University of Pisa
Master of Science in Computer Science
Course of Robotics (ROB)
A.Y. 2016/17

Introduction to Robotics and Biorobotics and introduction to the course

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

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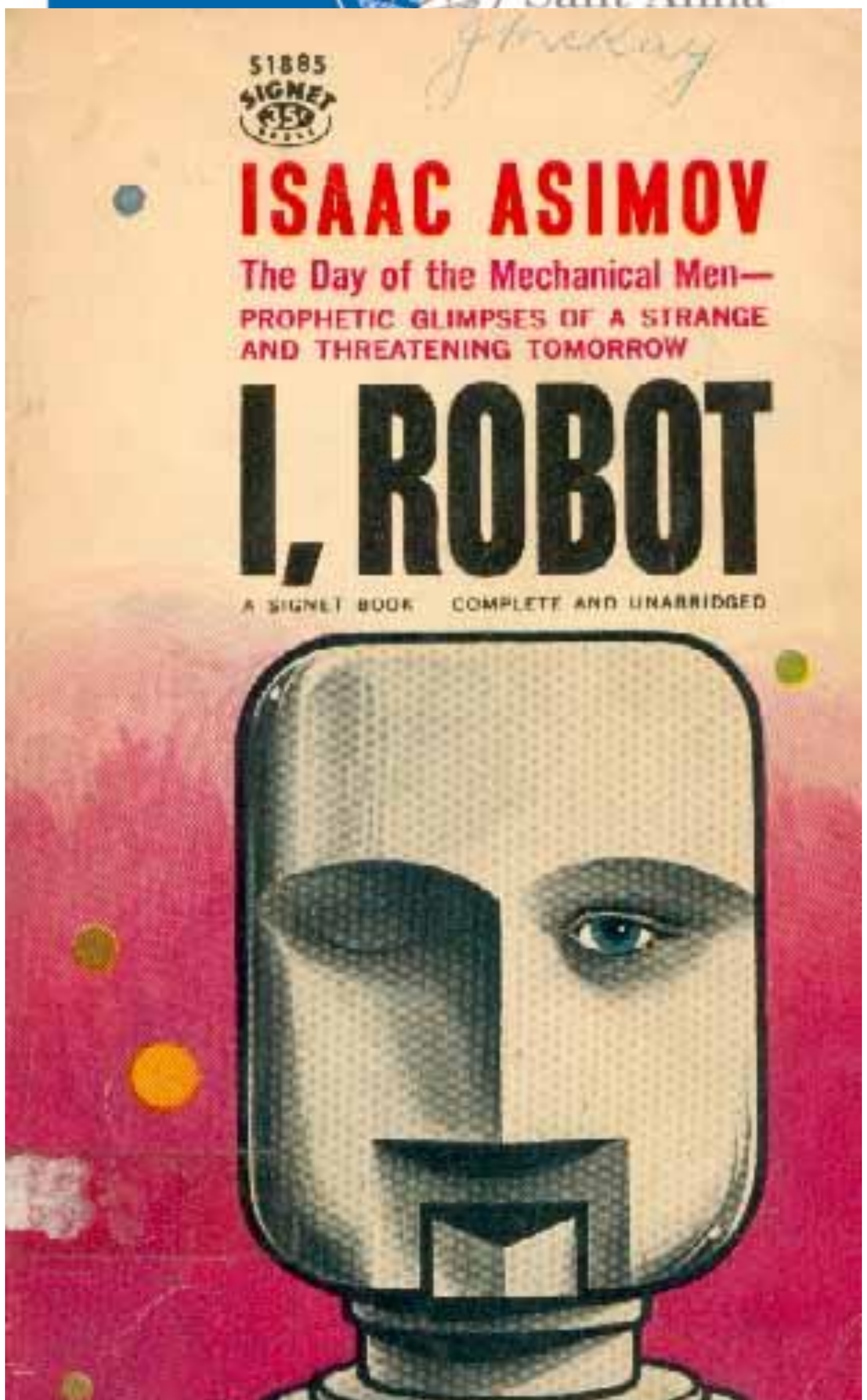
The origins of modern robotics



In 1960 the first industrial robot was installed in a manufacturing plant of General Motors in New Jersey (USA)

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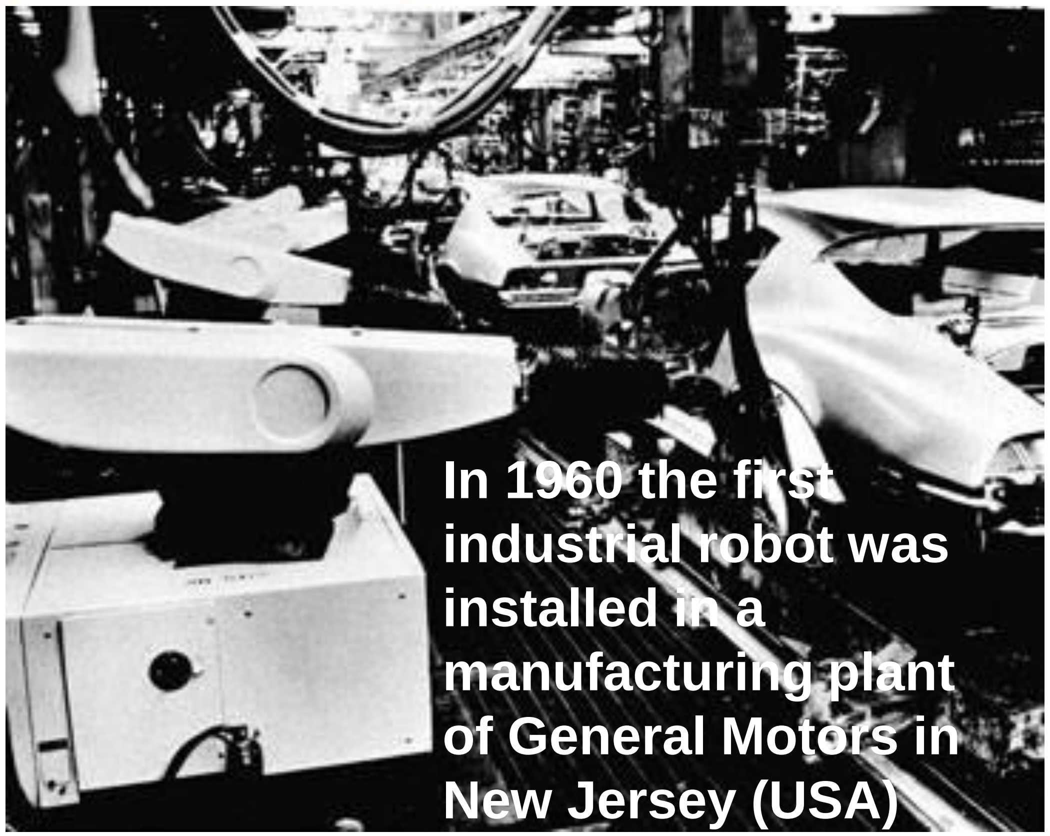
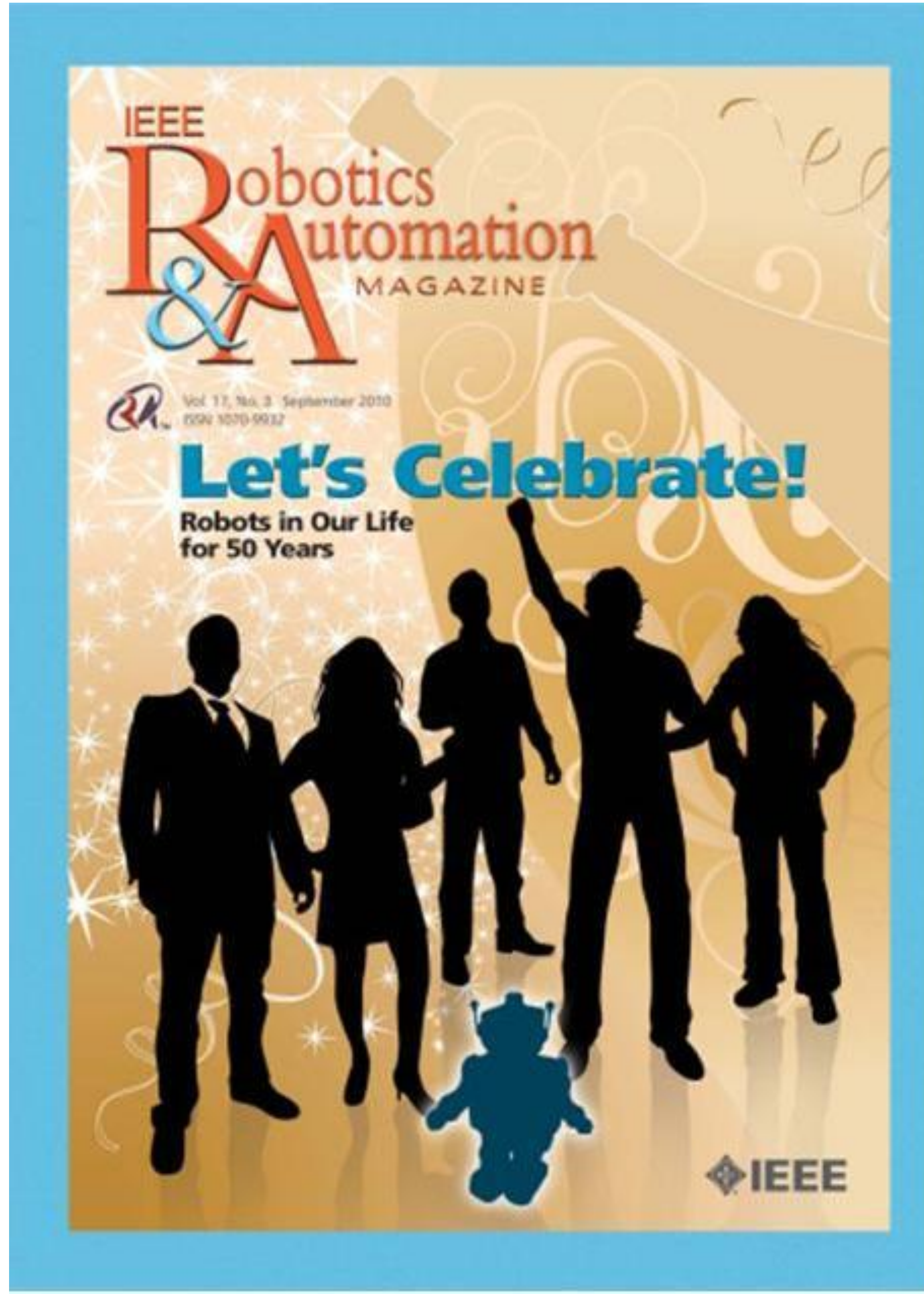


Robotics has grown exponentially in the last 50 years and the theories and techniques for robot control, fabrication and sensing represent an incredible wealth of knowledge
Robotics technologies are today very solid and robust, in the **accurate, fast, and reliable control of robot motion**



http://www.youtube.com/watch?feature=player_detailpage&v=7k20Zp5aPjY#t=26s

Industrial Automation: birth and development of Robotics

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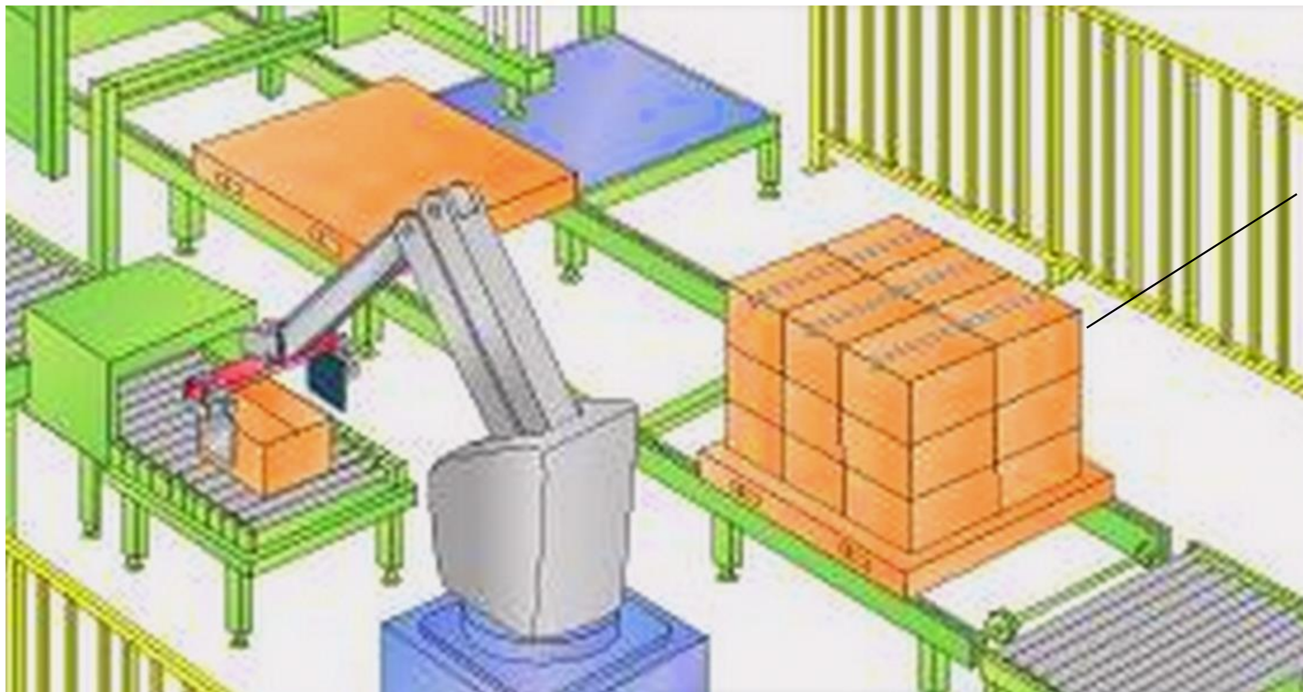
Typical scenario for industrial robotics



Structured environment

Known positions of the objects to manipulate

Birth and development of the theories and techniques for robot control

Manipulators with high performances, in terms of accuracy, repeatability, speed and robustness

Restricted human presence

Professional users (trained operators)

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 task
- *Un robot è un manipolatore multifunzionale riprogrammabile progettato per muovere materiali, componenti, o dispositivi specializzati, attraverso movimenti variabili programmati per lo svolgimento del compito*

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

Italy in industrial robotics from the very beginning

1973: The origin of Comau dates back to the **CO**nsorzio **MA**cchine **U**tensili established to gather all commercial activities of the Turin area manufacturers involved in the technological equipment supply of the Togliattigrad VAZ plant in Russia.

1977: A number of companies merge into a company named **Comau Industriale S.p.A.**: MST S.p.A., Morando S.p.A., I.M.P. S.p.A., Colubra Lamsat S.p.A.

Industrial Robotics: the drive for the development of robotics technologies

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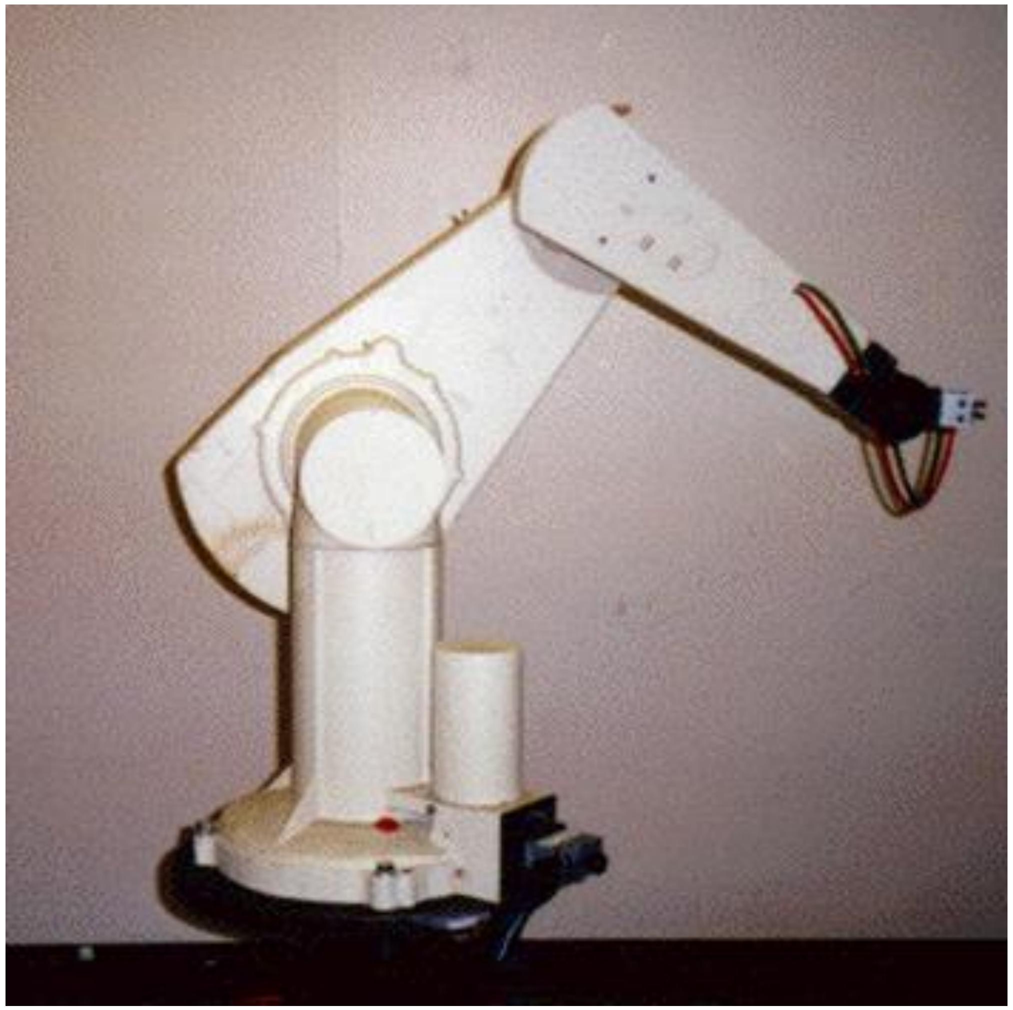
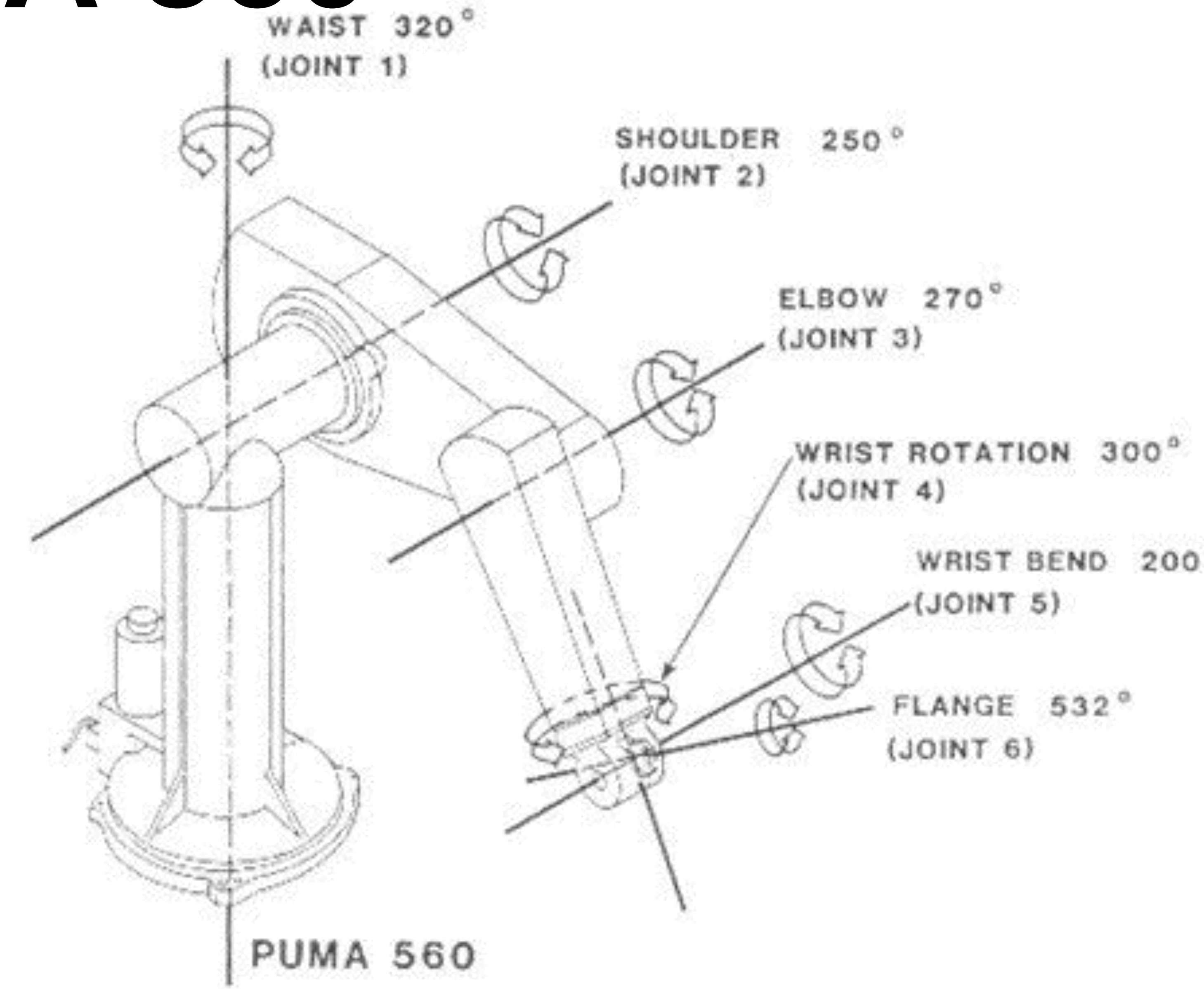
More than ***1 million operational industrial robots in the world***, with a growth rate of **6% per year** (*Source: IFR*)

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

PUMA 560



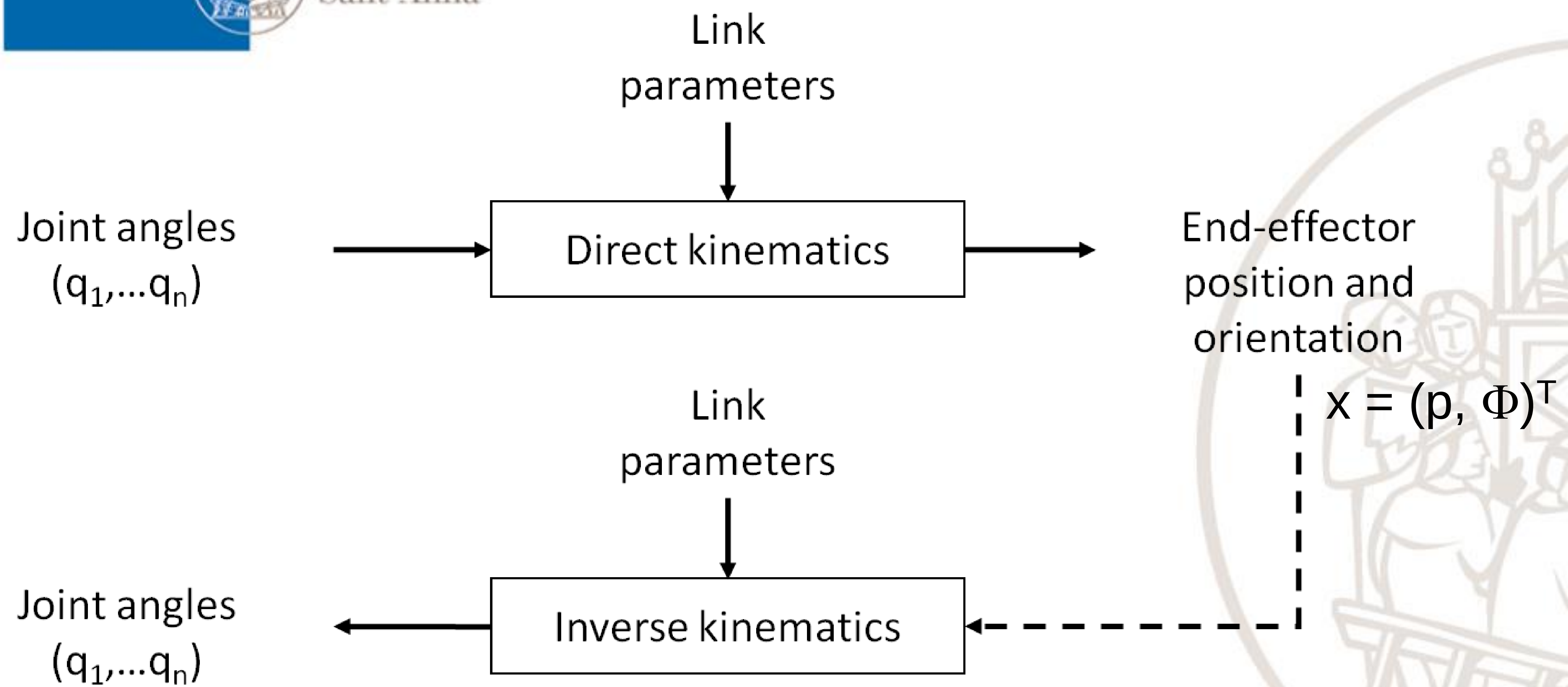


- Industrial Robot manipulator with 6 d.o.f
- The six degrees of freedom are controlled by six brushed DC servo motors
- Each motor is provided with a 500-1000 count 3 channel encoder and a potentiometer

	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

Direct and inverse kinematics



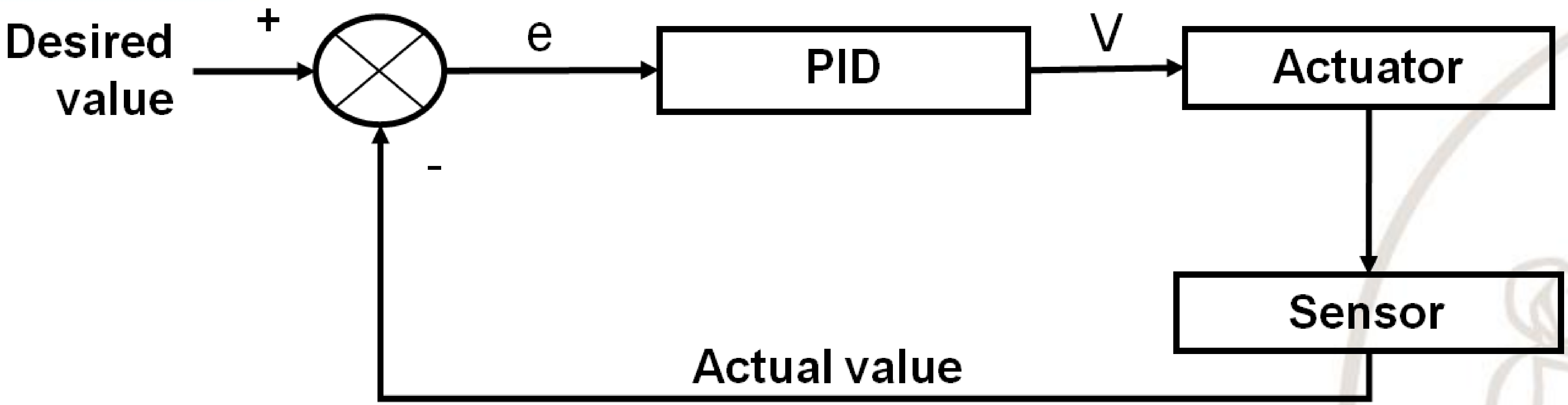
Direct kinematics

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

Inverse kinematics

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

Control of one joint motion (actuated by one motor)



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

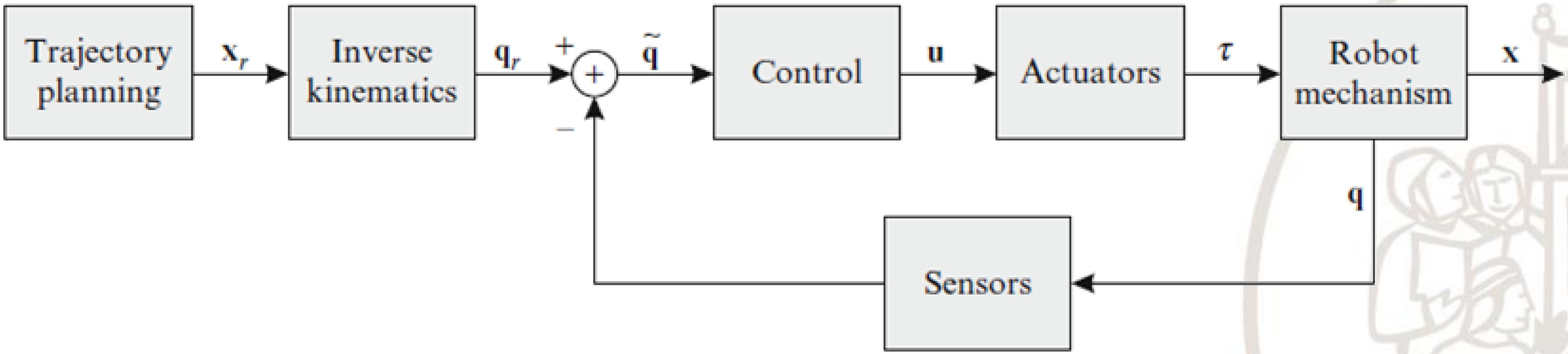
$$e_q = q_d - q$$

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

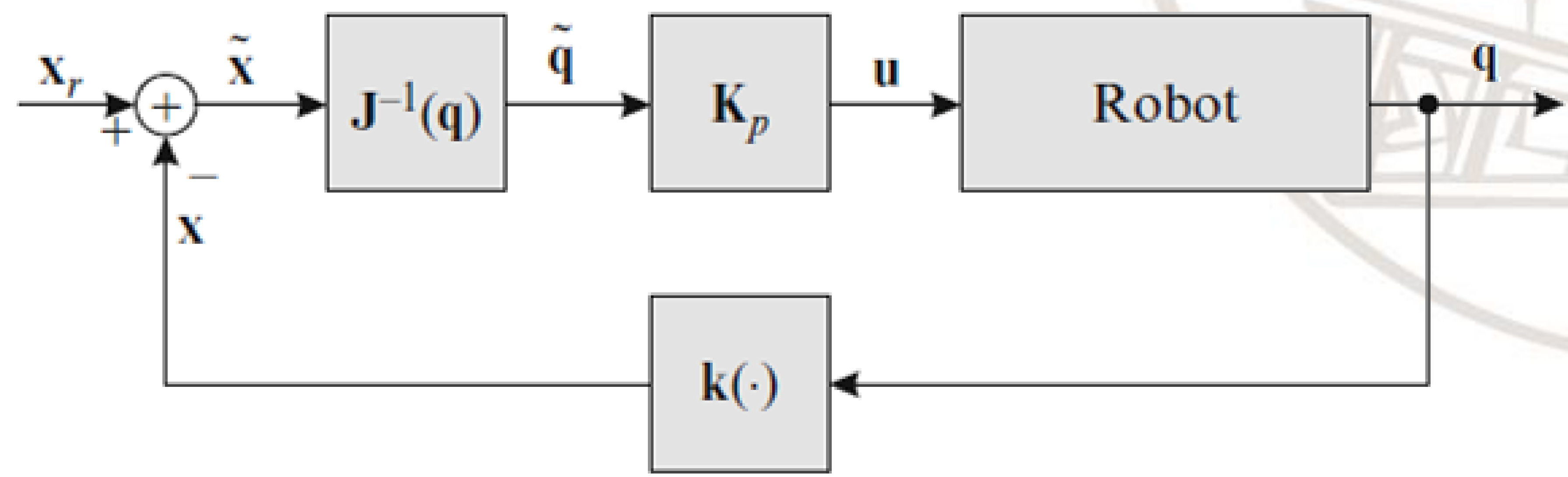
- $\boldsymbol{K_p}$ is the *proportional* gain
- $\boldsymbol{K_i}$ is the *integrative* gain
- $\boldsymbol{K_d}$ is the *derivative* gain
- ***e*** is the error, i.e. the difference between desired and actual value

