www.octopus-project.eu

OCTOPUS Meeting
Heraklion, Greece, April 27, 2009

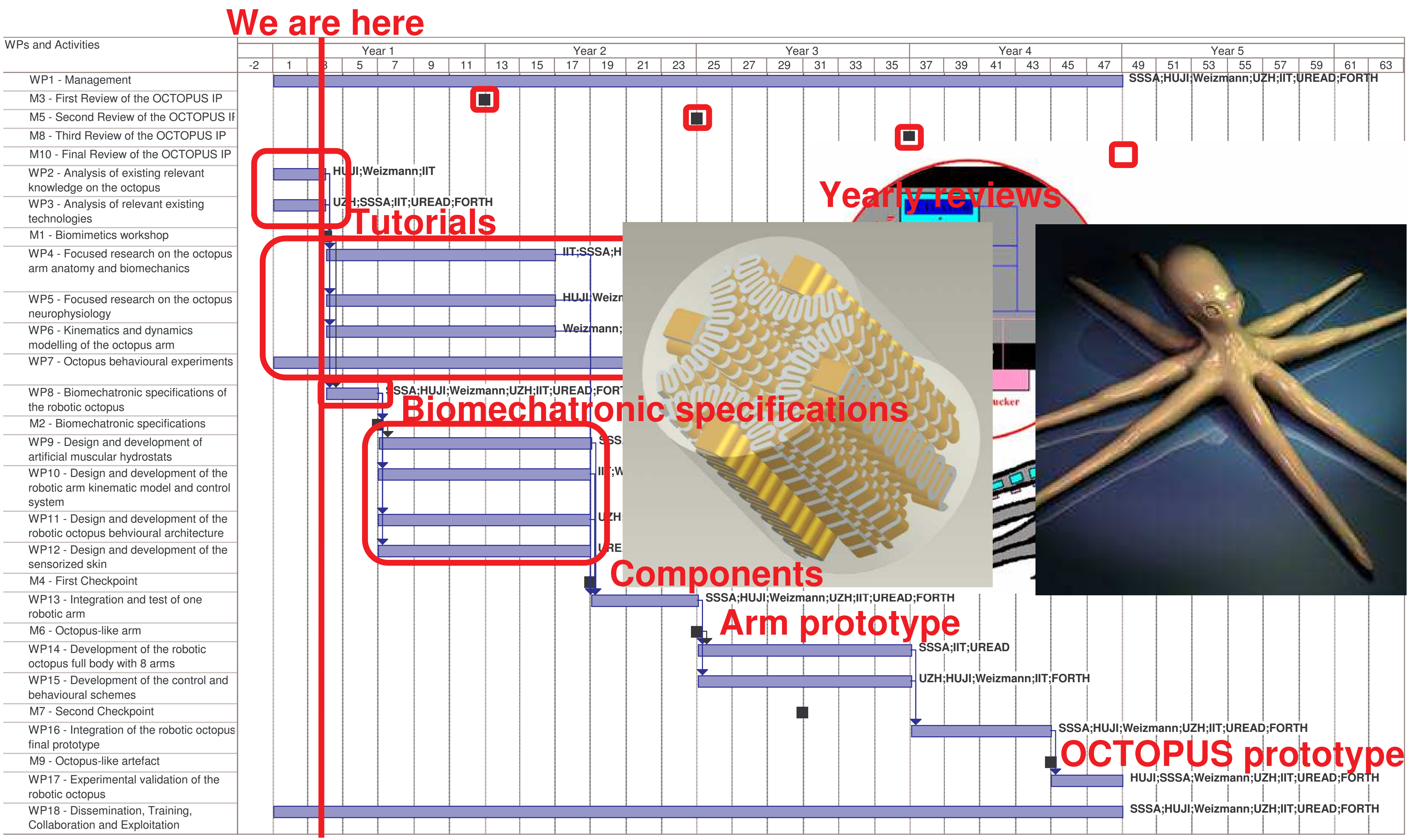
Overview and objectives of the meeting

Cecilia Laschi
Scuola Superiore Sant'Anna,
Pisa, Italy

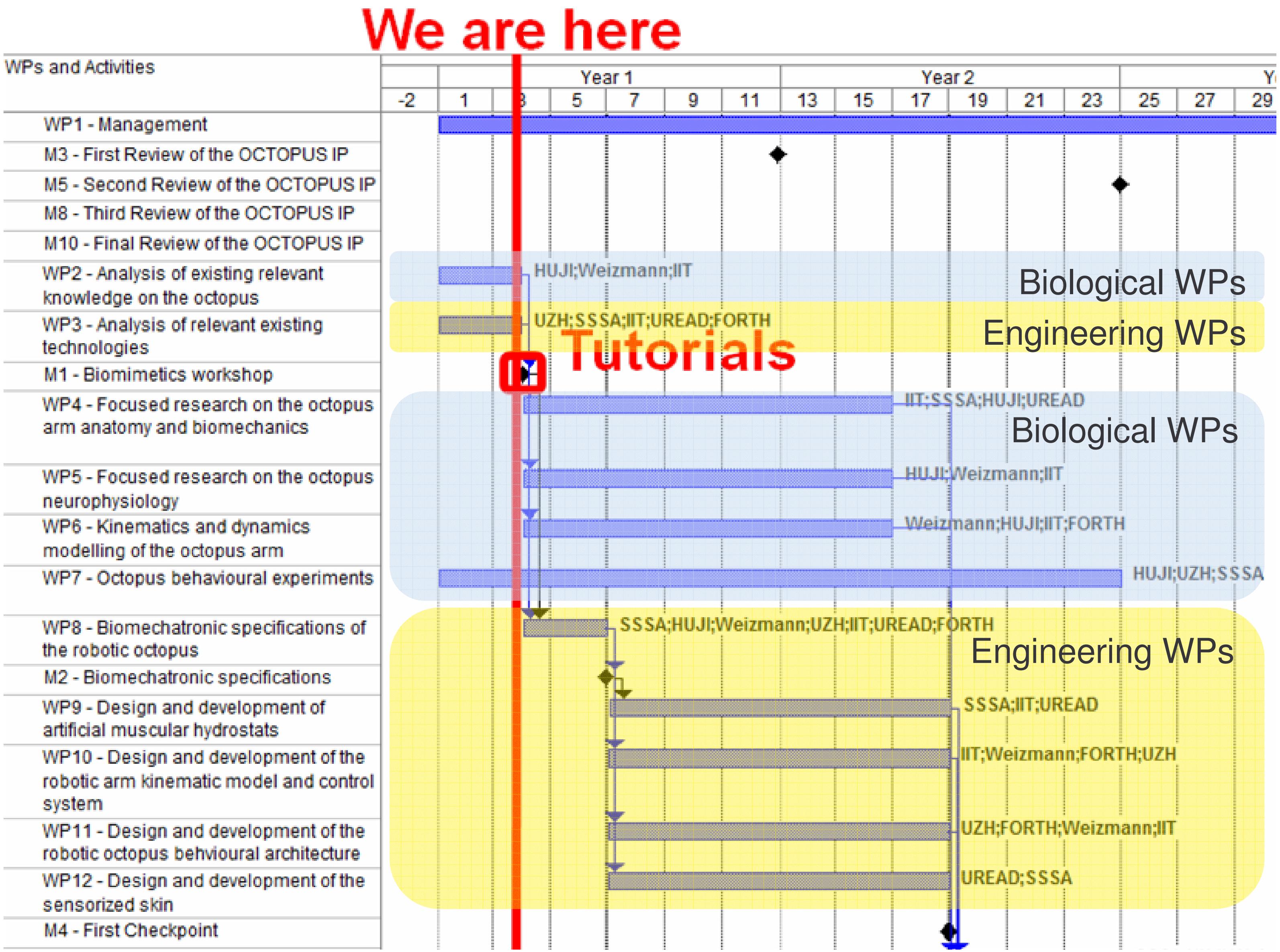
ARTS Lab

Scuola Superiore Sant'Anna
di Studi Universitari e di Perfezionamento

OCTOPUS workplan and current status



OCTOPUS workplan and current status



Objectives of this meeting:
1. Tutorials (deliverables D2.2 & D3.2)

Biological side

Due by April 30, 2009

WP2 – Analysis of existing relevant knowledge on the octopus

- Objectives: survey and systematization of existing knowledge on the octopus, as relevant to the development of the octopus-like robot
- Deliverable **D2.2** "Tutorial on fundamentals of octopus biology"

Engineering side

WP3 – Analysis of relevant existing technologies

- Objectives: survey and systematization of existing knowledge on the technologies needed for the development of the octopus-like robot (sensors, actuators, control, robot architectures, materials)
- Deliverable **D3.2** "Tutorial on technologies for biomimetic ICT and robotics"

Objectives of this meeting:
2. Brainstorming

Start-up of:

Biological side

- WP4 – Focused research on the octopus arm anatomy and biomechanics
- WP5 – Focused research on the octopus neurophysiology
- WP6 – Kinematic and dynamic modelling of the octopus arm
- WP7 – Octopus behavioural experiments

Engineering side

- WP8 – Biomechatronic specifications of the robotic octopus
- WP9 – Design and development of the artificial muscular hydrostat
- WP10 – Design and development of the robotic arm kinematic model and control system
- WP11 – Design and development of the robotic octopus behavioural architectures
- WP12 – Design and development of the sensorized skin

Wednesday, 22 April 2009

14.00 – 15.30

Embodied intelligence

Room: Leo

The principle of "embodiment" has shifted robotic research away from the traditional view which reduces adaptive behaviour to control and computation. It is based on the observation in nature that adaptive behaviour emerges from the complex and dynamic interaction between the body morphology, sensory-motor control, and environment. The session aims at discussing the scientific and technological state-of-the-art as well as future challenges in this field.

Speakers

Rolf Pfeifer, University of Zurich, Switzerland, **Paolo Dario**, Scuola Superiore Sant'Anna, Pisa, Italy, **Kenji Suzuki**, University of Tsukuba, Japan, **Eugenio Guglielmelli**, University Campus Bio-Medico, Rome, Italy, **Chiara Bartolozzi**, Italian Institute of Technology, **Lijin Aryananda**, University of Zurich, Switzerland, **Alin Albu-Schaeffer**, DLR, Germany, **Frédéric Boyer**, Ecole des Mines de Nantes, France.

Organized by

Cecilia Laschi, Scuola Superiore Sant'Anna, Pisa, Italy

Science beyond Fiction fet09 | 21-23 April 2009 | Prague

The European Future Technologies Conference

Future and Emerging Technologies

Session on "Embodied Intelligence"

14.00 – 14.10: Introduction to the session
Cecilia Laschi, Scuola Superiore Sant'Anna, Pisa, Italy

14.10 – 14.30: "Exploiting morphology, materials, and interaction for intelligent behavior"
Rolf Pfeifer, University of Zurich, Switzerland

14.30 – 14.50: "Biorobotics Science and Engineering: from bio-inspiration to bio-application"
Paolo Dario, Scuola Superiore Sant'Anna, Pisa, Italy

14.50 – 15.10: "Cybernoid technology for walking, grasping and smiling"
Kenji Suzuki, University of Tsukuba, Japan

15.10 – 15.30: Poster Session – Presentation of EMBODY[i] projects:
OCTOPUS, Cecilia Laschi, Scuola Superiore Sant'Anna, Pisa, Italy
EVRYON, Eugenio Guglielmelli, University Campus Bio-Medico, Rome, Italy
EMORPH, Chiara Bartolozzi, Italian Institute of Technology, Italy
LOCOMORPH, Lijin Aryananda, University of Zurich, Switzerland
VIACTORS, Alin Albu-Schaeffer, DLR, Germany
ANGELS, Frederic Boyer, Ecole del Mines de Nantes, France

Over 80 participants!

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OCTOPUS Meeting
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Tutorial
Robotic Technologies for Sensing and Actuation

Cecilia Laschi, Matteo Cianchetti, Laura Margheri, Barbara Mazzolai, Paolo Dario

Scuola Superiore Sant'Anna, Pisa, Italy

ARTS Lab

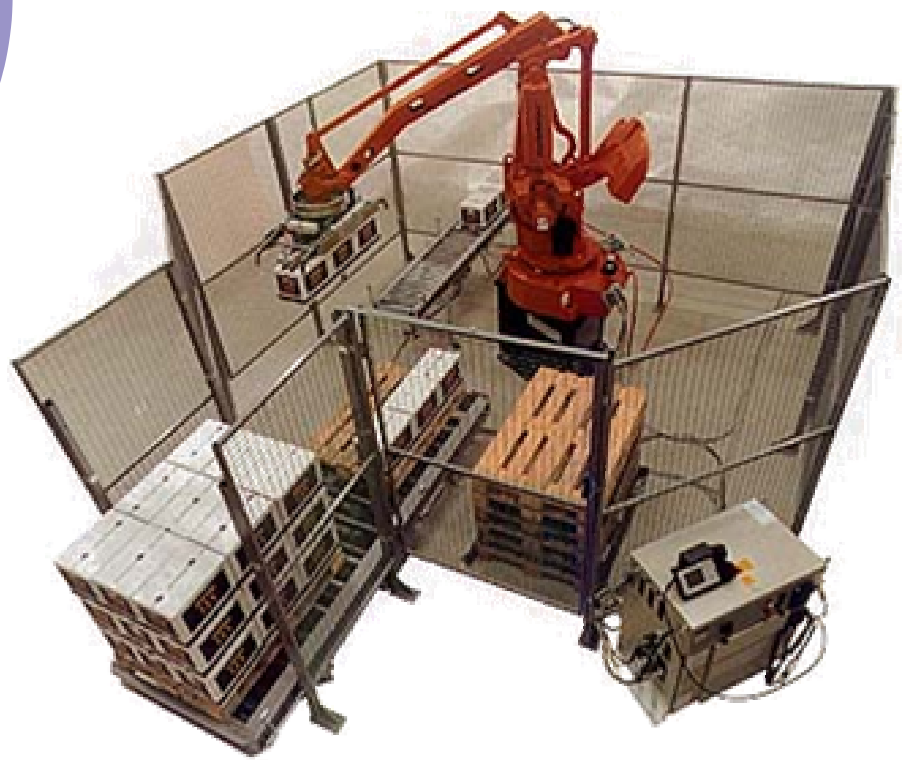
Scuola Superiore Sant'Anna
di Studi Universitari e di Perfezionamento

Evolution of Robotics

NEED for helpful machines

Industrial Robotics

Industrial Automation



Definitions of Robotics

- A robot is a **re-programmable**, **multi-functional** manipulator designed to move material, parts, or specialized devices through variable programmed motions for the performance of a variety of tasks

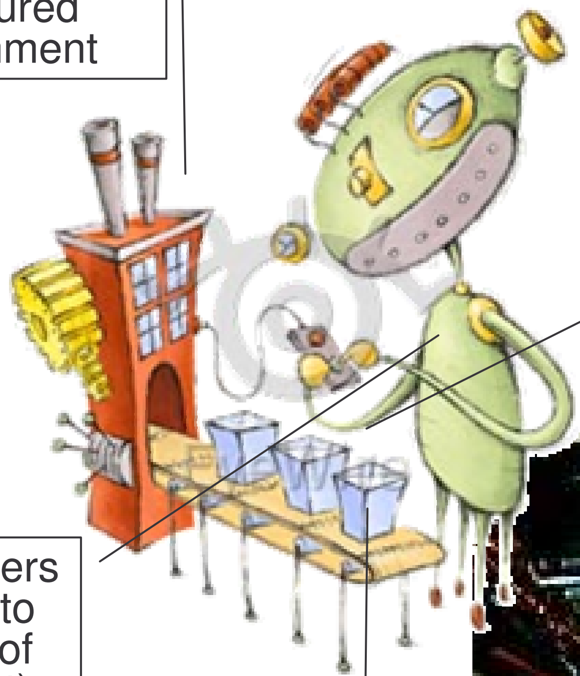
Robotics Industry Association (~1980)

Jablonsky J., Posey J. 1985. “Robotics Terminology”, in *Handbook of Industrial Robotics*, ed. S. Nof, J. Wiley, New York, pp.1271-1303

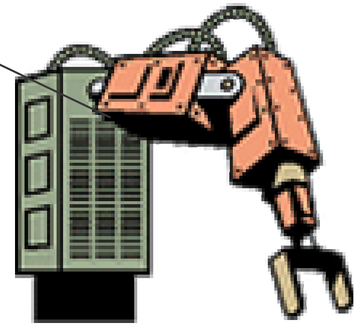
OCTOPUS

Typical industrial robotics scenario

Structured environment



Robot manipulators with high perfomance in terms of accuracy, repeatability, speed, and robustness

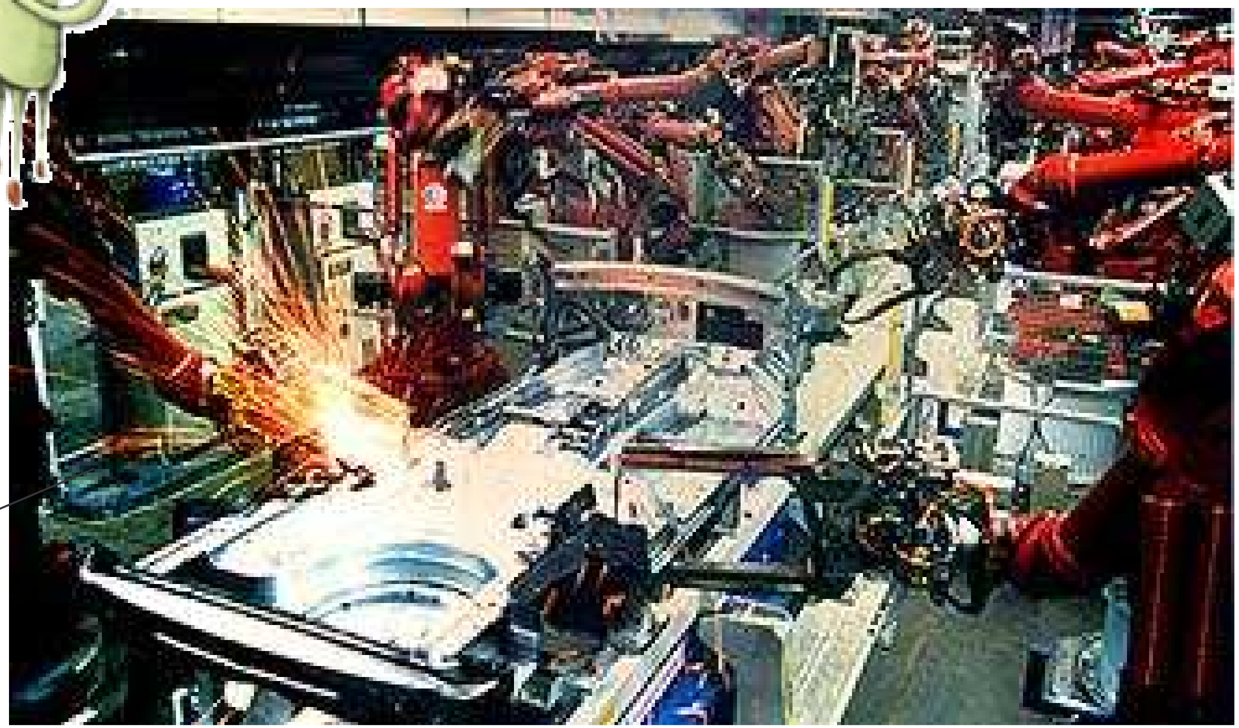


Well-defined repetitive procedures

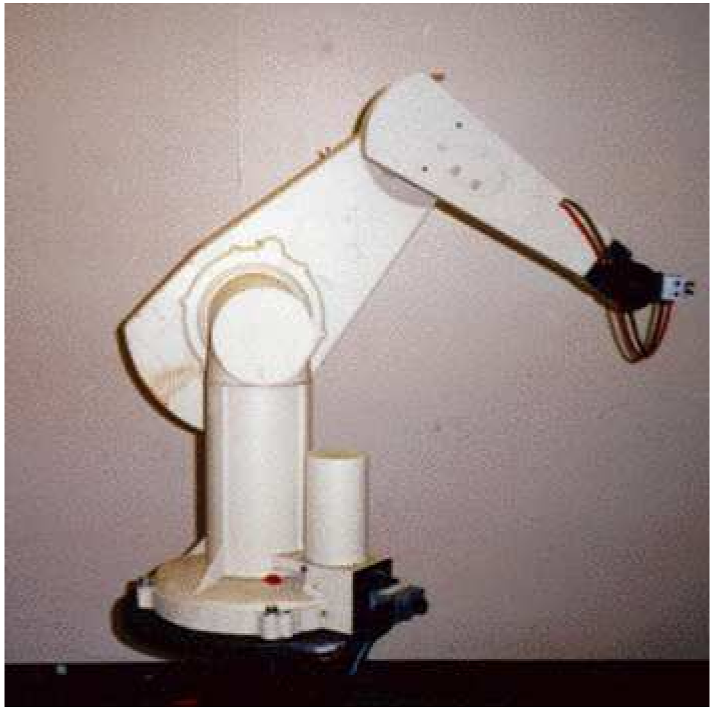
Expert users (trained to the use of the robot)

