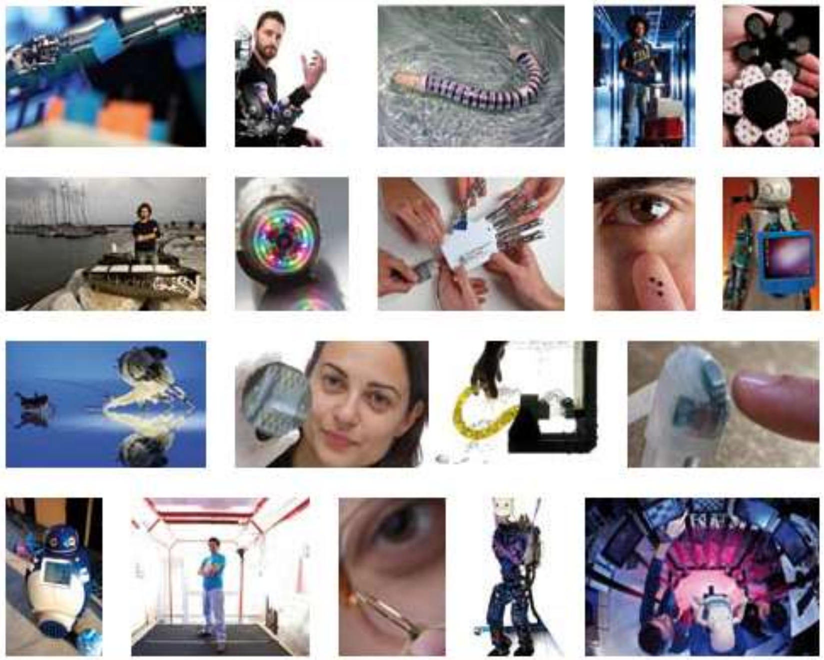
the BioRobotics Institute



Scuola Superiore Sant'Anna

di Studi Universitari e Perfezionamento

www.bioroboticsinstitute.eu

RoboSoft

Plenary Meeting
Scuola Superiore Sant'Anna, Pisa, Italy
March 31, 2014

Soft Robotics: a New Frontier for BioRobotics and Robot Companions

Paolo Dario

The BioRobotics Institute
Scuola Superiore Sant'Anna
Pisa, Italy

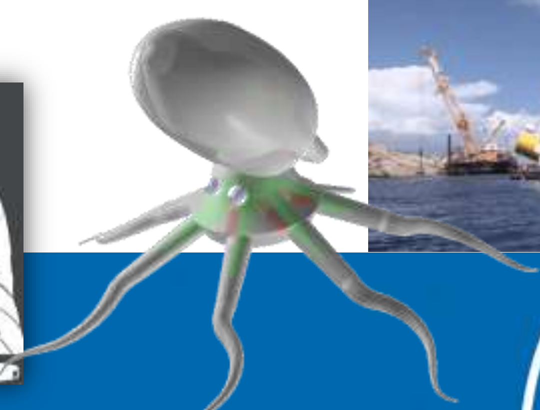
Outline

- BioRobotics and Soft Robotics
- What are *Robot Companions*?
- New frontiers for BioRobotics and Robot Companions using Soft Robotics
- Conclusions

Challenges for Soft Robotics

- Which are the **main scientific and technological challenges** for frontier research in soft robotics that need to be tackled in the next 10-20 years, and which is the nature of the challenges (vision-driven and high-risk, embryonic or foundational)?
- Which are the **main challenges** and which **impact** will have soft robotics technologies in **different applications fields**, like in service robotics (at home, at work), rehabilitation/prosthetics (soft-hard wearable robotics), surgical robotics, marine robotics, aerial robots, human-robot interactions?



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Robots are a real market

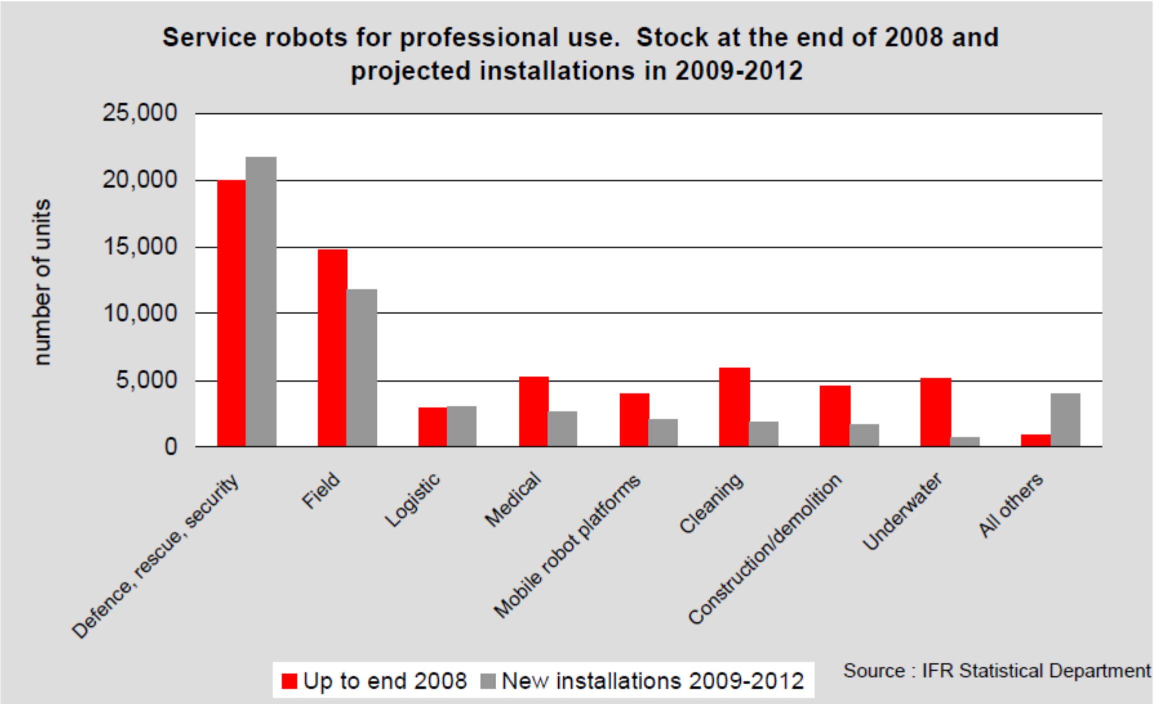
More than ***1 million operational industrial robots in the world***, with a growth rate of **6% per year** (*Source: IFR*)

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

Around ***5 millions service robots are sold annually***
Service robots are one of the fastest growing markets (~**14% per year**)
Professional service robots account for 80% of sales value

10.000.000+ Roomba Cleaning Robots sold so far!

The market of robots grows



Forecasts predict a **2-digit growth for the market of robots**, in particular for **service robots**, and an even sharper growth for **HEALTHCARE robots** (in **surgery**, **rehabilitation**, **assistance** to elderly and disabled persons)

Rise of the robots New roles for technology

The Economist March 29th, 2014

Special report: Robots

Immigrants from the future

The build-up
Good and ready

Military uses
Up in the air

Business service robots
The invisible unarmed

Labour markets
A mighty contest

Domestic service robots
Seal of approval

Regulation
That thou art mindful of him

"reliable robots—especially ones required to work beyond the safety cages of a factory floor—have proved hard to make, and robots are still pretty stupid. So although they fascinate people, they have not yet made much of a mark on the world. That seems about to change."

3 factors are at play:

1. **Robotics R&D is getting easier**. New shared standards make good ideas easily portable from one robot platform to another. Accumulated know-how means also lower cost.
2. **Investment**. The biggest robot news of 2013 was that Google bought eight promising robot startups.
3. **Imagination**. More people will grasp how a robotic attribute such as high precision or fast reactions or independent locomotion can be integrated into a profitable business; eventually some of them will build mass markets.

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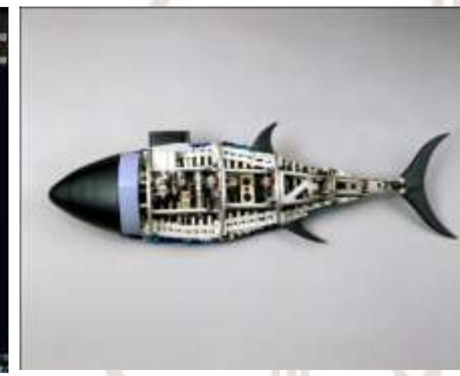
Sant'Anna

Robots outside factories…

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

Rescue

Underwater


Space

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

Robots outside factories…

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

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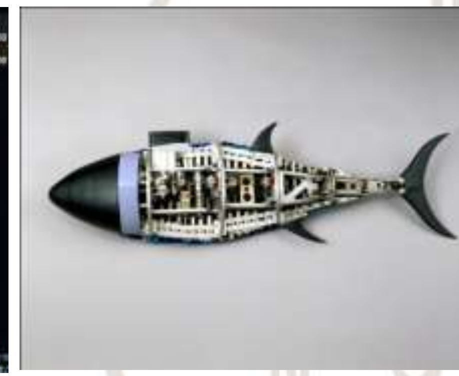
Biological systems represent an excellent source of inspiration for these robots

Rescue



Underwater

Space

- **Unstructured environment**
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- Shared workspace with human beings

FET Mission

Role of FET: Pasteur's Quadrant

	Consideration of use? *No*	Consideration of use? *Yes*
Quest for fundamental understanding? *Yes*	Pure basic research (Bohr) **Ideas ERC**	Use-inspired basic research (Pasteur) **FET**
Quest for fundamental understanding? *No*	N/A in ICT or ERC	Pure applied research (Edison) **ICT**

Science and (vs?) Technology
Pasteur's Quadrant

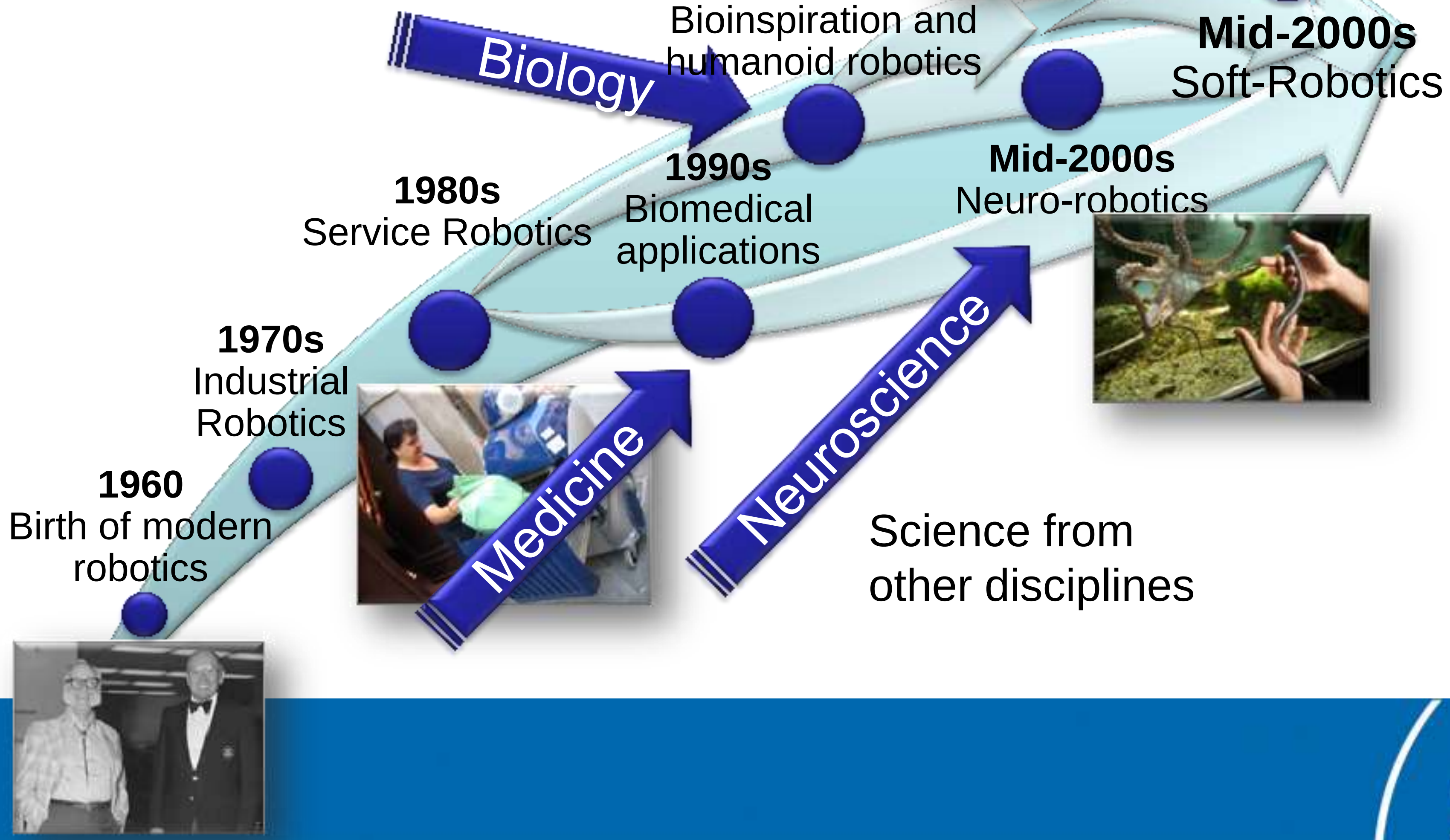
	Consideration of use? *No*	Consideration of use? *Yes*
Quest for fundamental understanding? *Yes*	Pure basic research (Bohr)	Use-inspired basic research (Pasteur)
Quest for fundamental understanding? *No*	N/A in ICT or ERC	Pure applied research (Edison)

BioRobotics Science and Engineering

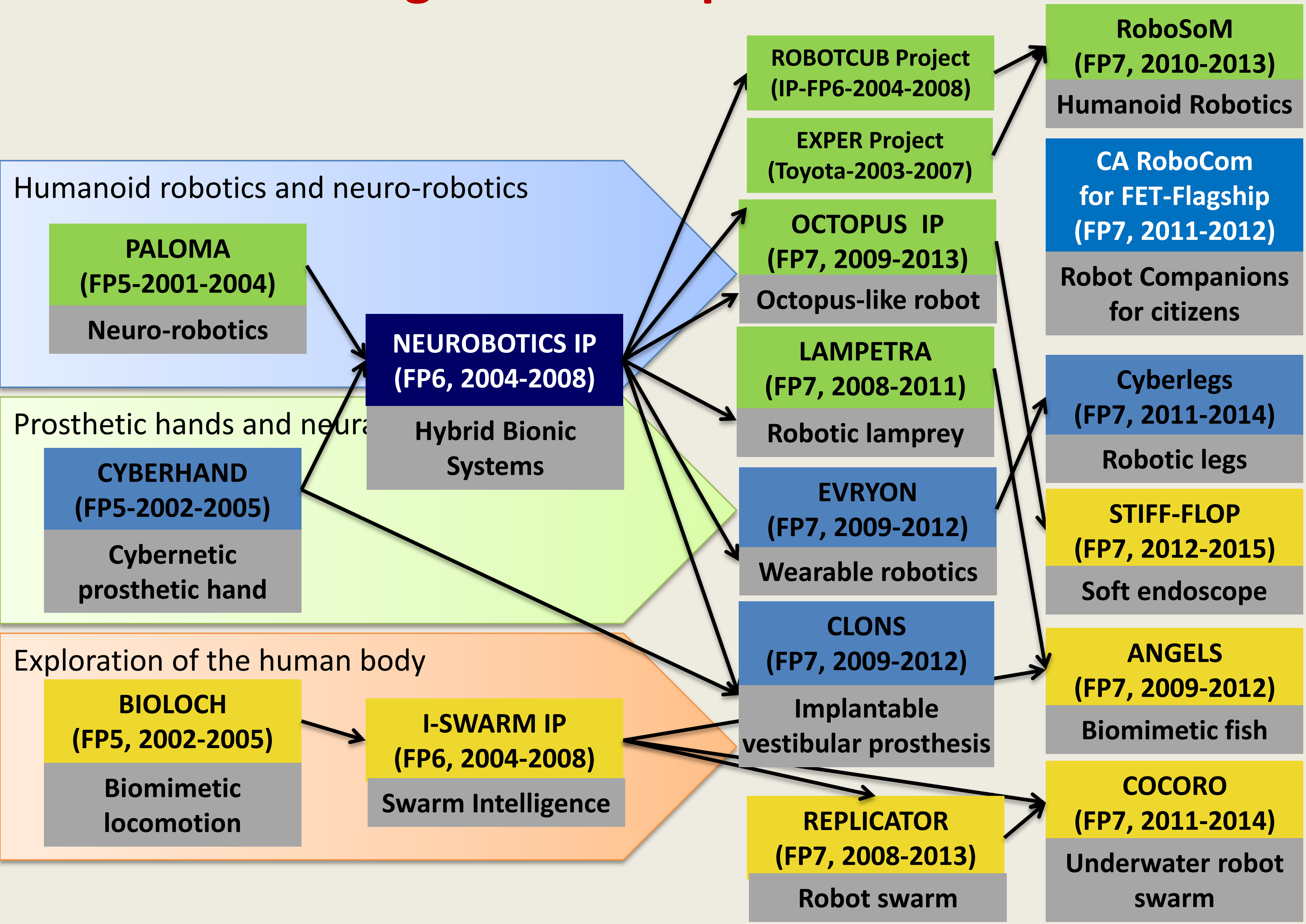
Milestones of BioRobotics…

Biorobotics Science and Engineering:

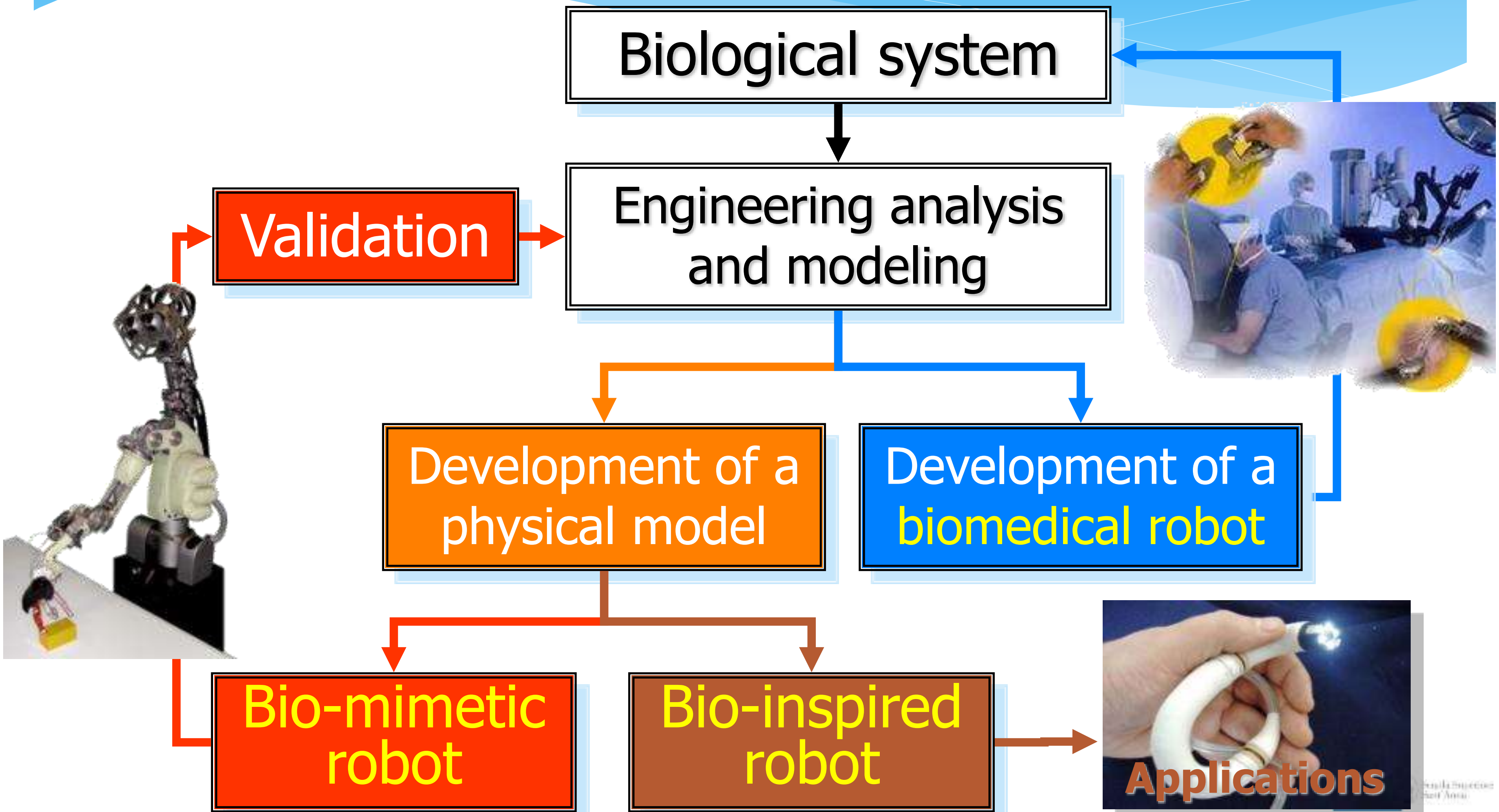
- Robots for biomedical applications (rehabilitation, surgery)
- Bioinspired robots



How the FET Programme shaped our Institute



BioRobotics: quest for fundamental understanding (science) **and** consideration of use (engineering)



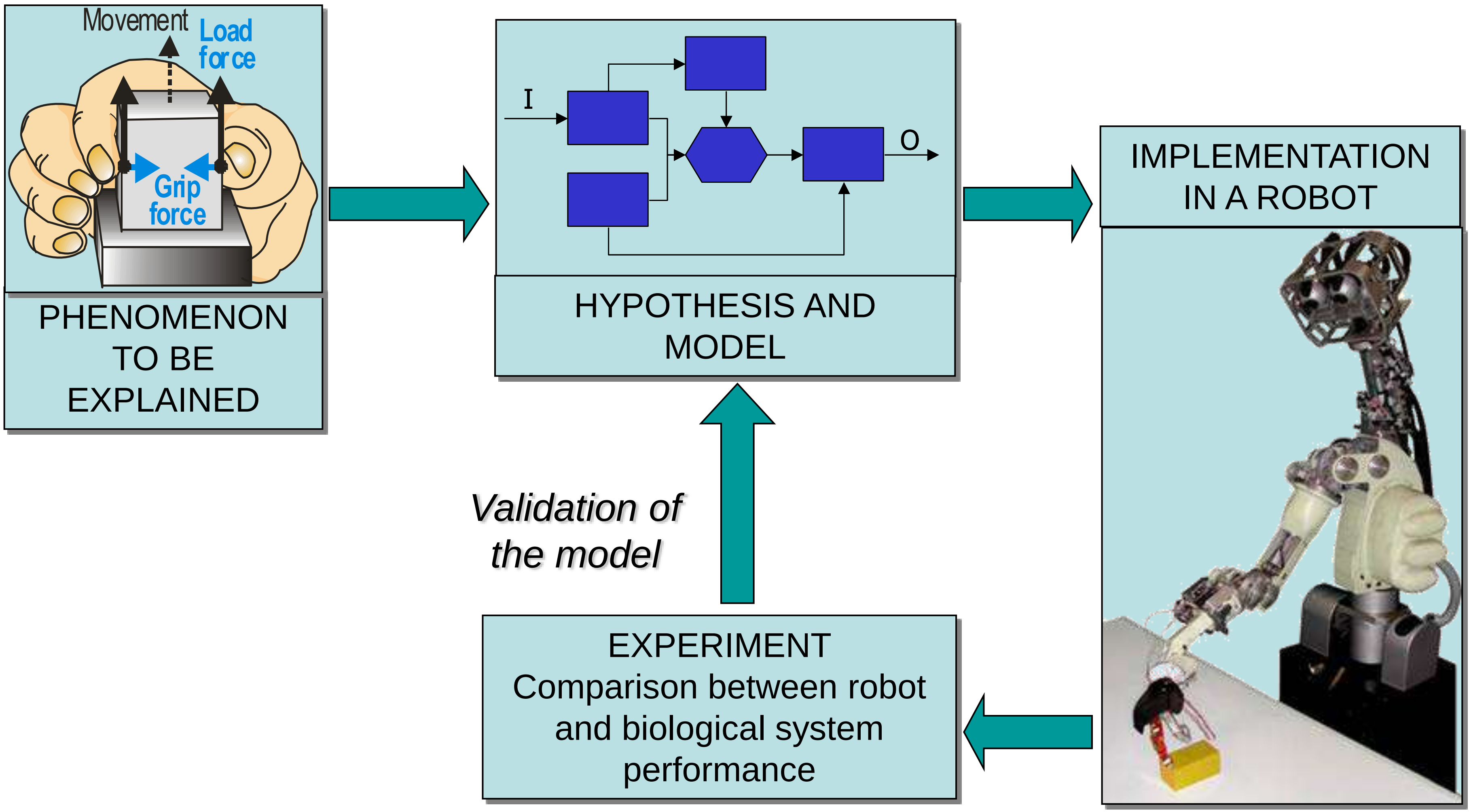
Biorobotics Science: using robotics to ***discover new principles***…

Biorobotics Engineering: using robotics to ***invent new solutions***….

Biorobotics Science: using robotics to ***discover new principles***…

Biorobotics Engineering: using robotics to ***invent new solutions***….

