Master in Bionics Engineering
University of Pisa and Scuola Superiore Sant'Anna

Human and Animal Models for BioRobotics

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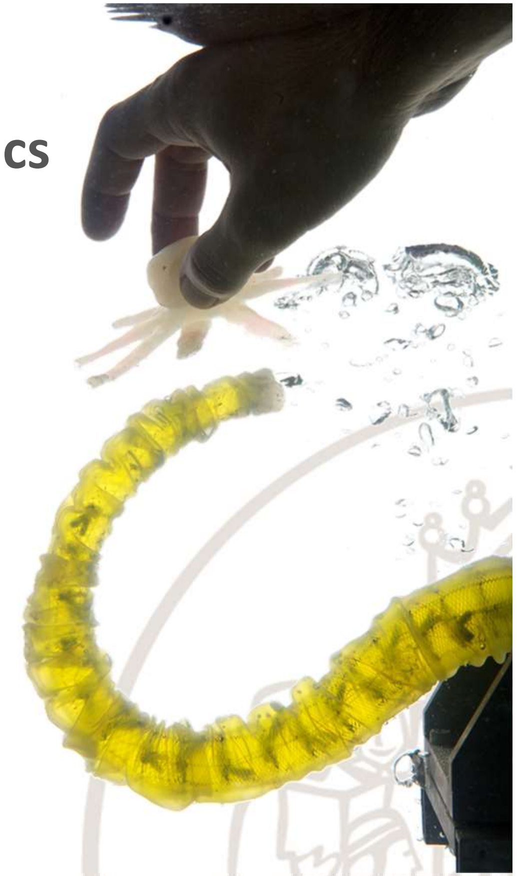

Introduction to bioinspired robotics

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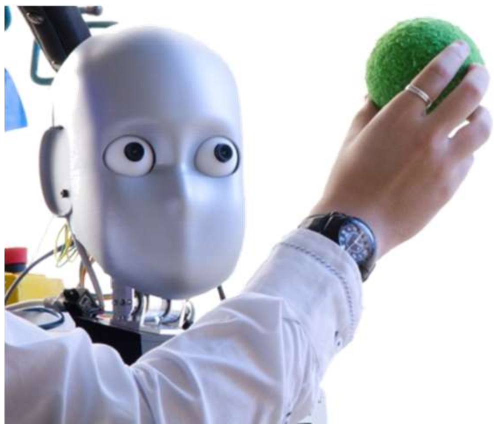


Lessons from Nature

Bioinspiration in robotics

Bioinspiration

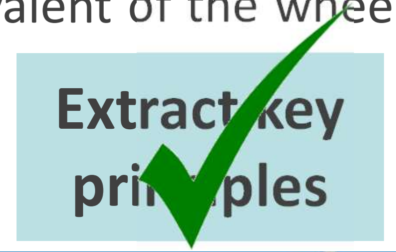
Nevertheless...   ...natural selection is not engineering

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

Too complex?

Rather too simple?

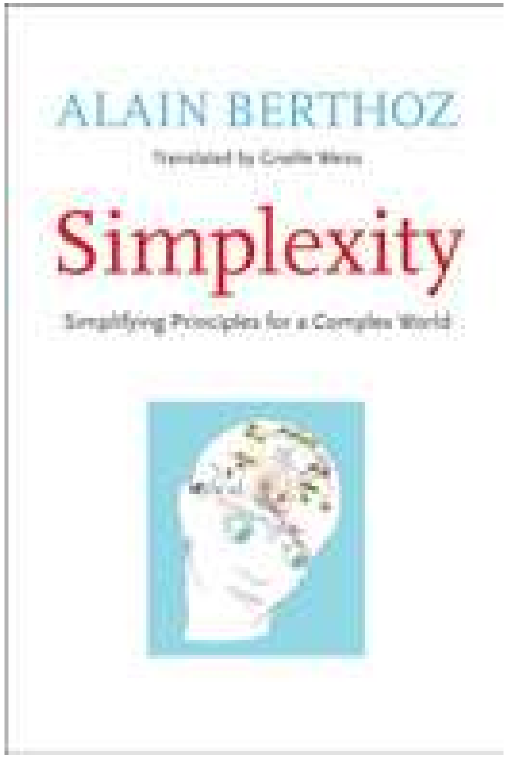
In robotics, we need **simplifying principles** for control and behavior

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:

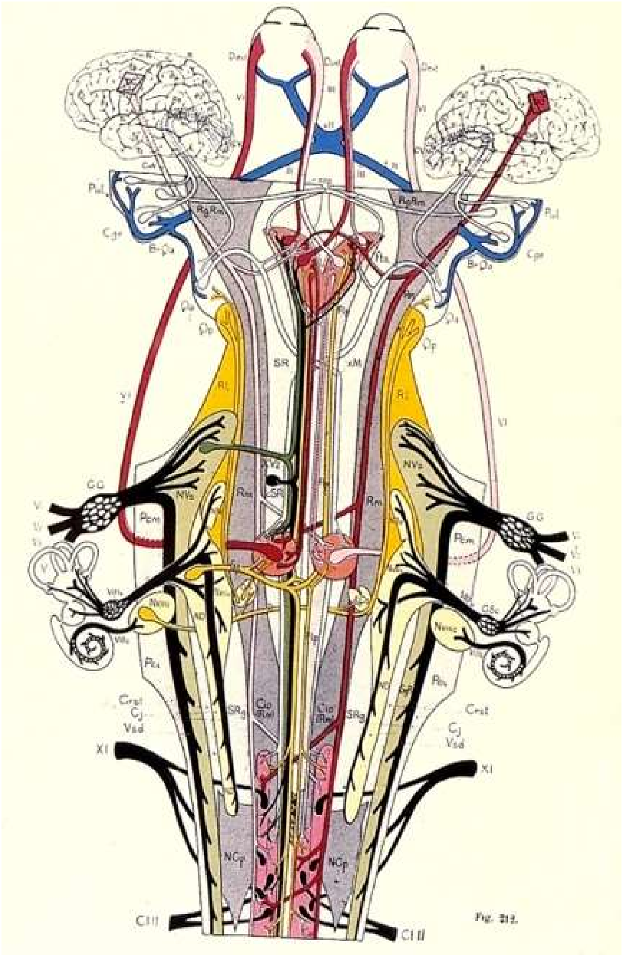
- Multiple reference frames
- Anticipation and prediction
- Inhibition to select and adapt
- Redundancy
- Biomechanics and internal models
- Synergies
- Laws of motion
- Emotion