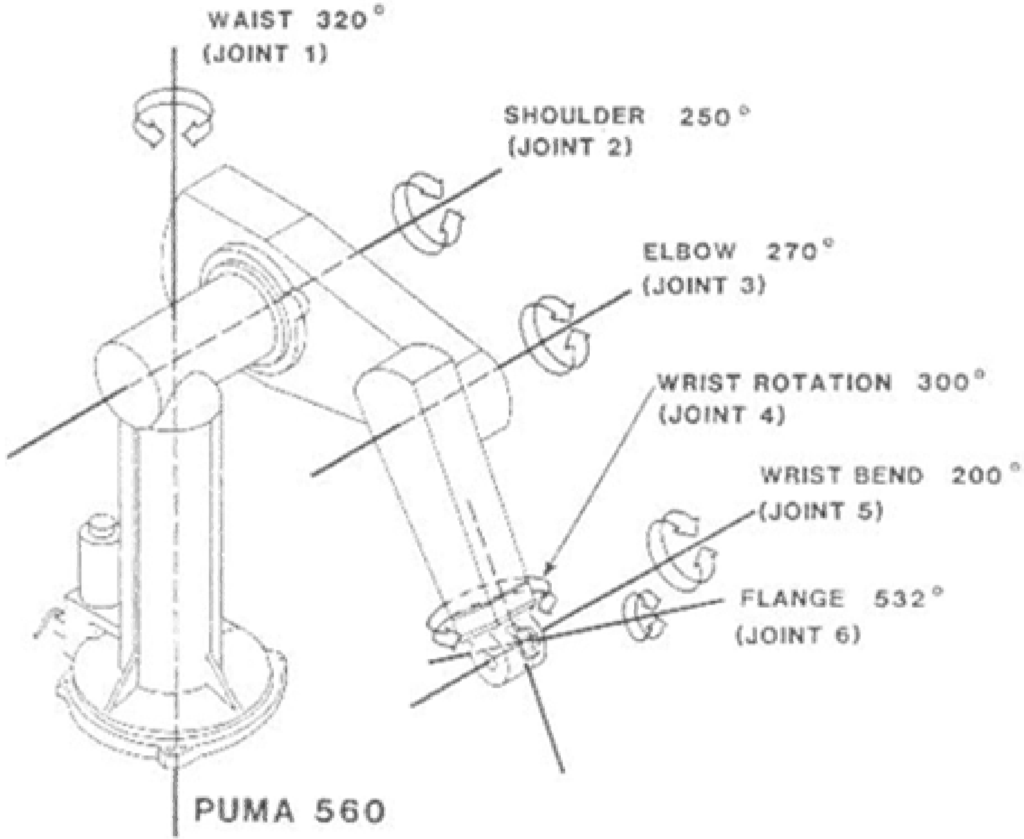
Objects to manipulate in predefined positions

Restricted human presence in the robot workspace



PUMA 560



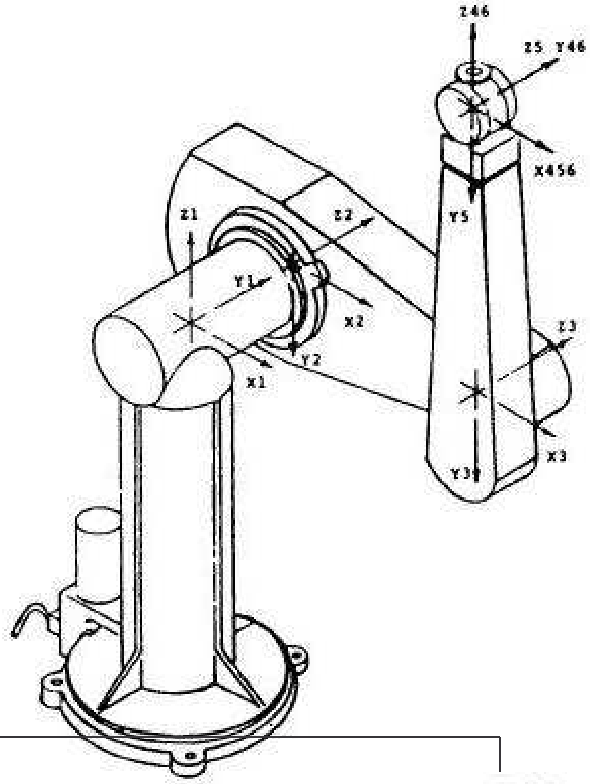


- Industrial Robot manipulator with 6 d.o.f
- The six degrees of freedom are controlled by six brushed DC servo motors
- Each motor is provided with a 500-1000 count 3 channel encoder and a potentiometer

	Repeatability	Operating velocity	Weight
PUMA 560	± 0.1 mm	1.0 m/s	120 lb

P.I. Corke and B. Armstrong-Helouvry. *A search for consensus among model parameters reported for the Puma 560 Robot.* Proc. IEEE Conf. Robotics and Automation, 1994 pp. 1608-1613

Puma kinematics and dynamics



i	α_i	A_i	D_i
1	90	0	0
2	0	431.8	0
3	-90	19.1	125.4
4	90	0	431.8
5	-90	0	0
6	0	0	0

Denavit-Hartenberg parameters

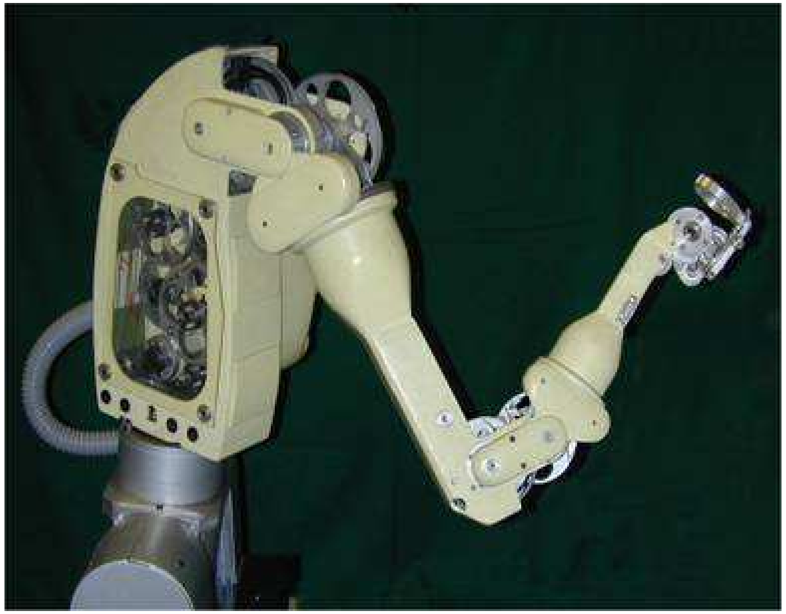
Table 4. Link Masses (kilograms; ±0.01 + 1%)

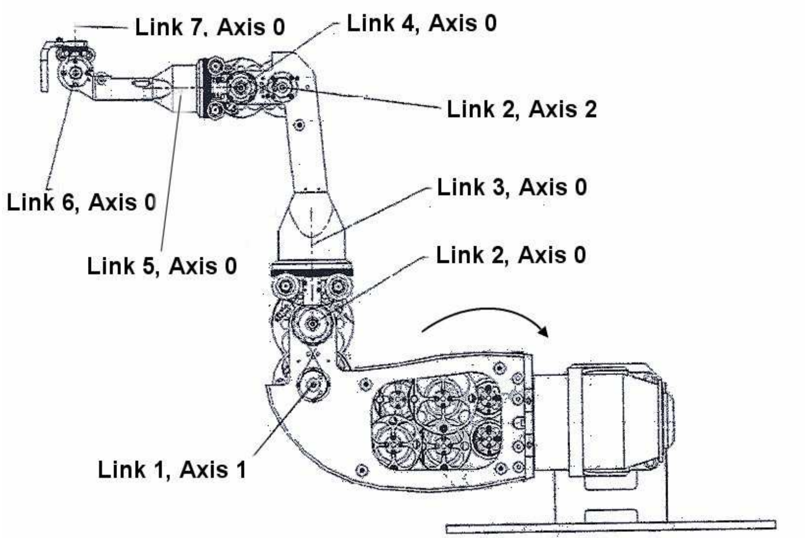
Link	Mass
Link 2	17.40
Link 3	4.80
Link 4*	0.82
Link 5*	0.34
Link 6*	0.09
Link 3 with Complete Wrist	6.04
Detached Wrist	2.24

Table 5. Centers of Gravity. (meters ±0.003)

Link	r_x	r_y	r_z
Link 2	0.068	0.006	-0.016
Link 3	0	-0.070	0.014
Link 3 With Wrist	0	-0.143	0.014
Link 4*	0	0	-0.019
Link 5*	0	0	0
Link 6*	0	0	0.032
Wrist	0	0	-0.064

The Dexter robot arm





- Anthropomorphic redundant robot arm (8 d.o.f.s)
- Cable-actuated mechanical structure (the transmission system is through pulleys and steel cables)

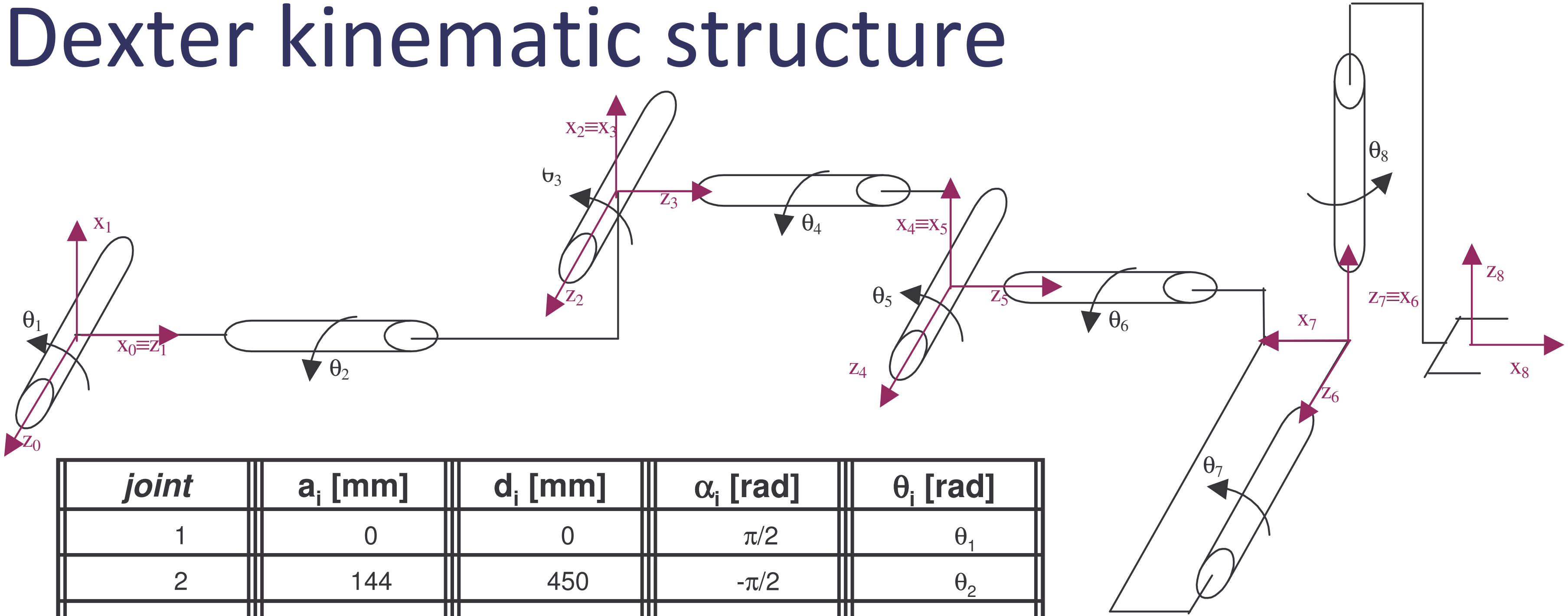
Pros

- light mechanical structure
- safe and intrinsically compliant structure
- human-like physical aspect

Cons

- sophisticated dynamics
- non-linear friction
- coupling in the degrees of freedom
- anthropomorphic distribution of the masses of the links

Dexter kinematic structure



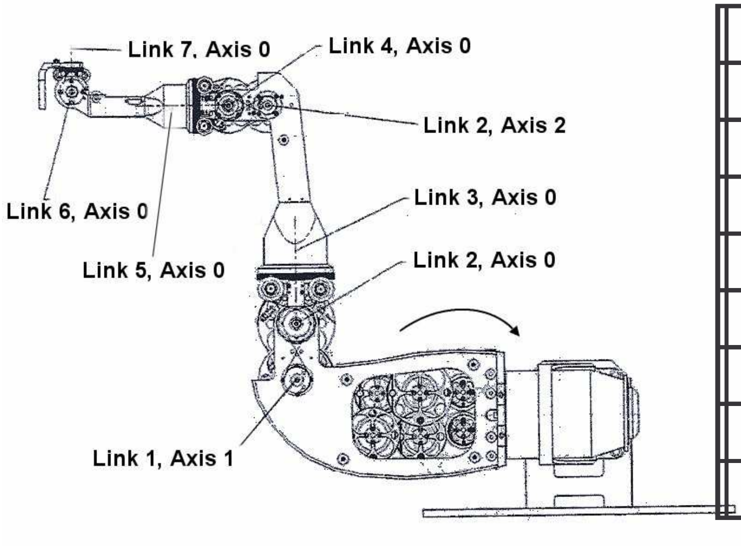
joint	a_i [mm]	d_i [mm]	α_i [rad]	θ_i [rad]
1	0	0	$\pi/2$	θ_1
2	144	450	$-\pi/2$	θ_2
3	0	0	$\pi/2$	θ_3
4	-100	350	$-\pi/2$	θ_4
5	0	0	$\pi/2$	θ_5
6	-24	250	$-\pi/2$	θ_6
7	0	0	$\pi/2$	θ_7
8	100	0	0	θ_8

Denavit-Hartenberg parameters

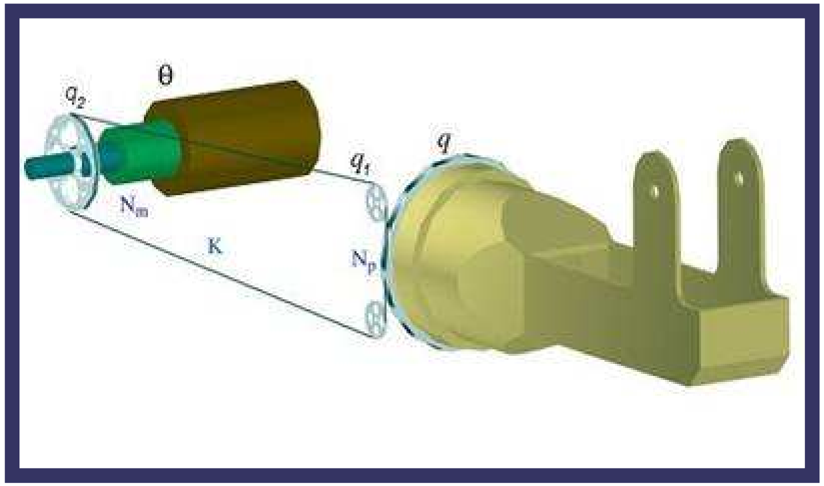
	Workspace	**Repeatability**	**Operating velocity**	**Payload**	**Overall dimensions**	**Weight**
Dexter	1200mm x 350°	± 1mm	0.2m/s	2Kg	400mm x 400mm x 950mm	40Kg

Functional specifications

Dexter dynamics



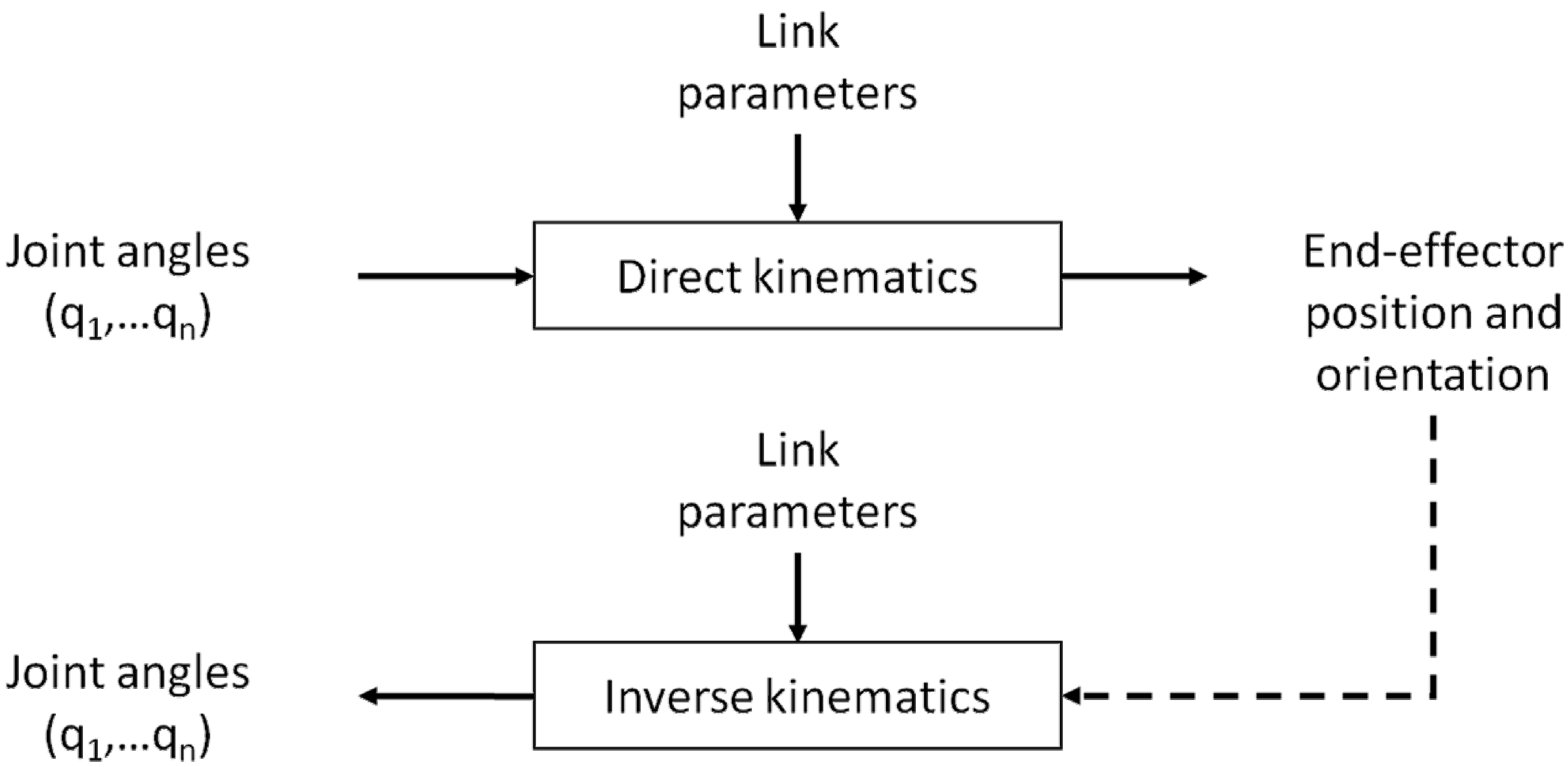
	r_x [mm]	r_y [mm]	r_z [mm]	*m* [Kg]
Link 0	0	6.92	27.72	9.429
Link 1	-139.35	174.49	46.08	12.051
Link 2	0	-6.11	34.59	1.627
Link 3	90.72	133.77	-0.24	2.488
Link 4	0.01	-3.72	20.30	0.818
Link 5	-24.01	141.05	0.11	0.541
Link 6	-0.05	2.36	6.78	0.266
Link 7	20.35	1.81	33.26	0.095