Robot control systems

Robot control in joint space



Robot control in operational space



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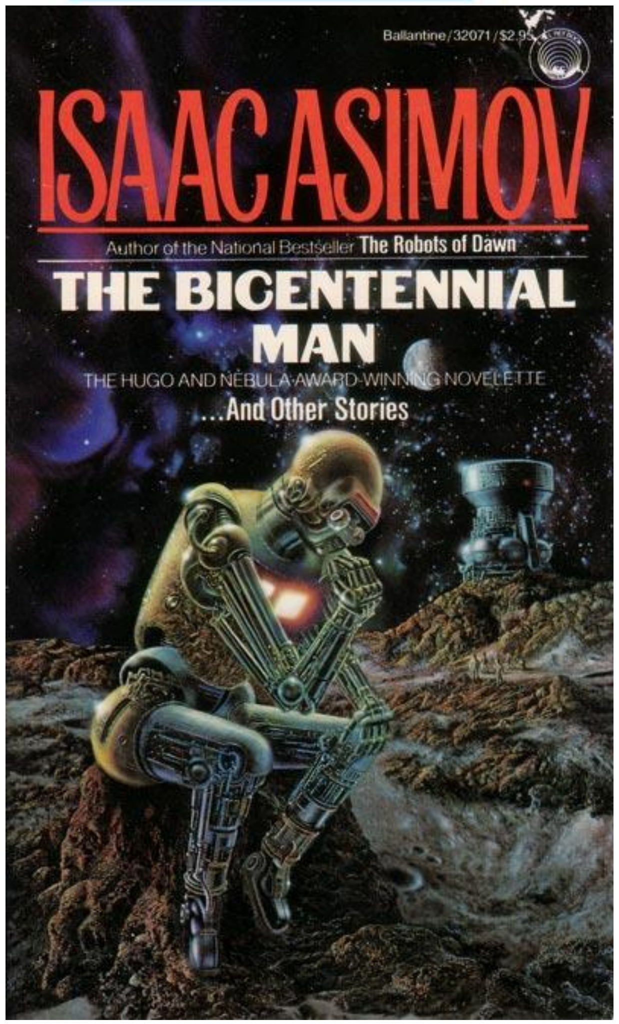
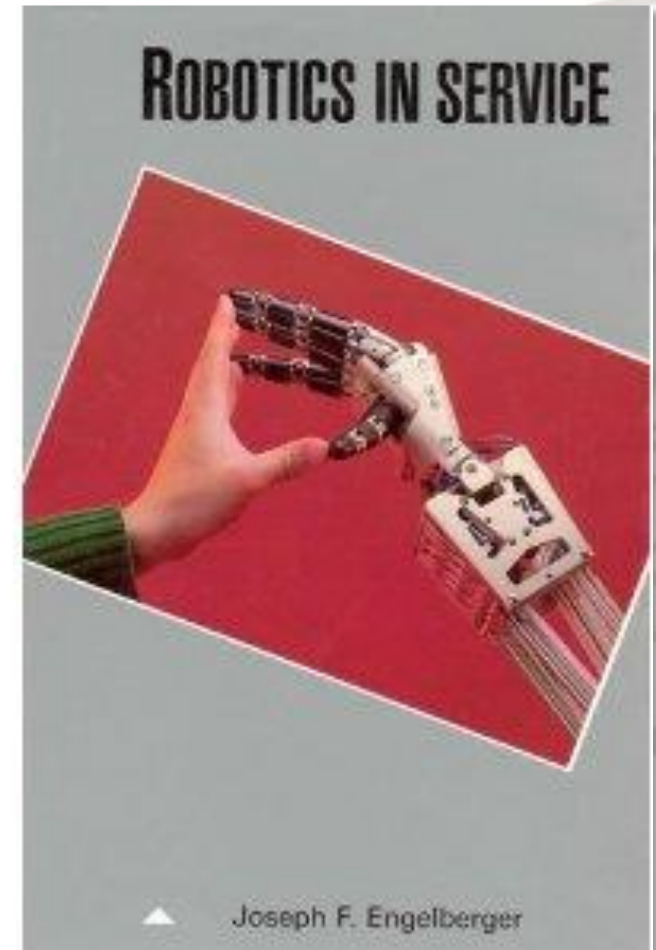
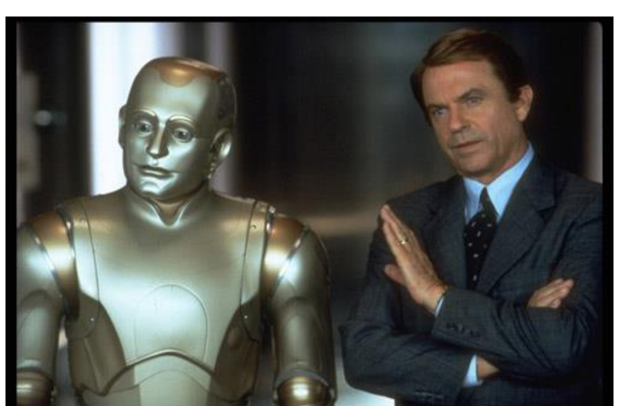
Robots outside of factories: Service Robotics




Isaac Asimov e Joseph Engelberger





January 2007

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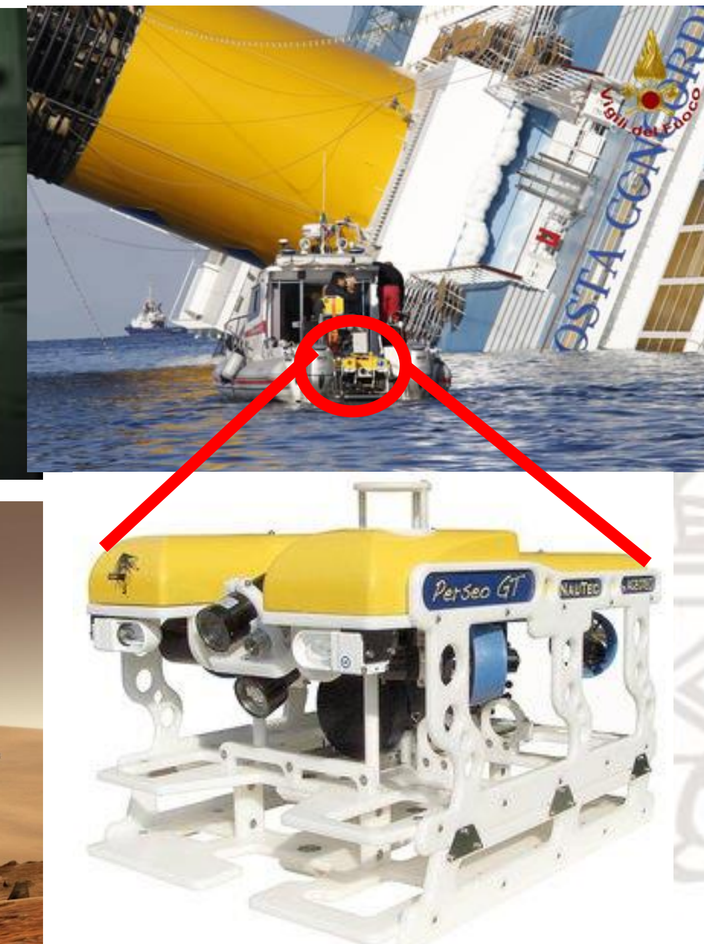
Robots outside factories: Service Robotics

Cleaning, environment

Photo: Center for Robot-Assisted Search and Rescue



- **Unstructured environment**
- Perception
- Reactive behaviour
- Shared workspace with human beings

Dangerous environments or unaccessible to human beings

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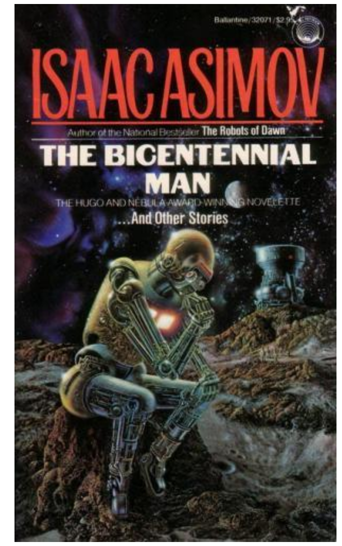

Industrial robotics:
birth and growth of theories and techniques for robot control

→

Service robotics:
birth and growth of theories and techniques for robot **perception & action** control

Structured environment

Unstructured environment

DustCart: The first service robot tested with citizens in its real use

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Peccioli (Pisa), June-August 2010

35 citizens – 402 services – 120Km run – 585Kg of garbage (paper, plastic and mixed)

ROBO TECH srl | Dedalus SOFTWARE FOR HEALTHCARE | Belvedere S.p.A. innovazione - progetti - sviluppo | Comune di Peccioli | Scuola Superiore Sant'Anna di Studi Universitari e di Perfezionamento | DustBot Networked and Cooperating Robots for Urban Hygiene

EU-IST Project no. FP6-045299
www.dustbot.org

DustCart: The first service robot tested with citizens in its real use

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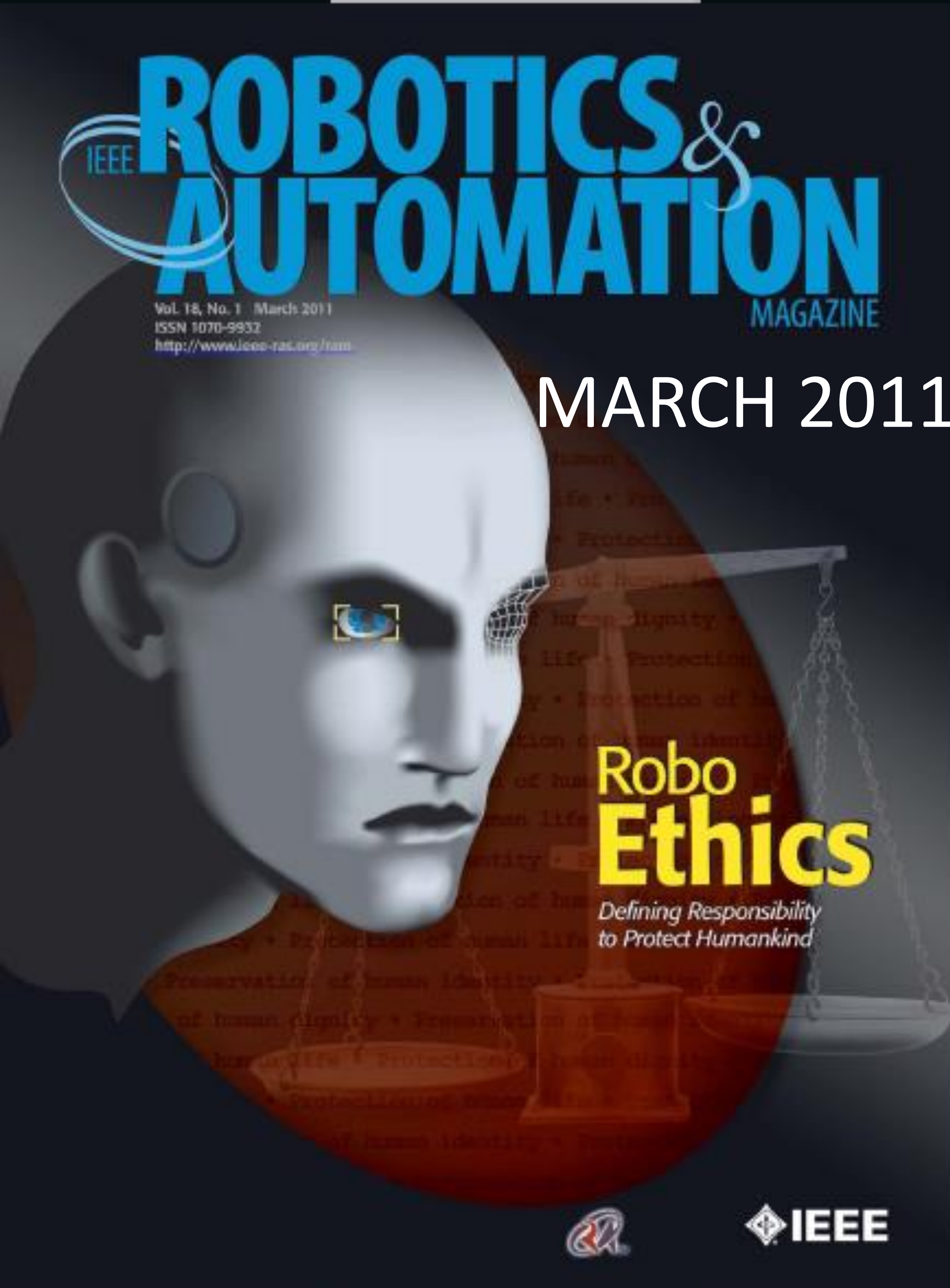


The Robot DustCart

By Pericle Salvini, Giancarlo Teti,
Enza Spadoni, Cecilia Laschi,
Barbara Mazzolai, and Paolo Dario

Focus on Social and Legal Challenges

Peccioli, a small medieval town in Italy, became one of the first places in the world where a robot was used (not demonstrated) to carry out a public service in the urban environment (from 15 June 2010 to 7 August 2010). Thirty-five real users *accepted* to trash their domestic waste using the robot DustCart, a mobile robot designed to collect, transport, and discharge rubbish bags in complete autonomy. During the testing period, the robot safely traveled along the public streets of Peccioli, carrying out its daily service and sharing the urban environment with the passers-by, bicycles, and cars, without causing any problems. Drawing on this unique event, in which the authors also participated, the article addresses some of the implications originating from the actual deployment of autonomous mobile robots in urban areas. Our reflections will gravitate around two major issues: legal regulations and social acceptance. More specifically, we will report on the legal solutions adopted for deploying DustCart in the streets of Peccioli and the activities carried out to increase the social acceptance of the robot.

Till today, the deployment of autonomous mobile robots in urban environments has been the talk of science fiction. A memorable example is a short story and the movie based on it, *I Robot* [1], where the robots carry out various kinds of services in human-inhabited settings. In a particular scene, humanoid robots are walking down the street, shoulder to shoulder with human beings. This is an exemplary case of coexistence between human beings and robots. In this article, we recount a similar story, but this time it is based on real facts: that of a service robot called DustCart, which was used for more than a month in a small Italian town to collect rubbish bags and then transport them to a discharge site. The robot, which was designed and developed within the framework of the European Union (EU) project DustBot [1], traveled on public roads in complete autonomy, interacting with people and cars and coexisting in the urban life of Peccioli. As far as we know, there are no references in literature to service robots being deployed in an urban environment or for such a lengthy period of time.

The objective of this article is to report on the testing of the robot DustCart in Peccioli and to point out some of the ethical, legal, and social implications that emerged before and during the test period.

Digital Object Identifier 10.1109/MRA.2010.940151
Date of publication: 14 April 2011

The RoboLaw Project

Programme "Capacities" - Call ID "FP7-SCIENCE-IN-SOCIETY-2011-1" Topic: SiS.2011.1.1.1-3 Regulating emerging scientific and technological developments. **EU Financial Contribution**: 1.497.966 EUR. **Duration:** 24 Months.

1) Scuola Superiore Sant'Anna, Pisa, Italy
2) Tilburg University, the Netherlands
3) University of Reading, England (UK)
4) University of Humboldt, Germany

"White Book on Regulating Robotics",

containing guidelines for the European Commission in the field of regulating emerging robotic technologies replying to the ethical concerns regarding its applications.

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 task
- *Un robot è un manipolatore multifunzionale riprogrammabile progettato per muovere materiali, componenti, o dispositivi specializzati, attraverso movimenti variabili programmati per lo svolgimento del compito*

Robotics Industry Association (~ 1980)

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

- Robotics is the intelligent connection of perception to action
- *Robotica è la connessione intelligente della percezione all’azione*

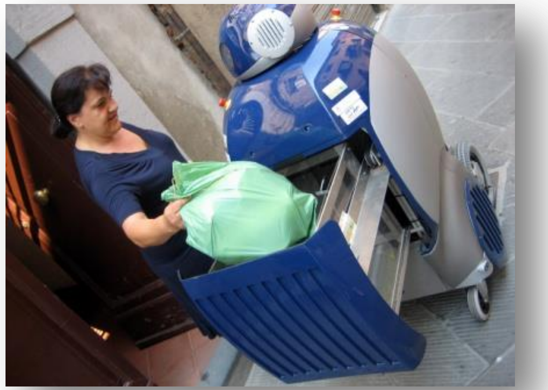
Michael Brady (~1985)

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

- A 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
- *Un robot è una macchina in grado di estrarre informazioni dall’ambiente e di usare la conoscenza sul mondo per muoversi in maniera sicura, significativa e intenzionale*

Ronald Arkin (~ 1990) R. Arkin, *Behaviour-based Robotics*, MIT Press, 1999

- Robotics is the science and technology of the design of mechatronic systems capable of generating and controlling motion and force
- *Robotica è la scienza e tecnologia della progettazione di sistemi meccatronici capaci di generare e controllare movimento e forza*



Paolo Dario (~ 2000)

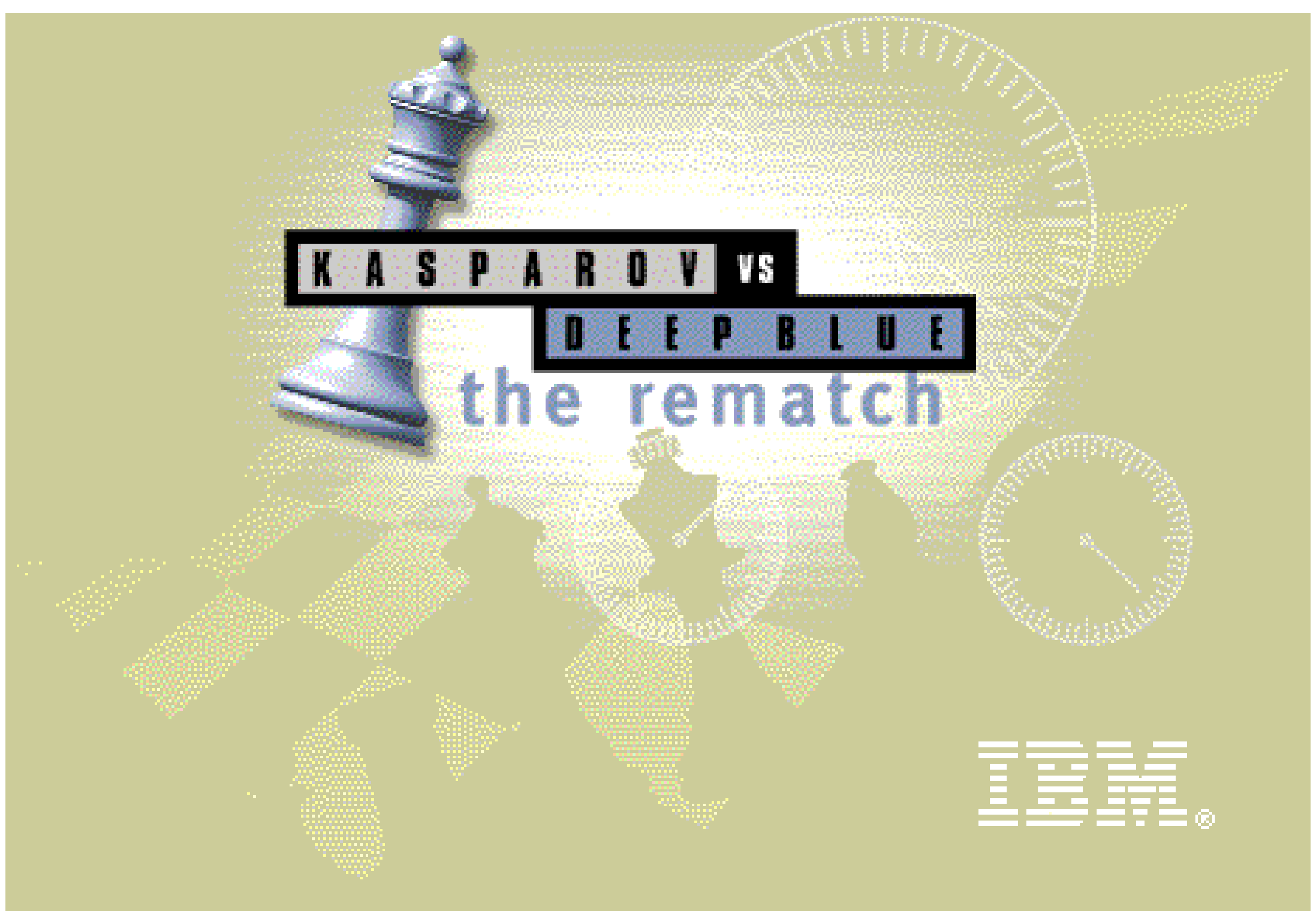
- A robot is an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals
- *Un robot è un sistema autonomo che esiste nel mondo fisico, percepisce l’ambiente e può agirvi per raggiungere un dato obiettivo*

Maja Mataric (~ 2000) M.Mataric, *The Robotics Primer*, MIT Press, 2007

The challenge of Artificial Intelligence (AI) in the ‘80s

Deep Blue, IBM

- The computer which defeated the chess world champion Kasparov



Embodiment Thesis

- "Many features of cognition are embodied in that they are deeply dependent upon characteristics of the physical body of an agent, such that the agent's beyond-the-brain body plays a significant causal role, or a physically constitutive role, in that agent's cognitive processing."
- Intelligence without representation

Rodney A. Brooks, "Intelligence without representation", *Artificial Intelligence*, 1991, 47: 139–159.

The new challenge: a humanoid robot soccer team

RoboCup

"By mid-21st century, a team of fully autonomous humanoid robot soccer players shall win the soccer game, comply with the official rule of the FIFA, against the winner of the most recent World Cup."

"RoboCup: The Robot World Cup Initiative". RoboCup. 1995

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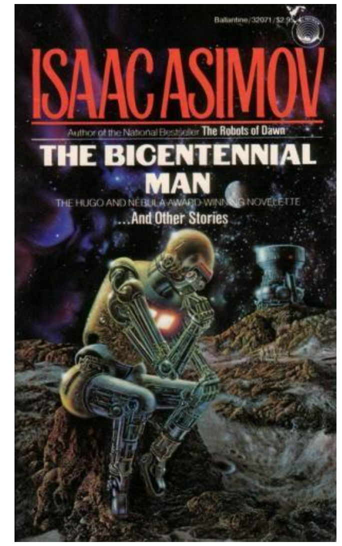


Industrial robotics: birth and growth of theories and techniques for robot control

→

Service robotics: birth and growth of theories and techniques for robot **perception & action** control

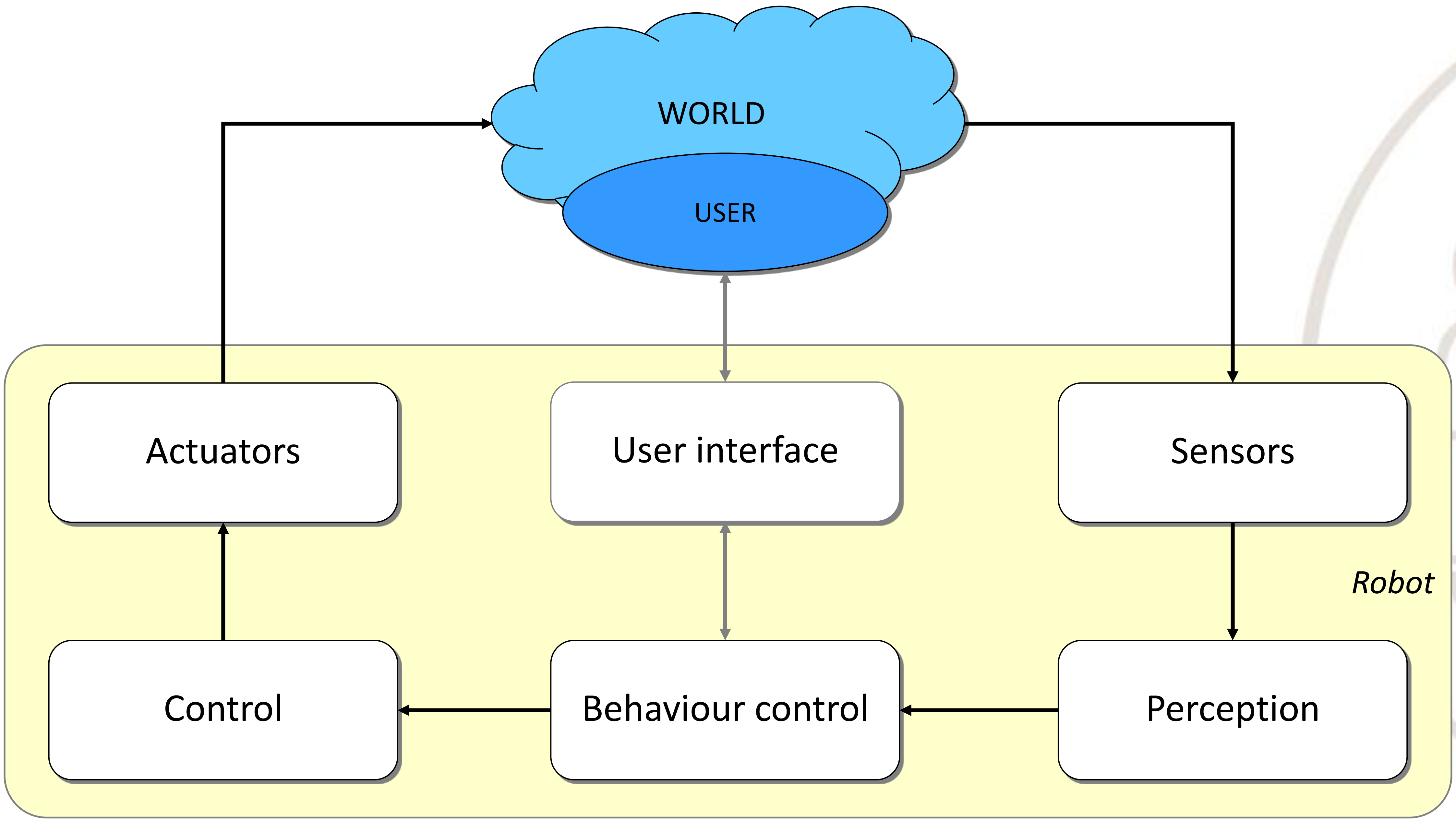
Structured environment

Unstructured environment

Photo: Center for Robot-Assisted Search and Rescue

Typical robot components

A robot is an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals



Typical robot components

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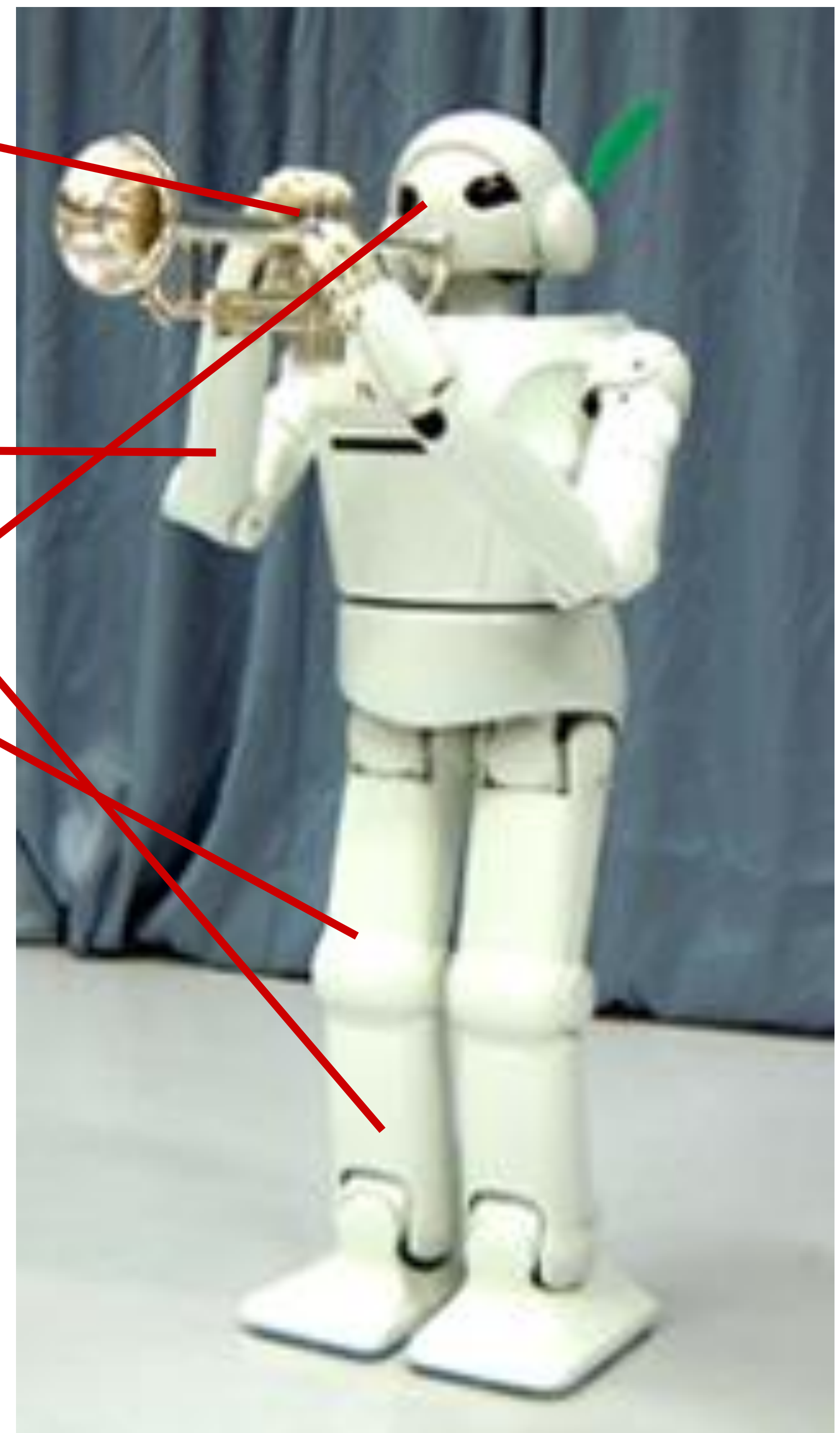
A robot is an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals

Behaviour control

Actuators

Sensors



Behavior control

Actuators

Sensors

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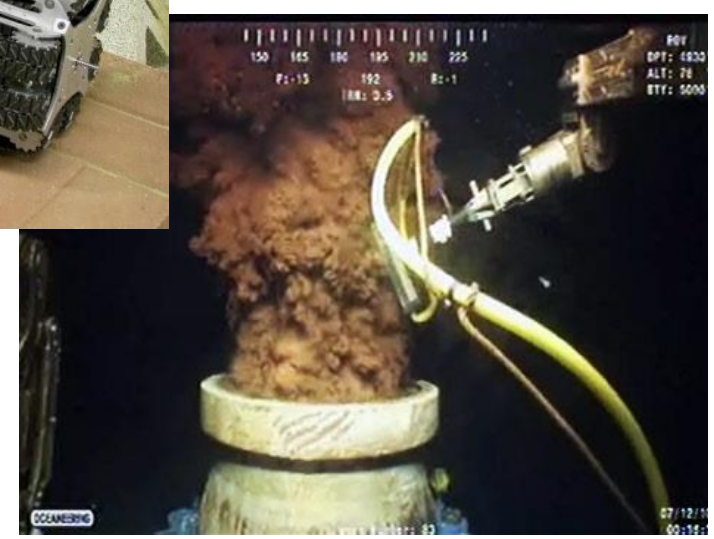
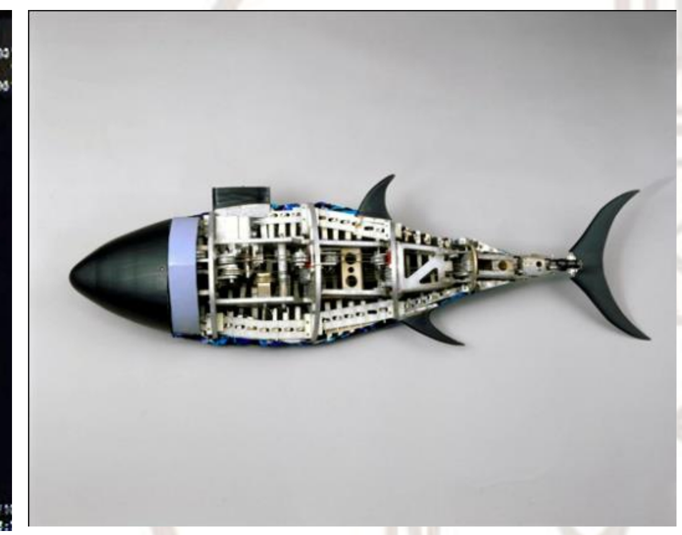
Robots outside factories…

…having to operate in the real world, they need to manage uncertainties and to react to changes in the environment

Biological systems represent an excellent source of inspiration

Rescue





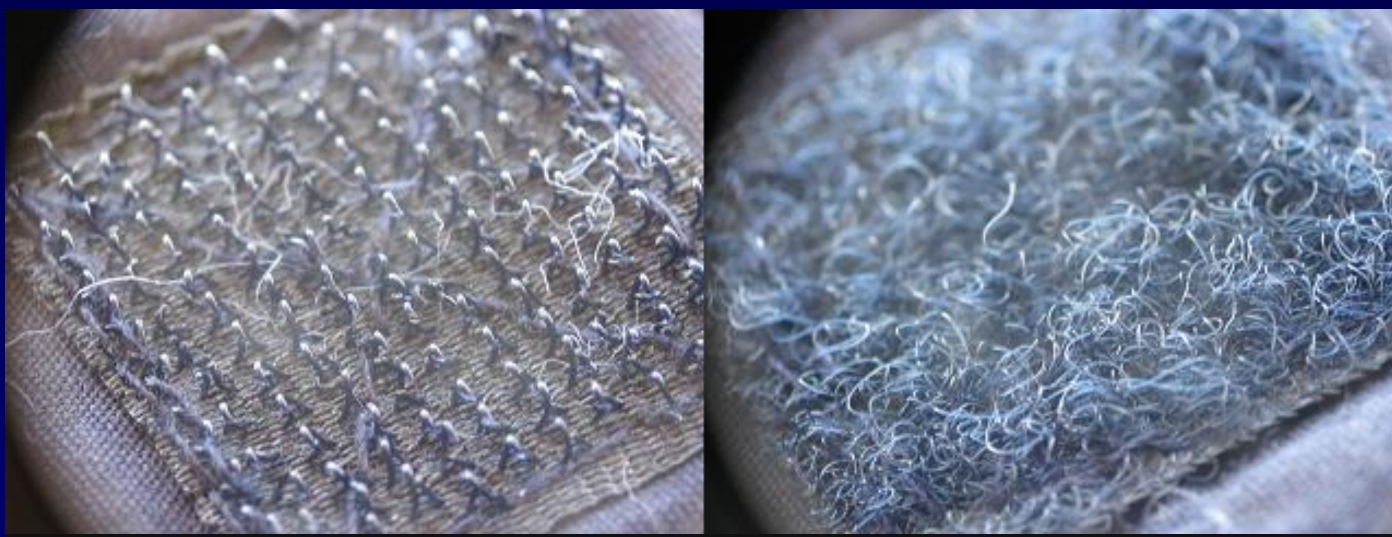
Underwater

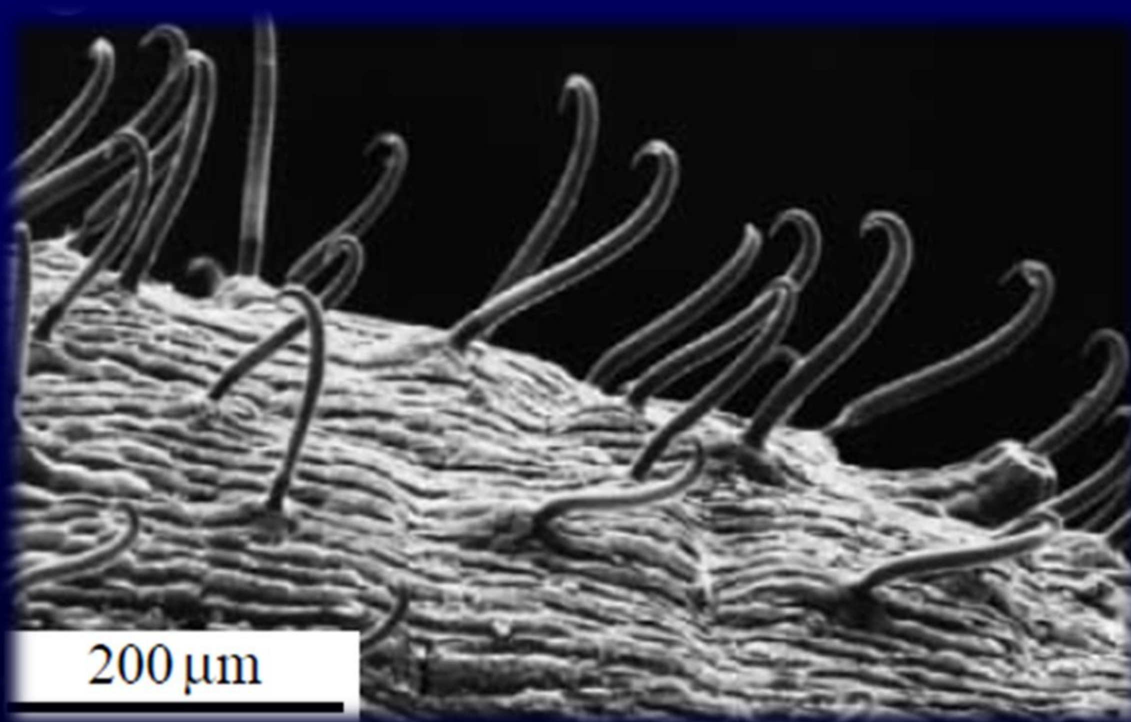
Space

- **Unstructured environment**
- Perception
- Reactive behaviour
- Shared workspace with human beings

Some examples of biomimetics in action

- 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.