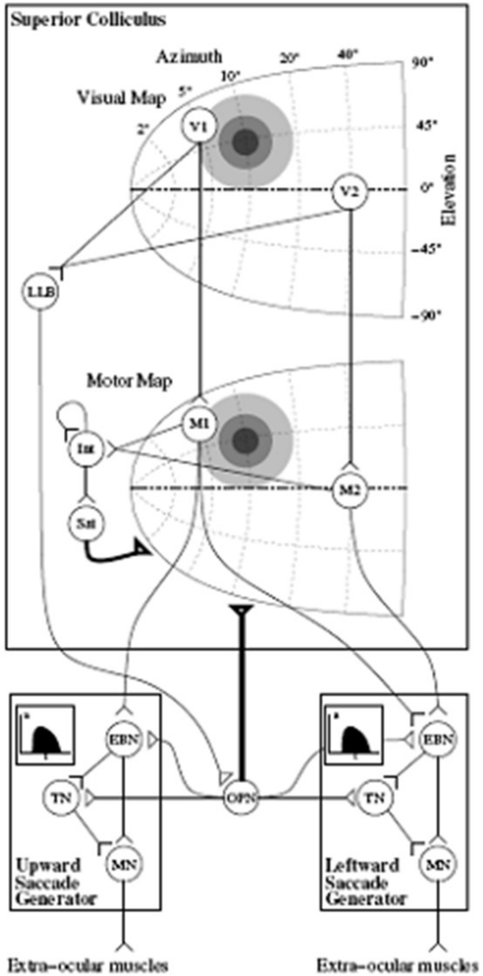


A. Berthoz (2012), *Simplexity: Simplifying principles for a Complex World*. Yale University Press.
U. Alon (2207), “Simplicity in Biology”, *Nature*, 446(7135):497

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.

Summary of bioinspired approaches to robotics (in this course...)

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Robot vision

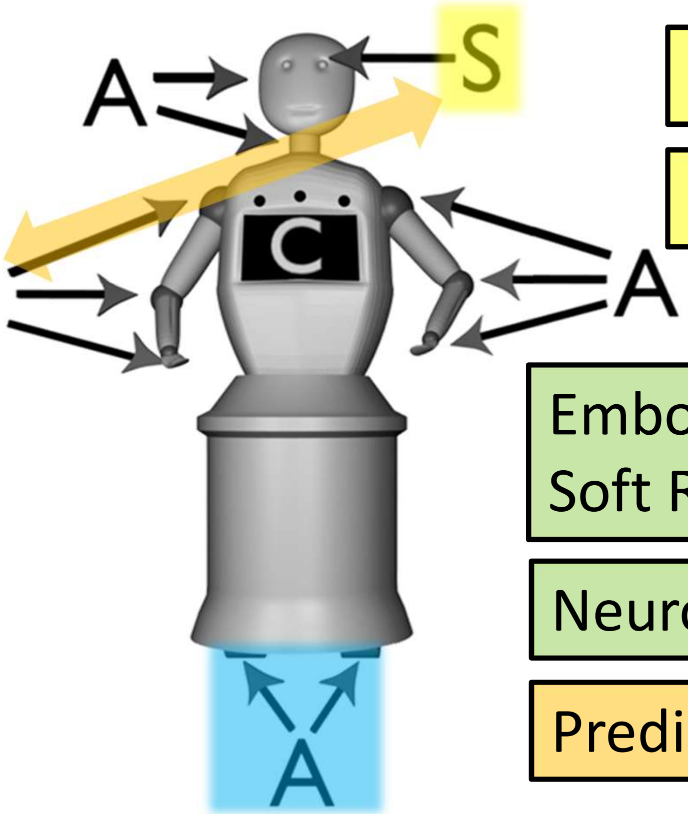
Robot sensors

Robot mechanics and kinematics

Robot control

Robot behaviour

Robot navigation



Bioinspired vision

Vestibular system

Embodied Intelligence, Soft Robotics

Neurocontrollers

Predictive behaviour

Bioinspired navigation, Soft locomotion

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Summary of bioinspired approaches to robotics (in this course...)

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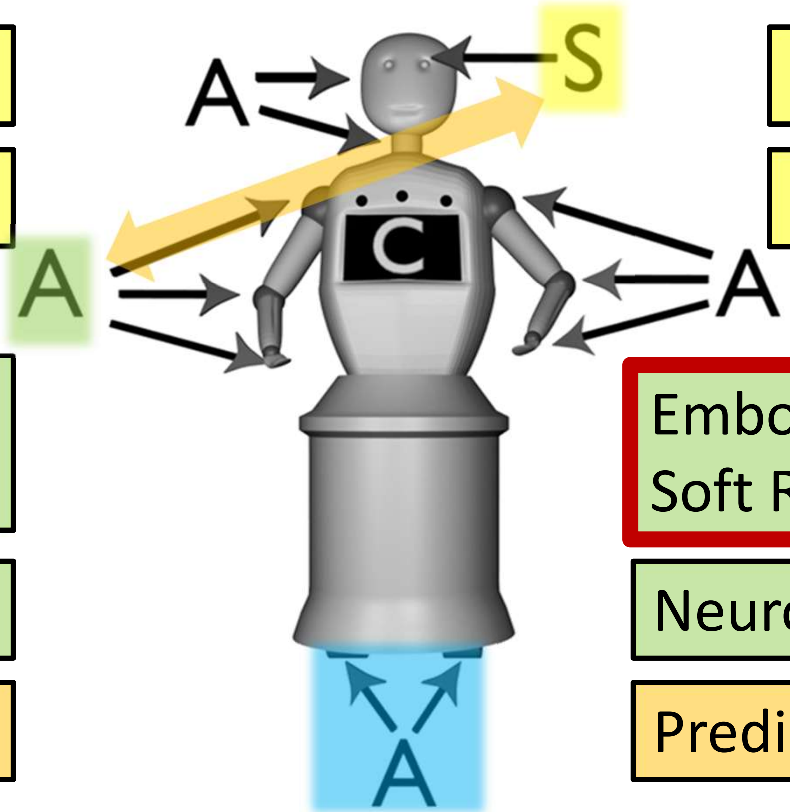

Bioinspired vision

Vestibular system

Embodied Intelligence, Soft Robotics

Neurocontrollers

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Bioinspired navigation, Soft locomotion

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Embodied Intelligence: the modern view of Artificial Intelligence

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

Properties of complete agents

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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

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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

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.