	Joint 1	Joint 2	Joint 3	Joint 4
Stiffness coefficient	10^5	10^5	$6.34 \cdot 10^3$	$3.60 \cdot 10^3$

	Joint 5	Joint 6	Joint 7	Joint 8
Stiffness coefficient	$2.69 \cdot 10^3$	$1.69 \cdot 10^3$	$1.23 \cdot 10^2$	$2.06 \cdot 10^2$

Direct and inverse kinematics



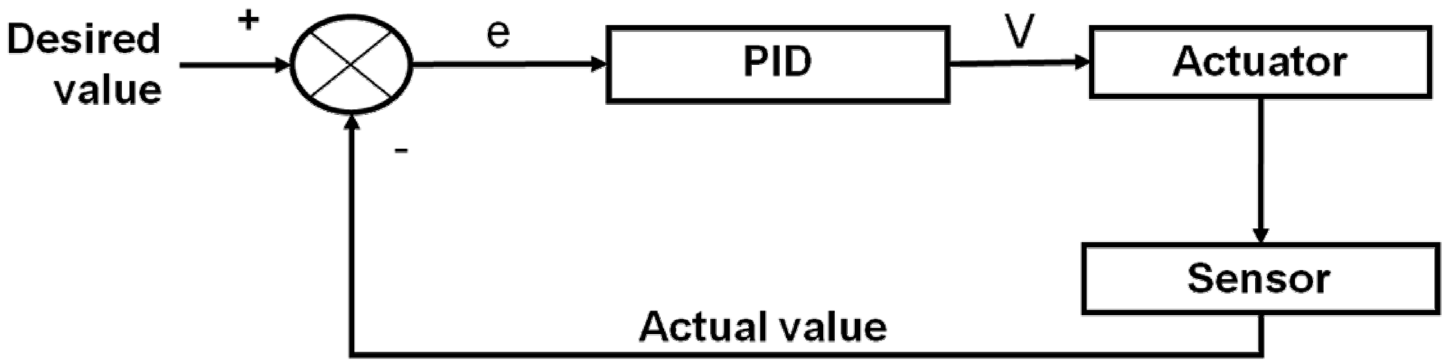
Direct kinematics

$\mathbf{x} = K(q)$

Inverse kinematics

$\mathbf{q} = K^{-1}(x)$

Control of one joint motion (actuated by one motor)



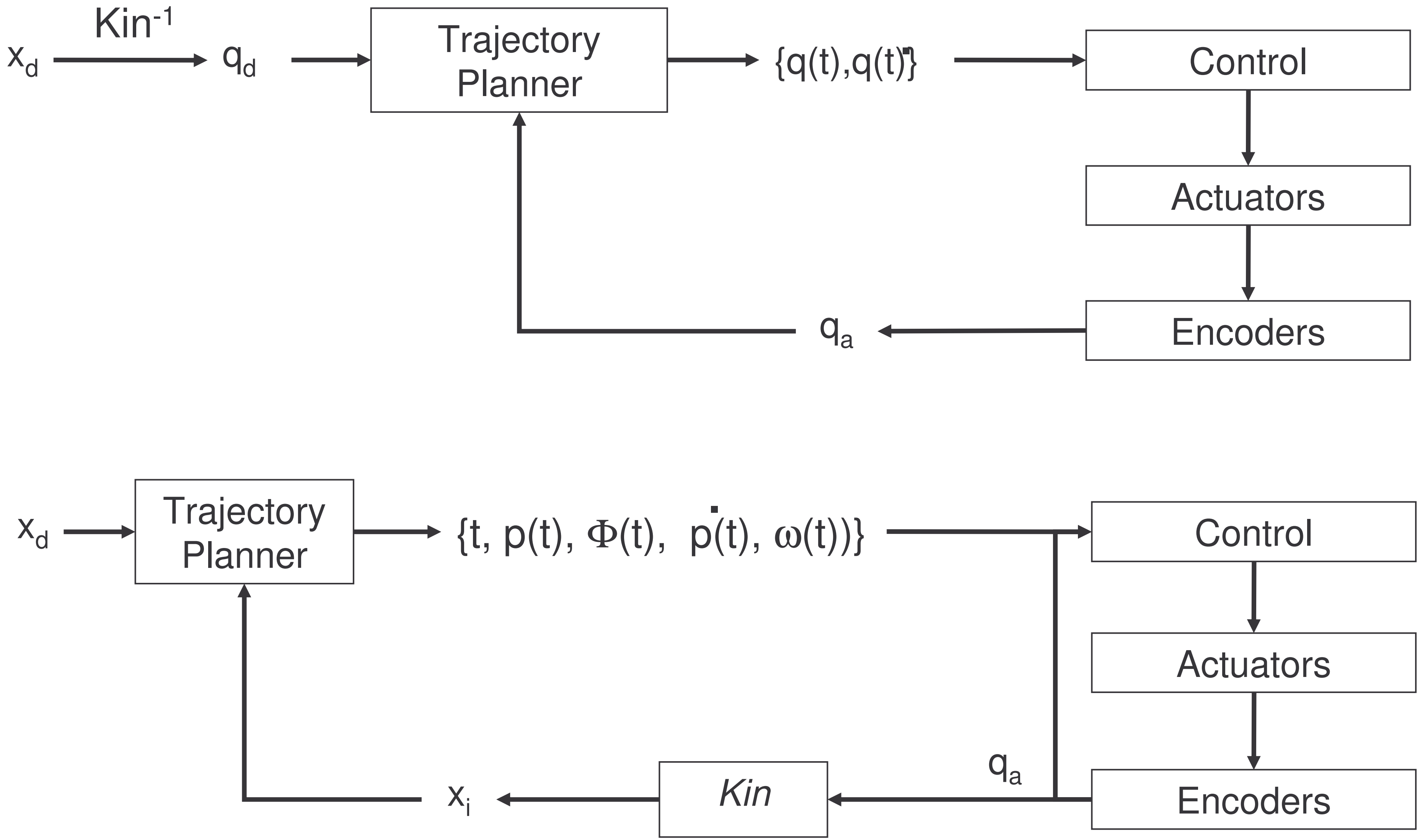
$$V = K_p e_q + K_d \dot{e}_q + K_i \int e_q(t)\,dt$$

$$e_q = q_d - q$$

$$\dot{e}_q = \frac{de_q}{dt}$$

- $\boldsymbol{K_p}$ is the *proportional* gain
- $\boldsymbol{K_i}$ is the *integrative* gain
- $\boldsymbol{K_d}$ is the *derivative* gain
- ***e*** is the error, i.e. the difference between desired and actual value

Control of the movement of a robot arm

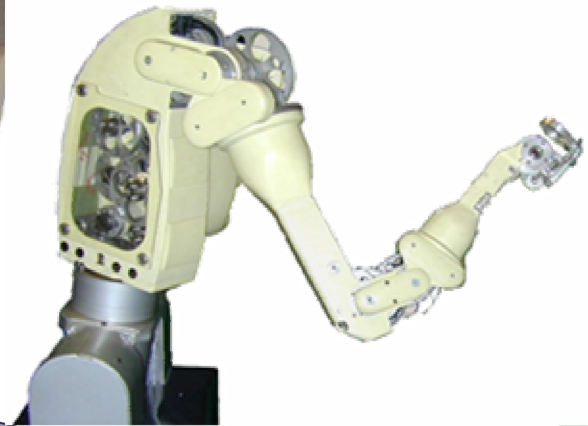


Evolution of robot arms

PUMA arm

Dexter arm (S.M.)

Low size and mass, thanks to cable transmission



WAM arm (Barrett Technologies)

High speed: 20 m/s

DLR lightweight arm

Payload/mass ratio = 1

‘70s

‘90s

today

- Rigid links
- Low payload/mass ratio

Evolution of Robotics

NEED for helpful machines

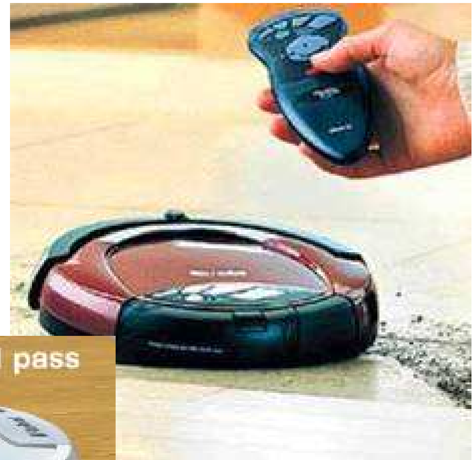
Industrial Robotics

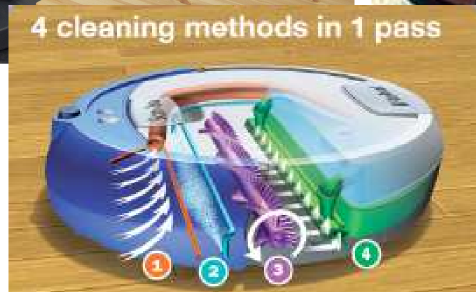
Industrial Automation

Service Robotics

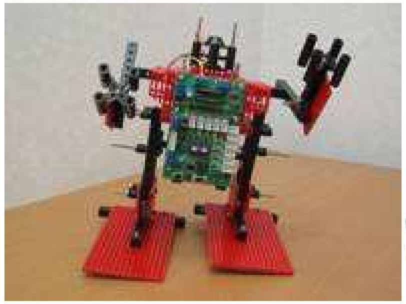
Service Applications

Applicazioni domestiche

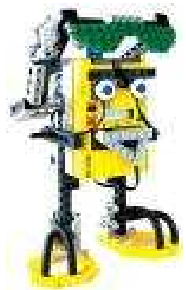




Robot per intrattenimento e edutainment



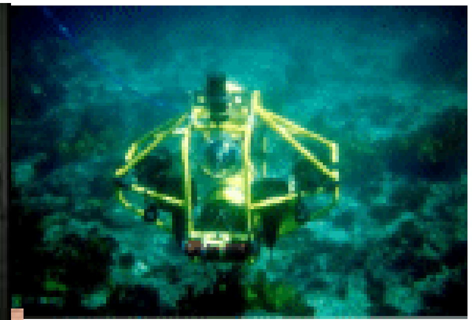





Robots ouside factories: Service Robotics

Photo: Center for Robot-Assisted Search and Rescue



Dangerous environments

Services

- Unstructured environment
- More important role of perception
- Reactive behaviour
- Sharing of the workspace with human beings

The DustCart robot for garbage collection

Definitions of Robotics

- A robot is a re-programmable, multi-functional manipulator designed to move material, parts, or specialized devices through variable programmed motions for the performance of a variety of tasks

Robotics Industry Association (~1980)

Jablonsky J., Posey J. 1985. “Robotics Terminology”, in *Handbook of Industrial Robotics*, ed. S. Nof, J. Wiley, New York, pp.1271-1303

- Robotics is the intelligent connection of perception to action

Brady, 1985

(M. Brady, 1985. “Artificial Intelligence and Robotics”, *Artificial Intelligence and Robotics*, Vol.26, pp.79-121)

- An intelligent robot is a machine able to extract information from its environment and use knowledge about its world to move safely in a meaningful and purposeful manner

Arkin, 1999

(Ronald Arkin, *Behaviour-based Robotics*, MIT Press, 1999)

- The science and technology of the design of mechatronic systems capable of generating and controlling motion and force

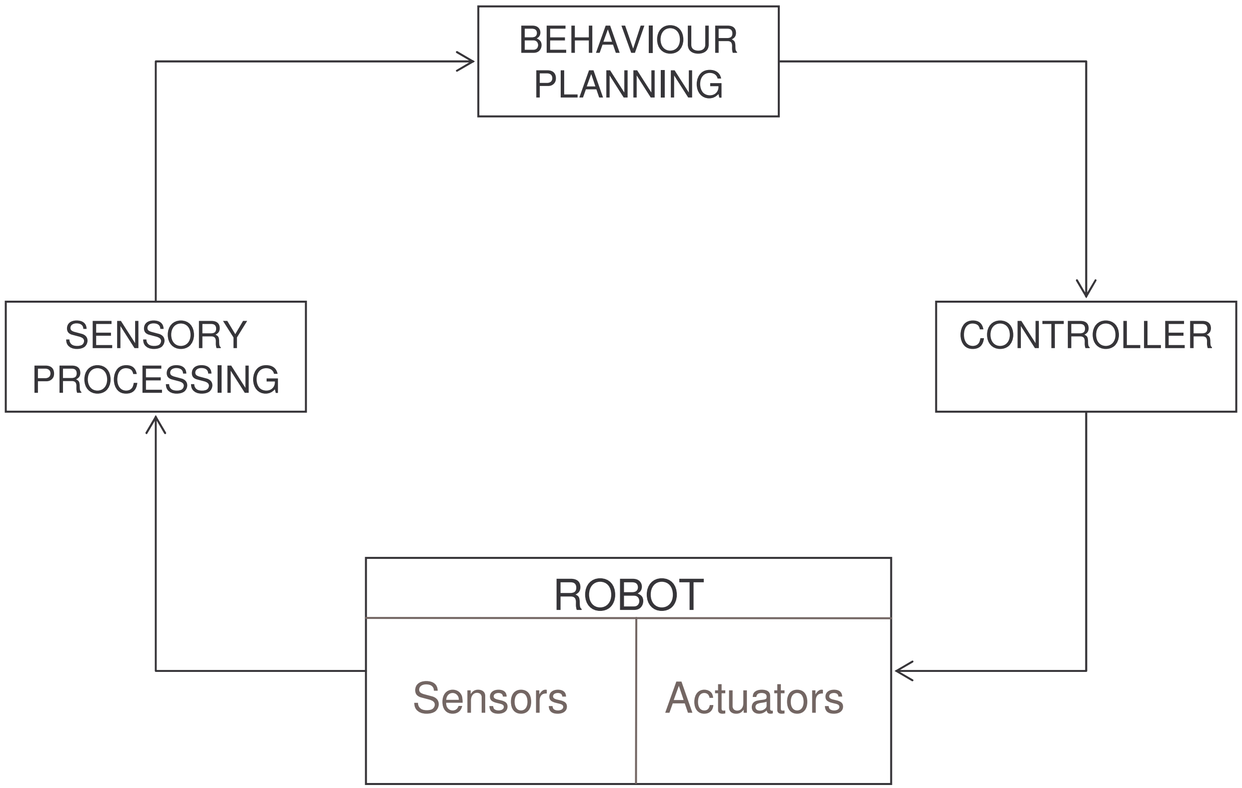
Paolo Dario (~2000)

Definition of “intelligent robot” or “autonomous robot”

- An intelligent robot is a mechanical creature which can function autonomously
- Autonomous robot: a machine that can accept and execute **autonomously** commands or missions in **unstructured environments without human intervention**
- Problems:
  dynamically planning robot behaviours in unknown and variable environments, according to a request for task execution

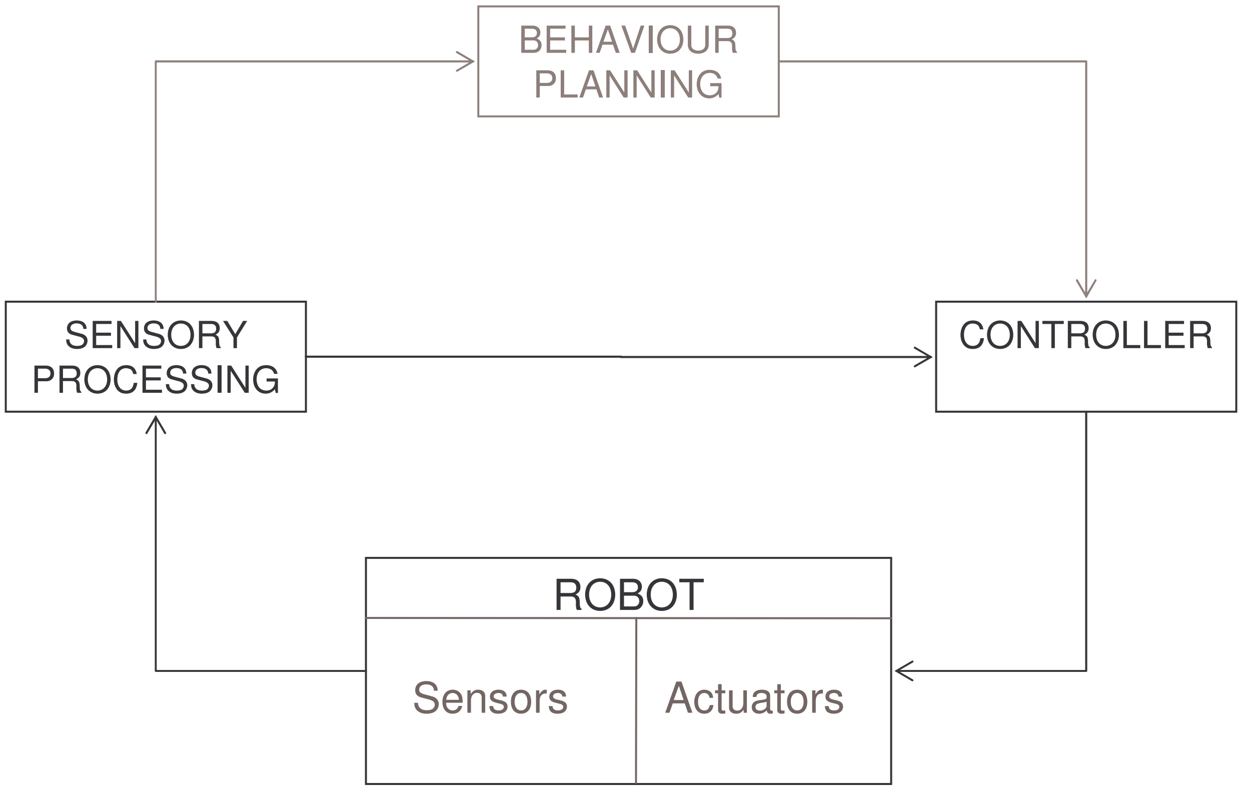
Robin Murphy, *Introduction to AI Robotics*, MIT Press, 2000