Biorobotics Science

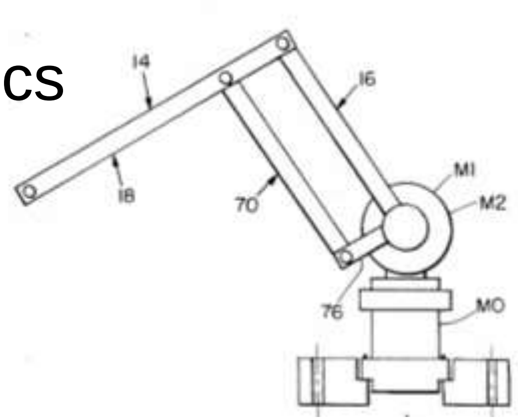


G. Tamburrini, E. Datteri, "Machine Experiments and Theoretical Modelling: from Cybernetic Methodology to Neuro-Robotics", *Minds and Machines*, 15, 3-4, 2005, pp. 335-58

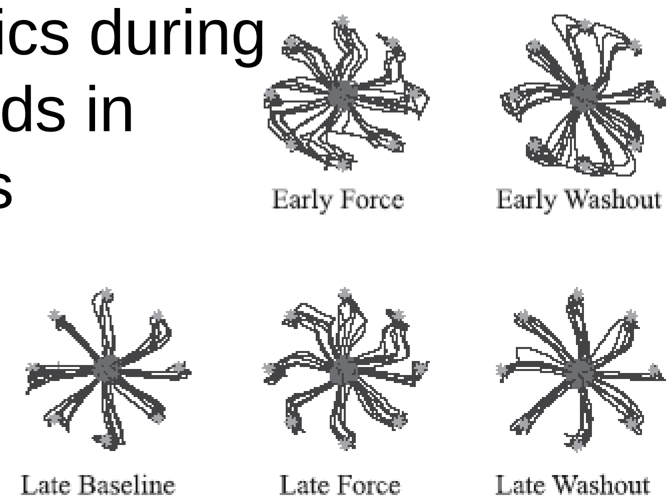
The MIT-MANUS
A robot designed for neuroscientific research

- In the late 80's, Emilio Bizzi (neuroscientist) and Neville Hogan (roboticist) **co-designed** the MIT-MANUS (a 2DOFs robot) **in order to help Bizzi to understand the way motor cortex M1 codes the kinematics and dynamics of upper limb movements**

The mechanics of the MIT-MANUS

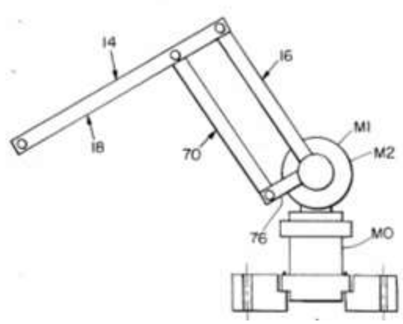


Kinematics during force fields in monkeys



The MIT-MANUS
A robot designed for neuroscientific research

- The MIT-MANUS is now used for different aims with very interesting results



Undestanding motor control in non-human primates (MIT: Bizzi)

Undestanding motor control in able-bodied young subjects (JHU: Shadmehr, NWU: Mussa-Ivaldi, Patton)

Restoration of upper limb function in stroke survivors (MIT: Hogan, Krebs)

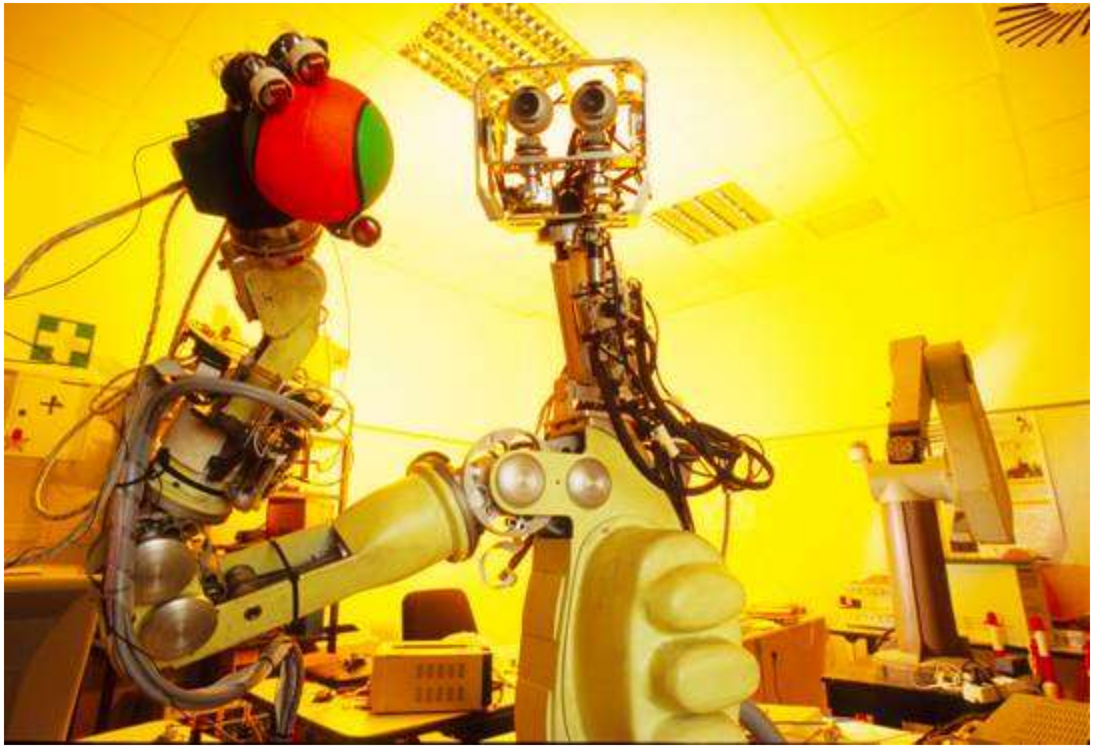
Undestanding motor control in able-bodied elderly subjects (SSSA: Dario, Micera)

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

Objectives:

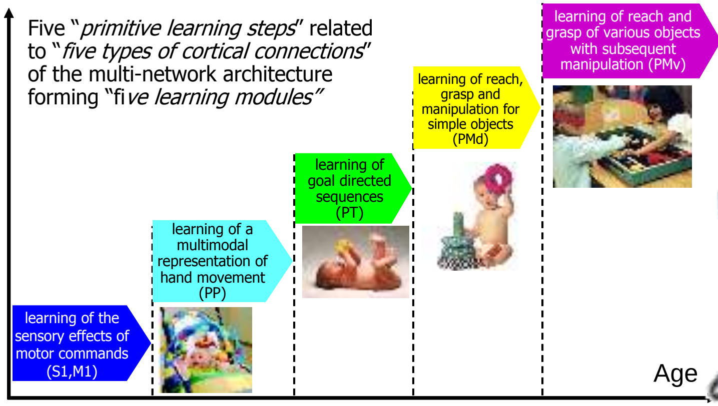
To increase knowledge of brain connectivity (architecture) and brain activity (functioning) concerning sensory motor coordination for object manipulation in children

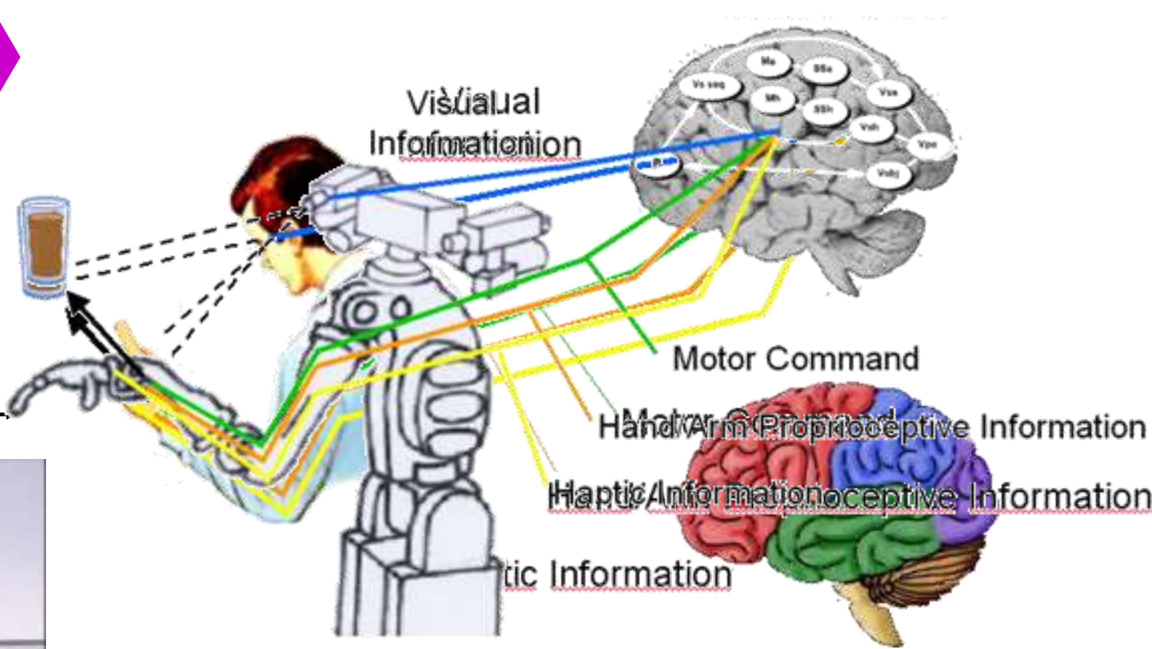
To integrate an anthropomorphic robotic platform for **grasping and manipulation** to validate a neurophysiological model of the **five learning phases** of **visuo-tactile-motor coordination** in infants

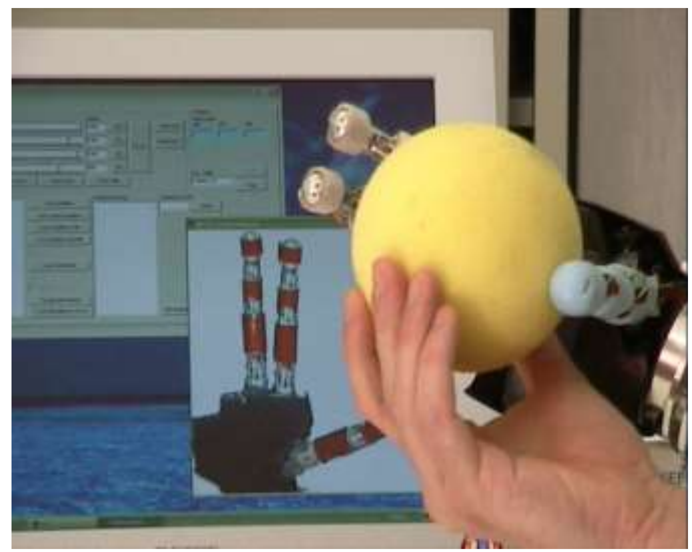


P. Dario, M.C. Carrozza, E. Guglielmelli, C. Laschi, A. Menciassi, S. Micera, F. Vecchi, “Robotics as a “Future and Emerging Technology: biomimetics, cybernetics and neuro-robotics in European projects”, *IEEE Robotics and Automation Magazine*, Vol.12, No.2, June 2005, pp.29-43.

The PALOMA EU FET Project







- ✓ *Evaluation of the system in the* ***same condition as the training,*** Success rate: 0.8, MET: 1.093
- ✓ *Evaluation of* ***generalization capability in position and orientation,*** Success rate: 0.775, MET: 2.0
- ✓ *Evaluation of* ***generalization capability in size and shape ,*** Success rate: 0.7, MET: 2.1786

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."

"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.

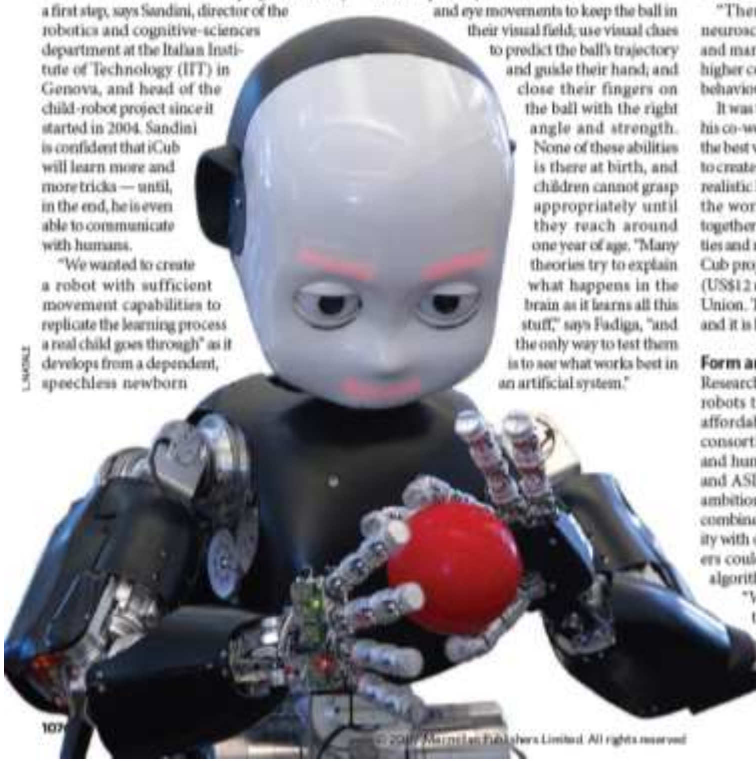
"There is ever-growing evidence from neuroscience that visuo–motor processing, and manipulation in particular, are crucial for higher cognitive development, including social behaviour and language," Sandini says.

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



L. NATALE

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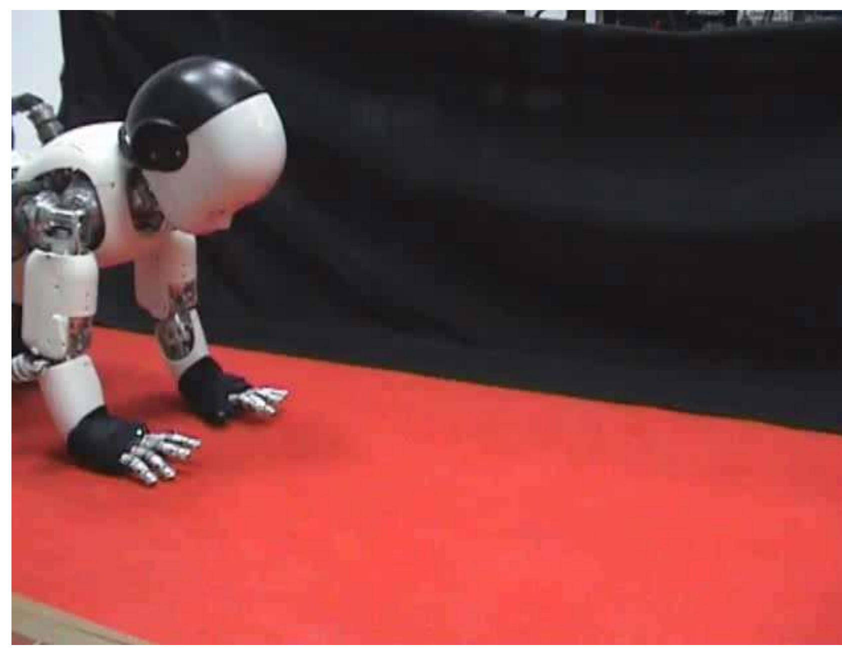
more uses than just
he robot look good
tional pictures, says
In the future, some
lan to try iCub with
vho are autistic, testing
ions to his expressions
ments".
Number 1 was never
be an only son. After
robot became opera-
consortium issued an
or proposals to conduct
nts. The six winners,
an independent 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-
ps," 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.

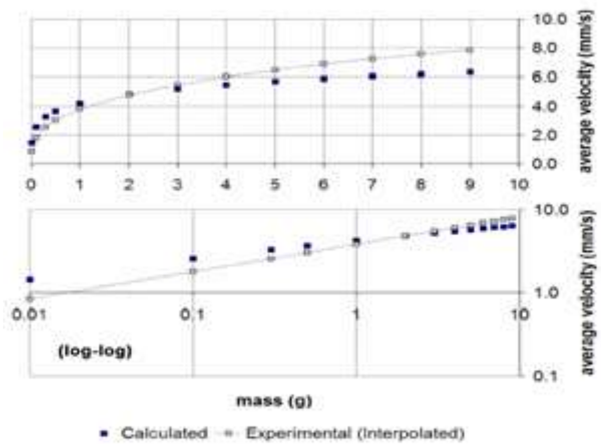


Biorobotics Science

Natural materials are ‘soft’ and characterized by low precision, but they are compliant and extremely reactive

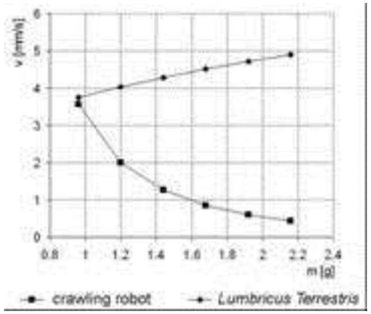
(Pfeifer et al. 2007)

PHENOMENON TO BE EXPLAINED (combination of friction and segment number for effective locomotion)



HYPOTHESIS AND MODEL (comparison between numerical results and interpolated experimental data of living oligochaeta)

IMPLEMENTATION IN A ROBOT



Validation of the model

EXPERIMENT Comparison between robot and biological system performance

The Scuola Superiore Sant'Anna "Zoo" (2008)

Biological model	Scientific problem
Oligochaeta	Role of friction in locomotion
Legged insects	Modeling compliant substrates
Polychaeta	New computational models of locomotion kinematics
Swimming cells	Swimming at low Re numbers
Cricket	Scale effects on locomotion
Lamprey	Neuroscientific models of goal-driven locomotion
Octopus	Motor performance of hydrostatic muscular limbs
Plant roots	Soil penetration mechanisms
Mouse	Animal-robot interaction
Homo Sapiens	Model of the sensorimotor system

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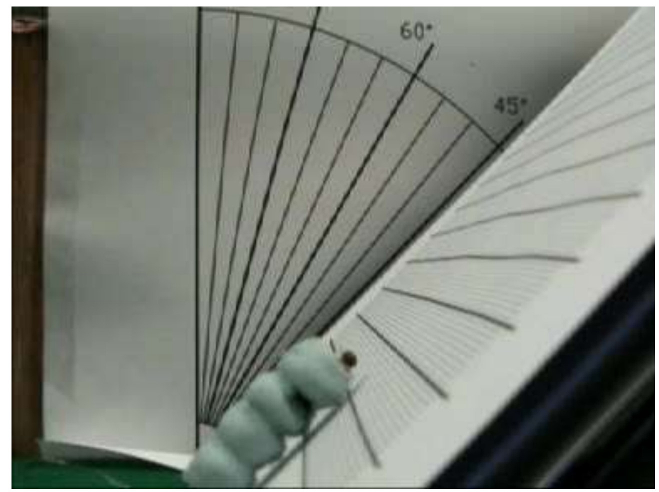
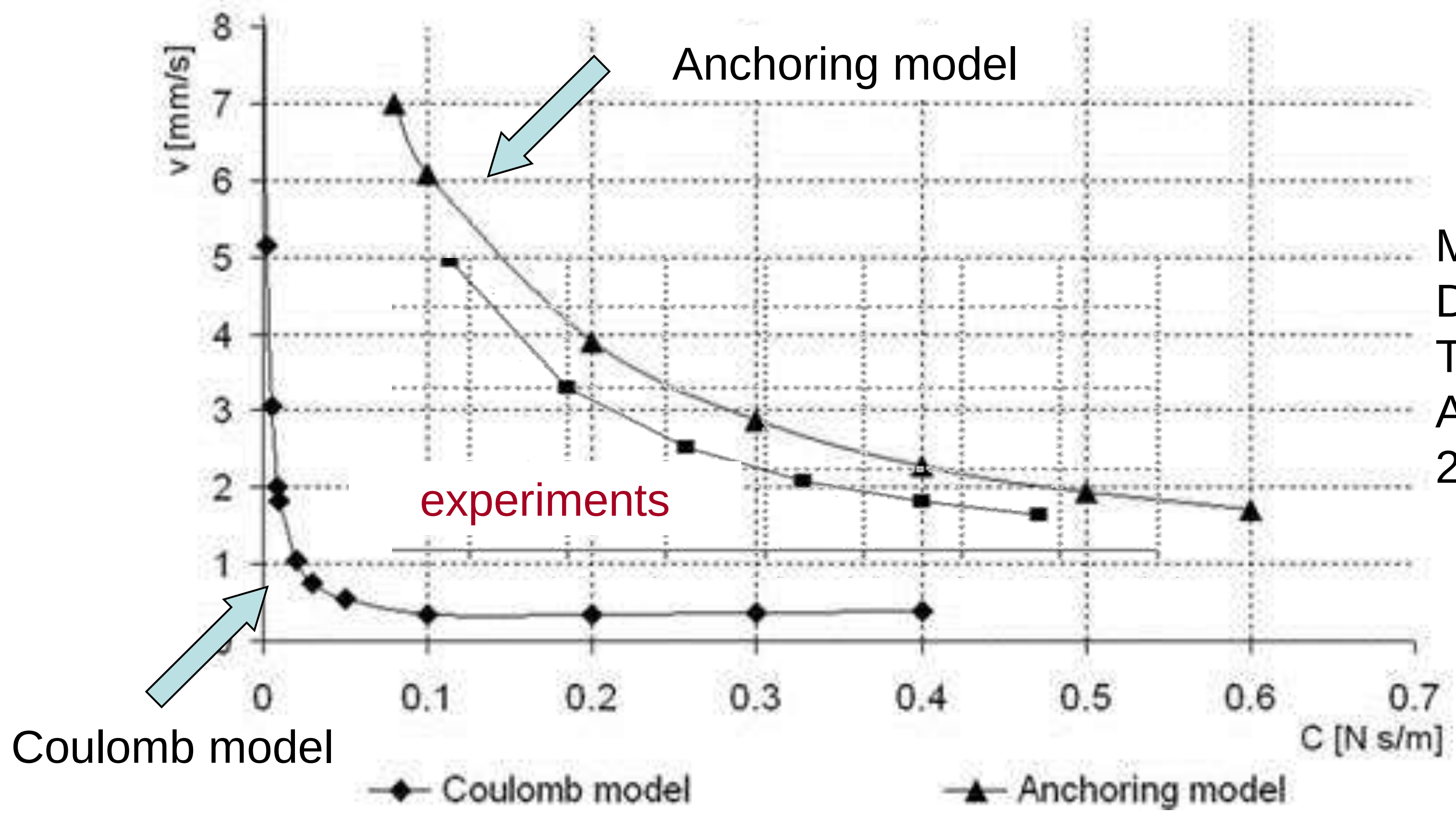
Undulatory locomotion of living earthworms



Natural and artificial ‘setae’
(precursors of legs)

Biomechanical model: equation of motion and results *(Accoto, Castrataro, Dario - 2004, J. Theor. Biology)*

Artificial worm: which friction model best explains the role of setae?



Menciassi and P. Dario, Philos. Transact. Roy. Soc. A Math. Phys. Eng., 2003

A comparison between the mean velocity of the centre of mass predicted using the Coulomb frinction model and the anchoring friction model, as a function of the damping coefficient C. The anchoring model is more accurate in the analysis of robot movements. **Velocities calculated by the anchoring model, for frequencies around 0.5 Hz, are in fair agreement with experimental data**

The Scuola Superiore Sant'Anna "Zoo" (2008)

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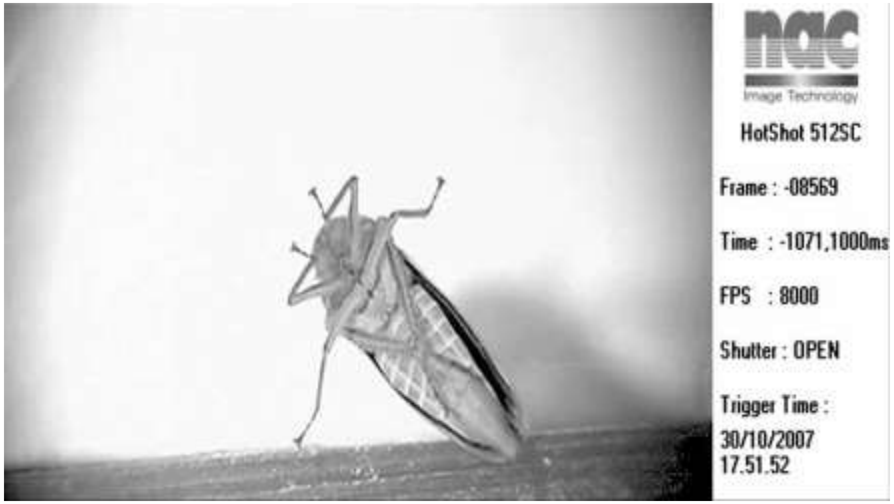
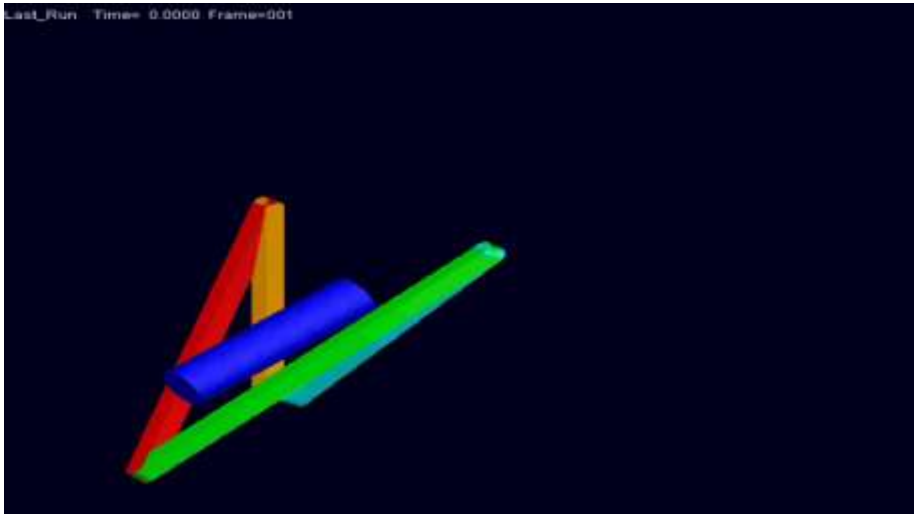
Jumping animals and robots





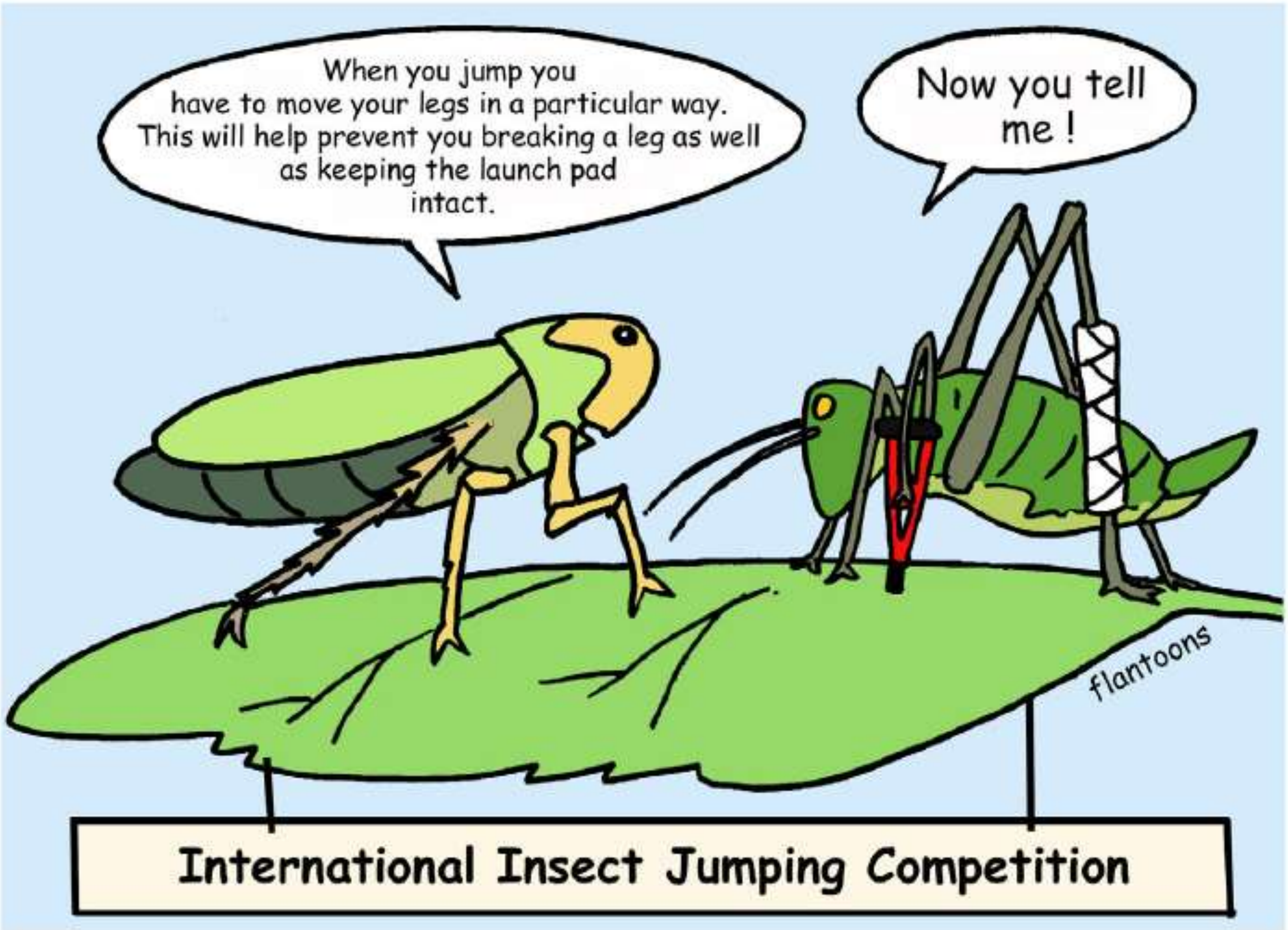
High speed camera (8000 fps)

