University of Pisa
Master of Science in Computer Science
Course of Robotics (ROB)
A.Y. 2018/19

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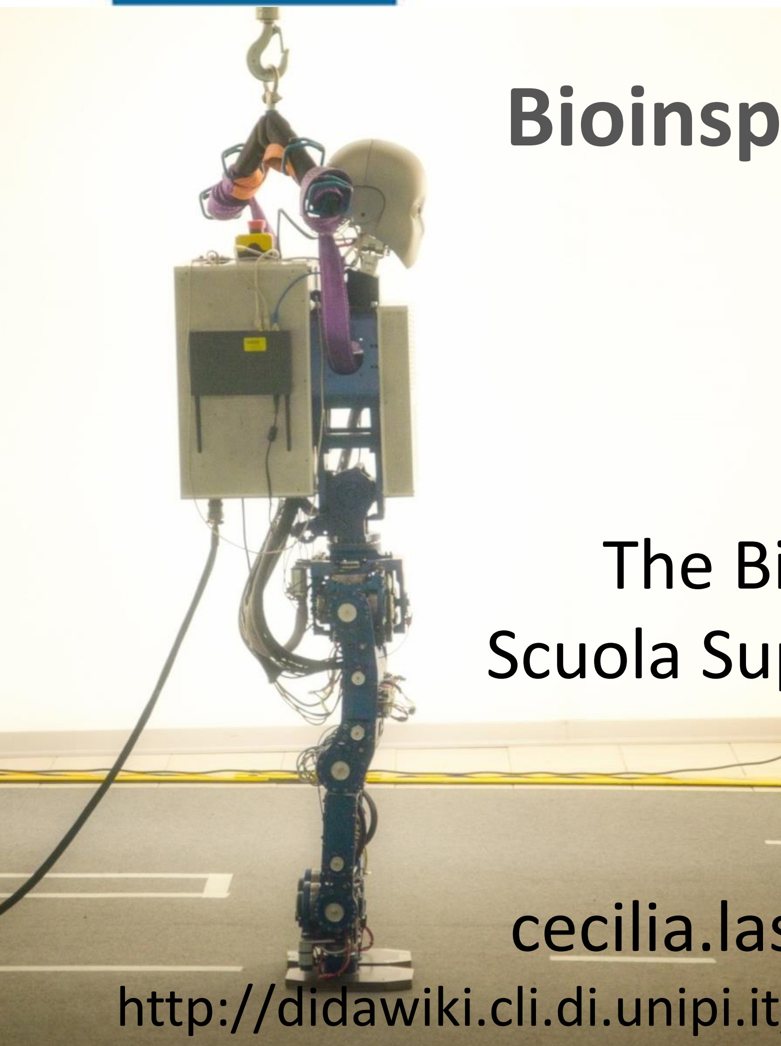
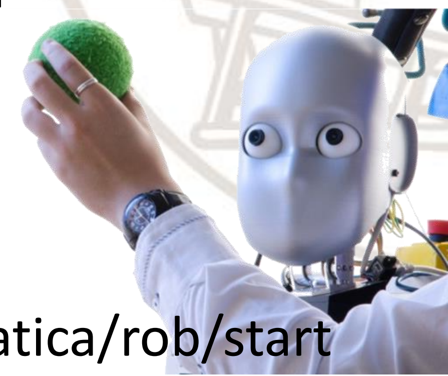


Bioinspired robotics

Cecilia Laschi
The BioRobotics Institute
Scuola Superiore Sant'Anna, Pisa

cecilia.laschi@santannapisa.it



http://didawiki.cli.di.unipi.it/doku.php/magistraleinformatica/rob/start

Outline of the lesson

- Scientific motivations to bioinspired robotics
- Bioinspired principles: simplexity and embodied intelligence
- Bioinspired control: neurocontrollers
- Bioinspired behaviour: predictive architectures
- Bioinspired perception

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- **Scientific motivations to bioinspired robotics**
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Evolution of robot abilities

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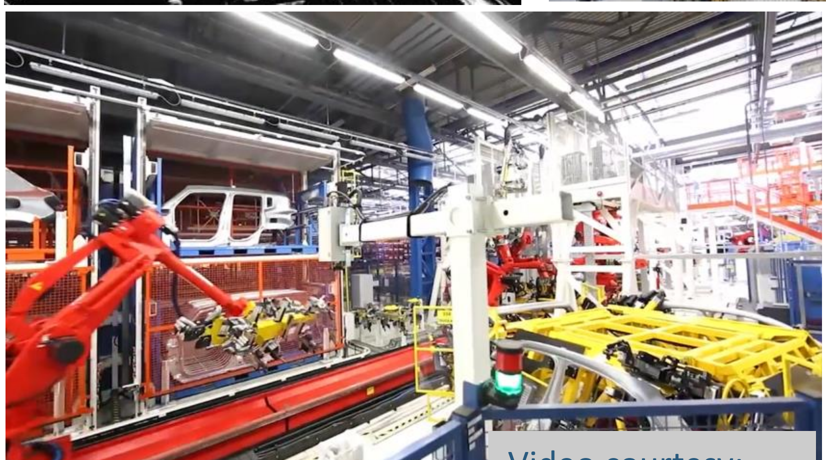
in industrial robotics

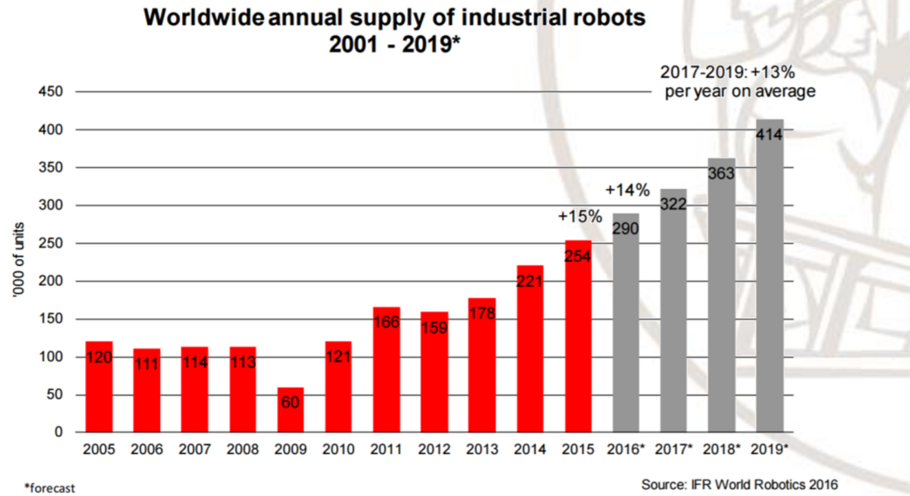

First industrial robot installed in GM plant in 1960


Massive introduction of robots in manufacturing since the '80s

Modern forms of collaborative robots


Video courtesy: COMAU

Reliability (minimal requested Mean Time Before Failure = 40,000 hrs
Efficiency η > 99.99875% *(Source: COMAU)*



2.6 million industrial robots in operation in the world, with a growth rate of 15% per year *(Source: IFR)*

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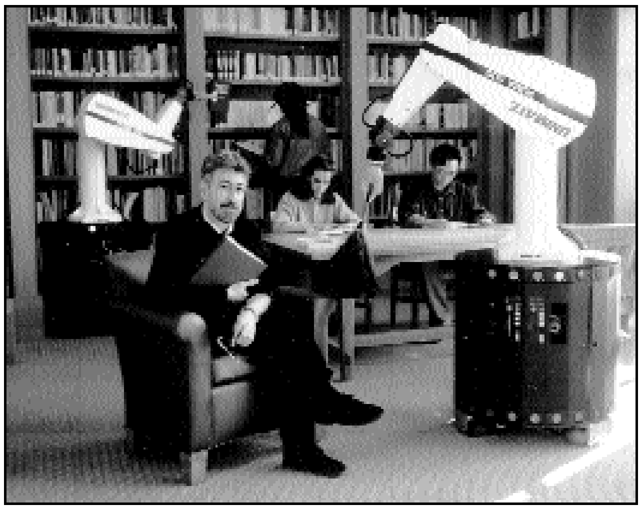
Evolution of robot abilities

in service robotics



Professional service

iRobot Roomba – 2.4M sold in 2015
double-digit growth of robot vacuum cleaner market

Autonomous cars

Evolution of robot abilities

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Abilities not yet reached by robots

Poor working conditions result in a total of 300,000 work-related deaths and economic losses of 4% of the gross domestic product of the European Region every year (Source: WHO)

Up to 50 hours per household lost each week to work and family life

Lessons from Nature

Bioinspiration and biomimetics in robotics

nature International weekly journal of science

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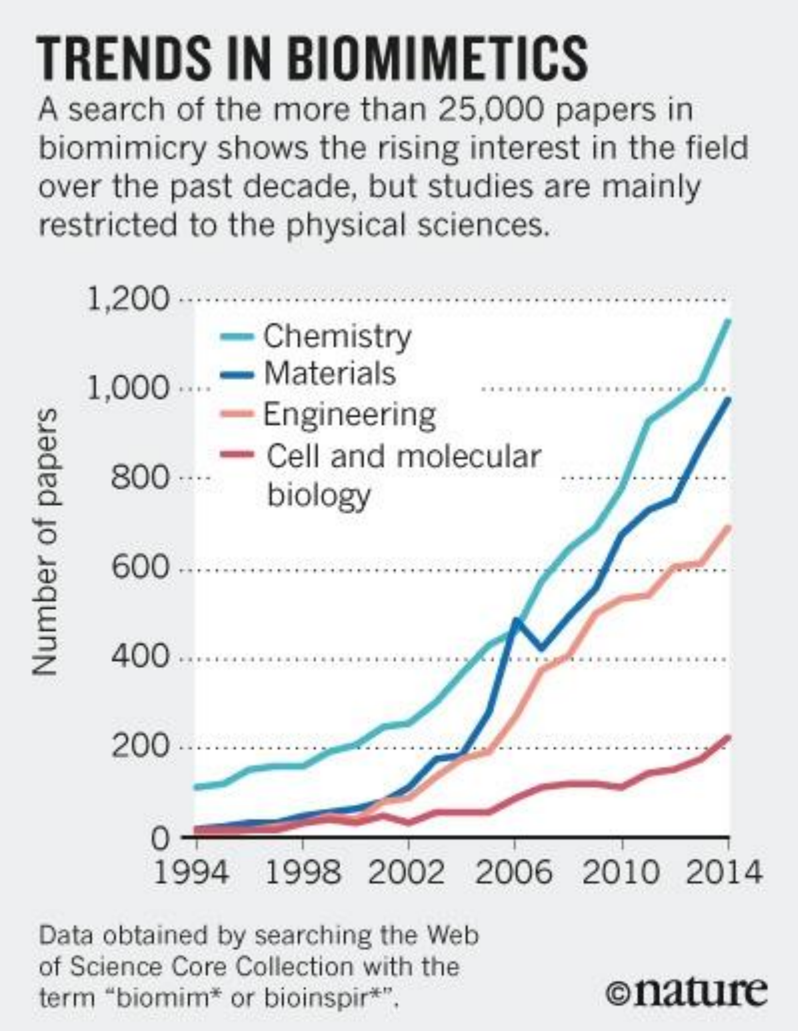
Interdisciplinarity: Bring biologists into biomimetics

"Engineers, chemists and others taking inspiration from biological systems for human applications must team up with biologists"



"[…] **Fewer than 8%** of the nearly 300 studies on biomimetics published in the past 3 months and indexed in the Thomson Reuters Web of Science **had an author working in a biology department** — a crude proxy for 'a biologist'."

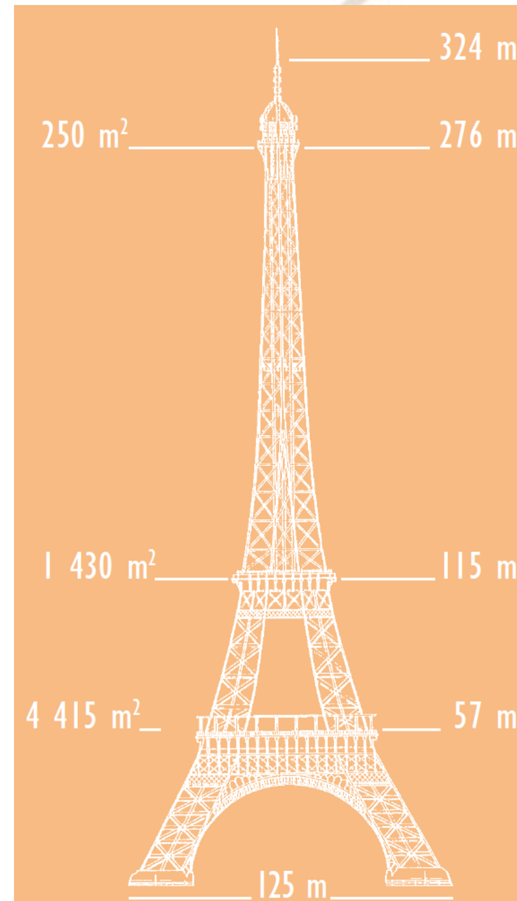
"[…] With around **1.5 million described species**, and probably some 9 million eukaryotic species in existence, researchers pursuing biomimetic approaches have barely **scratched the surface of biological inspiration**."

More biology education for engineers, in academy and in industry

Emilie Snell-Rood, "Interdisciplinarity: Bring biologists into biomimetics", *Nature* 529, 277–278 (21 January 2016) doi:10.1038/529277a

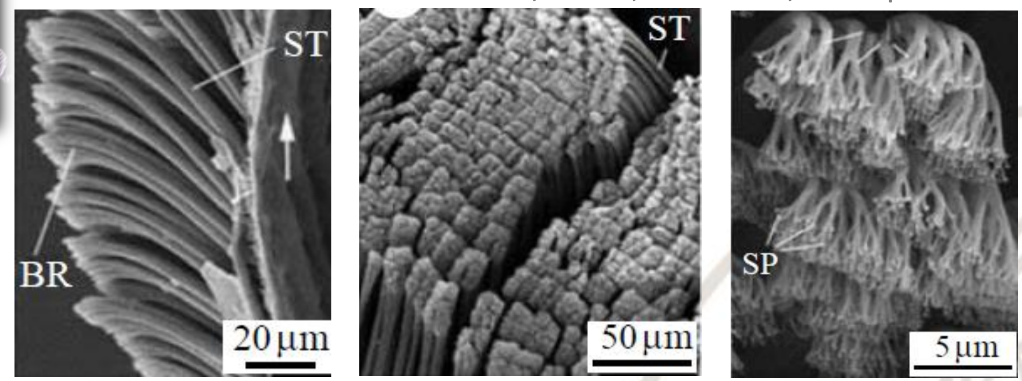
Examples of bioinspiration and biomimetics

The **Eiffel Tower**: the perfect structure of trabecular struts in the head of the human femur inspired a French engineer at the end of the 19th Century. He was intended to design the higher structure all the world. The name of this engineer is Gustave Eiffel. In 1889 the Tower is completed.

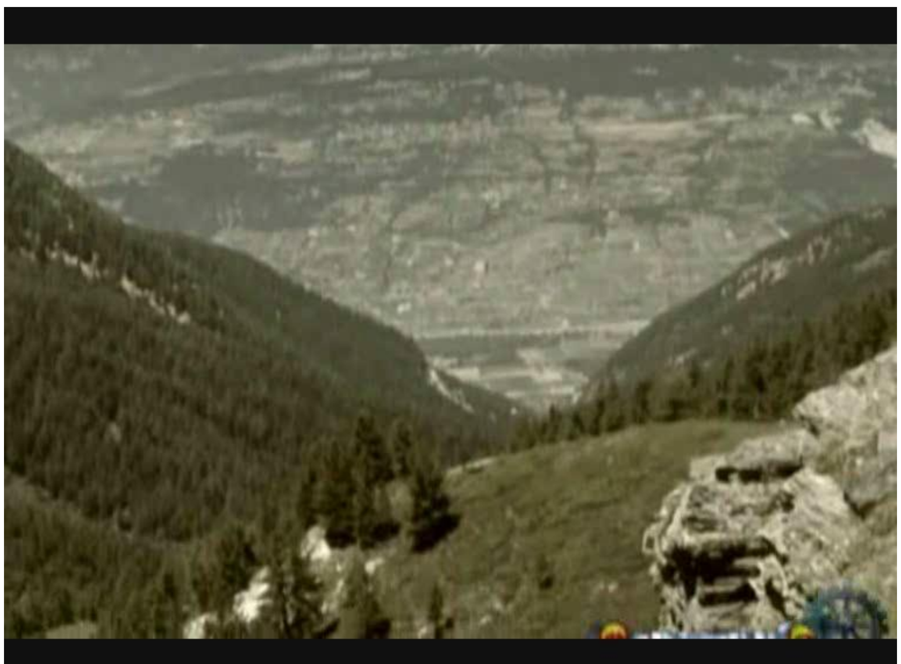


Examples of bioinspiration and biomimetics

A gecko is the largest animal that can produce (dry) adhesion to support its weight. The gecko foot comprises of a complex hierarchical structure of lamellae, setae, branches, and spatula.



Velcro resulted in 1948 from a Swiss engineer, George de Mestral, noticing how the hooks of the plant burrs (*Arctium lappa*) stuck in the fur of his dog.



M. R. Cutkosky, Climbing with adhesion: From bioinspiration to biounderstanding. *Interface Focus* 5, 20150015 (2015).

Bioinspiration and biomimetics

Nevertheless...

…natural selection is not engineering

Organisms that are capable of surviving are not necessarily **optimal** for their performance.

They need to survive long enough to reproduce.

Models are never complete or correct: need to interpret with caution.

"**Simply copying** a biological system is either **not feasible** (even a single neuron is too complicated to be synthesized artificially in every detail) or is **of little interest** (animals have to satisfy multiple constraints that do not apply to robots, such as keeping their metabolism running and getting rid of parasites), or **the technological solution is superior** to the one found in nature (for example, the biological equivalent of the wheel has yet to be discovered).

Rather, the goal is to work out **principles** of biological systems and transfer those to robot design." *Rolf Pfeifer*

R. Pfeifer, M. Lungarella, F. Iida, "Self-Organization, Embodiment, and Biologically Inspired Robotics", *Science* 318, 1088 (2007)

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Lessons from Nature: simplifying principles

Mechatronic approach:
integration of subsystems that are often already very complex (e.g. complex humanoids)

Today, more functionality means:
- **more** complexity, energy, computation,
- **less** controllability, efficiency, robustness, safety

Studying living organisms and understanding what makes their behavior so smart and efficient

In robotics, we need **simplifying principles** for control and behavior

Outline of the lesson

- Scientific motivations to bioinspired robotics
- **Bioinspired principles: simplexity** and embodied intelligence
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- Bioinspired perception

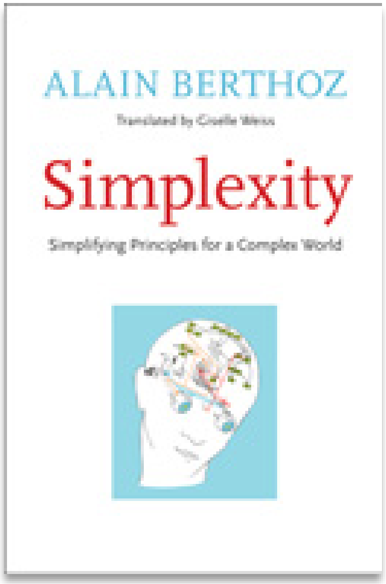
Simplexity

Simplexity comprises a **collection of solutions** that can be observed in living organisms which, despite the **complexity** of the world in which they live, allows them to **act and project the consequences of their actions into the future.**

It is **not** a matter of **simplified model** adoption, but rather an approach to **using simplifying principles**.

Biological systems can use:

- Multiple reference frames
- Anticipation and prediction
- Inhibition to select and adapt
- Redundancy
- Biomechanics and internal models
- Synergies
- Laws of motion
- Emotion



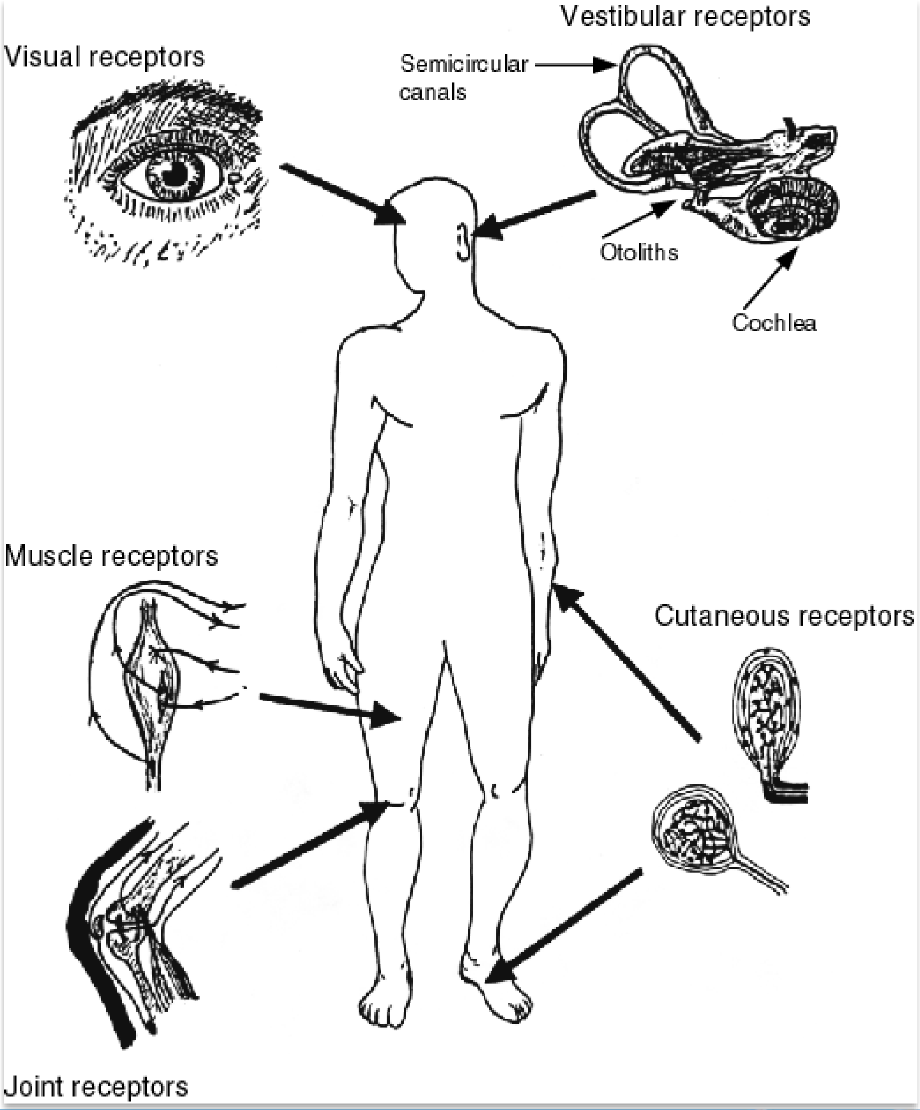
In robots, the concept of a unified inertial reference frame, together with gaze control, can represent one of the basic design principles for **simplifying the control of complex kinematic (human-like) structures**

A. Berthoz (2012), *Simplexity: Simplifying principles for a Complex World*. Yale University Press.
U. Alon (2207), “Simplicity in Biology”, *Nature*, 446(7135):497

The human “sense of movement”

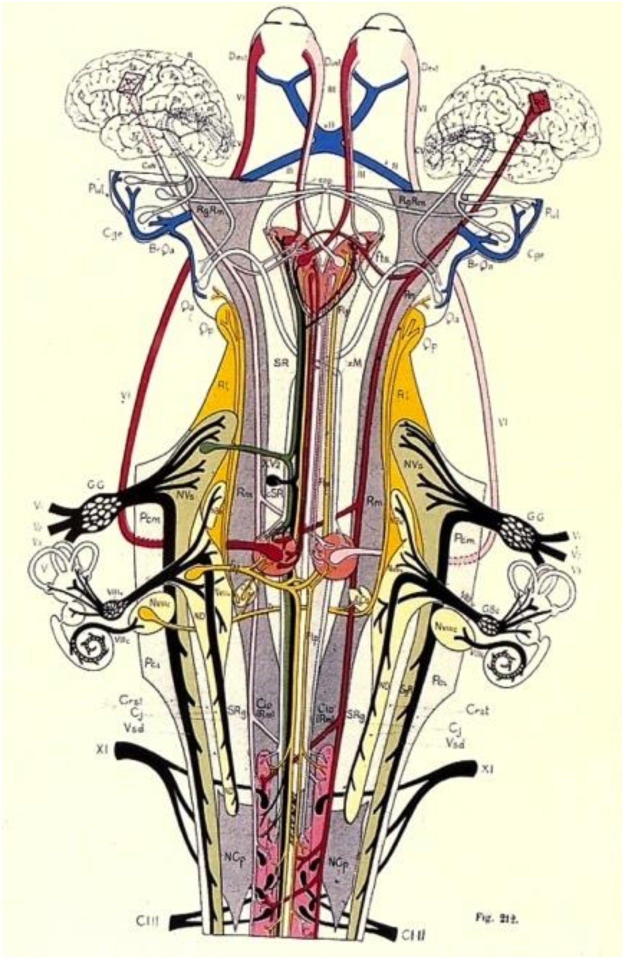
In humans the **sense of movement** is given by the integration of a variety of sensory signals, mostly proprioceptive.