Basic scheme for robot behaviour control



Hierarchical architectures

Basic scheme for robot behaviour control



Reactive architectures

From hierarchical to reactive architectures

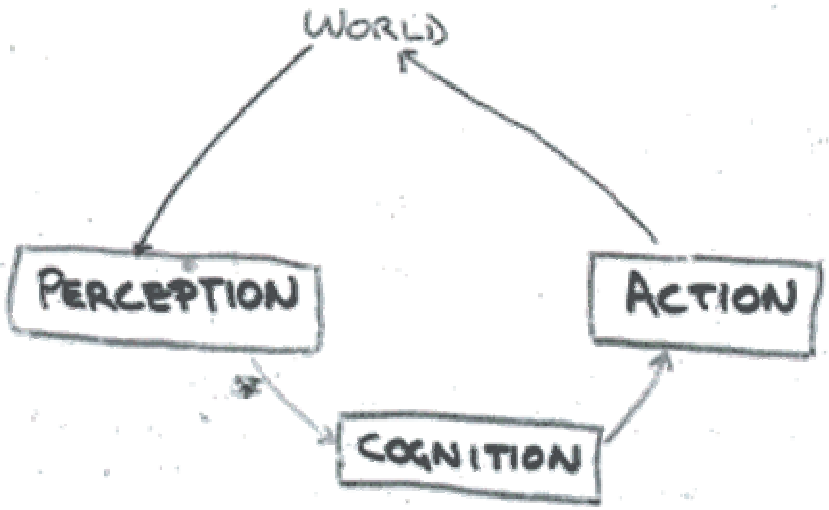


Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

deliberative, model-based

reactive, behavior-based

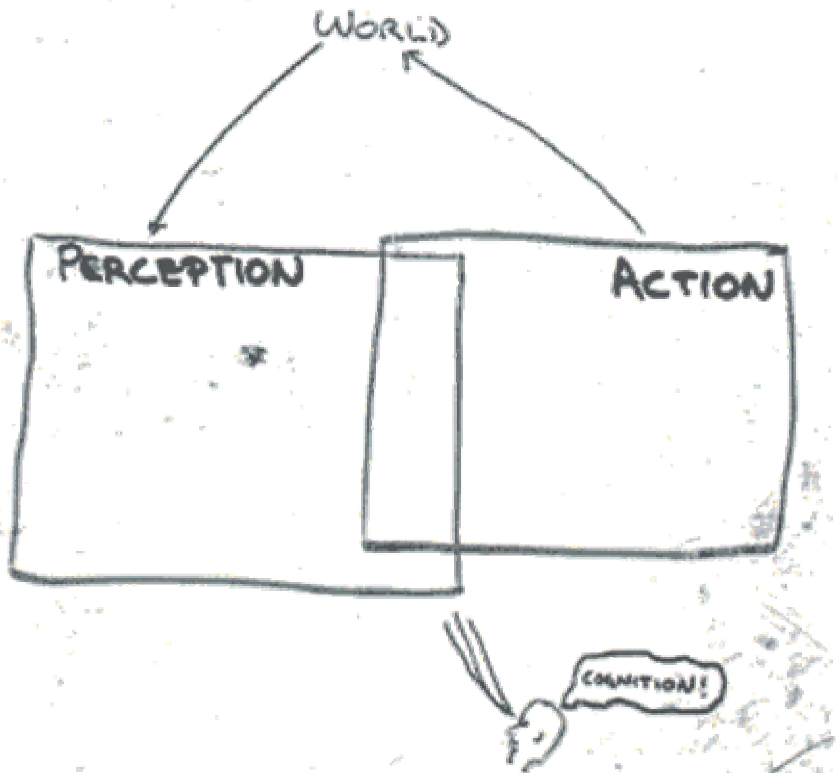
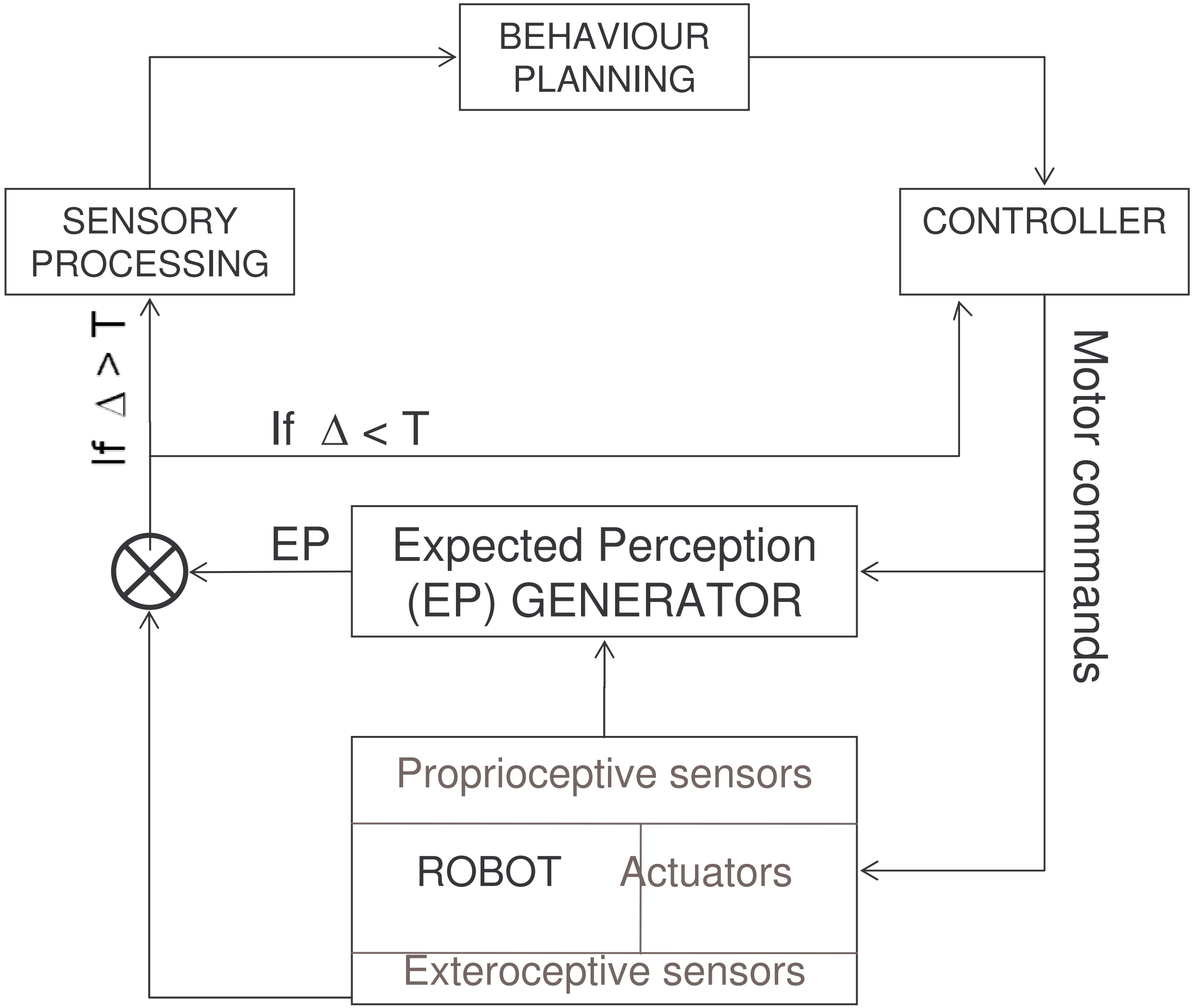


Figure 2: The new model, where the perceptual and action subsystems are all there really is. Cognition is only in the eye of an observer.

R. Brooks, *Cambrian Intelligence*
MIT Press, 2000

Basic scheme for robot behaviour control



Predictive architecture

Evolution of Robotics

NEED for helpful machines

Industrial Robotics

Industrial Automation

Service Robotics

Service Applications

Biomedical Robotics

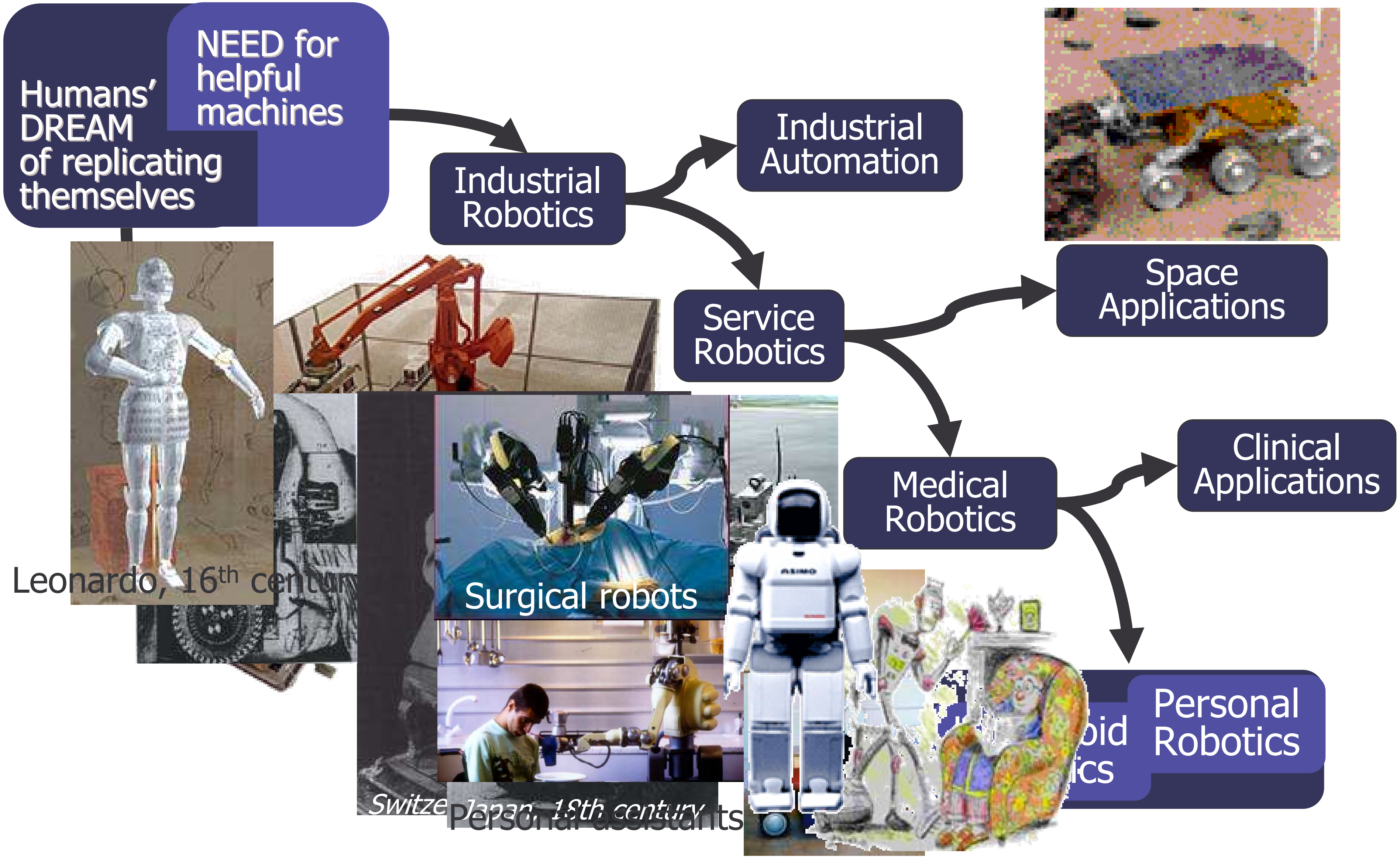
Clinical Applications

Personal Robotics

Surgical robots

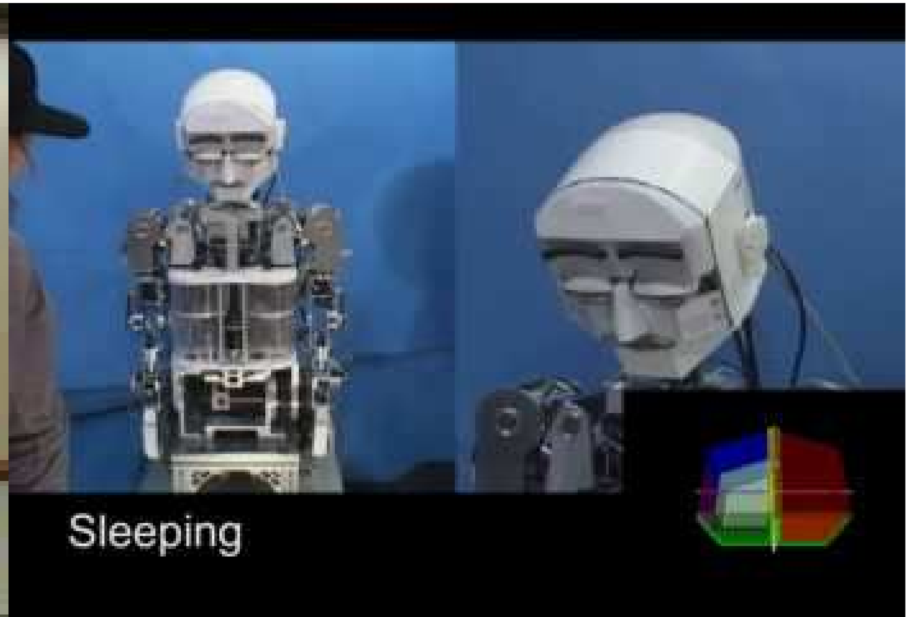
Personal assistants

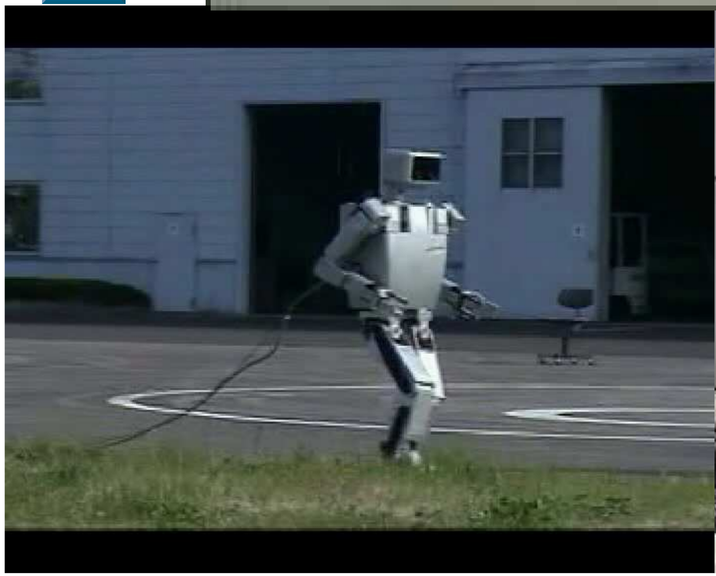
The Evolution of the Concept and Implementation of Robotics