The Journal of Experimental Biology publishes this discovery

Inside JEB

iii

BENT LEGS BEAT BREAKAGES DURING TAKE-OFF



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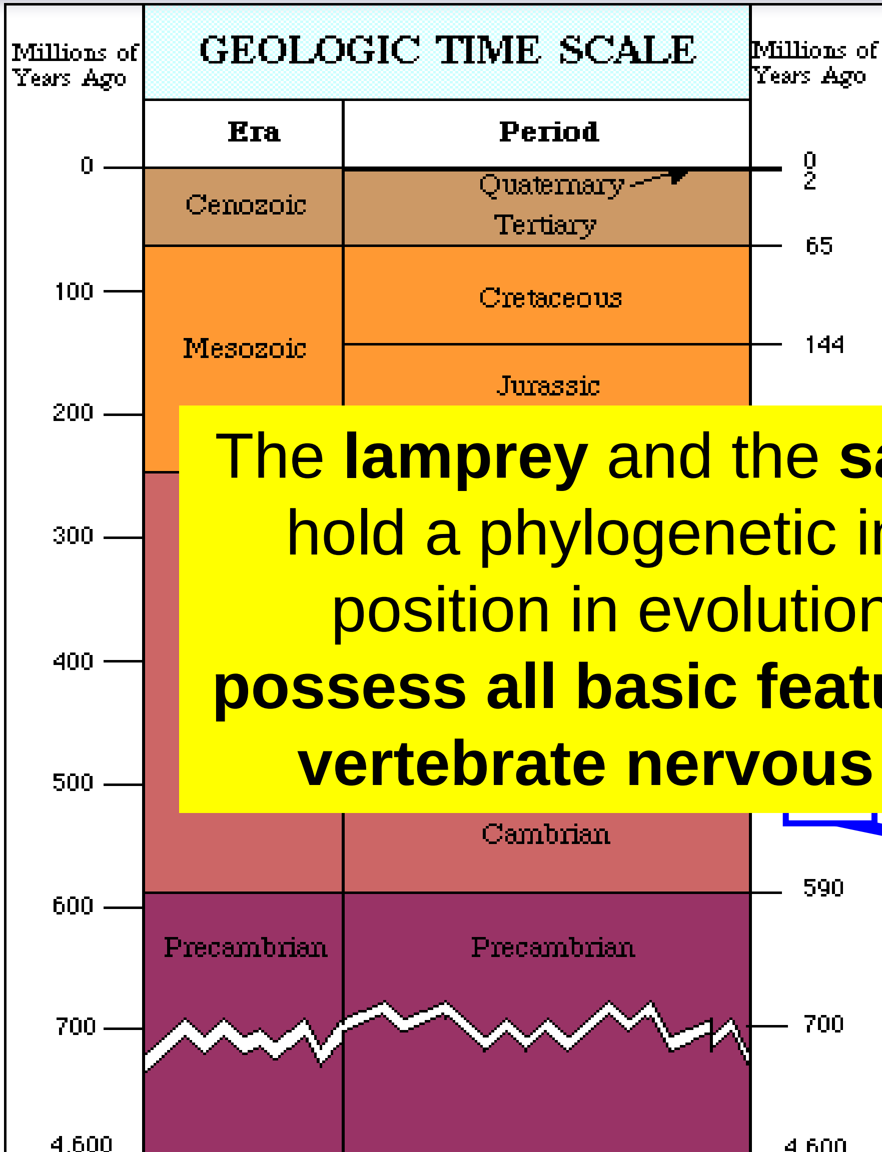
Early vertebrates as models to investigate



Phylogenetic tree

Salamander

End of the Dinosaurs

ls, Birds

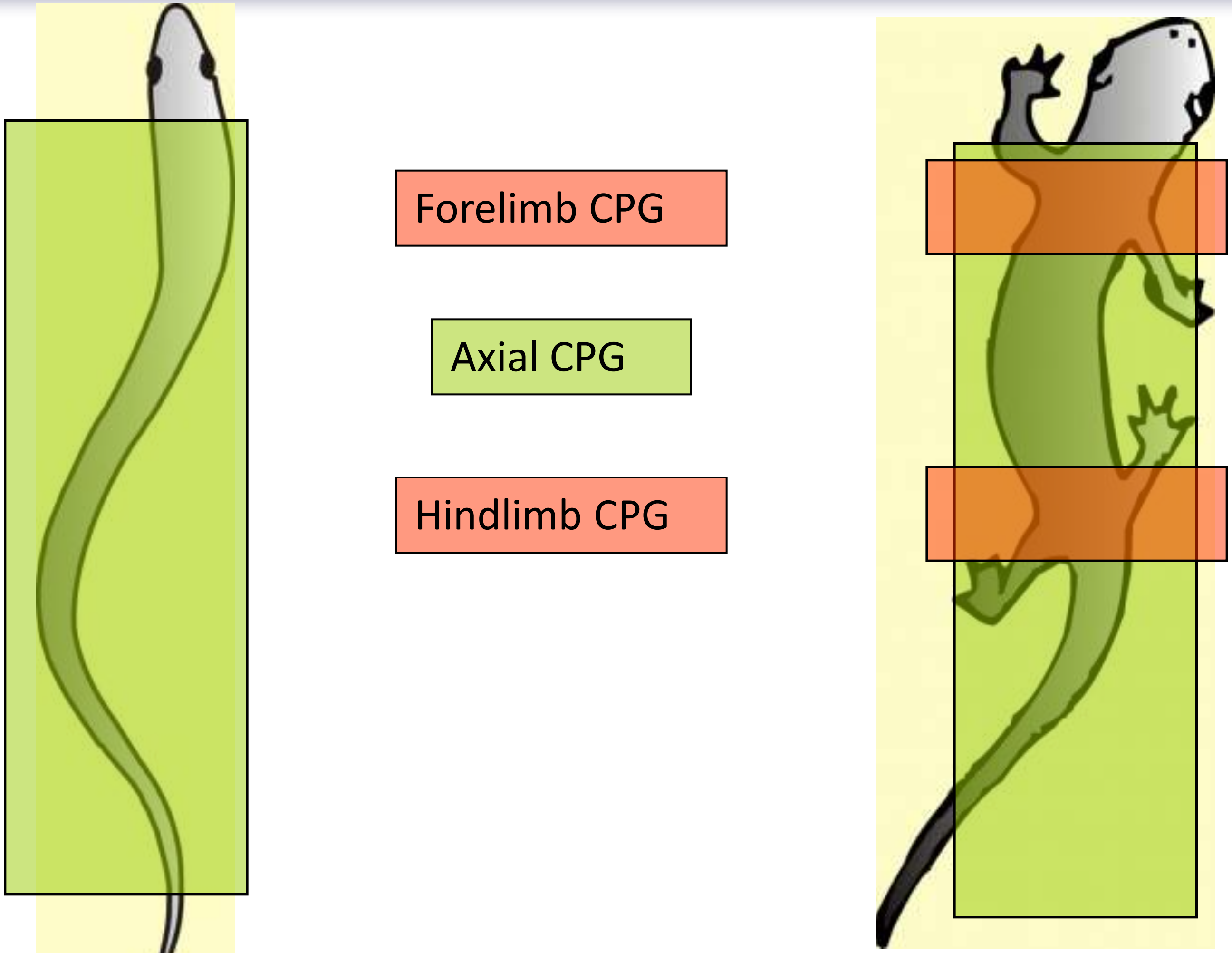
Ichtyostega

First Invertebrates

Lamprey

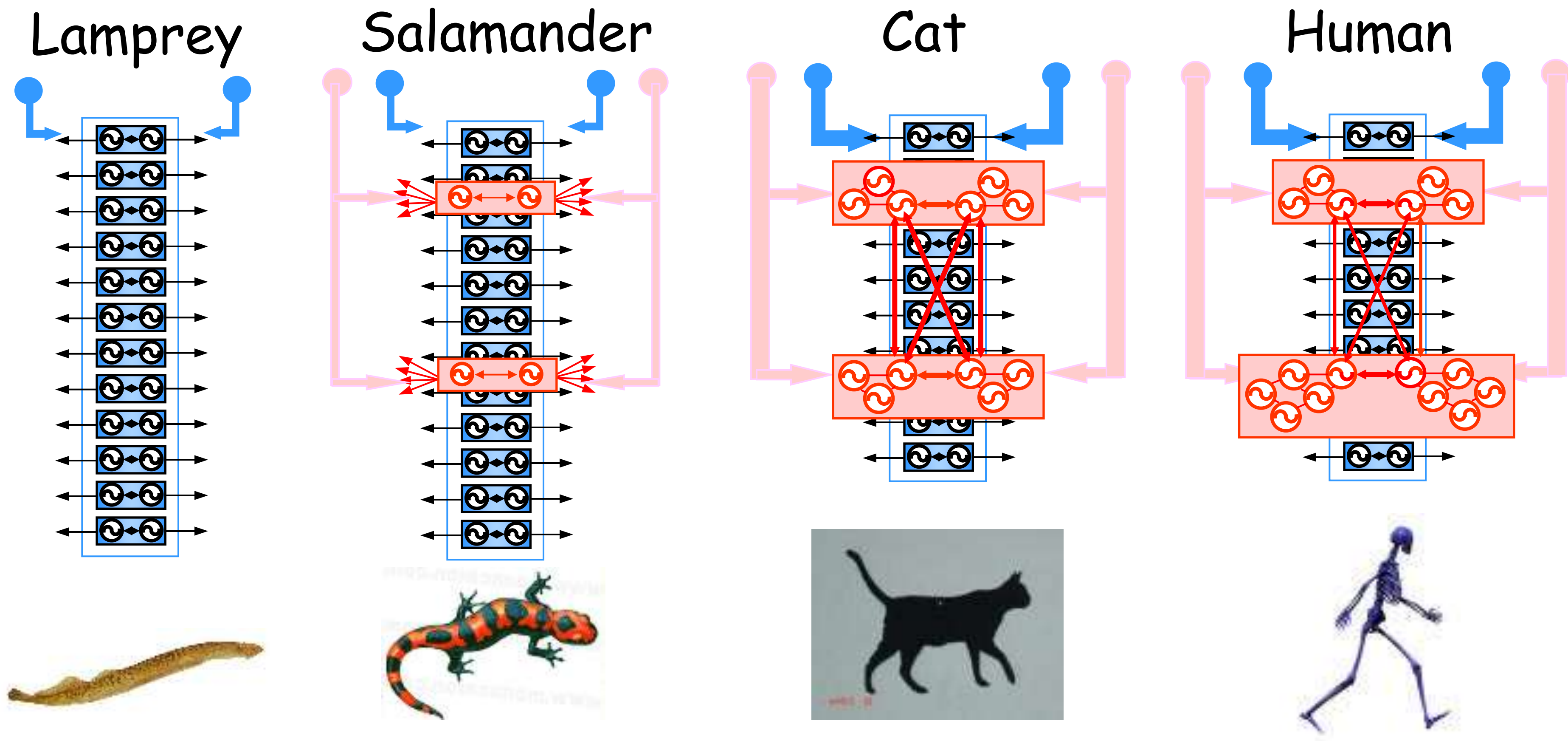
The **lamprey** and the **salamander** hold a phylogenetic important position in evolution. **They possess all basic features of the vertebrate nervous system**

From swimming to walking…



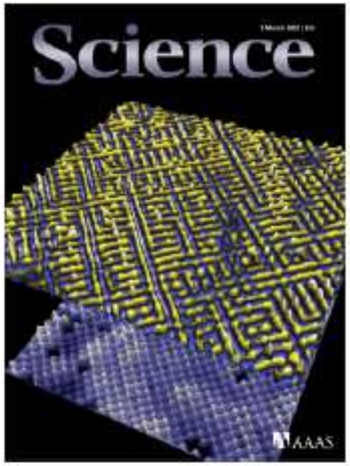
Salamander CPG = Lamprey-like axial CPG
extended with 2 limb CPGs

… to higher functions



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

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



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

The **first explanation of a mechanism of gait transition from swimming to walking**

The **first amphibious robot capable of swimming, crawling and walking**

Example of **a fruitful interaction between robotics and neuroscience.**

9 MARCH 2007 VOL 315 SCIENCE www.sciencemag.org

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

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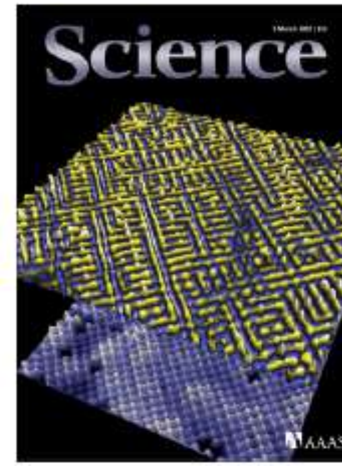


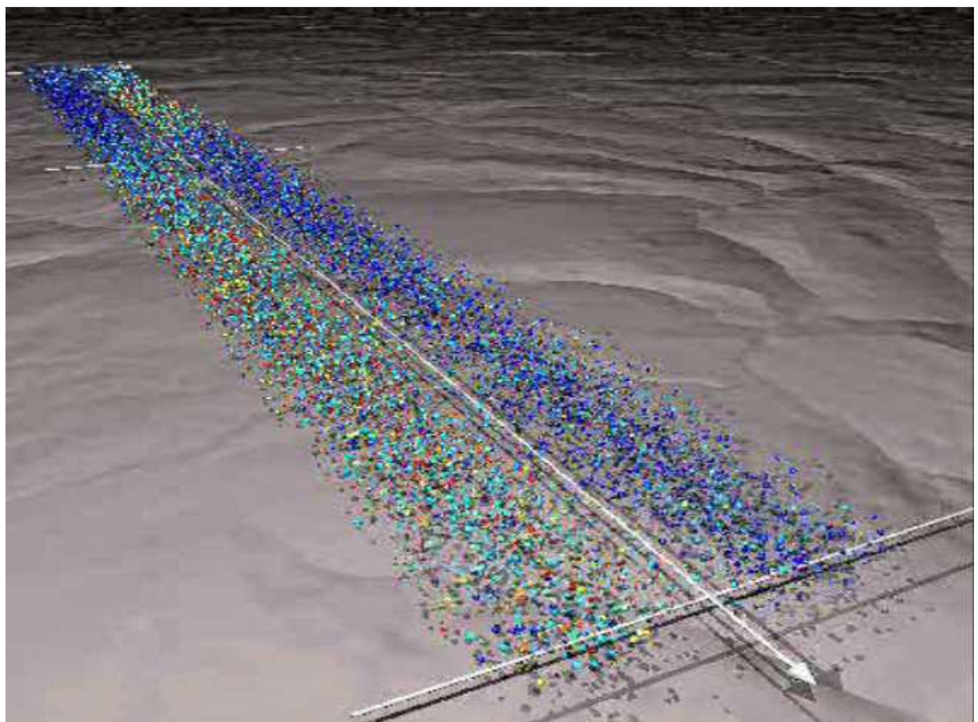
9 MARCH 2007 VOL 315 SCIENCE www.sciencemag.org

The LAMPETRA FET Project

Development and **use of lamprey/salamander bioinspired artefacts** in order to:

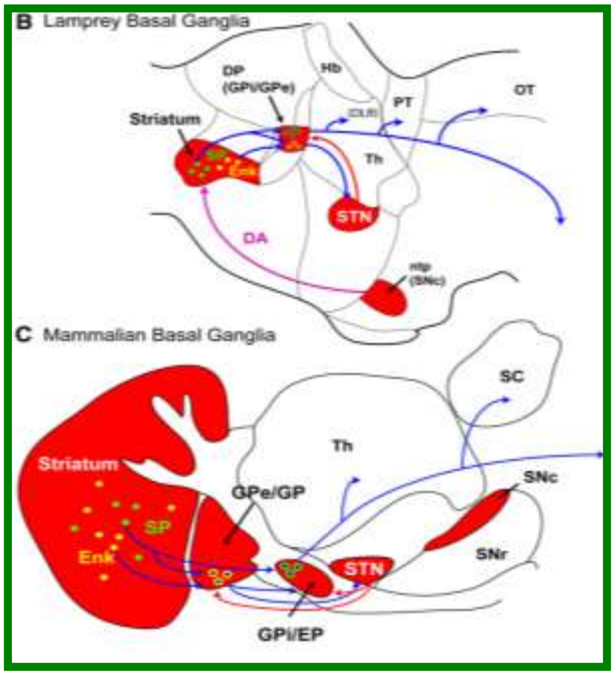
(a) conduct **neuroscientific studies** on vertebrate mechanisms involved in the neural control of goal-directed locomotion

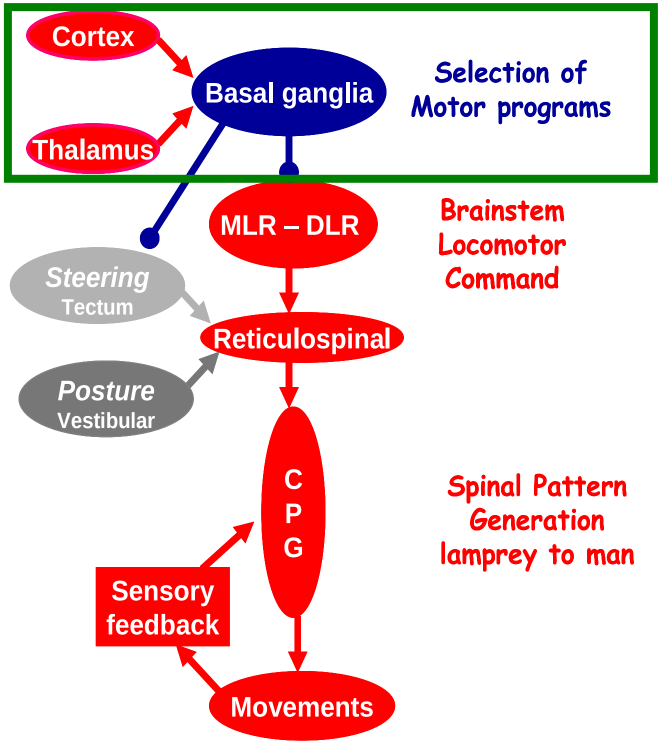
(b) Find new solutions for **high-performance artificial locomotion** in terms of fast-response, adaptability, reliability, energy efficiency, control

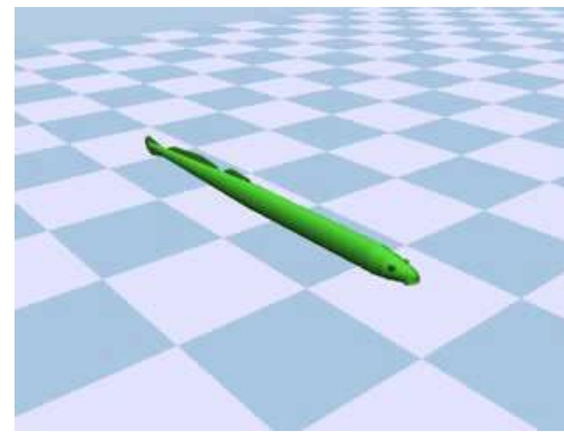


Not only locomotion….

Investigatiing the activity of **specific neuronal structures** in order to improve knowledge on neural mechanisms of **decision making** and **selection of behaviour**



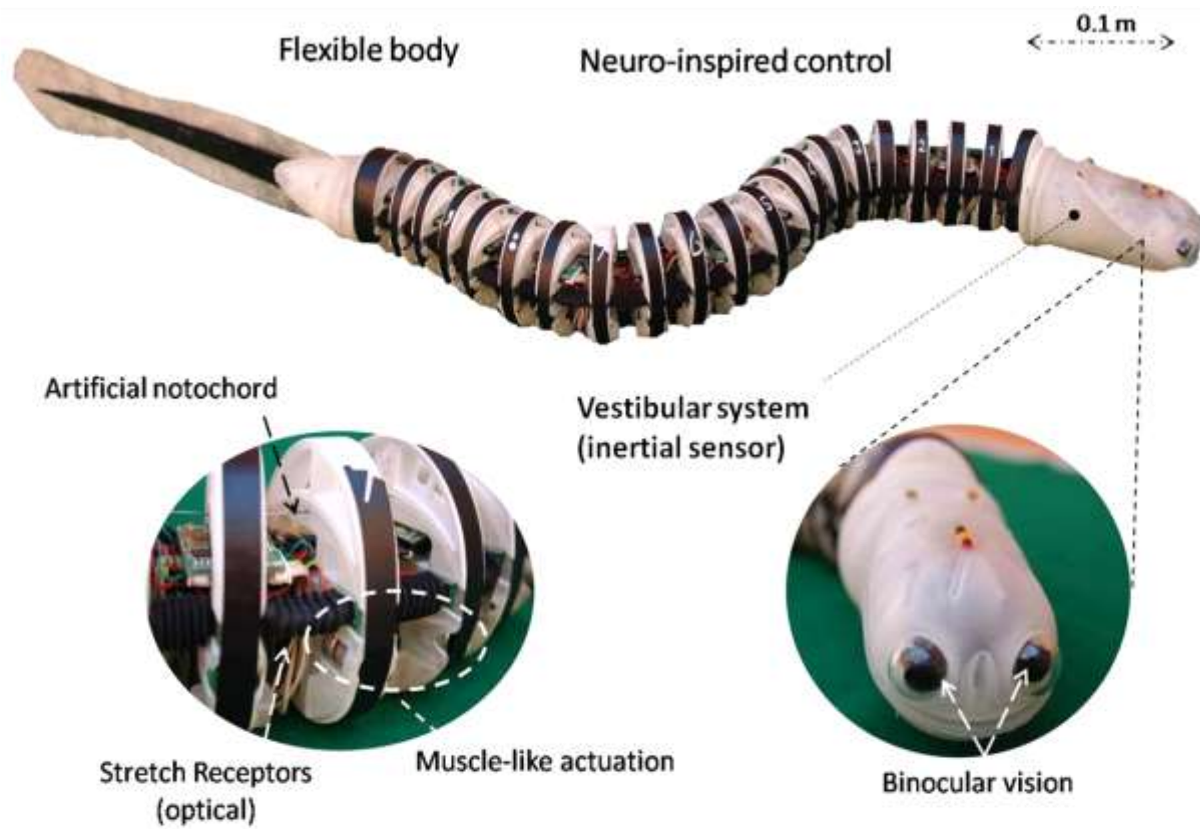


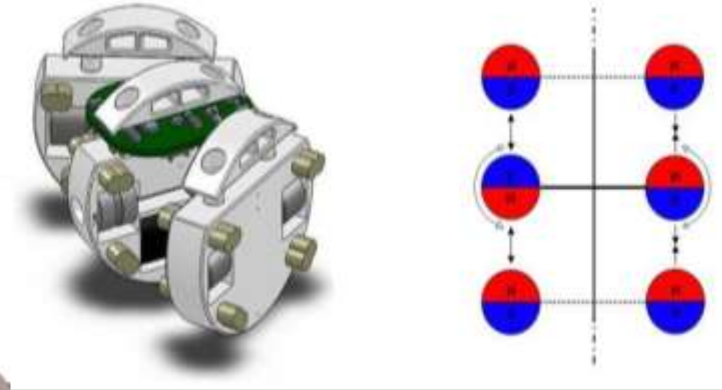


The organization of basal ganglia is considered to be subdivided in **separate modules**; each module controls a specific aspect of behaviour (e.g. locomotion).