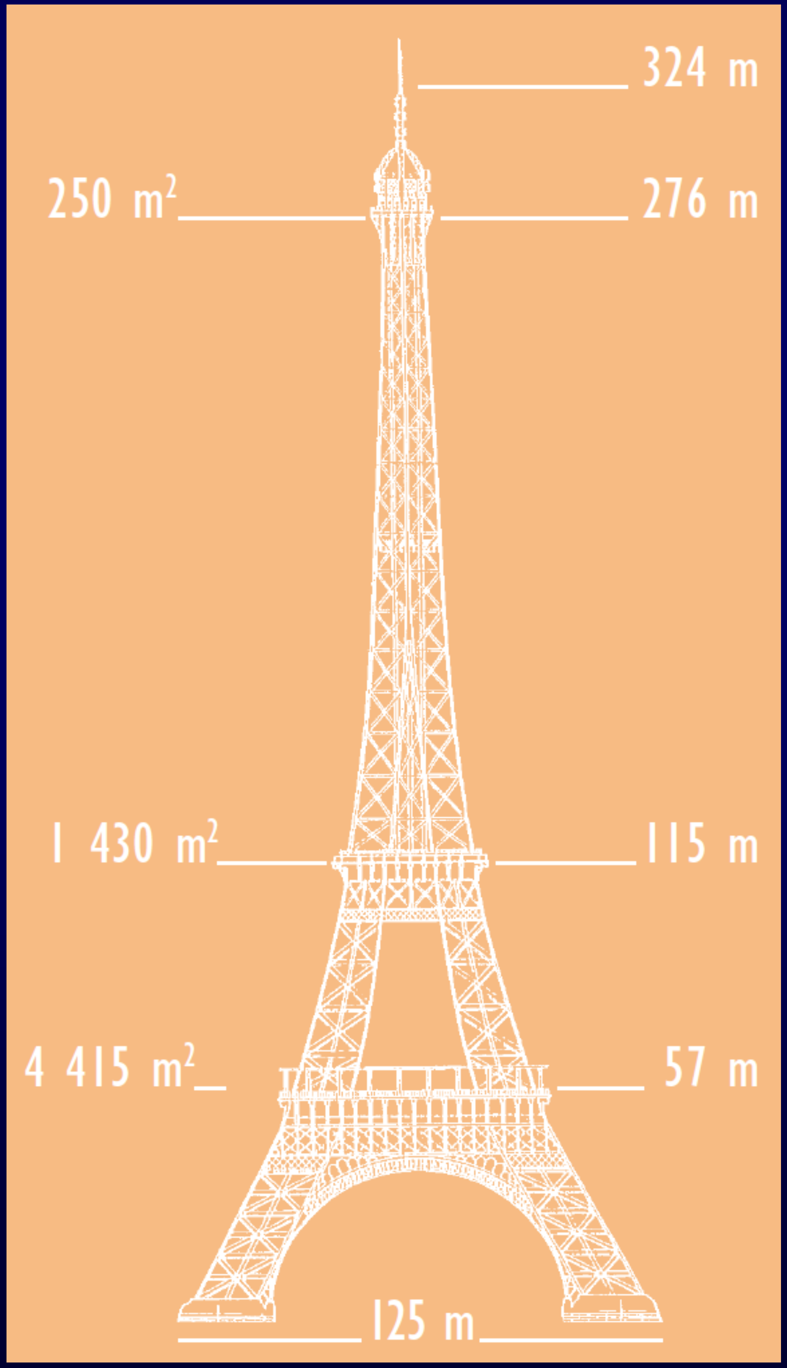




Some examples of biomimetics in action

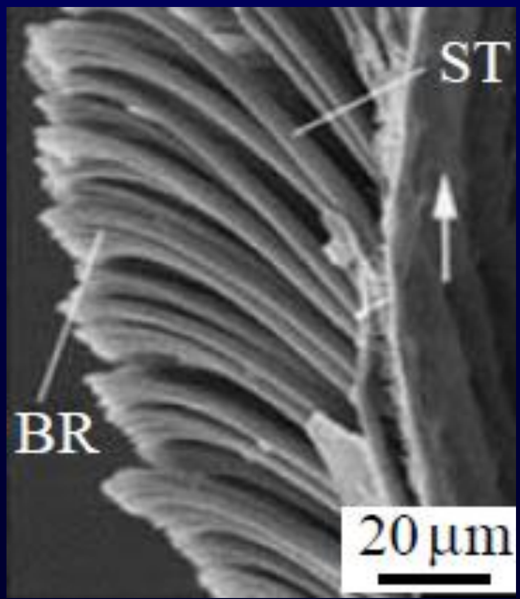
The **Eiffel Tower**: the perfect structure of trabecular struts in the head of the human femur inspired a French engineer at the end of the 19th Century. He was intended to design the higher structure all the world. The name of this engineer is Gustave Eiffel.

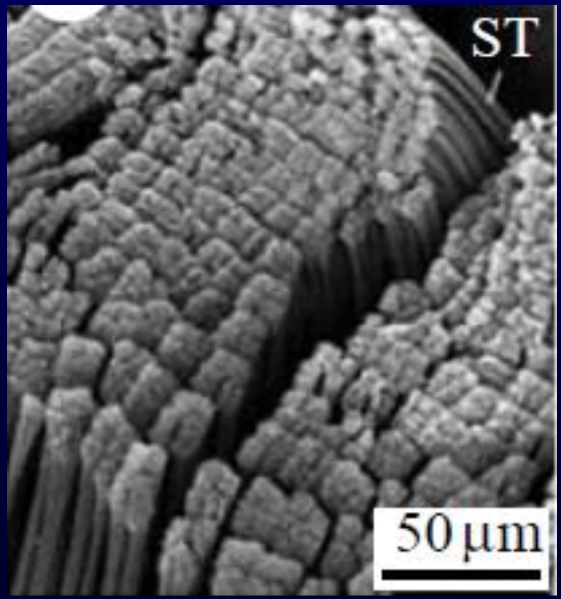
In 1889 the Tower is completed.

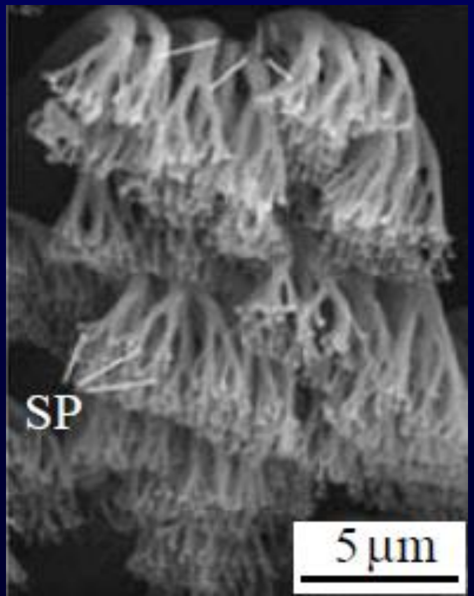


Some examples of biomimetics in action

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







Biomimetics: smart solutions from Nature

Nevertheless…   Natural selection is not Engineering

Organisms that are capable of surviving are not necessarily **optimal** for their technical 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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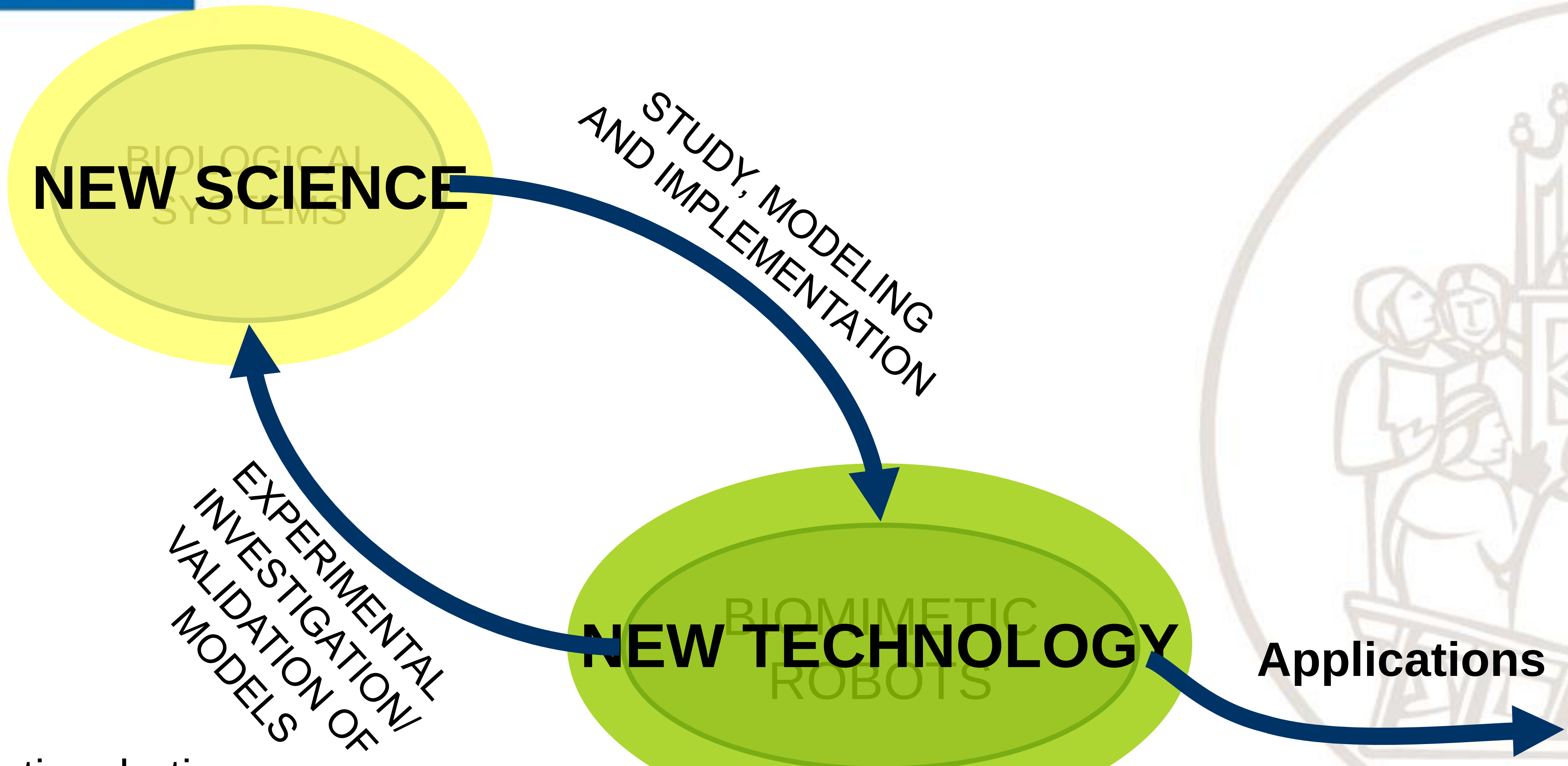
The two-fold relation between robotics and biology

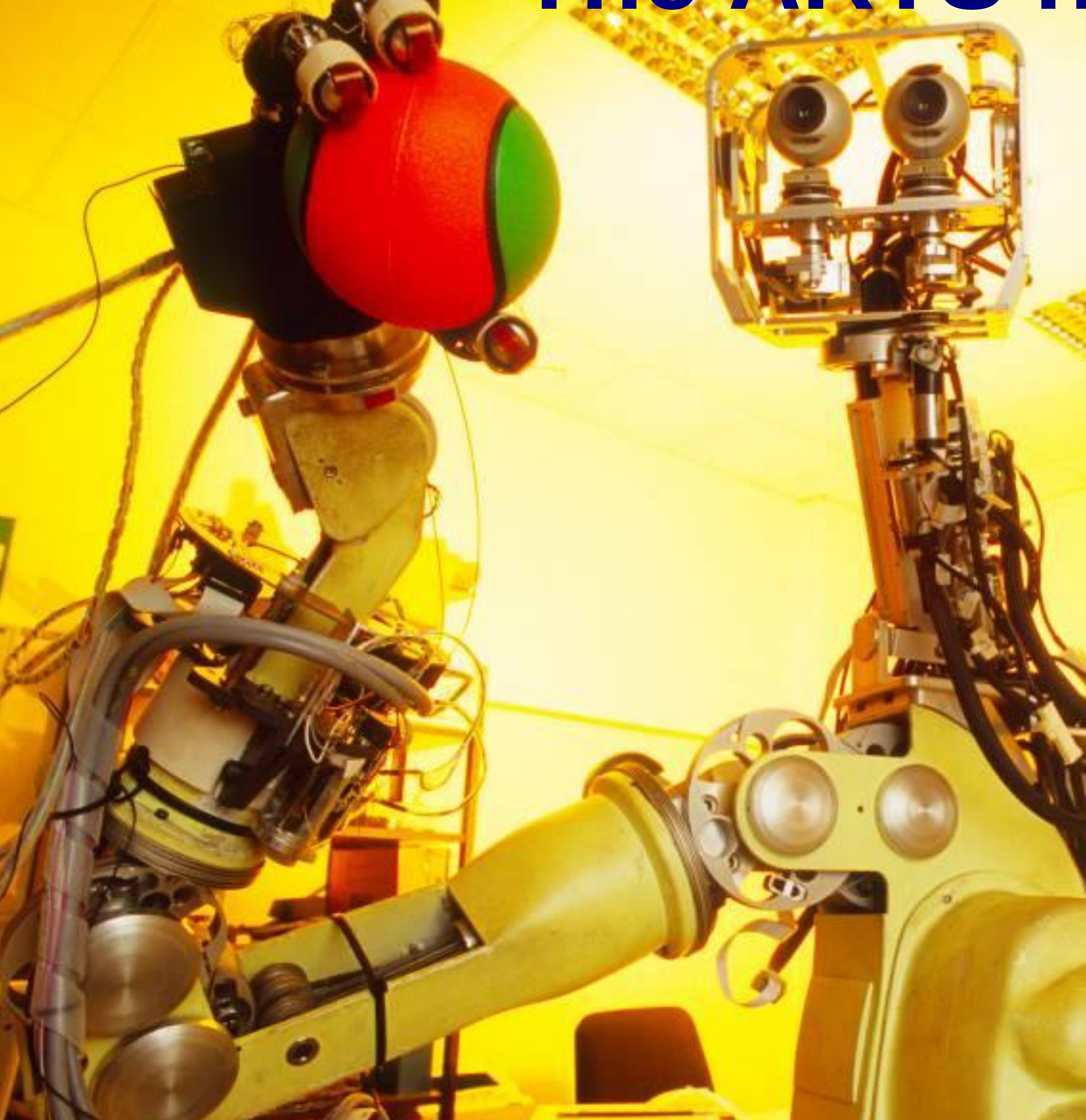


Biomimetic robotics:

- developing robots for real-world applications
- studying biological systems by robotic platforms

Unified approach to the study of living organisms and robots

The ARTS humanoid robot

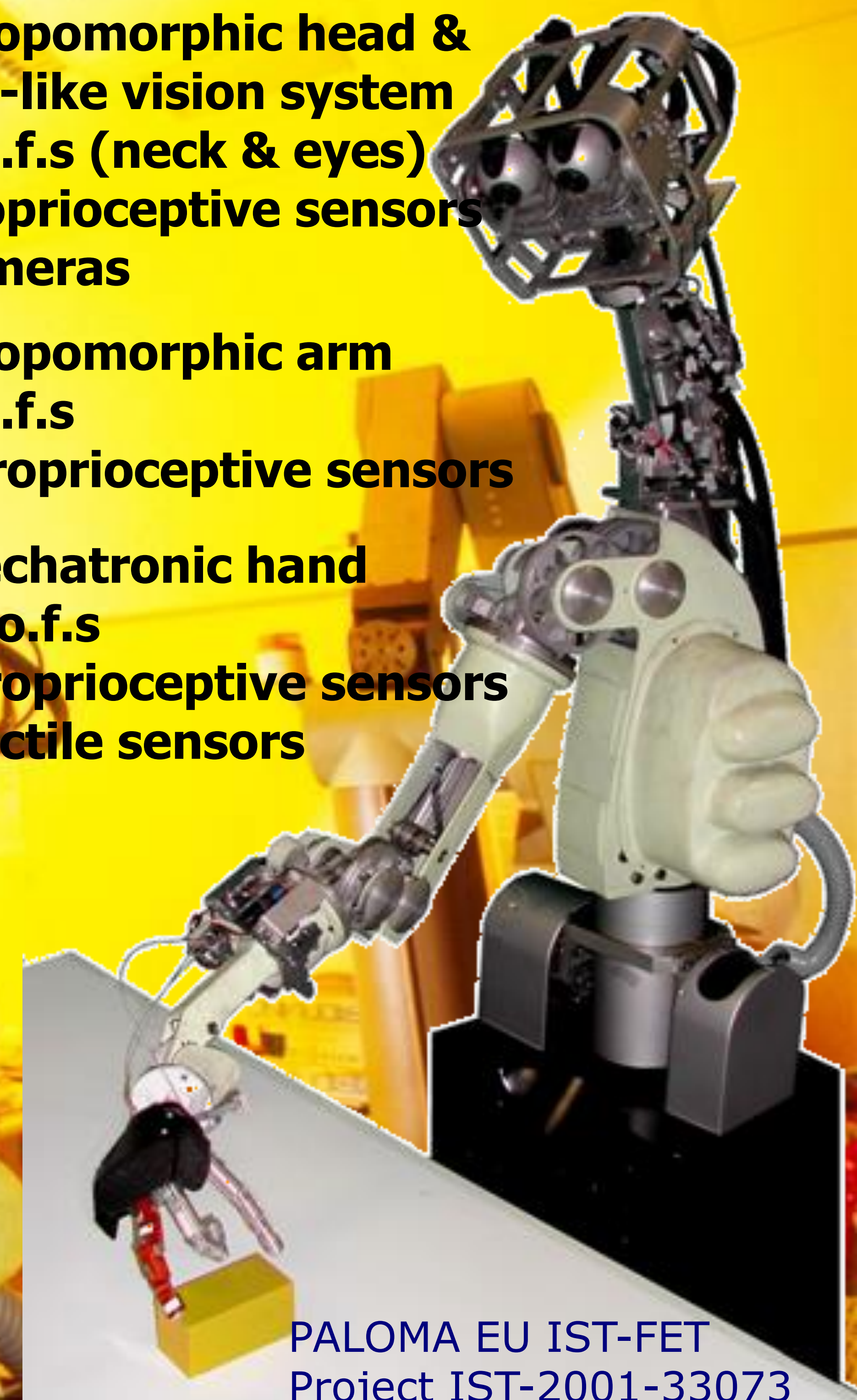


Total
- **d.o.f.s: 25**
- **Visual sensors: 2**
- **Proprioceptive sensors: 39**
- **Tactile sensors: 135**

Anthropomorphic head & retina-like vision system
- **7 d.o.f.s (neck & eyes)**
- **7 proprioceptive sensors**
- **2 cameras**

Anthropomorphic arm
- **8 d.o.f.s**
- **16 proprioceptive sensors**

Biomechatronic hand
- **10 d.o.f.s**
- **16 proprioceptive sensors**
- **21 tactile sensors**



PALOMA EU IST-FET
Project IST-2001-33073

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 Robotics and Automation Magazine*, Vol.12, No.2, June 2005, pp.29-43.

NATURE|Vol 460|27 August 2009

The bot that plays ball

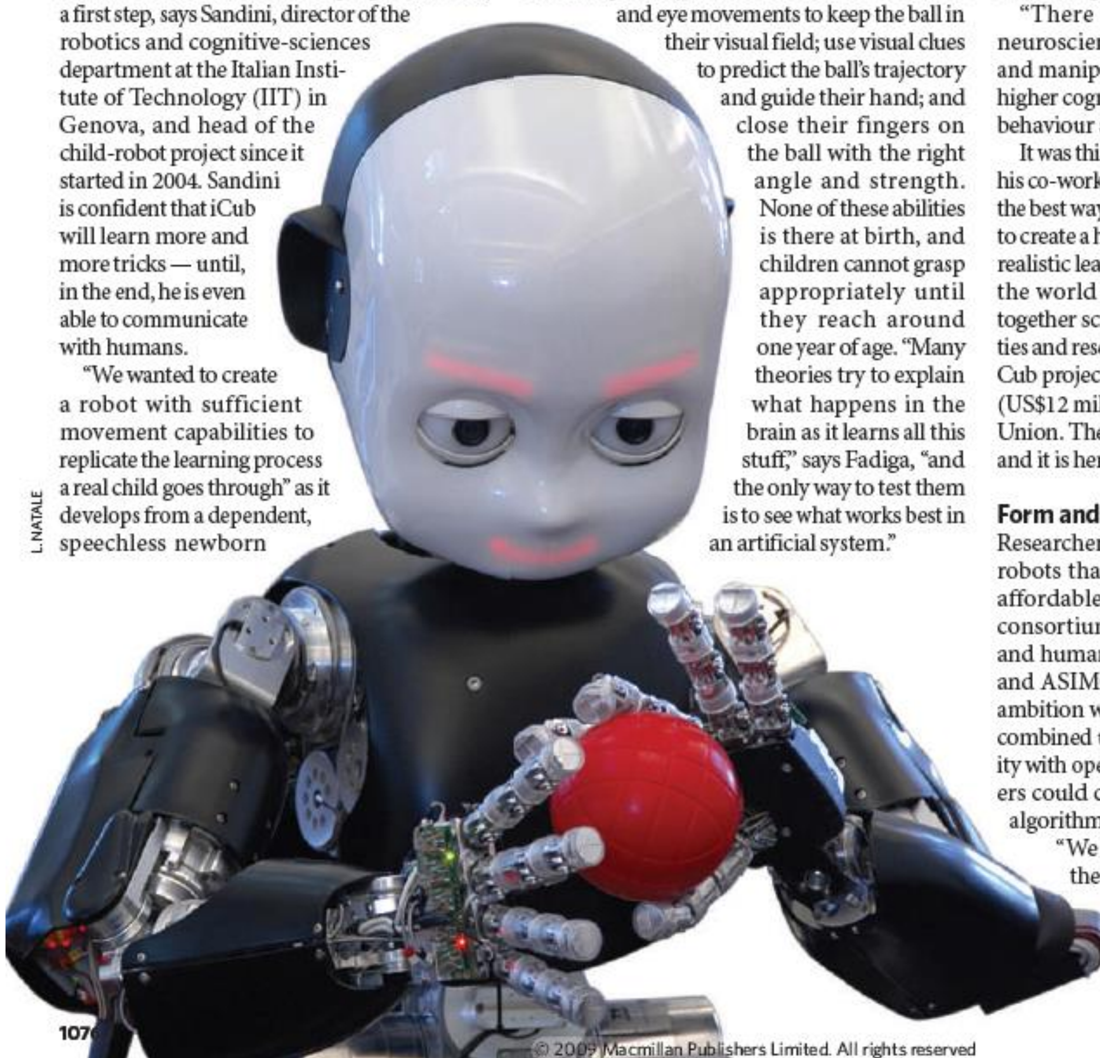
He looks like a child and plays like a child. But can the iCub robot reveal how a child learns and thinks? **Nicola Nosengo** reports.

Giulio Sandini cannot help smiling as his child reaches out a hand and tries to grasp the red ball that Sandini keeps waving before his eyes. "He is getting really good at it," he says, with the proud tone of any father. True, most fathers would expect more from their three-year-old than the ability to grasp a ball. But Sandini is indulgent: although the object of his affection has the wide eyes and rounded cheeks of a little boy, he is, in fact, a robot.

His name is iCub or, as the team calls him, iCub Number 1. Together with his brothers now in laboratories around the world, this little robot may help researchers to understand how humans learn and think. Grasping a ball is only a first step, says Sandini, director of the robotics and cognitive-sciences department at the Italian Institute of Technology (IIT) in Genova, and head of the child-robot project since it started in 2004. Sandini is confident that iCub will learn more and more tricks — until, in the end, he is even able to communicate with humans.

"We wanted to create a robot with sufficient movement capabilities to replicate the learning process a real child goes through" as it develops from a dependent, speechless newborn into a walking, talking being, Sandini says. So he and his colleagues have not only given iCub the hands, limbs and height of a toddler, they have also tried to give him the brain of one — a computer that runs algorithms allowing iCub to learn and develop as he interacts with his surroundings.

In a child, says Luciano Fadiga, a neurophysiologist at Italy's University of Ferrara who is part of the team that developed iCub, those interactions are essential for shaping the rapidly growing brain. Before children can grasp a moving ball, for example, they must learn to coordinate head and eye movements to keep the ball in their visual field; use visual clues to predict the ball's trajectory and guide their hand; and close their fingers on the ball with the right angle and strength. None of these abilities is there at birth, and children cannot grasp appropriately until they reach around one year of age. "Many theories try to explain what happens in the brain as it learns all this stuff," says Fadiga, "and the only way to test them is to see what works best in an artificial system."



L. NATALE

"This is not a car you just buy and start to drive around; we're in totally new ground." — Paul Verschure

Such testing is certainly not new. Cognitive scientists have been using computer models to simulate mental processes since the 1950s, including algorithms that mimic learning. But many of these simulations have focused on the high-level, conscious reasoning used to solve logical puzzles, play chess or make medical diagnoses. And many others — notably 'neural network' models — have simulated neurons. But Sandini and Fadiga are among the many researchers who have come to think that both types of simulations leave out something essential: the body.

"There is ever-growing evidence from neuroscience that visuo–motor processing, and manipulation in particular, are crucial for higher cognitive development, including social behaviour and language," Sandini says.

It was this line of thinking that led Sandini and his co-workers to their central hypothesis — that the best way to model the human mind would be to create a humanoid robot that is controlled by realistic learning algorithms, then let it explore the world as a child would. They gathered together scientists from 11 European universities and research institutions to form the RobotCub project, and began work with €8.5 million (US$12 million) in funding from the European Union. The IIT is the project's leading partner, and it is here that iCubs are born.

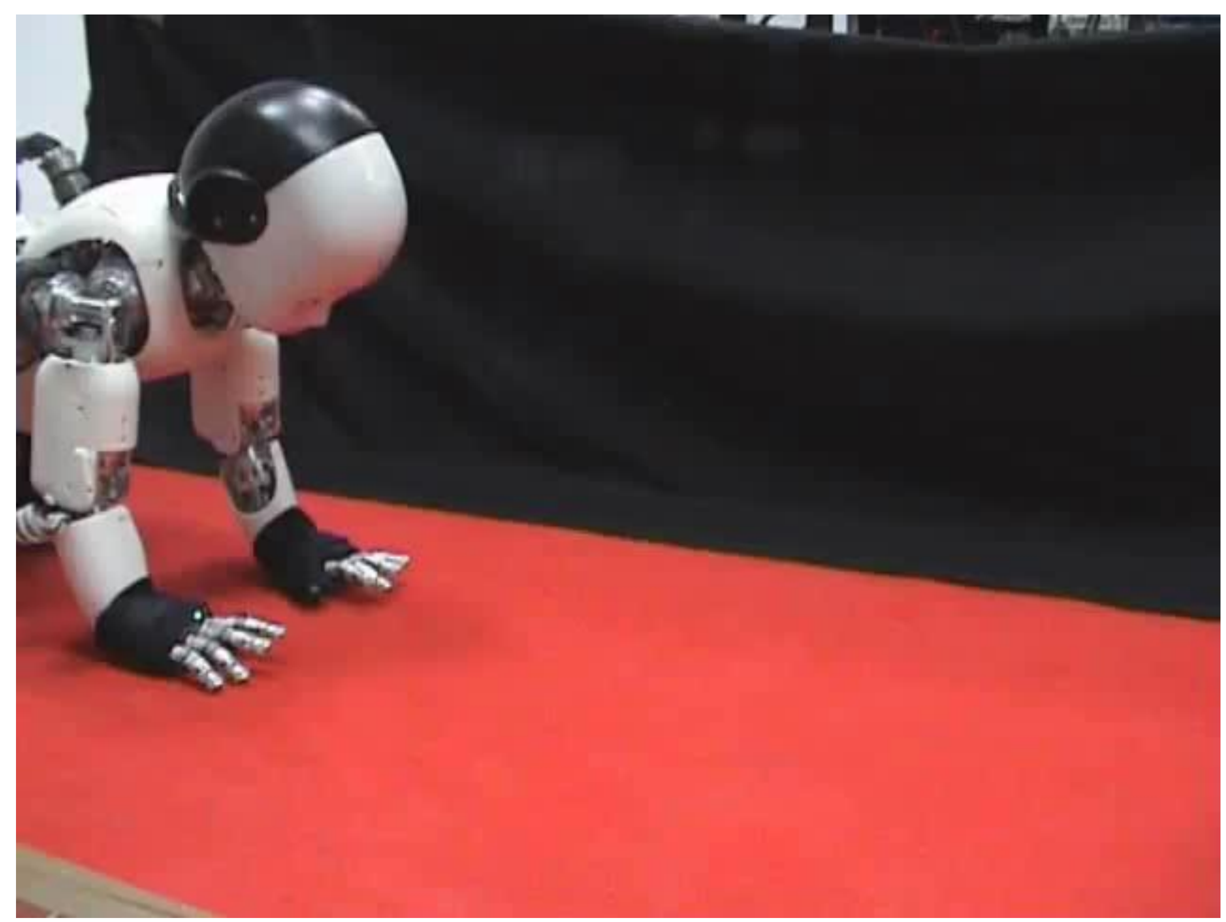
Form and function

Researchers can already choose from a list of robots that includes Khepera, a simple and affordable wheeled robot built by a Swiss consortium and used to study locomotion, and humanoid robots such as HRP-2, PINO and ASIMO, all built in Japan. But Sandini's ambition was to create a humanoid robot that combined unprecedented mechanical versatility with open-source software, so that researchers could change both the hardware and the algorithms as needed.

"We started from the hand, and built the rest of the robot around it," Sandini says. With seven degrees of freedom in the arm and nine in the hand, and its mechanical shoulders, elbows, wrists and fingers

more uses than just
he robot look good
tional pictures, says
In the future, some
lan to try iCub with
who are autistic, testing
ions to his expressions
ments".
Number 1 was never
be an only son. After
robot became opera-
consortium issued an
or proposals to conduct
nts. The six winners,
an independent panel
by the consortium and the European
ve received their own iCub for free.
ne else can order one for the cost of
g it, some €180,000–200,000. "It was
e deal with the European Union that
provide a number of robots to inter-
ups," Sandini says. This way, the team
reate a de facto standard in robotics,
g data exchange. "There is a desper-

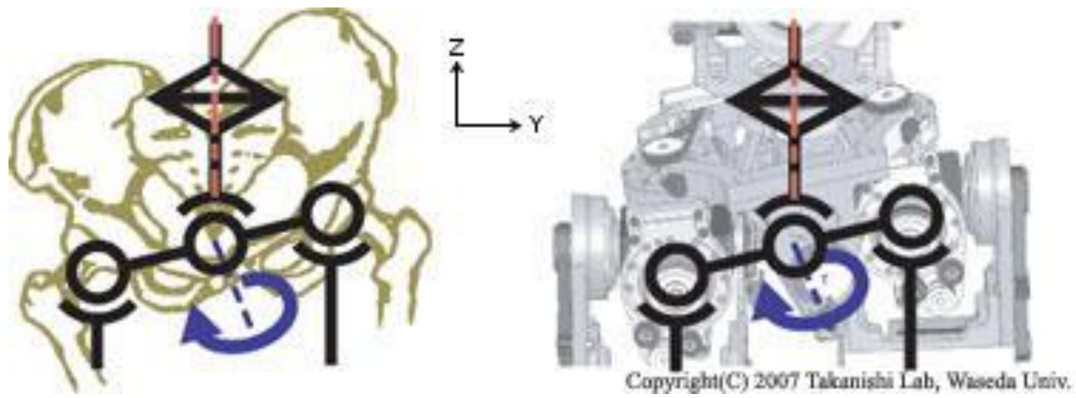
Giulio Sandini (left) and Giorgio Metta gradually pieced together a robot with an unprecedented level of dexterity and coordination.