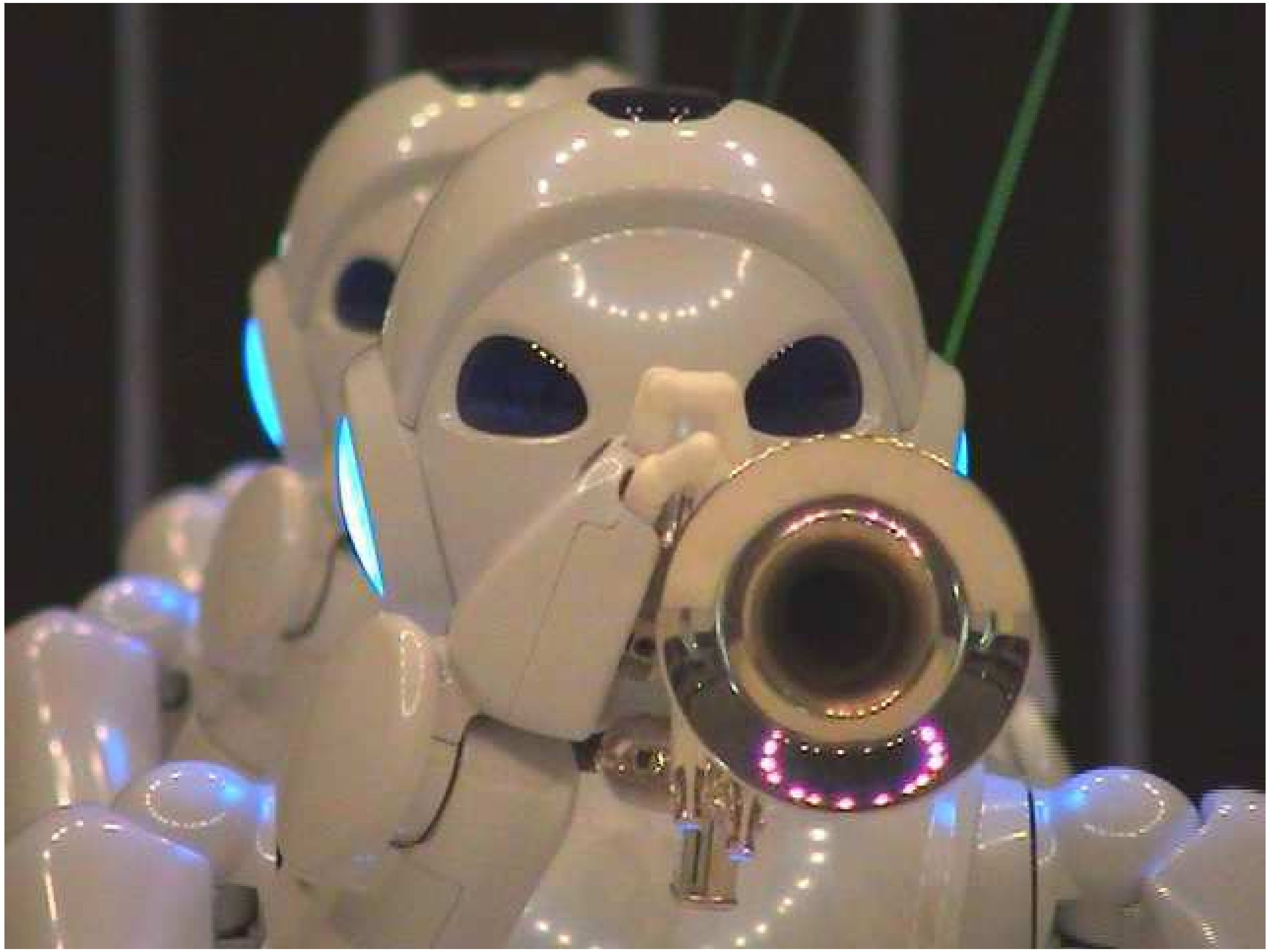
Few examples of today humanoid robotics

Few examples of humanoid robotics today





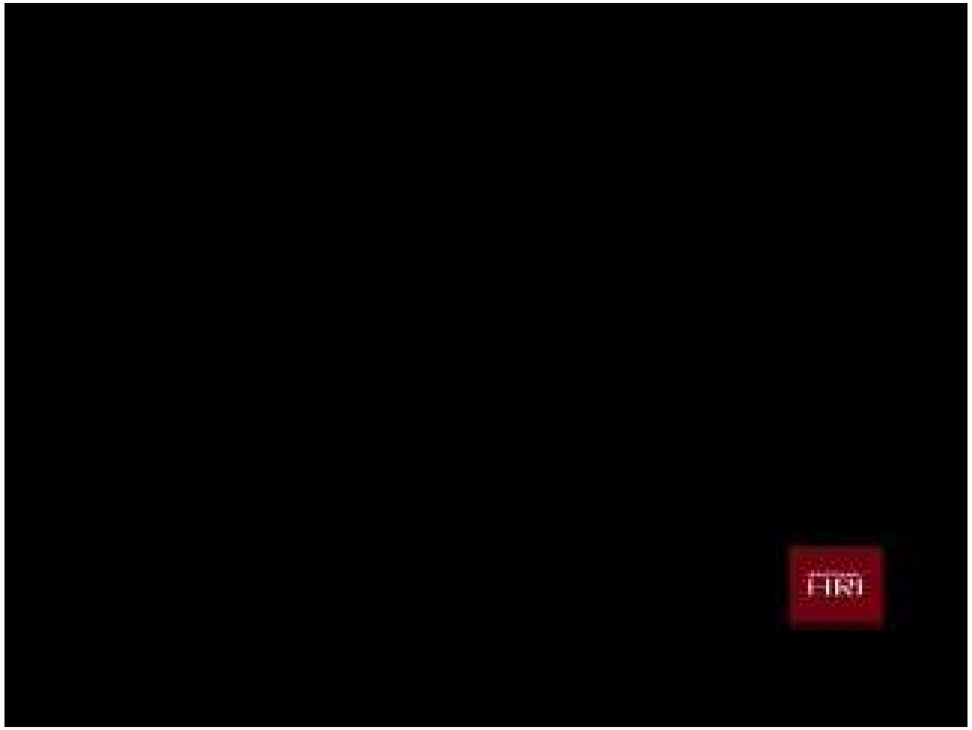
Toyota Partner Robot



The current challenge of humanoid robotics

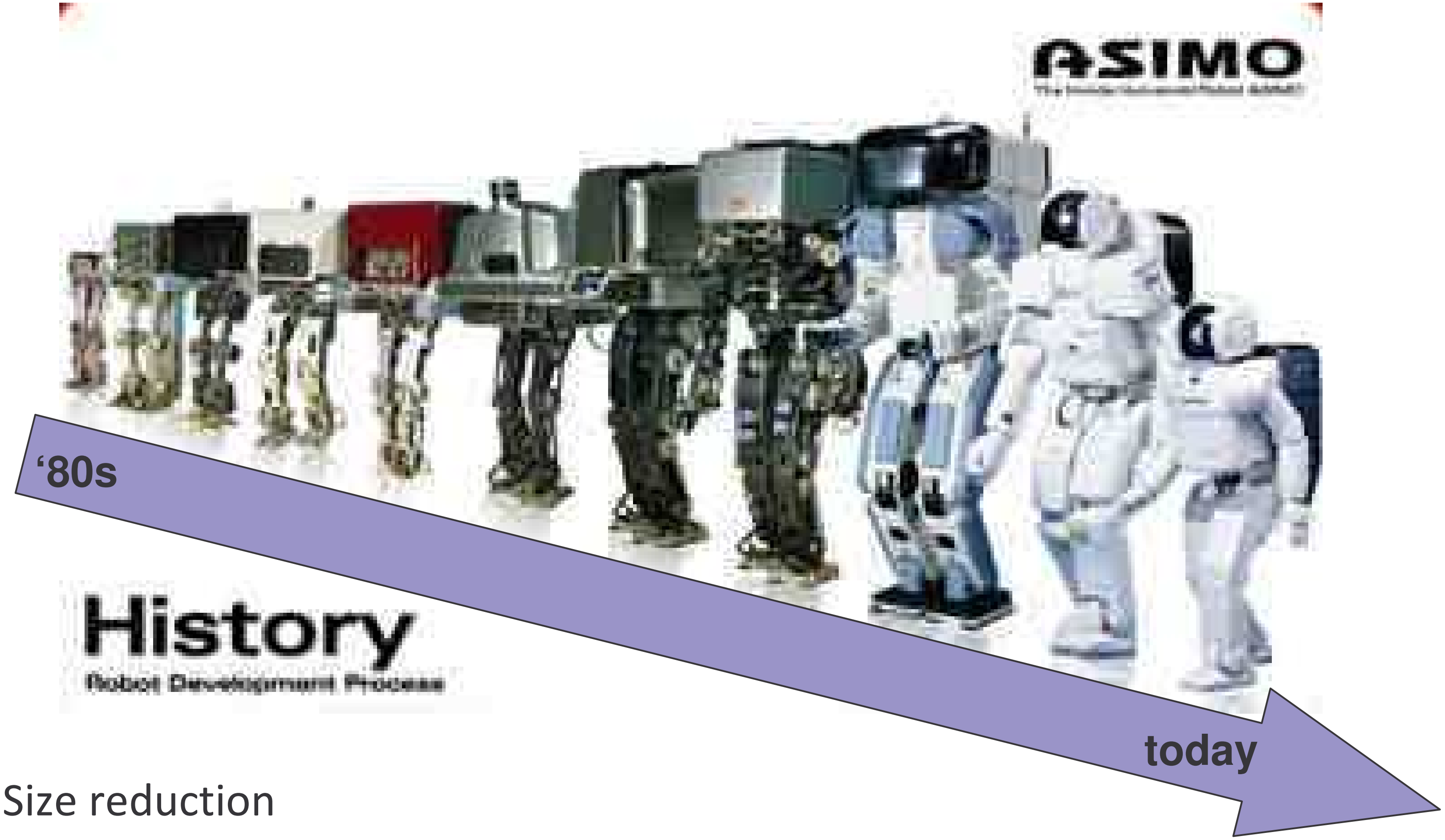
- A team of fully autonomous robots that can compete against the World Soccer Champion team by the year 2050

The evolution of walking abilities of humanoid robots at Waseda University, Tokyo



From early ’70 to 2006

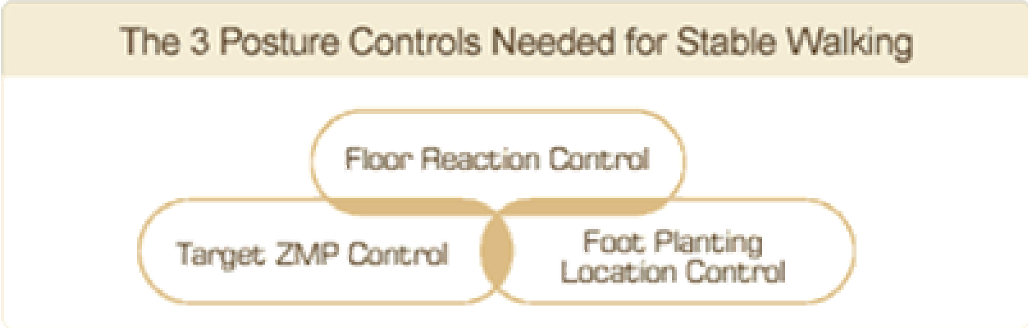
The evolution of Honda humanoid robot



- Size reduction
- Improvement of walking capabilities
- Current challenge: running

Honda walking strategy

A Posture Controls to Achieve Stable Walking

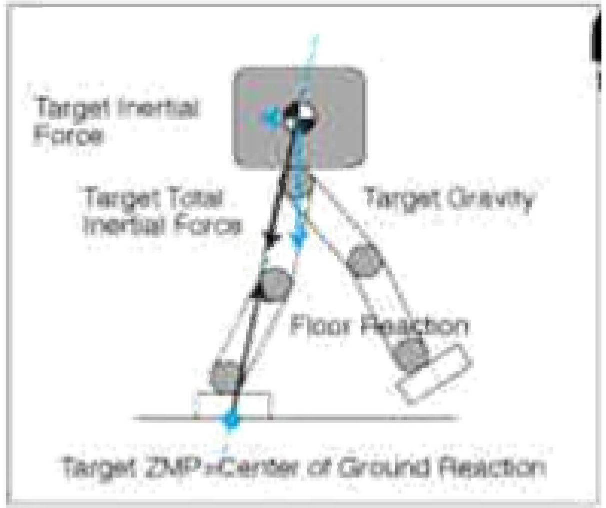


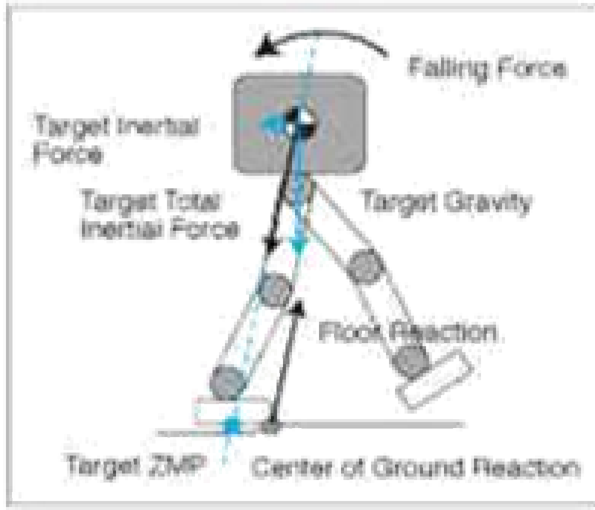
Floor Reaction Control : Firm standing control of the soles of the feet while absorbing floor unevenness.

Target ZMP Control : Control to maintain position by accelerating the upper torso in the direction in which it threatens to fall when the soles of the feet cannot stand firmly.

Foot Planting Location Control : Control using side steps to adjust for irregularities in the upper torso caused by target ZMP control.

* ZMP = Zero Moment Point: The point when total inertial force is 0.

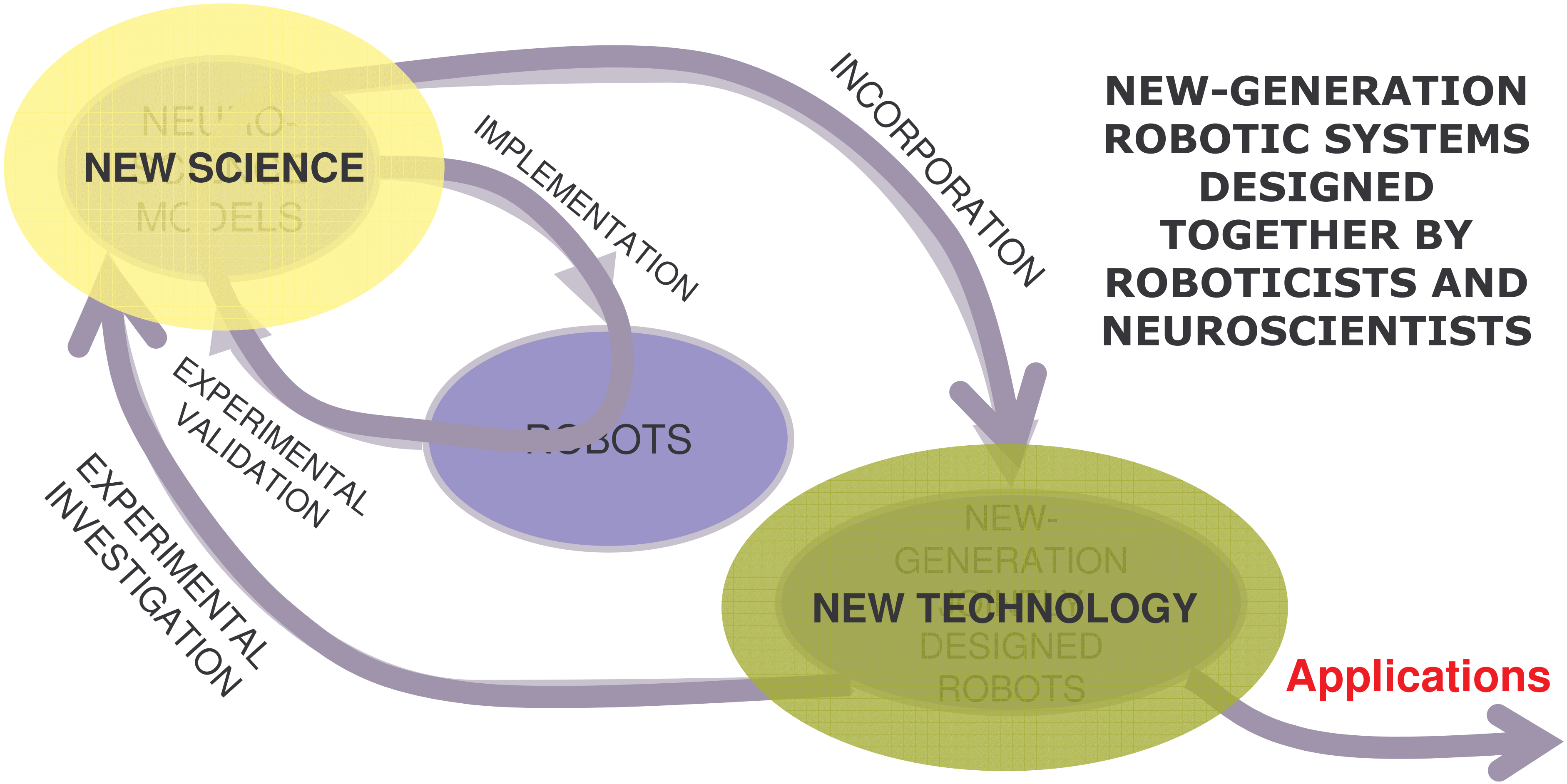




- Walking is based on stability

Joint design of new-generation robotic systems

A step further in the two-way collaboration between Neuroscience and Robotics



NEW-GENERATION ROBOTIC SYSTEMS DESIGNED TOGETHER BY ROBOTICISTS AND NEUROSCIENTISTS

Biomechatronic design

Biological system

Analysis and engineering modeling

Validation

Development of a physical model

Development of a biomedical robot

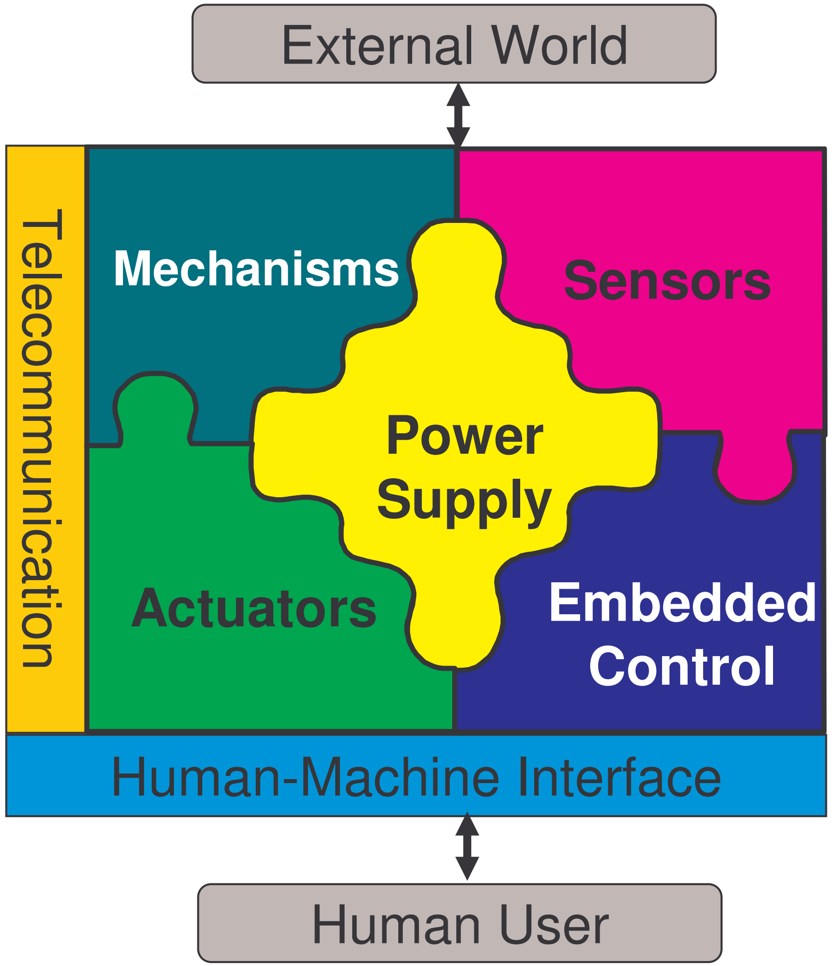
Bio-mimetic robot

Bio-inspired robot

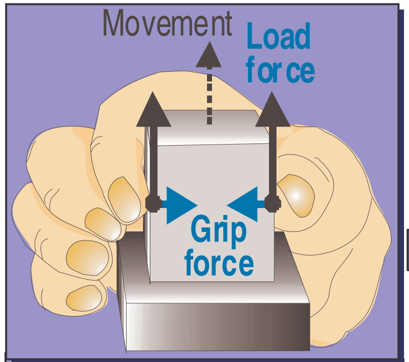
Applications

Biomechatronic design

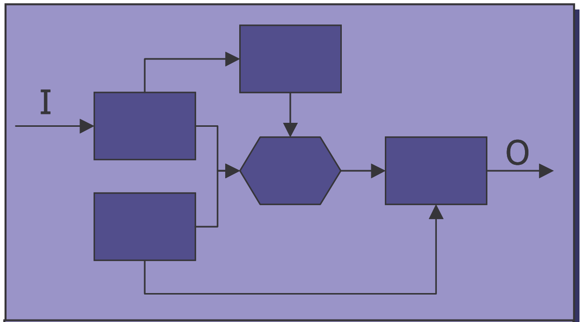
Joint design of the different components of the system