Stephenson-Jones et al. 2011

The biomimetic lamprey artefact





- <u>COMPLIANT BODY</u>
- 55 mm in diameter
- 860mm in length
- 10 motors
- 21 vertebras
- Magnetic actuators <u>(MUSCLE -LIKE)</u>
- 10 battery packs
- Stretch sensors
- 2 2D cameras
- Wireless communication
- Gyros and accelerometers

<u>Biological Cybernetics</u> and <u>Bioinspiration and Biomimetics</u>

Vision-driven locomotion

Light tracking

Final results of the LAMPETRA Project

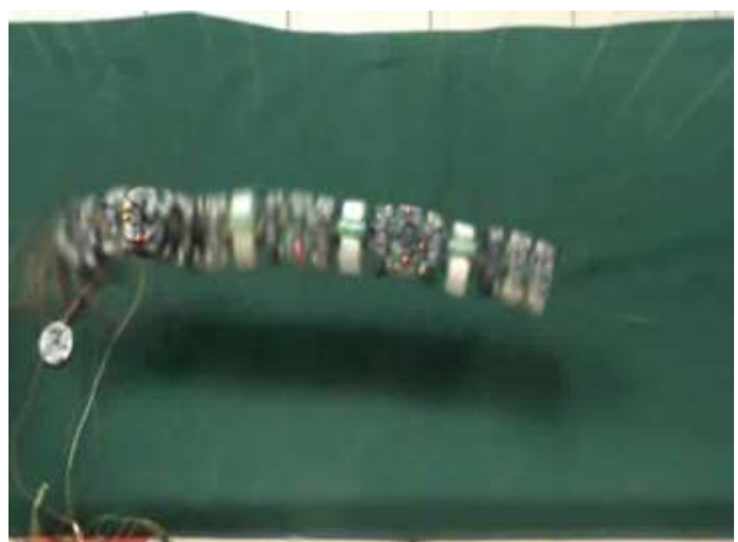
Biol Cybern (2013) 107:495–496
DOI 10.1007/s00422-013-0570-6

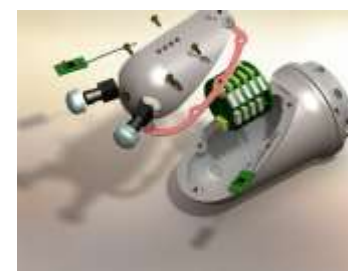
EDITORIAL

Biological Cybernetics

Foreword for the special issue on Lamprey and Salamander Robots and the Central Nervous System

Auke Jan Ijspeert · Sten Grillner · Paolo Dario





The Scuola Superiore Sant'Anna "Zoo" (2008)

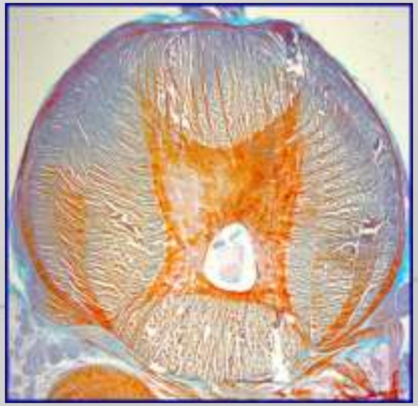
Biological model	**Scientific problem**
Oligochaeta	Role of friction in locomotion
Legged insects	Modeling compliant substrates
Polychaeta	New computational models of locomotion kinematics
Swimming cells	Swimming at low Re numbers
Cricket	Scale effects on locomotion
Lamprey	Neuroscientific models of goal-driven locomotion
Octopus	**Motor performance of hydrostatic muscular limbs**
Plant roots	Soil penetration mechanisms
Mouse	Animal-robot interaction
Homo Sapiens	Model of the sensorimotor system

The OCTOPUS FET Project

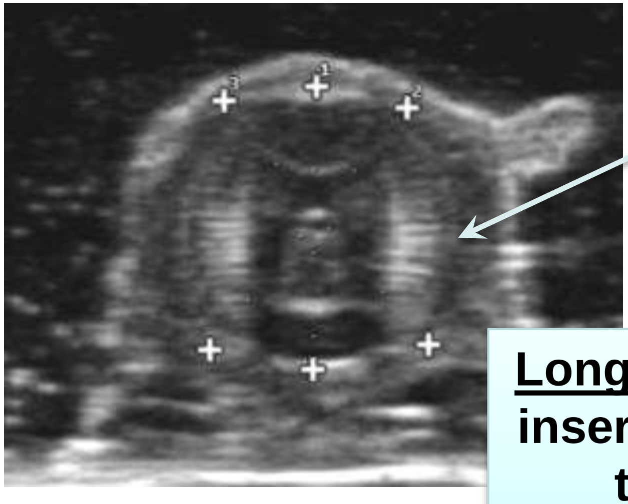
The octopus as a model for Soft Robotics and a paradigm for Embodied Intelligence

Octopus vulgaris
(phylum *Mollusca*,
class *Cephalopoda*)

- The octopus has no rigid structures
  - virtually infinite number of DOF
  - can squeeze into small apertures
  - unique biomechanical capabilities and rich repertoire of movements
- Variable and controllable stiffness
- Manipulation and locomotion capabilities
- The octopus shows rich behavior, learning capability, memory



Investigating octopus biomechanics

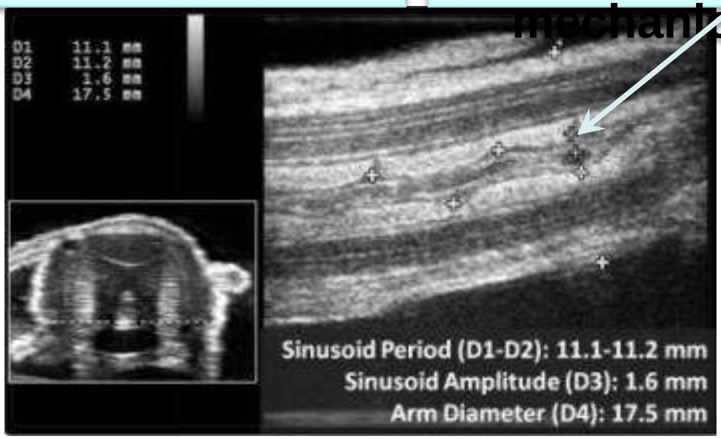


Results on Octopus Anatomy

<u>Transverse Muscles</u>: small decrease in diameter allows large elongation (constant volume property)

<u>Longitudinal Muscles</u>: insertion points along the arm allow local bending

<u>Nerve cord</u>: sinusoidal arrangement allows arms large elongation without mechanical constraint



L. Margheri, G. Ponte, B. Mazzolai, C. Laschi, G. Fiorito, "Non-invasive study of *Octopus vulgaris* arm morphology using ultrasound", *The Journal of Experimental Biology*, Vol.214, 2011, pp.3727-3731.

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and IIT Center on Micro-BioRobotics at SSSA

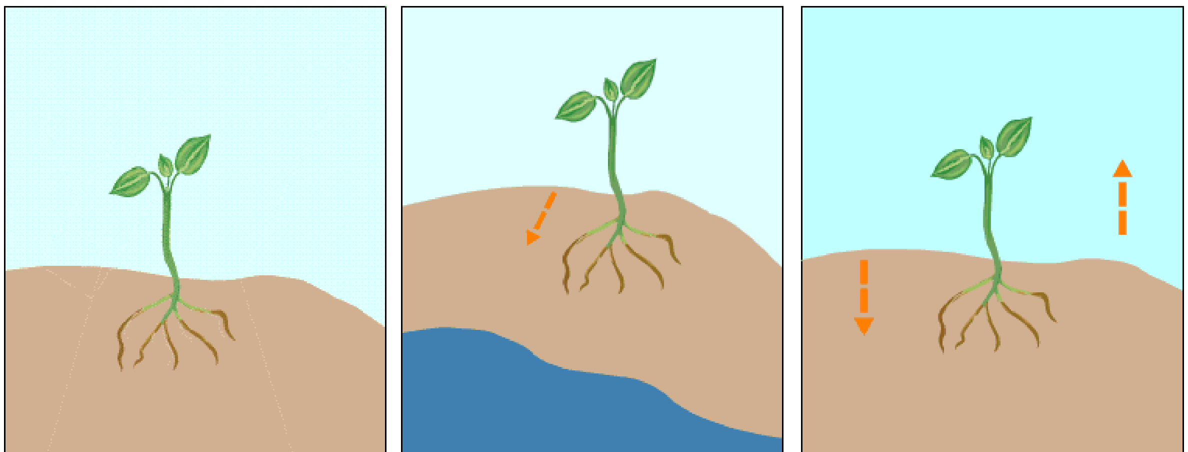
The PLANTOID FET Project

Plants are **photosynthetic**, **eukaryotic**, **multicellular** organisms characterized by an **aerial part** and a **root system**.

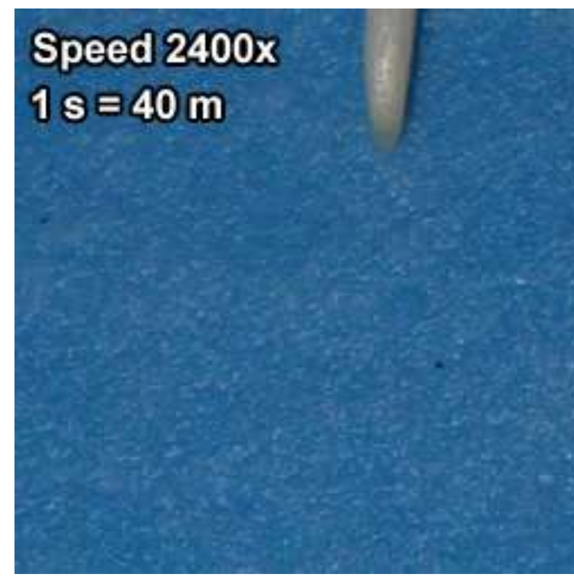
In an attempt to compensate for their **sessile** nature, they have developed growth response to deal with the copious and rapid changes in their environment. These responses are known as **tropisms**. The directional growth of plant organs in response to a directional environmental stimulus:

- **Phototropism: Light**
- **Gravitropism: Gravity**
- **Thigmotropism: Touch**
- **Hydrotropism: Water**
- **Chemotropism: Chemical**

Phototropism **Hydrotropism** **Gravitropism**



Font: http://virtualastronaut.jsc.nasa.gov/textonly/act25/text-plants.html

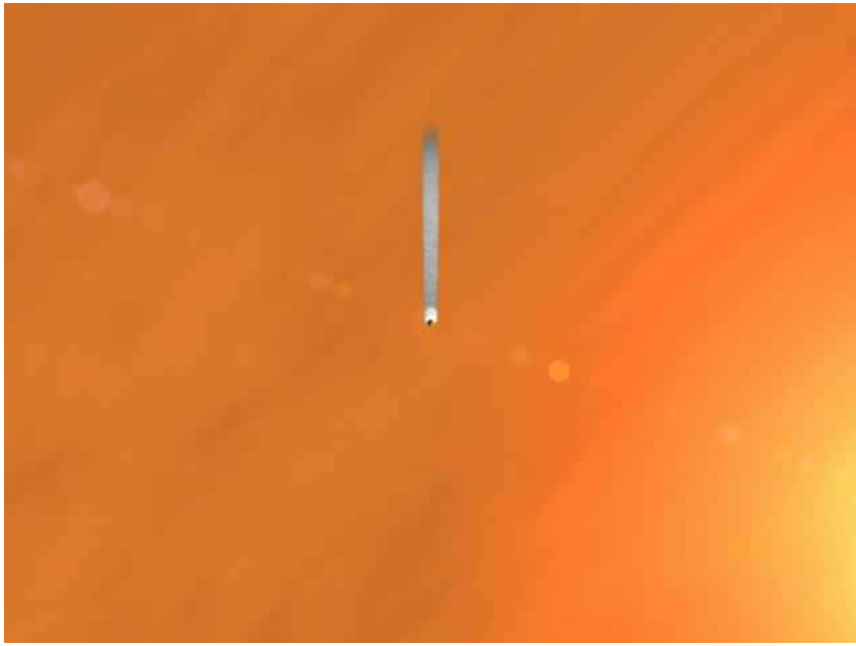


The combination of these mechanisms allows plants to overtake hostile or inaccessible environments and colonize the soil, leading to the generation of ramified root systems that assure their stability and survival.

Moreover…

… plants demonstrate to successfully reach their needs even without a conventional **locomotion system**. Although plants cannot physically move, active root growth allows **exploration of soil** niches for nutrition. This implies that root apices are not only sites of nutrient uptake but also sites of **forward movement**.

Why taking inspiration from plant's roots to build a robot for soil exploration?



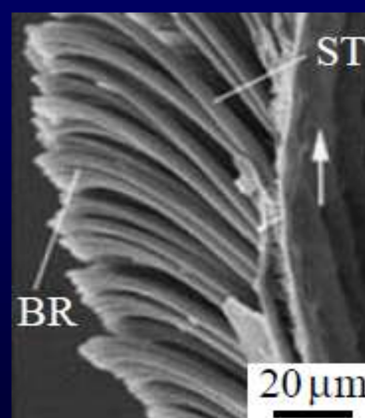
Plants use roots to:

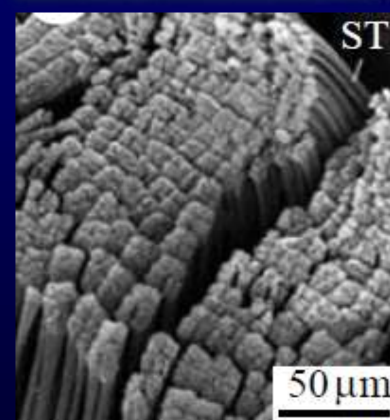
- **penetrate soil**,
- **anchor** themselves,
- **mine** the soil of minerals and water for their nourishment.

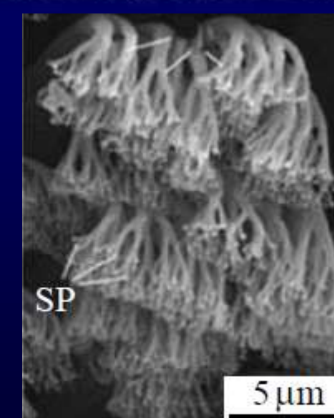
Plants explore soil in a **capillary way** by means of an expanded **network of roots and sensors**

Other examples of biomimetics in action

The 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.

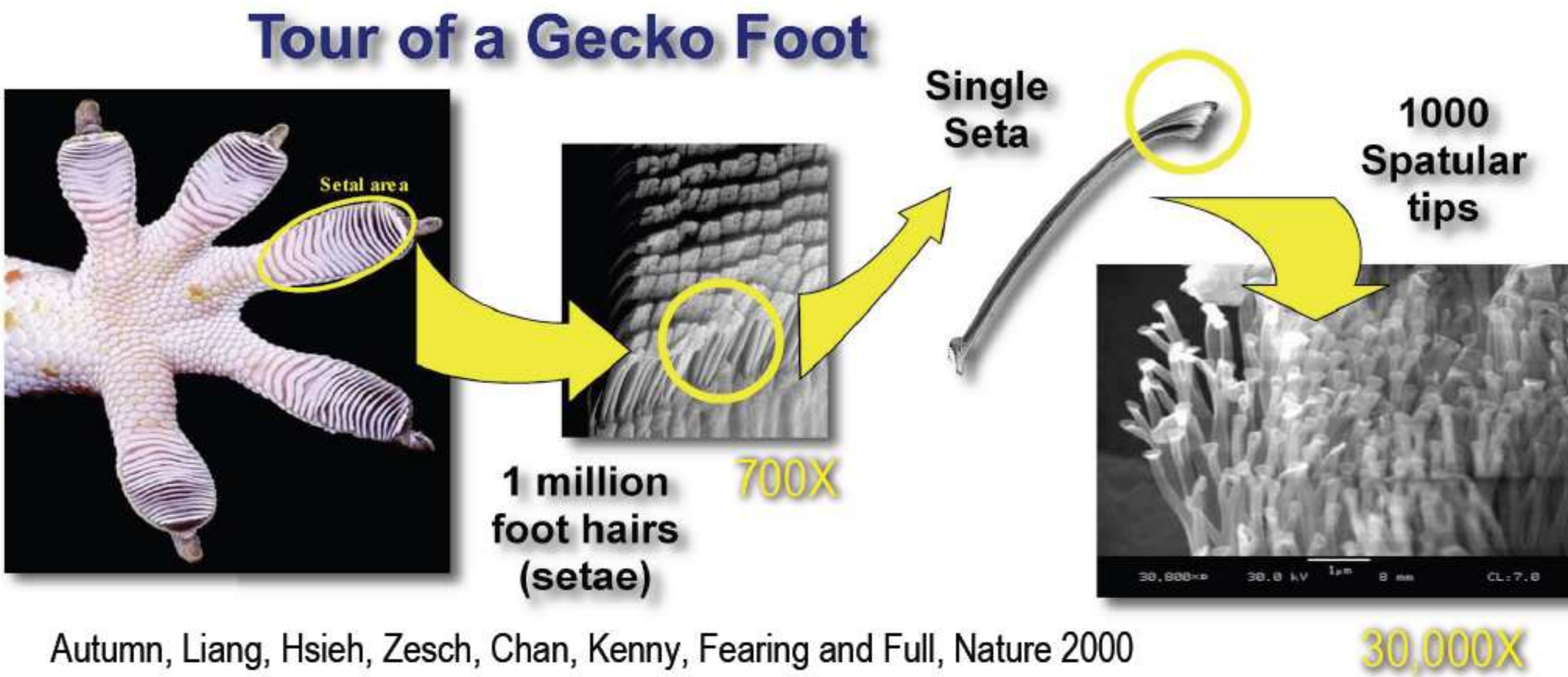






K. Autumn, M. Sitti, Y. Liang, A. Peattie, W. Hansen, S. Sponberg, T. Kenny, R. Fearing, J. Israelachvili, and R. Full. Evidence for van der waals adhesion in gecko setae. Proc. of the National Academy of Sciences of the USA, 99(19):12252–12256, 2002.

Hypotheses - regarding the principles at work



2 Billion Nano-sized split ends
Stick by van der Waals forces!

The Scuola Superiore Sant'Anna "Zoo" (2008)

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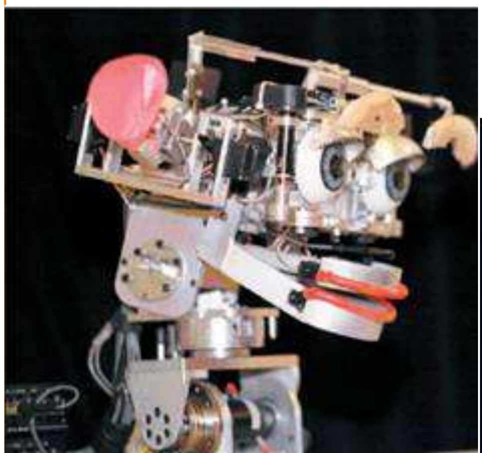
Homo Sapiens	**Model of the sensorimotor system**

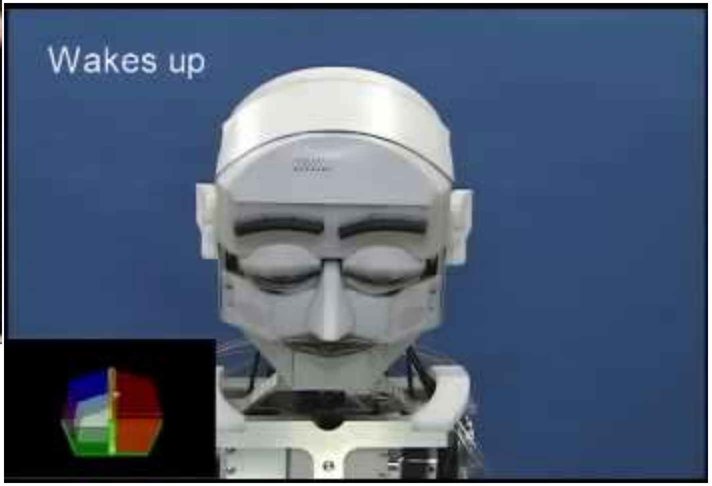
Soft robotics for emotional robots

Emotional robotics

Muppet/Pet-like



Anthropomorphic, but clearly artificial



'Android'

Three different approaches are possible

Paul Ekman's classification of emotions

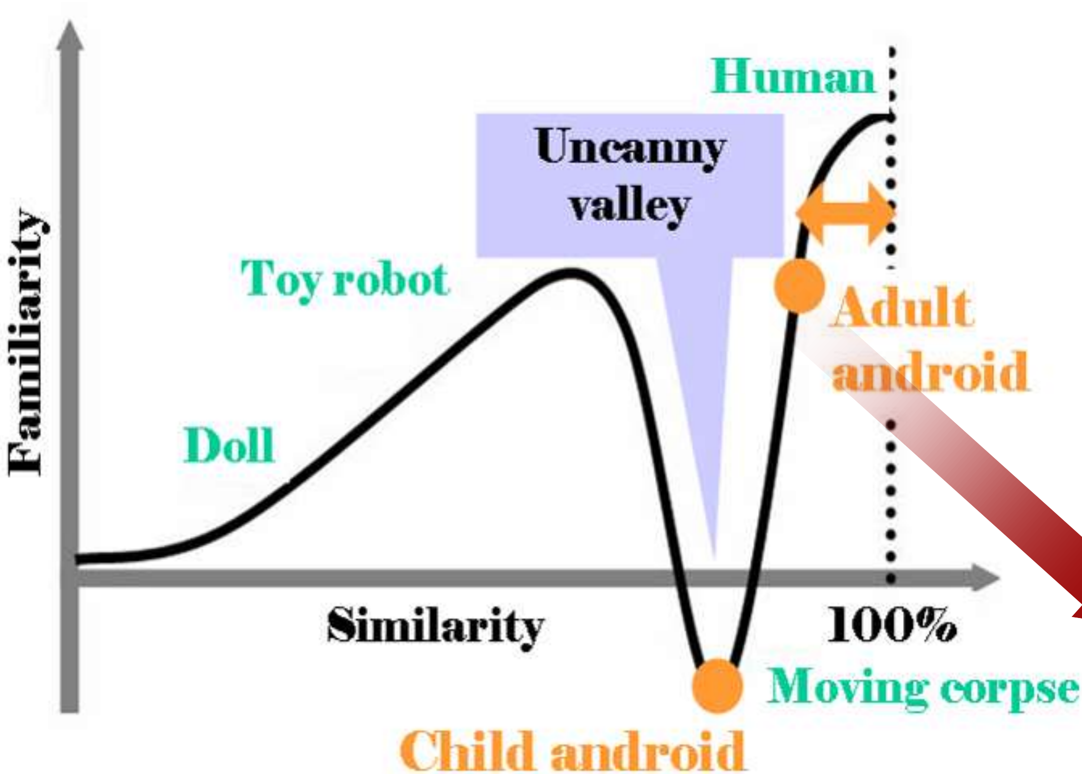
- **Ekman's list of basic emotions (1970'):**
  - **anger**
  - **fear**
  - **surprise**
  - **sadness**
  - **happiness**
  - **disgust**

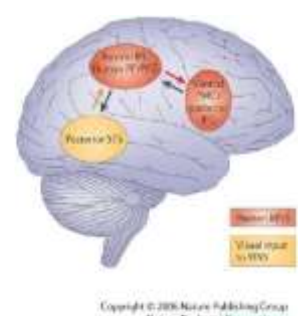
The facial expressions of the 6 primary emotions are common to all cultures

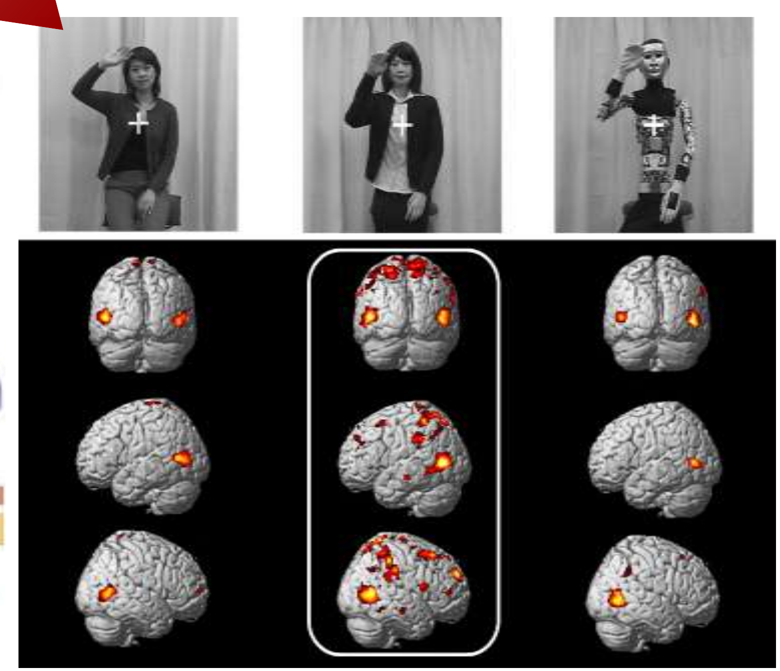
Hiroshi Ishiguro’s android science

Repliee Q1

Uncanny valley



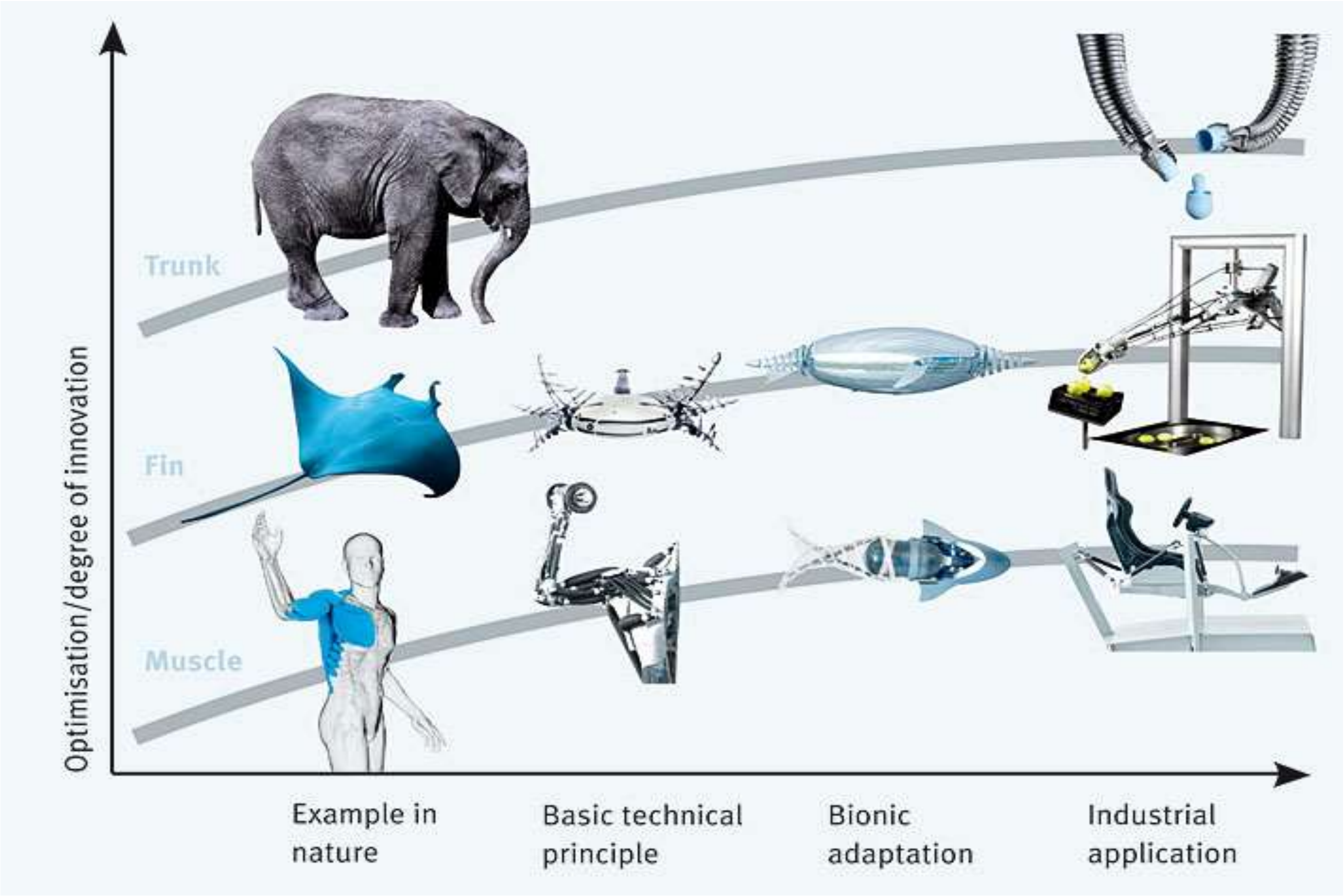




Biorobotics Science: using robotics to ***discover new principles***…

Biorobotics Engineering: using robotics to ***invent new solutions***….