The WABIAN humanoid robot as a Robotic Human Simulator

Wabian humanoid robot,
Waseda University, Tokyo, Japan

Anthropomorphic kinematic model



2-DOF model for the waist mechanism allowing knee stretch walking

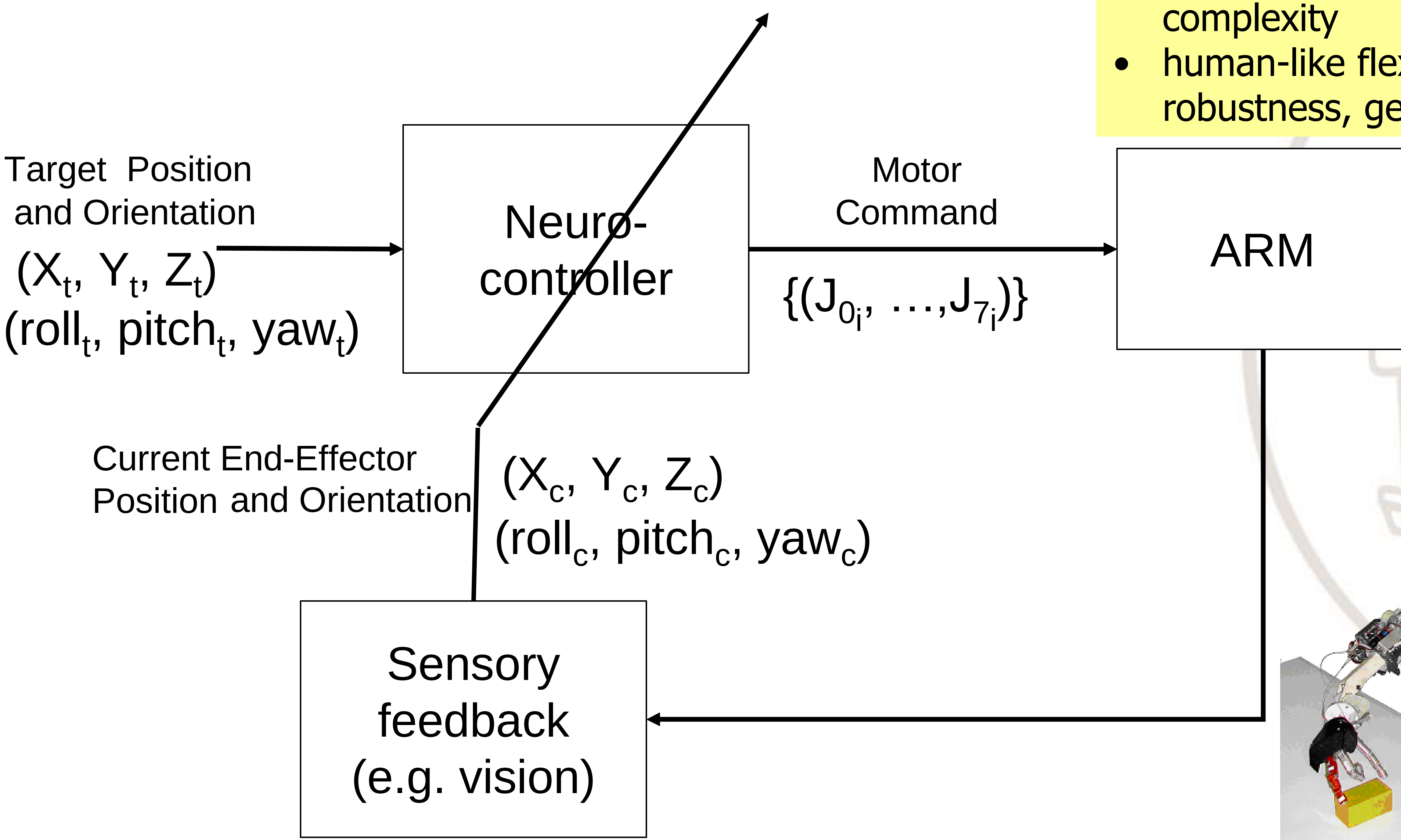
Height mm	1500
Weight kg	64 (with batteries)
Degrees of Freedom (DOF)	
Leg	6×2
Foot	1×2 (passive)
Waist	2
Trunk	2
Arm	7×2
Hand	3×2
Neck	3
Total	41

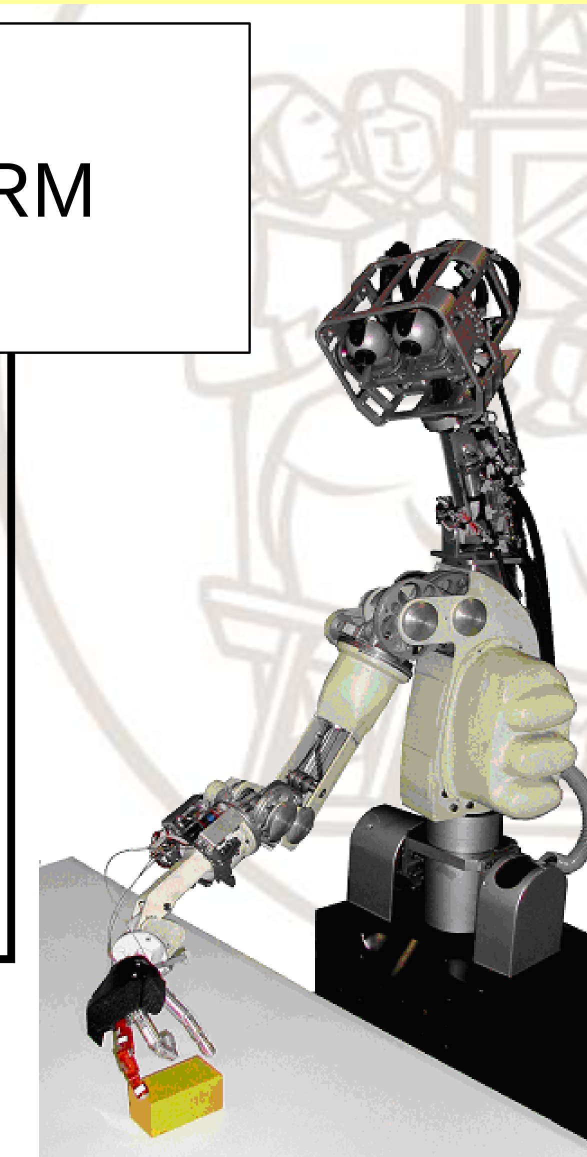
WABIAN testing the Walking Aid Robot for Elderly developed by HITACHI (WABOT-HOUSE Project, Gifu Prefecture)

WABIAN simulating the pathological walking of post-stroke patients

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





Experimental results on a 3-link arm in simulation

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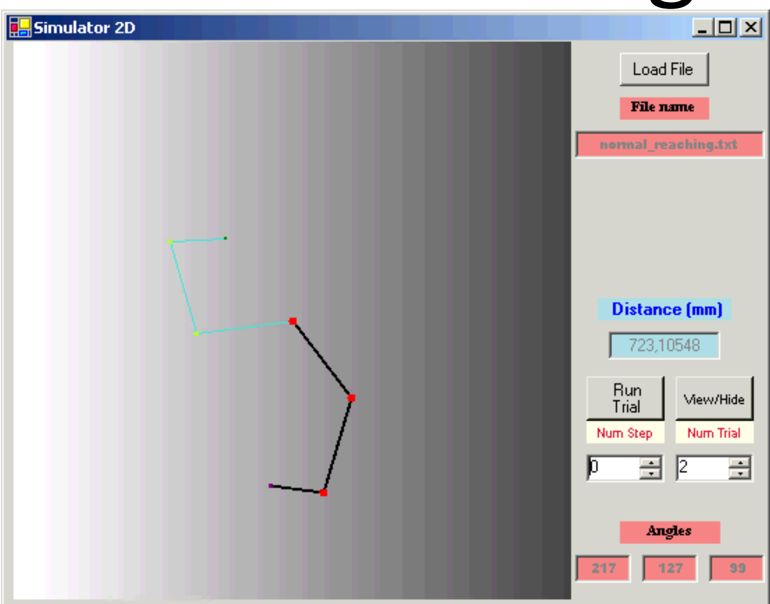
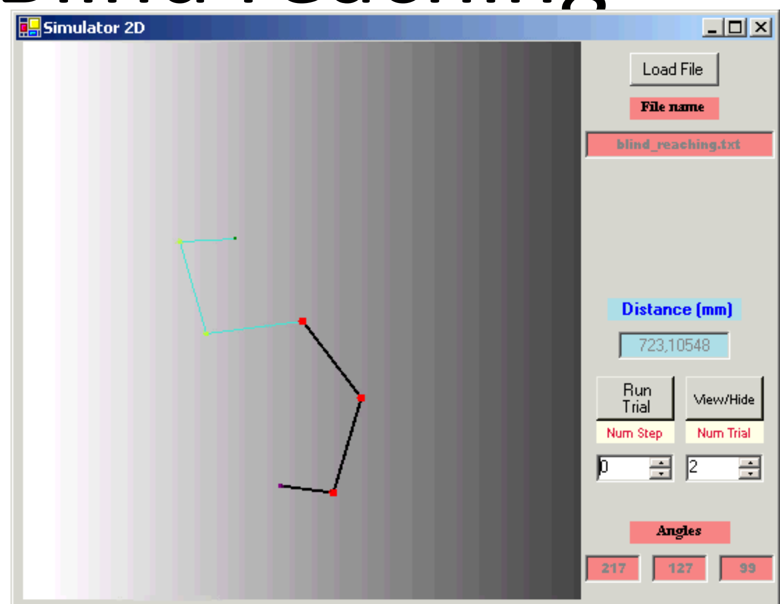
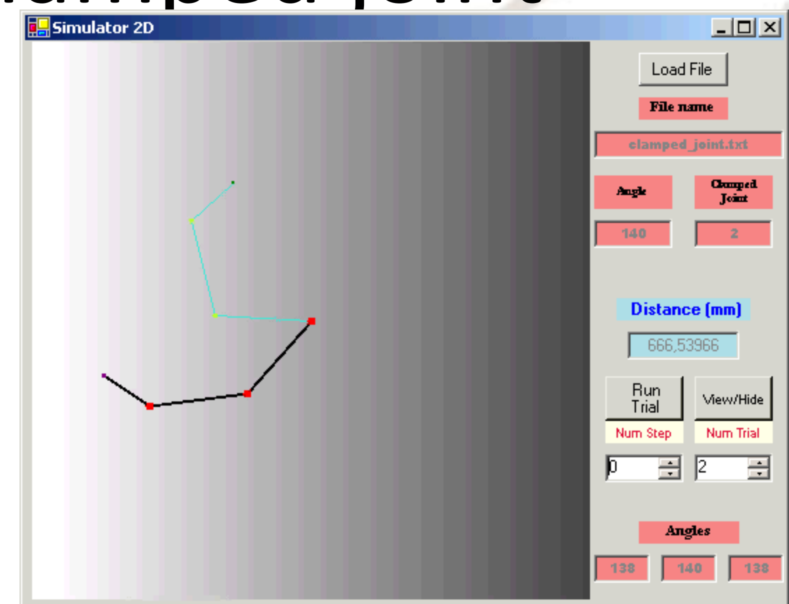
Normal reaching



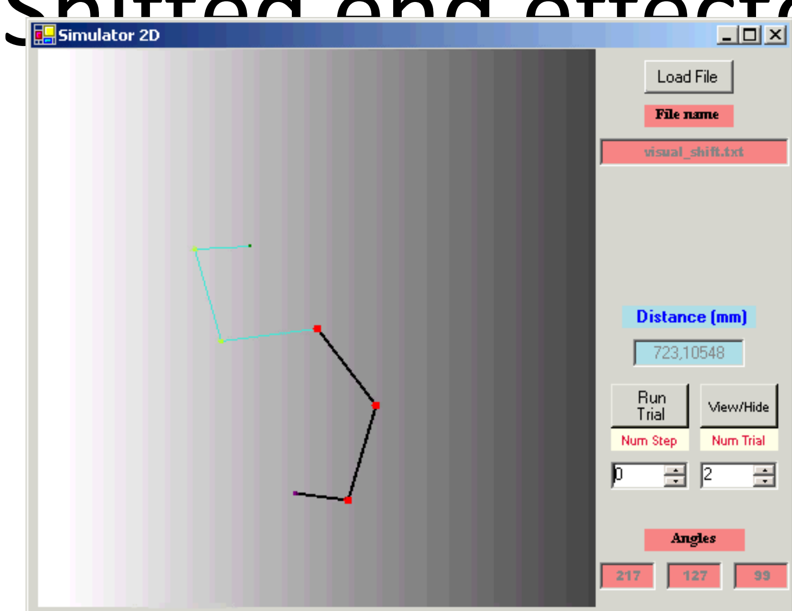
Blind reaching



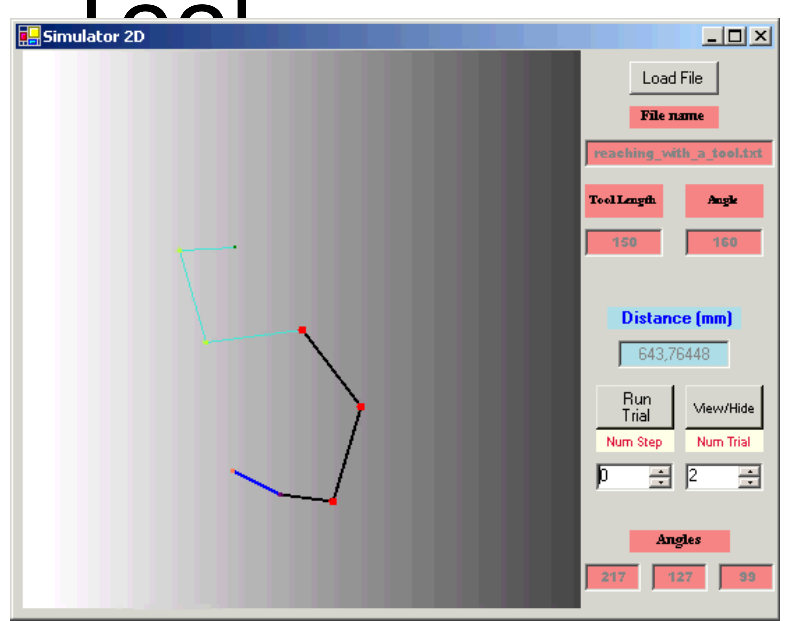
Clamped joint



Shifted end effector



Tool



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Experimental results on the DEXTER robotic arm

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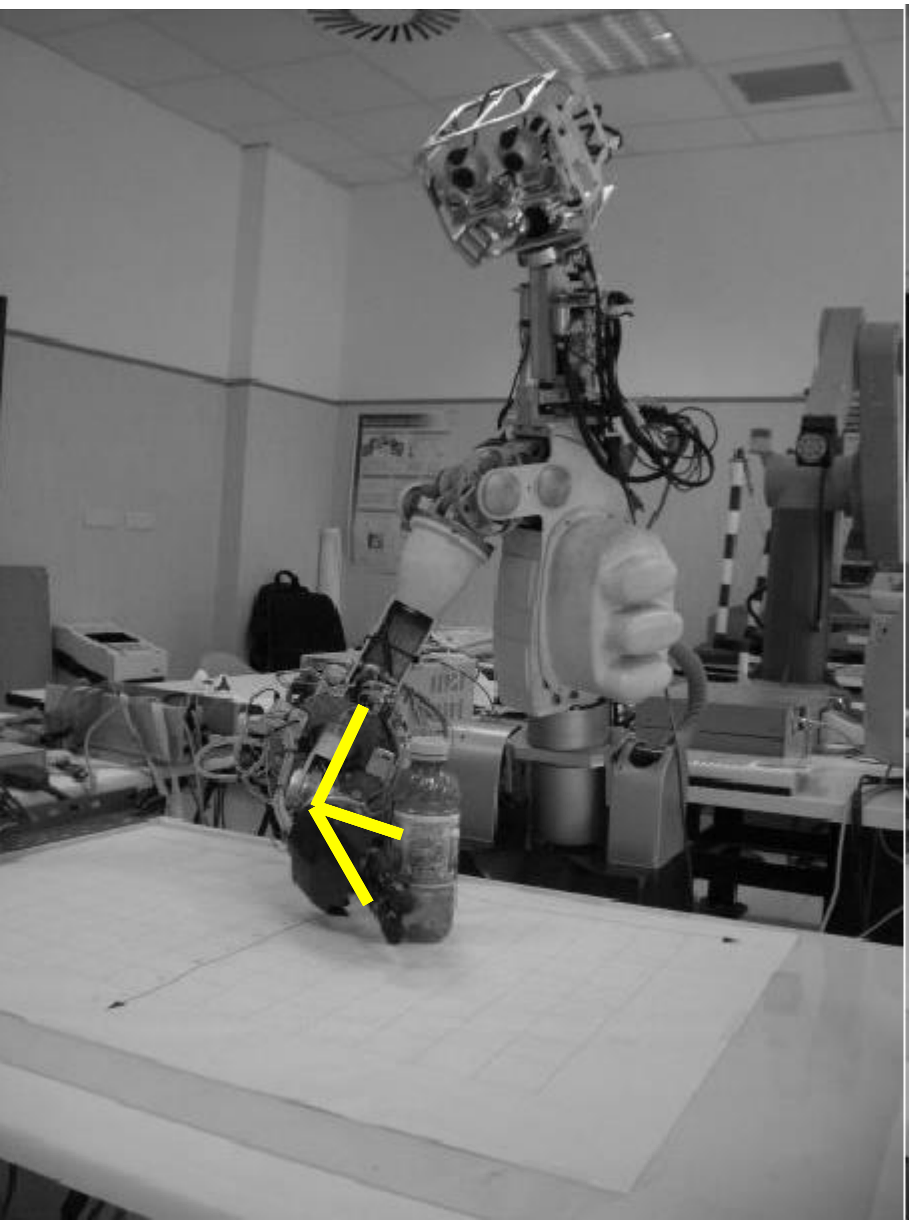
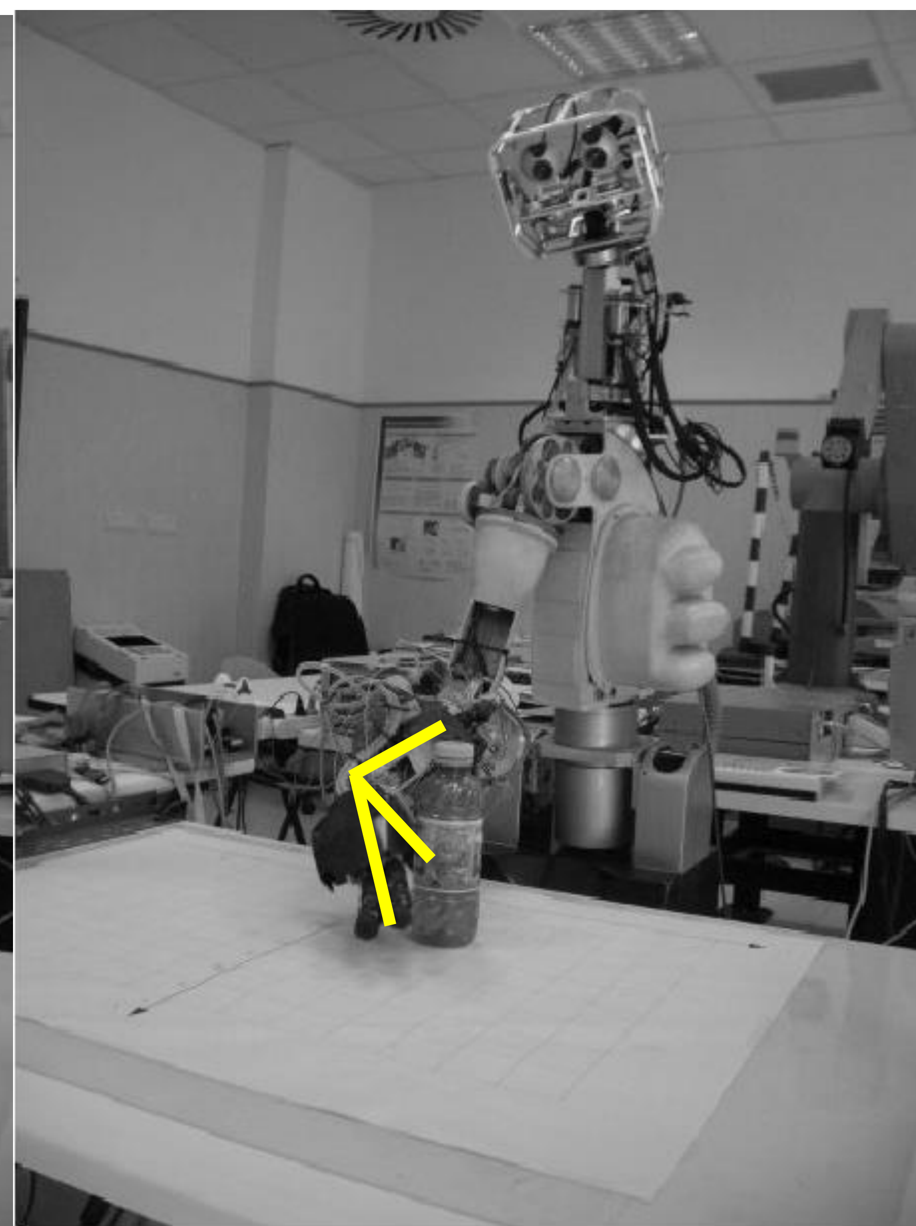
Target and final postures

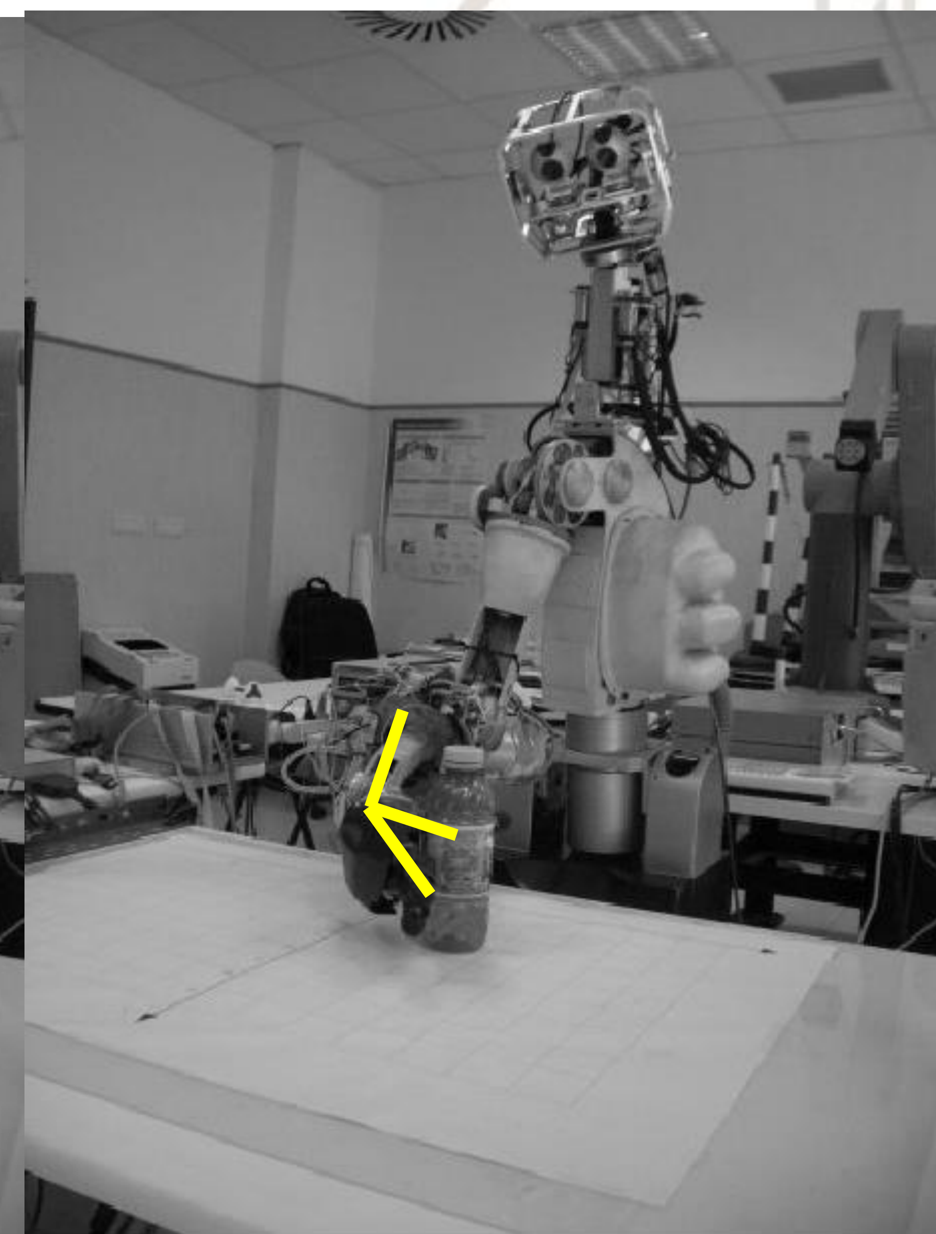
Target posture



Final posture (no orientation)



Final posture (with orientation)



Application to the robot head: control of gaze fixation point

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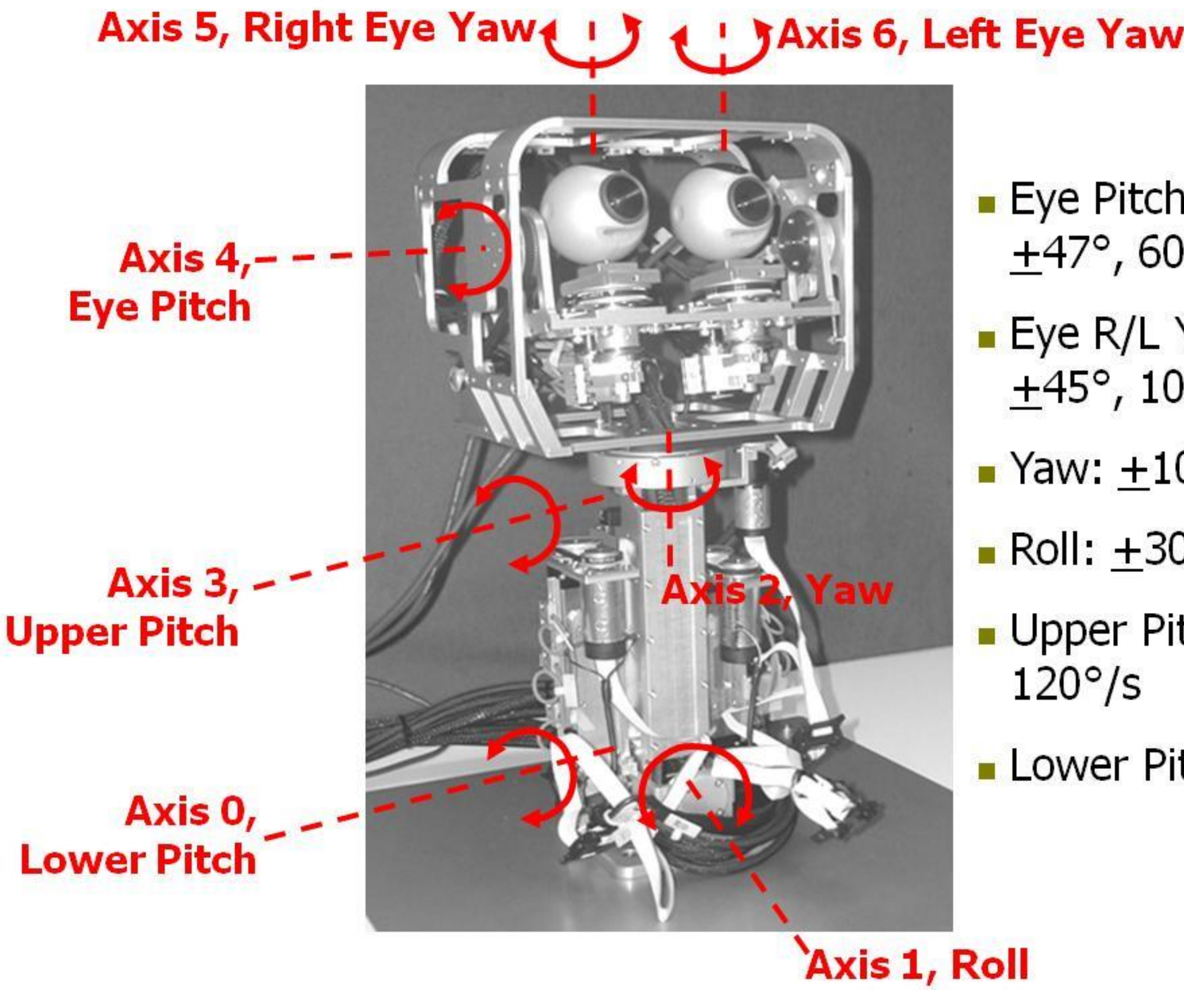
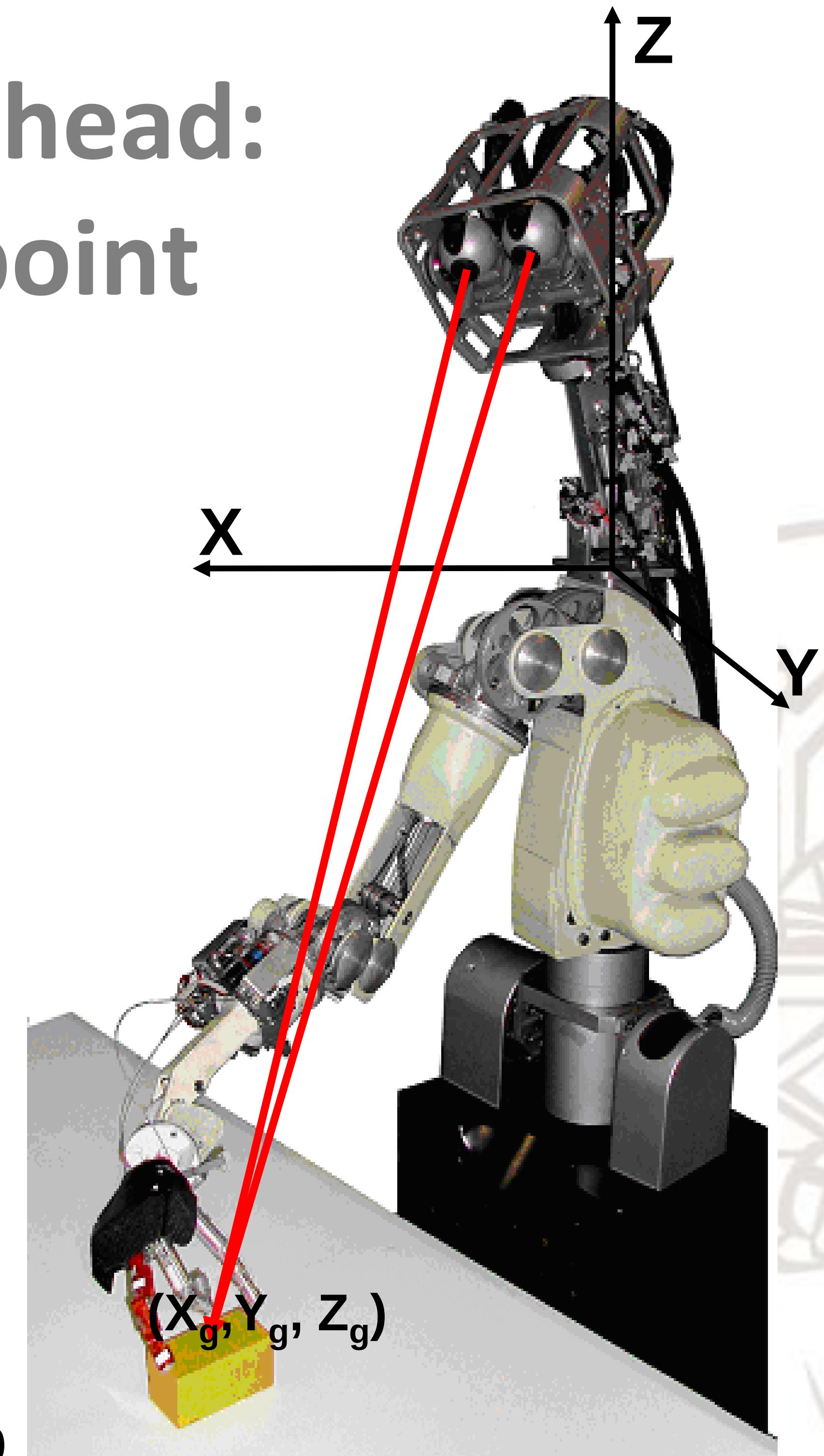


- Eye Pitch Axis: ±47°, 600°/s
- Eye R/L Yaw Axis: ±45°, 1000°/s
- Yaw: ±100°, 170°/s
- Roll: ±30°, 25°/s
- Upper Pitch: ±30°, 120°/s
- Lower Pitch: ±25°, 20°/s



Control module that receives in input a target gaze position and provides in output a command sequence to reach it

Target Gaze Fixation Point Position (X_t, Y_t, Z_t) → [?] → Motor Command $\{(J0_i, \ldots, J6_i)\}$ → [HEAD]

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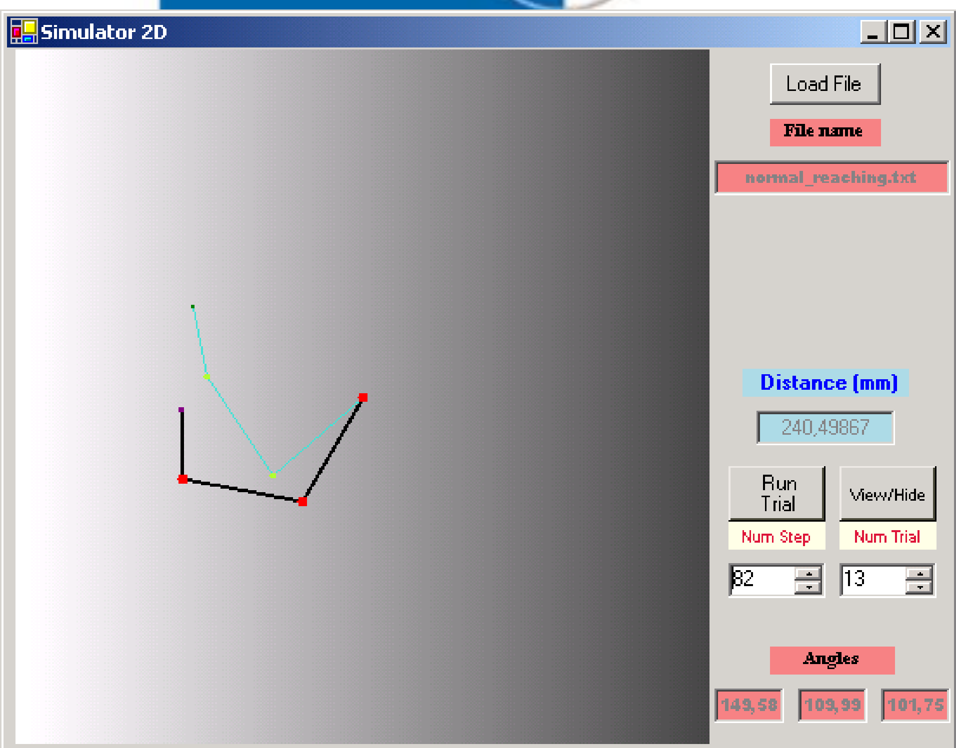
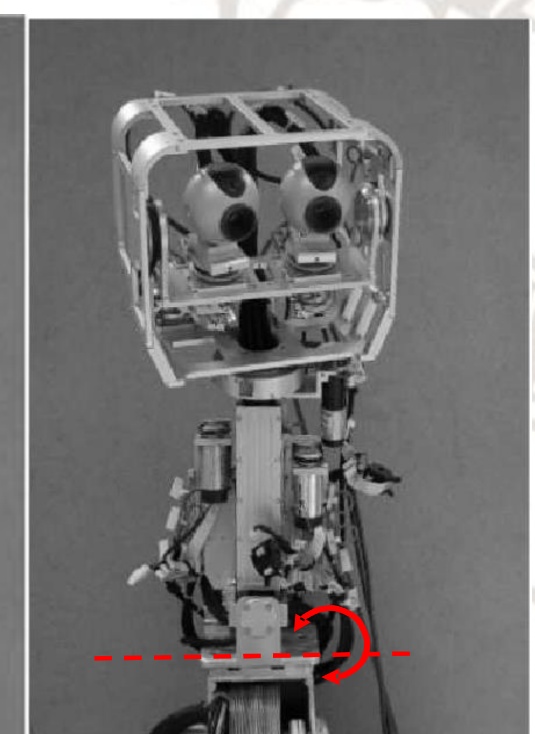
Application of the same approach to different robotic systems





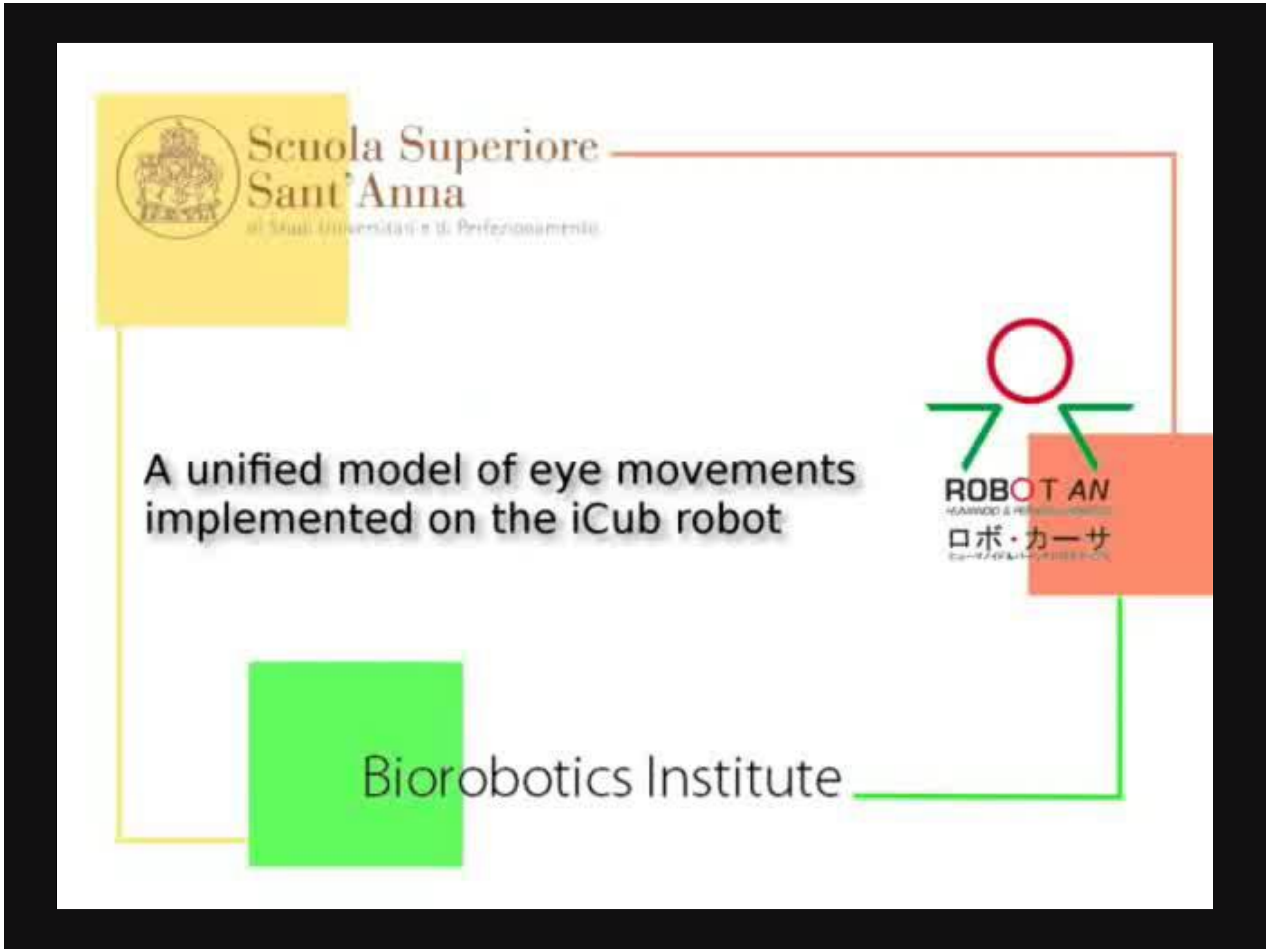
G. Asuni, Leoni F., Starita A., Guglielmelli E., Dario P., “A Neuro-controller for Robot Arms Based on Biologically-Inspired Visuo-Motor Coordination Neural Models”, *The 1st International IEEE EMBS Conference on Neural Engineering*, 20 - 22 March, 2003, Capri Island, Italy.