Biorobotics Science

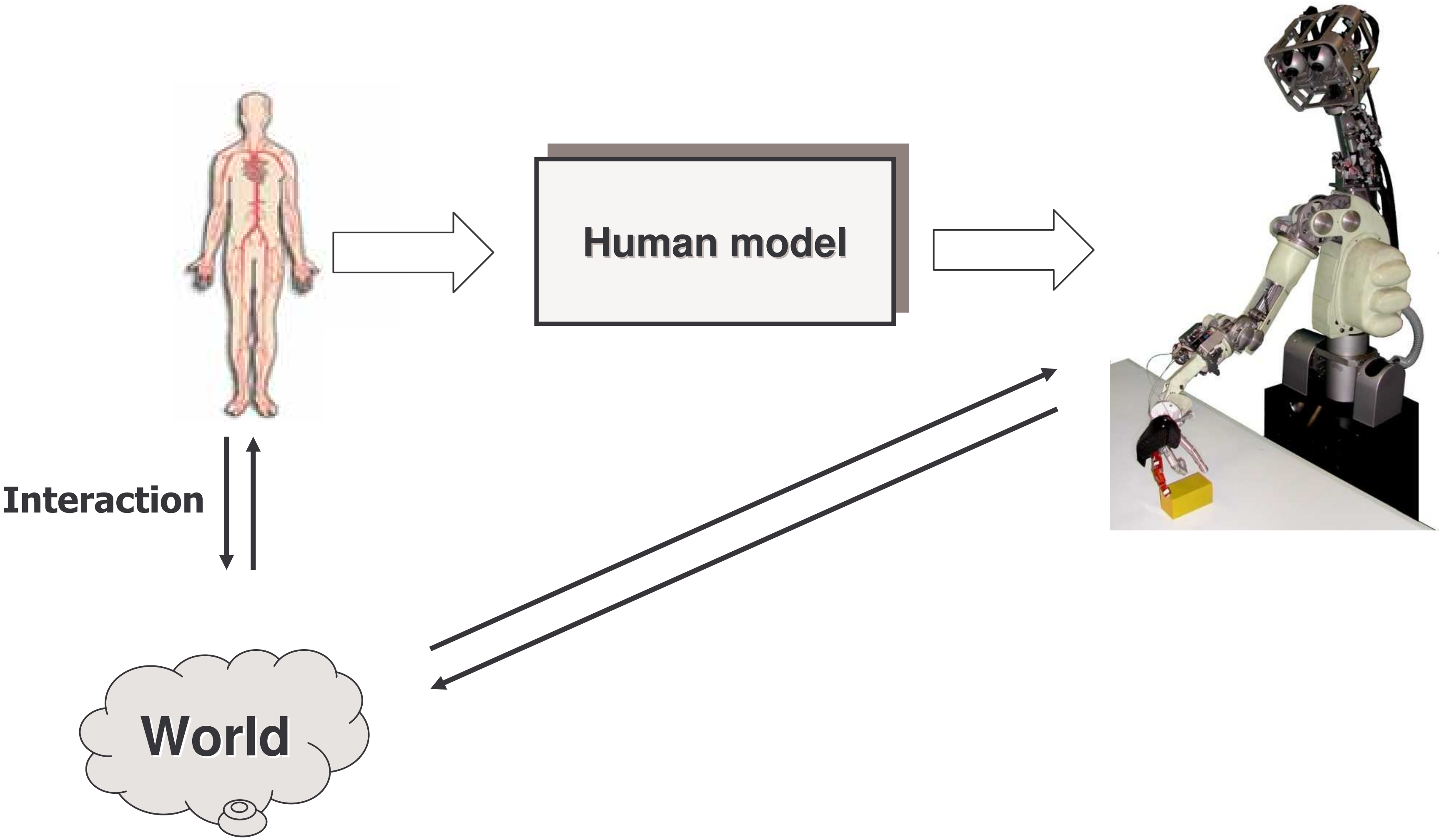


PHENOMENON TO BE EXPLAINED

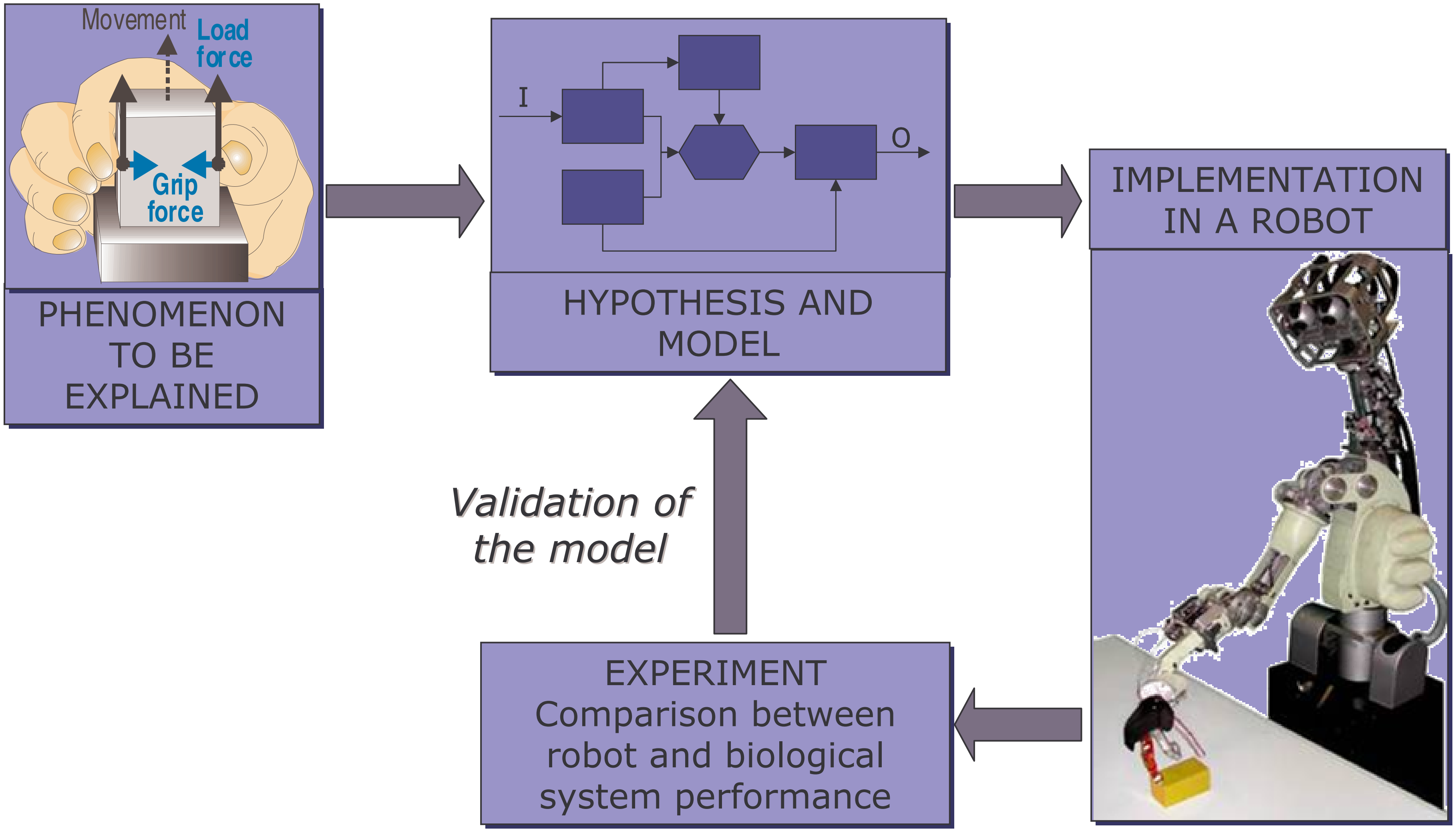


HYPOTHESIS AND MODEL

Biorobotics vs. simulation and animal models



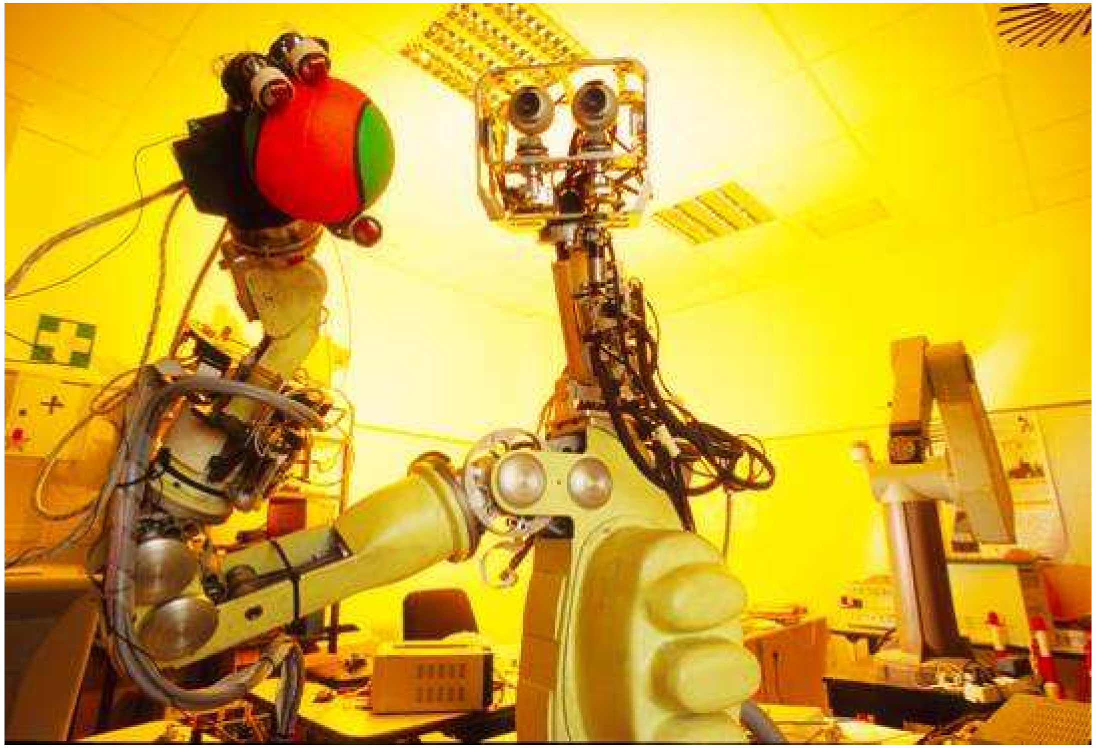
Biorobotics Science



A robotic platform for validating a model of development of sensory-motor grasp control

Objectives:

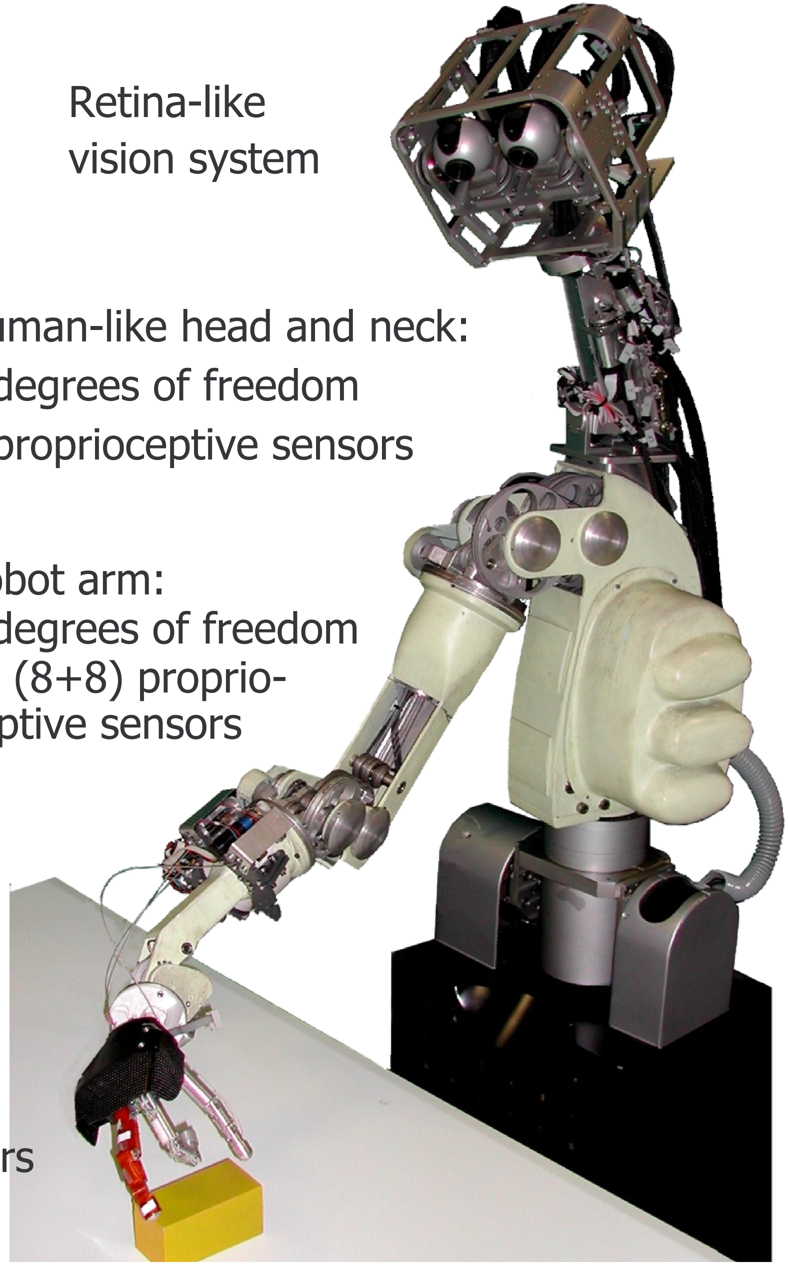
- To increase knowledge of brain connectivity (architecture) and brain activity (functioning) concerning sensory motor coordination for object manipulation in children
- To integrate an anthropomorphic robotic platform for **grasping and manipulation** to validate a neurophysiological model of the **five learning phases** of **visuo-tactile-motor coordination** in infants



P. Dario, M.C. Carrozza, E. Guglielmelli, C. Laschi, A. Menciassi, S. Micera, F. Vecchi, "Robotics as a "Future and Emerging Technology: biomimetics, cybernetics and neuro-robotics in European projects", *IEEE RAM*, Vol.12, No.2, June 2005, pp.29-43.

PALOMA EU IST-FET Project IST-2001-33073

Building a humanoid to understand human beings (human brain)



Retina-like
vision system

Human-like head and neck:
7 degrees of freedom
7 proprioceptive sensors

Robot arm:
8 degrees of freedom
16 (8+8) proprio-
ceptive sensors

Biomechatronic hand:
10 degrees of freedom
13 proprioceptive sensors
12 tactile sensors

Degrees of freedom	25
Proprioceptive sensors	36
Tactile sensors	12
Visual sensors	2

Biorobotics epistemology

Proto-Cybernetics (J. Loeb 1905, 1912; H. S. Jennings 1906)
Mechanicism Vs. Functionalism for studying the behavior of living organisms

If a machine is implemented on the basis of a theory of behavior, and *it behaves according to what this theory allows to predict*, this test reinforces the proposed theory

Cybernetics (Rosenblueth, Wiener, Bigelow 1943)

Unified approach to the study of living organisms and machines

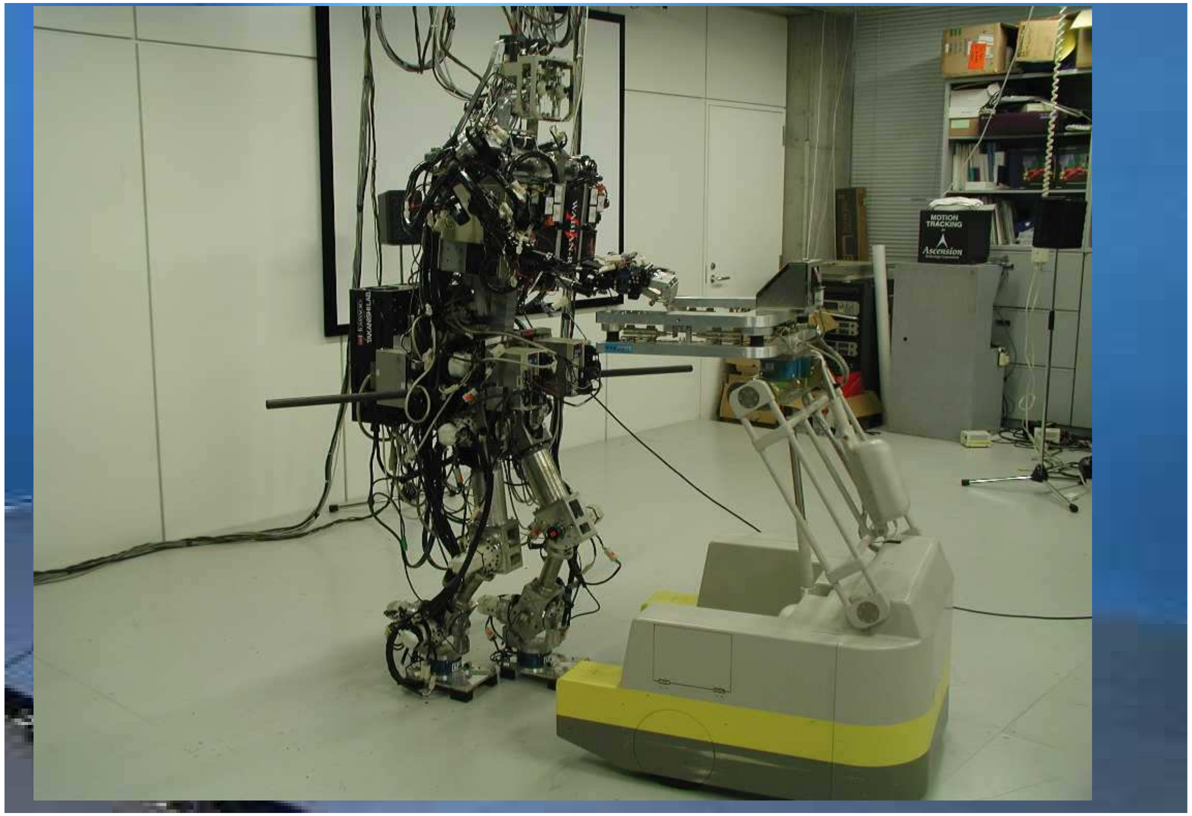
Purposive adaptive behaviors (in animals and humans) are produced by *feedback machines (teleology)*

Machines as 'material models' useful for testing scientific hypotheses

Machines are used for SCIENCE

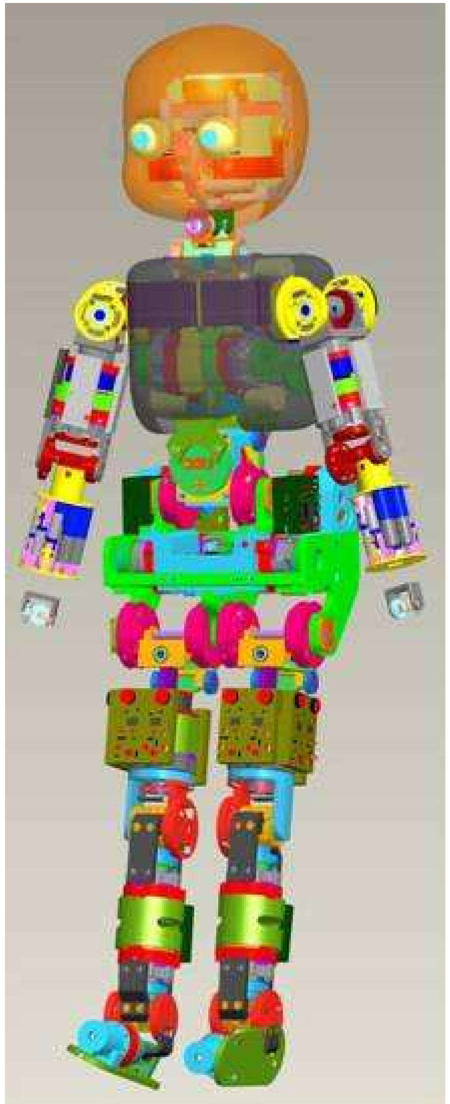
Un robot umanoide come modello del cammino umano

Walking robot Wabian-2R



WABIAN come simulatore dell'Uomo e strumento per la progettazione e la valutazione quantitativa di sipositivi di supporto alla deambulazione

Capire come il cervello degli esserei viventi trasforma l'input sensoriale in capacità motorie e cognitive, implementando modelli fisici di comportamenti senso-motori



EU RobotCub Project

G. Metta, G. Sandini, "Embodiment and complex systems. A commentary on Barbara Webb: Can robots make good models of biological behavior?", *Behavioral and Brain Sciences* 24(6) pp. 1068-1069, 2001.

From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model

Auke Jan Ijspeert,[1*] Alessandro Crespi,[1] Dimitri Ryczko,[2,3] Jean-Marie Cabelguen[2,3]

The transition from aquatic to terrestrial locomotion was a key development in vertebrate evolution.

An amphibious salamander robot demonstrates how a primitive neural circuit for swimming can be extended by phylogenetically more recent limb oscillatory centers to explain the ability of salamanders to switch between swimming and walking.

The model suggests neural mechanisms for modulation of velocity, direction, and type of gait that are relevant for ALL tetrapods.

9 MARCH 2007 VOL 315 SCIENCE www.sciencemag.org

CPG Model and the Robot

Unordered list of technological challenges in current robotics

- Flexibility of mechanical structures
- Compliance of joints
- Payload/mass ratio
- Miniaturization
- Distributed sensing
- Massive sensory processing
- Power supply
- User interfaces
- Human-robot interaction
- Cognitive capabilities
- Learning capabilities

(derived from draft EURON Roadmaps)

Organization of the survey on **sensors** and **actuators**

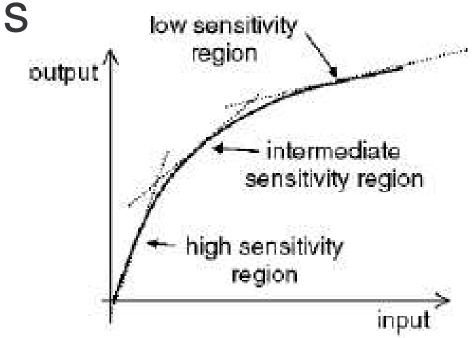
	SENSORS	ACTUATORS
SSSA	Inertial	EAP
IIT	Proprioceptive	Pneumatic SMA
UZH	Haptic	Piezoelectric
FORTH	Vision	

Fundamental characteristics of a sensor (1/3)

A sensor is a device that responds to a change of a physical phenomena (*stimulus* or *measurand*) and converts the physical quantity into an electric signal.