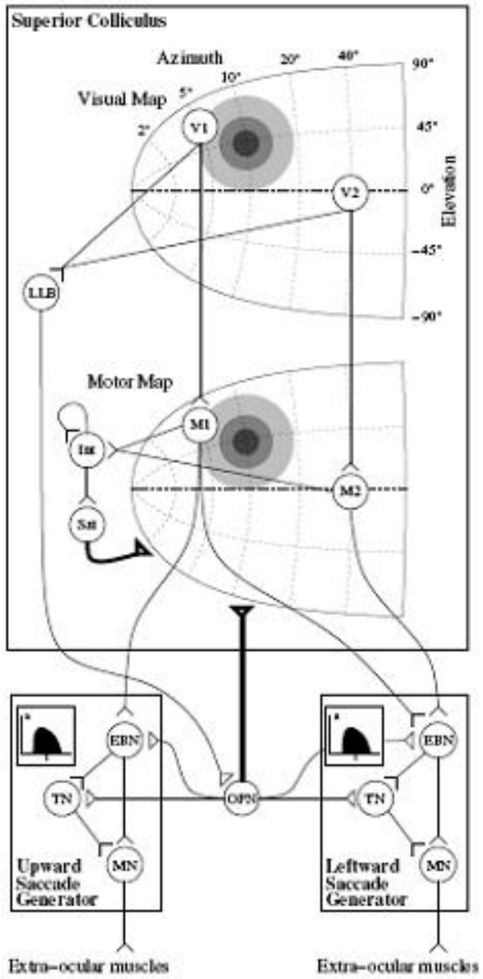
The **vestibular system** that provides perception of the head movements and postures relative to space plays a key role.



Model of fast gaze-shift control

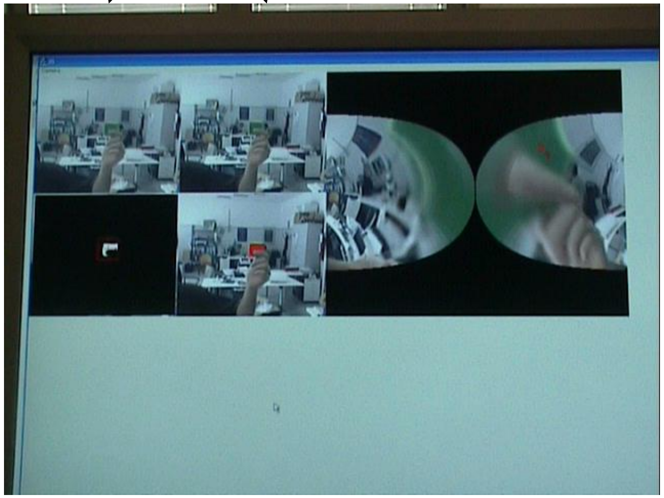
Mapping from the retina to the Superior Colliculus (SC)





Original images

Collicular mapping (red point: stimulus coordinates)



A. Berthoz (2012), *Simplexity: Simplifying principles for a Complex World*. Yale University Press.

C. Laschi, F. Patanè, E.S. Maini, L. Manfredi, G. Teti, L. Zollo, E. Guglielmelli, P. Dario, “An Anthropomorphic Robotic Head for Investigating Gaze Control”, *Advanced Robotics*, Vol.22, No.1, 2008, pp.57-89.

Humanoid robotics

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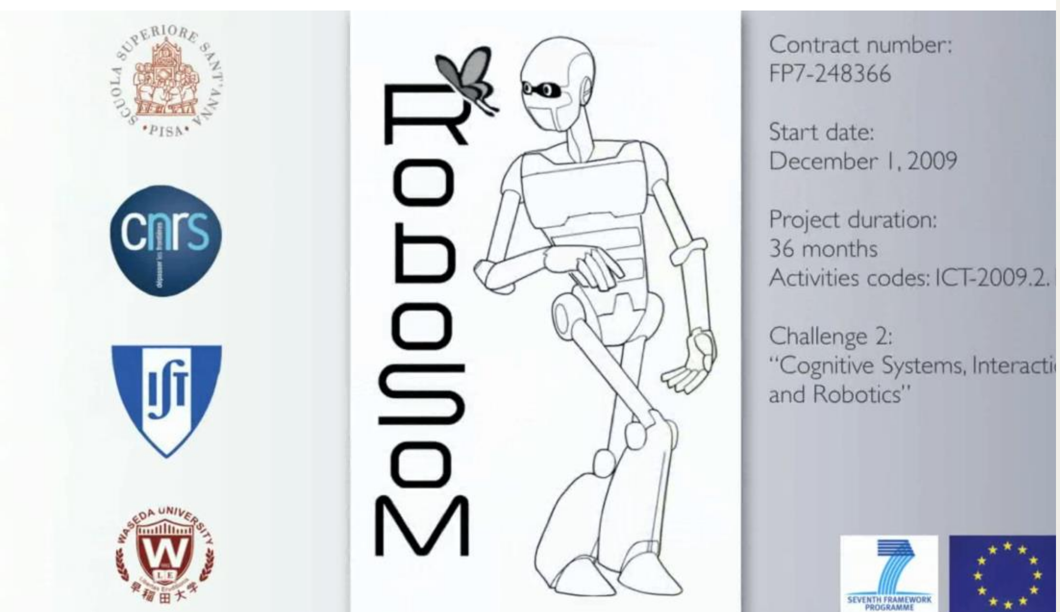
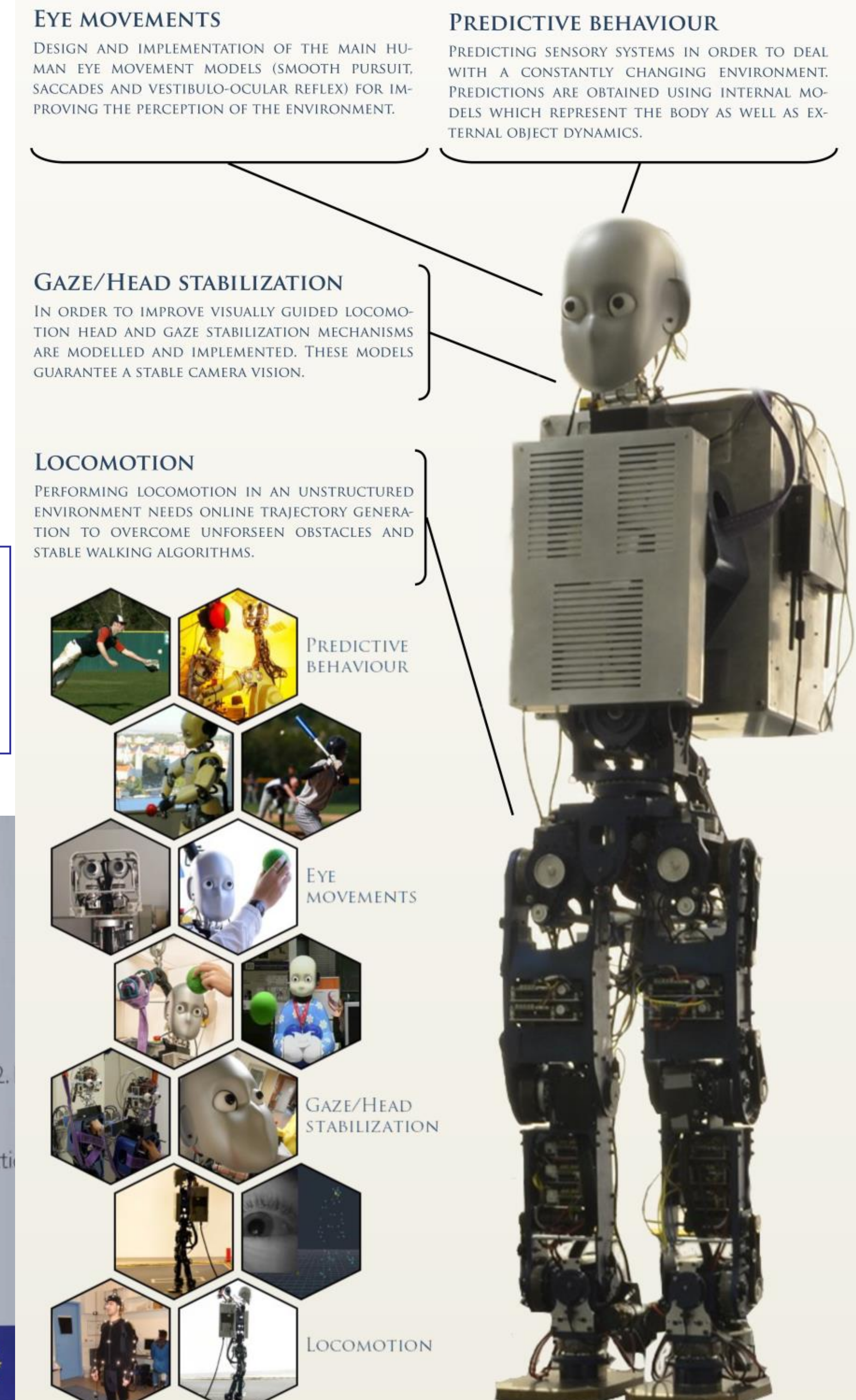
A Robotic Sense of Movement RoboSoM 2009-2013

Objective: to implement on humanoid robots the principles of the human '**sense of movement**', i.e. unified reference system, expected perception, and coordinated eye/head/leg movements in following a moving visual target





Outline of the lesson

- Scientific motivations to bioinspired robotics
- **Bioinspired principles:** simplexity and **embodied intelligence**
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Embodied Intelligence: the modern view of Artificial Intelligence

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Classical approach

- The focus is on the brain and central processing

Modern approach

The focus is on interaction with the environment. Cognition is emergent from system-environment interaction

Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

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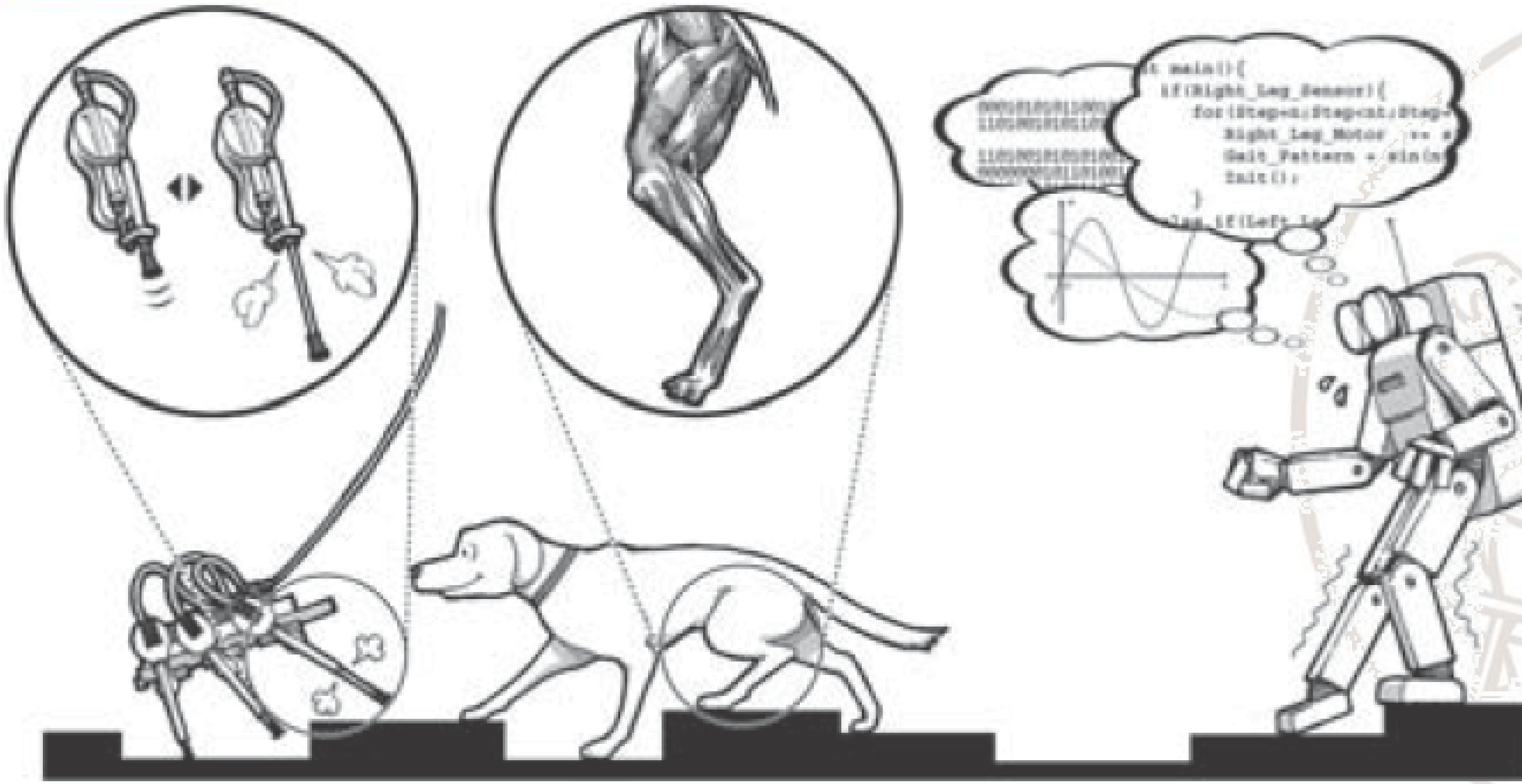
Embodied Intelligence
Morphological computation



Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

1. *They are subject to the laws of physics* (energy dissipation, friction, gravity).
2. *They generate sensory stimulation* through motion and generally through interaction with the real world.
3. *They affect the environment* through behavior.
4. *They are complex dynamical systems* which, when they interact with the environment, have *attractor states*.
5. *They perform morphological computation.*

These properties are simply unavoidable consequences of **embodiment**.

These are also the properties that can be exploited for generating behavior, and how this can be done is specified in the design principles.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

1. A complete agent is subject to the laws of physics.

Walking requires energy, friction, and gravity in order to work. Because the agent is embodied, it is a physical system (biological or not) and thus subject to the laws of physics from which it cannot possibly escape; it must comply with them. If an agent jumps up in the air, gravity will inevitably pull it back to the ground.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

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2. *A complete agent generates sensory stimulation.*
When we walk, we generate sensory stimulation, whether we like it or not: when we move, objects seem to flow past us (this is known as optic flow);
by moving we induce wind that we then sense with our skin and our hair;
walking also produces pressure patterns on our feet;
and we can feel the regular flexing and relaxing of our muscles as our legs move.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

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3. *A complete agent affects its environment.*
When we walk across a lawn, the grass is crushed underfoot;
when we breathe, we blow air into the environment;
when we walk and burn energy, we heat the environment;
when we drink from a cup, we reduce the amount of liquid in the glass;
when we drop a cup it breaks;
when we talk we put pressure waves out into the air;
when we sit down in a chair it squeaks and the cushion is squashed.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

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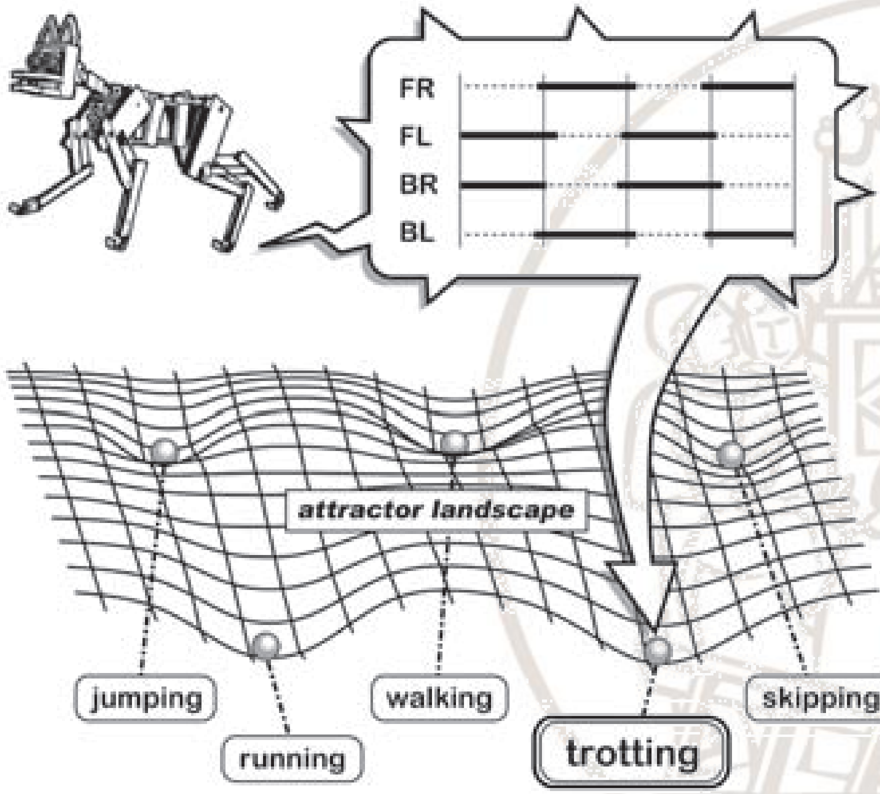
4. *Agents tend to settle into attractor states.* Agents are dynamical systems, and as such they have a tendency to settle into so-called attractor states. Horses, for example, can walk, trot, canter, and gallop, and we—or at least experts—can clearly identify when the horse is in one of these walking modes, or gaits, the more technical word for these behaviors.

These gaits can be viewed as **attractor states**. The horse is always in one of these states, except for short periods of time when it transitions between two of them, for example from canter to gallop.

We should point out here that the attractor states into which an agent settles are always the result of the interaction of three systems: the agent's body, its brain (or control system), and its environment.



Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

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5. *Complete agents perform morphological computation.*

By "morphological computation" we mean that certain processes are performed by the body that otherwise would have to be performed by the brain.

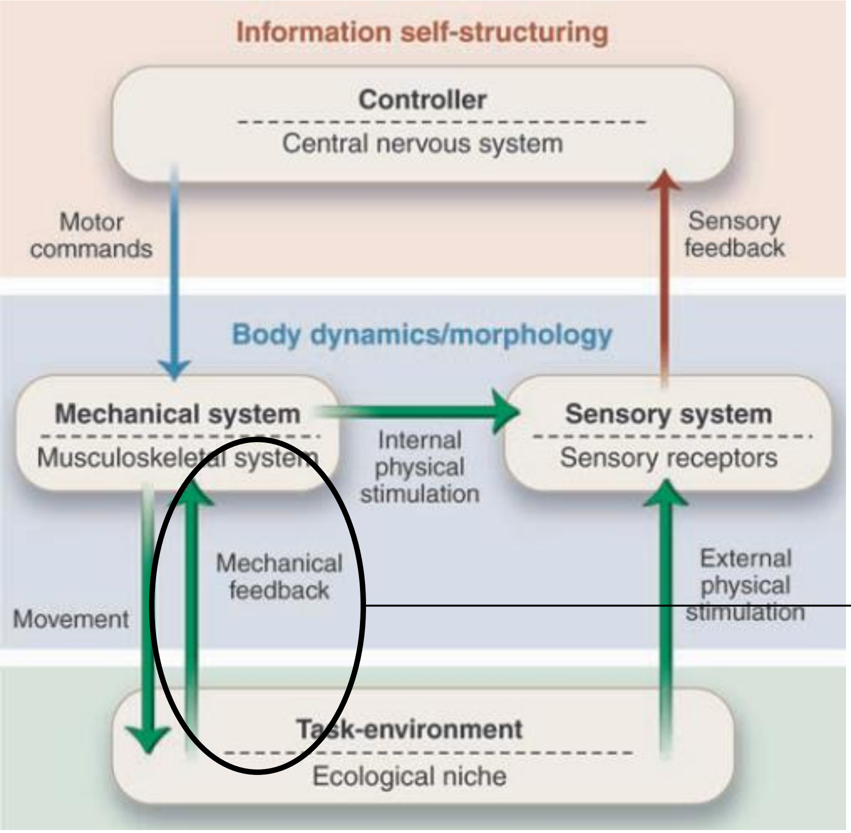
An example is the fact that the human leg's muscles and tendons are elastic so that the knee, when the leg impacts the ground while running, performs small adaptive movements without neural control.

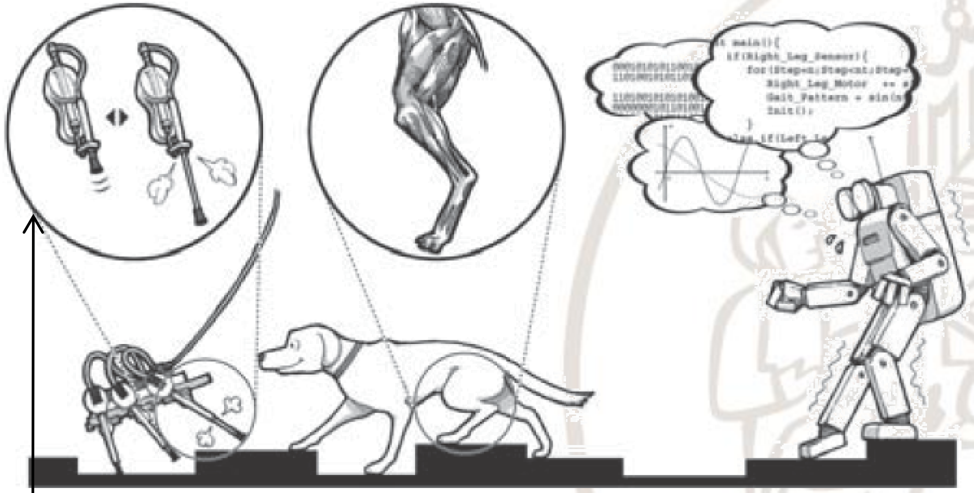
The control is supplied by the muscle-tendon system itself, which is part of the morphology of the agent.