Biorobotics Engineering



Using **biological principles** of functioning to develop **new engineering solutions**

The Scuola Superiore Sant'Anna "Zoo"

Biological model	Scientific problem	Engineering application
Oligochaeta	Role of friction in locomotion	Endoscopy of GI tract
Legged insects	Modeling compliant substrates	Endoscopy of GI tract
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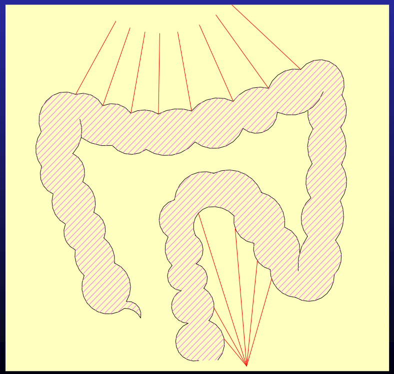
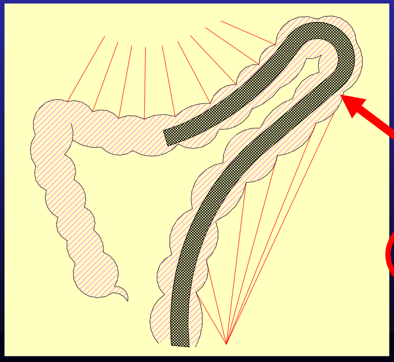
Early Detection of Colon Cancer Saves Life. Colonoscopy is the Gold Standard. But…

- Pain and disconfort for the patient
- Complex and demanding procedure for the doctor

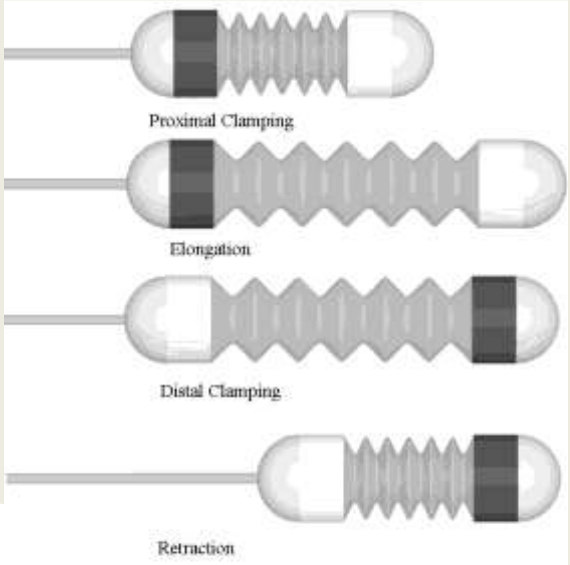
- The active part of the colonoscope is the head, that incorporates the visualization system (optical fibers or camera, optics, illumination)
- The head must be inserted along the colon by maneuvering and pushing, from outside the body, a relatively stiff shaft
- These actions stretch the colon and originate pain





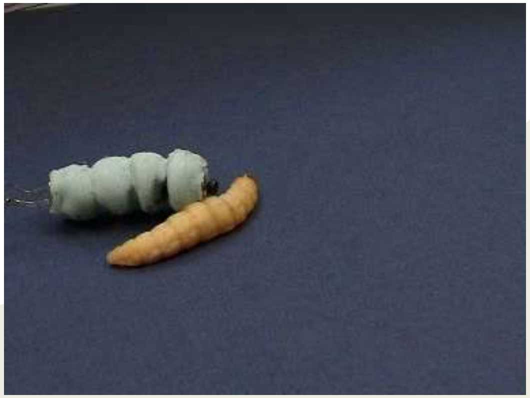
From **bio-inspiration** to **bio-application**
(the EU FET BIOLOCH and the EMIL IMC Projects)

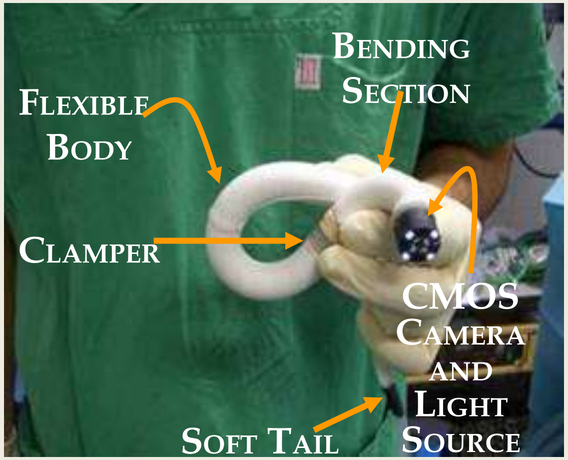
Problems in colonoscopy: pain, difficult maneuverability…



Semi-autonomous inchworm-like locomotion

...like a worm in the gut...





The E-WORM Painless Colonoscopy System

Int J Artif Organs. 2009 Oct 21;32(8):517-527. [Epub ahead of print]

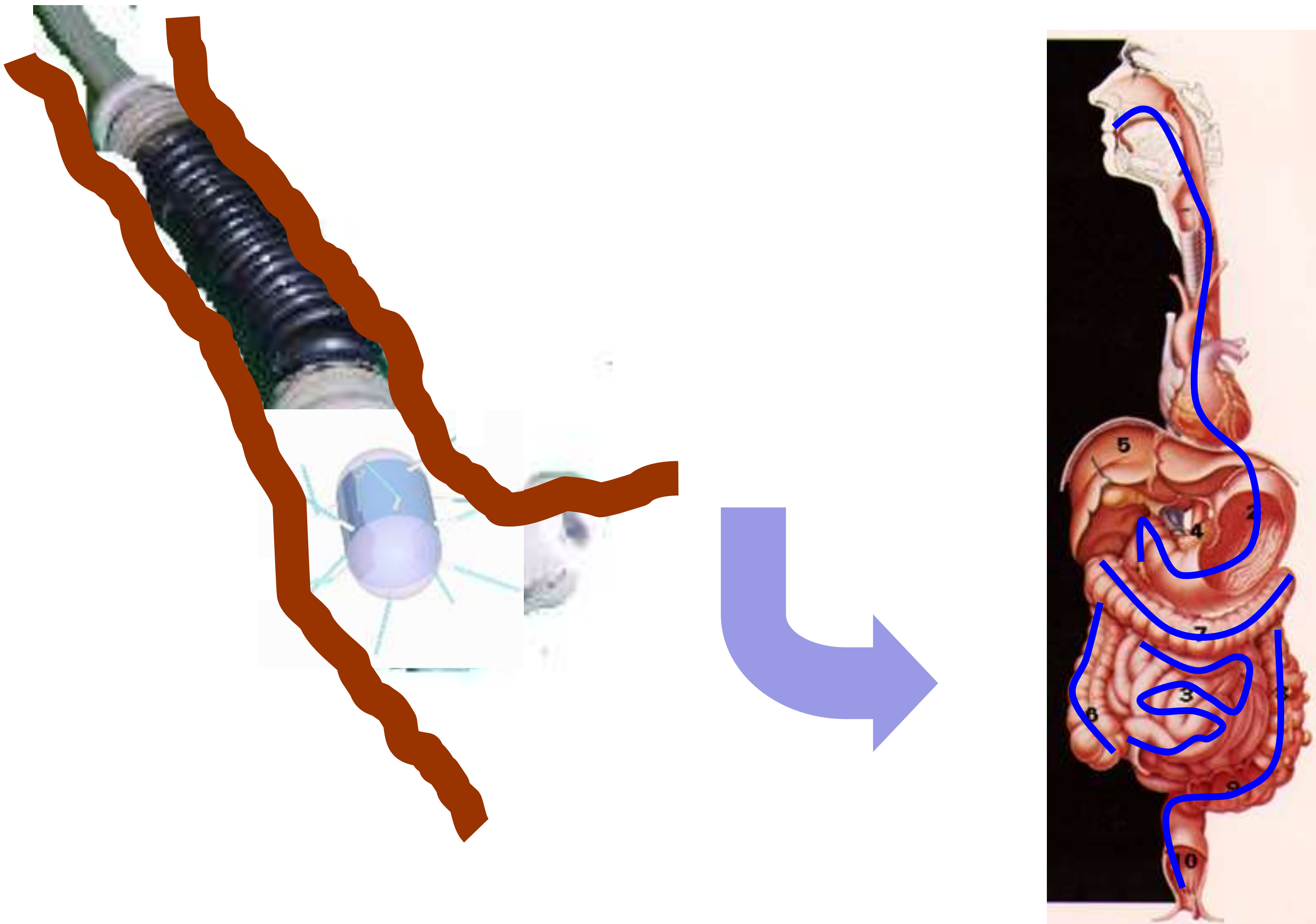
Functional evaluation of the Endotics System, a new disposable self-propelled robotic colonoscope: in vitro tests and clinical trial.

Cosentino F, Tumino E, Rubis Passoni G, Morandi E, Capria A.
Gastroenterology and Digestive Endoscopy, San Giuseppe Hospital, Milan - Italy.

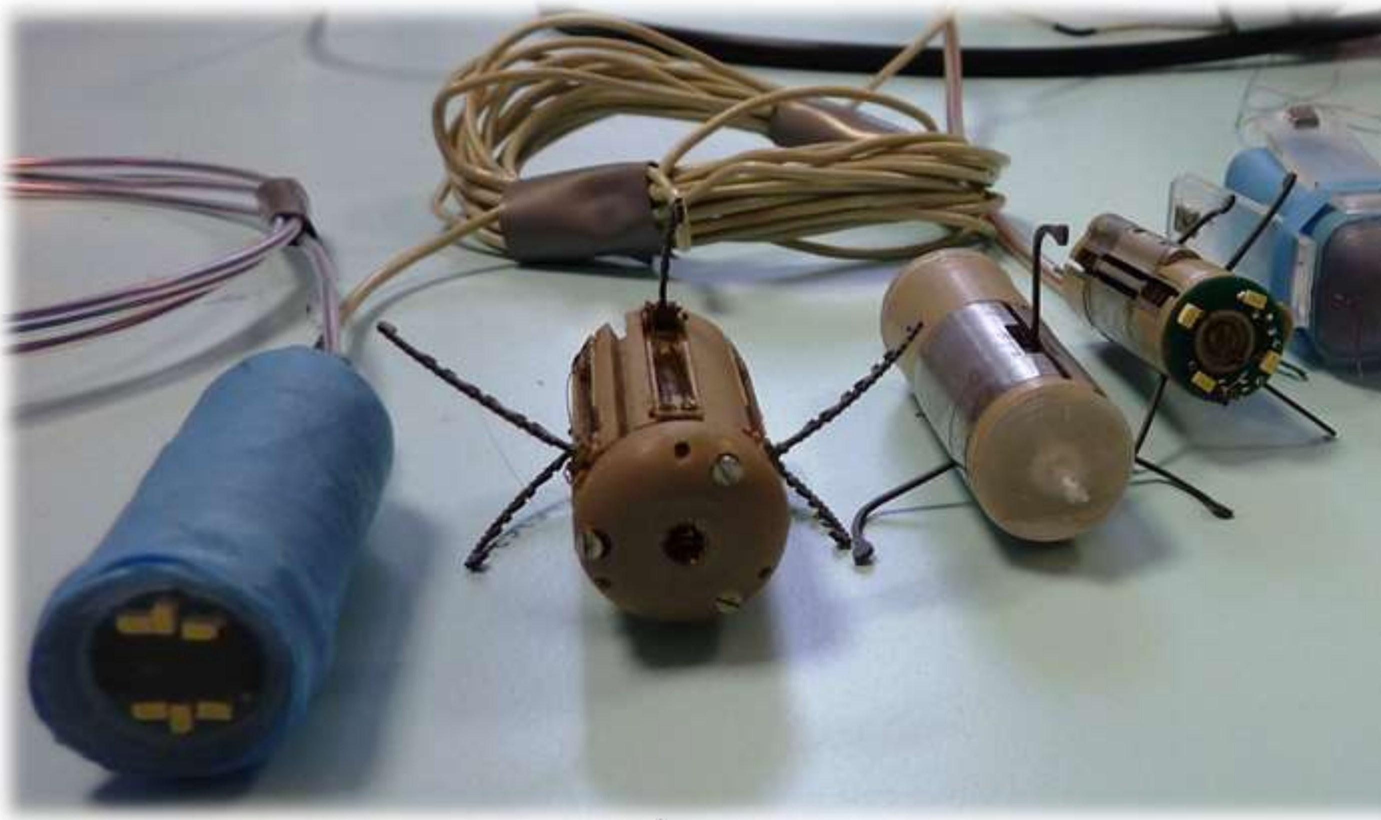
Abstract

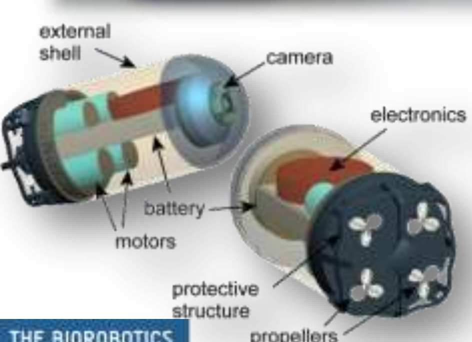
Objective: Currently, the best method for CRC screening is colonoscopy, which ideally (where possible) is performed under partial or deep sedation. This study aims to evaluate the efficacy of the Endotics System, a new robotic device composed of a workstation and a disposable probe, in performing accurate and well-tolerated colonoscopies. This new system could also be considered a precursor of other innovating vectors for atraumatic locomotion through natural orifices such as the bowel. The flexible probe adapts its shape to the complex contours of the colon, thereby exerting **low strenuous forces during its movement**. These novel characteristics allow for a painless and safe colonoscopy, thus eliminating all major associated risks such as infection, cardiopulmonary complications and colon perforation. Methods: An experimental study was devised to investigate stress pattern differences between traditional and robotic colonoscopy, in which **40 enrolled patients underwent both robotic and standard colonoscopy within the same day**. Results: The stress pattern related to robotic colonoscopy was **90% lower than that of standard colonoscopy**. Additionally, the robotic colonoscopy demonstrated a **higher diagnostic accuracy**, since, due to the lower insufflation rate, it was able to visualize small polyps and angiodysplasias not seen during the standard colonoscopy. **All patients rated the robotic colonoscopy as virtually painless compared to the standard colonoscopy, ranking pain and discomfort as 0.9 and 1.1 respectively, on a scale of 0 to 10, versus 6.9 and 6.8 respectively for the standard device**. Conclusions: The new Endotics System demonstrates efficacy in the diagnosis of colonic pathologies using a procedure nearly completely devoid of pain. Therefore, this system can also be looked upon as the first step toward developing and implementing colonoscopy with atraumatic locomotion through the bowel while maintaining a high level of diagnostic accuracy.

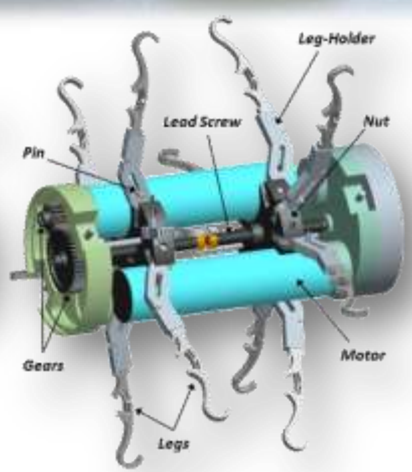
From “wired”painless colonoscopy to “wireless” GI endoscopy



ACTIVE capsules developed at The BioRobotics Institute





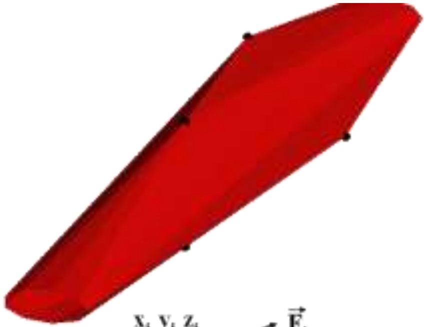


THE BIOROBOTICS INSTITUTE

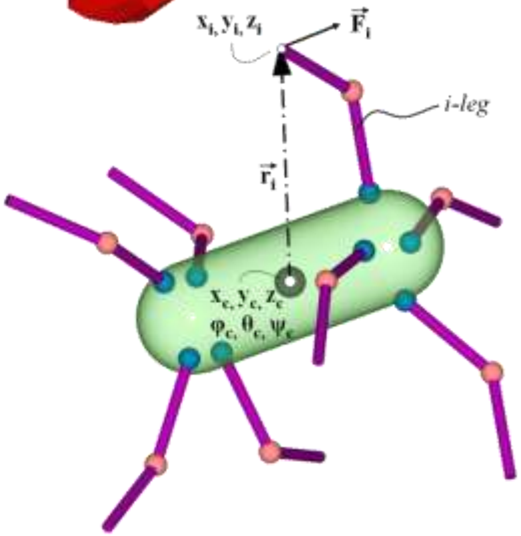
Scuola Superiore Sant'Anna

Modeling legged robot locomotion on soft compliant substrates

Tissue characterization, for determining gut biotribology and longitudinal + transversal bioelasticity

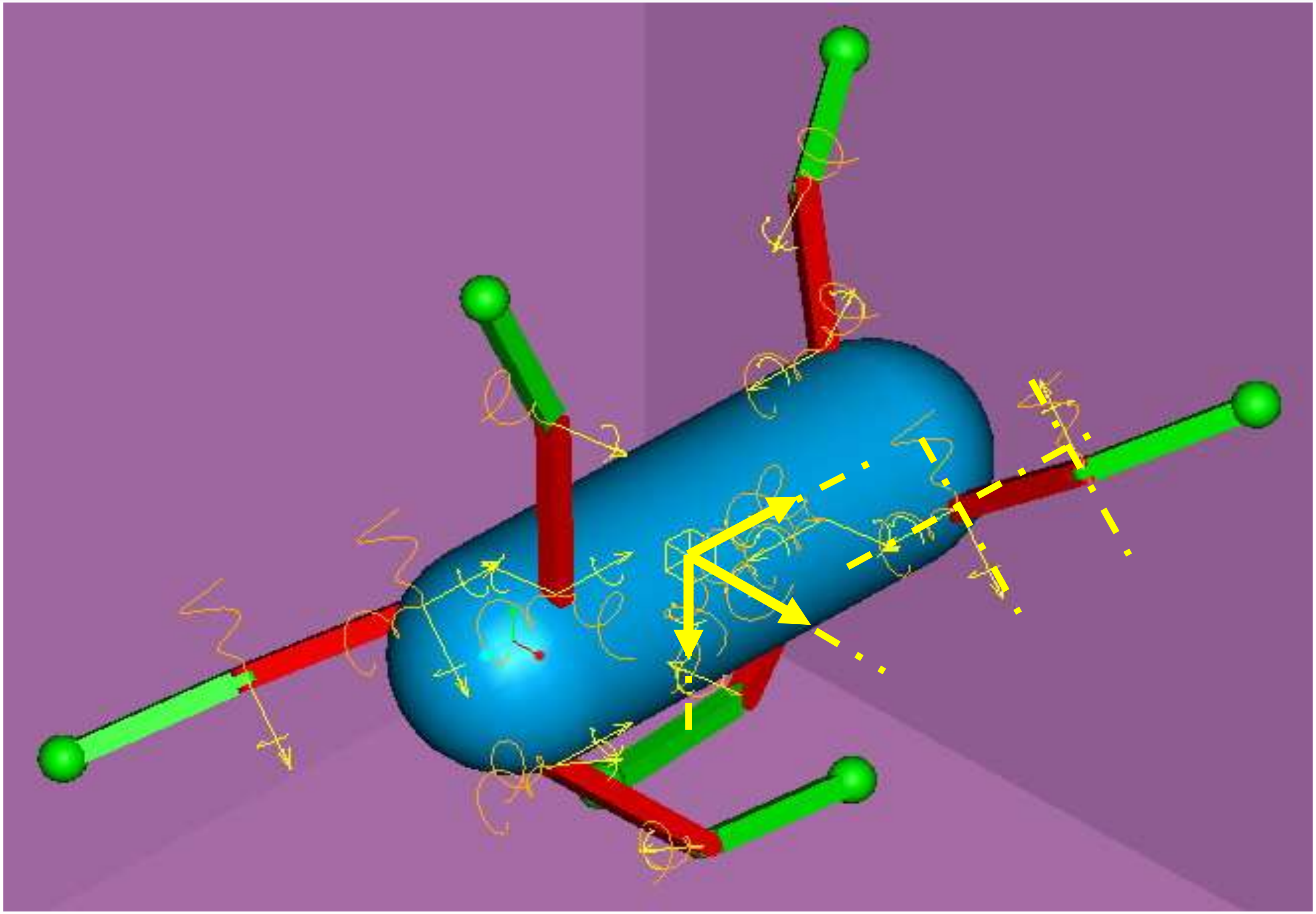


Geometrical description of the deformed GI tract as convex hull of the set of points given by feet contacts



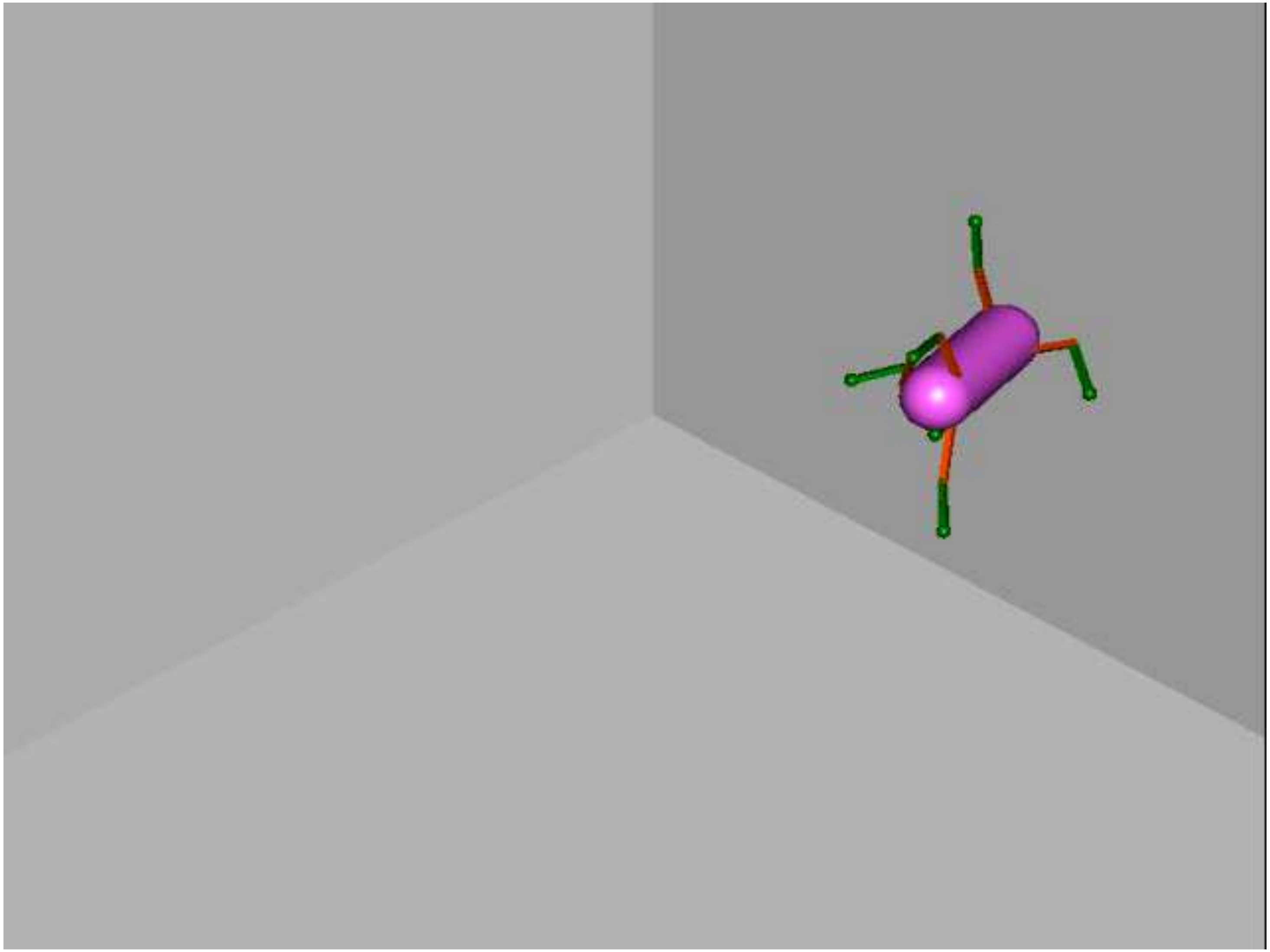
Modeling equations of capsule kinematics and capsule / tissue interaction

Free body kinematics



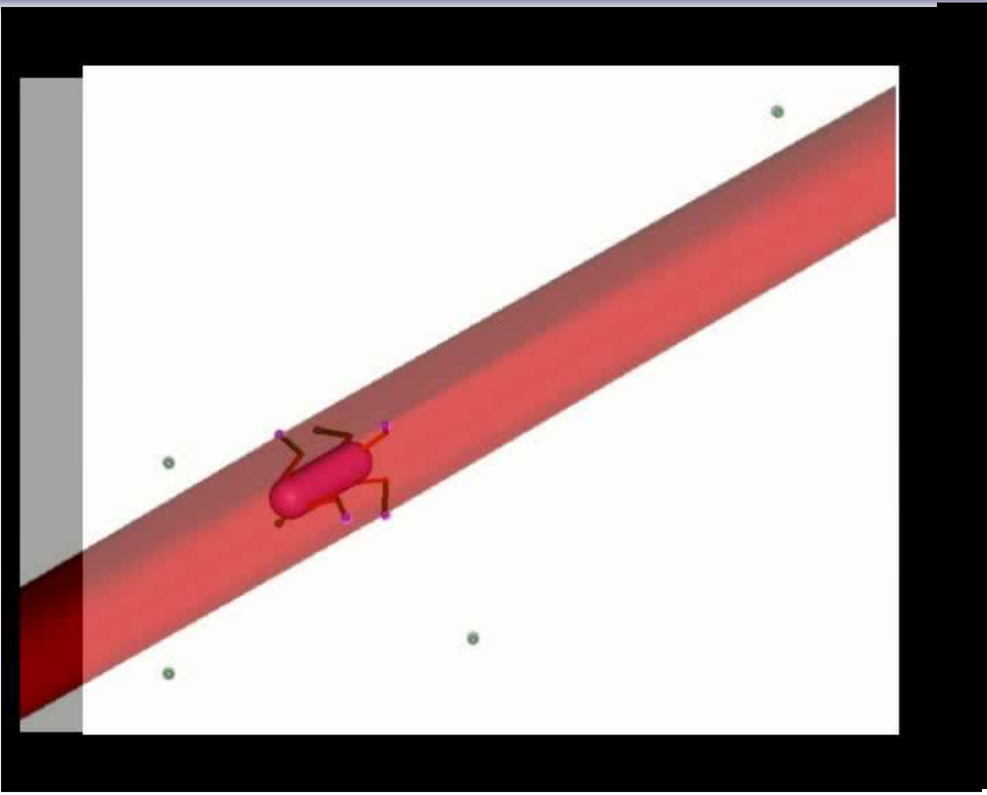
Modeled degrees of freedom: 3 (body trans.) + 3 (body rot.) + 3n (legs)