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

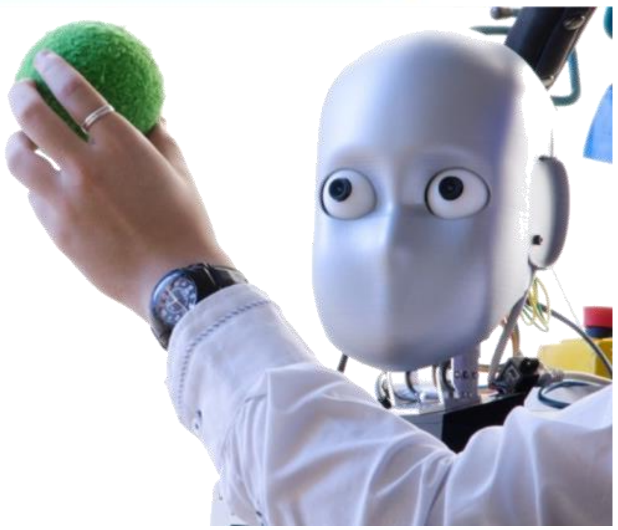
Humanoid robots as platforms for neuroscience

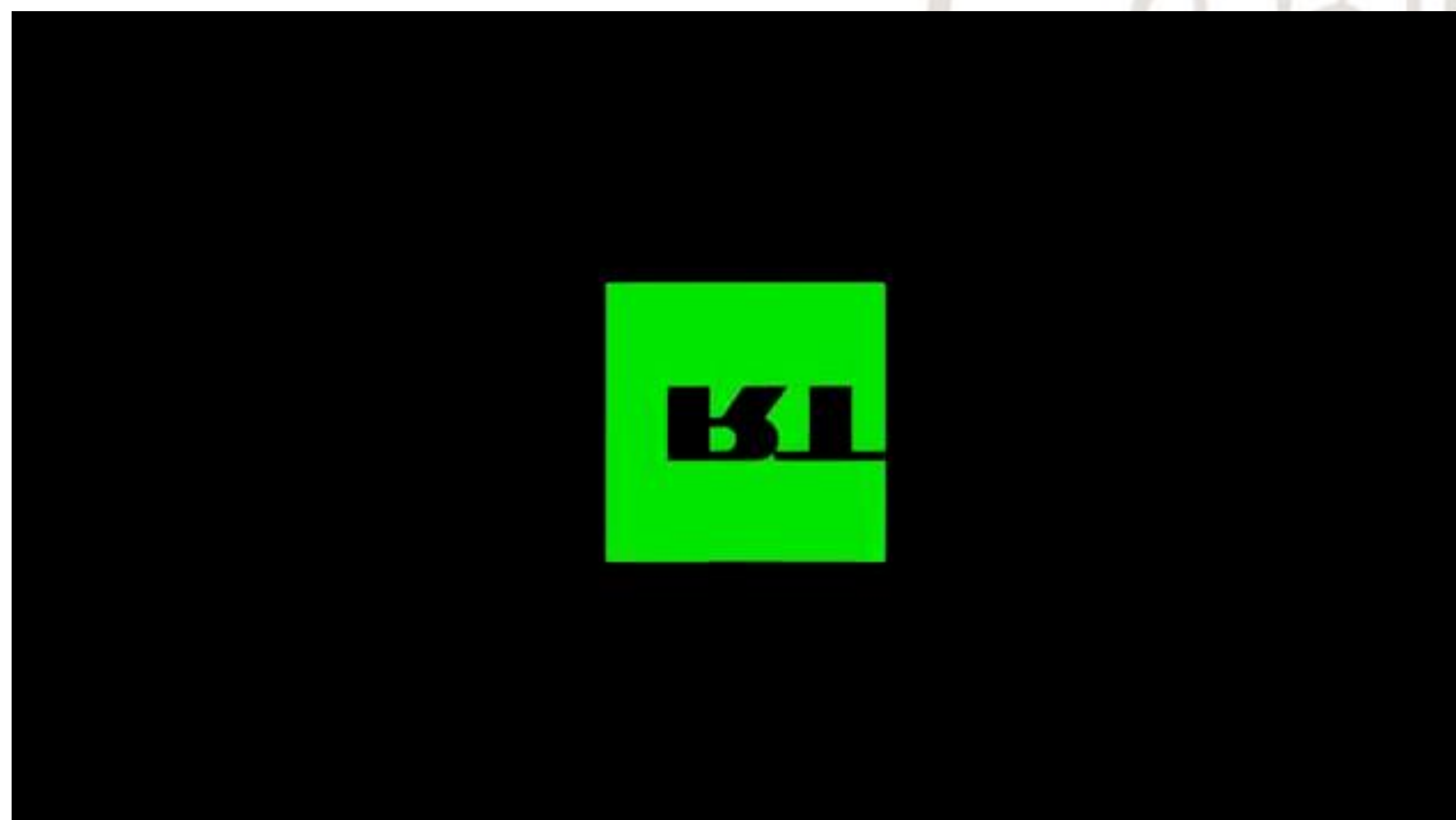
Robotic implementation of gaze control, integrating different eye movements



E. Falotico. D. Zambrano, C. Laschi, P. Dario, “Bioinspired integrated eye movements in a humanoid robot”, (in preparation) Autonomous Robots
D. Zambrano, E. Falotico. C. Laschi, P. Dario, “A model of basal ganglia for robotic eye movement control”, (in preparation) Autonomous Robots

Why bioinspiration in robotics?





Today, more functionality means

more complexity, energy, computation,

less controllability, efficiency, robustness, safety

Lessons from Nature: simplification mechanisms

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In robotics, we need **simplification mechanisms** for control and new materials, fabrication technologies and energy forms

- Studying natural organisms and understanding what makes them so smart and efficient
- Studying tasks that only living organisms can do, and how they do it

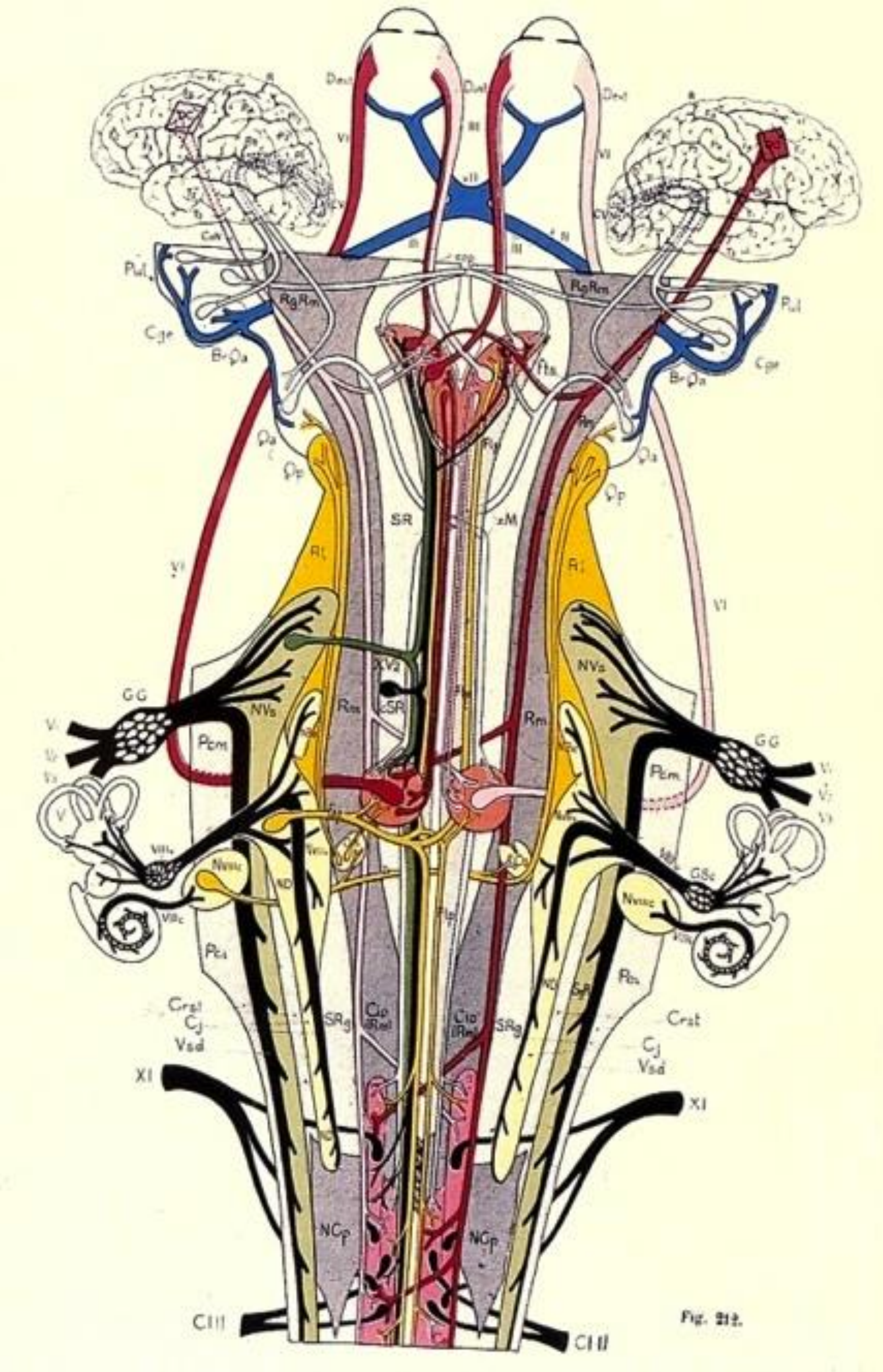
Simplexity

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



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

U. Alon (2207), “Simplicity in Biology,” *Nature*, 446 (7135) : 497

Simplexity

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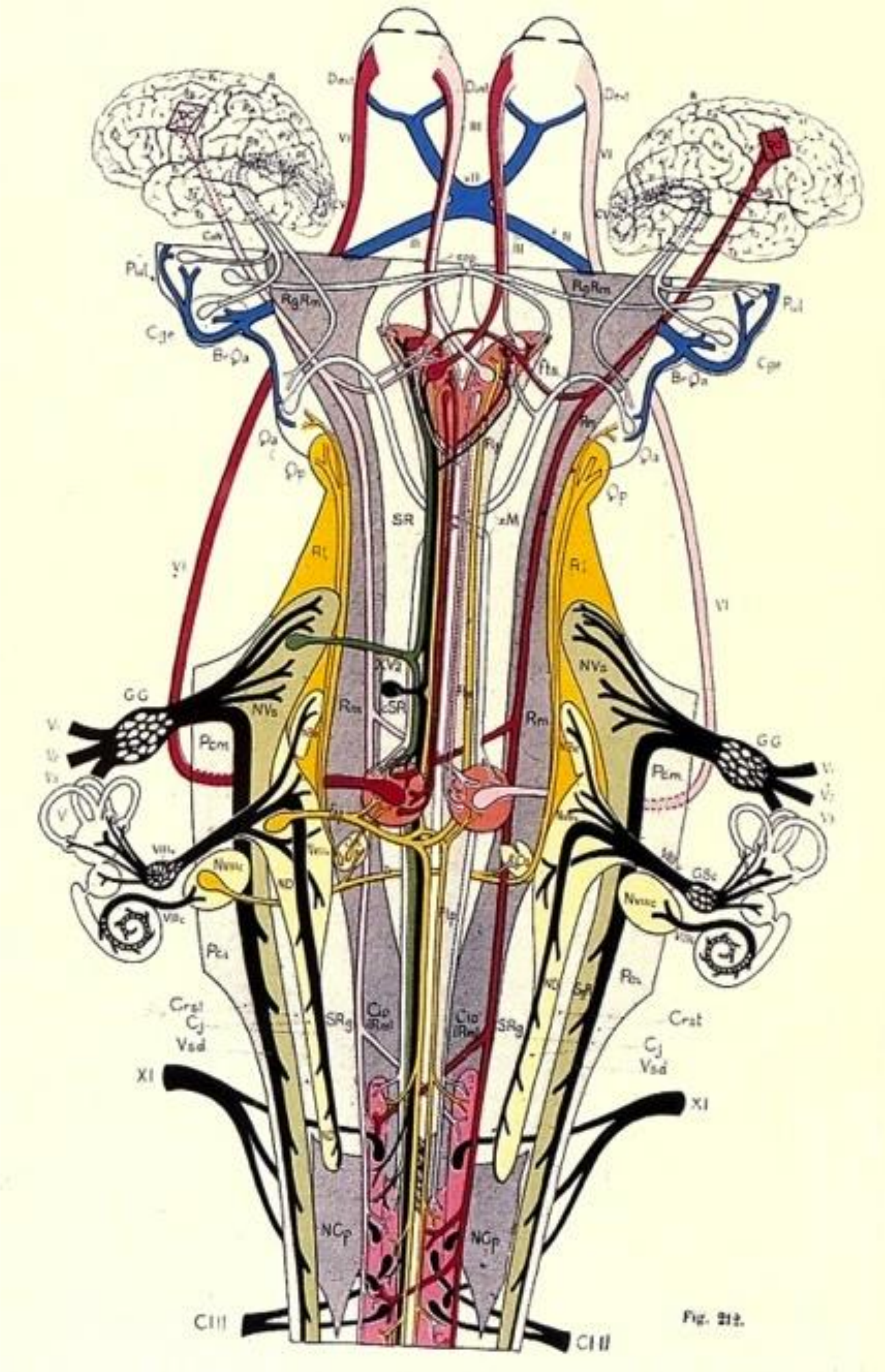
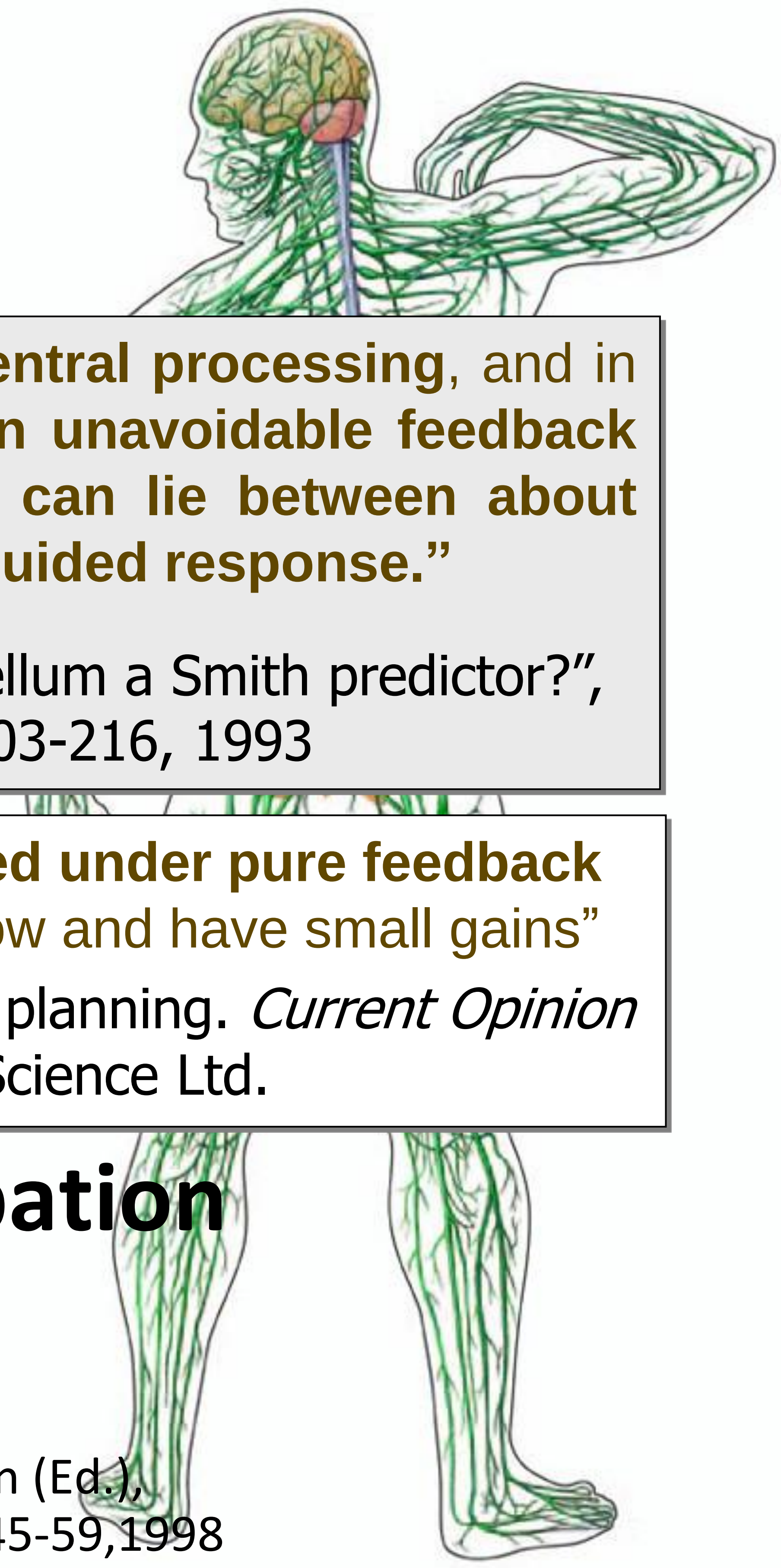


In robots, the concept of a unified inertial reference frame, together with gaze control, can represent one of the basic design principles for **simplifying the control of complex kinematic (human-like) structures**

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

U. Alon (2207), “Simplicity in Biology,” *Nature*, 446 (7135) : 497

Delays in the human nervous system



"In motor control **delays** arise in **sensory transduction**, **central processing**, and in the **motor output**. […] **These delays combine to give an unavoidable feedback delay within the negative feedback control loop, and can lie between about 30ms 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 lesson from neuroscience: anticipation

- 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

Predictive sensory-motor coordination

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*** (Berthoz, 2002): 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 sense of movement*. Harvard University Press

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Predictive smooth pursuit eye movement

The retinal slip (target velocity onto the retina) reaches zero after the algorithm convergence.

When the target is unexpectedly stopped, the system continues to follow the target for a short period.

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***

Embodied Intelligence or Morphological Computation: 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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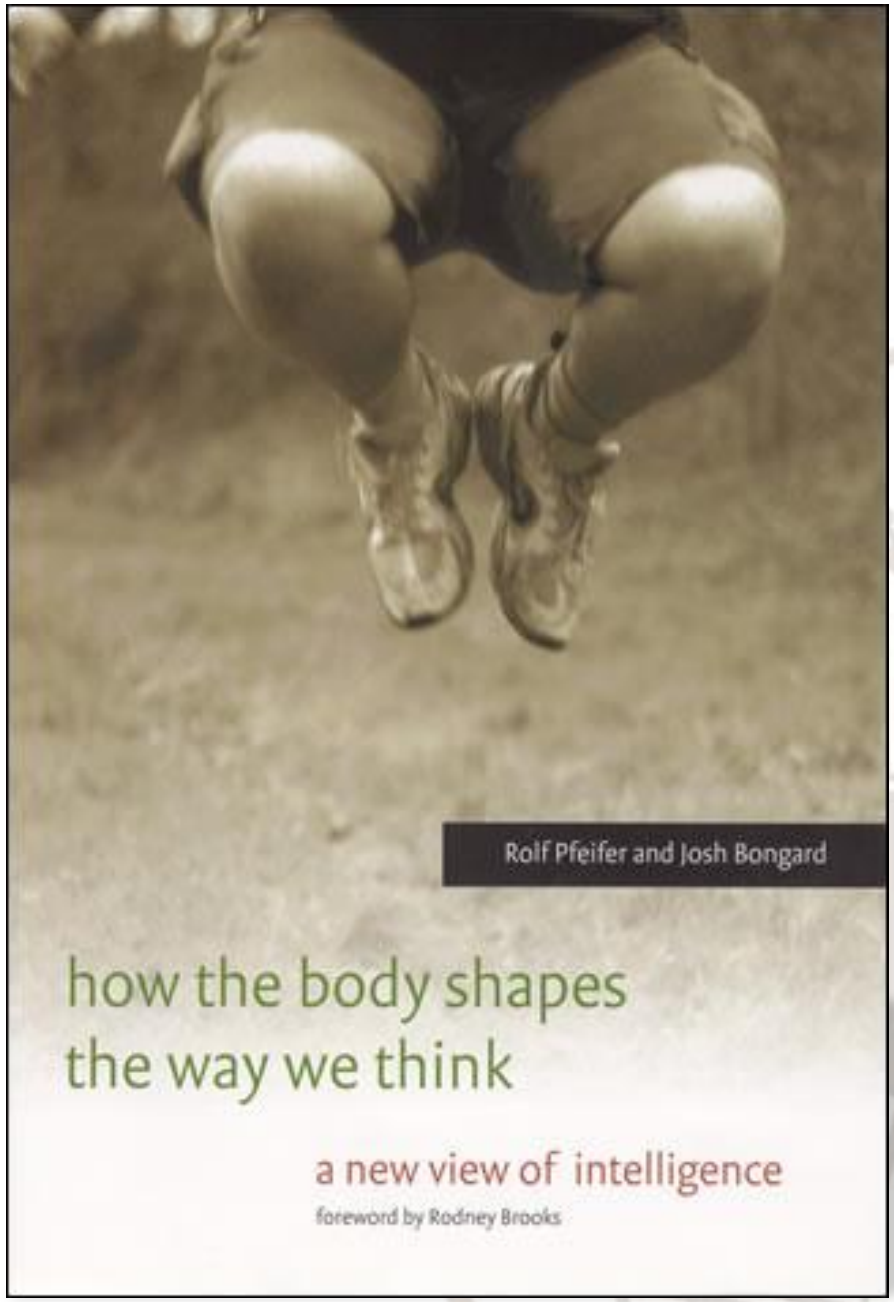
Embodied Intelligence

Il comportamento adattivo non è dato solo da controllo e calcolo, ma emerge dall'interazione complessa e dinamica tra la morfologia del corpo, il controllo senso-motorio e l'ambiente. Molti compiti risultano più semplici tenendo in considerazione l'Embodied Intelligence.

"Mechanical Intelligence"

"Morphological Computation"



La natura della mente umana è largamente determinata dalla forma del corpo

Rolf Pfeifer and J. 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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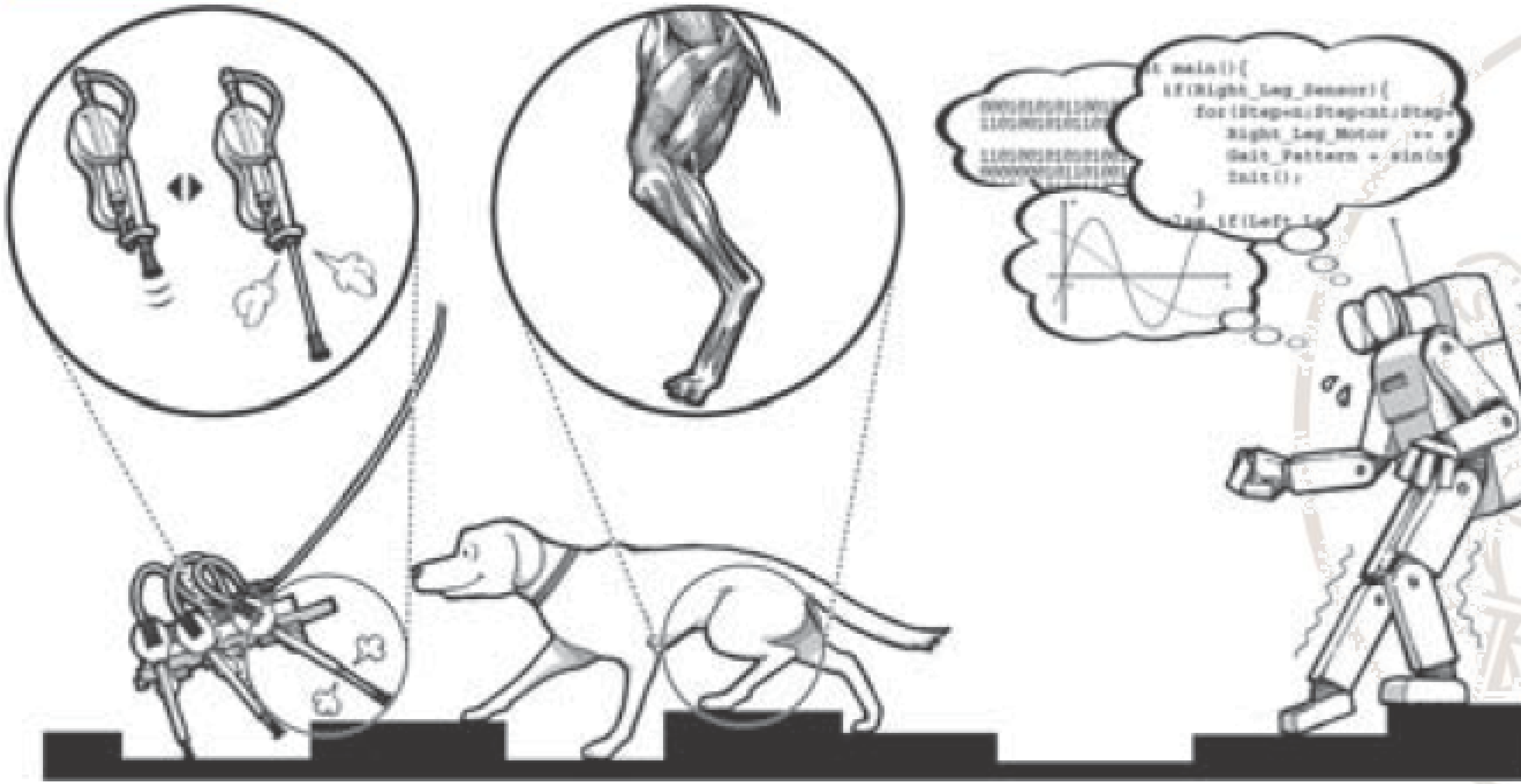
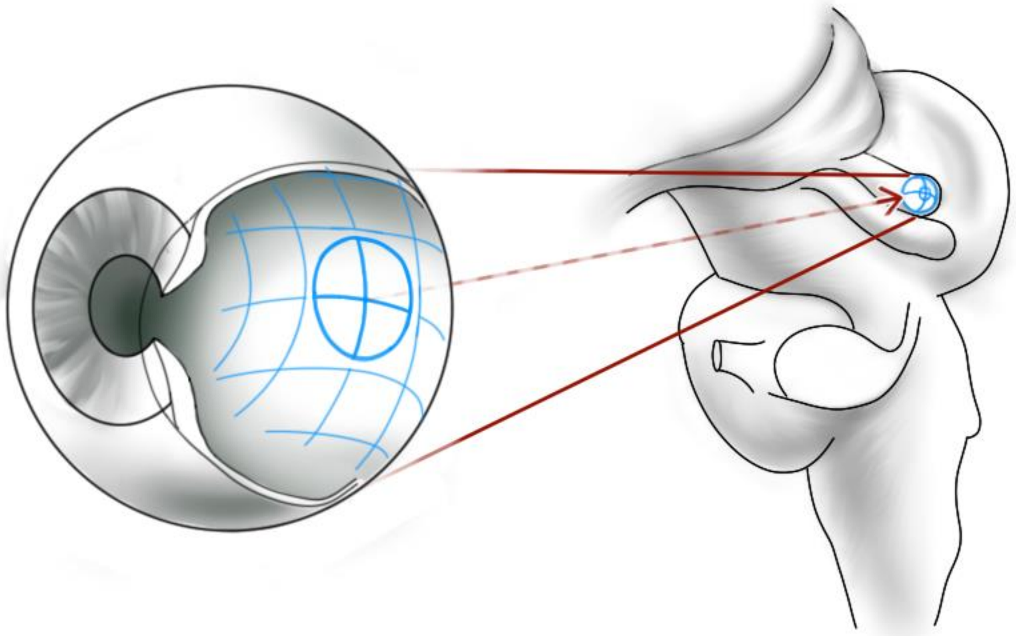
Embodied Intelligence or Morphological computation



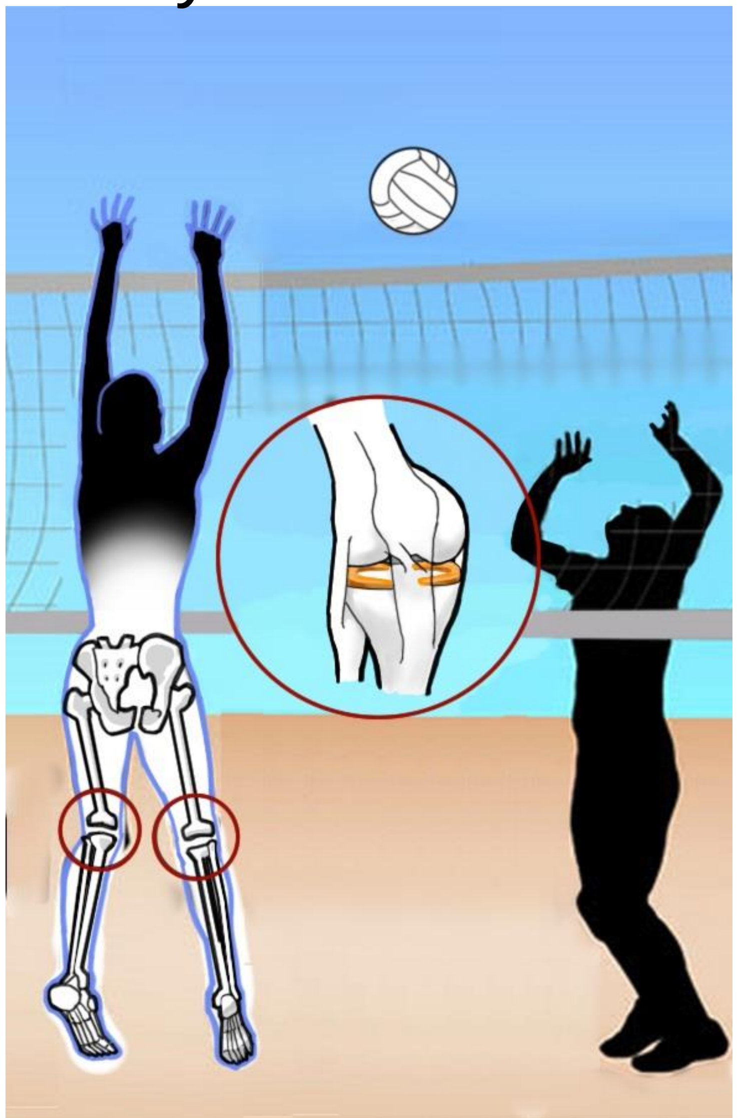
Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Morphological Computation / Embodied Intelligence (examples)