- **Transfer function:** the relationship between the input stimulus and its output response

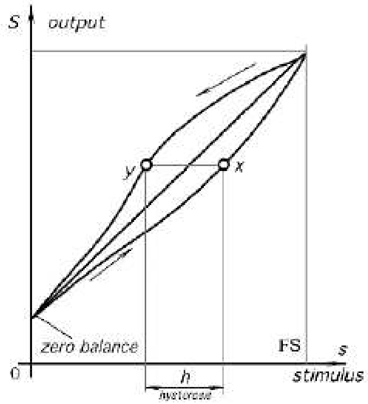
- **Range (or span):** the difference between the minimum and maximum inputs that will give a valid output
- **Resolution:** the minimal variation of the stimulus value that can be measured
- **Sensitivity:** the ratio between the change in the output signal and the change in the input stimulus



- **Calibration:** process used to know the actual relationship between an output value and its corresponding input value

Fundamental characteristics of a sensor (2/3)

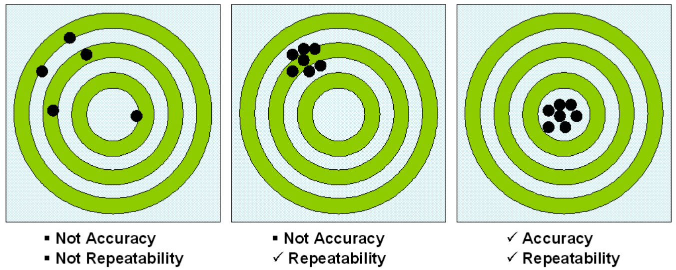
- **Hysteresis:** the maximal difference between the two tracts (curve of increasing values and curve of decreasing values) of the hysteresis loop



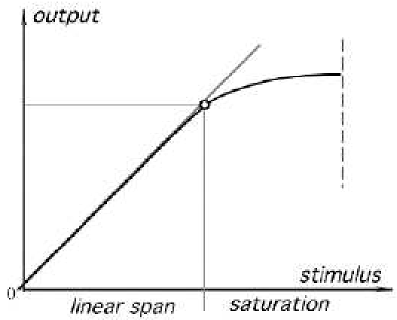
- **Error:** the difference between a measured value and the true input value (systematic error vs. random error)
- **Linearity:** maximal difference between the hysteresis loop and the ideal straight line of linearity
- **Repeatability:** the sensor's capacity of responding with the same output to identical input values given, under the stated conditions
- **Reliability:** the capacity of a sensor to perform in a defined manner and know modality, under stated condition and for a stated period

Fundamental characteristics of a sensor (3/3)

- **Accuracy:** the sensor's maximal deviation value from the output value and the true value of the stimulus



- **Saturation:** level limit, after that a further increase in stimulus doesn't generate an noticeable signal in output



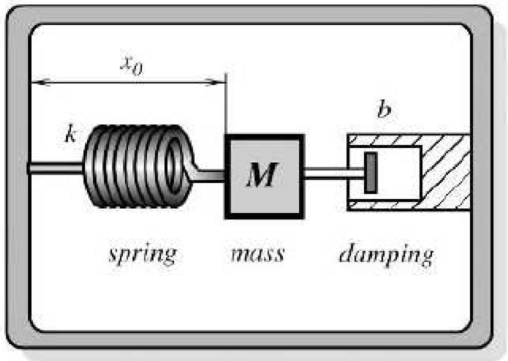
- **Dead Band:** insensitivity range inside the total input signal range, where the output signal approximately has the same value (usually near zero) for the entire dead band zone
- **Dynamic characteristics:** all the time-dependent parameters: zero-shift error, sensibility drift, warm-up time...

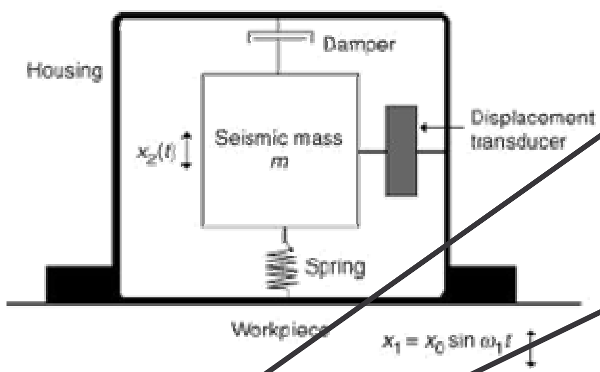
Organization of the survey on **sensors** and **actuators**

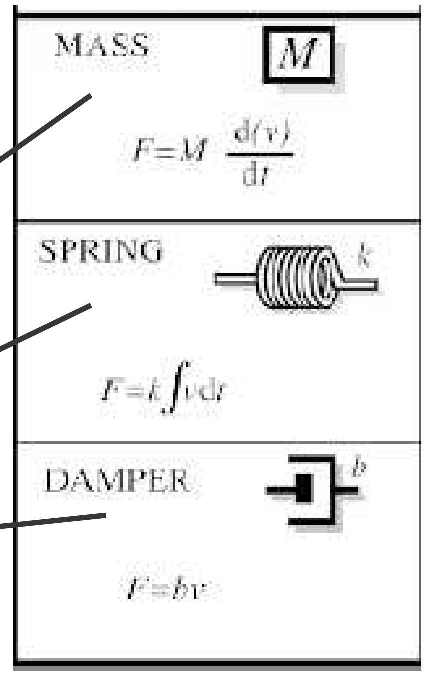
	SENSORS	ACTUATORS
SSSA	Inertial	EAP
IIT	Proprioceptive	Pneumatic SMA
UZH	Haptic	Piezoelectric
FORTH	Vision	

Inertial sensors: Accelerometers

A basic principle behind the transduction of velocity or acceleration is the measurement of the displacement of an object in respect to a reference system, which is usually integral part of the sensor itself.



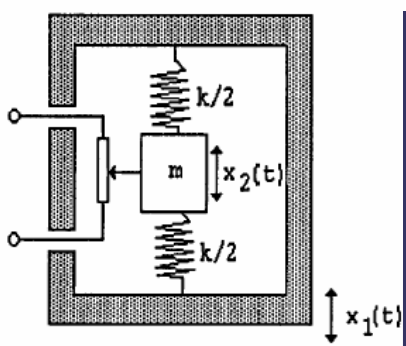


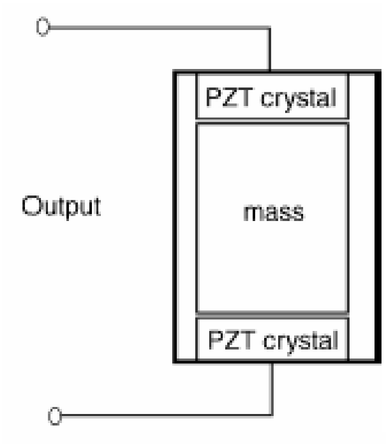


$$
\begin{cases}
Mf = -kx - b\dfrac{dx}{dt} \\
f = \dfrac{d^2x}{dt^2} - \dfrac{d^2y}{dt^2} \\
M\dfrac{d^2x}{dt^2} + b\dfrac{dx}{dt} + kx = M\dfrac{d^2y}{dt^2}
\end{cases}
$$

Principles of Accelerometers

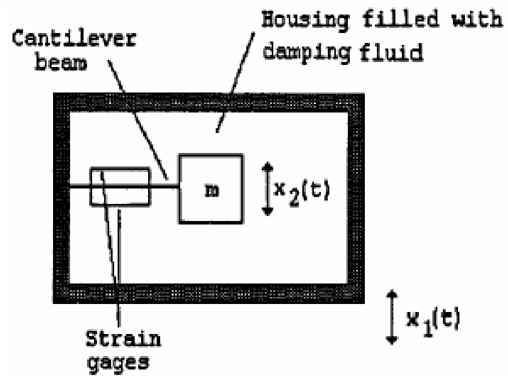
Potentiometric



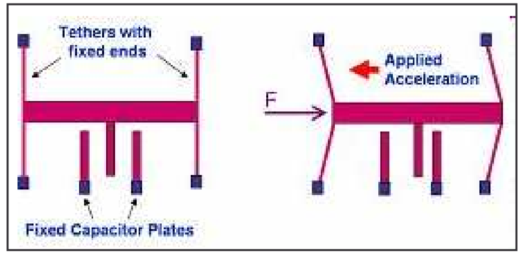


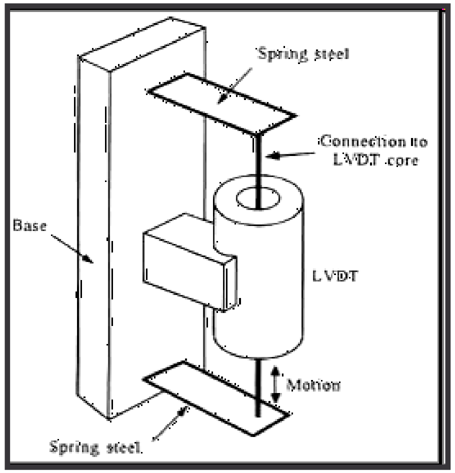
Piezoelectric

Piezoresistive



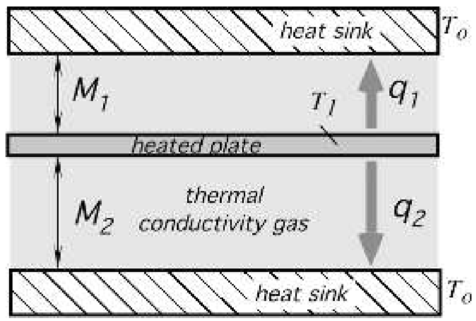
Capacitive





Inductive

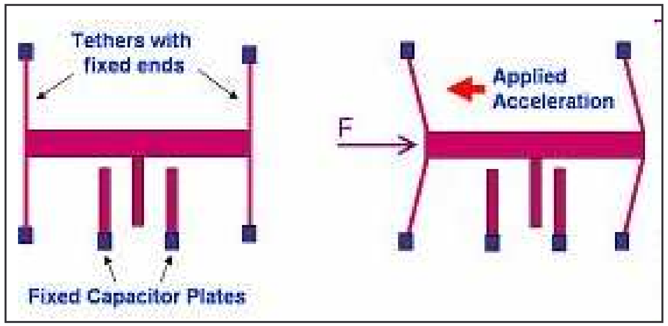
Thermal

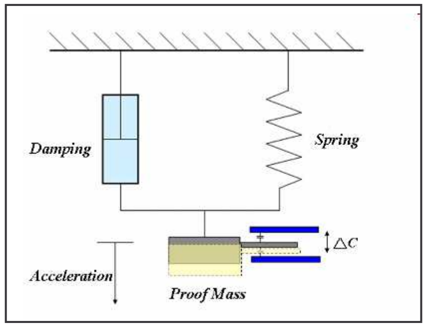


Practical examples: *Nintendo Wii*

The Wii Remote has the ability to sense acceleration along three axes through the use of an ADXL330 accelerometer

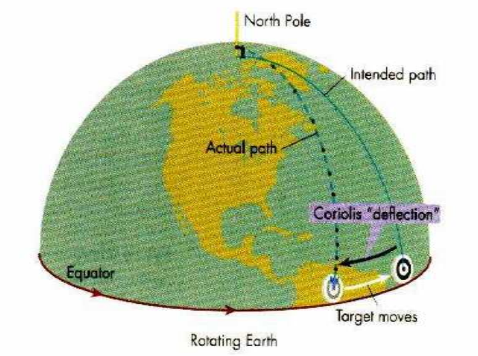
The sensor is a polysilicon surface micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. Acceleration deflects the moving mass and unbalances the differential capacitor resulting in a sensor output whose amplitude is proportional to acceleration.

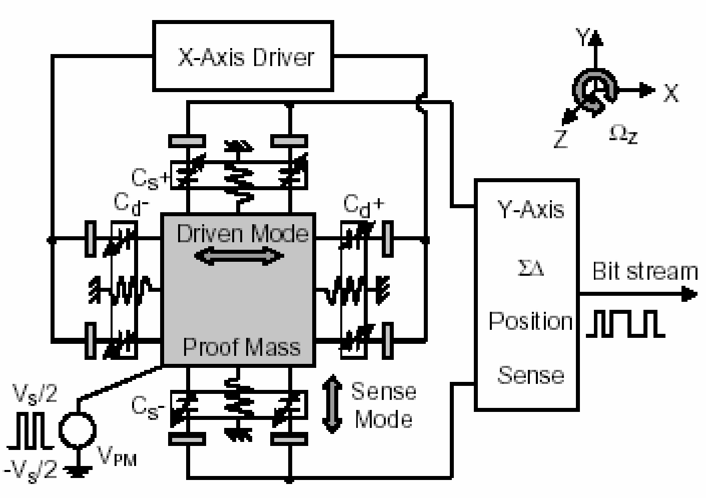




Inertial sensors: Gyroscopes

The basic principle of operation of such sensors is that the vibratory motion of part of the instrument creates an oscillatory linear velocity. If the sensor is rotated about an axis orthogonal to this velocity, a **Coriolis acceleration** is induced. This acceleration modifies the motion of the vibrating element and it will indicate the magnitude of the applied rotation.





Vibrating mass gyroscopes

A vibrating element (vibrating resonator) creates an oscillatory linear velocity

Sensor rotation about an axis orthogonal to its velocity

⬇

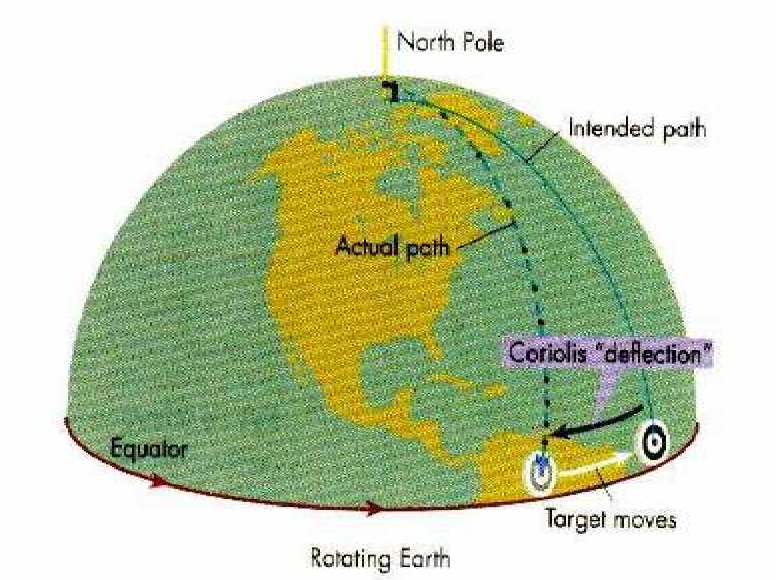
Coriolis force $F_C = -2m(\omega \times v)$

⬇

secondary vibration orthogonal to the original vibrating direction

⬇

detection of the *rate of turn*


North Pole
Intended path
Actual path
Coriolis "deflection"
Equator
Target moves
Rotating Earth

Practical examples: *xsens*

The MTi is a miniature size and low weight 3DOF Attitude and Heading Reference System (AHRS).

- **3D Gyroscopes**
- **3D Accelerometers**
- **3D Magnetometers**

The gyroscopes are used to calculate orientation. Integration drift is inevitable whilst using gyroscopes. To compensate for drift completely, the MTi corrects its orientation every sample using the gravity and the earth magnetic field as reference vectors.

Practical examples

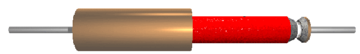
http://www.invensense.com/support/videolibrary.html

What is an Actuator?

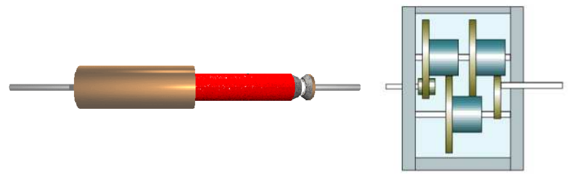
Actuators can be seen as a system that establishes a flow of energy converting some form of input power (typically electrical power) into mechanical power.

Considering actuators merely from the point of view of their energy conversion principle can be misleading. The actuator is in fact a system, where motion conversion plays a central role. Three cases (SMA, PZT and Electromagnetic) are here considered as “Effectors”, “Motors”, “Autonomous Effectors” and “Autonomous Motors”.

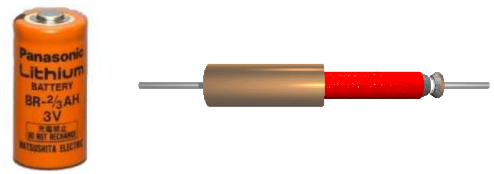
Actuator = “<u>Effector</u>”



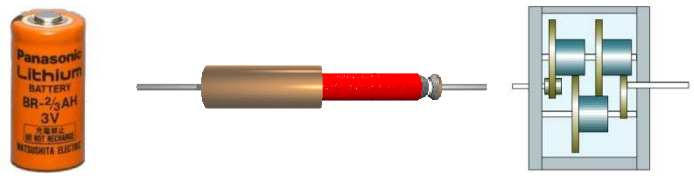
Actuator = “<u>Motor</u>”



Actuator = “<u>Autonomous Effector</u>”



Actuator = “<u>Autonomous Motor</u>”



Fundamental characteristics of an actuator (1/2)

- **Stress:** the typical force (*F*) per cross-sectional area (*A*) under which the actuator materials are tested

$$\sigma = \frac{F}{A} \qquad \left[\frac{N}{m^2} = Pa\right]$$

- **Strain:** the displacement (l_f-l_0) normalized by the original material length (l_0) in the direction of actuation

$$\varepsilon = \frac{l_f - l_0}{l_0} \qquad \left[\frac{m}{m}\right]$$

- **Strain rate:** is the average change in strain per unit time during an actuator stroke
- **Power density:** the power output (P_{out}) per unit volume (*V*) of actuator material and represents a measure of the rate of energy delivery at the mechanical port

$$P_V = \frac{P_{out}}{V} \qquad \left[\frac{W}{m^3}\right]$$

- **Work density:** the amount of work generated in one actuator cycle (W_{out}) normalized by actuator volume (*V*)

$$W_V = \frac{W_{out}}{V} \qquad \left[\frac{W}{m^3}\right]$$

- **Time constant:** the time taken for the output parameter of a first order system to reach 63.2% of its final value upon the application of a step input

Fundamental characteristics of an actuator (2/2)

- **Frequency bandwidth:** the available bandwidth of an actuator defined by the "cutoff frequency", that is the frequency at which strain drops to half of its low frequency amplitude

$$f = \frac{1}{2\pi\tau} \qquad [Hz]$$

- **Efficiency:** the transduction process of an actuator and is defined as the ratio of work generated (L_U) to input energy expended (E_i)

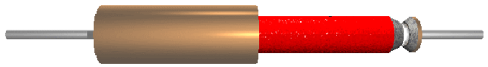
$$\eta = \frac{L_U}{E_i} \qquad \left[\frac{J}{J}\right]$$

- **Cycle life:** number of useful strokes that the material is known to be able to undergo
- **Elastic Modulus:** the material stiffness (K) multiplied by sample length (l_0) and divided by cross-sectional area (A), important as it determines the actuator's passive ability to reject load changes and disturbances

$$E = K\frac{l_0}{A} \qquad \left[\frac{N}{m}\frac{m}{m^2} = \frac{N}{m^2} = Pa\right]$$

The Actuator as a system

Actuator = "Effector" = Energy transducer

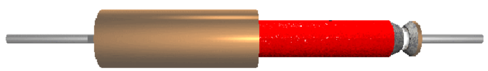


	Stress (MPa)	Strain	Efficiency	Bandwidth (Hz)	Power (W/cm^3)
Electromagnetic	0.02	0.5	90 %	20	0.1
SMA	200	0.1	3 %	3	30
Piezoelectric	35	0.002	50 %	5000	175

$$Power_{density,effector} = \frac{1}{2} \cdot \varepsilon\sigma \cdot BW$$

The Actuator as a system

Actuator = “Autonomous Effector”:
Energy transducer + supply

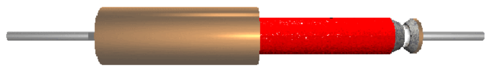


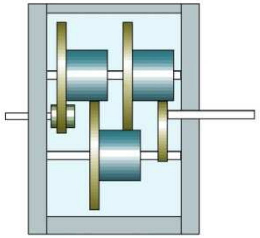

	Stress (MPa)	Strain	Efficiency	Bandwidth (Hz)	Power (W/cm³)
Electromagnetic	0.02	0.5	90 %	20	0.08
SMA	200	0.1	3 %	3	0.01
Piezoelectric	35	0.002	50 %	5000	0.2

$$Power_{density,aut.\_effector} = \frac{power_{density,effector}}{1 + \frac{1}{\eta_{transducer}} \cdot \frac{power_{density,effector}}{power_{density,battery}}}$$

The Actuator as a system

Actuator = "<u>Motor</u>":
Energy transducer + motion converter



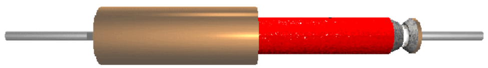


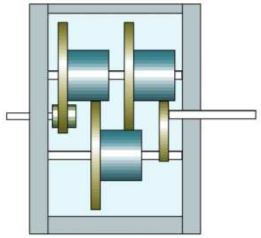
	Motion converter bulk ratio	Motion converter efficiency	Power (W/cm³)
Electromagnetic	1	80 %	0.04
SMA	10	50 %	1.4
Piezoelectric	100	30 %	0.52

$$Power_{density,motor} = \frac{power_{density,effector}}{1 + BR} \cdot \eta$$

The Actuator as a system

Actuator = "Autonomous Motor":
Energy transducer + supply + motion converter





	Motion converter bulk ratio	Motion converter efficiency	Power (W/cm^3)
Electromagnetic	1	80 %	0.035
SMA	10	50 %	0.006
Piezoelectric	100	30 %	0.054

$$Power_{density,aut.\_motor} = \frac{power_{density,effector}}{1+\frac{1}{\eta_{transducer}}\cdot\frac{power_{density,effector}}{power_{density,battery}}+BR}\cdot\eta$$

Transduction mechanism

- **Fluid-mechanical transduction:** convert the pressure of a fluid into mechanical energy, either rotational or translational
  - Pneumatic actuators
  - Hydraulic actuators

- **Thermomechanical transduction:** the input energy is in the thermal domain and the output energy in the mechanical domain
  - SMA
  - Thermal Active Polymers

- **Magnetomechanical transduction:** energy flow from the magnetic domain to the mechanical domain and vice versa

- **Electromechanical transduction:** the input electrical domain is transformed into mechanical energy
  - Piezoelectric actuators
  - SMA
  - EAP

Organization of the survey on **sensors** and **actuators**

	SENSORS	ACTUATORS
SSSA	Inertial	EAP
IIT	Proprioceptive	Pneumatic SMA
UZH	Haptic	Piezoelectric
FORTH	Vision	

ElectroActive Polymers (EAP)

Electro Active Polymers are an emergent class of materials that have the capability to modify their dimensions and shape when an electric stimulus is applied.