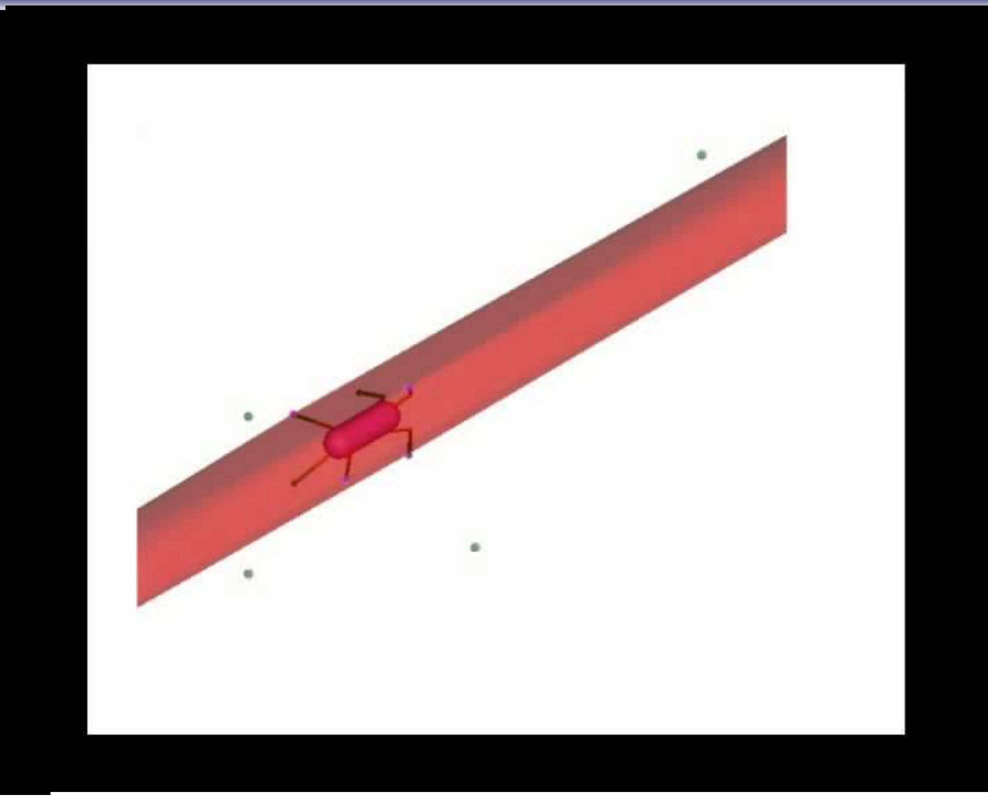
Free body kinematics



Modeled degrees of freedom: 3 (body trans.) + 3 (body rot.) + 3n (legs)

Comparing different gait patterns



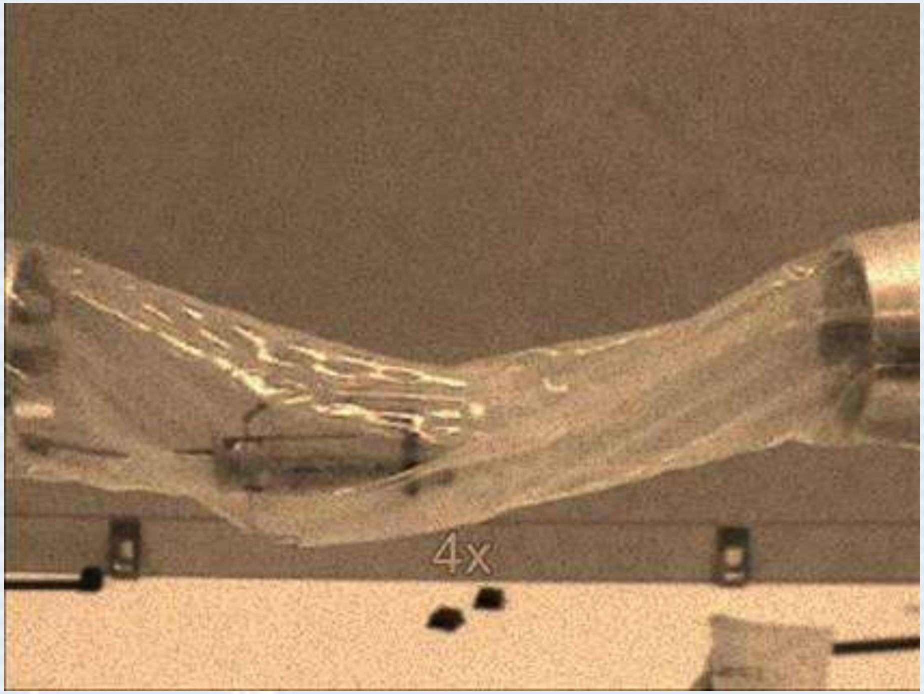


Front/rear phase:	**0°**	**Front/rear phase:**	**180°**
Period:	**3 s**	**Period:**	**3 s**
Full interval:	**12 s**	**Full interval:**	**12 s**
Traveled distance:	**23 mm**	**Traveled distance:**	**144 mm**

"Rower Gait" **"Out of phase rower gait"**

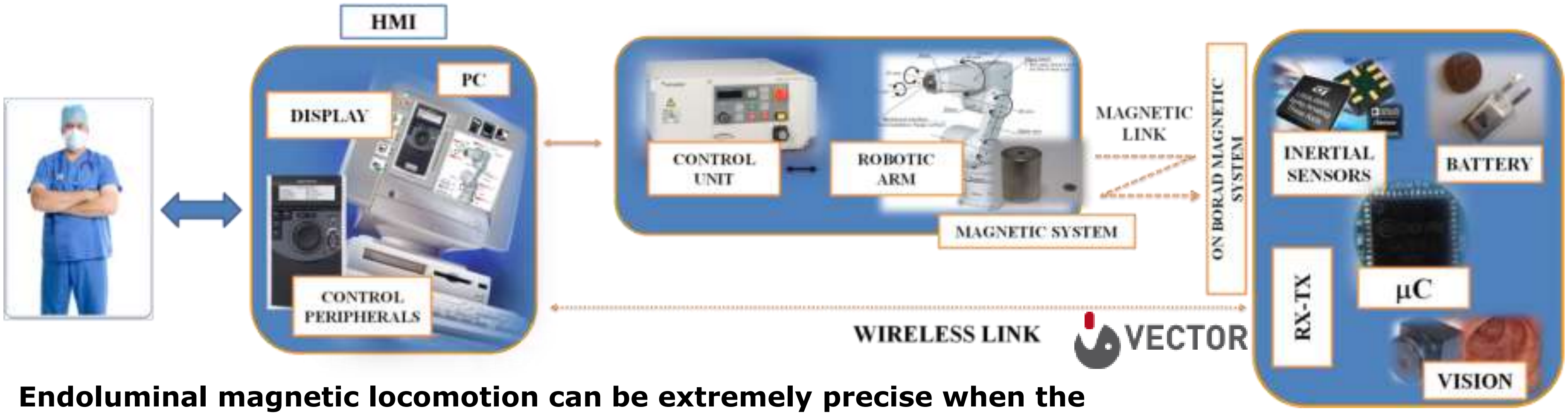
In vitro tests of legged locomotion IMC

*4-leg capsule **with** front balloon*

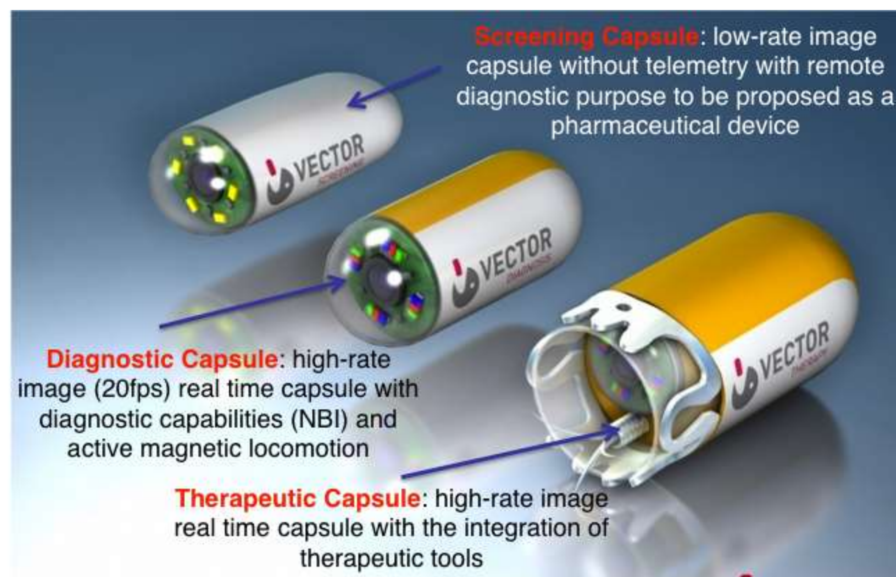


*8-leg capsule **without** front balloon*

How to overcome the energy problem in active capsular endoscopy: magnetic assisted locomotion



Endoluminal magnetic locomotion can be extremely precise when the external magnet (s) is/are moved by means of high precision robot(s)



FP6 European Project VECTOR – "Versatile Endoscopic Capsule for gastrointestinal Tumor Recognition and Therapy" (EU/IST-2006-033970) (http://www.vector-project.com/)

VECTOR

The Scuola Superiore Sant'Anna "Zoo"

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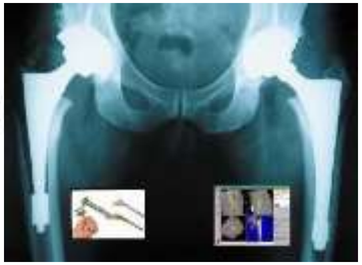
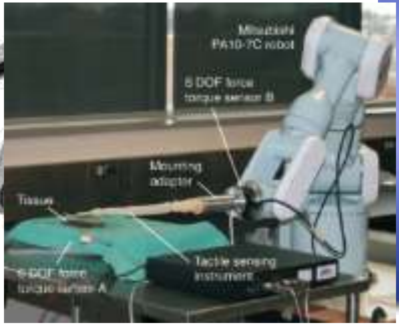
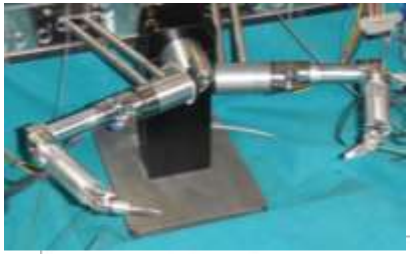
Medical Robotics: an increasingly successful clinical and industrial field







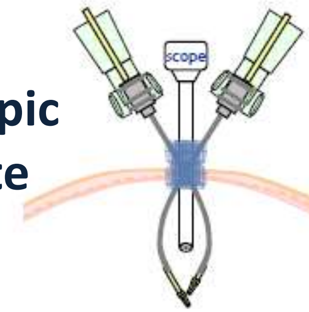
Minimally Invasive Surgery

Vitiello et al., *Biomedical Engineering, IEEE Reviews,* 2013

- Open surgery

- Laparoscopic surgery

- Laparo-endoscopic single site surgery



- Natural Orifice translumenal endoscopic surgery

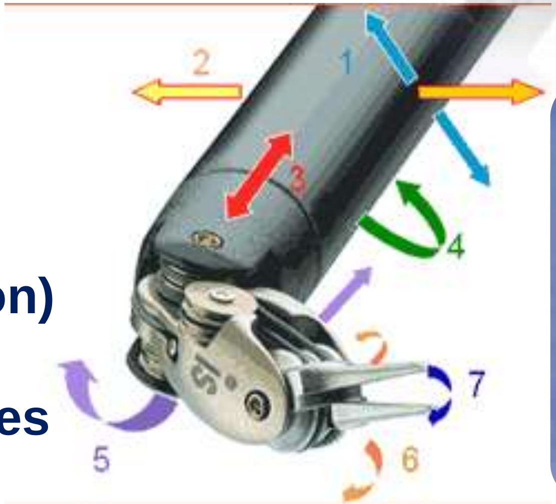
INVASIVENESS

Achievements of Robotics Surgery

- Game-changing applications
- Technically advanced and dependable systems
- Widely accepted and used in clinical practice by surgeons, by patients and by hospital administrations: 450.000+ surgical interventions worldwide in 2012
- Real IMPACT on health, and on economy (real products, real jobs)

The "Secrets" of the DaVinci Robot Success: Accuracy, Dexterity, Intuitiveness

- Outstanding mechanical design
- Excellent optics (2D and 3D vision)
- Smart and friendly interfaces



Robotics Surgery: Lessons Learned

- **Real application domains** and procedures that benefit
- **Cost/benefit** clearly proved
- **Time of intervention** kept short
- **Time and complexity for set-up** to be **minimized**

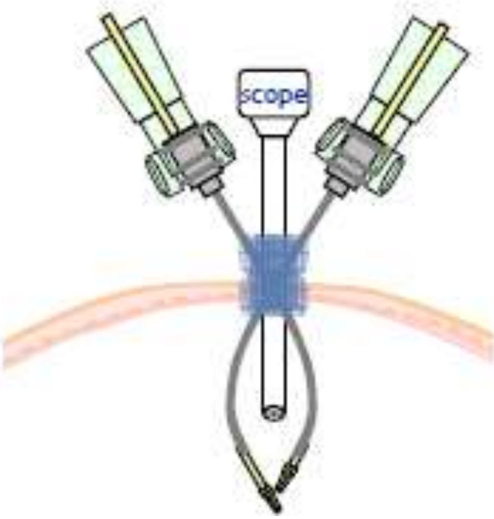
What’s next?

- Consolidating the success story of Robotics Surgery by addressing the still many open research issues and technical/clinical/industrial limitations
- Simplifying the complexity and reducing the cost of procedures
- Exploring new avenues and paradigms (one more ‘game change’ in surgery with robots?)

Towards effective reduction of invasiveness of surgical interventions

single site/port surgery

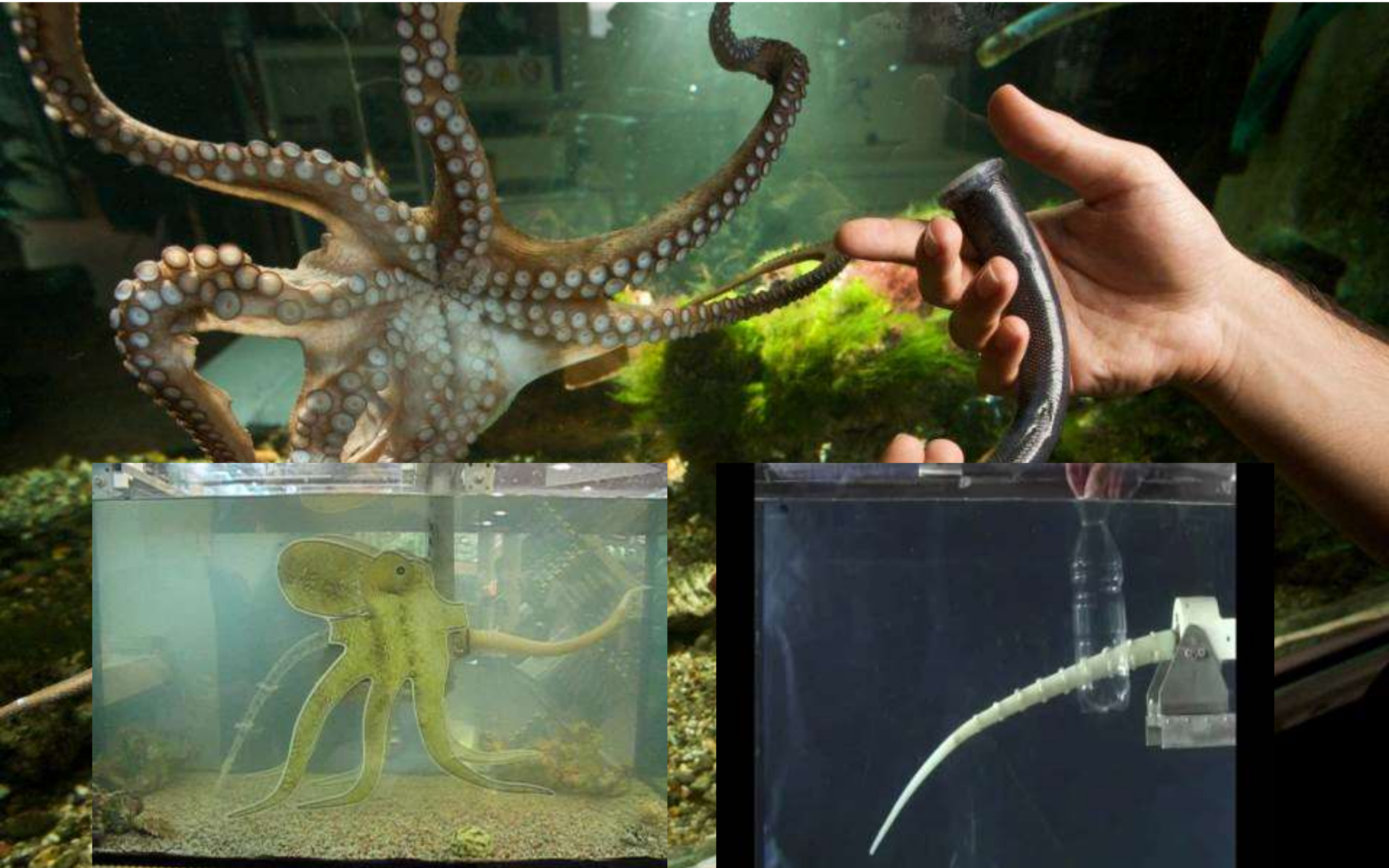
Galvao Neto et al., Techniques in Gastrointestinal Endoscopy, 2009.



Da Vinci robot with single port instrumentation during an intervention

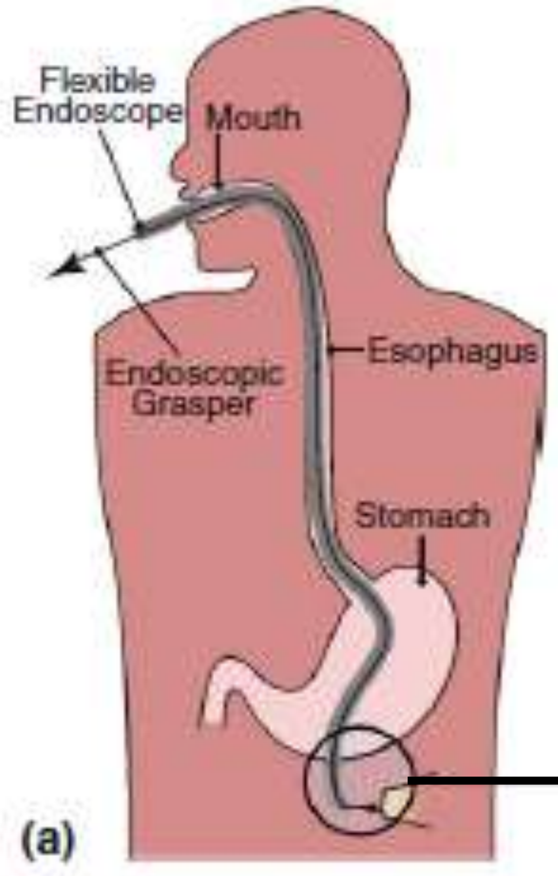
- **Limited manoevrability**
- **Lack of triangulation**
- **Clashing of instruments**

From biology to soft robots for surgery

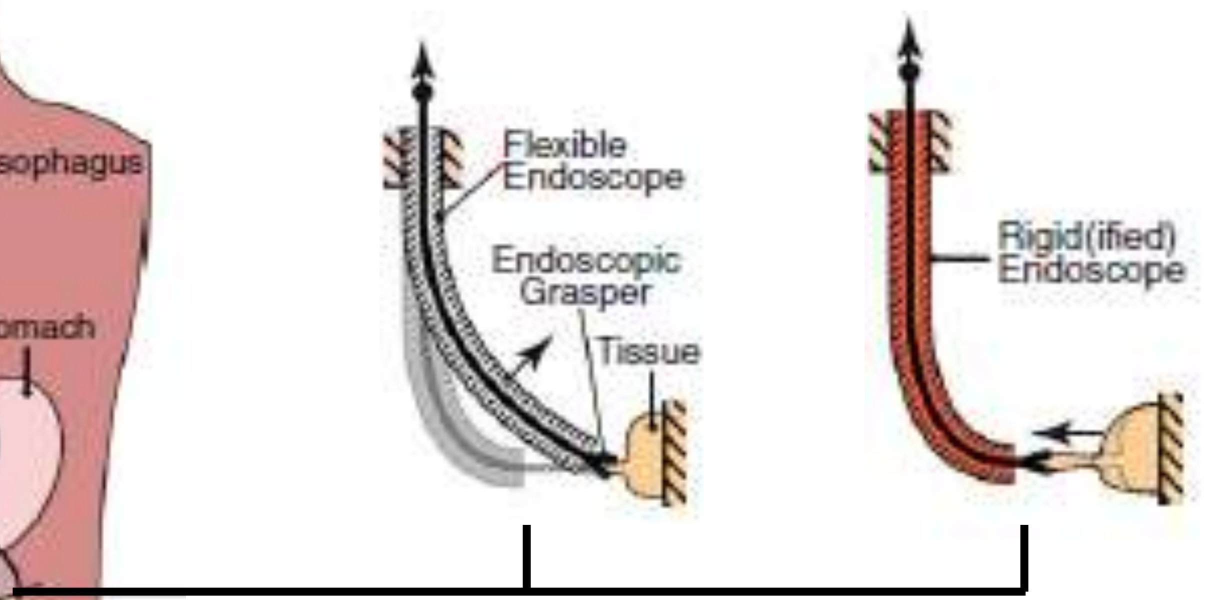


Towards effective reduction of invasiveness of surgical interventions

NOTES interventions



- **Low dexterity and forces at the surgical target**
- **Lack of stability (stiffness)**

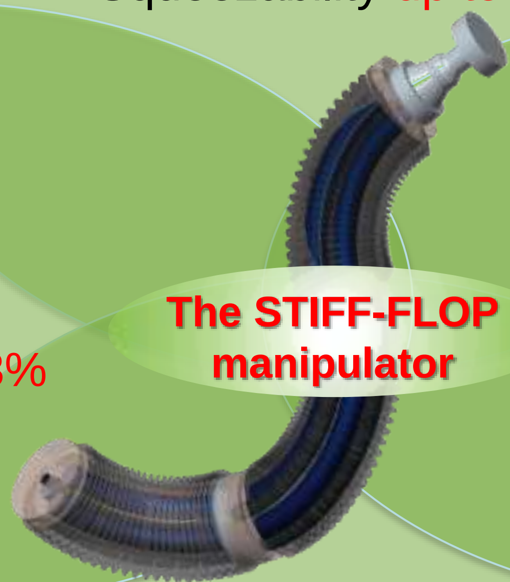


Loeve et al., *Pulse, IEEE*, 2010

Matching all requirements for surgery…

NOTES and Single port procedures
Squeezability up to 40%

High dexterity
- Omnidirectional bending up to 120°
- Elongation up to 86.3%
- Precise manoeuvres



The STIFF-FLOP manipulator

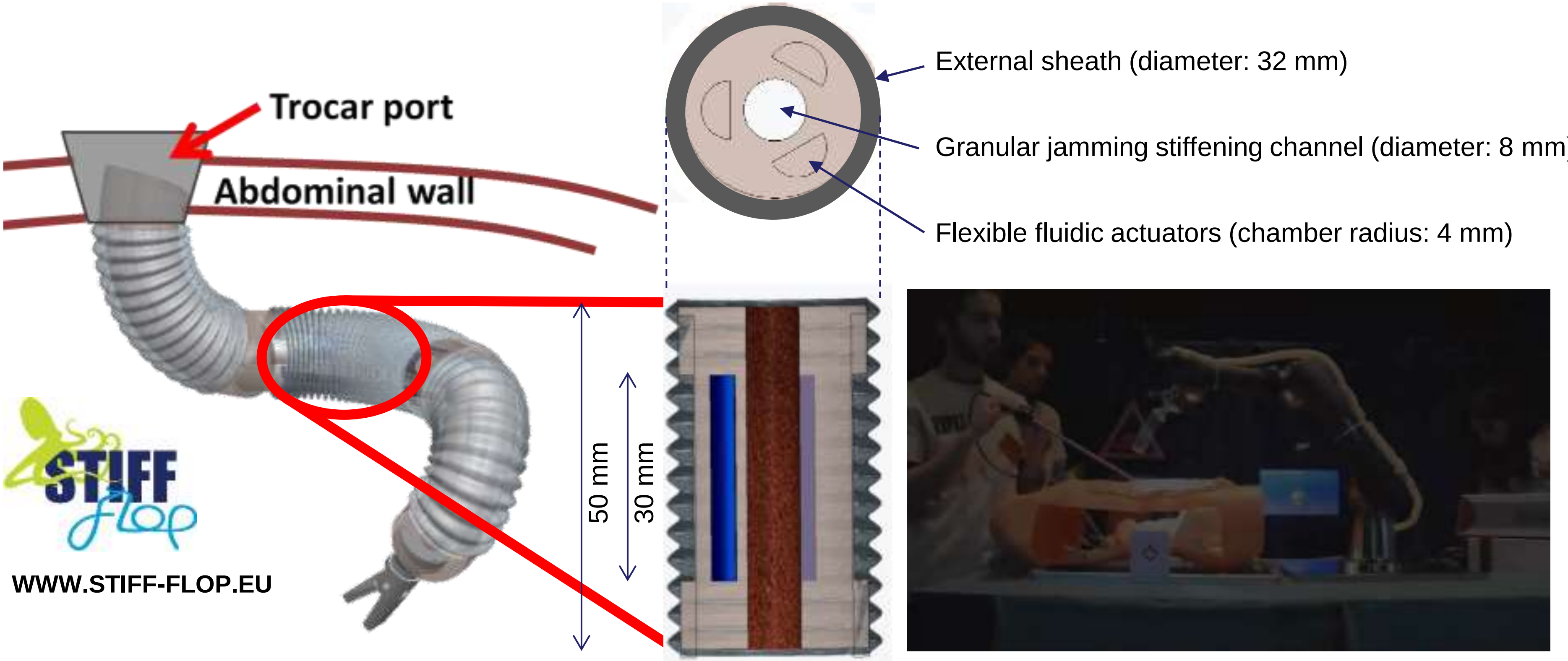
Force
for reliable traction
up to 47N

Controllable stiffness
Adaptation of compliance to different organs
up to +36%

Cianchetti M, Ranzani T, Gerboni G, De Falco I, Laschi C, Menciassi A (2013) "STIFF-FLOP Surgical Manipulator: mechanical design and experimental characterization of the single module", *Conf Proc IEEE on Intelligent and Robotic Systems* – IROS 2013, 3567-3581

The STIFF-FLOP robotic manipualtor

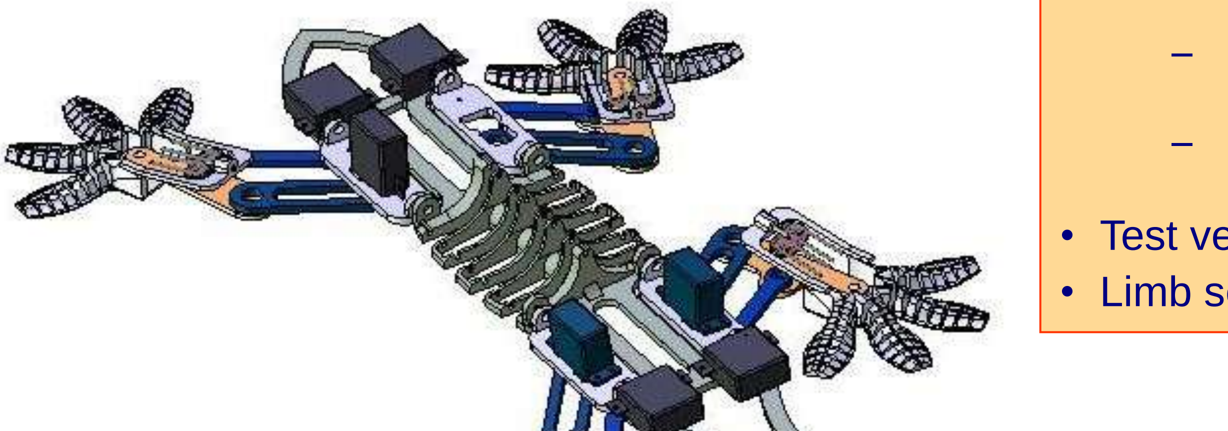
STIFFness controllable Flexible and Learn-able manipulator for surgical OPerations

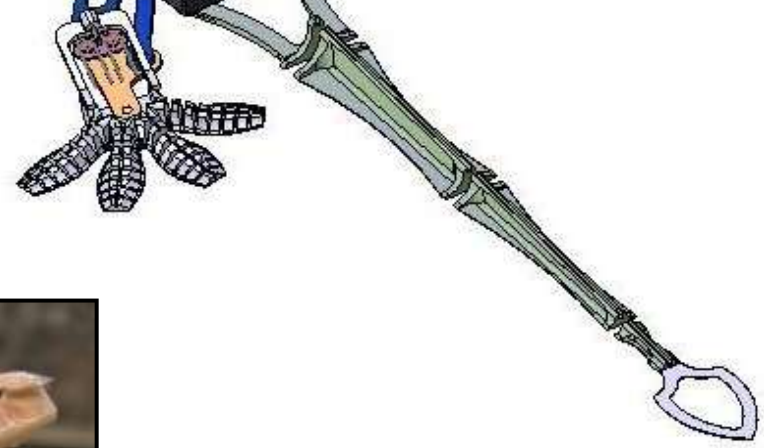


Cianchetti M, Ranzani T, Gerboni G, Nanayakkara T, Althoefer K, Dasgupta P, Menciassi A “Soft robotics technologies to address shortcomings in today’s minimally invasive surgery: the STIFF-FLOP approach” to appear in *Soft Robotics*.