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

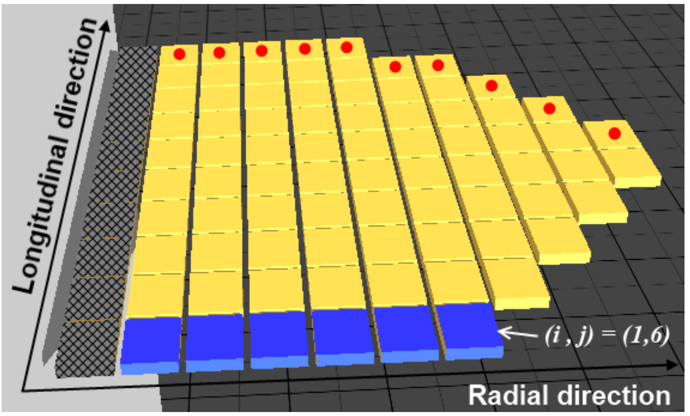


The shape
as body structure, specifies the behavioral response of the agent

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

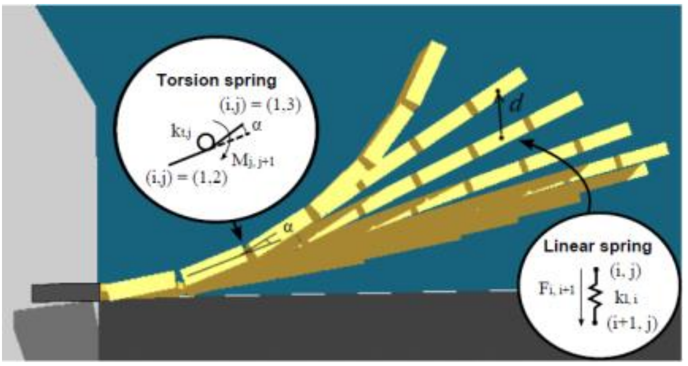
Batoids and embodied intelligence

- Co-evolution of morphology (stiffness) and control (flapping frequency and amplitude), in different environments
- A lumped parameters model of a compliant wing was developed, and optimized to evolve optimal swimming in different enviroment by means of evolutionary algorithms (genetic algorithms)
- Optimization target: Strouhal number (describes vortices dynamics, linked to swimming efficiency)



Batoid fishes (rays, skates) can be source of inspiration for robotics:

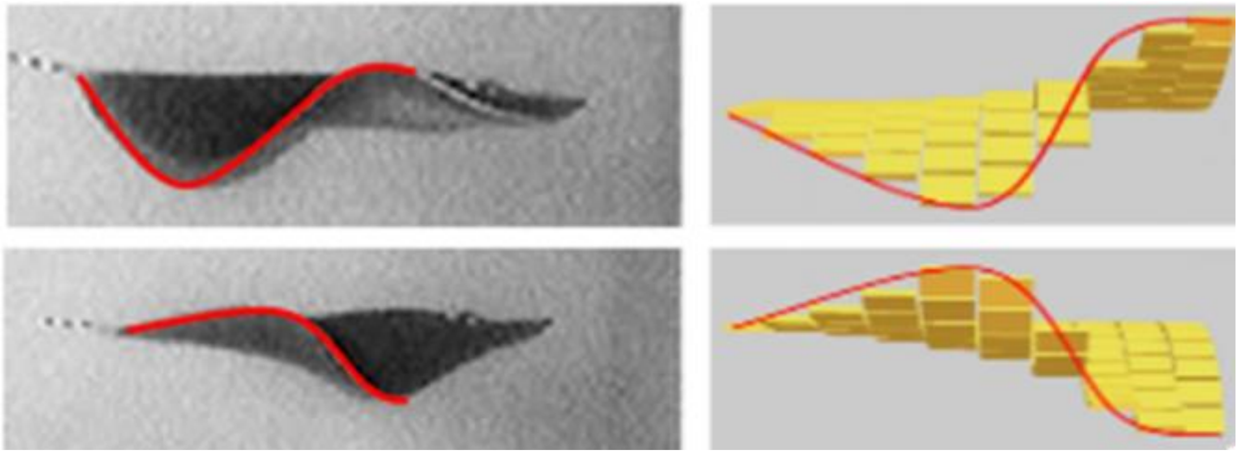
- Marine robotics: Smaller species are agile and quick, bigger ones are able to cruise for long distances still preserving high manoeuvrability → development of ROVs, UAVs
- Soft robotics: Cartilagineous body, largely underactuated (pectoral muscles → passive propagation of the motion)
- Embodied intelligence: rich behavior emerges from the interaction of a complex morphology with the environment in presence of simple control

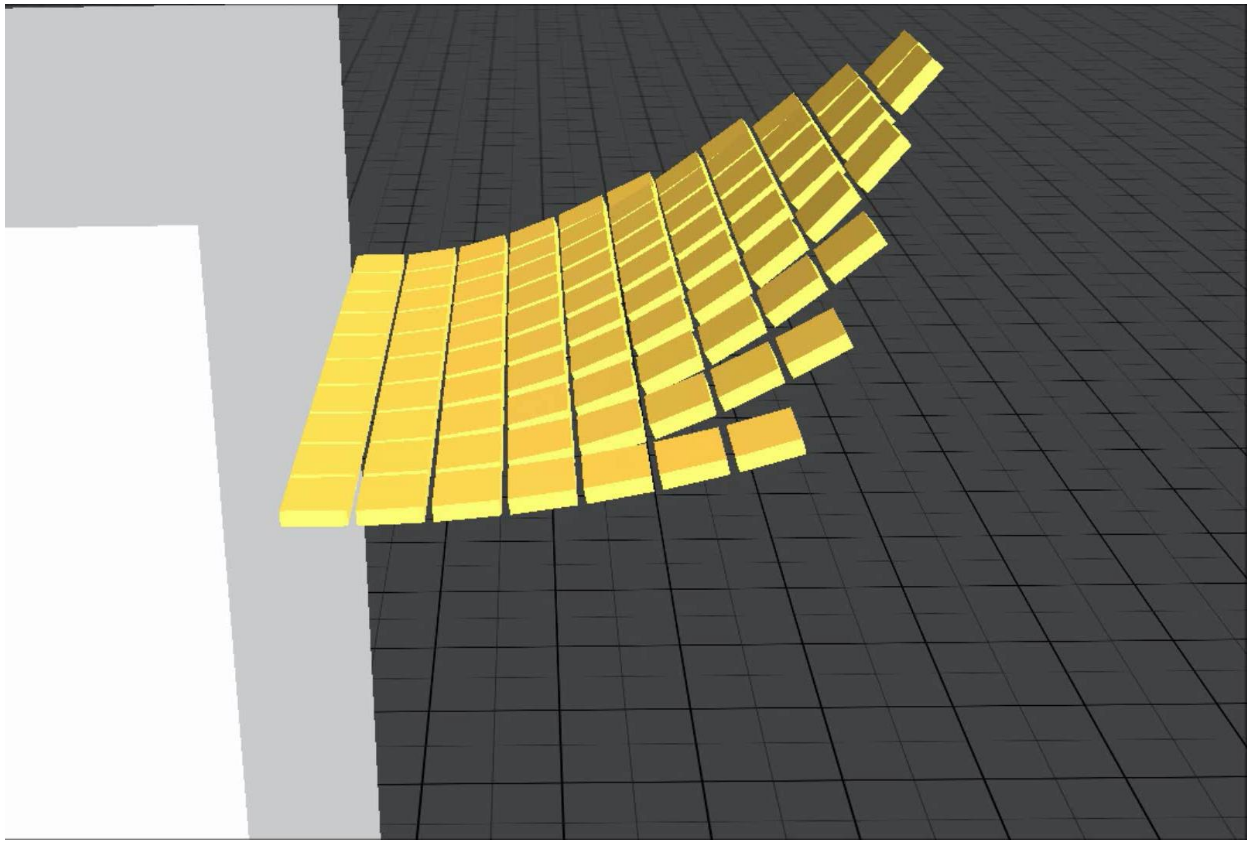


Cacucciolo, V., Corucci, F., Cianchetti, M., & Laschi, C. (2014). *Evolving Optimal Swimming in Different Fluids: A Study Inspired by batoid Fishes*. In *Biomimetic and Biohybrid Systems* (pp. 23-34). Springer International Publishing.

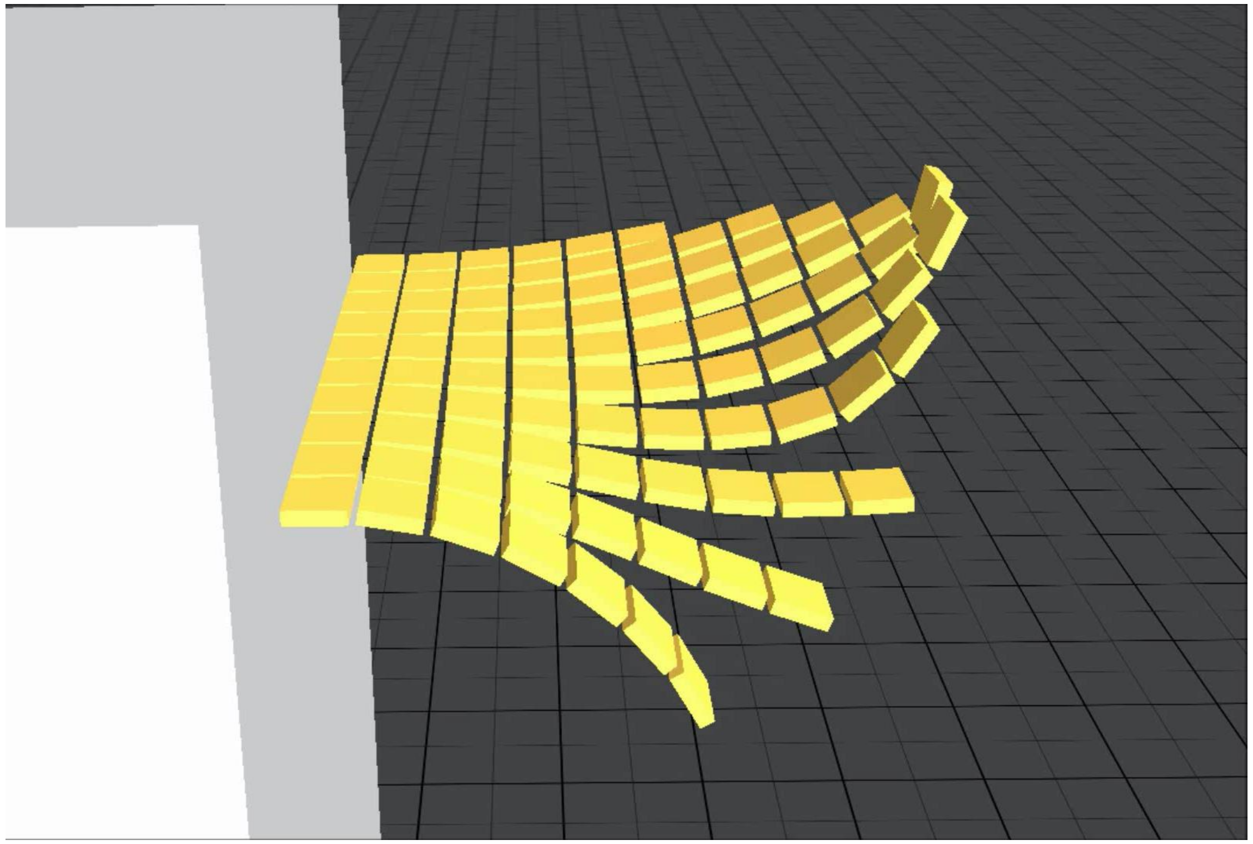
Batoids and embodied intelligence

- Emergence of oscillatory phenomena (undulation, oscillation) observed in the animal is demonstrated
- Adaptation to different fluids
- Evolved frequency and amplitude consistent with some species





Water
$\rho = 1000\ kg \cdot m^{-3}$



Tetrachloroethylene
$\rho = 1622\ kg \cdot m^{-3}$

Cacucciolo, V., Corucci, F., Cianchetti, M., & Laschi, C. (2014). *Evolving Optimal Swimming in Different Fluids:A Study Inspired by batoid Fishes*. In *Biomimetic and Biohybrid Systems* (pp. 23-34). Springer International Publishing.

Embodied Intelligence or Morphological Computation: the modern view of Artificial Intelligence

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

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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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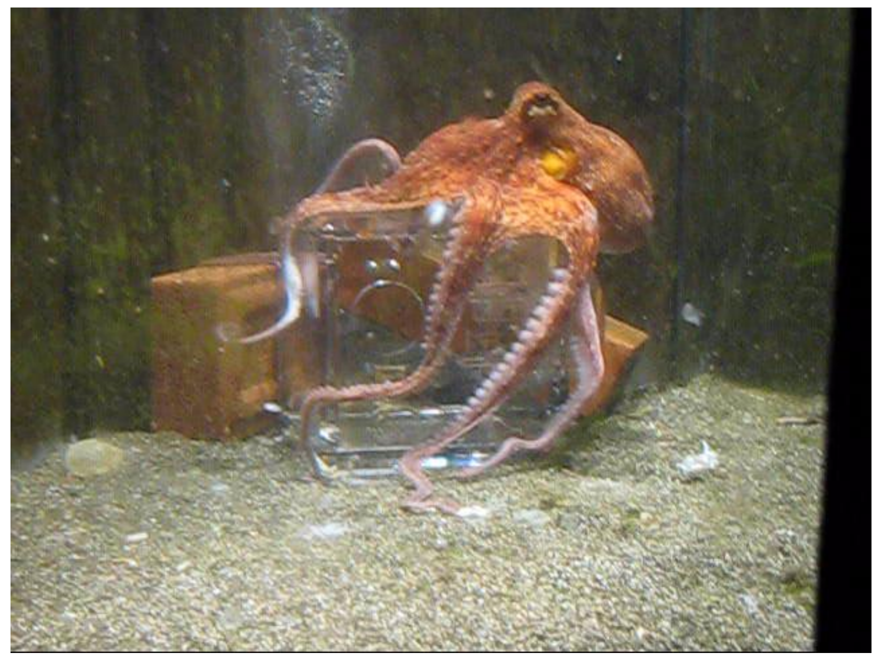
The octopus as a model for embodied intelligence

The *Octopus vulgaris* is a paradigm of the tight relation between the morphology of the body and the behaviour and the development of intelligence

Crawling and swimming



Opening a box

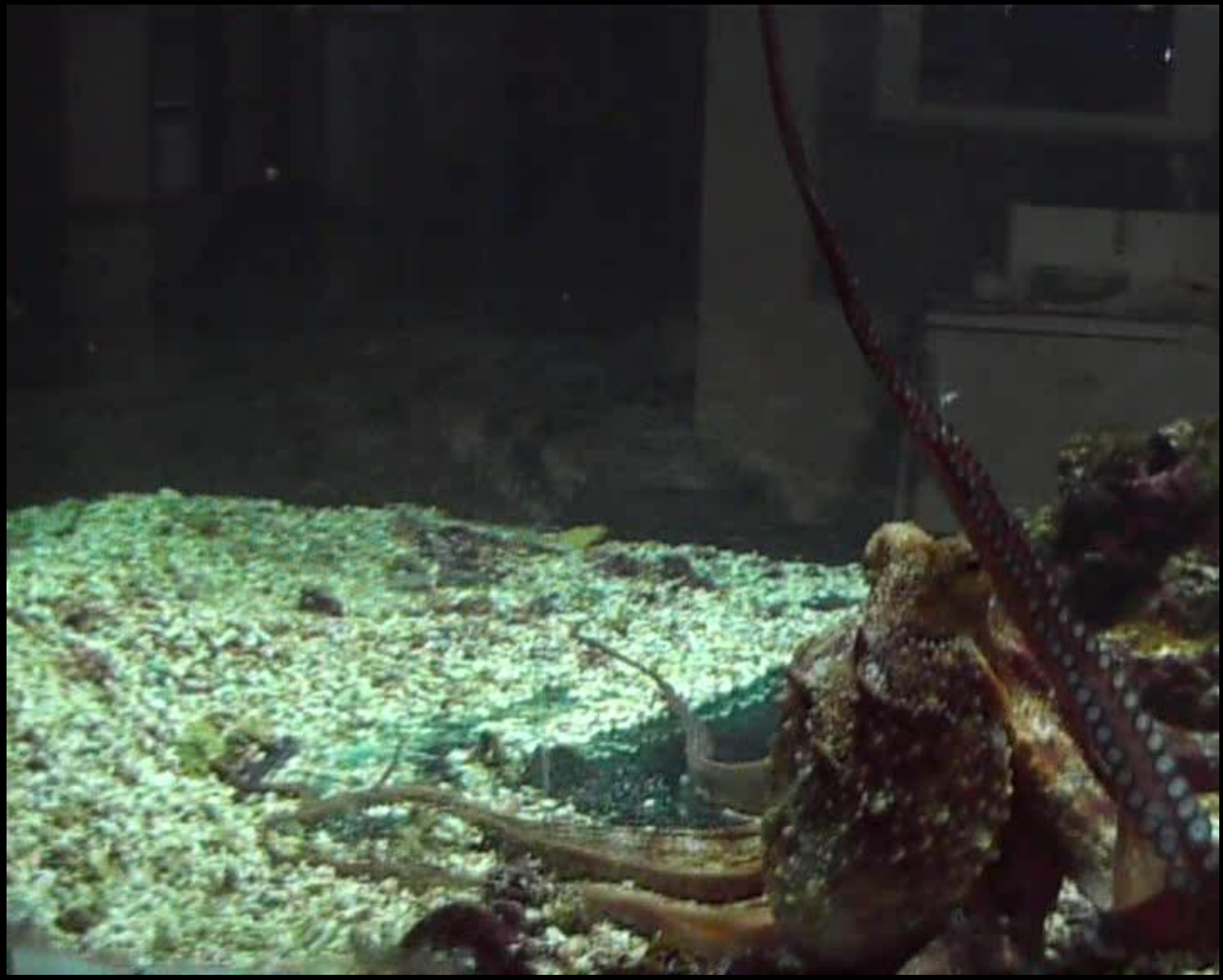
Camoufflage

Probing the environment

Unscrewing a jar cap

Self-cleaning

The octopus embodied intelligence



The OCTOPUS Project

Image: London Science Museum/Jennie Hills

OCTOPUS IP (2009-2013)

Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus

EU-funded Project # 231608
ICT-FET Proactive:
ICT-2007.8.5 "Embodied Intelligence"
Total grant: 7.6 M€

C. Laschi, B. Mazzolai, M. Cianchetti, L. Margheri, M. Follador, P. Dario, "A Soft Robot Arm Inspired by the Octopus", *Advanced Robotics (Special Issue on Soft Robotics)*, Vol.26, No.7, 2012.
M. 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 & Biomimetics*, Vol.6, No.3, 2011, 10 pp.
C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, P. Dario, "Design of a biomimetic robotic octopus arm", *Bioinspiration&Biomimetics*, Vol.4, No.1, 2009.

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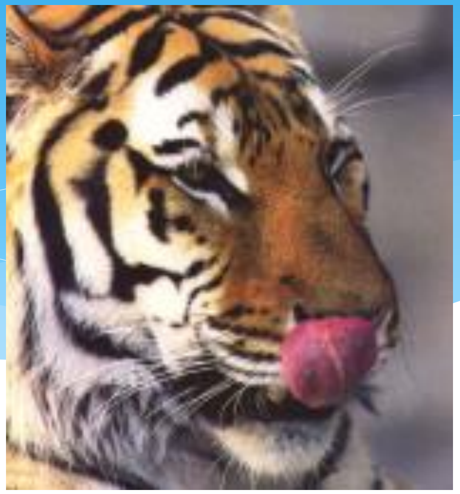
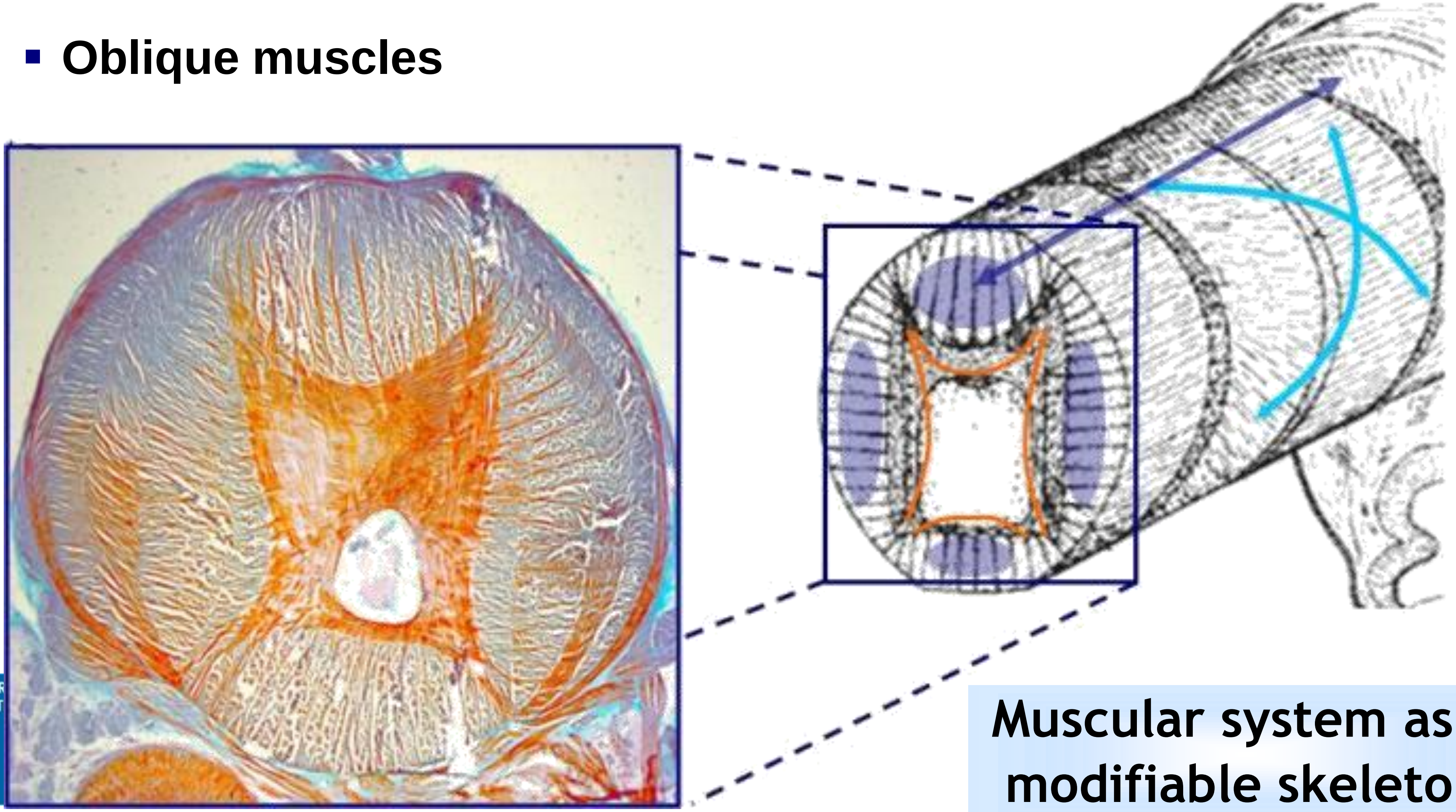
The octopus muscular hydrostat

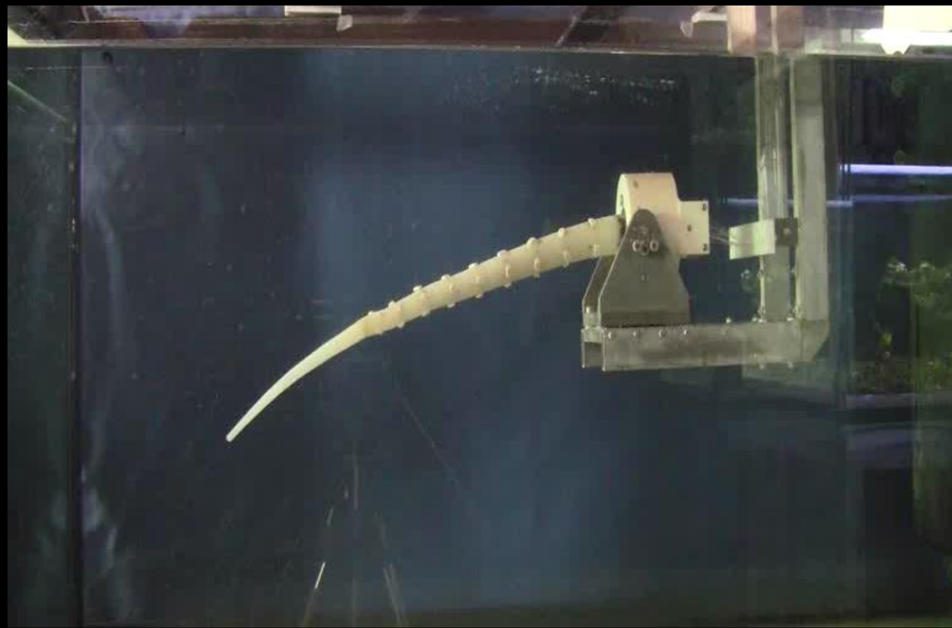
Constant volume during contractions

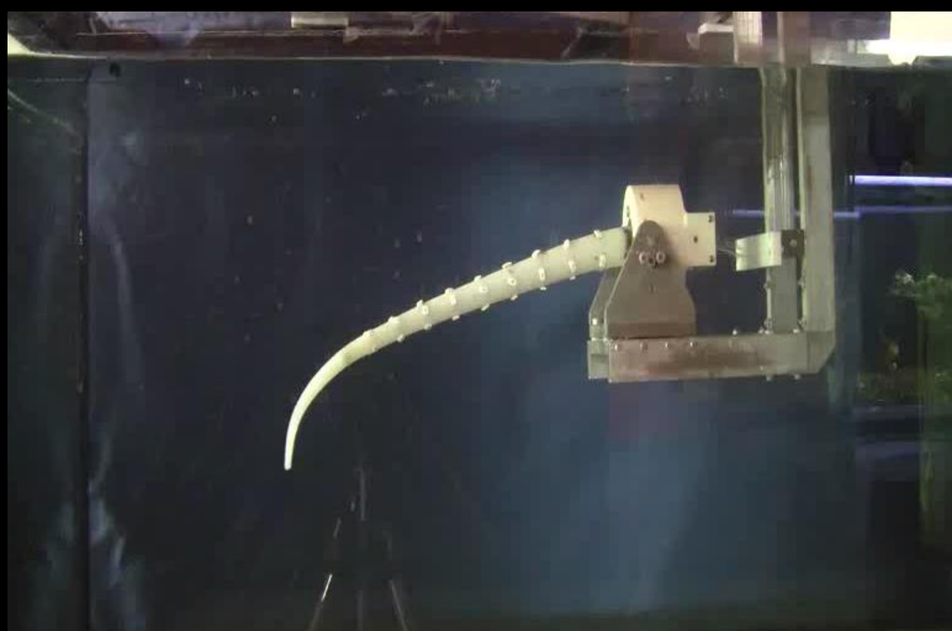
- **Longitudinal muscles**
- **Transverse muscles**
- **Oblique muscles**

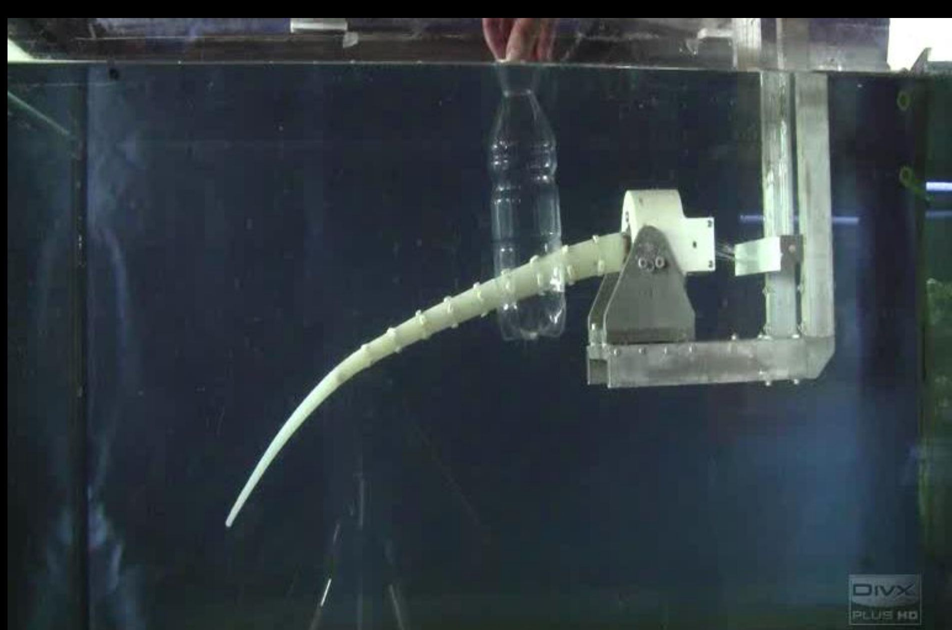


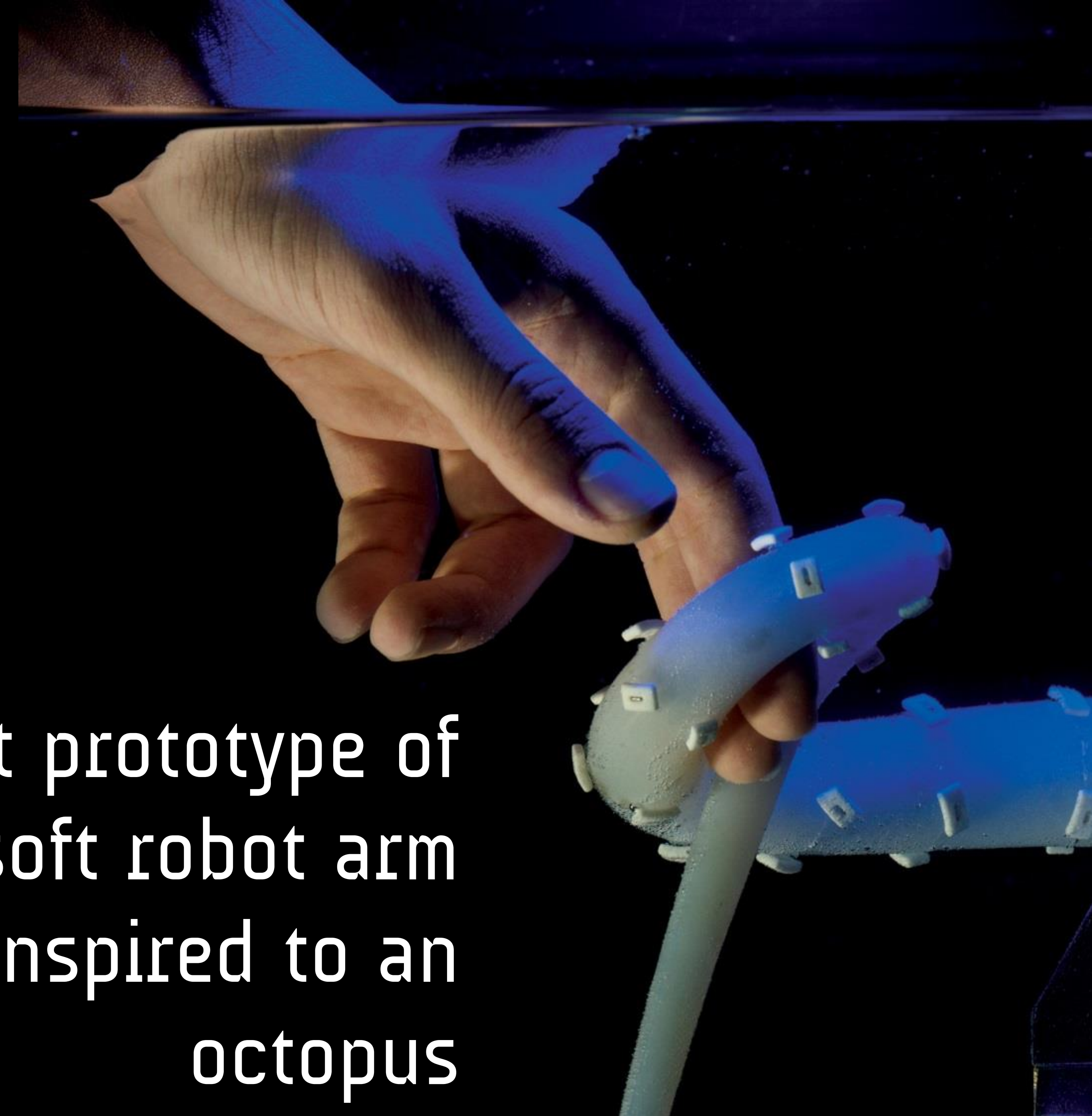


Muscular system as a modifiable skeleton

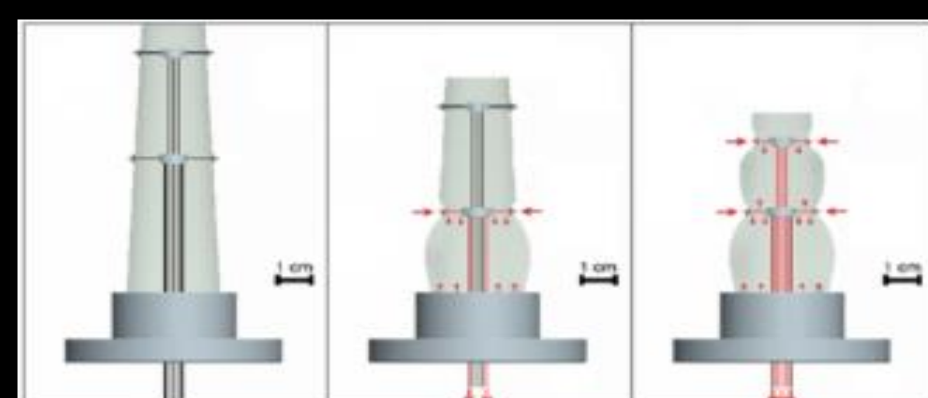






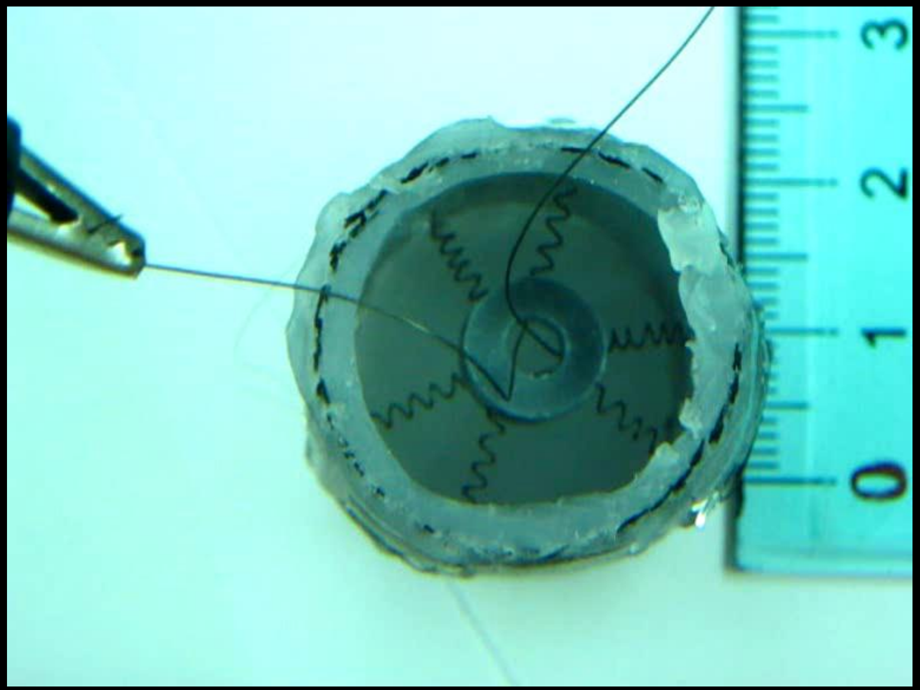


First prototype of soft robot arm inspired to an octopus



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.