It is interesting to note that systems that are not complete, in the sense of the word used here, hardly ever possess all of these properties. For example, a vision system consisting of a fixed camera and a desktop computer does not generate sensory stimulation because it cannot produce behavior, and it influences the environment only by emitting heat and light from the computer screen. Moreover, it does not perform morphological computation and does not have physical attractor states that could be useful to the system.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Morphological computation

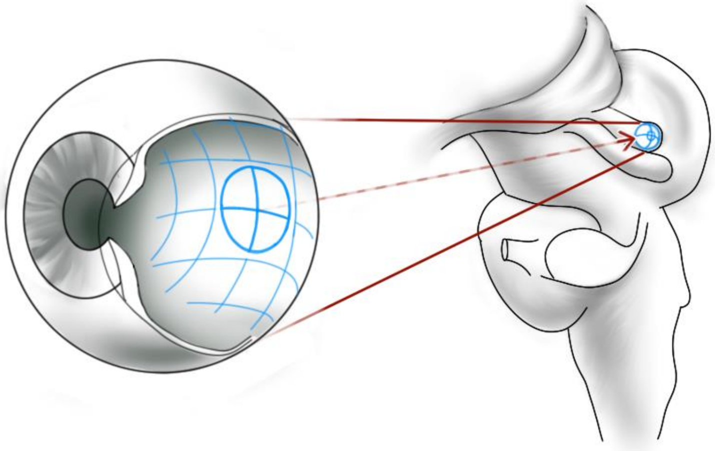


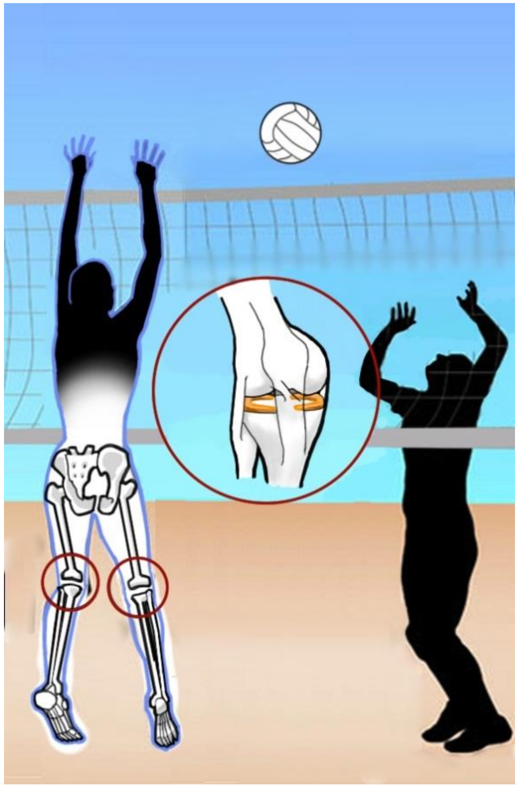


Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Morphological Computation

As any transformation of information can be named as *computing*, *Morphological Computation* endows all those behaviours where computing is mediated by the mechanical properties of the physical body





The arrangement
of the motor, perceptive and processing units

The shape
as body structure, specifies the behavioral response of the agent

The mechanical properties
allow emergent behaviors and highly adaptive interaction with the environment

Zambrano D, Cianchetti M, Laschi C (2014) “The Morphological Computation Principles as a New Paradigm for Robotic Design” in *Opinions and Outlooks on Morphological Computation*, H. Hauser, R. M. Füchslin, R. Pfeifer (Ed.s), pp. 214-225.

Agent Design Principle 1

The **three-costituents** principle:

- define the ecological niche — ENVIRONMENT
- define the desired behaviour and tasks — TASK
- design the agent — BODY

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 2

The **complete-agent** principle:

- think about the complete agent behaving in the real world

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

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Agent Design Principle 3

Cheap design:

- If agents are built to exploit the properties of the ecological niche and the characteristics of the interaction with the environment, their design and construction will be much easier, or 'cheaper'

Passive walker

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 4

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Redundancy:

- Intelligent agents must be designed in such a way that
  - (a) their different sub-systems function on the basis of different physical processes, and
  - (b) there is partial overlap of functionality between the different sub-systems

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

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Agent Design Principle 5

Sensory-Motor Coordination:

- through sensory-motor coordination, structured sensory stimulation is induced.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 6

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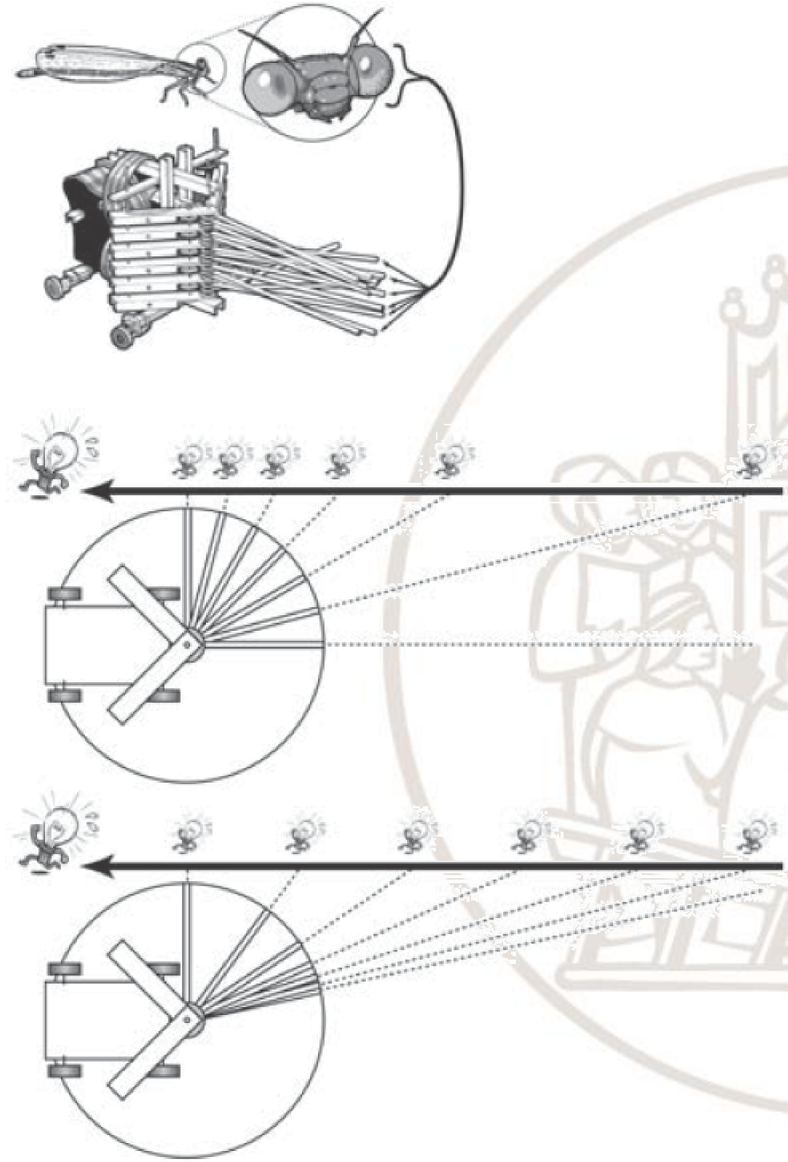
Ecological balance:

1. given a certain task environment, there has to be a match between the complexities of the agent's sensory, motor, and neural systems
2. there is a certain balance or task distribution between morphology, materials, control, and environment.



Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 7

Parallel, loosely coupled processes:
intelligence is emergent from a large number of parallel processes that are often coordinated through embodiment, in particular via the embodied interaction with the environment

Reactive architectures

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 8

Value:
agents are equipped with a value system which constitutes a basic set of assumptions about what is good for the agent

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Embodied Intelligence and soft robotics

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Any cognitive activity arises from the ***interaction*** between the body, the brain and the environment.

Adaptive behaviour is not just control and computation, but it emerges from the complex and dynamic interaction between the morphology of the body, sensory-motor control, and environment.

Many tasks become much easier if morphological computation is taken into account.

=> A new soft bodyware is needed

Modern approach

The focus is on interaction with the environment. Cognition is emergent from system-environment interaction

Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

A ‘soft’ animal world

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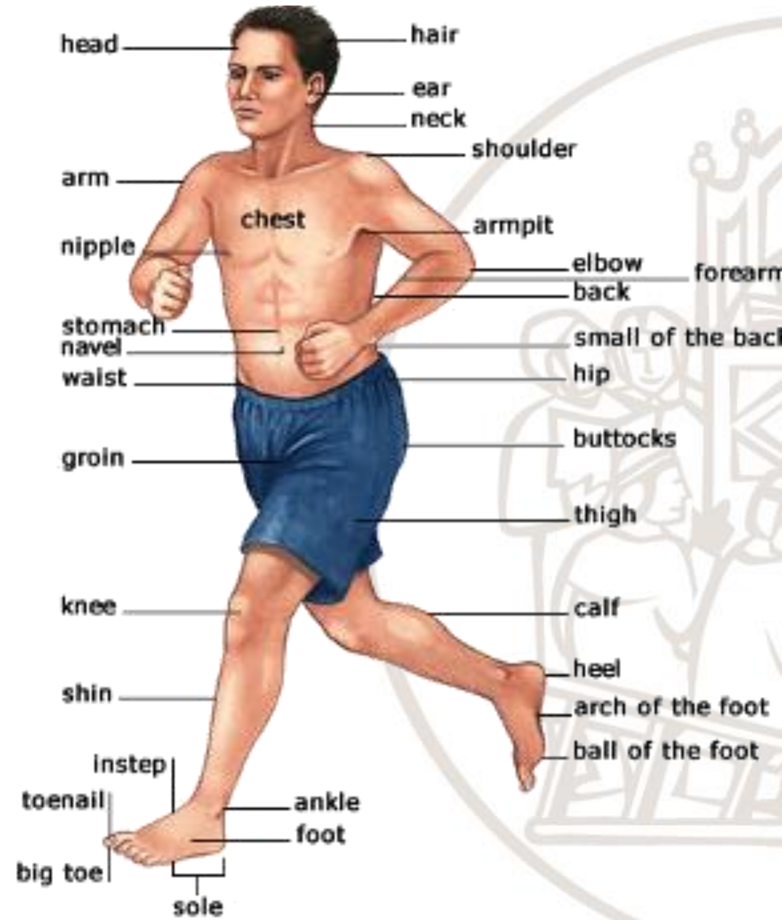
- The vast majority of animals are soft-bodied
- Animals with stiff exoskeletons such as insects have long-lived life stages wherein they are almost entirely soft (maggots, grubs, and caterpillars).
- Animals with stiff endoskeletons are mainly composed of soft tissues and liquids.

the human skeleton typically contributes only 11% of the body mass of an adult male



skeletal muscle contributes an average 42% of body mass

Kim S., Laschi C., and Trimmer B. (2013) Soft robotics: a bioinspired evolution in robotics, *Trends in Biotechnology*, April 2013.

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A 'soft' animal world

- Soft animals tend to be **small** because it is difficult for them to support their own body weight without a skeleton.
- All of the extremely large soft invertebrates are found either
  - **in water** (squid and jellyfish) or
  - **underground** (giant earthworms),

  where their body is supported by the surrounding medium.

Kim S., Laschi C., and Trimmer B. (2013) Soft robotics: a bioinspired evolution in robotics, *Trends in Biotechnology*, April 2013.

Defining Soft Robotics: a first broad classification

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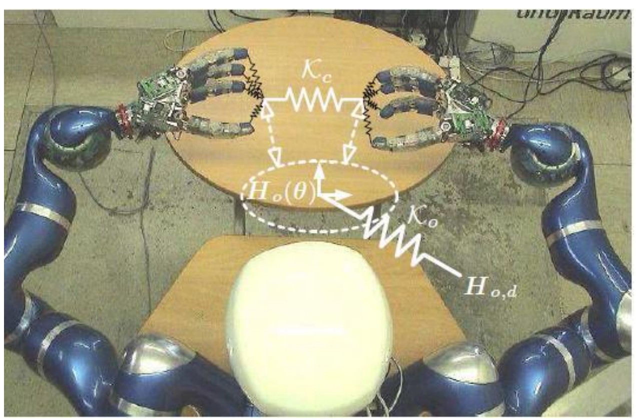
Variable impedance actuators and stiffness control

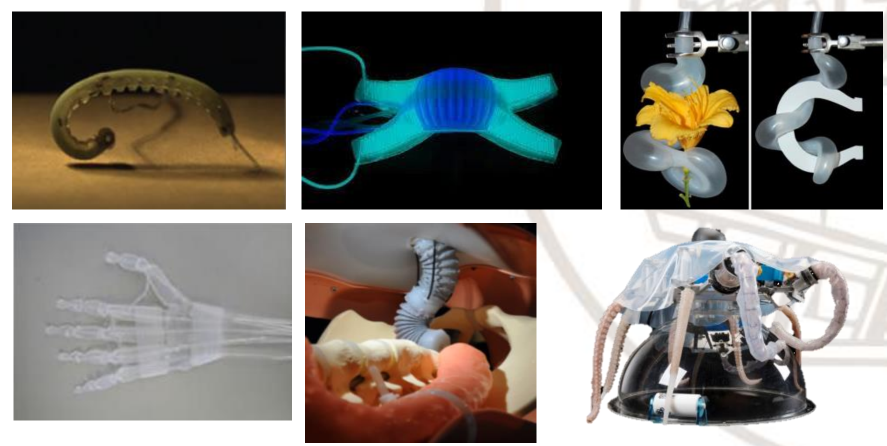
- mechanically (or passively) compliant joints with variable stiffness
- compliance or impedance control



IEEE Robotics and Automation Magazine, Special Issue on Soft Robotics, 2008

Use of soft materials in robotics

- Robots made of soft materials or structures that undergo high deformations in interaction
- Soft actuators and soft components

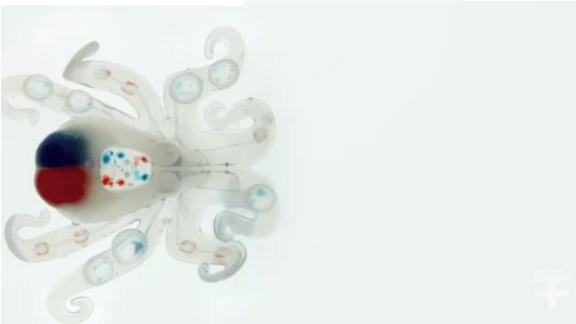


Laschi C. and Cianchetti M. (2014) "Soft Robotics: new perspectives for robot bodyware and control" *Frontiers in Bioengineering & Biotechnology*, 2(3)

"Soft robot/devices that can actively interact with the environment and can undergo 'large' deformations relying on inherent or structural compliance"

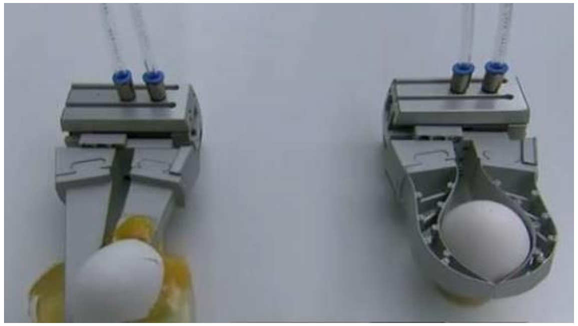
Soft Robotics may exploit materials which present:

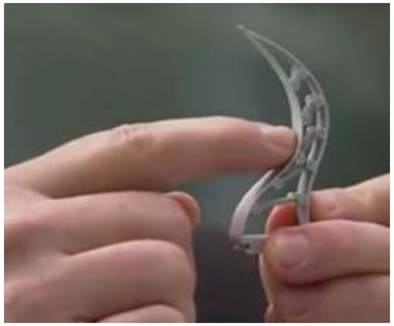
- INHERENT MATERIAL compliance: bulk material properties (elastomers, low elastic modulus polymers, gels…)

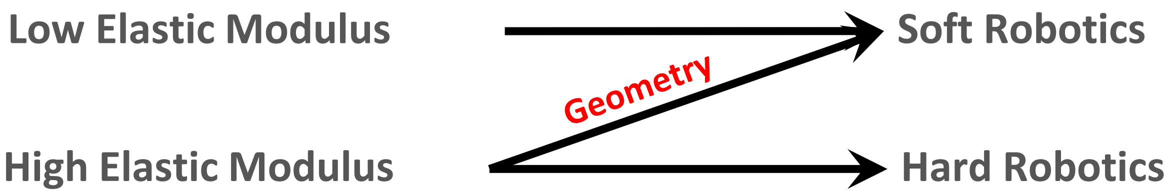


M. Wehner, R.L. Truby, D.J. Fitzgerald, B. Mosadegh, G.M. Whitesides, J.A. Lewis, R.J. Wood, An integrated design and fabrication strategy for entirely soft, autonomous robots, *Nature* 536, 451–455

- STRUCTURAL compliance: geometric features or arrangement can allow magnified strains compared with local material deformation



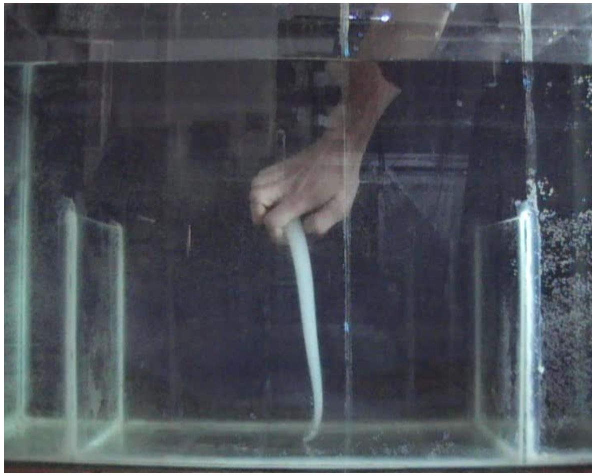


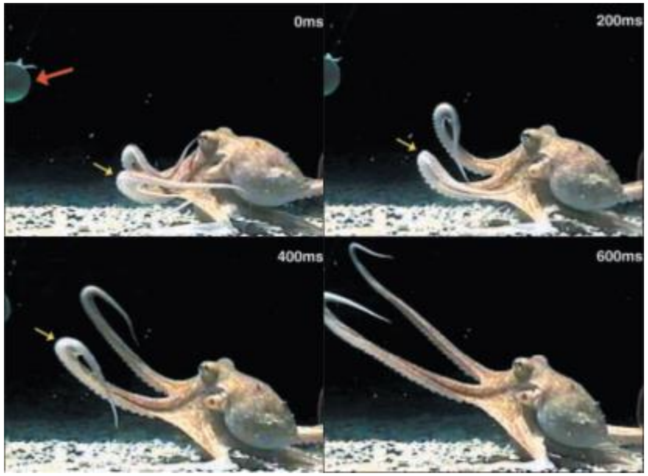


C. Laschi, B. Mazzolai, M. Cianchetti, "Soft robotics: technologies and systems pushing the boundaries of robot abilities", *Science Robotics* 1(1), 2016

Simplifying principles in reaching

The octopus arm embodied intelligence



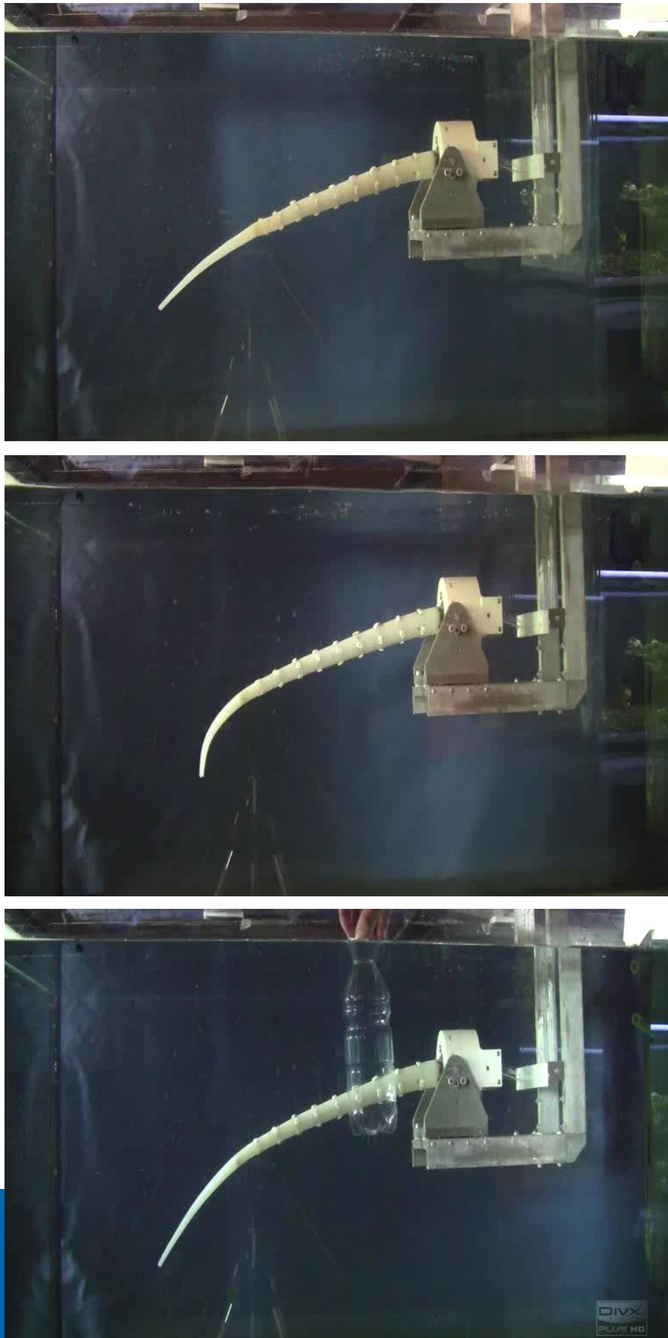


- stiffening wave from base to distal part, that can start from any part of the arm;
- movement executed in about 1 second, velocities in the range of 20–60 cm/s;
- control divided between central and peripheral: from brain: **3 parameters** (yaw and pitch of arm base and peak velocity of bend-point); locally: propagation of stiffness