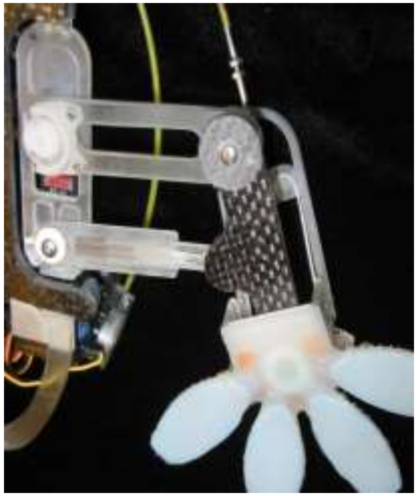
Robotics - Implementations of gecko's principles

StickyBot





- Hierarchical compliance:
  - 4 grades of polymer, carbon fibers and fabric for directional stiffening
  - Highly under-actuated: 12 servos, 38 DOF.
  - Double differential toe mechanism for conforming and peeling
- Test vehicle for directional adhesives
- Limb sensors for force control.



http://bdml.stanford.edu/twiki/bin/view/Main/StickyBot

SpinyBot II

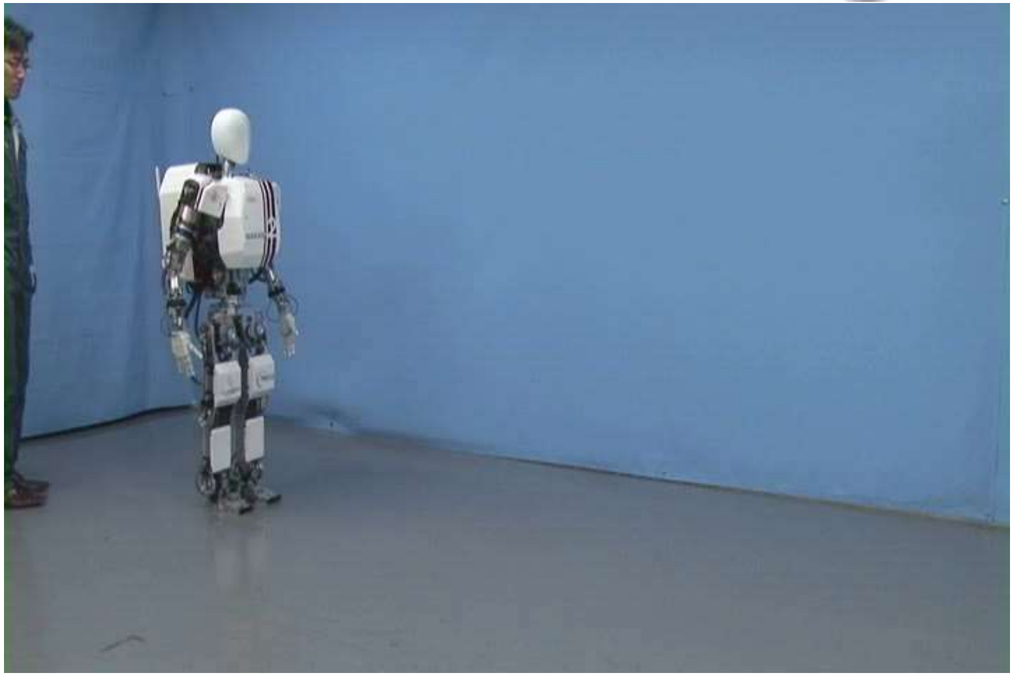
Stanford University
October 21-22, 2004

The Scuola Superiore Sant'Anna "Zoo"

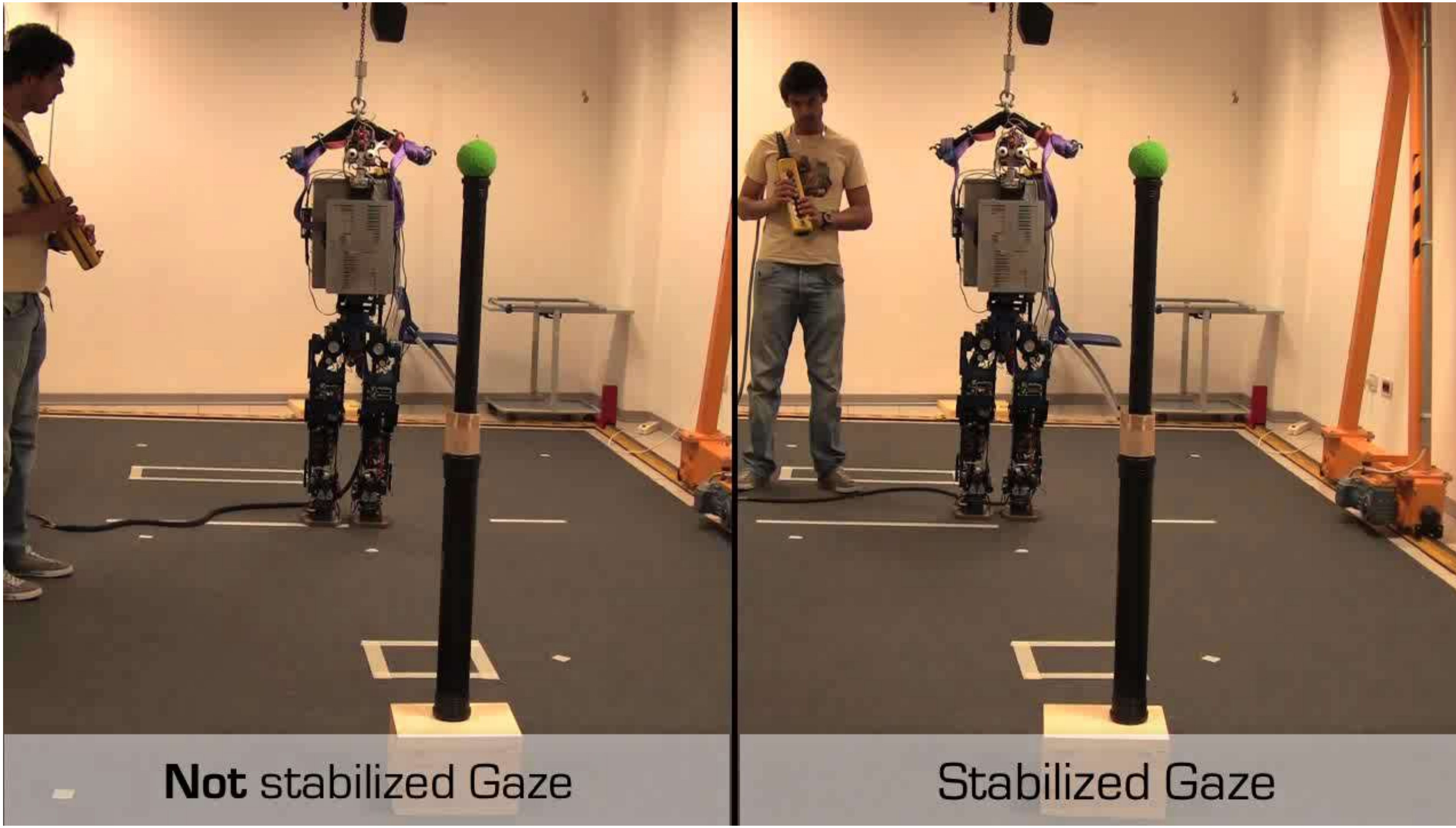
Biological model	Scientific problem	Engineering application
Oligochaeta	Role of friction in locomotion	Endoscopy of GI tract
Legged insects	Modeling compliant substrates	Endoscopy of GI tract
Polychaeta	New computational models of locomotion kinematics	Rescue, field robotics
Swimming cells	Swimming at low Re numbers	Neuroendoscopy
Cricket	Scale effects on locomotion	Mobile sensor networks
Lamprey	Neuroscientific models of goal-driven locomotion	River exploration, new robots (soft bodied)
Octopus	Motor performance of hydrostatic muscular limbs	Infinite DOF robots, rescue, marine
Plant roots	Soil penetration mechanisms	Environmental robotics
Mouse	Animal-robot interaction	Entertainment, …
Homo Sapiens	**Model of the sensorimotor system**	**Advances in humanoid robots**

Neuroscientific models may be useful to improve the performance and robustness of current humanoid robots

Asimo falling



The ‘WABIAN’ Humanoid by Waseda University, Tokyo



The 'SABIAN' Humanoid Robot by Scuola Superiore Sant'Anna and Waseda University, used for tests on neuroscience-based locomotion control theory

The ‘SABIAN’ Humanoid Robot by Scuola Superiore Sant’Anna and Waseda University, used for tests on neuroscience-based locomotion control theory

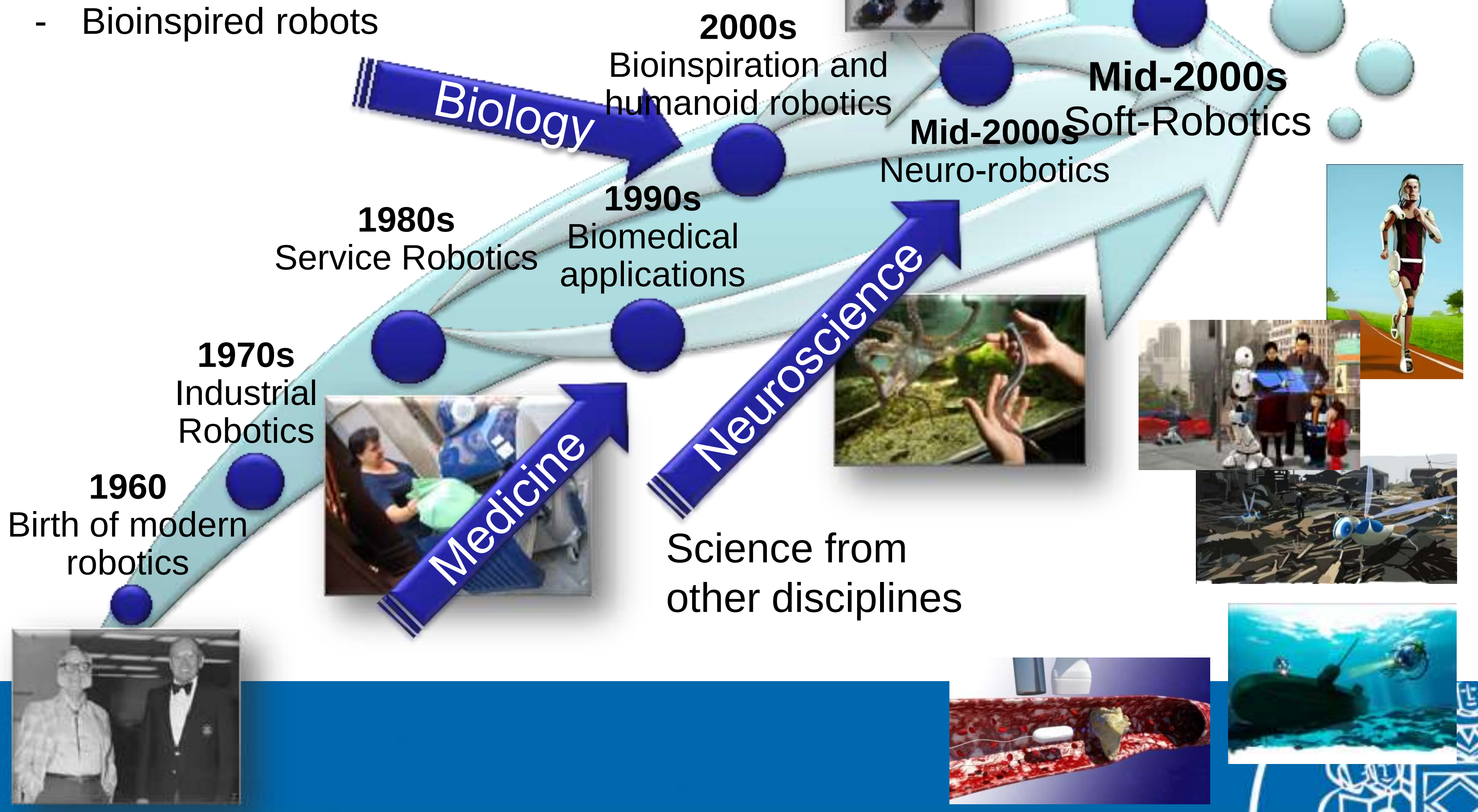
Soft «huggable» robot

http://www.youtube.com/watch?feature=player_embedded&v=nJXkL7bcQR0

Milestones of BioRobotics… …towards Robot Companions

Biorobotics Science and Engineering:

- Robots for biomedical applications (rehabilitation, surgery)
- Bioinspired robots



Outline

- BioRobotics and Soft Robotics
- What are *Robot Companions*?
- New frontiers for BioRobotics and Robot Companions with Soft Robotics
- Conclusions

Life Companions

Robot Companions for all ages

Preterm birth — Extended independent life

Infancy

Maturity

Old age

Neurodevelopmental bioengineering

Robotics for frail age to prolong autonomy

Robotics at work

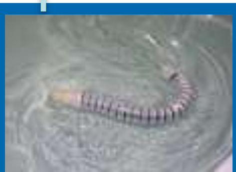
Educational robotics

Ambient Assisted Living (AAL)

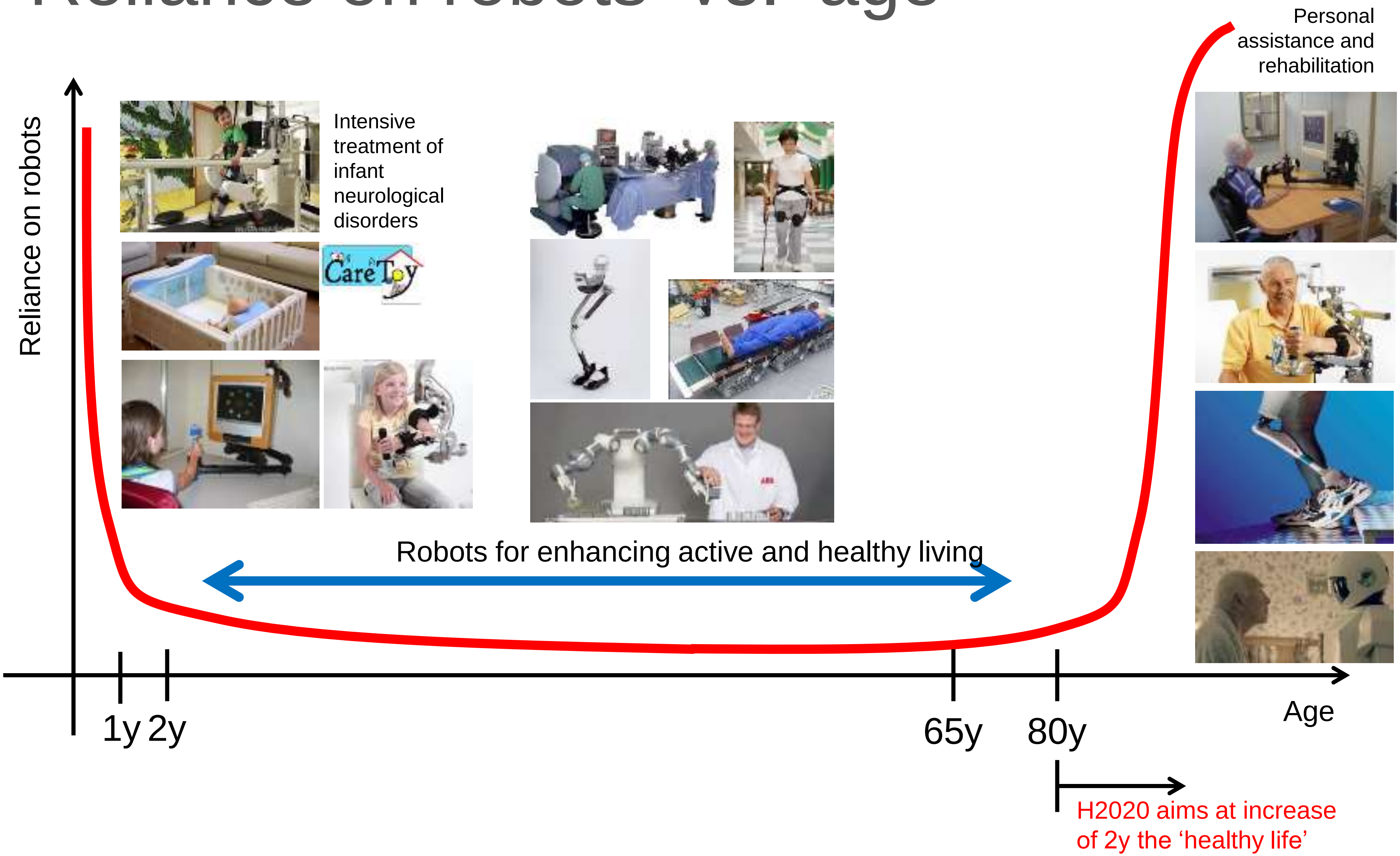
Search and rescue

Service robotics

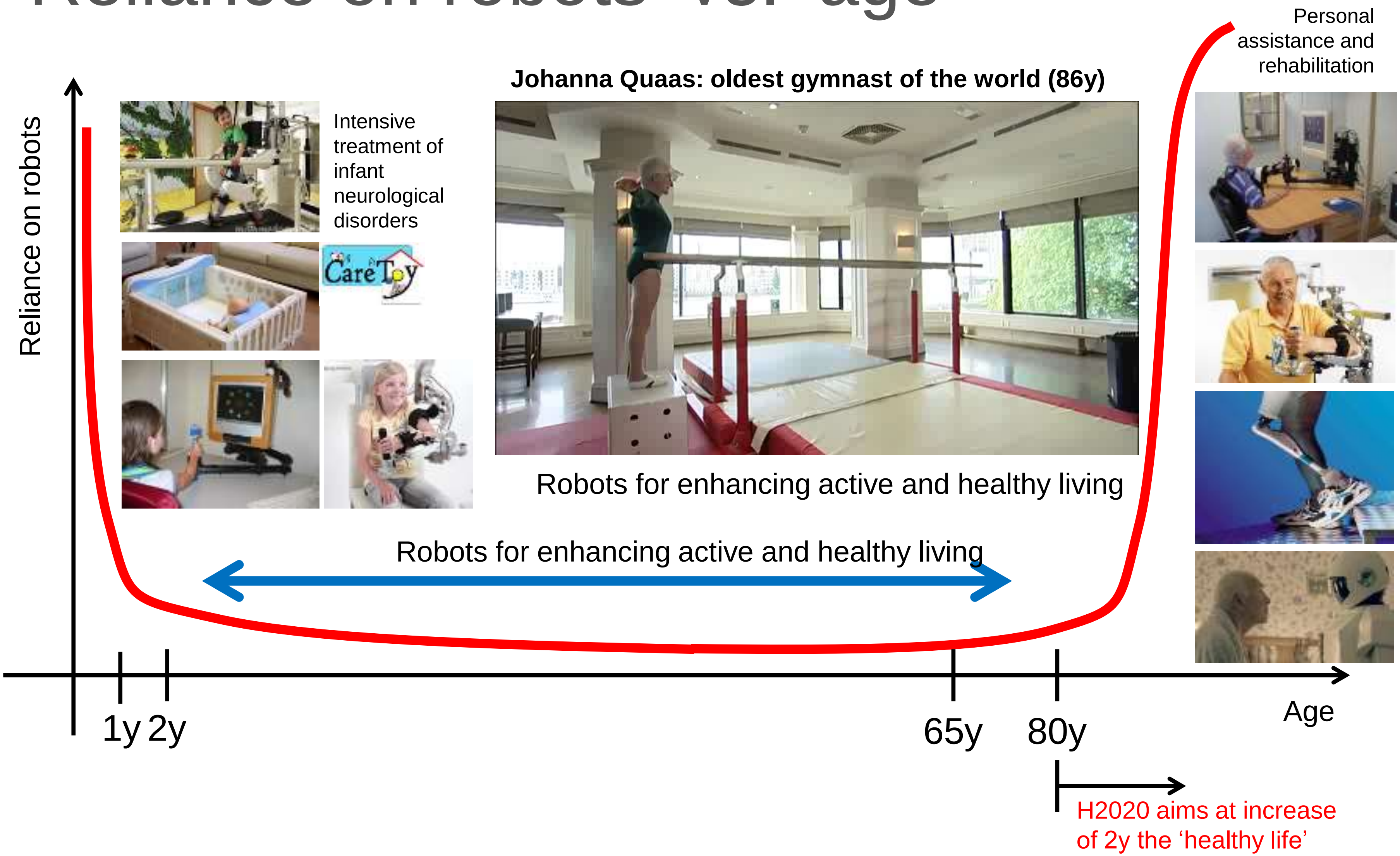
Surgery/rehabilitation



‘Reliance on robots’ vs. ‘age’



‘Reliance on robots’ vs. ‘age’



Outline

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- What are *Robot Companions*?
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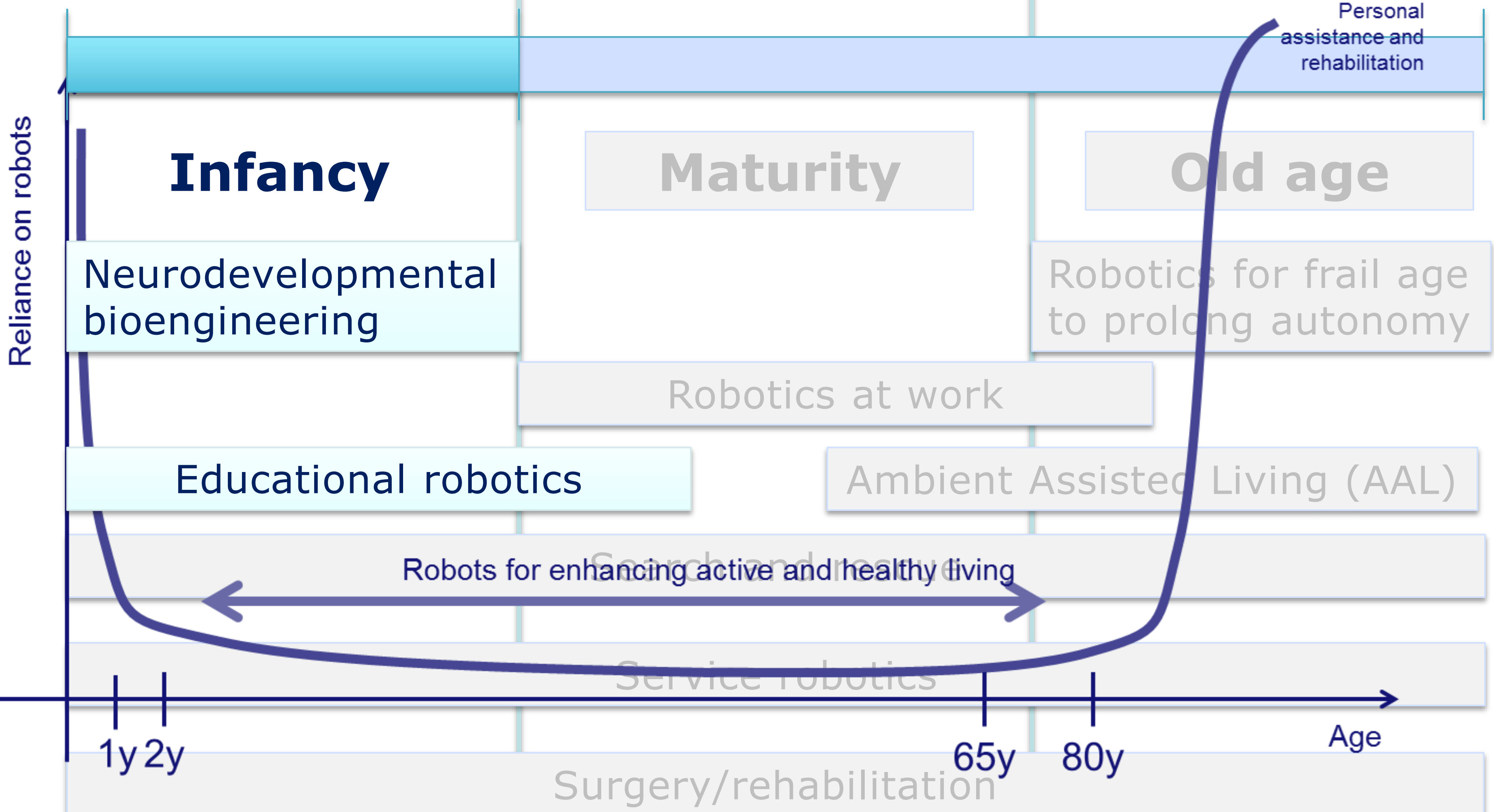
Robot Companions for all ages








Birth 3 months 6 months 12 months 6 years 12 years

High-fidelity simulator

MERESSINA PROJECT
Mechatronic Respiratory System Simulator for Neonatal Applications

Mirror neurons system stimulation

EGO & BOOM projects

Early diagnosis

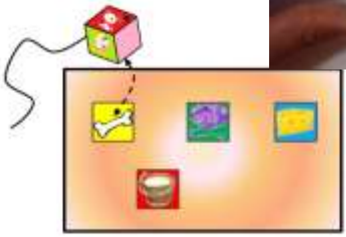
MechToy project

Early intervention

CareToy project

Rehabilitation

RODDI project

Educational robotics

Robot companions for children

Social Assistive Robotics (SAR) for children with Autism Spectrum Disorders (ASD)


Keepon, BeatBots, US


Paro, AIST, JP


Robota, EPFL, Switzerland


ESRA (Yale Univ.)