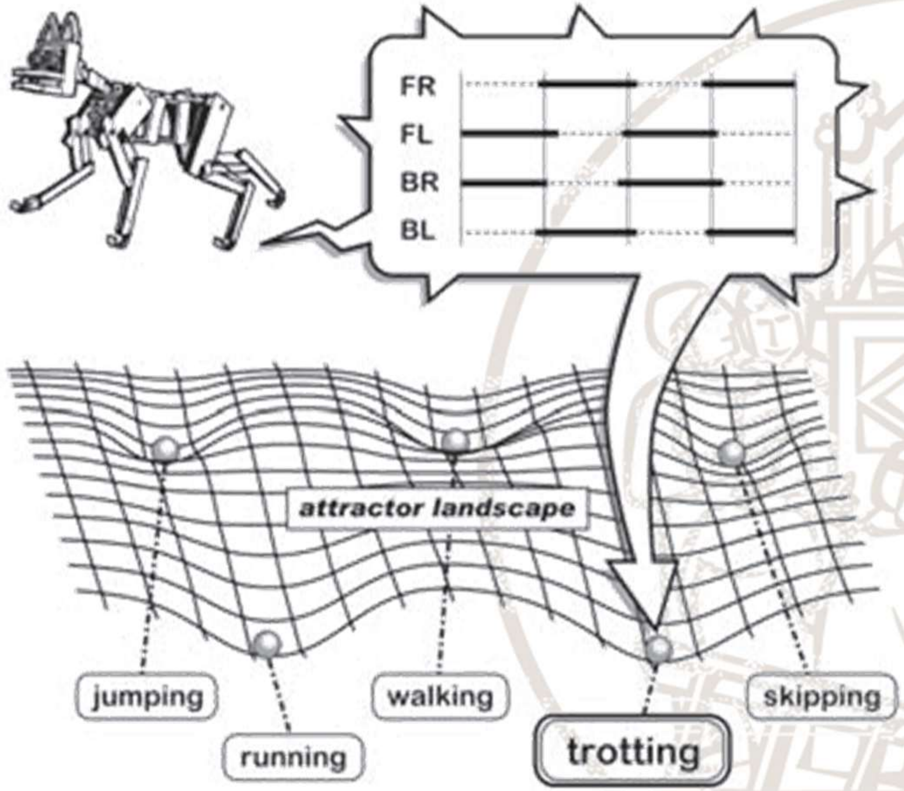
Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

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.

Properties of complete agents

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

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.

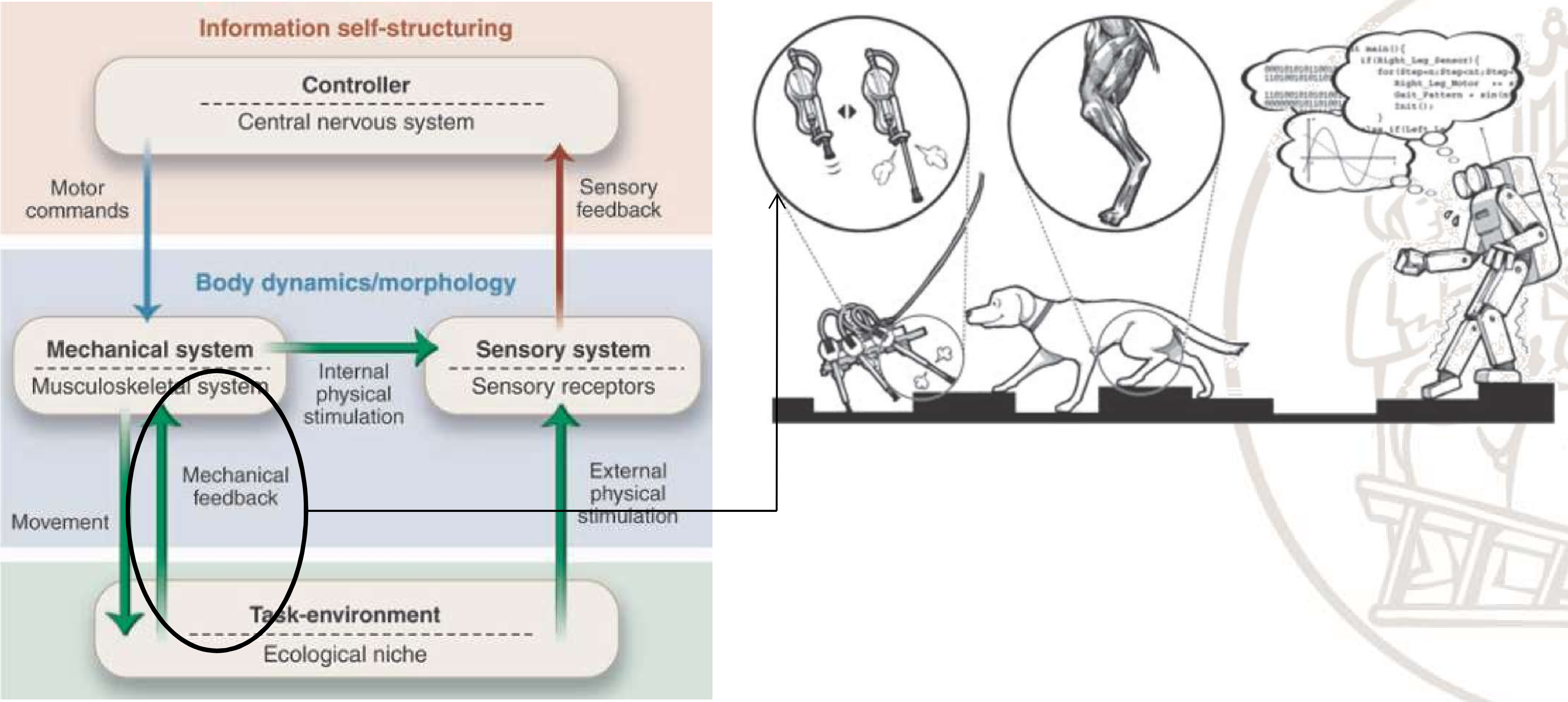
An example is the fact that the human leg’s muscles and tendons are elastic so that the knee, when the leg impacts the ground while running, performs small adaptive movements without neural control.

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

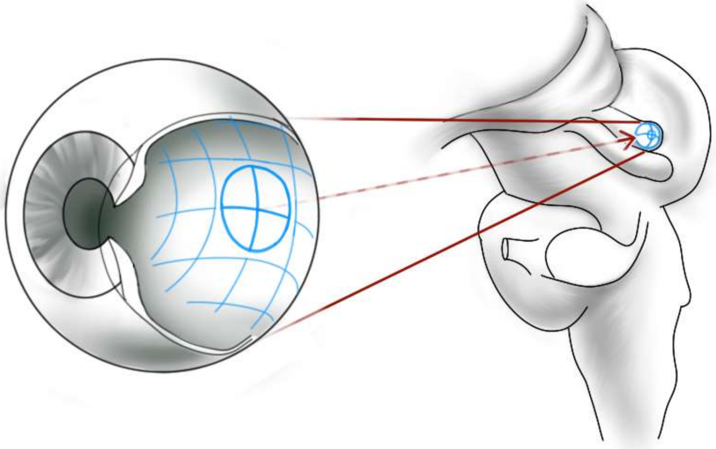
Morphological computation



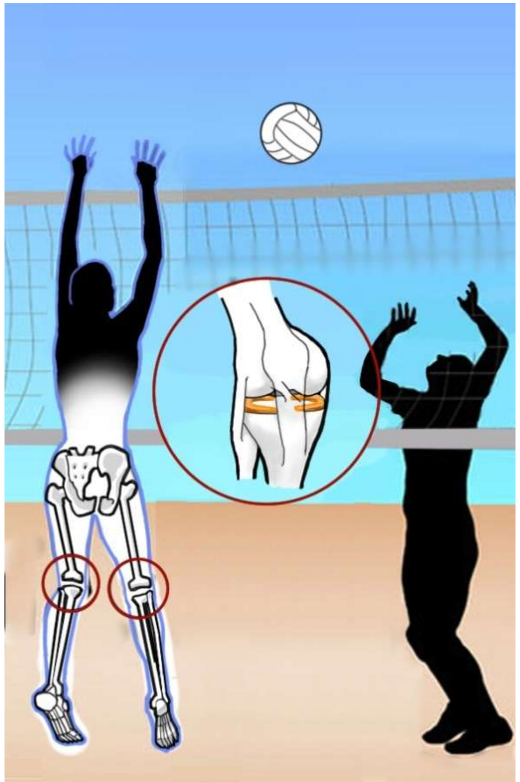
Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