Image: Massimo Brega



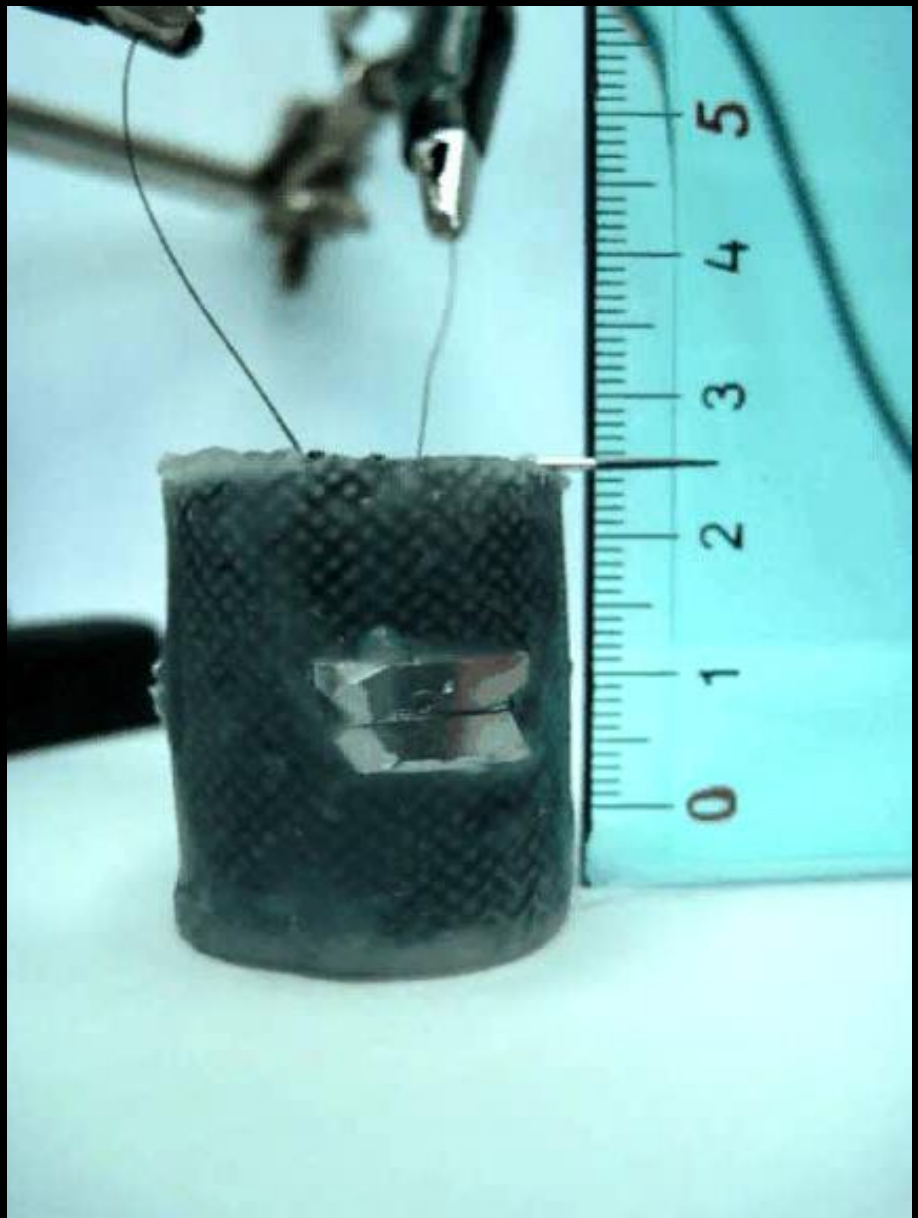
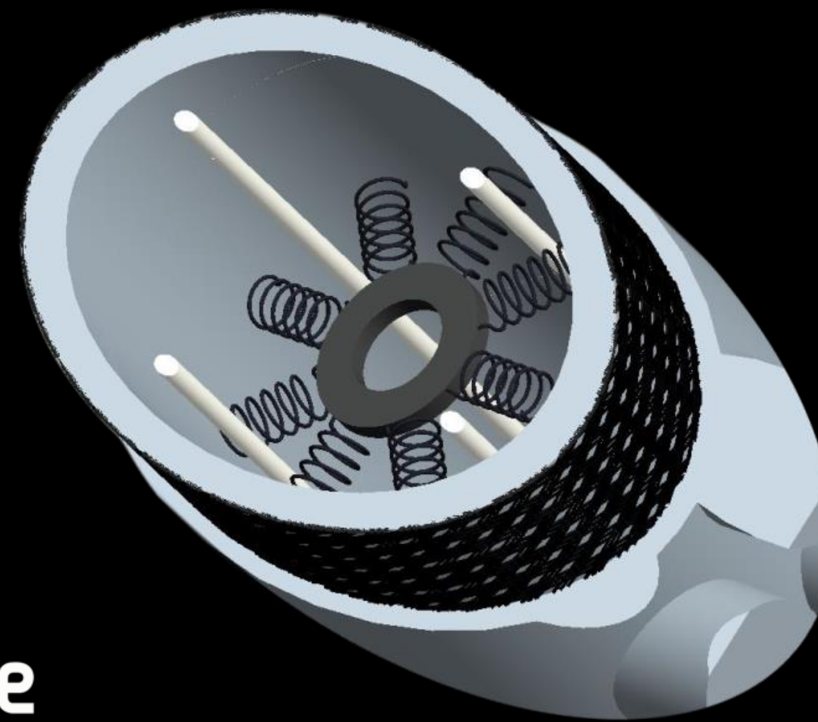
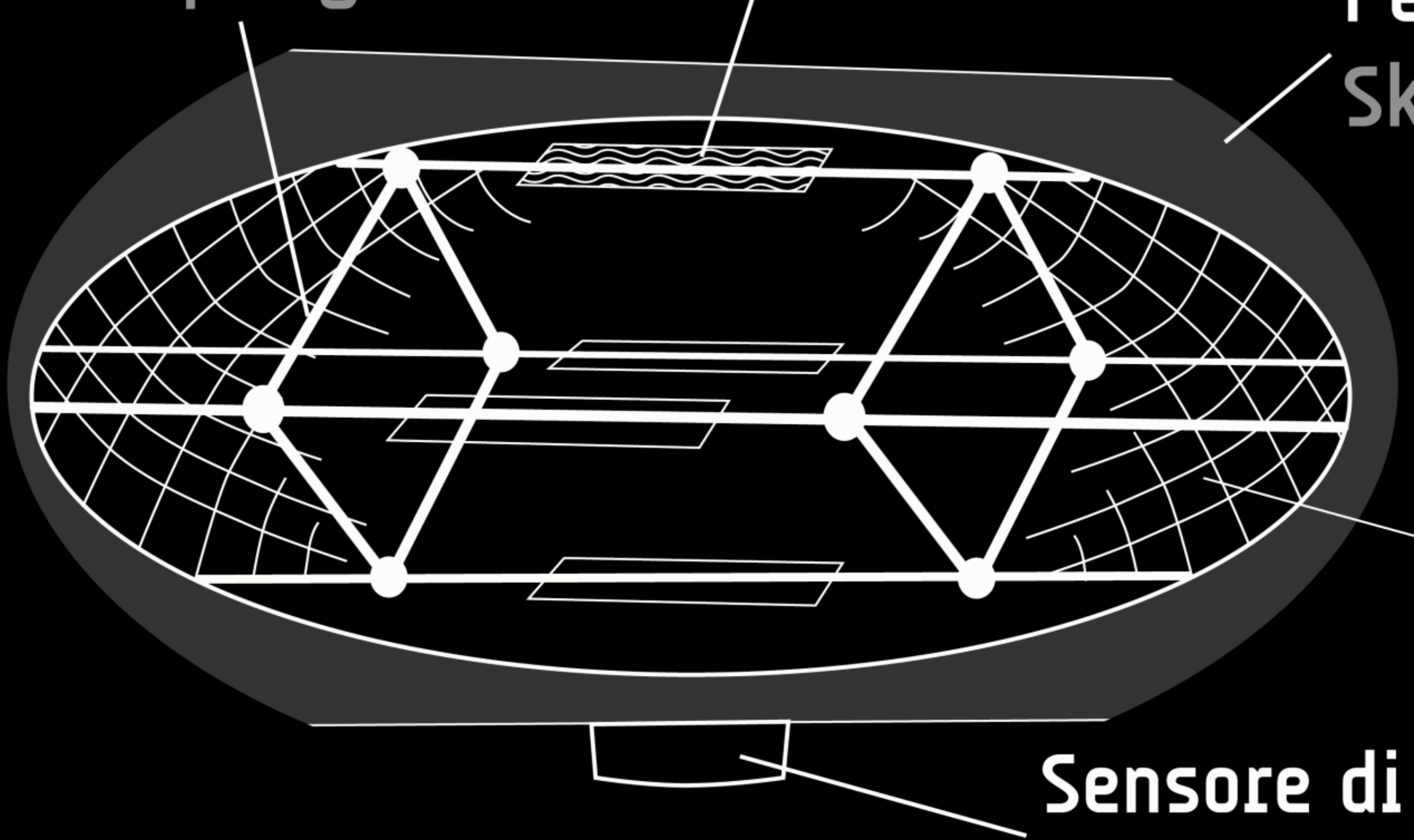


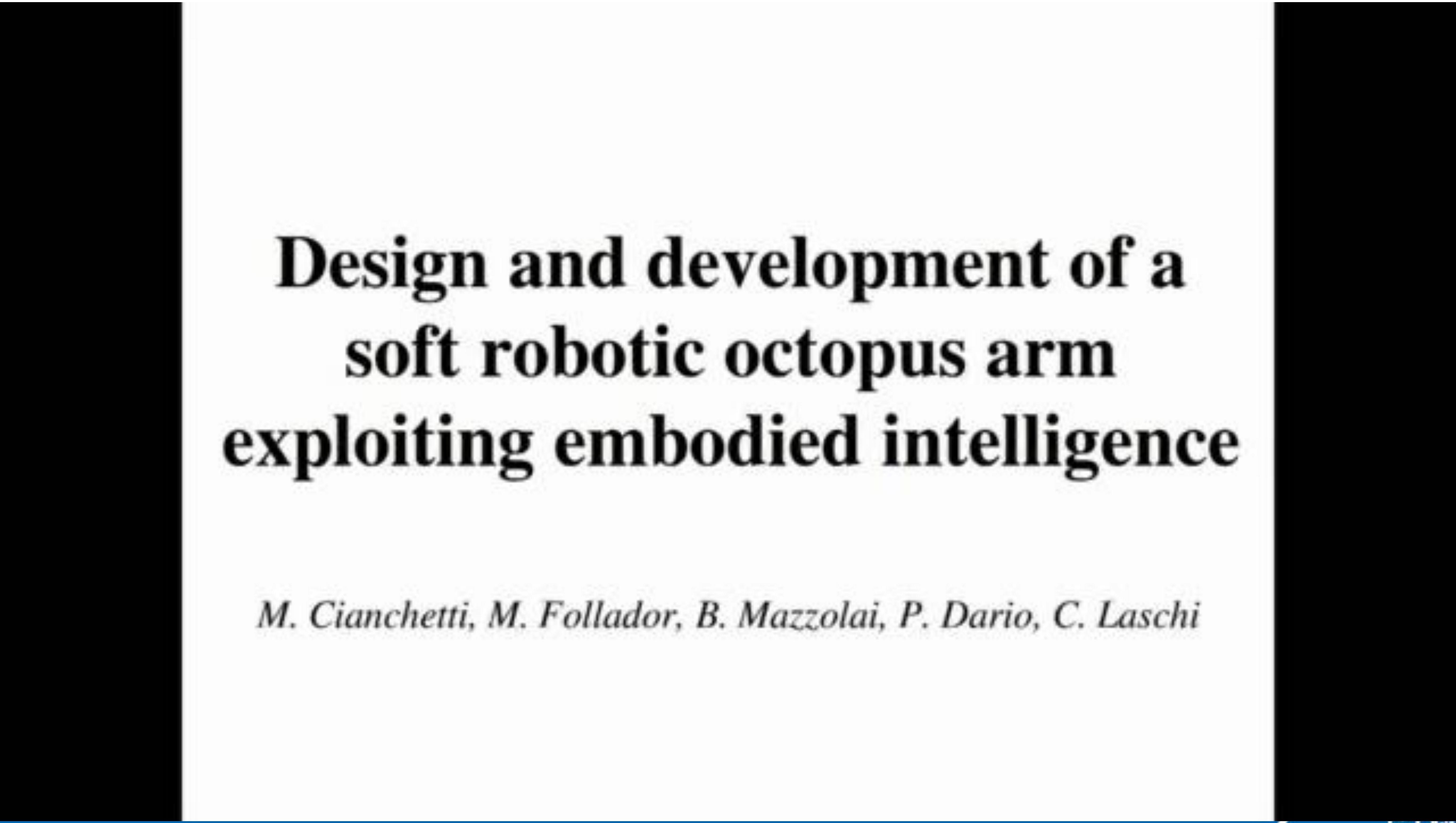
Image: Massimo Brega

Robotics muscolar hydrostat

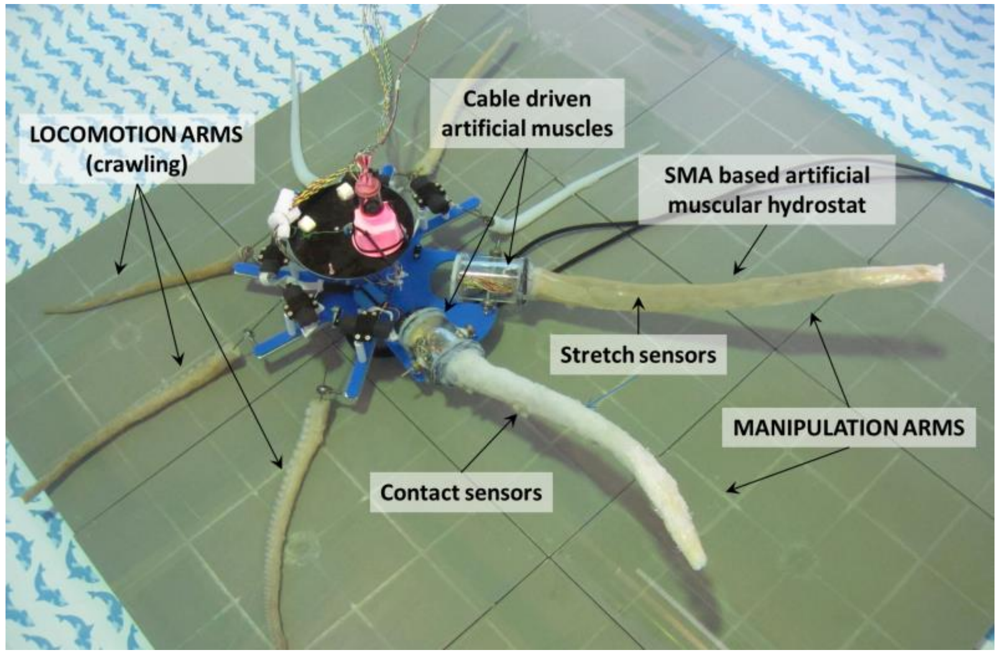


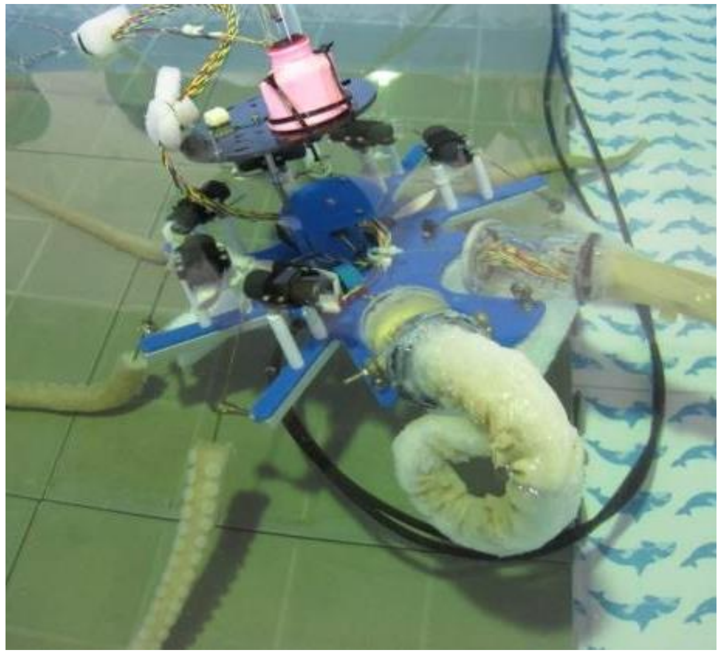


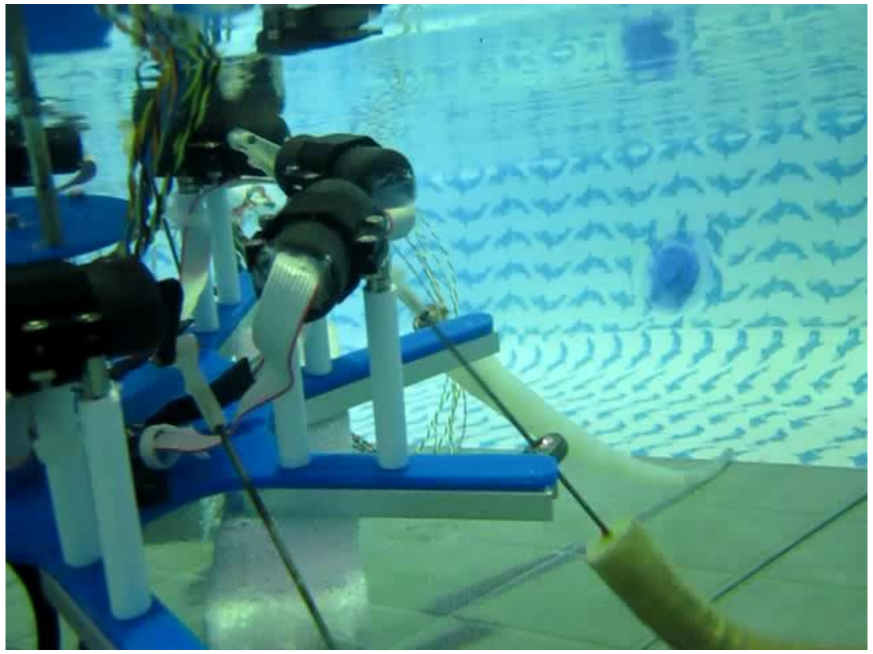
Octopus-like robot arm



OCTOPUS robot



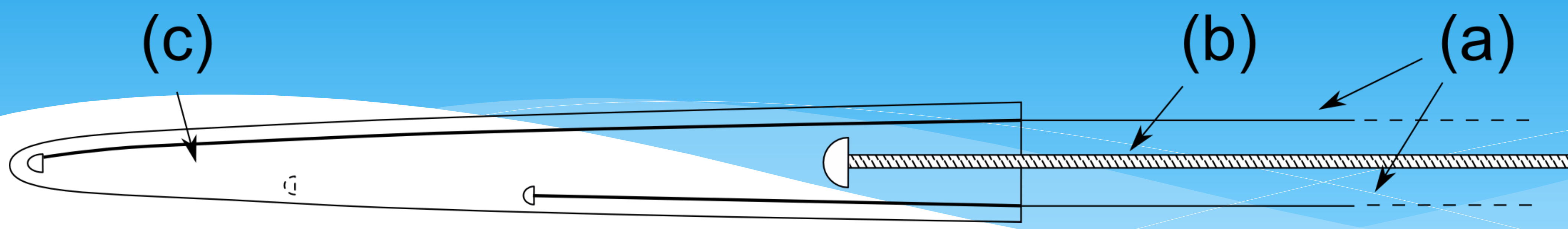


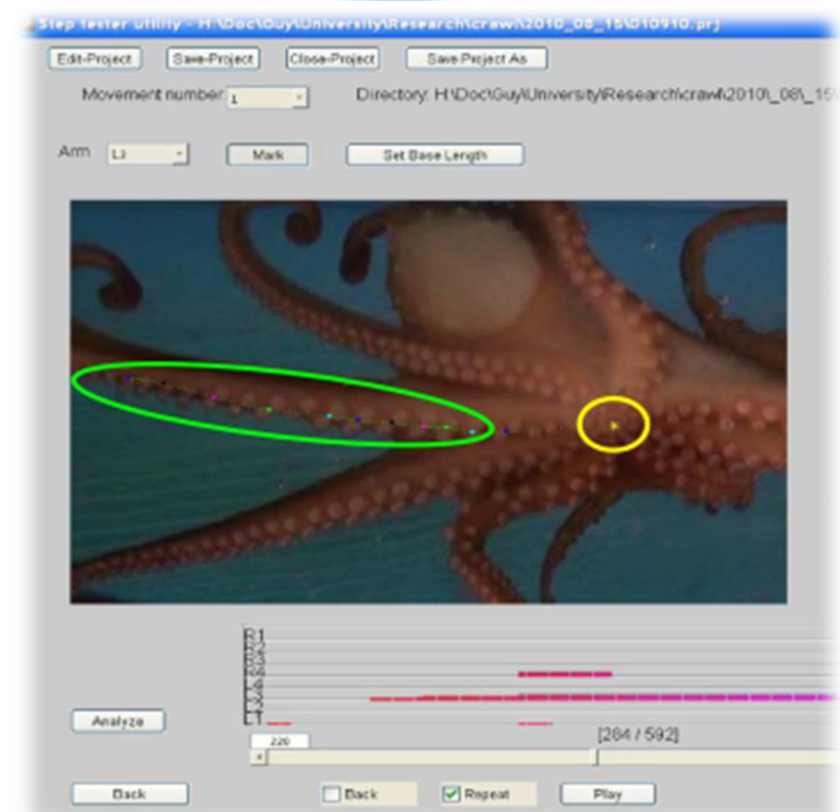


- Wide range of grasping capabilities
- Max force: 10.8 N
- Speed: typical 1.9 cm/s - max: 5 cm/s
- CoT: 2.9

Cianchetti M., Calisti M., Margheri L., Kuba M., Laschi C., “Bioinspired locomotion and grasping in water: the soft eight-arm OCTOPUS robot" , *Bioinspiration & Biomimetics*, in press

Octopus walking

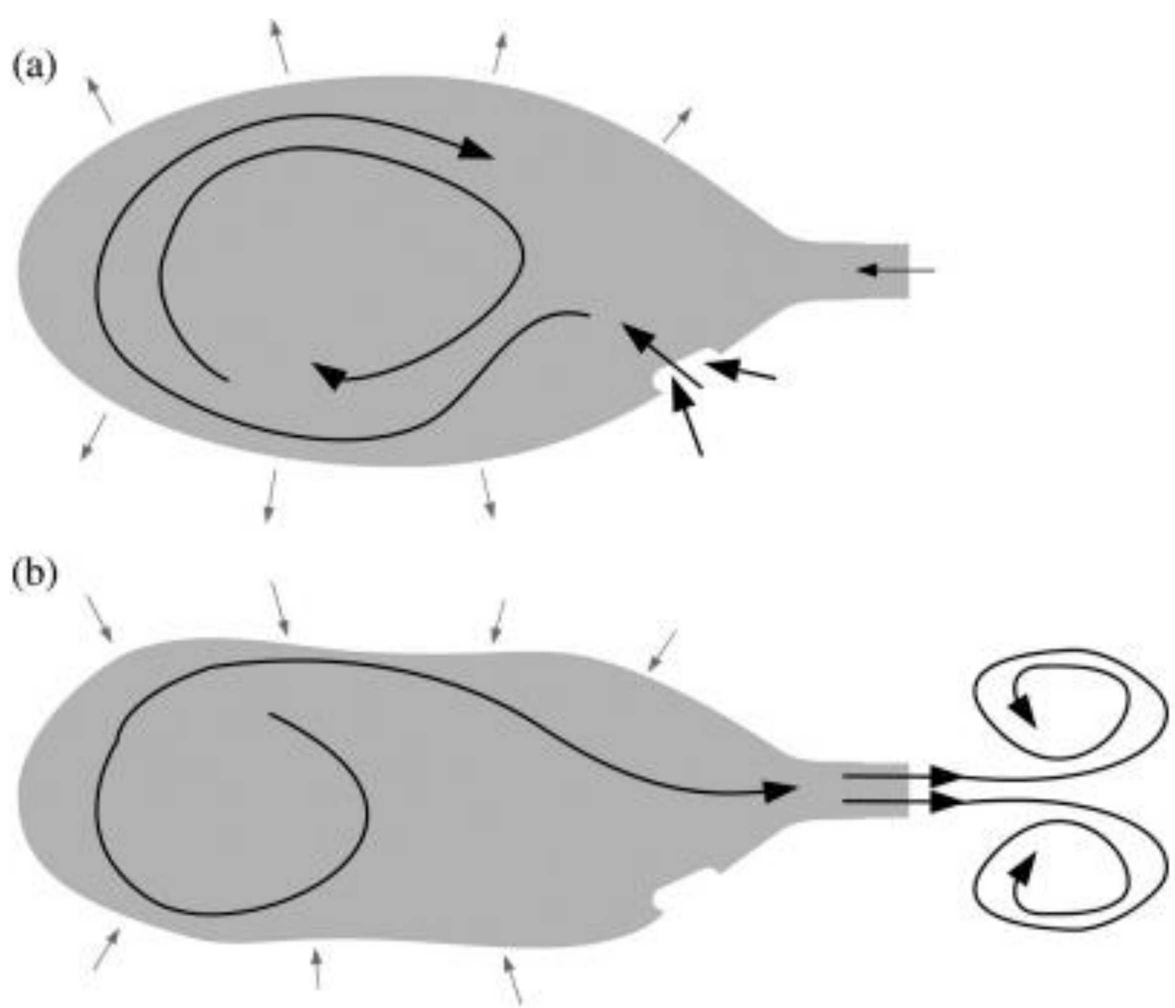




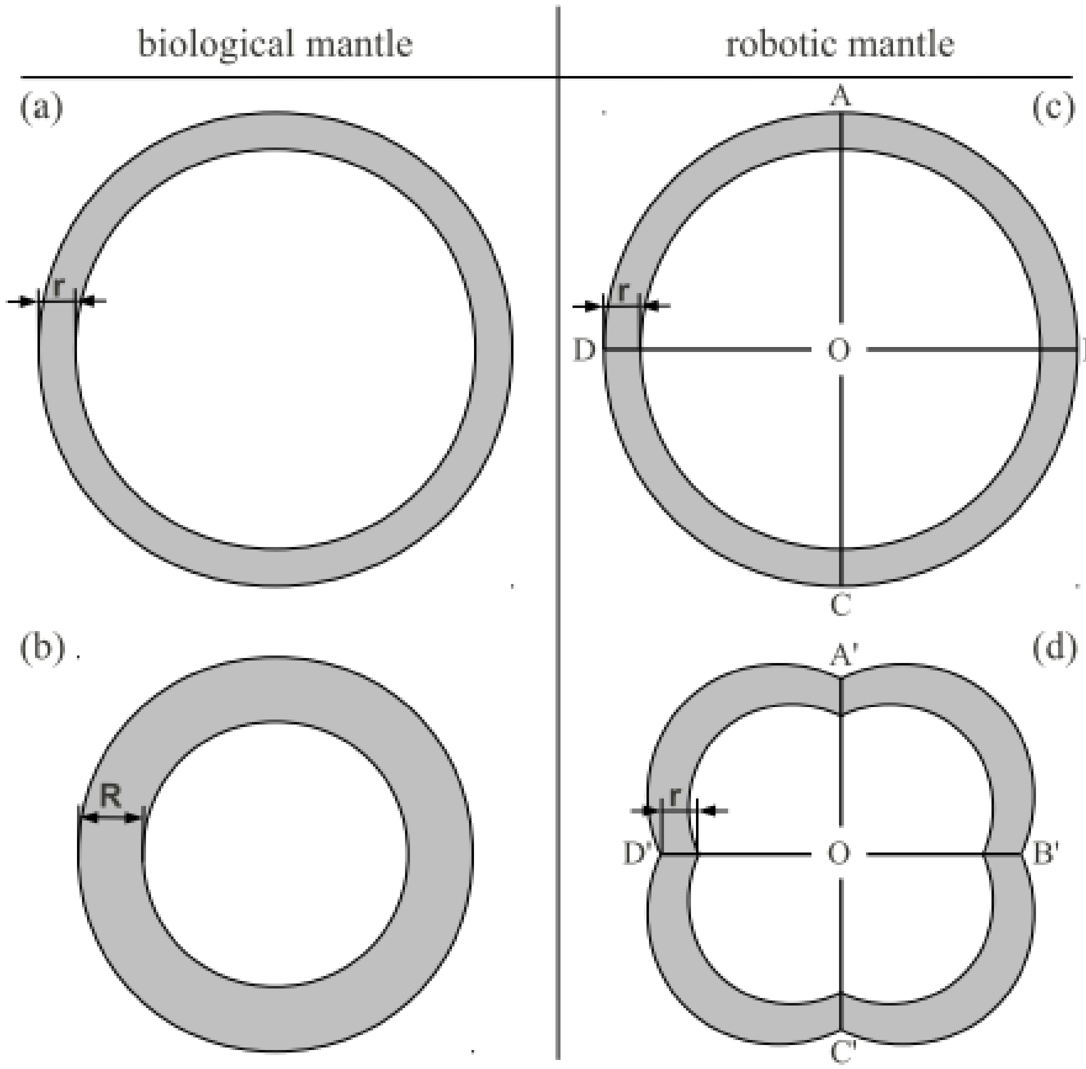
M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, P. Dario, "An octopus-bioinspired solution to movement and manipulation for soft robots", *Bioinspiration & Biomimetics*, Vol.6, No.3, 2011, 10 pp.

Pulsed-jet swimming in cephalopods

How does a cephalopod swim?



How can we translate it in a soft robot?