ELECTRIC (DRY) EAP

Materials that undergo to dimensional change in response to an electric field

Advantage	Disadvantage
Can operate in room conditions for long periods of time	Requires high voltages (~150 MV/m)
Rapid response time (mSec levels)	Requires compromise between strain and stress
Can hold strains under DC activation	Glass transition temperature is inadequate for low temperature actuation tasks
Induces relatively large actuation forces	

IONIC (WET) EAP

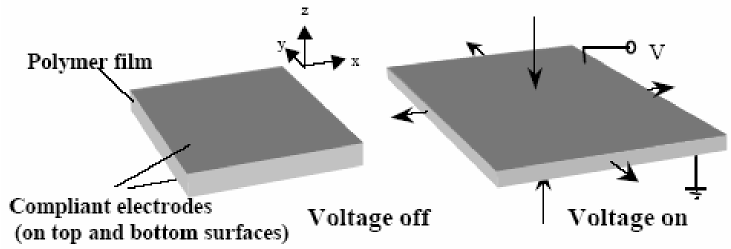
Materials that needs the presence and movement of ions to make actuation possible

Advantage	Disadvantage
Requires low voltage	Except for Conductive Polymers, Ionic EAPs don't hold strain under DC voltage
Provides predominately bending actuation (longitudinal mechanisms can be constructed)	Slow response (fraction of a second)
Exhibits large bending displacements	Bending EAPs induce a relatively low actuation force
	Except Conductive Polymers & Carbon Nanotubes, it is difficult to produce a consistent material (particularly Ionomeric Polymer-Metal Composites)
	In aqueous systems the material sustains hydrolysis at > 1.23V

Electric EAP 1/2

- **Dielectric Elastomers**

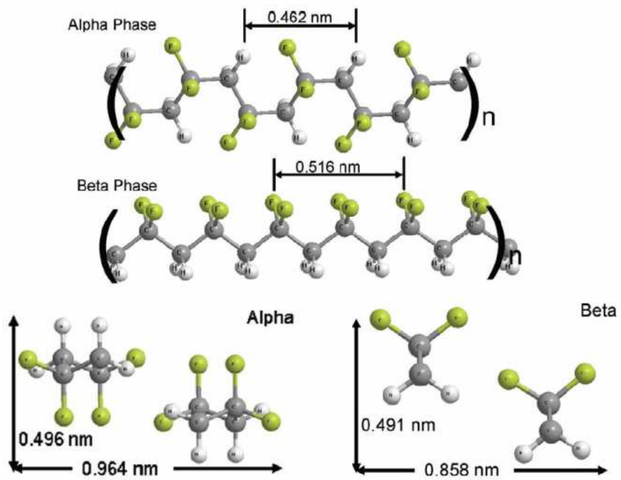
An electric field is applied across the sheet thickness through two compliant electrodes. The electrostatic interaction between the two electrodes with opposite electric charge causes a significant stress in the dielectric, known as Maxwell stress, which can compress and elongate the dielectric material at high strain rates



$$F = -\frac{dU}{dz} = \frac{\varepsilon_r \varepsilon_0 V^2}{z^2} A$$

- **Ferroelectric Polymers**

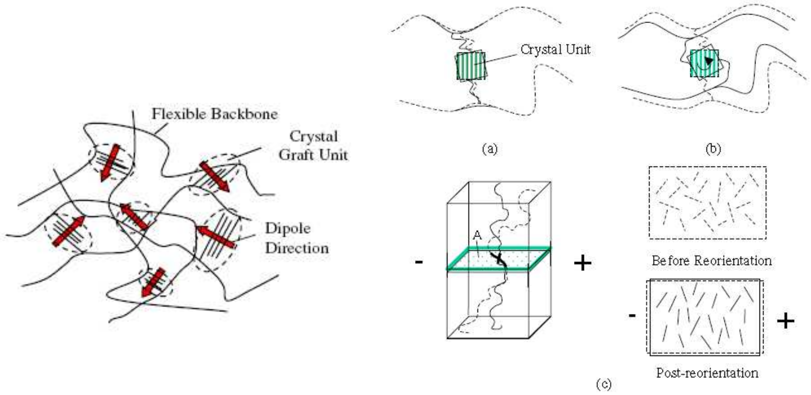
Ferroelectric materials, like ferromagnets, have dipoles that can be aligned producing permanent dimensional changes in response to an applied electric field (electrostrictive effect)



Electric EAP 2/2

- **Electrostrictive Graft Elastomers**

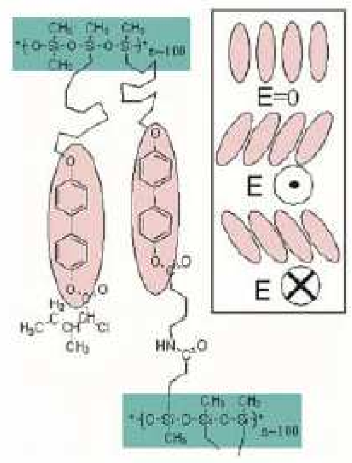
The flexible backbone chain and the crystal graft unit consist of polarized monomers, which contain atoms with electric partial charges, generating dipole moments. Upon application of an electric field to the polymer, force is applied to each partial charge, forming a force moment.



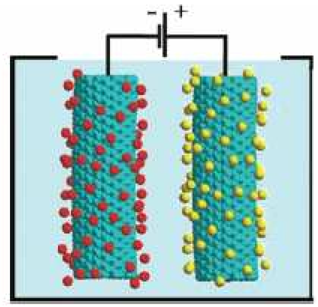
- **Liquid Crystal Elastomers**

Liquid crystals are known to change phase and orientation under the influence of an electrostatic force.

By incorporating mesogens into a compliant polymer backbone or as side chains, field-induced changes in phase can be used to produce actuation



Ionic EAP 1/2



- **Carbon Nanotubes**

The actuation principle of operation of CNTs is based on the use of these structures as electrodes in electrochemical supercapacitors.

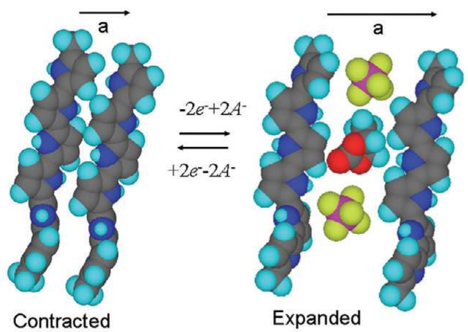
A voltage applied between an actuating nanotube electrode and a counter electrode (usually another CNT), both dipped in an ion containing solution, leads to charging.

Electrostatic repulsive forces between like charges on the CNTs work against the stiff carbon-carbon nanotubes bonds to elongate and expand the nanotubes.

- **Conducting Polymers**

The mechanism of actuation is based on the dimensional changes resulting from electrochemical uptake or expulsion of ions and solvent

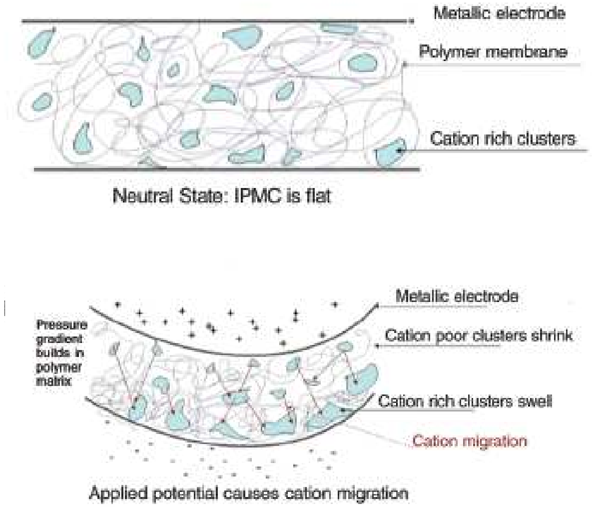
- Polypyrrole
- Polyanyline
- Polythiophene



Ionic EAP 2/2

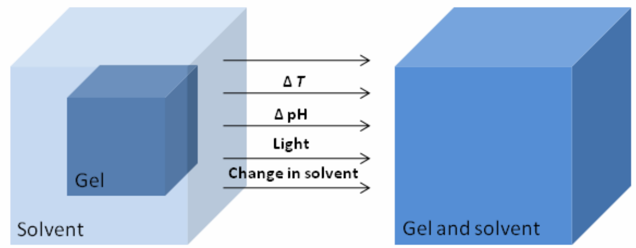
- **Ionic Plymer-Metal Composite**

This type of electrochemical artificial muscle employs a polyelectrolyte as an ion exchange membrane and metal thin layers as electrodes. The polyelectrolyte is sandwiched between the two flexible electrodes, which interpenetrate the polyelectrolyte. When a voltage is applied between the electrodes, the counterions tend to diffuse to the corresponding electrode, thus solvated mobile cations move toward the oppositely charged electrode, resulting in a migration that causes the deflection of the multi layered structure toward one of the metal electrode.



- **Active Gels**

The presence of the solvent inside the polymer network determines the physical properties (stiffness, shape etc) of the gel. By electrical means, polymer gels are able to swell by the uptake of solvent within the polymer matrix



EAP comparison

Actuator type	Strain (max) (%)	Stress (max) (MPa)	Work density (max) (J/cm³)	Specific power (max) (W/g)	Max strain rate (%/s)	Elastic module (MPa)	Max efficiency (%)
Skeletal Muscle	20 (40)	0.1 (0.35)	0.008	0.05	500	10 - 60	40
Dielectric Elastomers	25 (>300)	1.0 (7.0)	0.01 (3.4)	0.5	>450	0.1 – 10	80
Ferroelectric Polymer	3.5 (10)	20 (45)	0.32 (1)	NA	>2000	800	40
Electrostrictive Graft Elastomers	2.5	NA	0.5	NA	NA	600	NA
Liquid Crystal Elastomers	2 (4)	0.12 (0.45)	0.02	NA	1000	100	75
Carbon Nanotubes	<2	>10	1	0.01 (0.27)	19	1000 (sheet) 10000 (fibre)	<1
Conductive Polymers	2 (20)	5 (34)	0.1 (1.0)	(0.1)	10	800 – 3000	1
Ionic Polymer - Metal Composites	0.5 (3.3)	3 (30)	(0.006)	0.003	3.3	50 – 100	1.5 – 3
Active Gels	30	0.2 (1.2)	NA	0.001	NA	<10	NA

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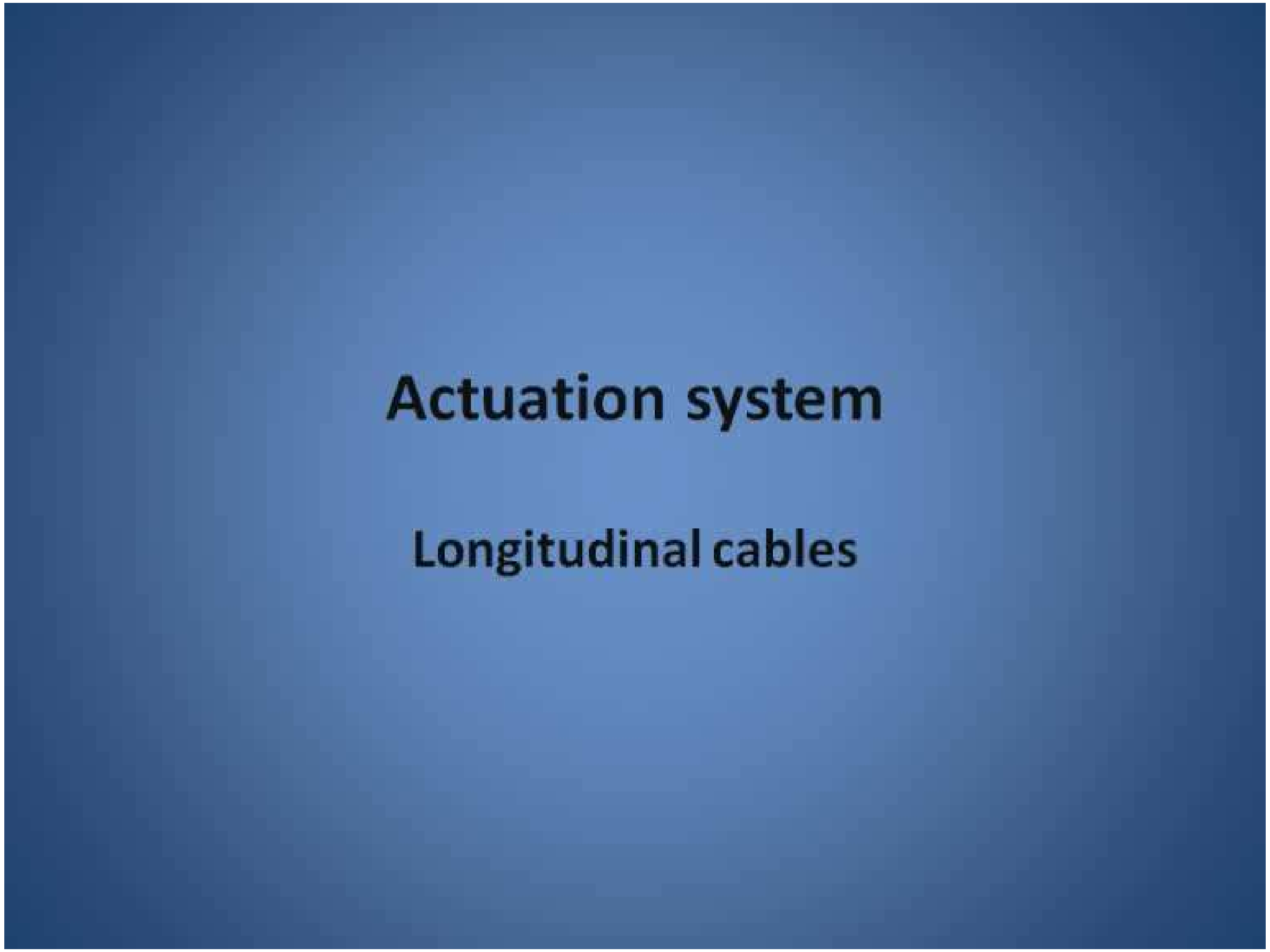
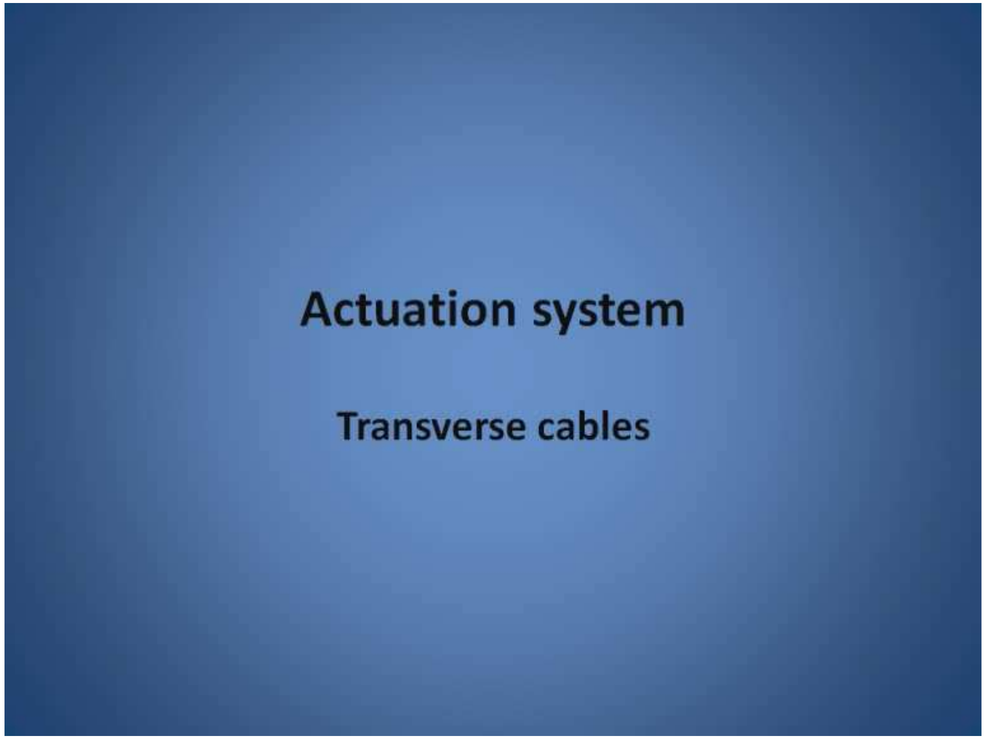
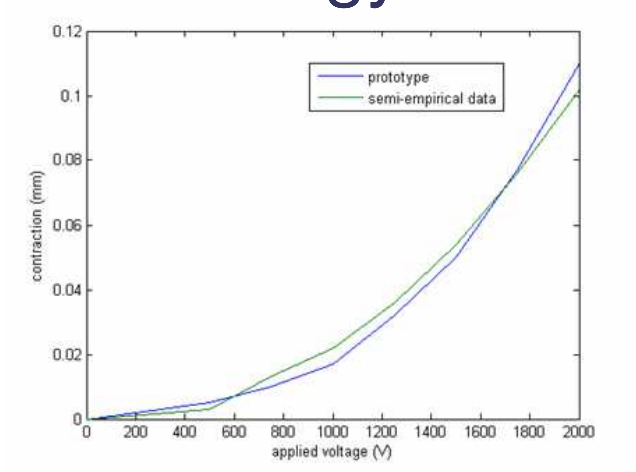
Actuation system - Longitudinal



Experiemental evaluation of EAP technology



Target: 20% contraction



- 300 µm silicone film
- 90 nm gold electrodes
- Laser measurement of contraction
- Labview interface to control the applied voltage