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:

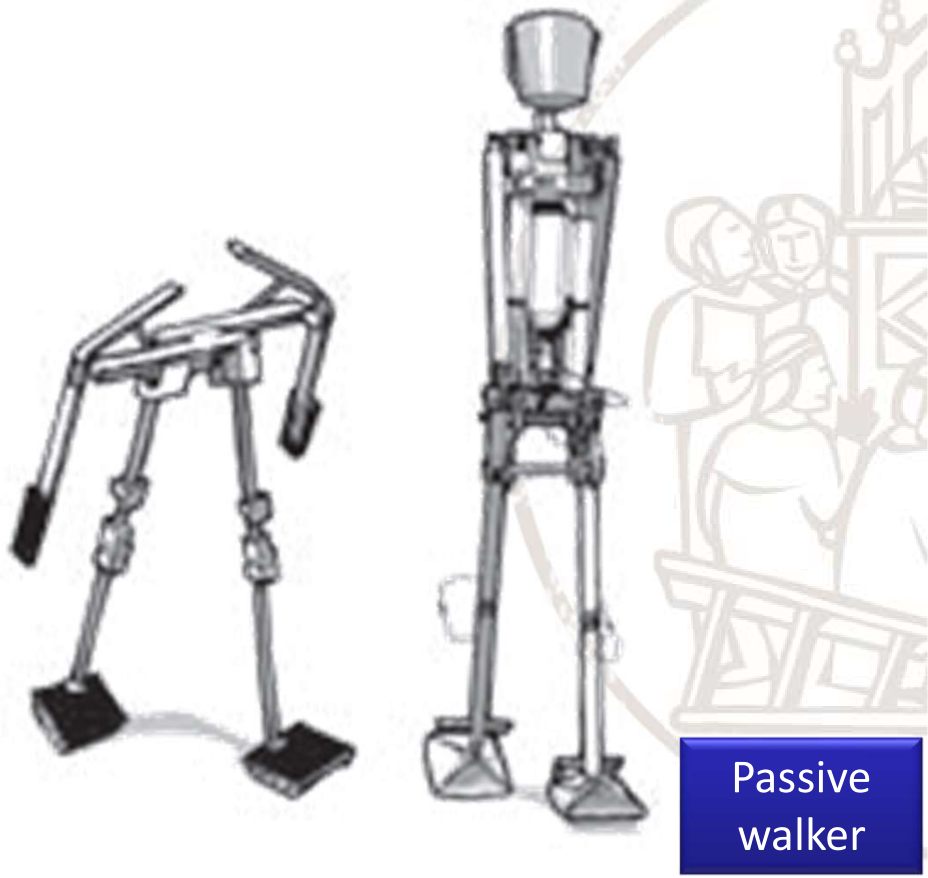
- think about the complete agent behaving in the real world

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

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'



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

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

Agent Design Principle 5

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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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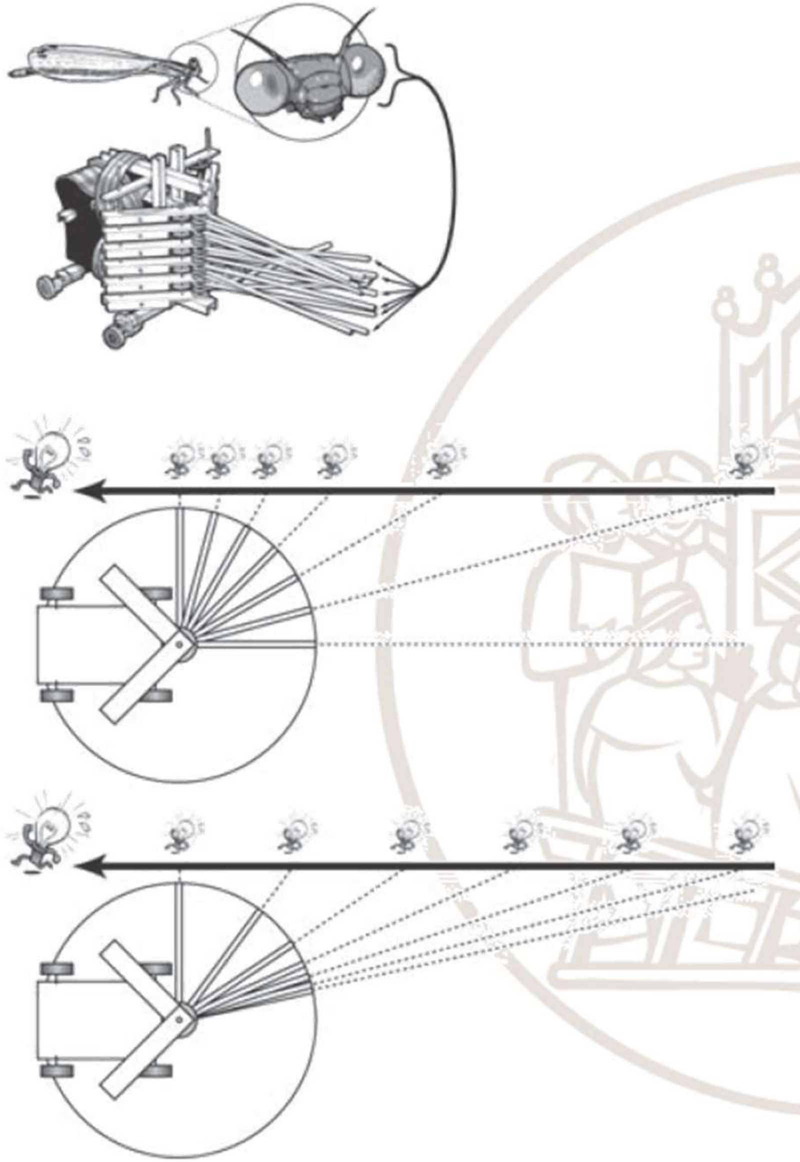
Ecological balance:

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

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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

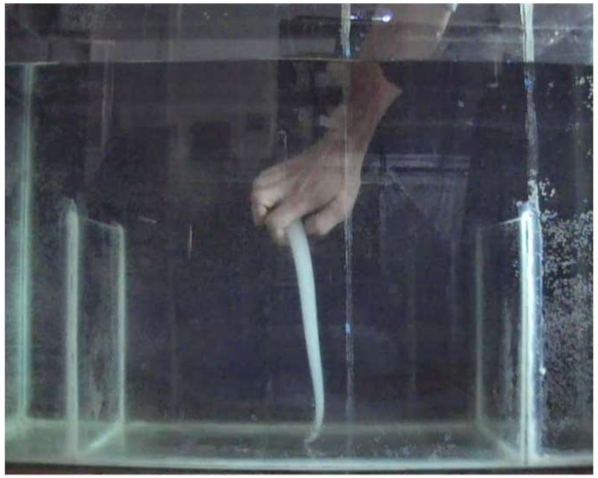
Value:

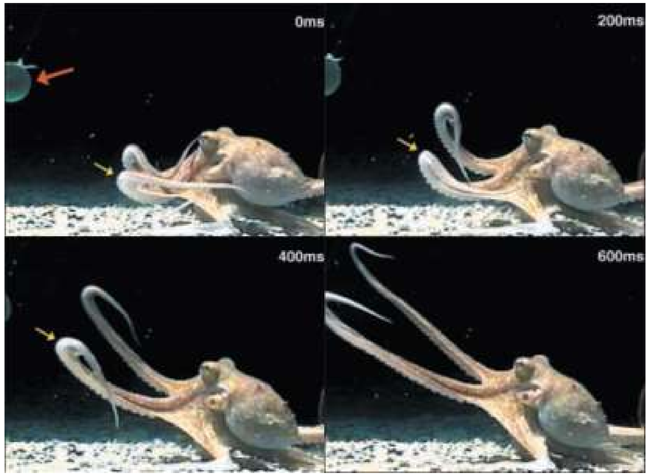
agents are equipped with a value system which constitutes a basic set of assumptions about what is good for the agent

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

Simplifying principles in reaching

The octopus arm embodied intelligence



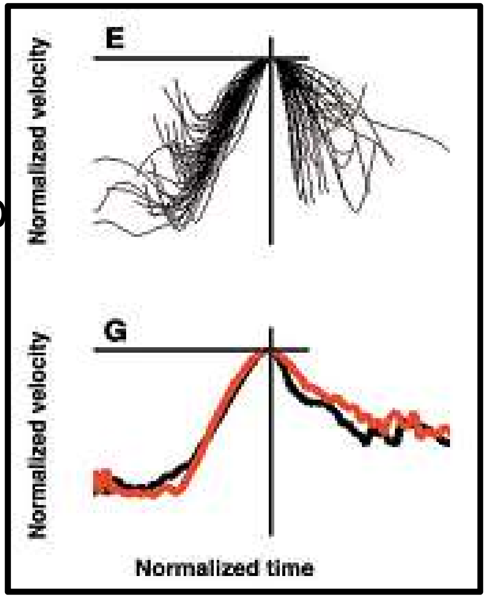


- stiffening wave from base to distal part, that can start from any part of the arm;
- movement executed in about 1 second, velocities in the range of 20–60 cm/s;
- control divided between central and peripheral: from brain: **3 parameters** (yaw and pitch of arm base and peak velocity of bend-point);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

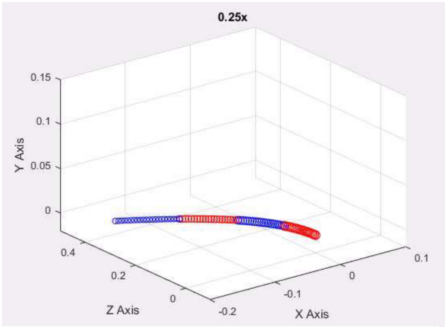
Simplifying principles in reaching

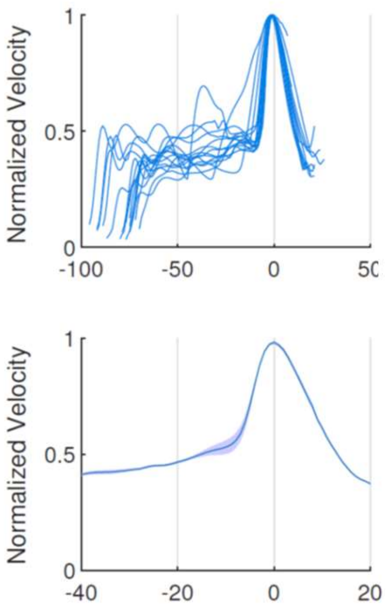
Biological behaviour



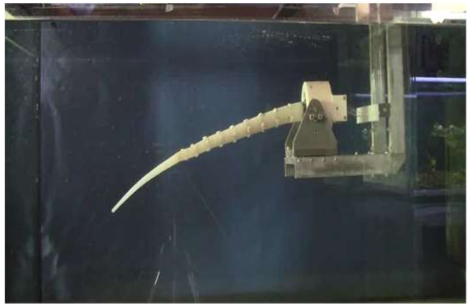
TANGENTIAL BEND PROPAGATION VELOCITY OF THE OCTOPUS ARM

Robot behaviour





TANGENTIAL BEND PROPAGATION VELOCITY OF THE SOFT ROBOT



- Soft robot
- Passive distal part
- Water
- Neural controller (not octopus-like!)

Environmental properties

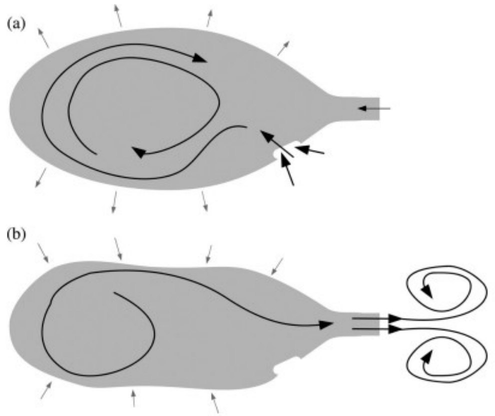
Configuration	Learnable	Bend Propagation Strategy
Lower Environment Density (air)	No	N/A
Lower Environment Density (air) + Higher Body Stiffness and Viscosity	Yes	No
Actuators at Tip (4th Section)	No	N/A
Actuators at 3rd Section	Yes	No
Only two actuators at the base	Yes	Yes
Three Actuators at base + One at the tip	Yes	Yes
Shorter Manipulator (Only two sections)	Yes	No
Cylindrical Shape	No	N/A
Double module experiment	Yes	No

Morphological properties

Morphological and environmental properties are the factors that affect the invariant velocity profile observed

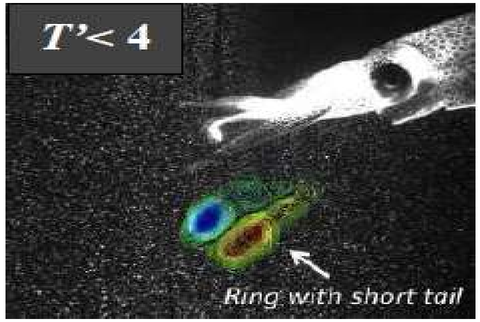
T. G. Thuruthel, E. Falotico, F. Renda, T. Flash, C. Laschi, **Emergence of Behavior from Morphology: A Case study on an Octopus Inspired Manipulator**, *Royal Society Open Science* , under review