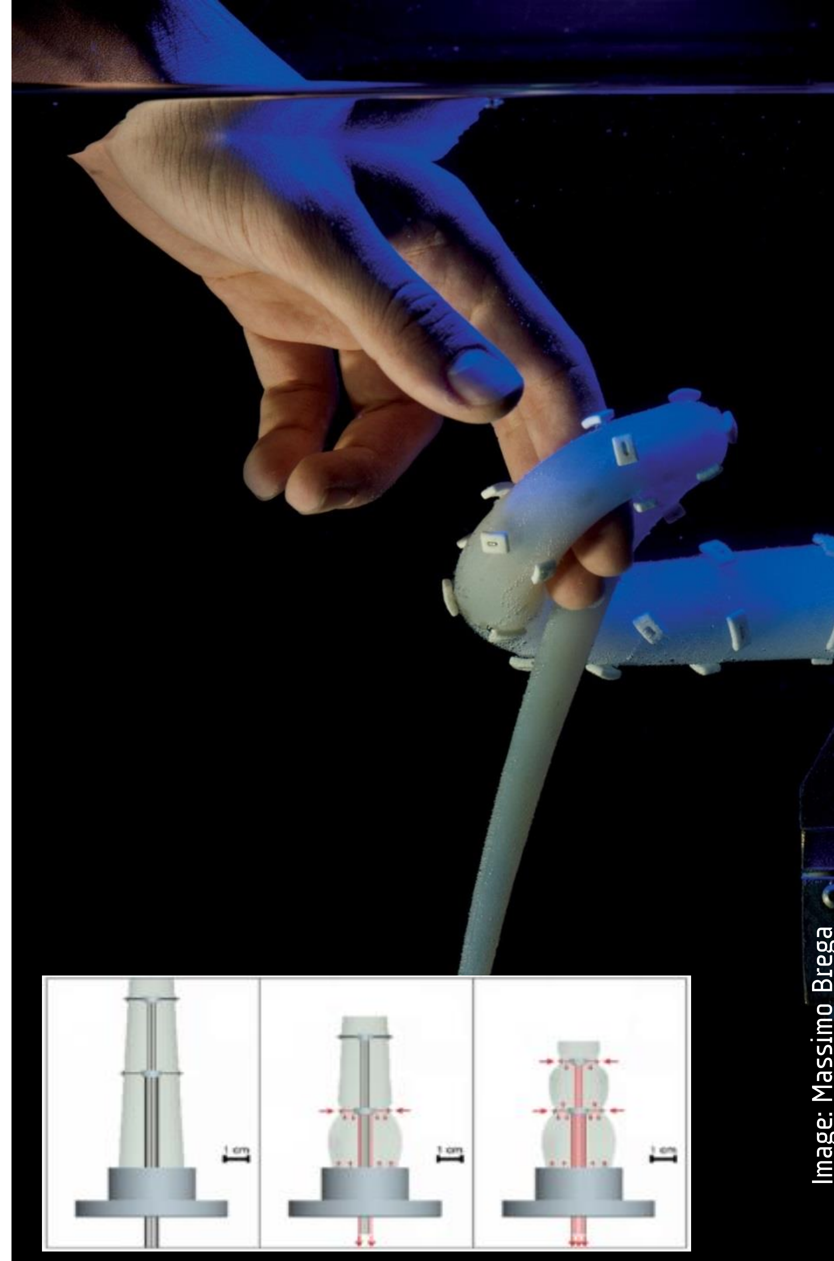
I. Zelman, M. Galun, A. Akselrod-Ballin, Y. Yekutieli, B. Hochner, and T. Flash (2009) Nearly automatic motion capture system for tracking octopus arm movements in 3D space, *Journal of Neuroscience Methods, Volume 182: 97-109*

L. Zullo, G. Sumbre, C. Agnisola, T. Flash, B. Hochner (2009) Nonsomatotopic Organization of the Higher Motor Centers in Octopus, *Current Biology, 19:1632-1636.*

Simplifying principles in reaching

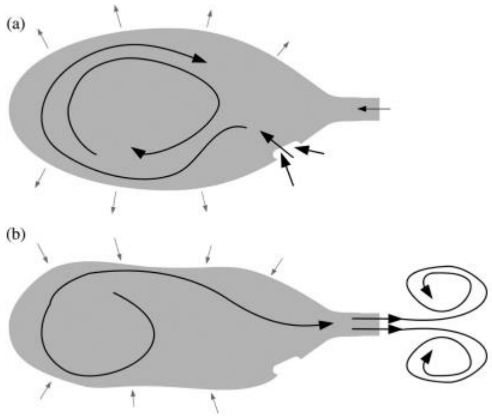


- Silicone
- 9 sections of transverse and longitudinal cables (coupled)
- Simple activation pattern: sequential activation of sections, with equal activation of 4 longi-transverse cables per section



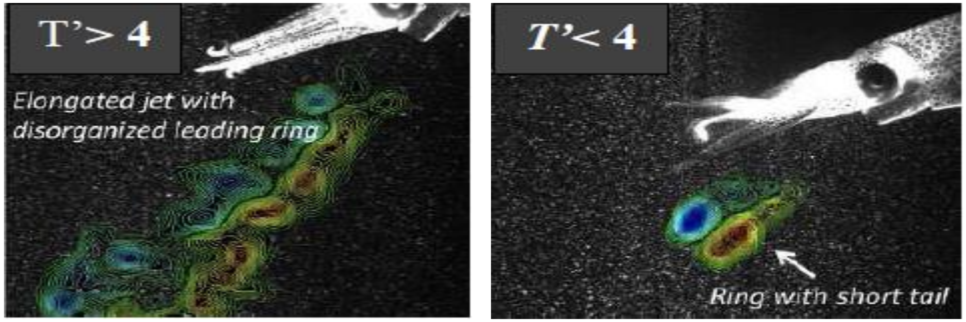
Cianchetti, M., Arienti, A., Follador, M., Mazzolai, B., Dario, P., Laschi, C. "Design concept and validation of a robotic arm inspired by the octopus", *Materials Science and Engineering C*, Vol.31, 2011, pp.1230-1239.

Pulsed-jet swimming in cephalopods



REFILL PHASE
- mantle expansion
- refilling of the mantle cavity through water inlets

JET PHASE
- mantle contraction
- expulsion of a fluid slug through the funnel (siphon)

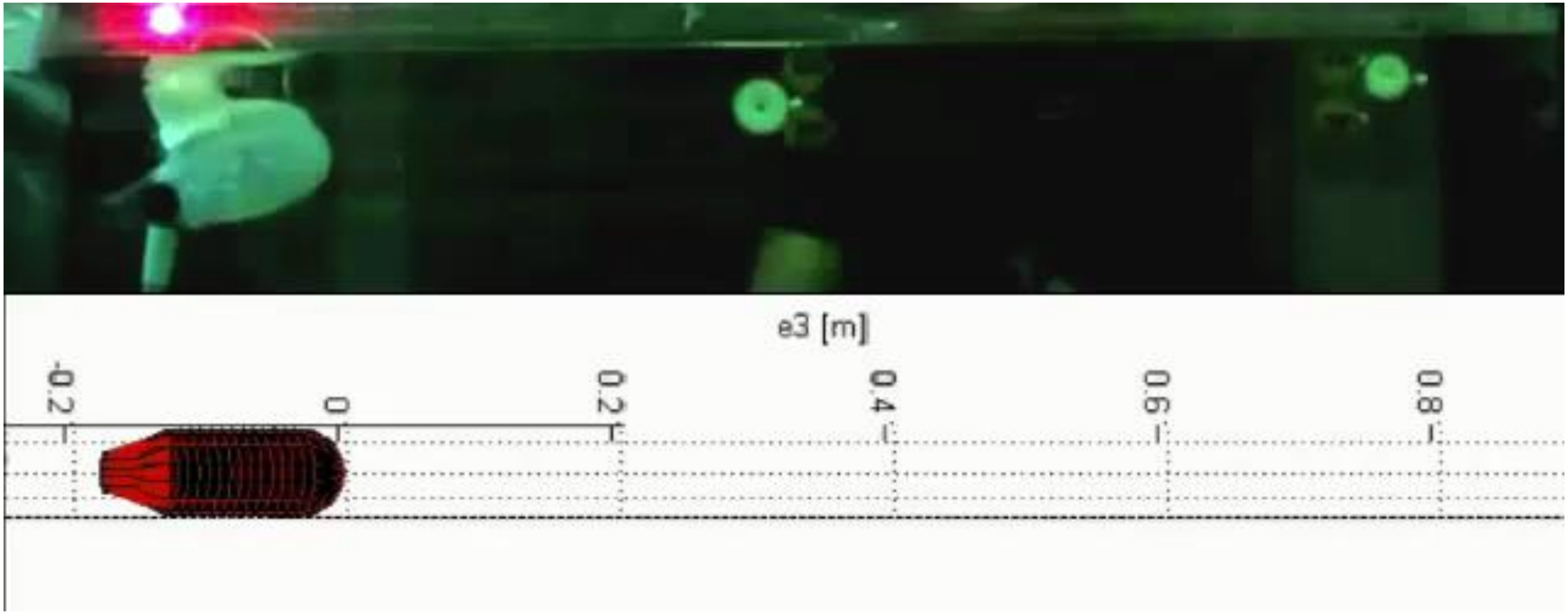


Ejection of a discontinuos stream of fluid through a nozzle that produces **ring vortexes**.
The generation of ring vortexes provides an additional thrust to the one generated by a continuous jet, by generating an additional pressure at the nozzle orifice

The mantle and siphon **morphology** and the pulsed jet **frequency** optimize propulsion, producing **ring vortexes**

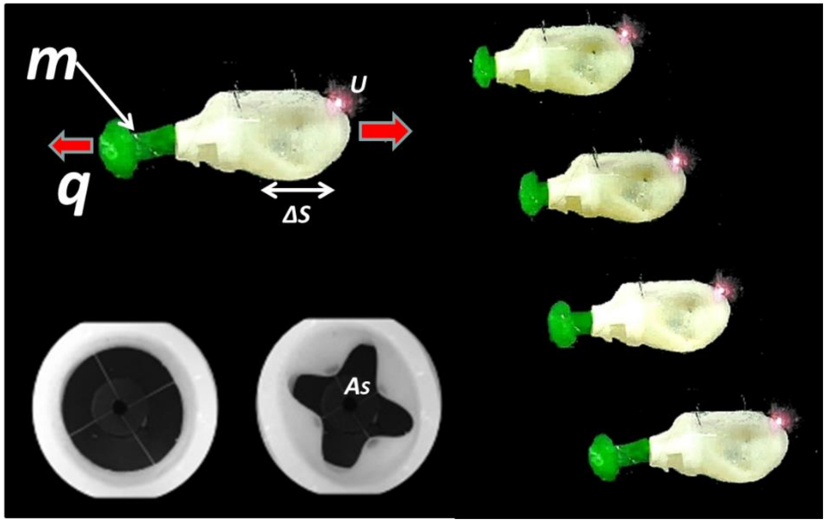
Giorgio Serchi F., Arienti A. and Laschi C. (2013) "Biomimetic Vortex Propulsion: Toward the New Paradigm of Soft Unmanned Underwater Vehicles", *IEEE/ASME Transactions on Mechatronics*, 18(**2**), pp. 484-493

Pulsed-jet swimming in cephalopods



Giorgio-Serchi et al., "Underwater Soft-bodied Pulsed-Jet Thrusters: actuator, modelling and performance profiling«, *International Journal of Robotics Research,* 2016

Pulsed-jet swimming soft robot



Silicone and cables, 1 DOF

PoseiDrone

The mantle and siphon **morphology** and the pulsed jet **frequency** optimize propulsion, producing ring vortexes (in green)

Giorgio-Serchi F., Arienti A., Laschi C. (2016), "Underwater Soft-bodied Pulsed-Jet Thrusters: actuator, modelling and performance profiling", *International Journal of Robotics Research,* 35 (11), 1308-1329

Simplifying principles in underwater locomotion

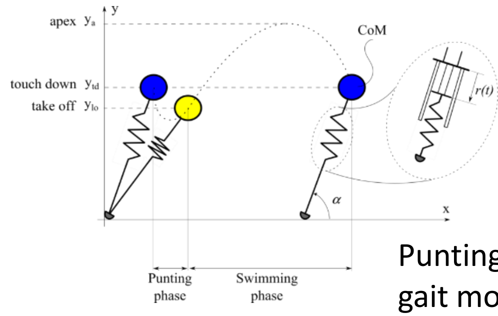
Octopus crawling

Locomotion is based on **cyclic** control of **two** back arms, while the body is raised thanks to **neutral buoyance**. Locomotion consists of 4 phases:

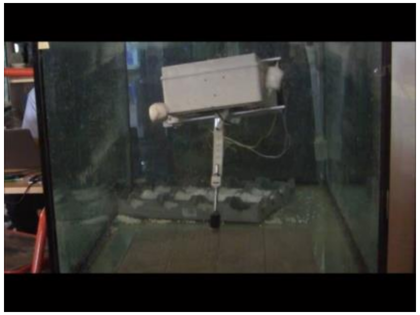
1. Arm shortening
2. Attaching to the floor
3. Elongation (pushing the body forward)
4. Detaching

U-SLIP model

Water drag, added mass, buoyancy and pushing propulsion have been added to the SLIP model

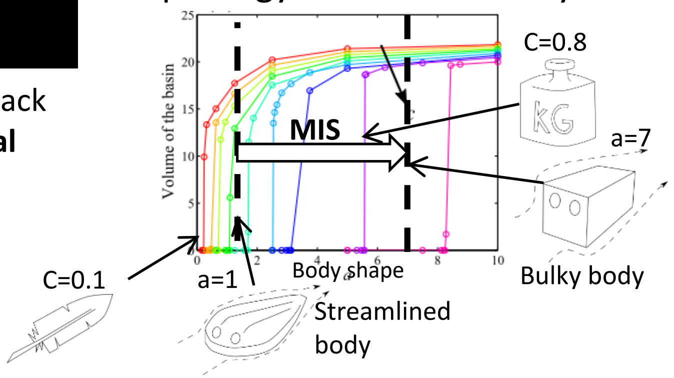


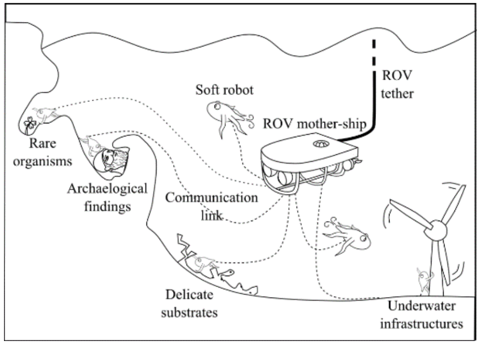
Punting gait model



2 control parameters **4 design parameters**

Morphology-Induced Stability





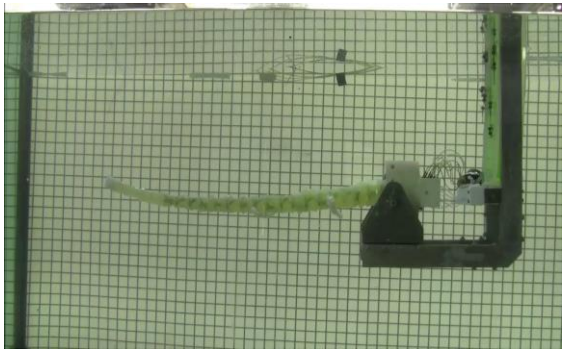
New concept of soft underwater robots

Body matters: compliant legs or a soft body directly influence stability and speed

Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, P. Dario, "An octopus-bioinspired solution to movement and manipulation for soft robots", *Bioinspiration and Biomimetics* Vol.6, No.3, 2011, 10 pp.
Calisti, M., Corucci, F., Arienti, A., & Laschi, C. (2015). Dynamics of underwater legged locomotion: modeling and experiments on an octopus-inspired robot. *Bioinspiration & biomimetics*, *10*(4), 046012.
Calisti, M., G. Picardi, and C. Laschi. "Fundamentals of soft robot locomotion." *Journal of The Royal Society Interface* 14.130

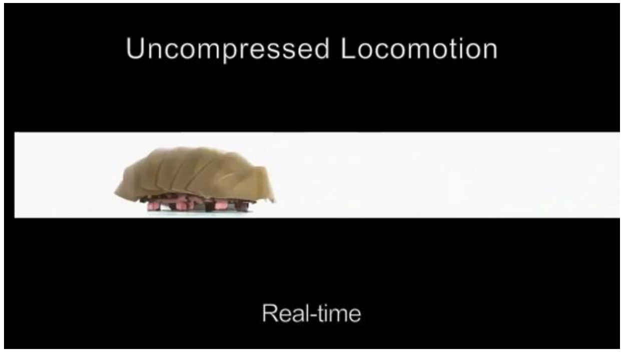
New abilities that robots have reached

Stretching & shortening

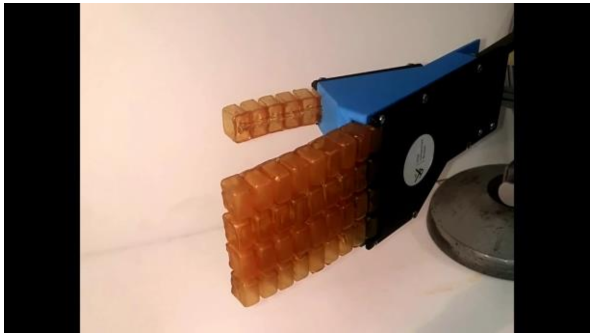


Deforming

Squeezing



Growing



Self-healing

Being squashed

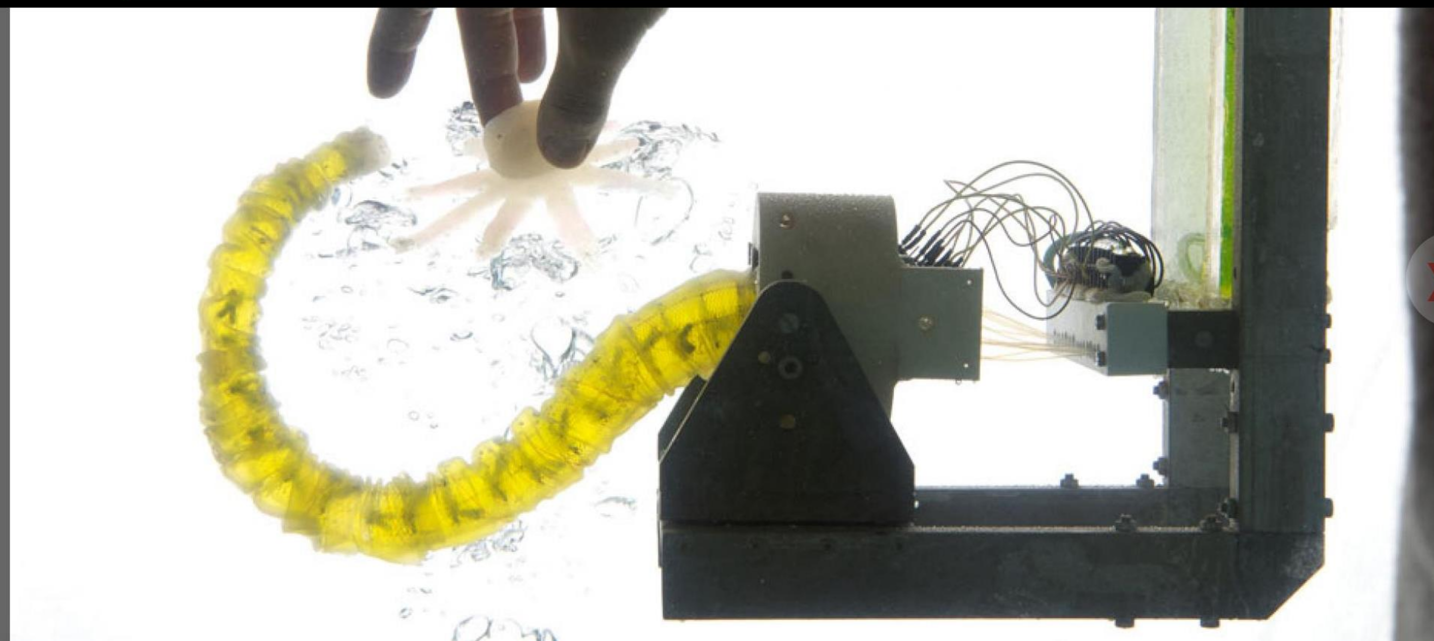
C. Laschi, B. Mazzolai, M. Cianchetti, "Soft robotics: technologies and systems pushing the boundaries of robot abilities", *Science Robotics* 1(1), 2016

Science Robotics AAAS

Softness is a strength

Soft robotics expand the boundaries of robot abilities

Massimo Brega/Kepach Production



REVIEW | SOFT ROBOTICS

Soft robotics: Technologies and systems pushing the boundaries of robot abilities

Cecilia Laschi[1,*], Barbara Mazzolai[2] and Matteo Cianchetti[1]

+ Author Affiliations

*Corresponding author. Email: cecilia.laschi@sssup.it

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Science Robotics

Vol 1, Issue 1
06 December 2016

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Outline of the lesson

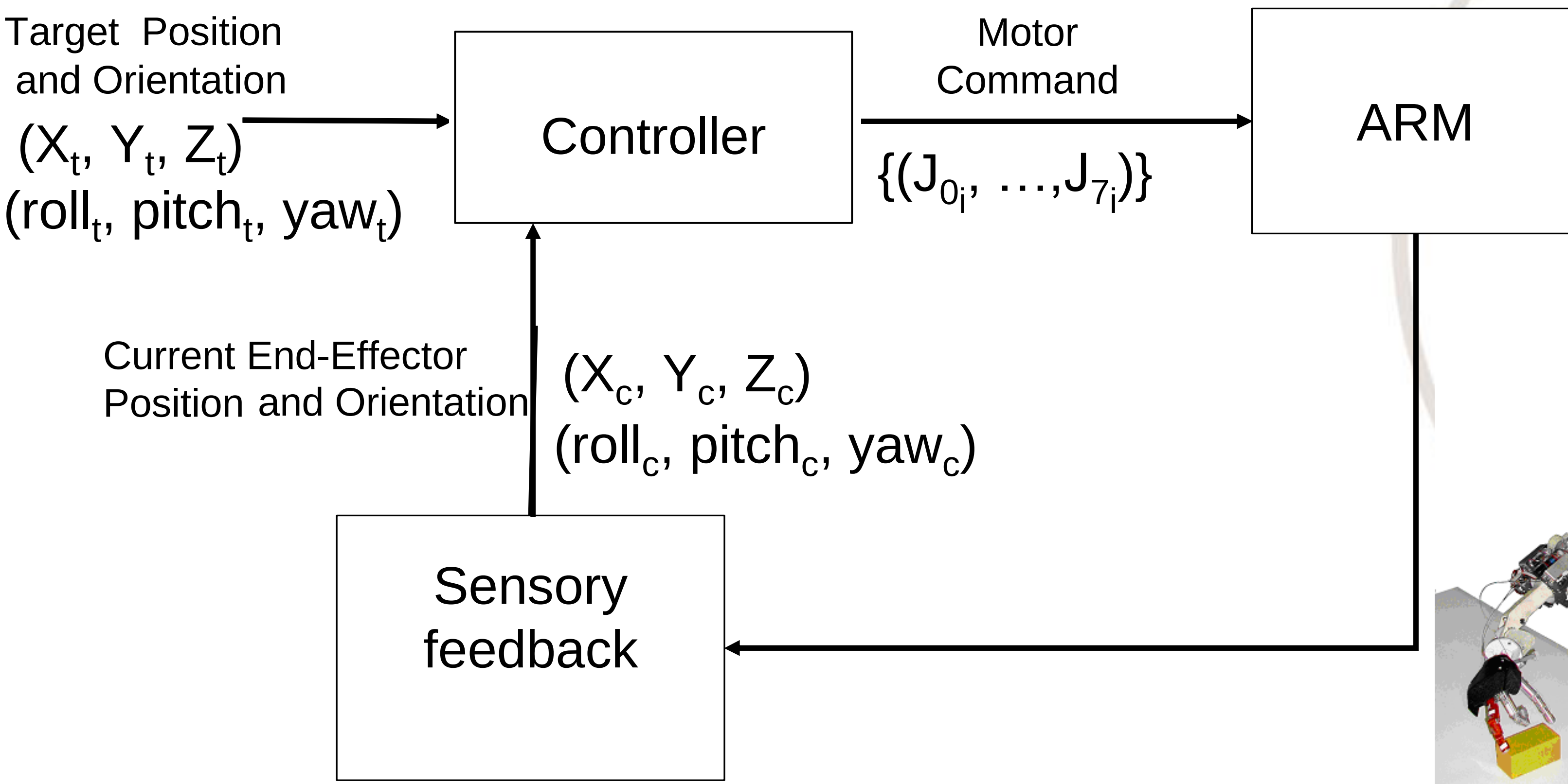
- Scientific motivations to bioinspired robotics
- Bioinspired principles: simplexity and embodied intelligence
- **Bioinspired control: neurocontrollers**
- Bioinspired behaviour: predictive architectures
- Bioinspired perception