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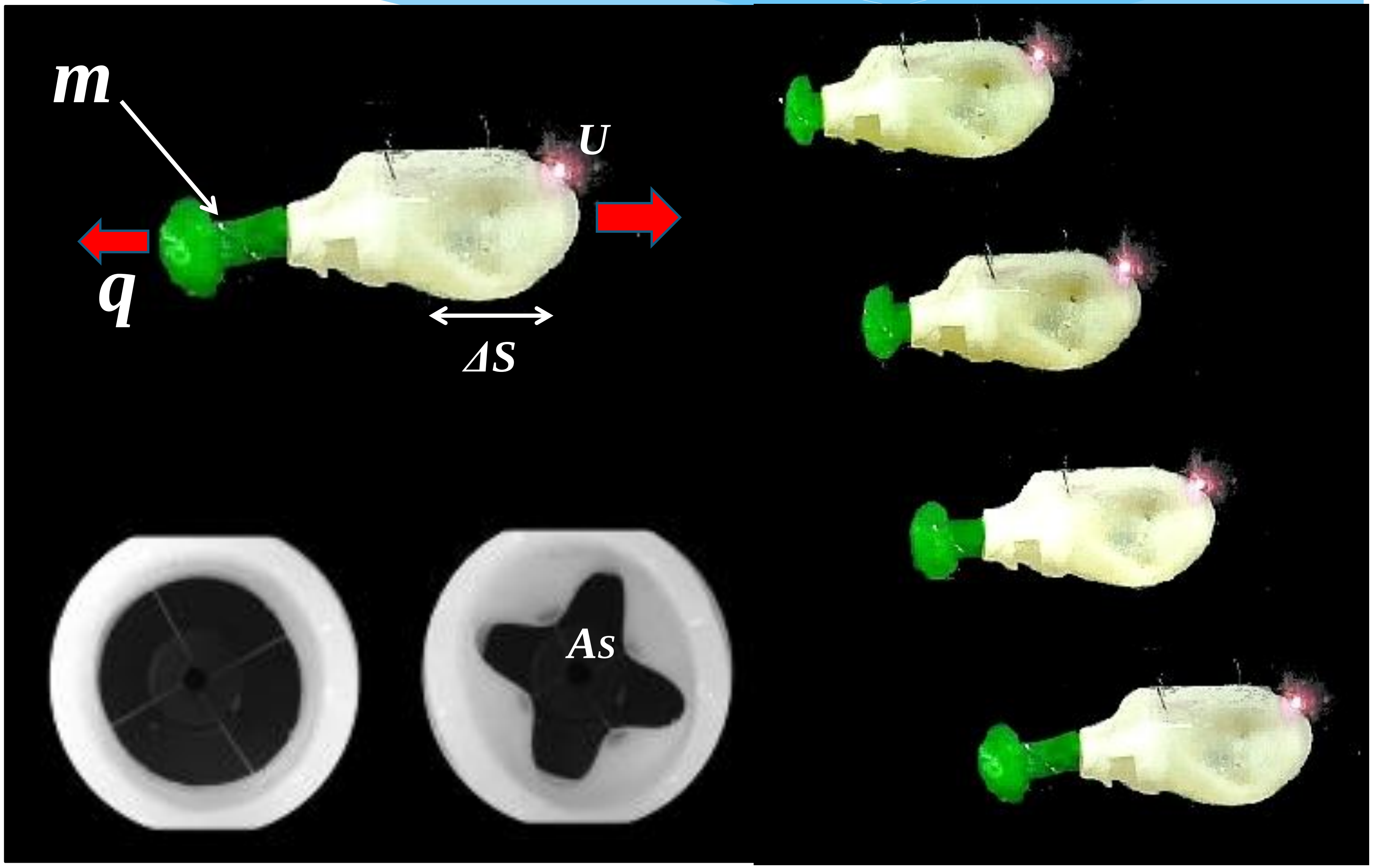
Giorgio Serchi F., Arienti A. and Laschi C. (2013) "Biomimetic Vortex Propulsion: Toward the New Paradigm of Soft Unmanned Underwater Vehicles", *IEEE/ASME Transactions on Mechatronics*, 18(**2**), pp. 484-493

Pulsed-jet swimming in cephalopods

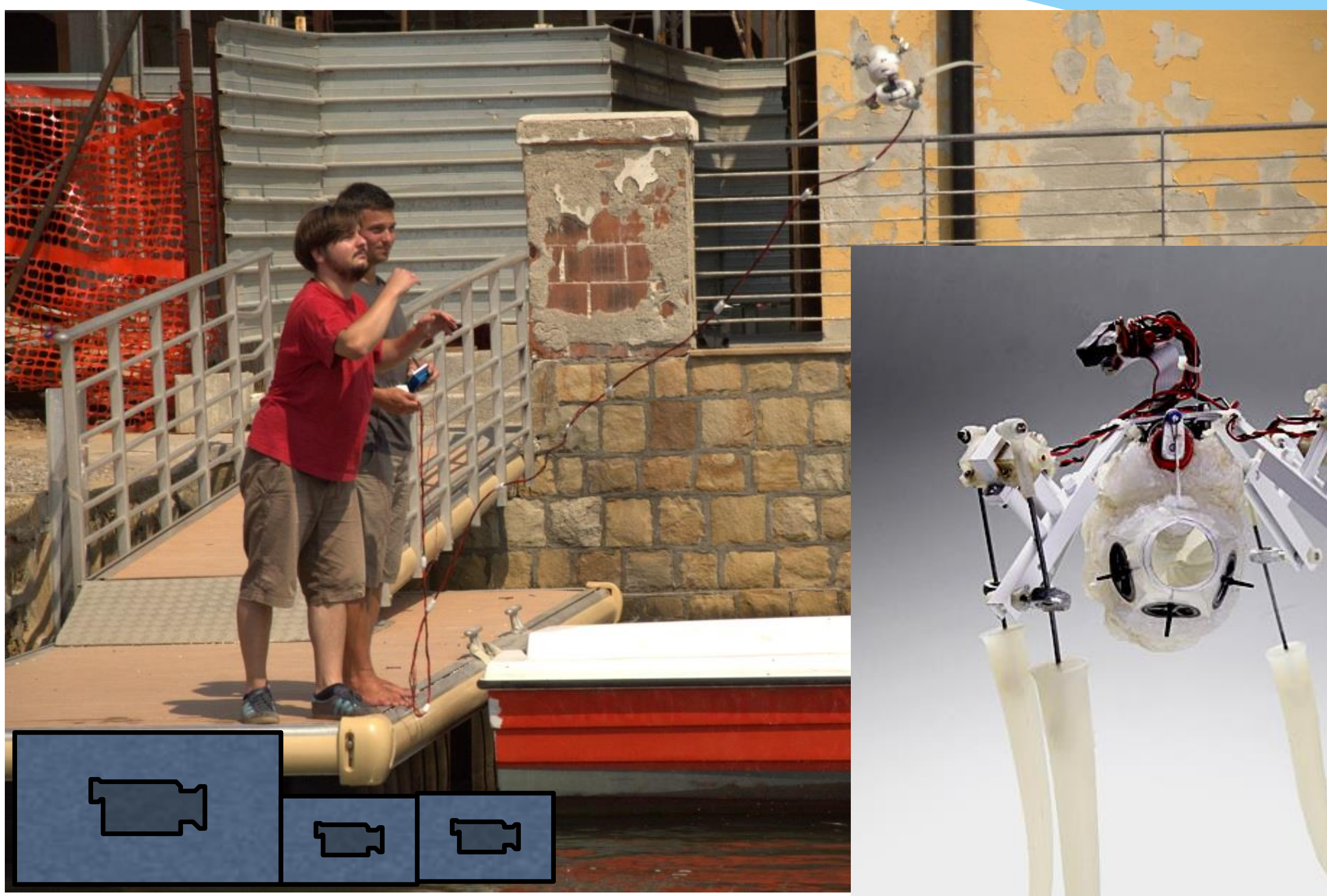
Mantle and siphon **morphologies** and **frequency** of the pulsed jet optimize propulsion, producing **ring vortexes** (in green)

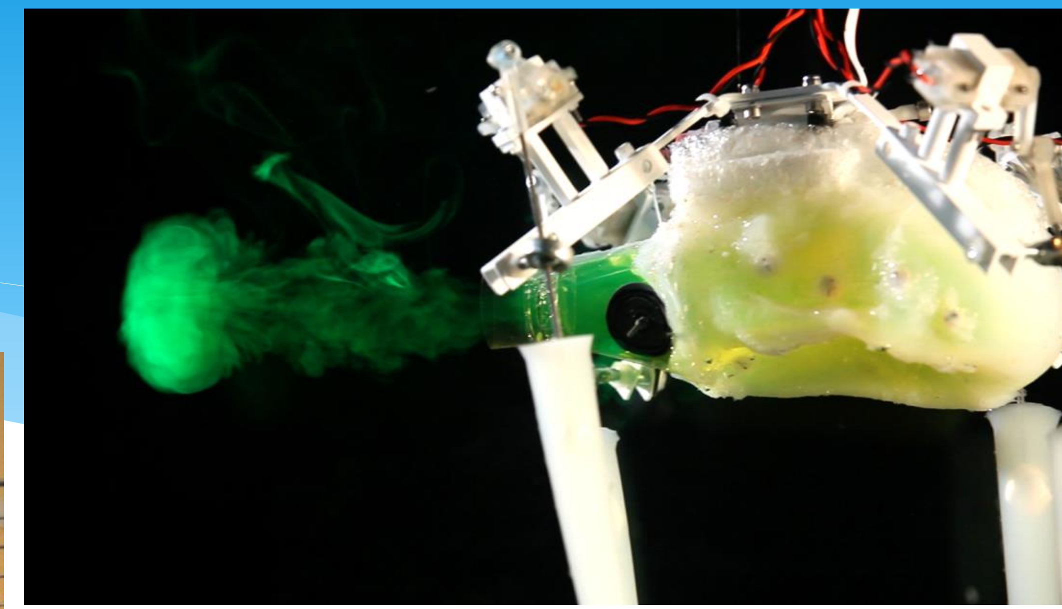


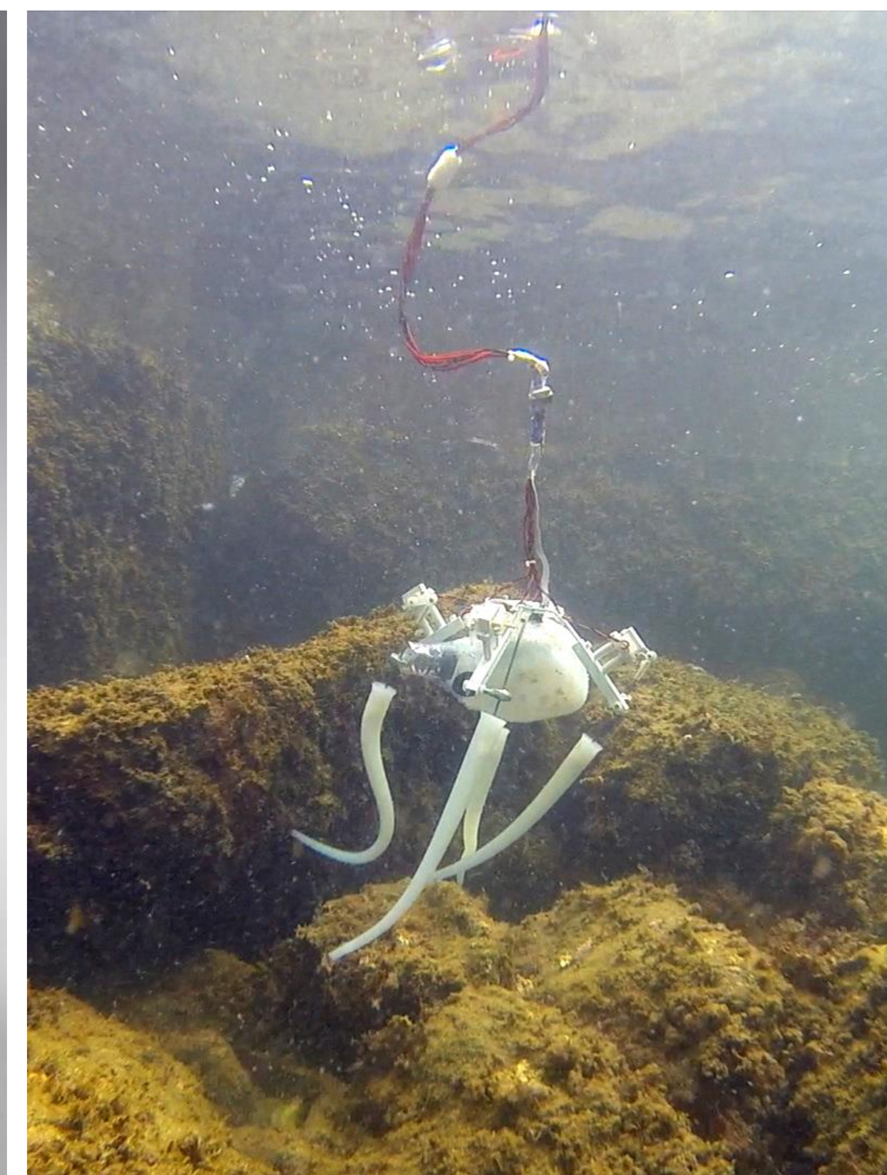
Giorgio Serchi F., Arienti A. and Laschi C. (2013) "Biomimetic Vortex Propulsion: Toward the New Paradigm of Soft Unmanned Underwater Vehicles", *IEEE/ASME Transactions on Mechatronics*, 18(**2**), pp. 484-493

Swimming and walking

First PoseiDRONE prototype







F. Giorgio Serchi, et al, 2013 OCEANS

M. Giorelli et al, 2013 OCEANS

A. Arienti et al, 2013 OCEANS

M. Calisti et al, 2013 SoftRob

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Self-stabilized locomotion: complex design for simple control

- Octopus pushing-based locomotion strategy
- Just one motor per leg, soft silicone limbs
- Complex, dynamic, self-stabilized behaviors emerge from a simple open-loop actuation

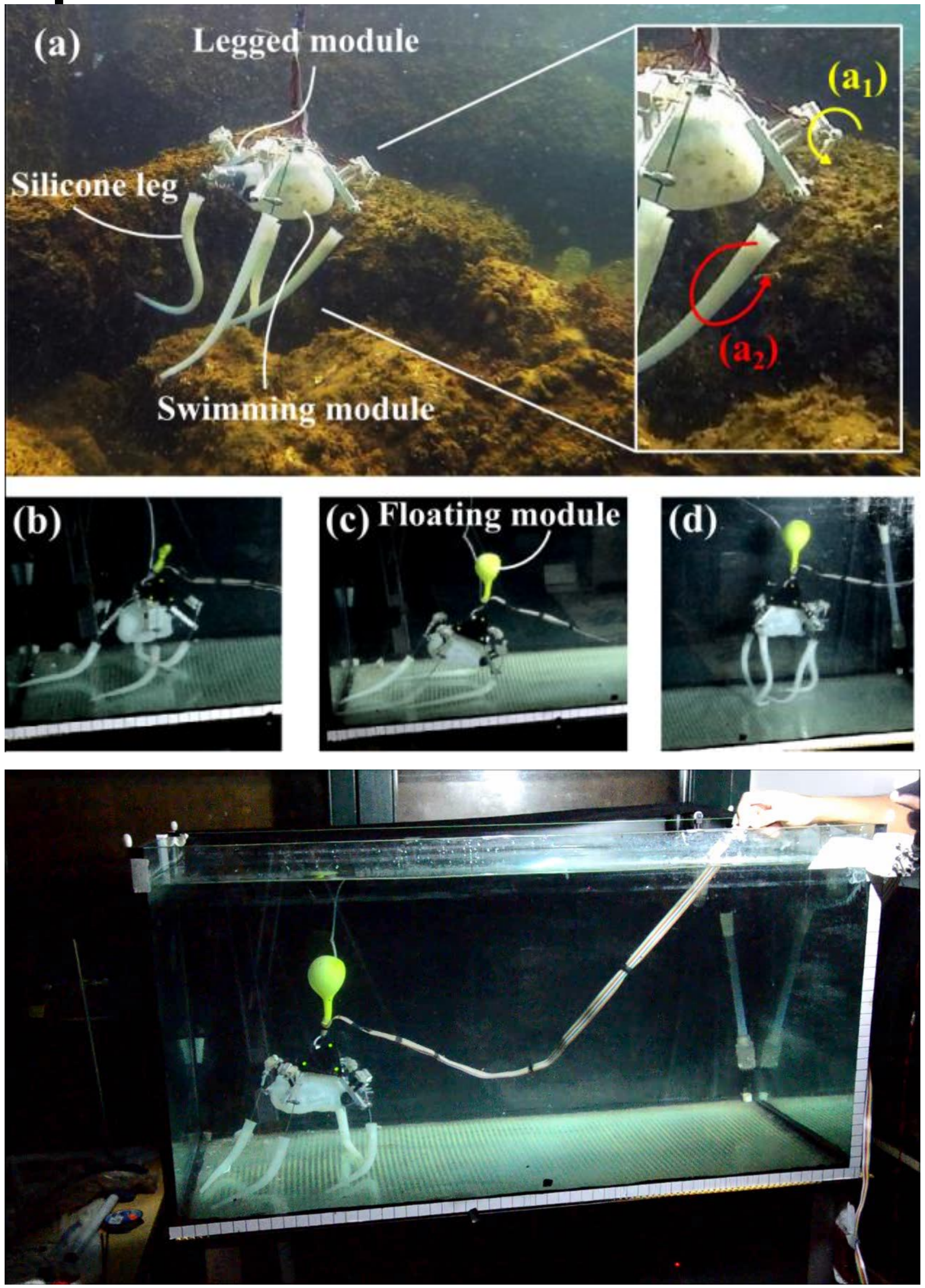
  → <u>Embodied intelligence</u>

<u>Evolutionary design:</u>

- From carefully hand-designed solutions to the systematic production of embodied solutions
- Adaptation to the environment, exploitation of the complex dynamical coupling between body and environment
- Possibility to <u>discover</u> and suggest elaborate solutions, beyond the skills and creativity of human designers (human-competitive design)

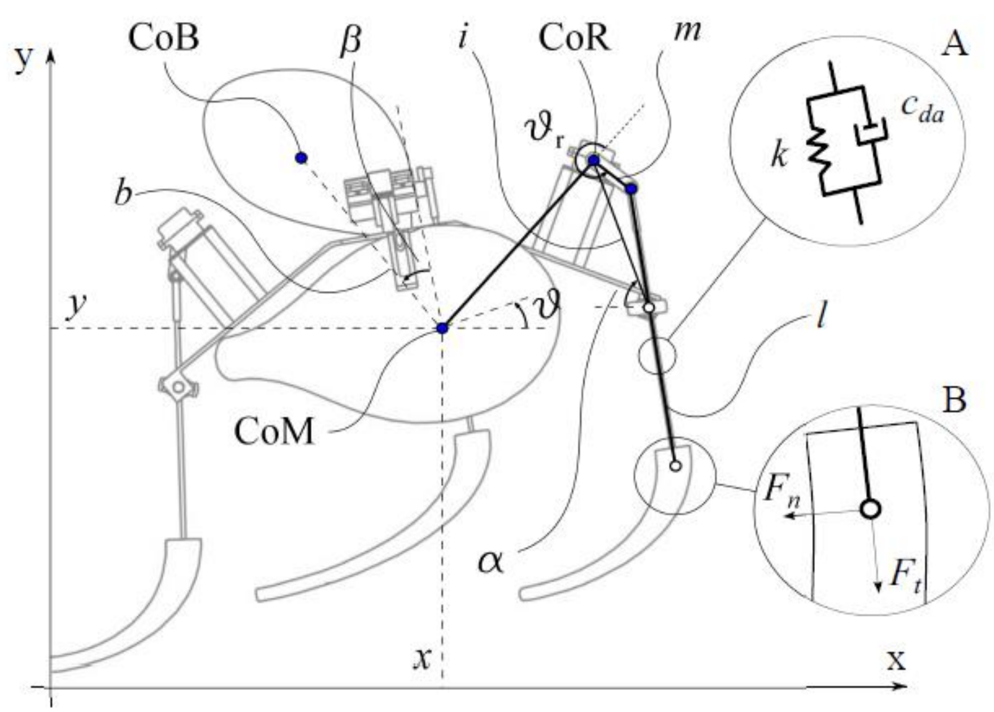
<u>Morpho-functional robot:</u>

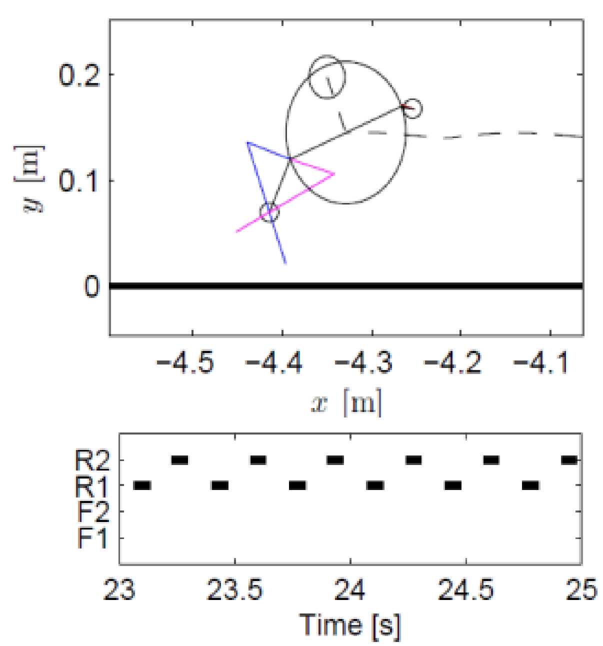
- Possibility to control slight morphological changes to achieve a diversity of behaviors

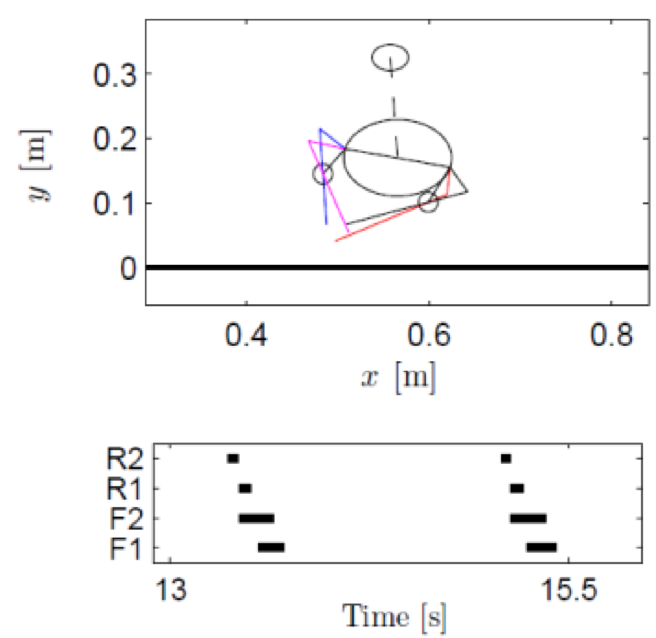


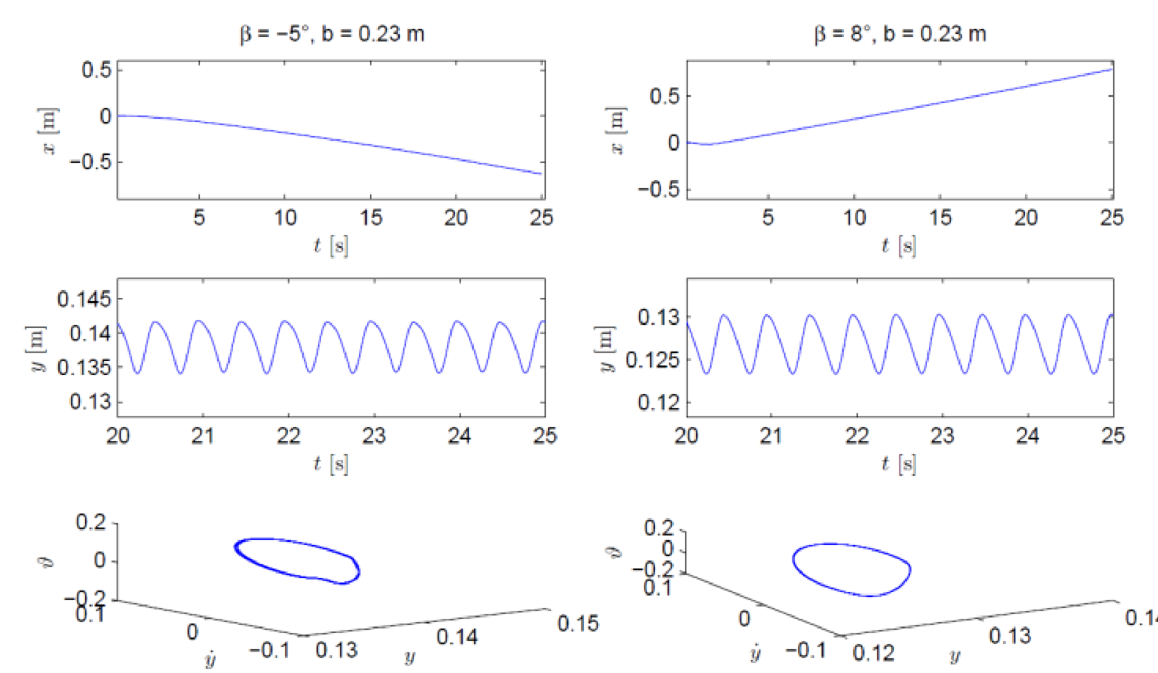
Self-stabilized locomotion

- Evolutionary algorithms are applied to discover interesting morphologies capable of highly dynamic gaits
- Elaborated behaviors are produced, featuring a highly dynamic coupling with the environment
- It is possible to switch among different gaits by controlling slight morphological changes
- e.g. by changing just one morphological parameter, the speed and the direction of the locomotion can be









Corucci, F., Calisti, M., & Laschi, C. (2014). Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot (under review)

Calisti, M., Corucci, F., & Laschi, C (2014). Underwater legged locomotion of a bio-inspired robot (unpublished)

Calisti, M., Corucci, F., Arienti, A., & Laschi, C. (2014). Bipedal Walking of an Octopus-Inspired Robot. In *Biomimetic and Biohybrid Systems* (pp.

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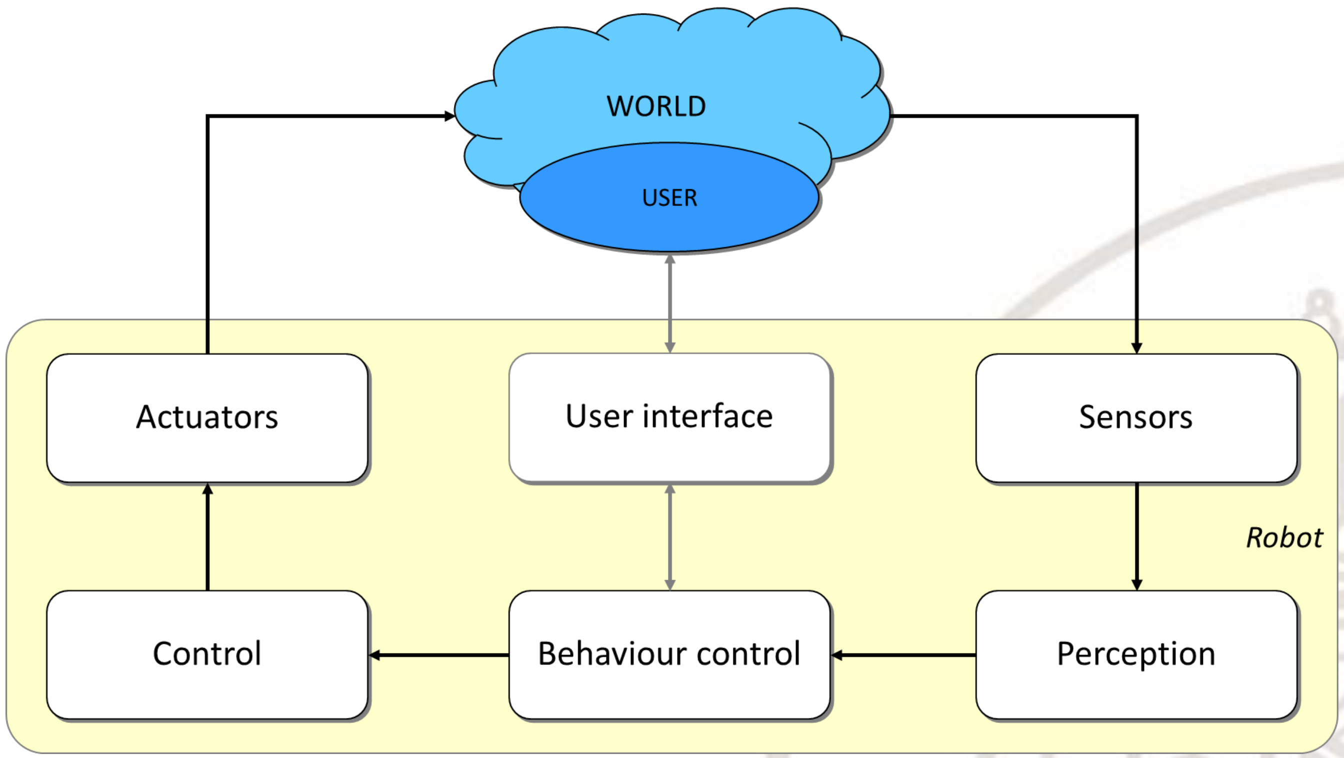
Course syllabus



- Robot mechanics and kinematics
- Robot sensors
- Robot control
- Robot vision
- Architectures for behaviour control
- Robot navigation techniques

- Bioinspired senses
- Humanoid robotics
- Neurocontrollers
- Embodied intelligence & soft robotics
- Evolutionary algorithms in robotics

Course and exam modality

- Classes till the end of April
- Hands-on projects till the end of May, at the BioRobotics Institute

- Exam = project presentation + Oral exam
- Mark = average of the two marks

- Written test at the end of classes (early/mid-May), which may replace the oral exam, if the student accepts the mark obtained.

Exam

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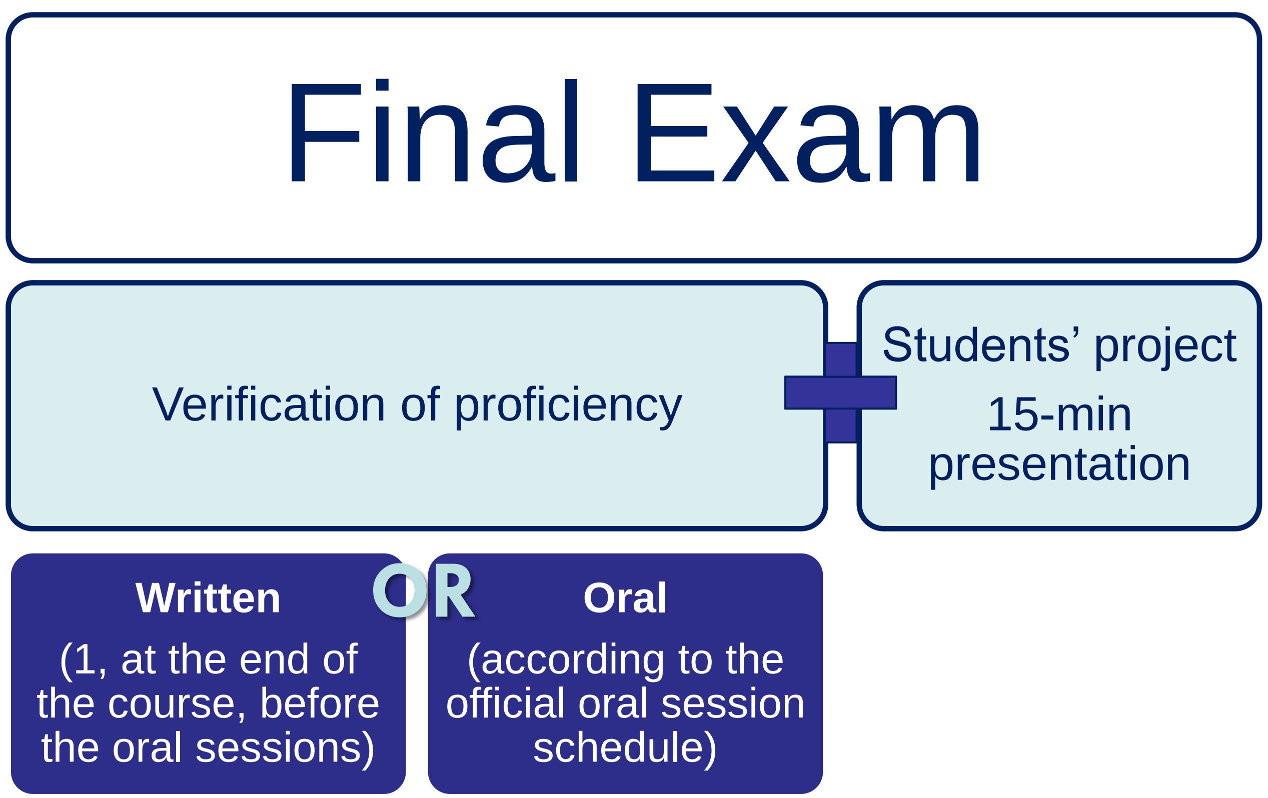
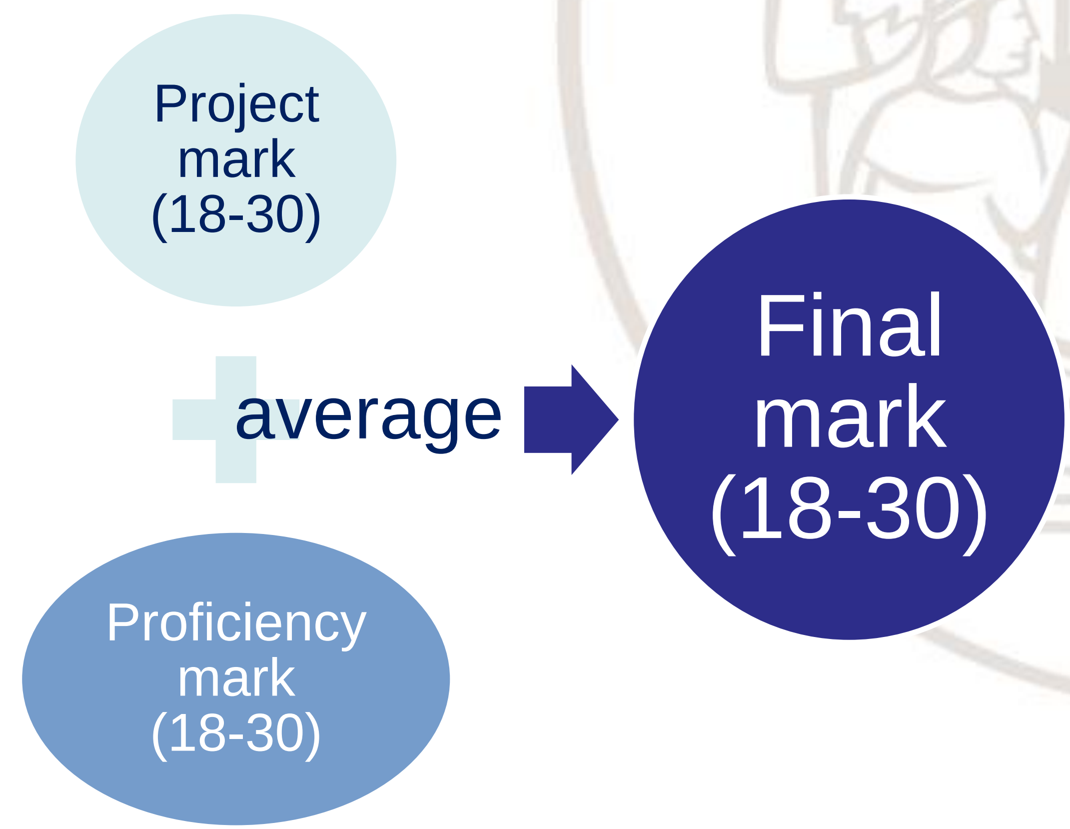
- Presentation of the **project work**, with slides and/or demos, 15 to 20 minutes
- Optional **written test**, 1 date at the end of the course, before the oral sessions
- **Oral test**, if the student does not choose the written test or if the students does not accept the written test mark





Practical information

Please send an email to:

cecilia.laschi@santannapisa.it

with subject: Robotics Course

Course materials:

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