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)

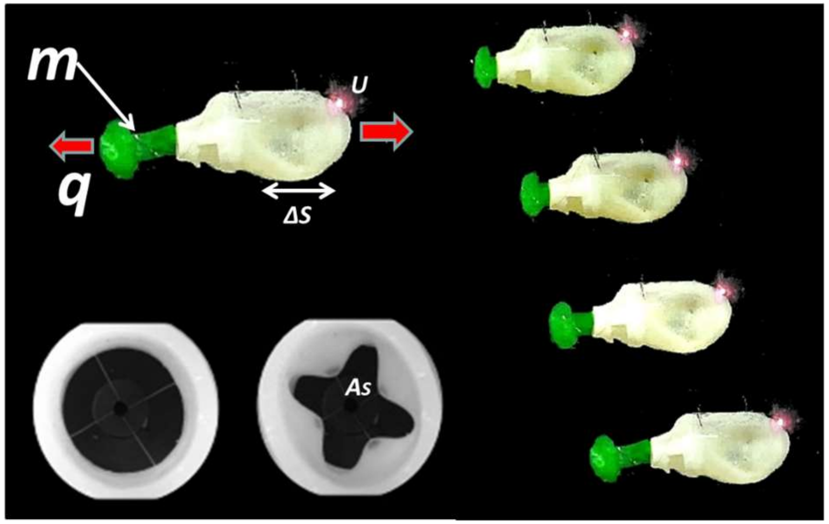


Ejection of a discontinuos stream of fluid through a nozzle that produces **ring vortexes**.
The generation of ring vortexes provides an additional thrust to the one generated by a continuous jet, by generating an additional pressure at the nozzle orifice

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 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

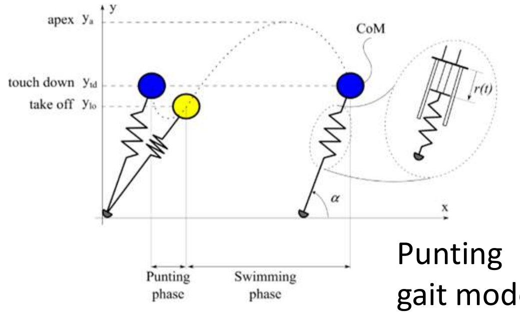
Octopus crawling

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

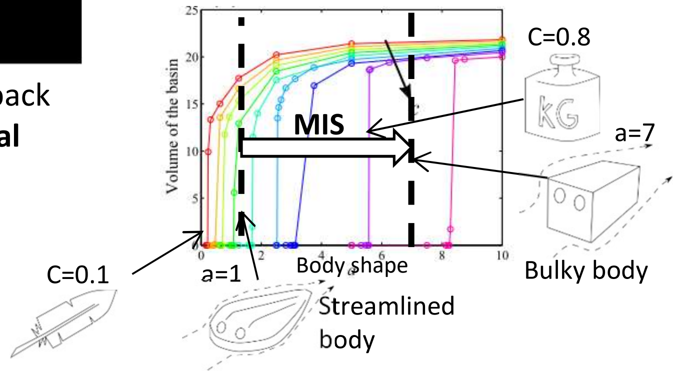
Water drag, added mass, buoyancy and pushing propulsion have been added to the SLIP model

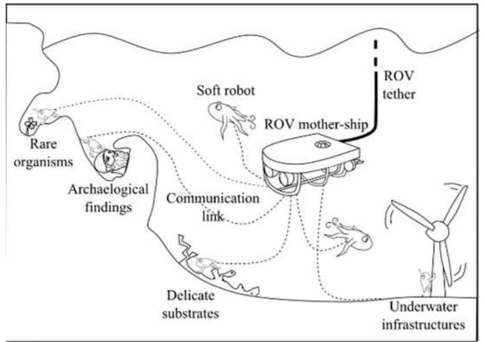


Punting gait model

2 control parameters **4 design parameters**

Morphology-Induced Stability





New concept of soft underwater robots

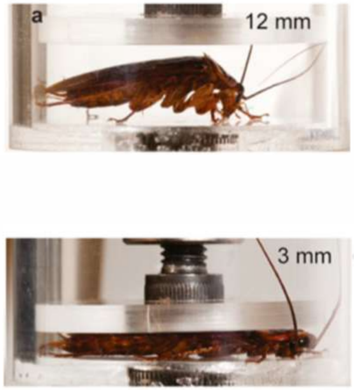
Body matters: compliant legs or a soft body directly influence stability and speed

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

Symplifying principles in squeezing

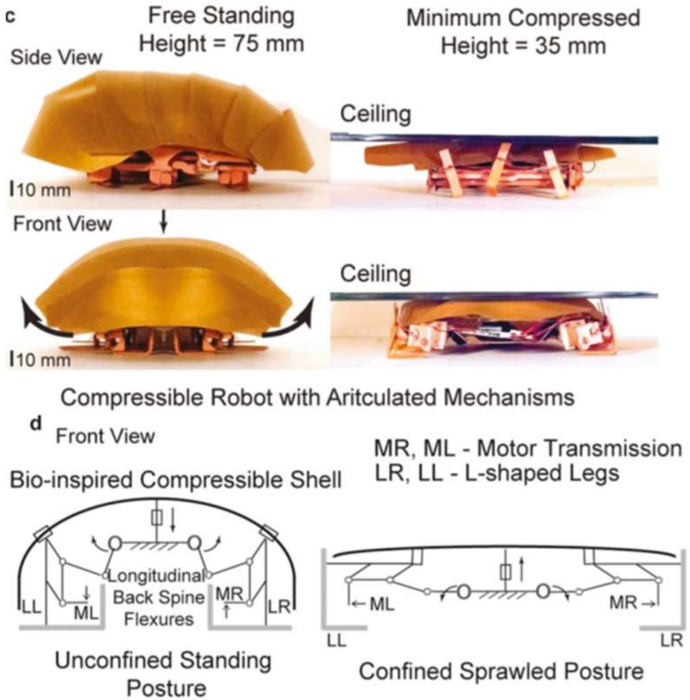
Compliant articulate exoskeleton

Cockroaches intrude everywhere by exploiting their soft-bodied, shape-changing ability. They traversed horizontal crevices smaller than 25% of their height in less than 1s by compressing their bodies' compliant exoskeletons in half.



Once inside vertically confined spaces, cockroaches still locomoted rapidly at 20 body lengths per second using an unexplored mode of locomotion "body-friction legged crawling".

Soft, legged search-and-rescue robot that may penetrate rubble generated by tornados, earthquakes, or explosions.



- Mechanical adaptation to available space
- 1 DOF

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.