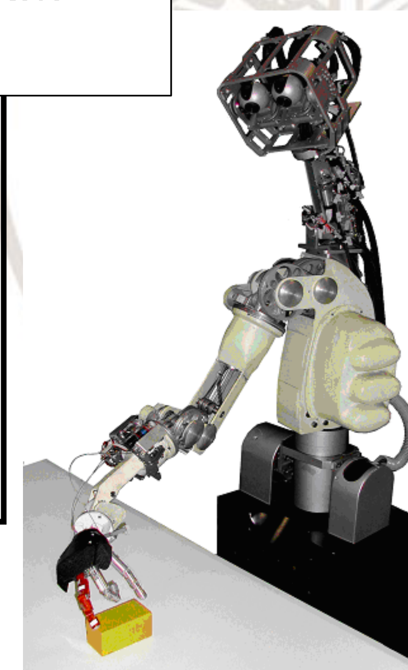
ISTITUTO DI BIOROBOTICA

Scuola Superiore Sant'Anna

Model-based closed-loop schemes for controlling arm position and orientation

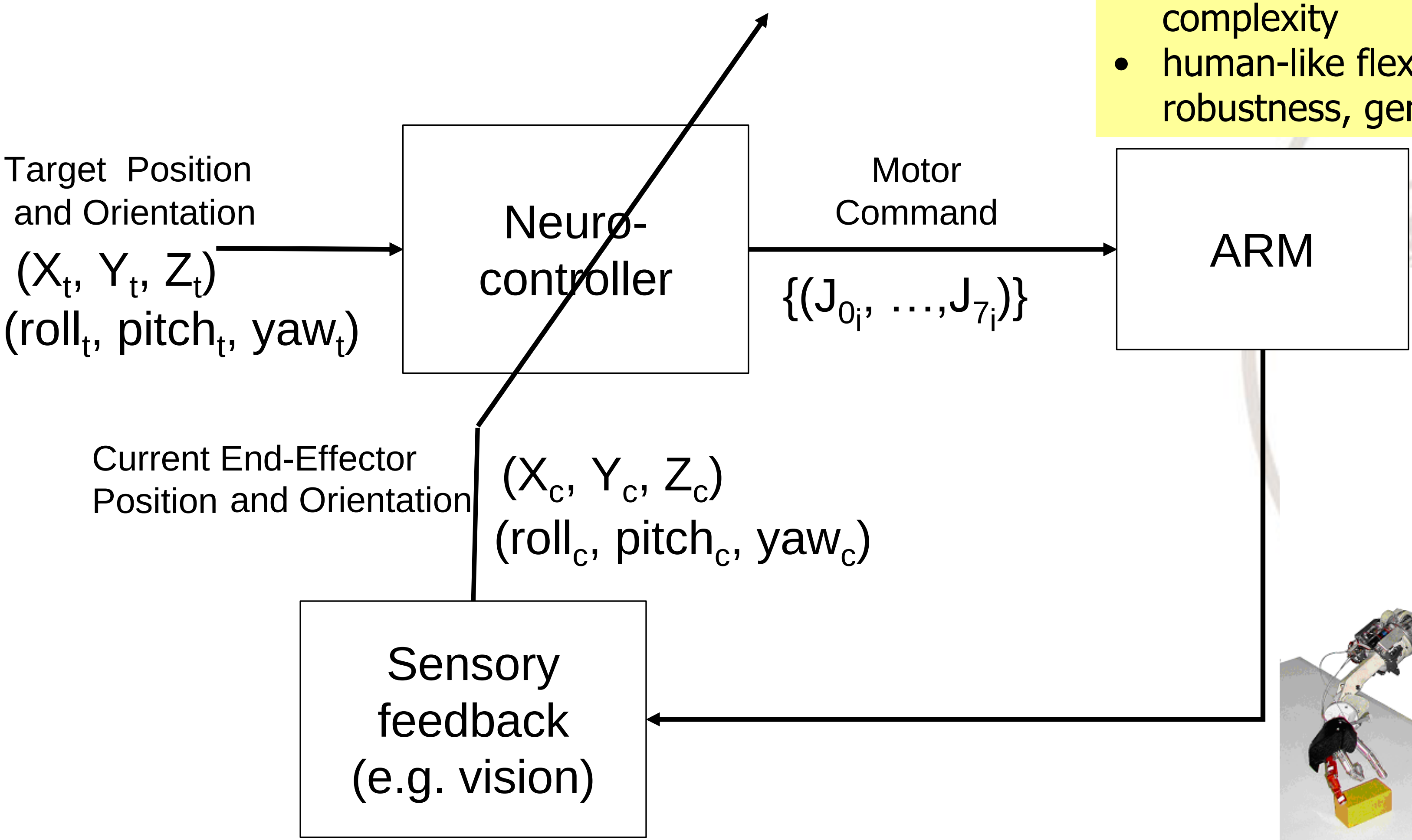
- A priori knowledge on the geometry, kinematics and dynamics of the robot is required
- High computational complexity
- Little flexibility and generalization
- High accuracy

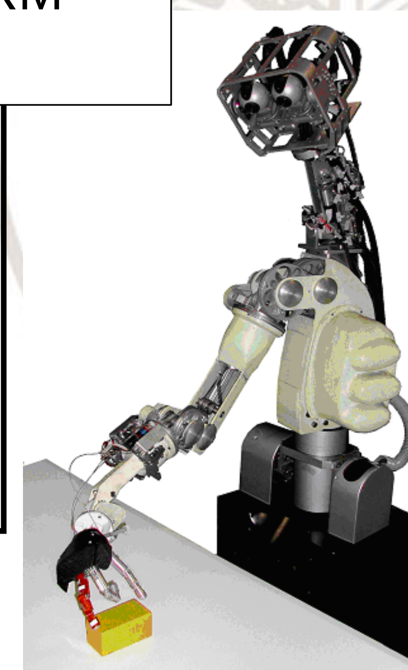




Learning motor control: **neurocontroller** for controlling arm position and orientation

- No a priori knowledge on the geometry, kinematics and dynamics of the robot is required
- ***learning*** capability, to develop an internal model that builds such knowledge
- low computational complexity
- human-like flexibility, robustness, generalization





ISTITUTO
DI BIOROBOTICA

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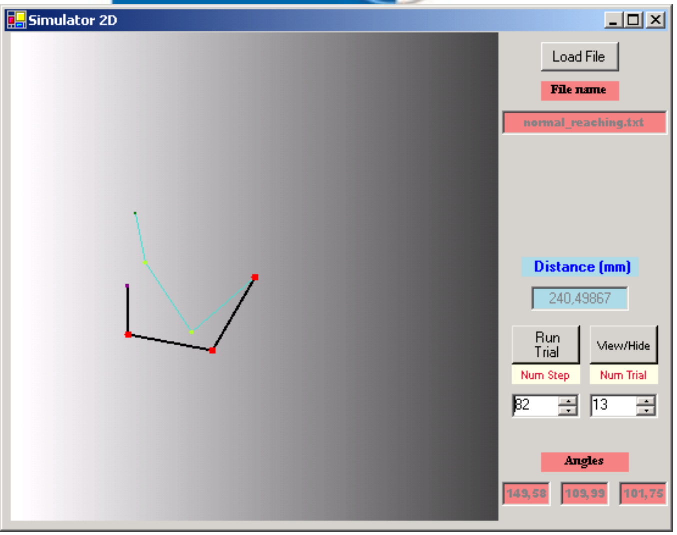
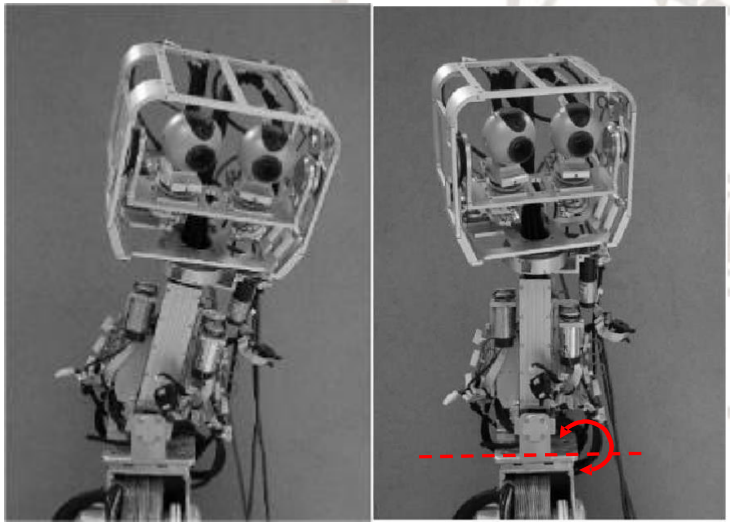
Sant'Anna

Application of the same approach to different robotic systems





G. Asuni, Leoni F., Starita A., Guglielmelli E., Dario P., "A Neuro-controller for Robot Arms Based on Biologically-Inspired Visuo-Motor Coordination Neural Models", *The 1st International IEEE EMBS Conference on Neural Engineering*, 20 - 22 March, 2003, Capri Island, Italy.

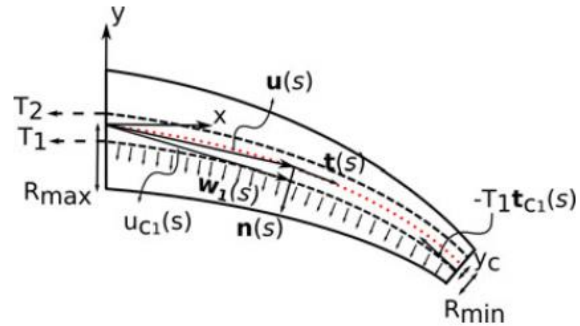
E.Guglielmelli G. Asuni, F. Leoni, A. Starita, P. Dario, "A Neuro-controller for Robot Arms Based on Biologically-Inspired Visuo-Motor Co-ordination Neural Models", *IEEE Handbook of Neural Engineering*, M. Akay (Ed.), IEEE Press, 2007.

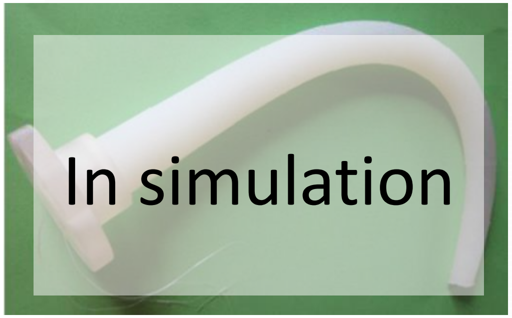
G. Asuni, G. Teti, C. Laschi, E. Guglielmelli, P. Dario, "A Robotic Head Neuro-controller on Biologically-Inspired Neural Models", *IEEE International Conference on Robotics and Automation* April 18-22, 2005, Barcelona, Spain

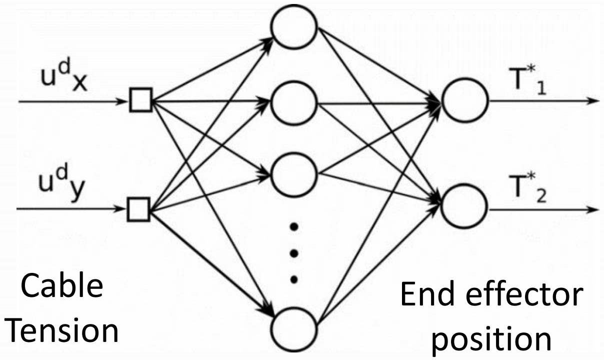
Comparison of a model-based and a model-free approaches

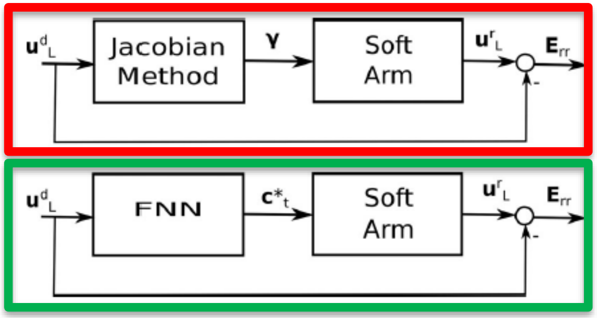
1. Jacobian-based Inverse Static Controller
2. Learning-based Control, by learning the inverse model.
   Learning by collecting points and exploiting the approximation capability of a FNN, as for rigid robots

control the end effector position through the cable tension









Method (Cost)	Statistics Index	ERR/L [%]
JM (351ms)	Mean	0.27
	Std	0.03
	Max	0.32
NN (0.125ms)	Mean	0.73
	Std	0.55
	Max	3.1

Giorelli, M., Renda, F., Calisti, M., Arienti, A., Ferri, G., & Laschi, C. (2015). Neural network and Jacobian method for solving the inverse statics of a cable-driven soft arm with nonconstant curvature. *IEEE Transactions on Robotics*, *31*(4), 823-834.

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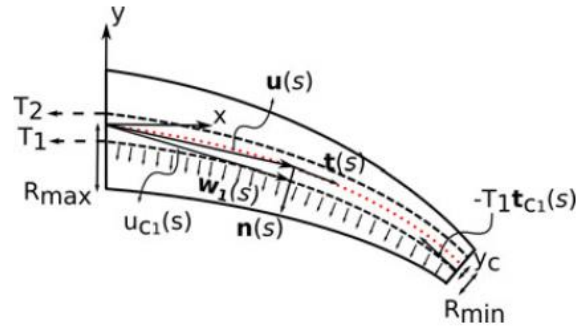

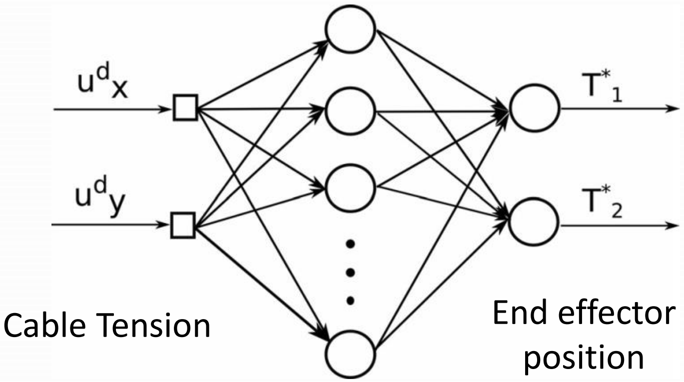

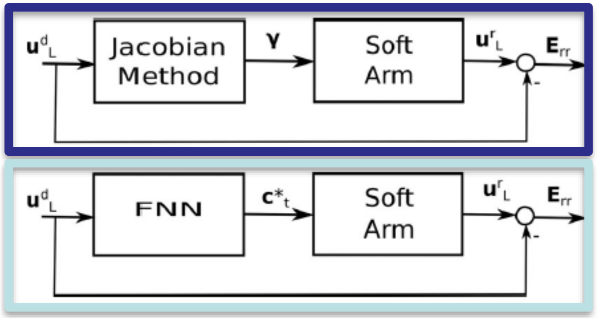

Method		Absolute (mm)	Percentage (%)
Jacobian method	*mean*	15.12	5.4
	std	8.10	2.89
	max	31.76	11.34
	$p_{\%}$		43.18
FNN	*mean*	7.35	2.62
	std	4.75	1.7
	max	22.22	7.94
	$p_{\%}$		91

Giorelli, M., Renda, F., Calisti, M., Arienti, A., Ferri, G., & Laschi, C. (2015). Neural network and Jacobian method for solving the inverse statics of a cable-driven soft arm with nonconstant curvature. *IEEE Transactions on Robotics*, *31*(4), 823-834.

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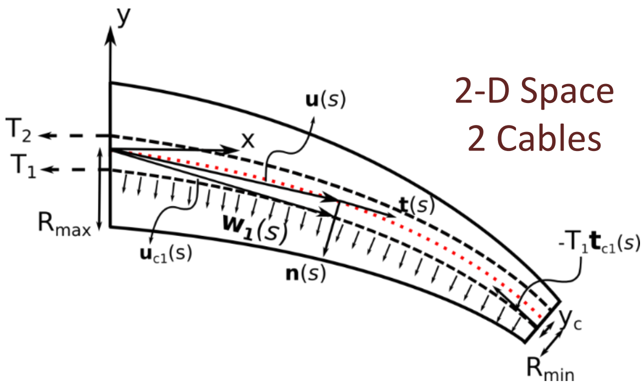
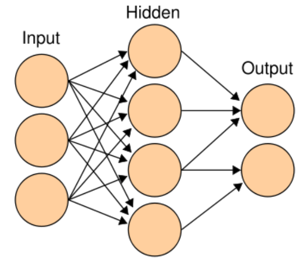


2-D Space
2 Cables

Tip Position



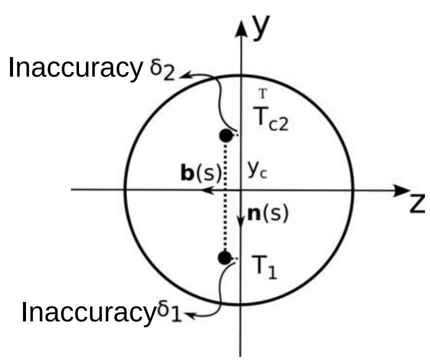
Cable Forces

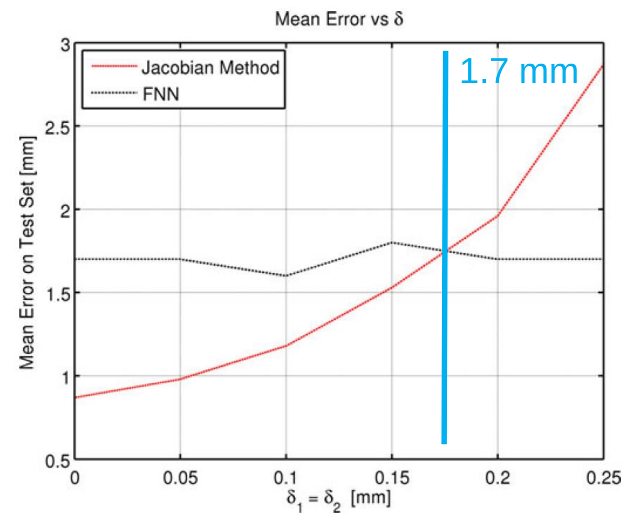
Increasing inaccuracy values

	Inaccuracies		Jacobian	FNN
Case	δ_1	δ_2	*mean*	*mean*
1	−0.25	0.25	1.02	1.5
2	0.25	0	1.26	1.8
3	0	0	0.87	1.7
4	0.05	0.05	0.98	1.7
5	0.1	0.1	1.18	1.6
6	0.15	0.15	1.53	1.8
7	0.2	0.2	1.96	1.7
8	0.25	0.25	2.87	1.7

All values are expressed in millimeters.

Simulated Defective Model





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Inverse Kinematic Controller

Kinematics: based on steady state assumptions

$\dot{x} = J(q)\dot{q}$ ➡ $\Delta x \approx J(q)\Delta q$

Learning a **Differential Inverse Kinematics** formulation : $\dot{x} = J(q^o)\,\dot{q}$

This allows for redundancy resolution, robustness to modelling errors

The learned mapping is : $(x_{i+1}, q_i, x_i) \rightarrow (q_{i+1})$

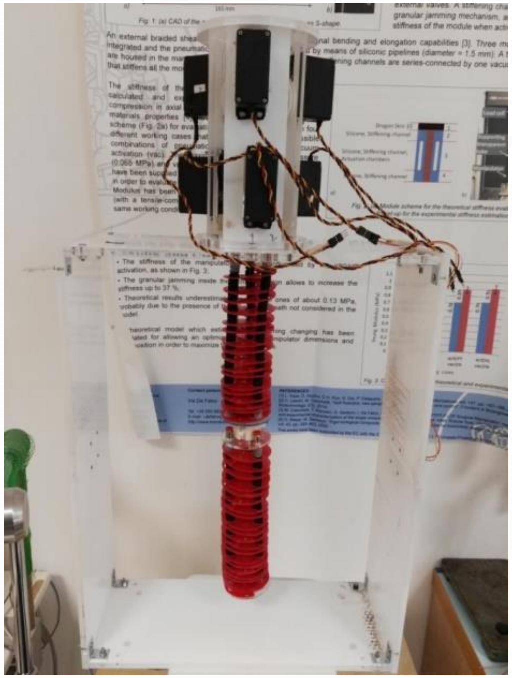
LEARNING

- 2000 sample points divided in the ratio 70:30 for training and testing respectively
- 2 hours for data collection, training, set-up

TESTS

25 random points selected from workspace

	Mean Error	Standard Deviation
Position (mm)	5.58	3.08
X- axis rotation (degrees)	2.76	5.42
Y- axis rotation (degrees)	1.84	1.83
Z- axis rotation (degrees)	3.85	7.02



I-Support Prototype

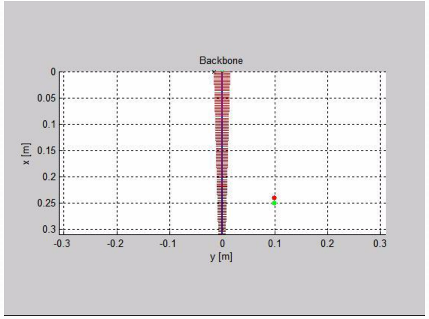
Six DoF Hybrid System
(Pneumatic and Tendon)

George Thuruthel T, Falotico E., et al. "Learning closed loop kinematic controllers for continuum manipulators in unstructured environments." *Soft robotics* 4.3 (2017): 285-296.

