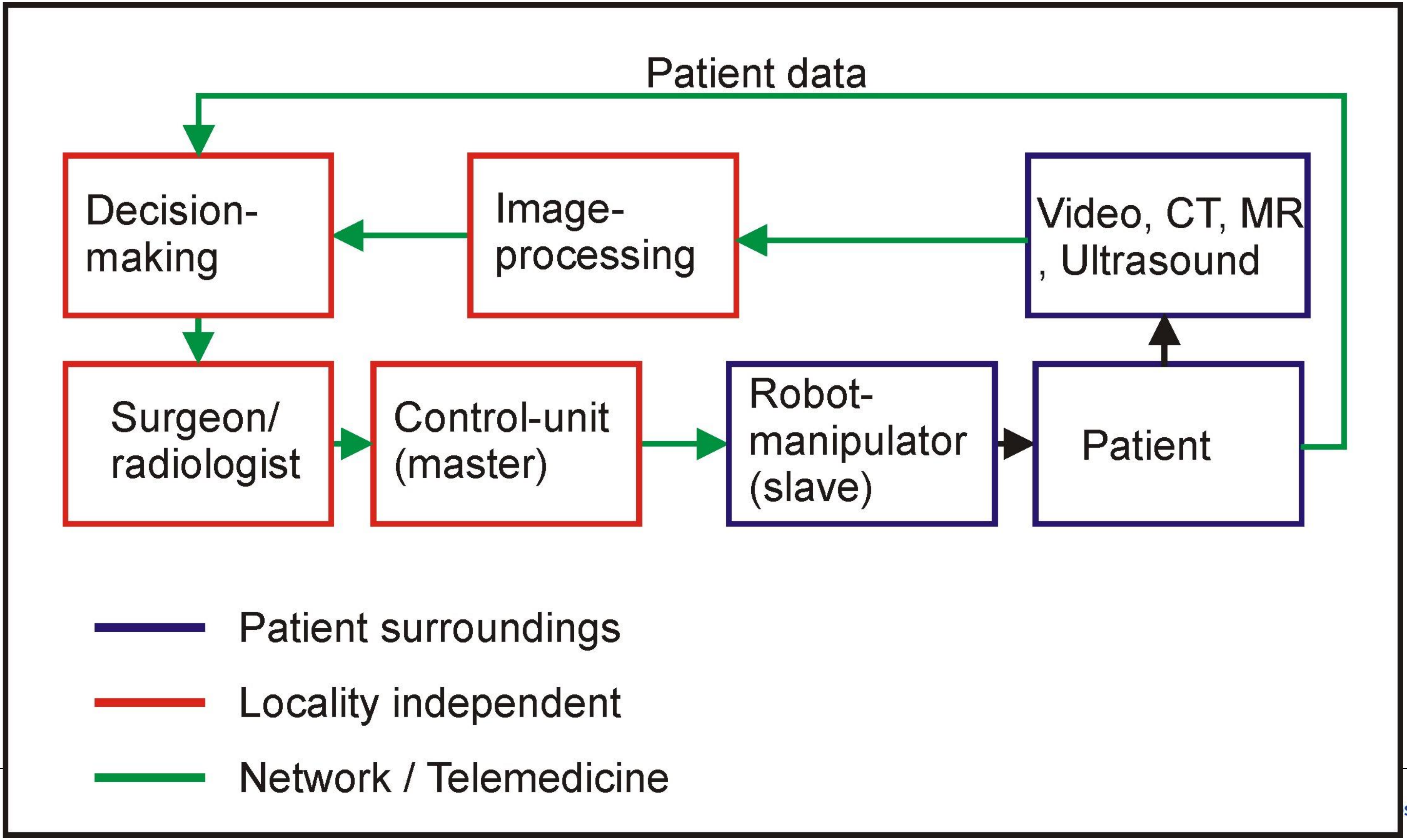
Surgical telemanipulators

Zeus-
ComputerMotion Inc.



DaVinci-
Intuitive Surgical Inc.

Control loop - Tele manipulation



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

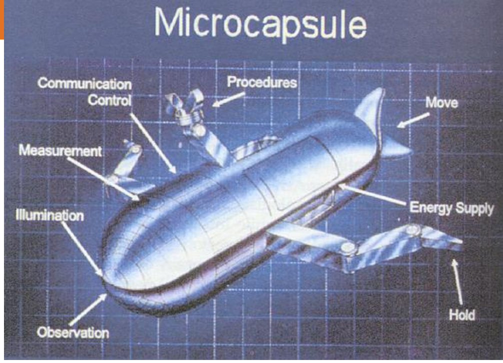
Surgical robotics

Minimally invasive surgery

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

Future robots - Micro

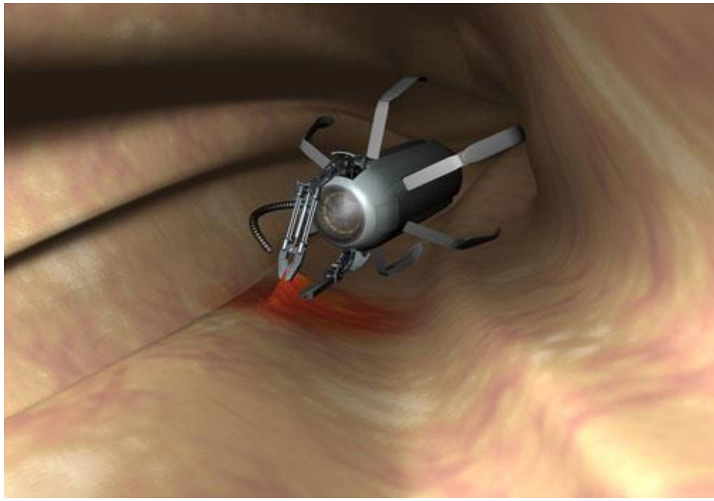
- Automated systems with artificial intelligence
- Miniatyrized telemanipulators
- Cross-linked with medical information



Olympus trawing board, 1997

2001: Capsule endoscopy

VECTOR-Versatile Endoscopic Capsule for gastrointestinal TumOr Recognition

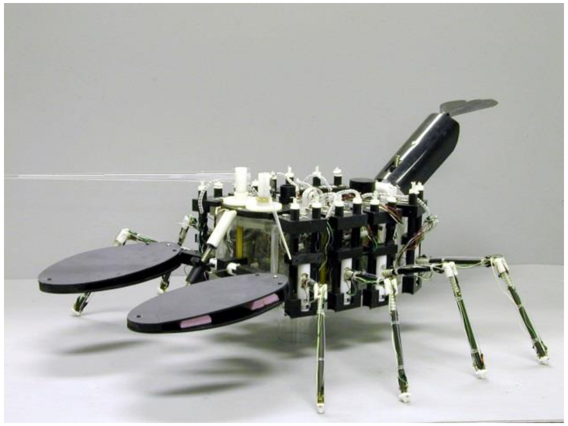


Tele-operated Endoscopic Capsule with Active Locomotion
Scuola Superiore Sant'Anna, Italy (research project)

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.

Next class...

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.

HELSE SØR-ØST

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