<u>Many tasks become much easier if morphological computation is taken into account.</u>

=> 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

Defining Soft Robotics: a first broad classification

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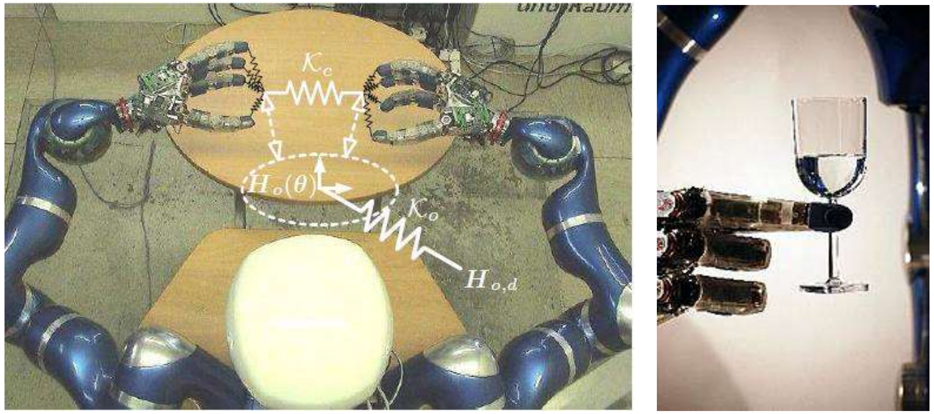
Variable impedance actuators and stiffness control

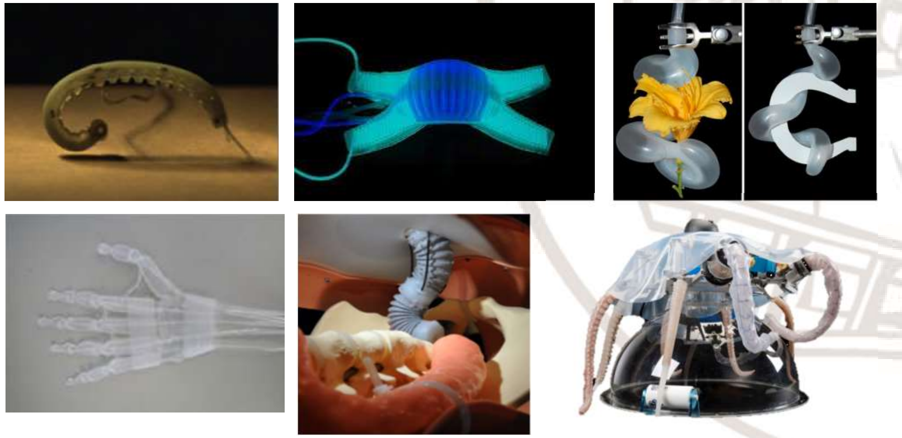
- mechanically (or passively) compliant joints with variable stiffness
- compliance or impedance control



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



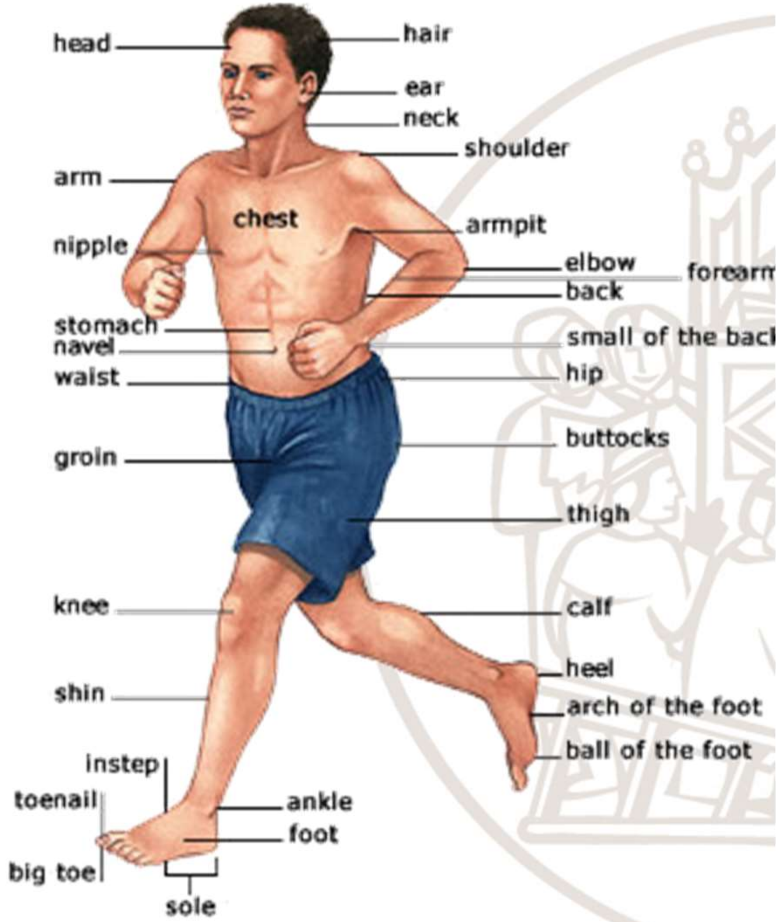
Laschi C. and Cianchetti M. (2014) "Soft Robotics: new perspectives for robot bodyware and control" *Frontiers in Bioengineering & Biotechnology*, 2(3)

A 'soft' animal world

- 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.

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

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



skeletal muscle contributes an average 42% of body mass

A 'soft' animal world

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- 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

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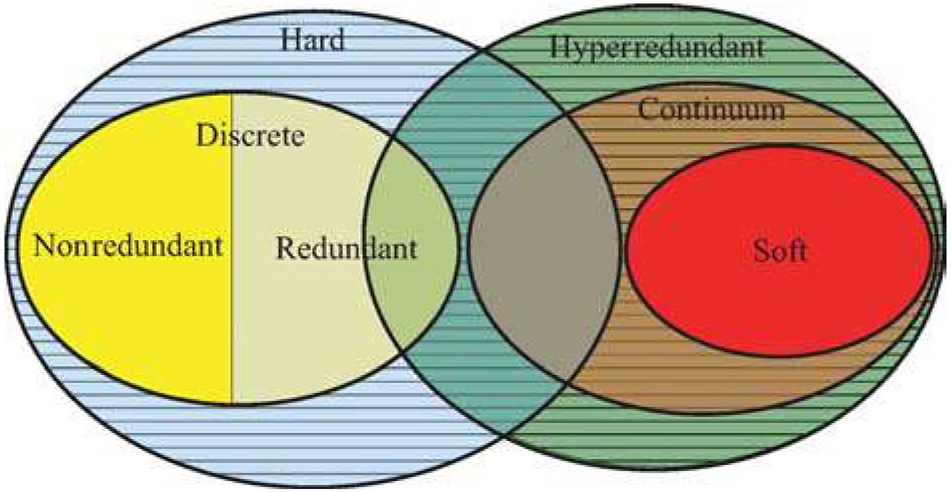
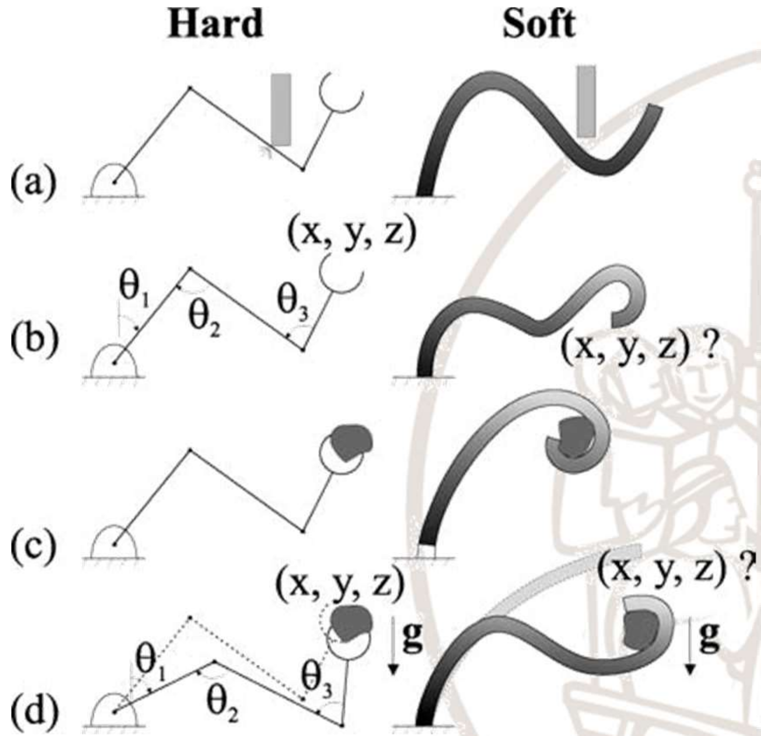
Continuum robots: capable of bending via elastic deformation, and differing from traditional robots with rigid links and serpentine robots with a large number of short rigid links and degrees of freedom