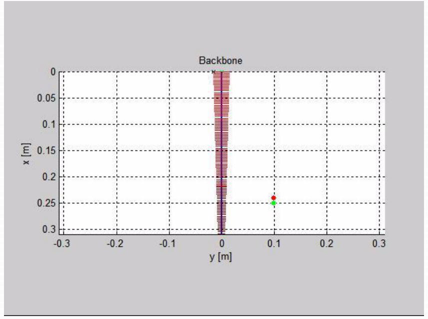
Inverse Kinematic Controller – results in simulation

Only Position Control

Green Point is the target position

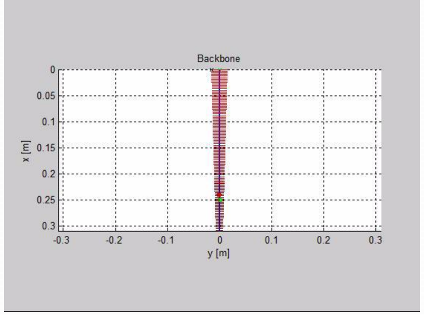


Position and Orientation Control



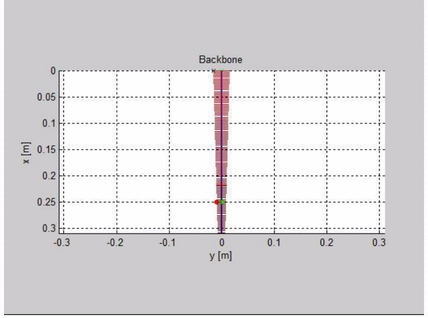
Target Orientation: the vector from the red point to the green point , i,.e parallel to X axis

Behavior at unreachable 'points'



In this case, some of the target orientations are impossible to reach, however we can still see stable behavior of the solver

Varying Orientation

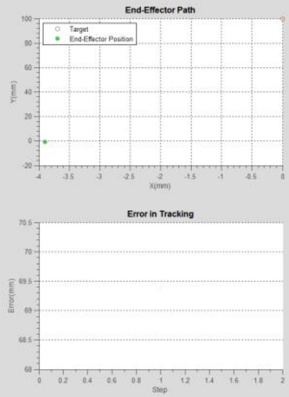


180° rotation of the manipulator without changing the position

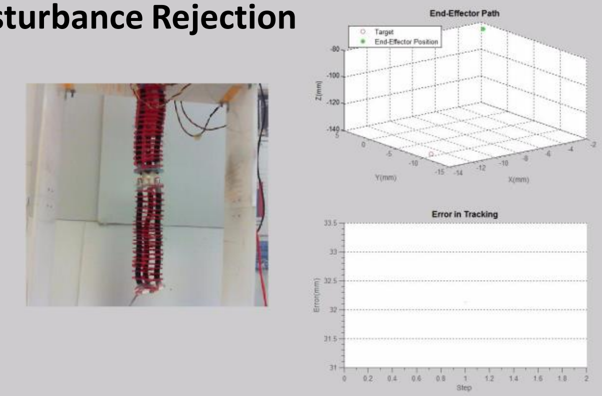
T. G. Thuruthel, E. Falotico, M.Cianchetti, F. Renda, C. Laschi, (2016). " Learning Global Inverse Statics Solution for a Redundant Soft Robot", *In Proceedings of the13th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2016),* pp 303-310

Inverse Kinematic Controller – results on the robot

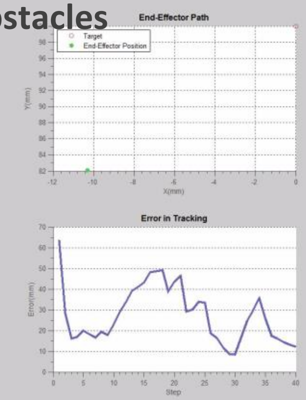
Line Following



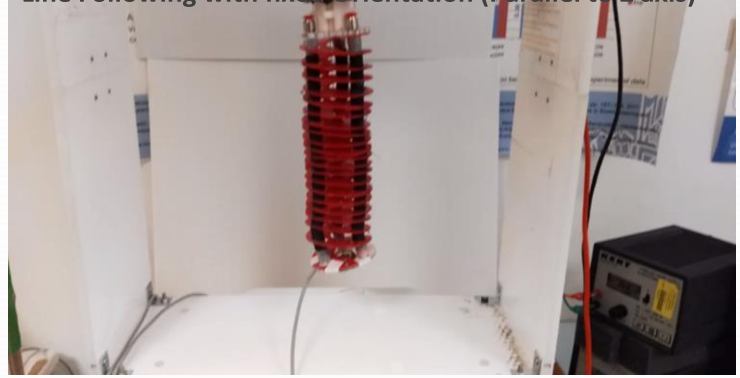
Disturbance Rejection

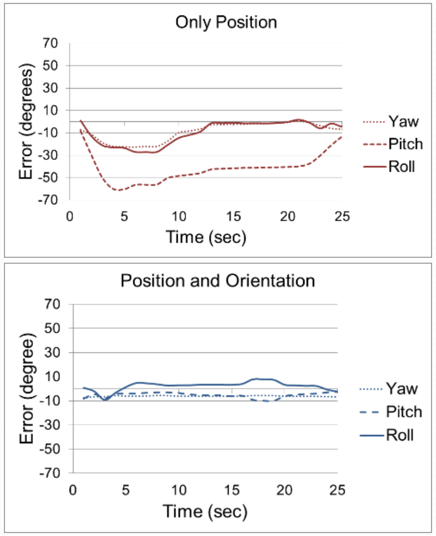


Line Following with obstacles



Line Following with fixed Orientation (Parallel to Z axis)





George Thuruthel T, Falotico E., et al. "Learning closed loop kinematic controllers for continuum manipulators in unstructured environments." *Soft robotics* 4.3 (2017): 285-296.

Outline of the lesson

- Scientific motivations to bioinspired robotics
- Bioinspired principles: simplexity and embodied intelligence
- Bioinspired control: neurocontrollers
- **Bioinspired behaviour: predictive architectures**
- Bioinspired perception

From hierarchical to reactive architectures in robotics

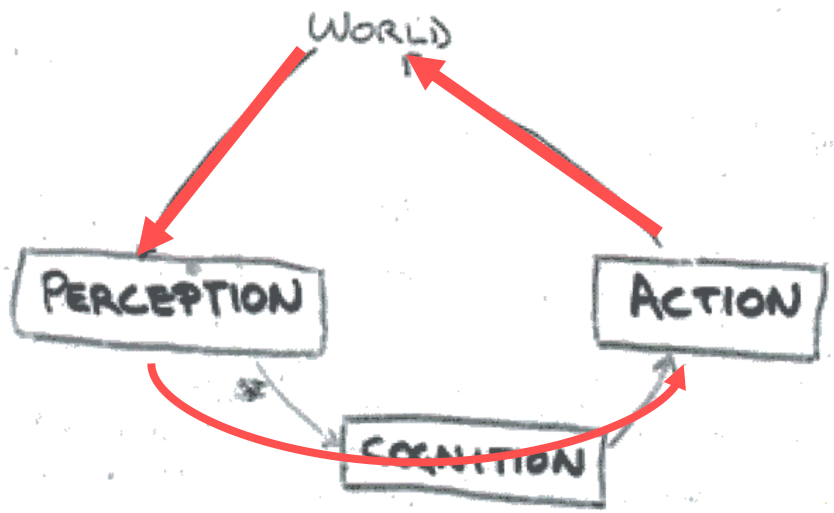


Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

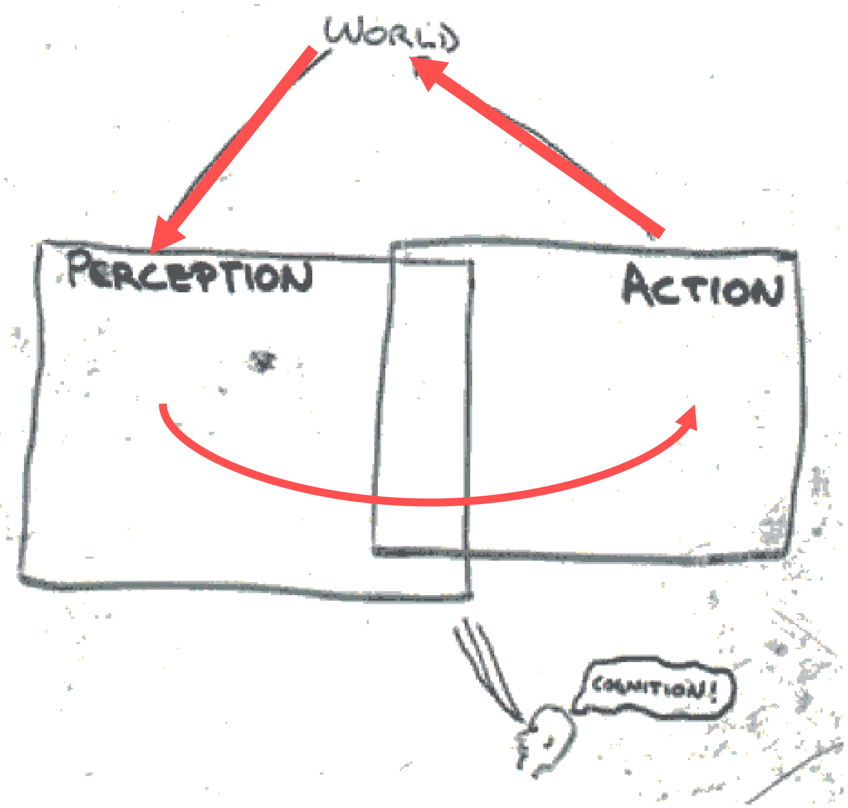


Figure 2: The new model, where the perceptual and action subsystems are all there really is. Cognition is only in the eye of an observer.

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

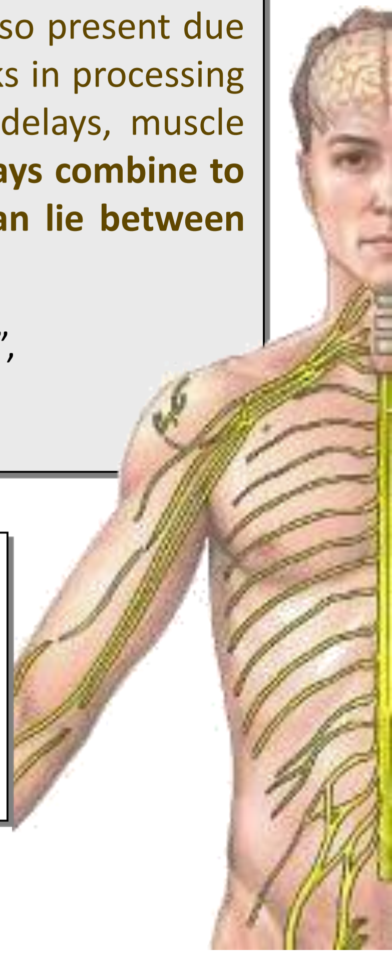
Delays in the human nervous system

"In motor control **delays** arise in **sensory transduction**, **central processing**, and in the **motor output**. Sensor transduction latencies are most noticeable in the visual system where the retina introduces a delay of 30-60 ms, but sensory conduction delays can also be appreciable. Central delays are also present due to such ill-defined events such as neural computation, decision making and the bottlenecks in processing command. Delays in the motor output result from motorneuronal axonal conduction delays, muscle exictation-contraction delays, and phase lags due to the intertia of the system. **These delays combine to give an unavoidable feedback delay within the negative feedback control loop, and can lie between about 30 ms for a spinal reflex up to 200-300 ms for a visually guided response."**

R.C. Miall, D.J. Weir, D.M. Wolpert, J.F. Stein, "Is the cerebellum a Smith predictor?", *Journal of Motor Behavior*, vol. 25, no. 3, pp. 203-216, 1993

"Fast and coordinated arm movements **cannot be executed under pure feedback control** because biological feedback loops are both too slow and have small gains"

M. Kawato, Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9, 718-727(1999). Elsevier Science Ltd.

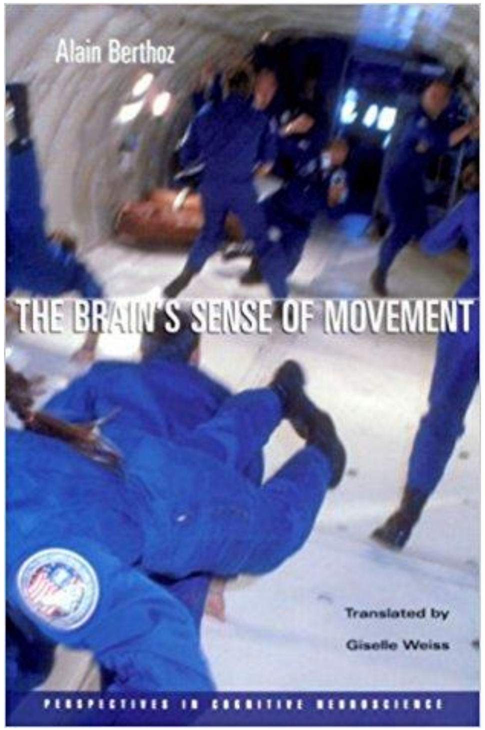


A. Berthoz, *Le sens du mouvement*. Odile Jacob, Paris, 1997
R.S. Johansson, "Sensory input and control of grip", in M. Glickstein (Ed.), *Sensory Guidance of Movements*. John Wiley, Chichester, UK, pp. 45-59,1998

Prediction and anticipation strategies in the human brain

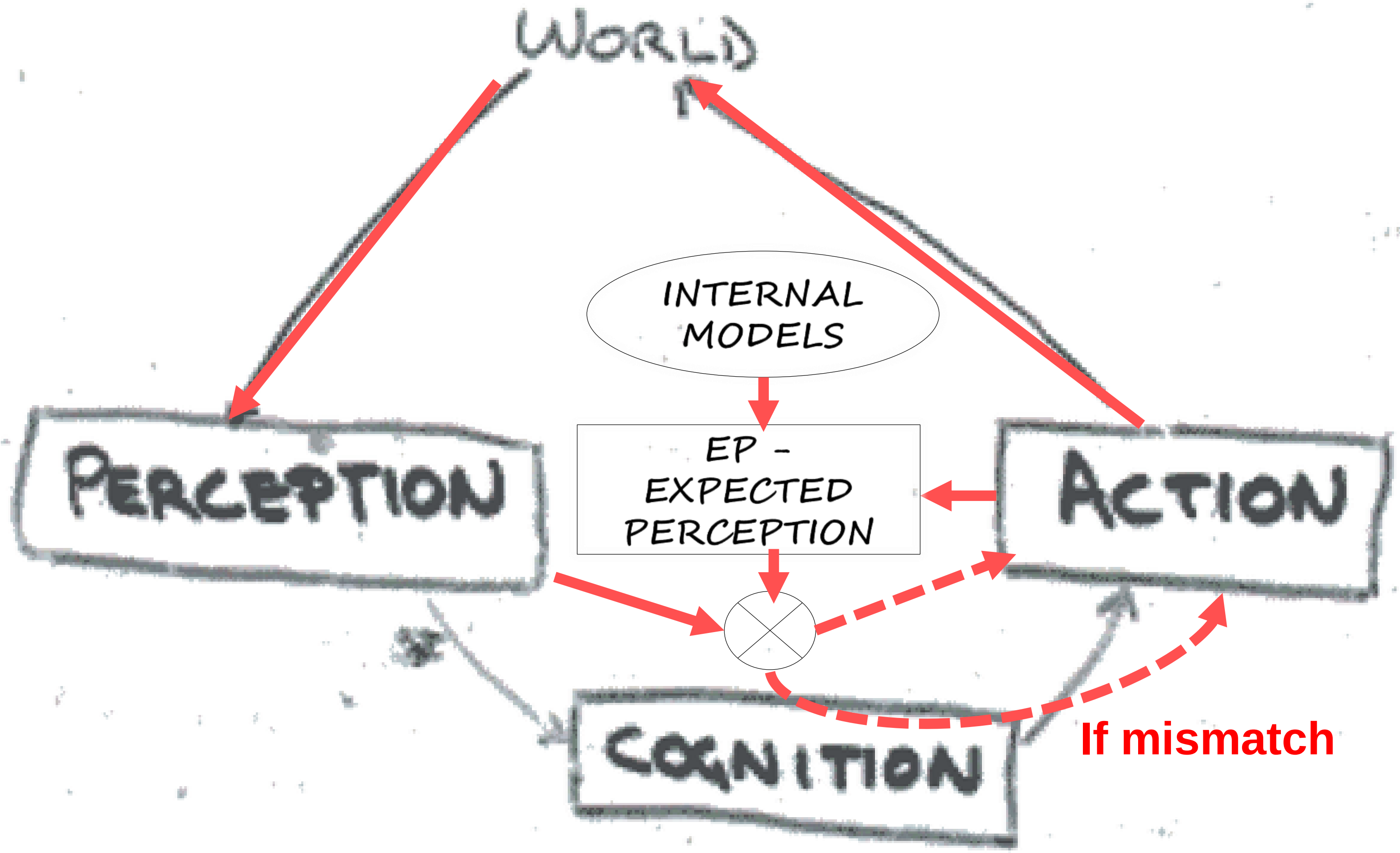
In humans, perception is not just the interpretation of sensory signals, but a prediction of consequences of actions

"Perception can be defined as a ***simulated action***: perceptual activity is not confined to the interpretation of sensory information but it **anticipates** the consequences of action, so it is an internal simulation of action.
Each time it is engaged in an **action**, the brain constructs hypotheses about the state of a variegated group of **sensory** parameters throughout the movement."



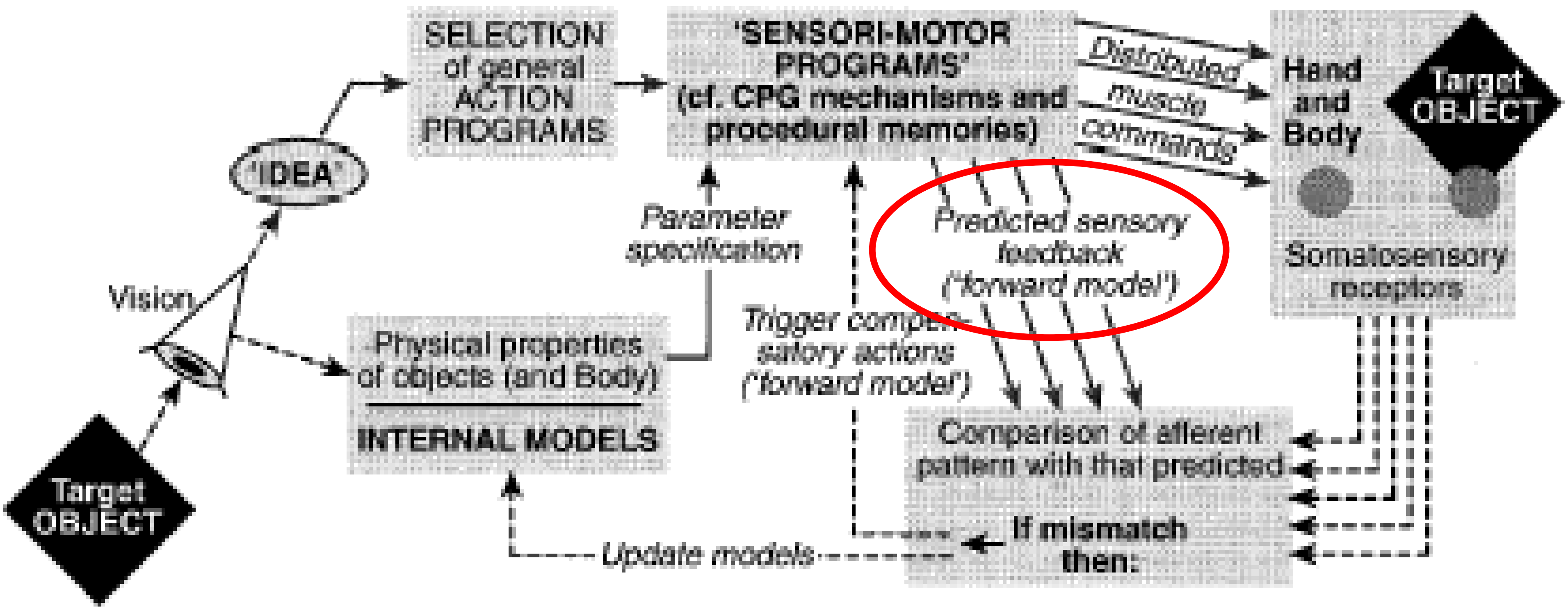
Berthoz A. (2002), *The brain's sense of movement*. Harvard University Press

…to predictive architectures



Sensory prediction proposed by R. Johansson

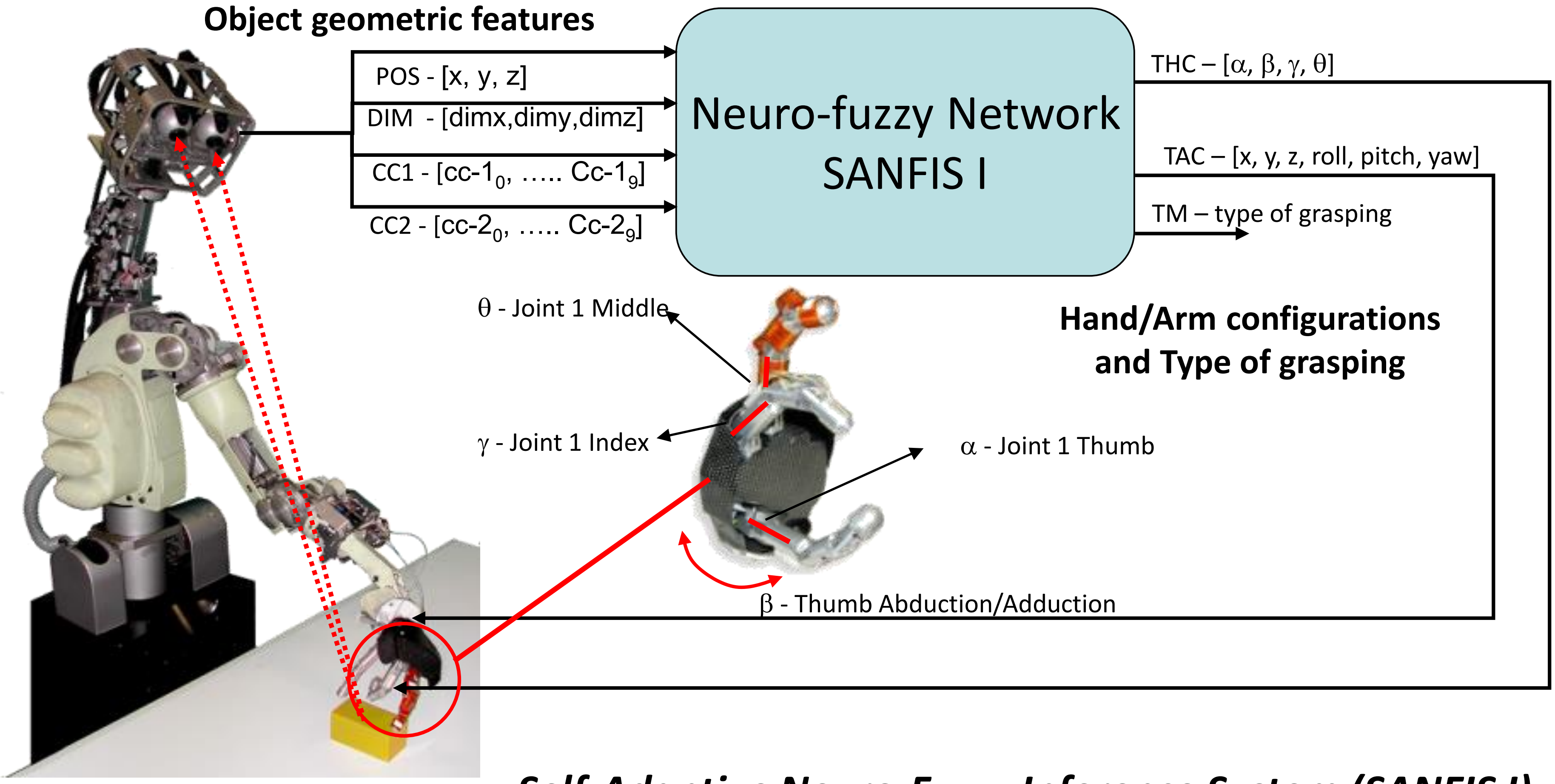
"Because of the long time delays with feedback control the swift coordination of fingertip forces during self-paced everyday manipulation of ordinary 'passive' objects must be explained by other mechanisms. **Indeed, the brain relies on feedforward control mechanisms and takes advantage of the stable and predictable physical properties of these objects by parametrically adapting force motor commands to the relevant physical properties of the target object**."



Corrections are generated when expected sensory inputs do not match the actual ones

R.S. Johansson, "Sensory input and control of grip". In *Sensory Guidance of Movements*, John Wiley, Chichester, UK, pp. 45-59, 1998

Preshaping Module



Self-Adaptive Neuro-Fuzzy Inference System (SANFIS I)

- *Combine advantages NN and Fuzzy Logic*
- *Learning, adaptation, and connectionist structure*
- *Ability to exact explicit IF-THEN rules from training data*

EP Generator (preshaping) Module

Object geometric features

POS - [x, y, z]

DIM - [dimx,dimy,dimz]

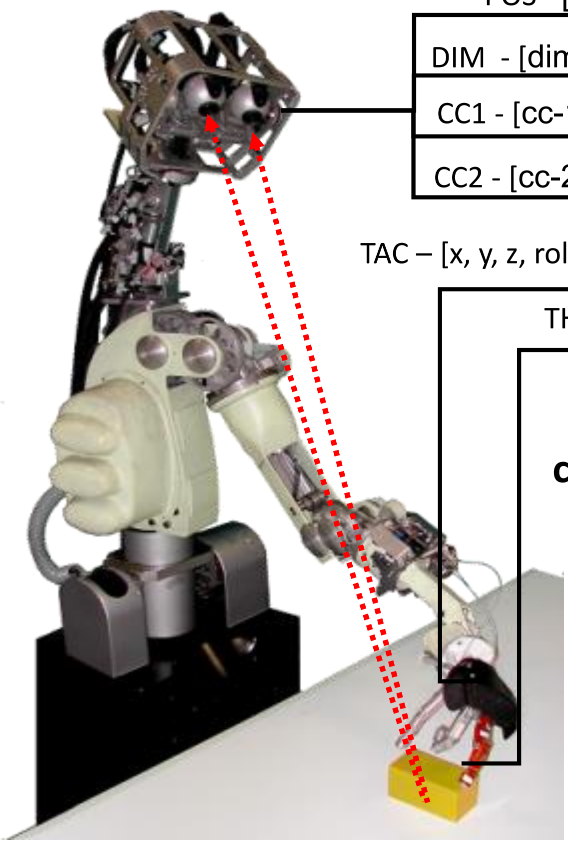
CC1 - [$cc\text{-}1_0$, ….. $Cc\text{-}1_9$]

CC2 - [$cc\text{-}2_0$, ….. $Cc\text{-}2_9$]

TAC – [x, y, z, roll, pitch, yaw]

THC – [α, β, γ, θ]

Hand/Arm configurations



Neuro-fuzzy Network SANFIS II

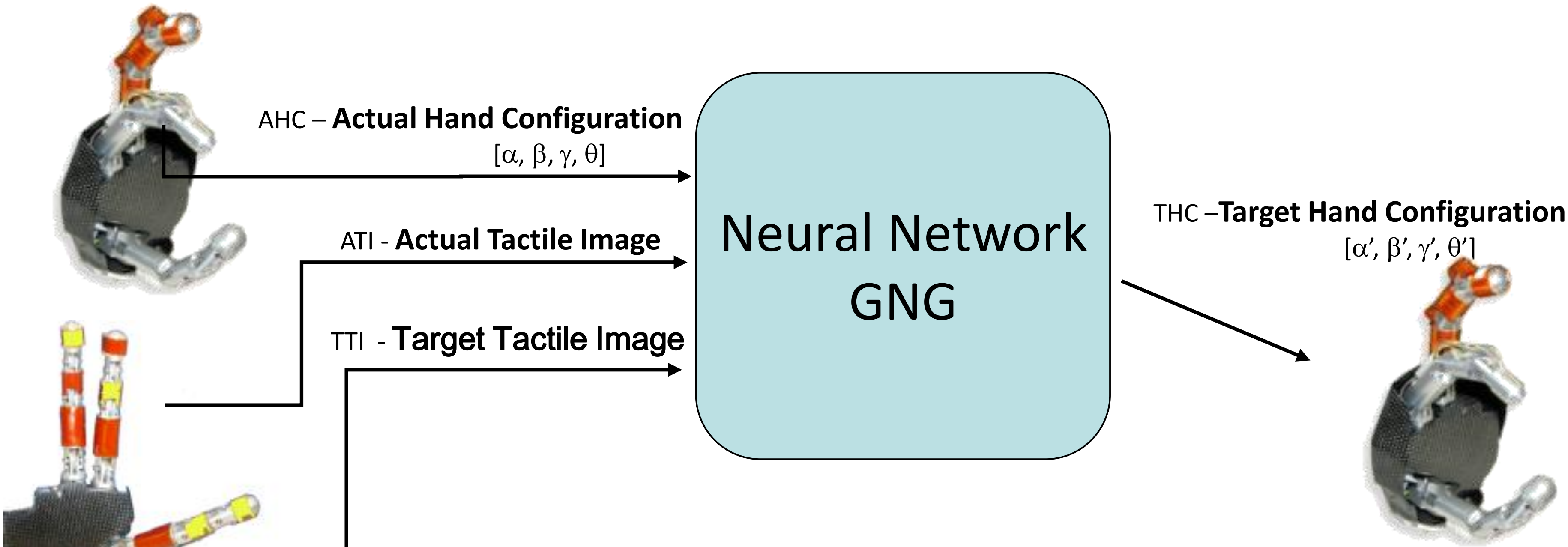
TTI - **Target Tactile Image**

[tt_1, tt_2, …, tt_m]
where:
m=9
tt_i = i-th value for the tactile sensor $\in$ {0,1}

SANFIS II

- *Combine advantages NN and Fuzzy Logic*
- *Learning, adaptation, and connectionist structure*
- *Ability to exact explicit IF-THEN rules from training data*
- *Output space not very complex*

EP-based Grasping Module



Growing Neural Gas + Grossberg's Outstars

•Unsupervised learning paradigm

•Competitive learning methods (winner-takes-all)

•Generation of a topology-preserving mapping from the input space onto a topological structure of equal or lower dimension

•Network topology is unconstrained

•Uses growth mechanism (the network size does not need be predefined)

Building the Preshaping Module and the EP Generator Module

Collection of training data

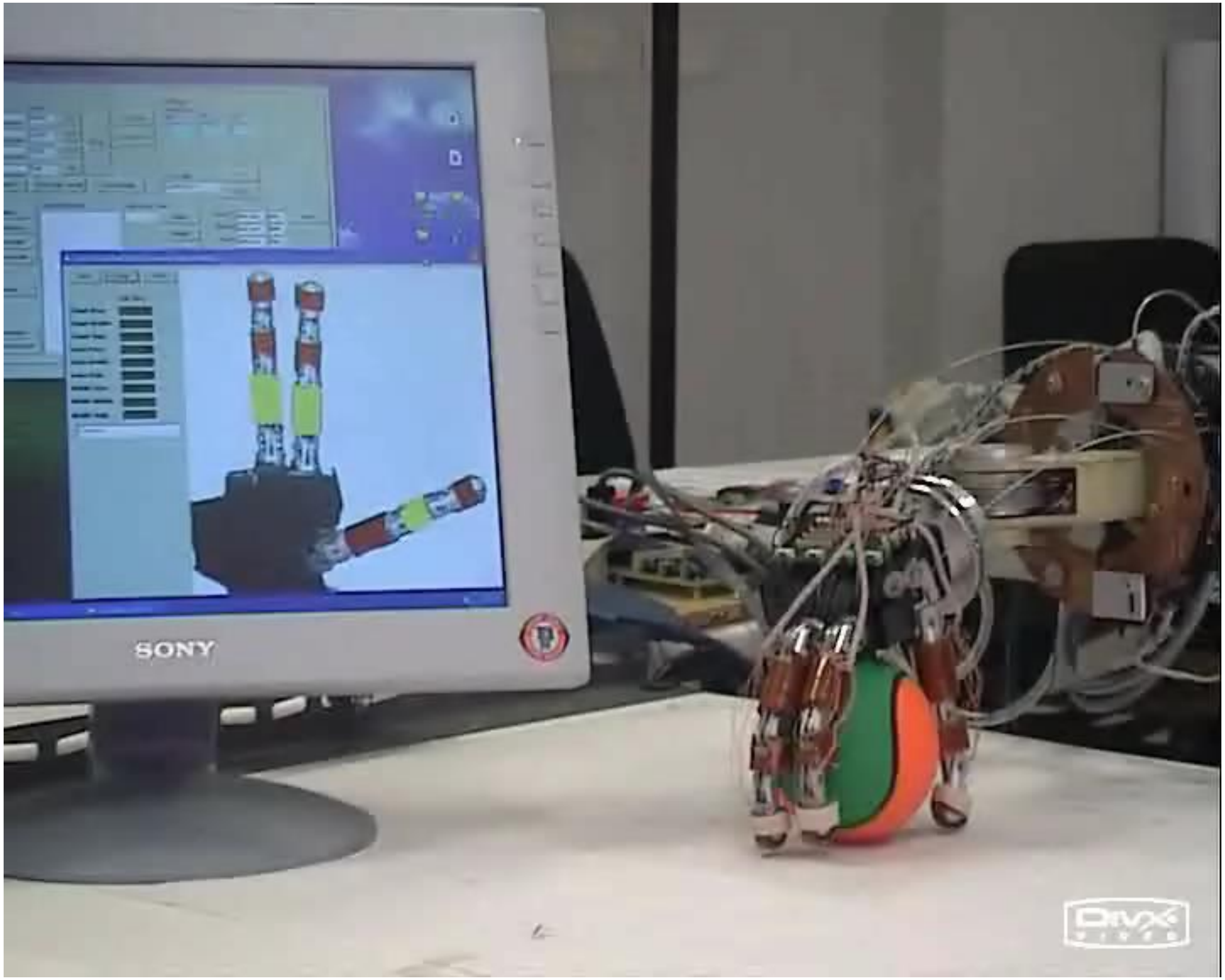
- Large ball in 12 positions

- Bottle in 12 positions in standing position

- Bottle in 12 positions lying with 5 different orientations for each position

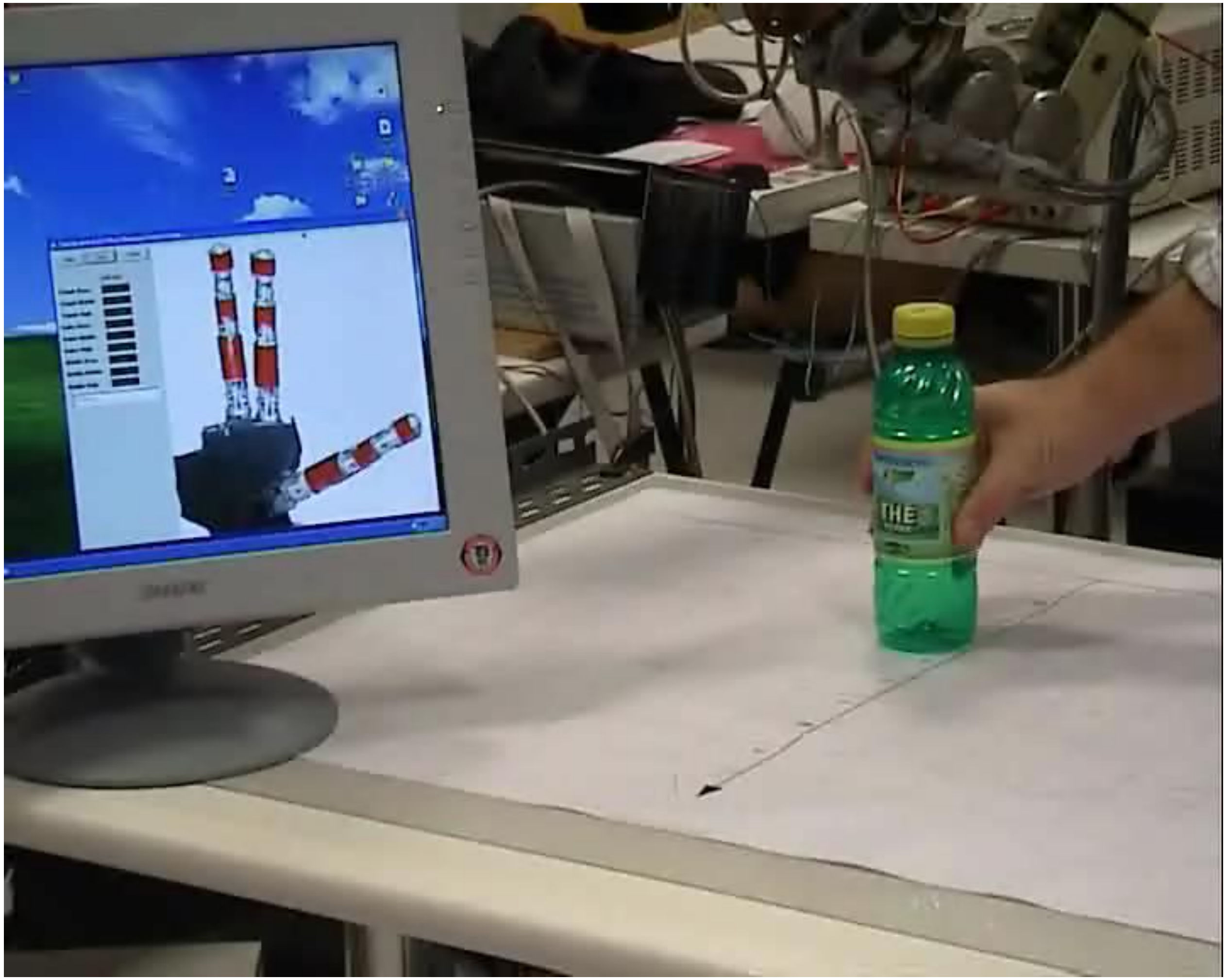
- Cassette in 12 positions with 3 different orientations for each position

Learning of grasping module



Learning phase:
About 40000 random movements

Grasping the bottle



C. Laschi, G. Asuni, E. Guglielmelli, G. Teti, R. Johansson, M.C. Carrozza, P. Dario, "A Bio-inspired Neural Sensory-Motor Coordination Scheme for Robot Reaching and Preshaping", *Autonomous Robots*, Vol.5, 2008, pp.85-101.

Expected Perception in the visual space

EP architecture applied to 3D reconstruction of the environment


09ar0078cl [RF] © www.visualphotos.com

Task: free walking in an unknown room with obstacles

Classical approach:

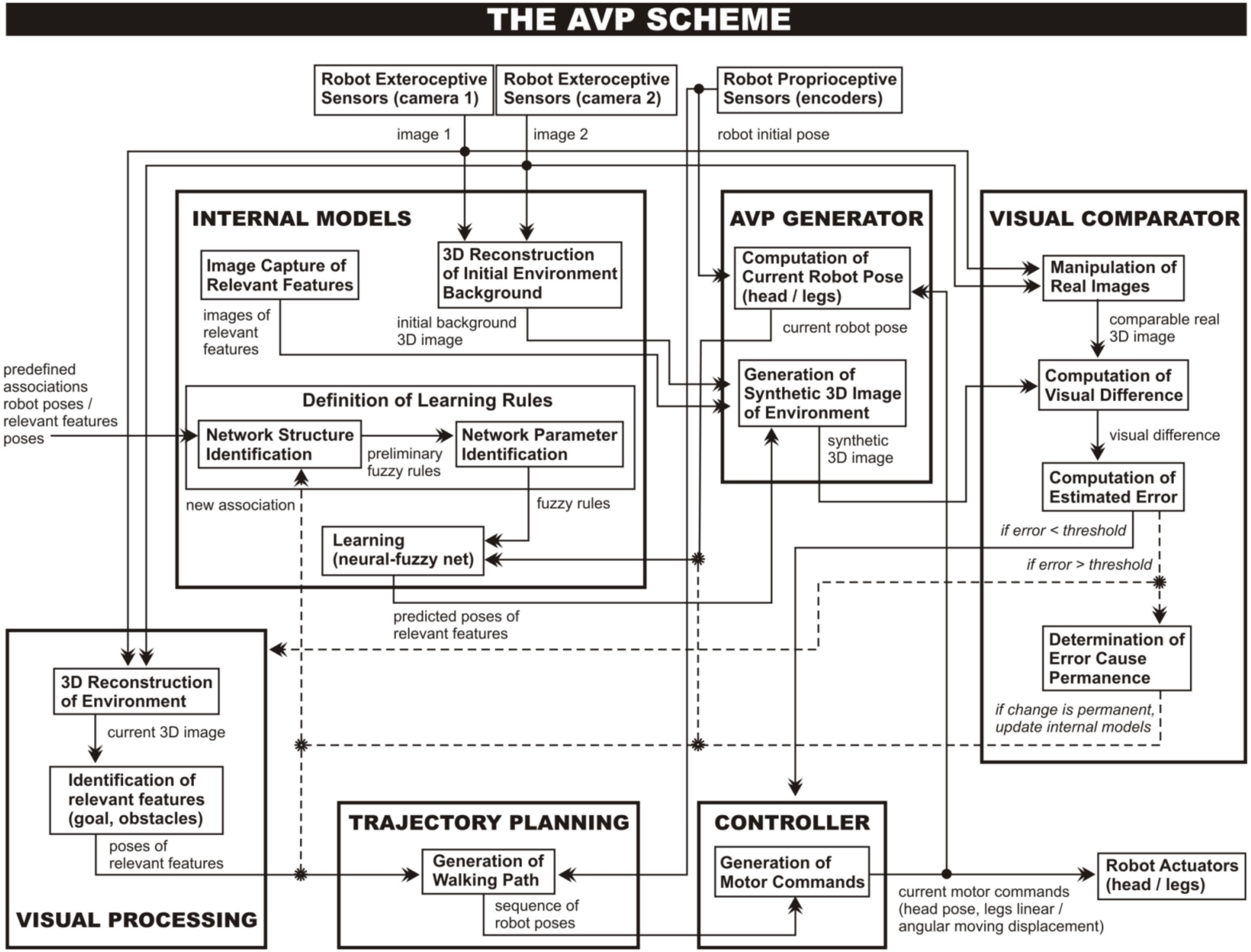
- 3D reconstruction of the environment
- path planning for collision-free walking

-> large computational burden

In a Visual EP architecture, after a first 3D reconstruction of the environment, images can be predicted, based on internal models and on the ongoing movement.

Predicted images are compared with actual ones and in case of unexpected obstacles a mismatch occurs and the motor action is re-planned

Visual EP scheme



Barrera, A. & Laschi, C. “Anticipatory visual perception as a bio-inspired mechanism underlying robot locomotion “, *IEEE Int. Conf. on Engineering in Medicine and Biology Society (EMBC)*, Minneapolis, MN, USA, September 2010, pp.3206-3209

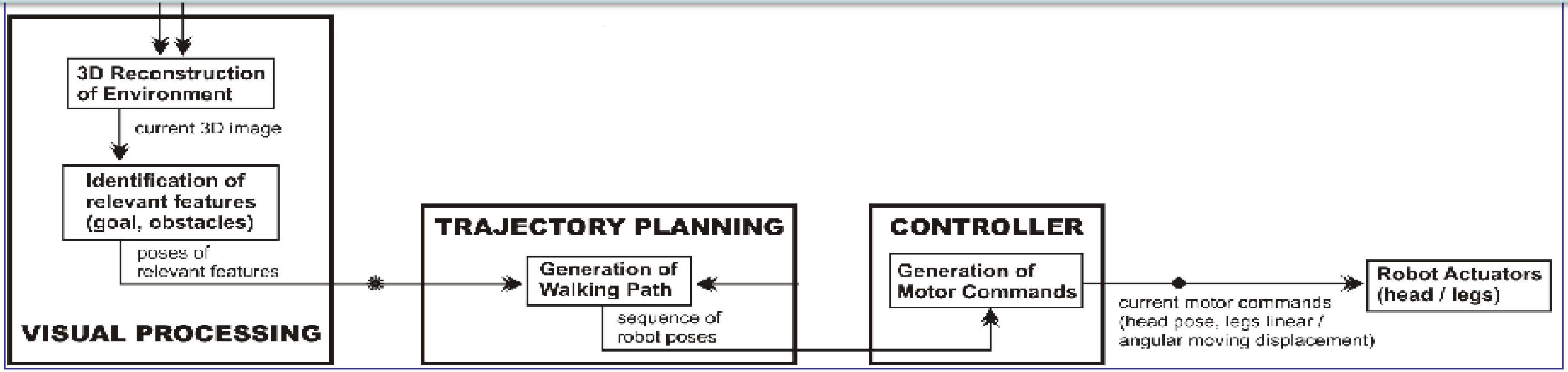
AVP architecture (I)

- **Visual Processing** module takes as input current images from both robot cameras to reconstruct the environment producing the **relevant feature position.**

- The poses of relevant features are sent to a **Trajectory Planning** module to generate the walking path

- The **Controller** module then takes the first robot pose from the sequence of poses planned by the Trajectory Planning module and produces the corresponding motor commands

-This cycle continues until the robot reaches the target.