G. Robinson, J. B. C. Davies, "Continuum robots - a state of the art", *IEEE International Conference on Robotics and Automation*, (Detroit, MI, 1999), pp. 2849-2854.

Shift from robots with rigid links to bio-inspired continuum robots that are "inherently compliant and exhibit large strains in normal operations"



"soft robotic manipulators are continuum robots made of soft materials that undergo continuous elastic deformation and produce motion through the generation of a smooth backbone curve [15]".

D. Trivedi, C. D. Rahn, W. M. Kier, I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research", *Applied Bionics and Biomechanics*, 5, 99-117 (2008)

Defining Soft Robotics

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- “Soft-bodied robots”, in analogy with soft-bodied animals

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

- “Robots built with soft materials”

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

Defining Soft Robotics

- "systems that are capable of autonomous behavior, and that are primarily composed of materials with moduli in the range of that of soft biological materials"

D. Rus, M. T. Tolley, Design, fabrication and control of soft robots. *Nature* 521, 467-475 (2015).

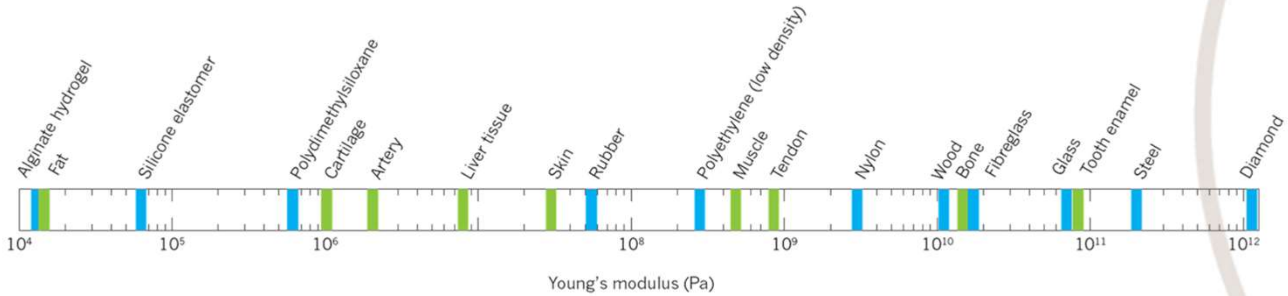

Figure 2 | Approximate tensile modulus (Young's modulus) of selected engineering and biological materials. Soft robots are composed primarily of materials with moduli comparable with those of soft biological materials (muscles, skin, cartilage, and so on), or of less than around 1 gigapascal. These materials exhibit considerable compliance under normal loading conditions.

- "soft-matter robotics", based on the well-known concept of "soft matter" used for materials

L. Wang, F. Iida, Deformation in Soft-Matter Robotics: A Categorization and Quantitative Characterization. *IEEE Robotics & Automation Magazine* 22(3), 125-139 (2015).

Defining Soft Robotics

First RoboSoft Working Paper – September 2014

On the basis of the above statements, the RoboSoft community proposed and agreed on the following definition of Soft Robotics:

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

Definition of Soft Robotics by RoboSoft Community

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RoboSoft is a Coordination Action on Soft Robotics funded by the European Commission.
The RoboSoft Community accounts for 34 member institutions for a total of 100+ scientists

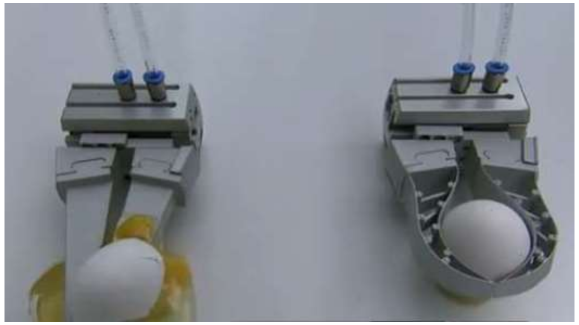
"Soft robot/devices that can actively interact with the environment and can undergo 'large' deformations relying on inherent or structural compliance"

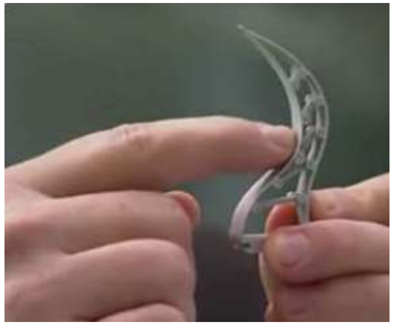
Soft Robotics may exploit materials which present:

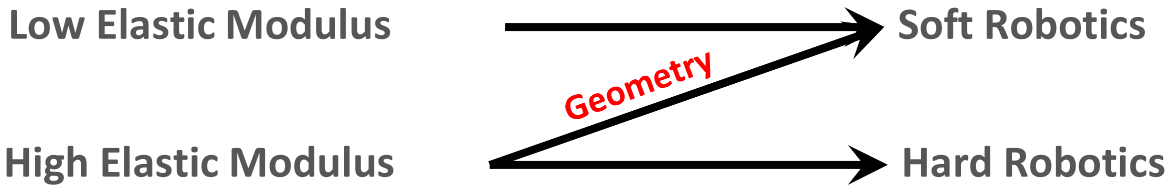
- INHERENT MATERIAL compliance: bulk material properties (elastomers, low elastic modulus polymers, gels…)

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