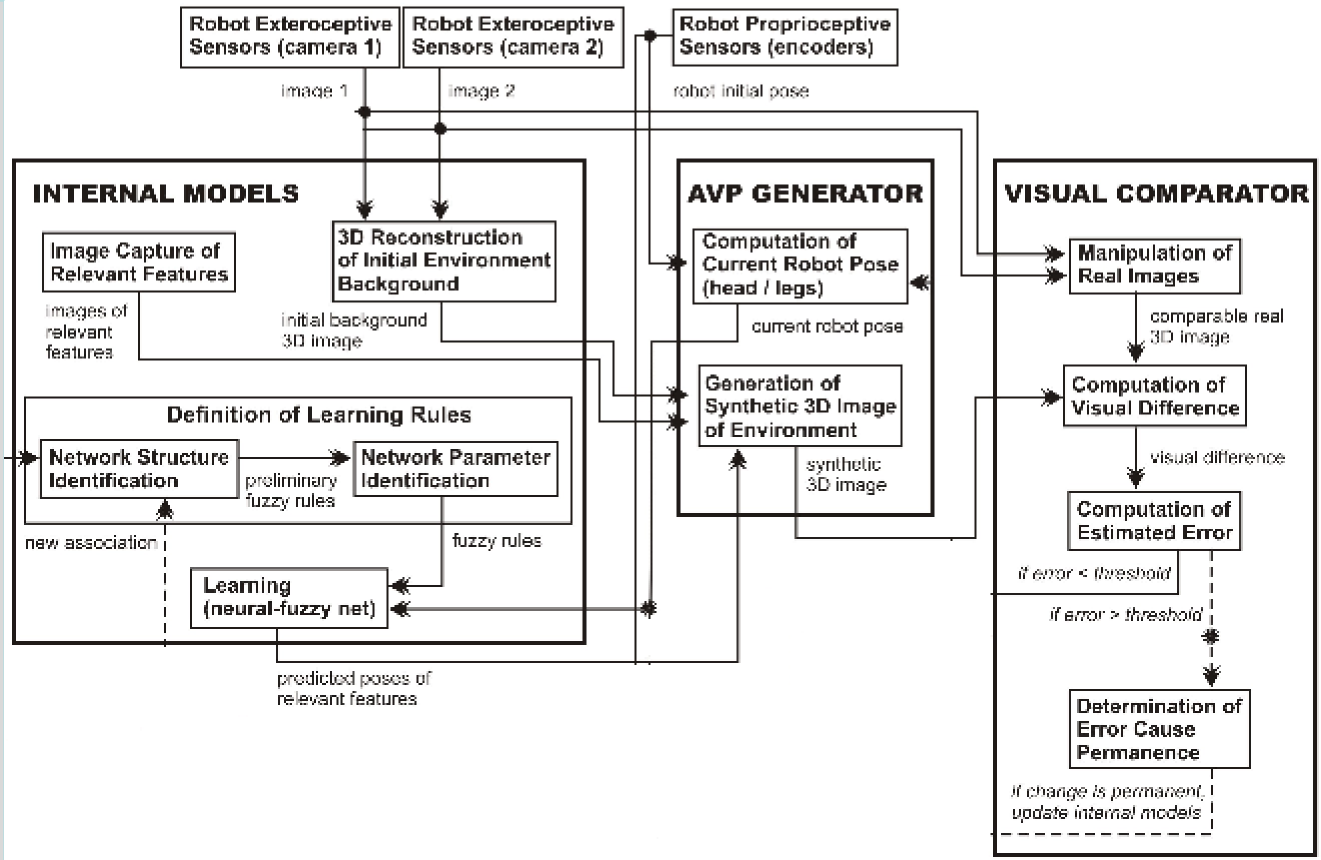


Barrera, A. & Laschi, C. "Anticipatory visual perception as a bio-inspired mechanism underlying robot locomotion ", *IEEE Int. Conf. on Engineering in Medicine and Biology Society (EMBC)*, Minneapolis, MN, USA, September 2010, pp.3206-3209

AVP architecture (II)

- **Internal Models** of the environment and of the task to be performed are necessary to *predict future visual perceptions*.

- Images of different features relevant to the locomotion task are captured and memorized



Barrera, A. & Laschi, C. “Anticipatory visual perception as a bio-inspired mechanism underlying robot locomotion “, *IEEE Int. Conf. on Engineering in Medicine and Biology Society (EMBC)*, Minneapolis, MN, USA, September 2010, pp.3206-3209

Visual EP System (implementation)

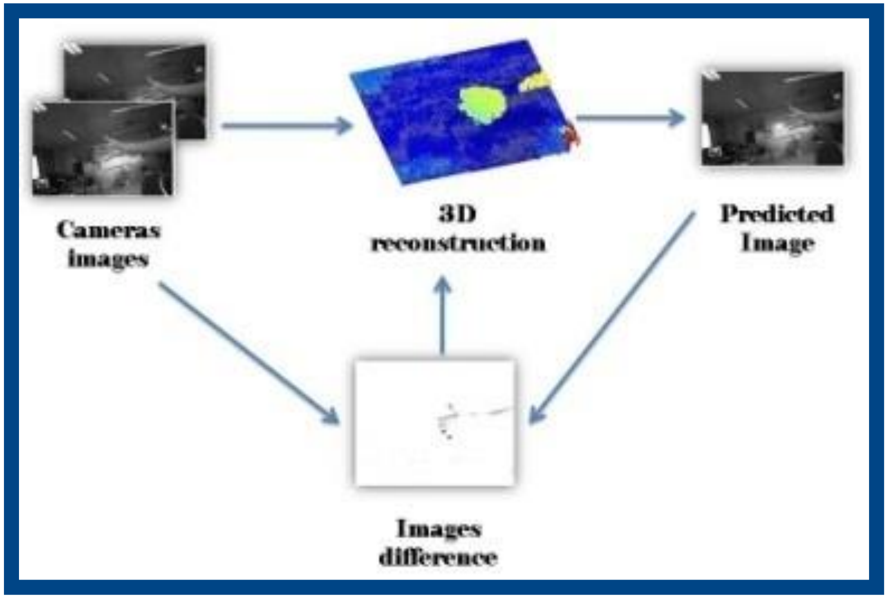
The system performs a real time 3D reconstruction of the environment (30fps) used to generate an **expected synthetic camera image**. The cloud of 3D points is updated using an image sensory-motor prediction.

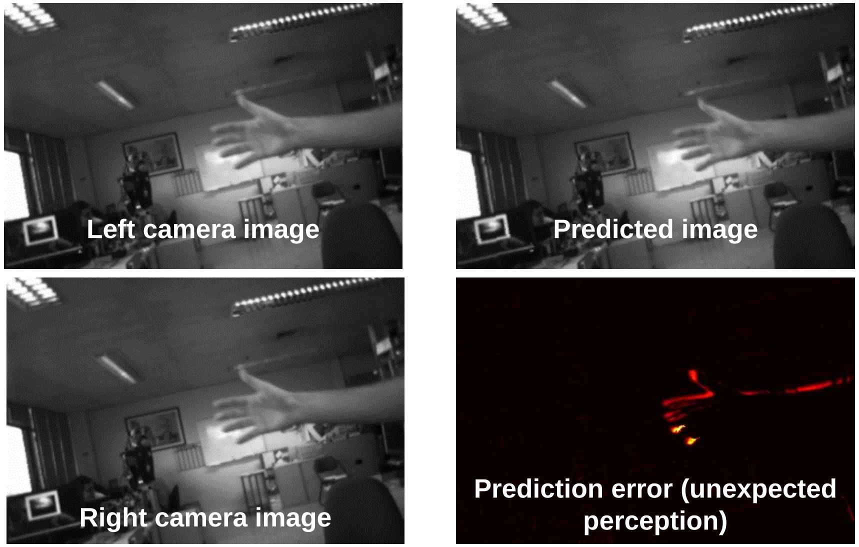
At each step:

- the next predicted image (EP) is calculated.
- the predicted and actual cameras images are compared.
- the 3D reconstruction of the visible environment is updated based on the prediction error

The system has 2 advantages:

- A faster real-time 3D reconstruction
- Recognition of the unexpected objects in the scene





Moutinho, N.; Cauli, N.; Falotico, E.; Ferreira, R.; Gaspar, J.; Bernardino, A.; Santos-Victor, J.; Dario, P.; Laschi, C.; 2011. "An expected perception architecture using visual 3D reconstruction for a humanoid robot," *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, San Francisco, CA, USA, 25-30 Sept. 2011 , pp.4826-4831.

EP of external moving objects
Prediction of movements of other agents

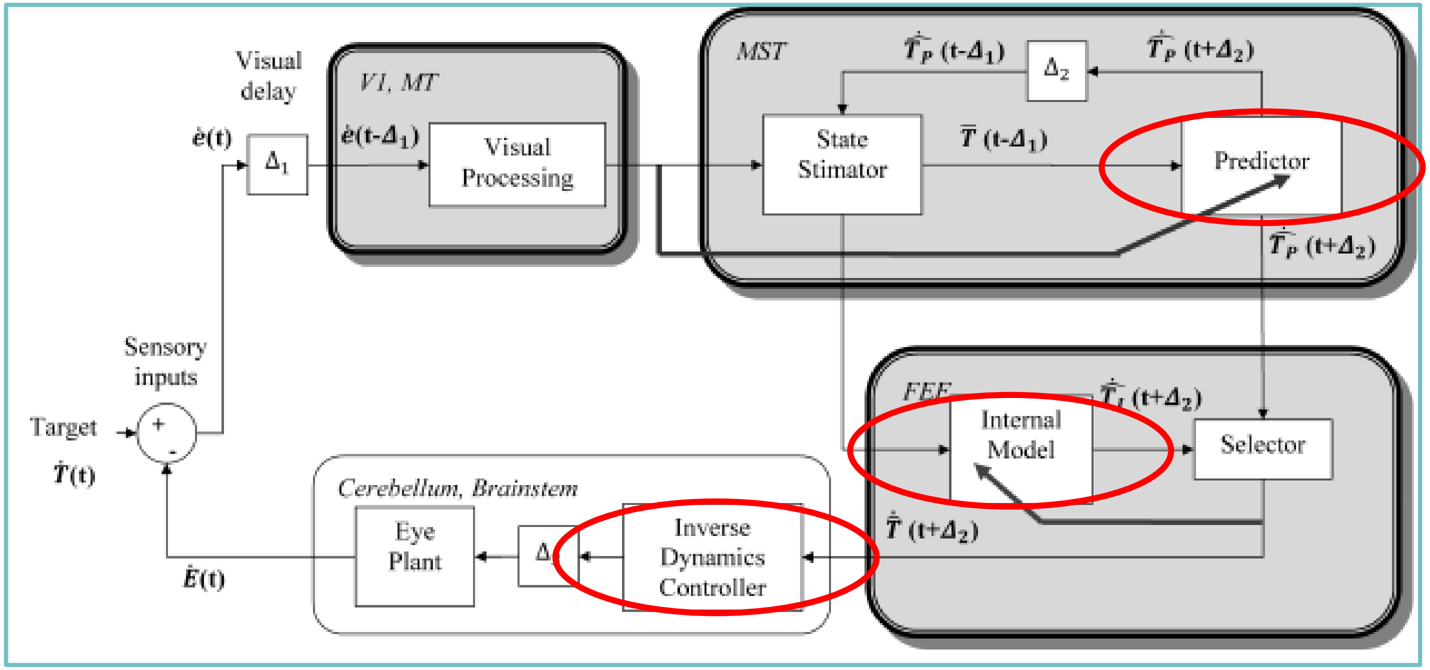
Applications: avoiding, reaching, hitting or caching moving objects

- The Expected Perception is not only generated by self motion

- Movements of other agents can be predicted, when their motion dynamics follows rules that can be learnt
(e.g. laws of physics)

- In this case the planning is based on a long term prediction (more than one step ahead) of the object trajectory

A predictive model for smooth pursuit

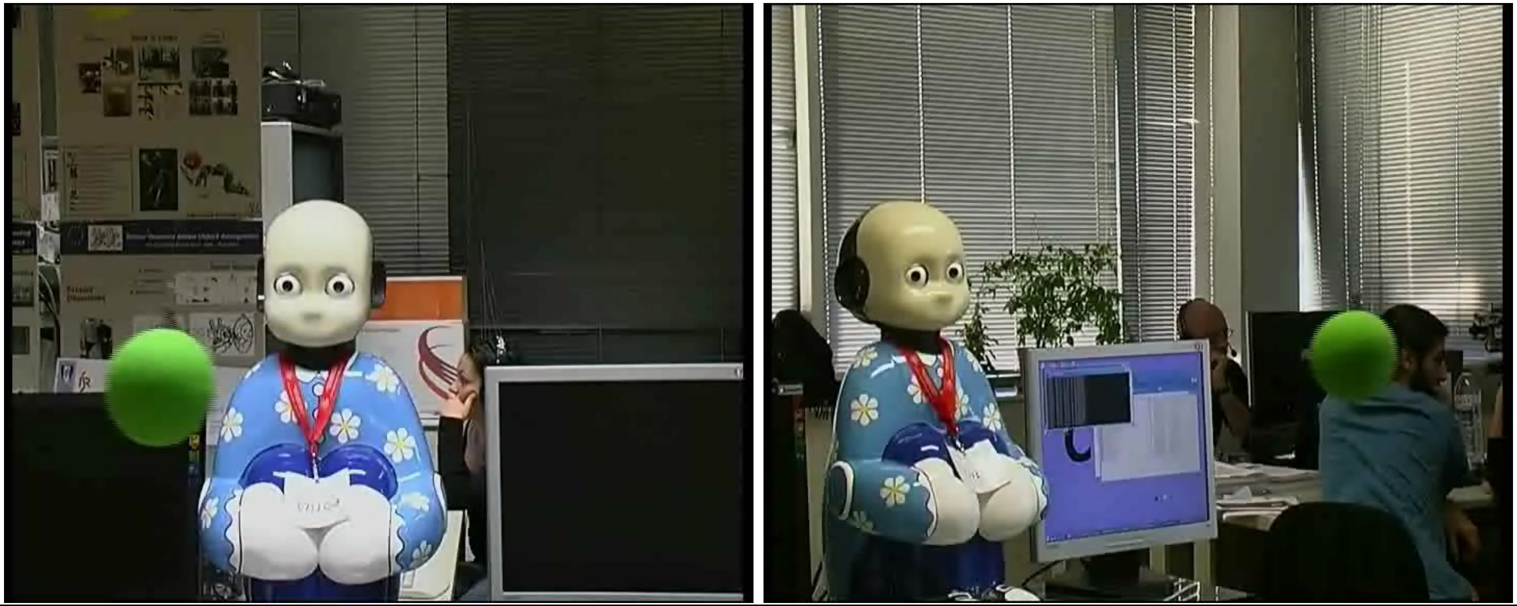


This circuit is based on Shibata and Schaal's model (*Shibata 2005*) of smooth pursuit and consists of **three subsystems**:

1. a **recurrent neural network** (RNN) mapped onto medial superior temporal area (MST), which receives the retinal slip with delays and ***predicts*** the current target motion,
2. an **inverse dynamics controller** (IDC) of the oculomotor system, mapped onto the cerebellum and the brainstem,
3. and **a memory block** that recognizes the target dynamics and provides the correct weights values before the RNN.

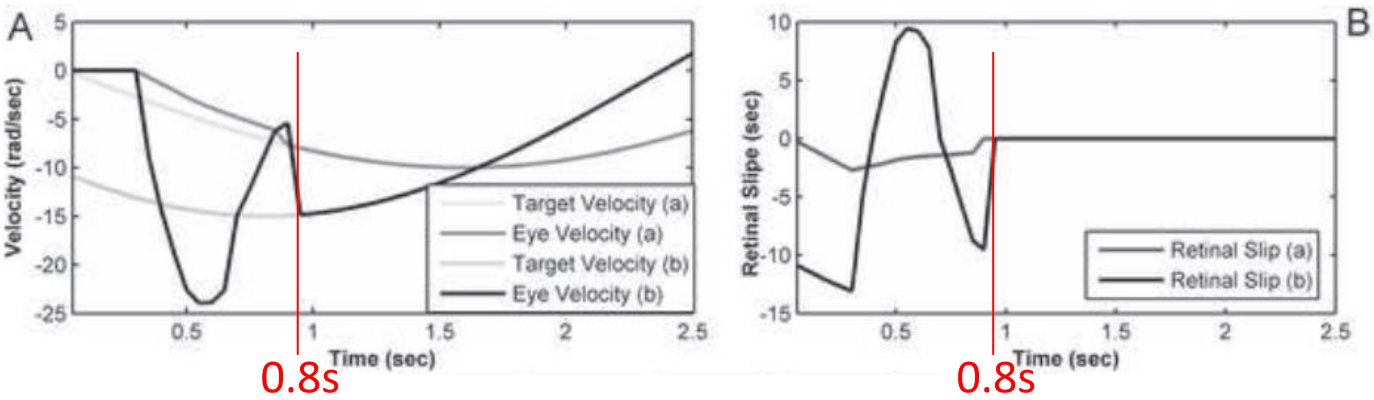
Zambrano D, Falotico E, Manfredi L, and Laschi C. (2010). "A model of the smooth pursuit eye movement with prediction and learning". *Applied Bionics and Biomechanics*

Predictive smooth pursuit on a robot head



iCub platform head, 6 dof:
3 for the eyes
3 for the neck

The *retinal slip* (target velocity onto the retina) reaches zero after that the algorithm converges.
When the target is unexpectedly stopped, the system goes on tracking the target for a short time.

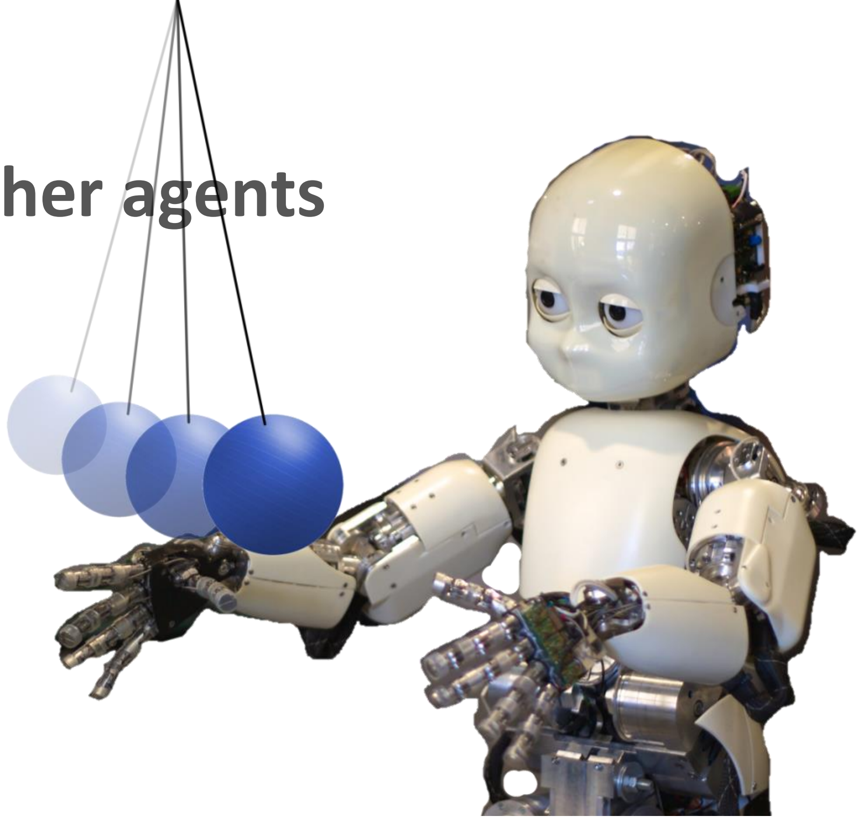


Sinusoidal dynamics:

a) angular frequency: 1 rad/s, amplitude: 10 rad, phase: π/2
b) angular frequency: 1 rad/s, amplitude: 15 rad, phase of ¾ π

EP of external moving objects
Prediction of movements of other agents

Punching a moving target

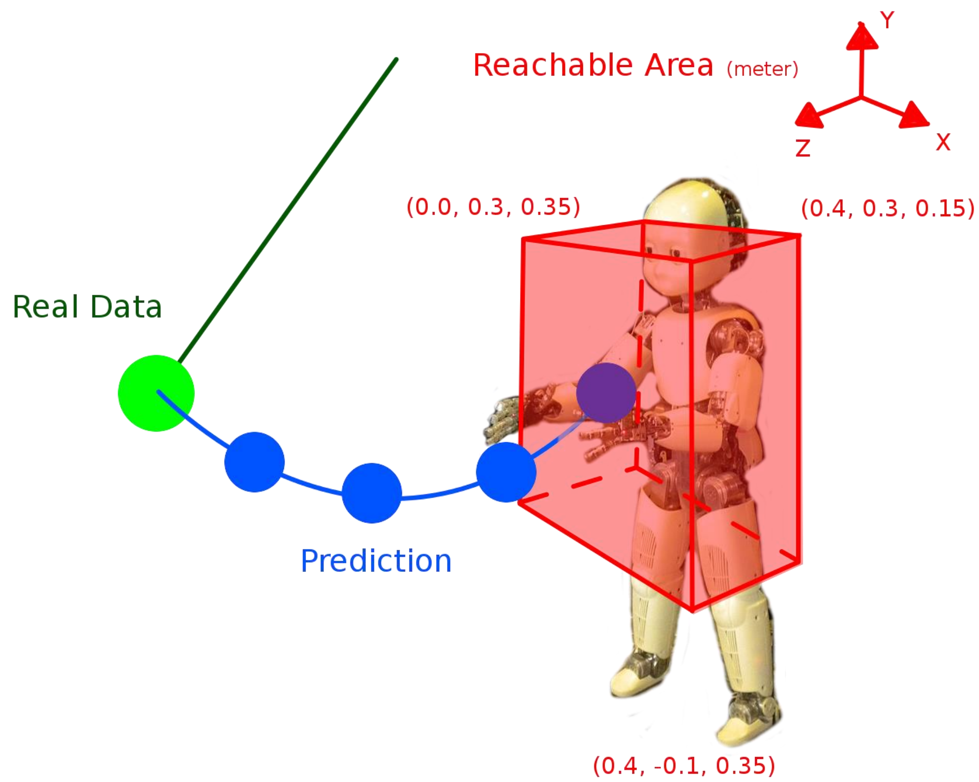


The robot punches a target oscillating in front of it with a predictable dynamics (pendulum)

An internal model is used to predict the dynamics of the moving target

The prediction allows to anticipate the movement of the arm and hit the ball

Punching a moving target
Experiment on Simulation/Robot



Experiment environment:

- A pendulum oscillates in front of the robot

Goal:

- Punching a predictable moving target when it reaches the robot arm workspace

Solution:

- *External model* used to predict the trajectory of the target (position through time) using a *Kalman Filter*
- Arm controller used to move the hand towards the desired position with a fixed time delay

Punching a moving target - robot experiments

The prediction is iterated ahead 0.5 seconds
As the predicted target is inside the arm workspace, the robot executes a movement to punch the ball in the ***predicted position***

N. Cauli, E. Falotico, A. Bernardino, J. Santos-Victor, C. Laschi, "Correcting for Changes: Expected Perception-Based Control for Reaching a Moving Target", *IEEE Robotics and Automation Magazine*, 23 (1), pp.63-70, 2016.

Summary
Bioinspired simplifying principles

- Simplexity (and humanoid robotics)
- Embodied Intelligence (and soft robotics)
- Neuro-controllers
- Predictive architectures

Journal Club

THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

Group (2 students) assignment:

Read one the following papers:

1. M.O. Franz, H.A. Mallot, "Biomimetic robot navigation", *Robotics and Autonomous Systems*, 30, 2000.
2. D. Floreano, A. Ijspeert, S. Schaal, "Robotics and Neuroscience", *Current Biology*, 24, 2014
3. T. George Thuruthel, Y. Ansari, E. Falotico, C. Laschi, "Control Strategies for Soft Robotic Manipulators: A Survey", *Soft Robotics* 5(2), 2018, pp.149-163.
4. N. Cauli, E. Falotico, A. Bernardino, J. Santos-Victor, C. Laschi, "Correcting for Changes: Expected Perception-Based Control for Reaching a Moving Target", *IEEE Robotics and Automation Magazine*, 23 (1), pp.63-70, 2016.

@ class of April 29:

- Present the bioinspired approach described in the paper
- Explain how it responds to our bioinspiration definition
- Show main simplifying principles, if any