Face, Univ. Pisa, Italy


Kismet, MIT, US


Probo, Vrije Universiteit Brussel


Kaspar, Univ. Hertfordshire, UK

Interaction with children:
- Platforms well accepted by ASDs and can be consequently used **as novel therapy** for social skills training.
- The robot served as a **salient object mediating** and encouraging interaction between the children and co-present adults.

Robot as **social mediator** for increasing involvement and interactions with the **therapist**

Towards soft companions...

Belpaeme et al. Multimodal Child-Robot Interaction: *Building Social Bonds*, Journal of Human-Robot Interaction, Vol.1, No.2, 2012, Pages 33–53,

Paro robot

Fujitsu's Teddy Bear Social Robot

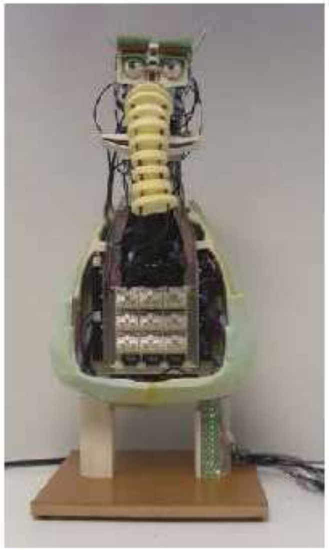
Pleo by Ubisoft

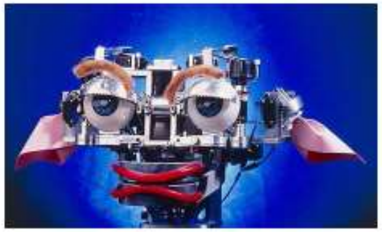
Keepon robot

MIT's 'Huggable' Telepresence Bear

...and new challenges

Components and materials





Ethics

The crying shame of robot nannies

An ethical appraisal

Noel Sharkey & Amanda Sharkey
University of Sheffield, UK

Interaction Studies 11:2 (2010), 161-190

- **Privacy**
- **Restraint**: how much autonomous decision authority should we give to a robot childminder?
- **Deception**: Is it ethically acceptable to create a robot that fools people into believing that it has mental states and emotional understanding?
- **Accountability**: Who is morally responsible for leaving children in the care of robots?
- **Psychological damage**: Is it ethically acceptable to use a robot as a nanny substitute or as a primary carer?

Robot Companions for all ages

Infancy	Maturity	Old age

Neurodevelopmental bioengineering

Robotics for frail age to prolong autonomy

Robotics at work

Educational robotics

Ambient Assisted Living (AAL)

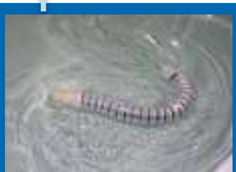
Search and rescue

Service robotics

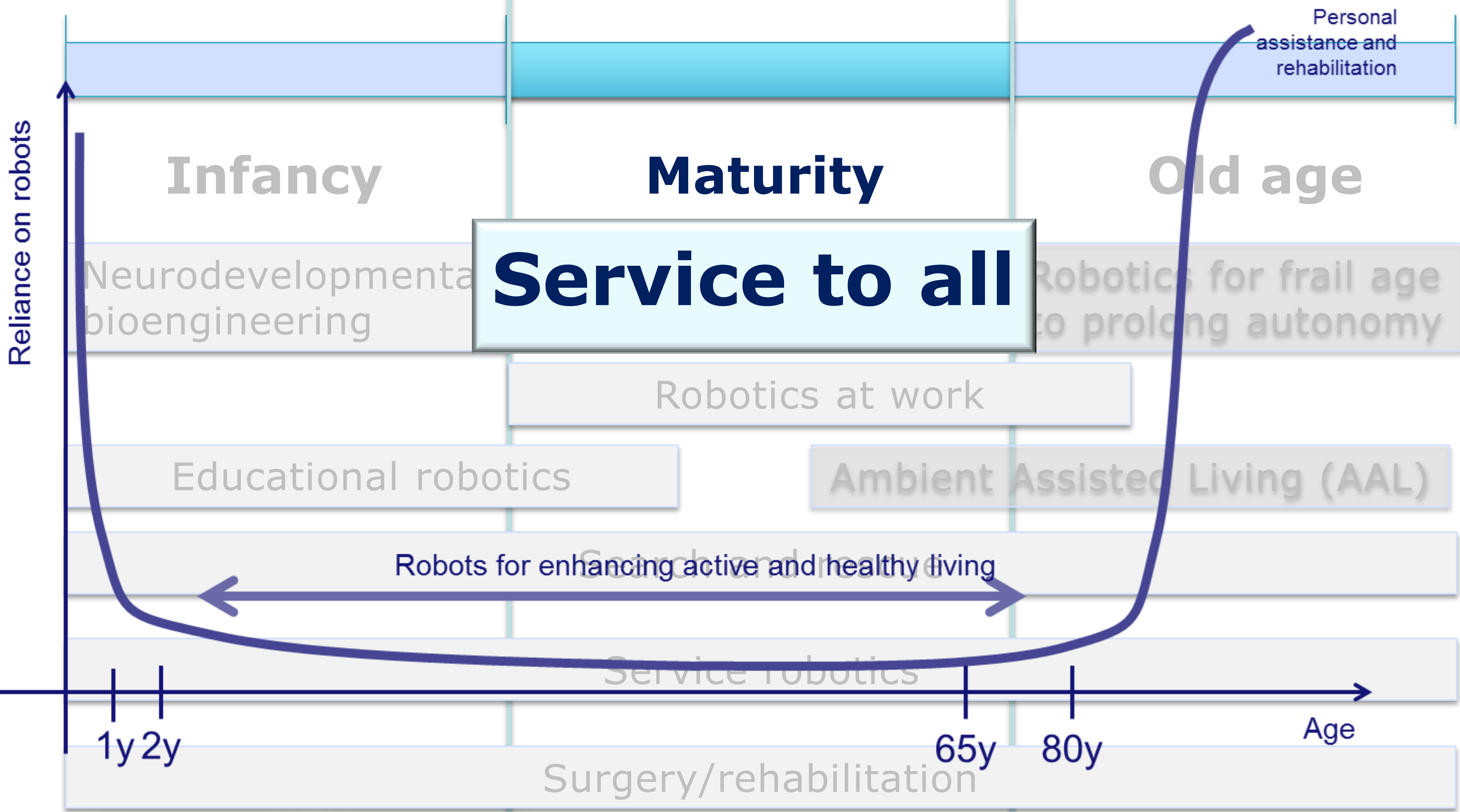
Surgery/rehabilitation








Robot Companions for all ages



Robotics at work

Ageing workers: the case of AUDI

Silverline Program

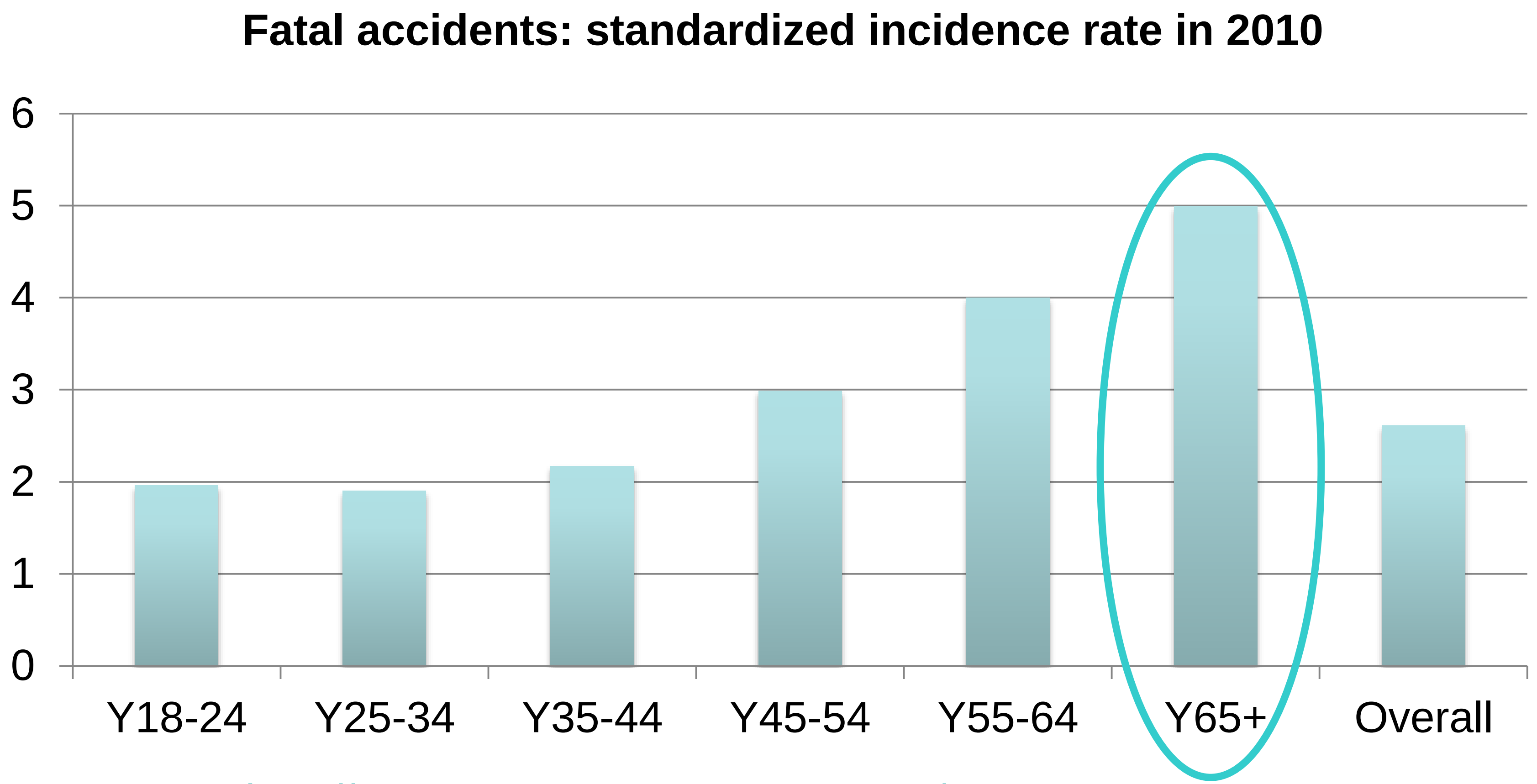
The average Audi production worker is today aged 40 and in 5 years more than 1-in-3 workers will be aged 50+ years (at least 7,000 workers in Germany)

Audi recently launched its Silverline Program, to find out how best to keep older workers productive and included

Audi is increasing production of the new R8 sports car, and is focusing on older workers for this – **because experience is better than physical fitness here**

Source: Press reports, May 2007

Fatal accidents at work vs. age in EU27



Source: http://appsso.eurostat.ec.europa.eu/

Examples of **robotic co-workers** (Kuka and Baxter)

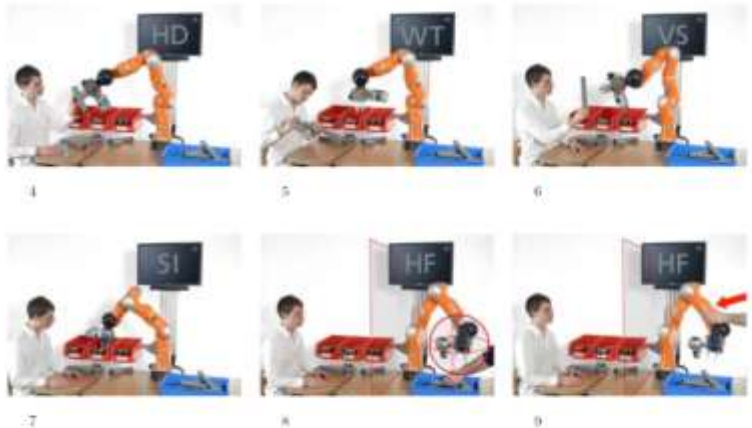


Fig. 16. Interactive bin picking.

The Baxter Robot by Rethinking Robotics

Towards Safe Robots: Approaching Asimov's 1st Law

Thesis winner of
Georges Giralt PhD award 2012

Von der Fakultät für Elektrotechnik und Informationstechnik
der Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines Doktors der
Ingenieurswissenschaften genehmigte Dissertation
vorgelegt von

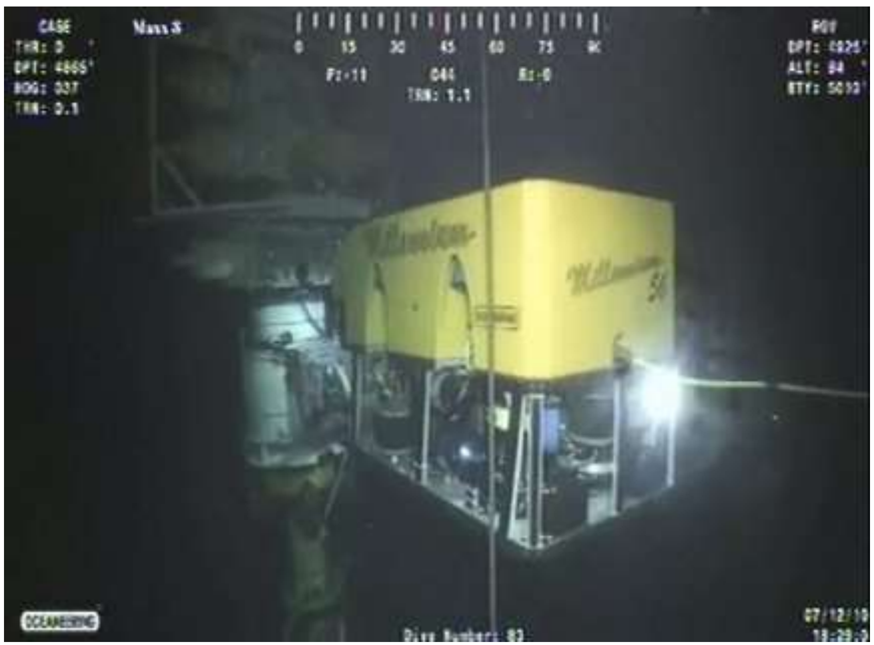
Dipl.-Ing., M.Sc. Sami Haddadin
aus Neustadt am Rübenberge, Niedersachsen

Berichter: Univ.-Prof. Dr.-Ing. Jürgen Roßmann
Hon.-Prof. Dr.-Ing. Gerd Hirzinger

Robots to the Rescue

Undersea robots are heroes of Gulf of Mexico oil spill fight (2010)

Capable of going where no man can go, powerful enough to lift 1,000 pounds and able to apparently stop a gushing oil well, a colony of undersea robots has emerged as unsung superheroes in the months-long effort to halt the geyser of oil spewing into the Gulf of Mexico.



What are ROV/AUV not able to do?

* Underwater painting
* Welding (dry or wet)
* Marine growth removal
* Mooring chain inspection
* Jetty inspection & maintainance
* Marine construction support
* Cropping and rebalancing of damaged propeller

Mainly provided by divers

Safe contact with the environment

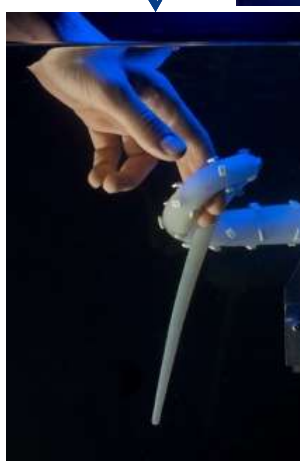
THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

PoseiDrone Project: marine applications for the OCTOPUS robot

Fondazione Livorno, 2012 & 2015

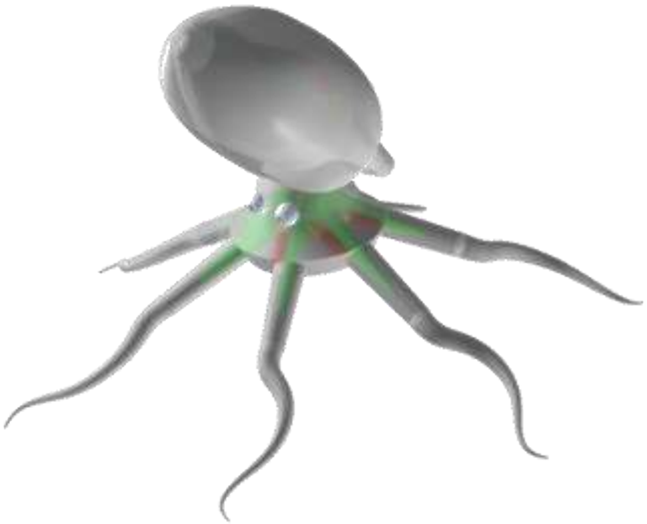
- Crawling
- Grasping
- Pulsed-jet locomotion



THE BIOROBOTICS INSTITUTE

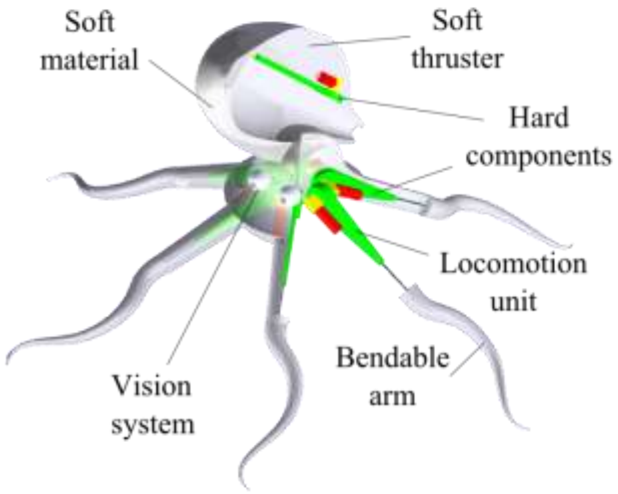
Scuola Superiore Sant'Anna

A Soft Unmanned Underwater Vehicle

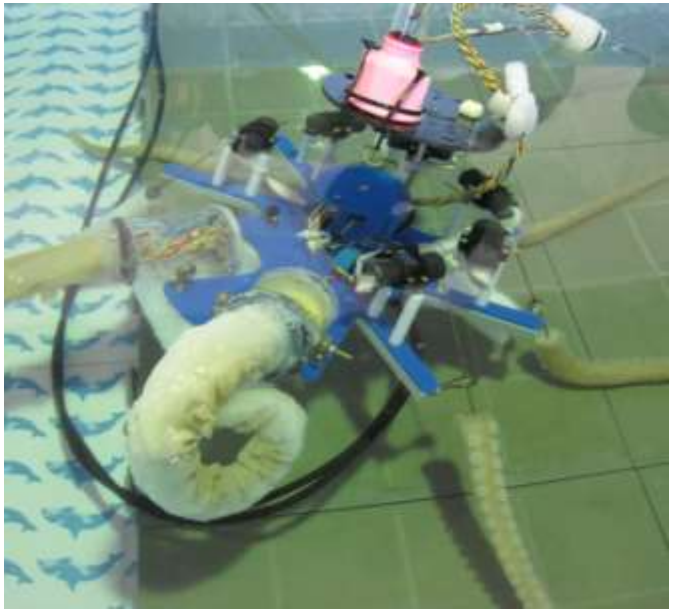


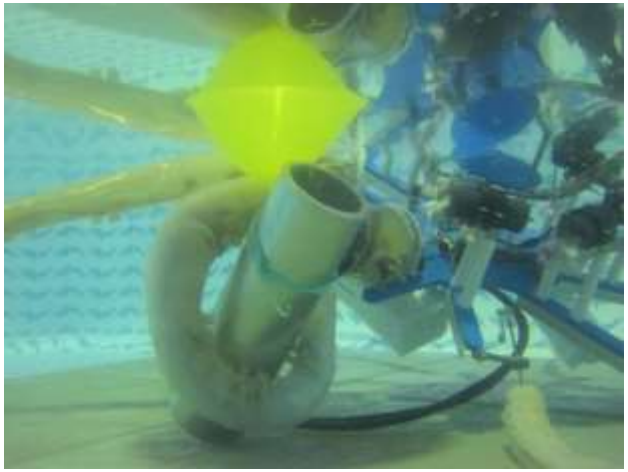
- Soft body
  - 80% in volume of rubber-like materials;
  - continuum single body;
  - intrinsic waterproof insulation;
  - low inertia.

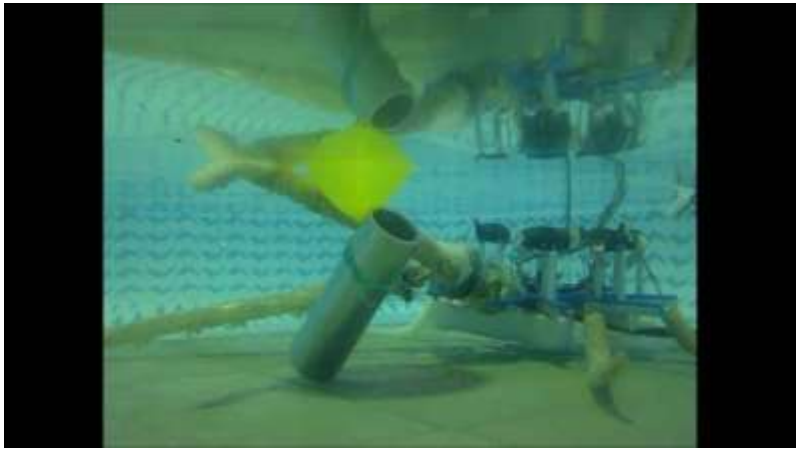
- Multi-Skill
  - legged locomotion;
  - manipulation capability;
  - pulsed-jet propulsion.



Multi-arm robotic octopus prototype

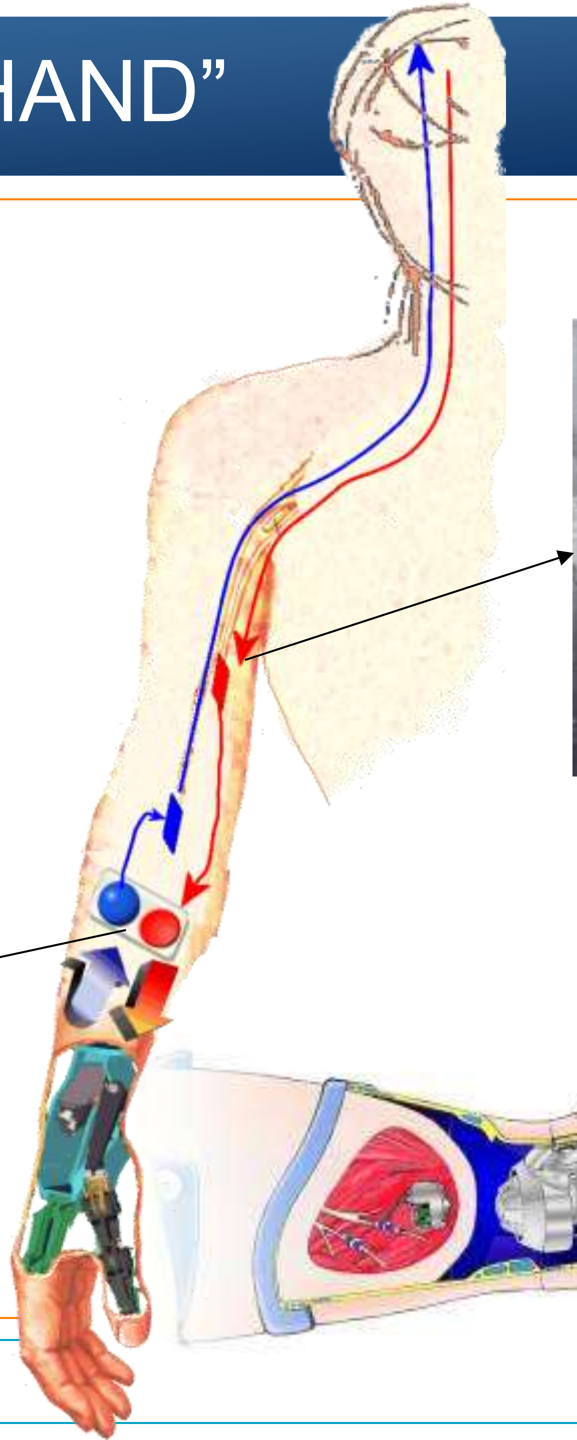


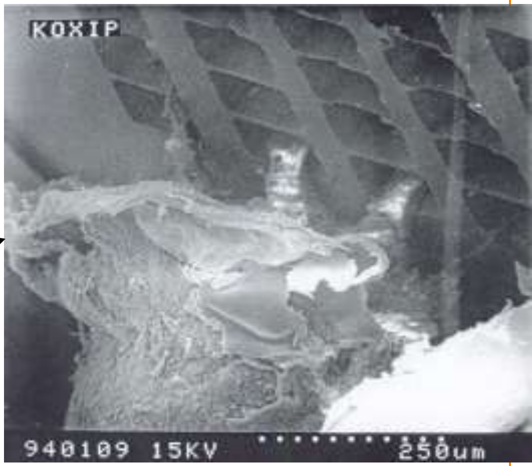


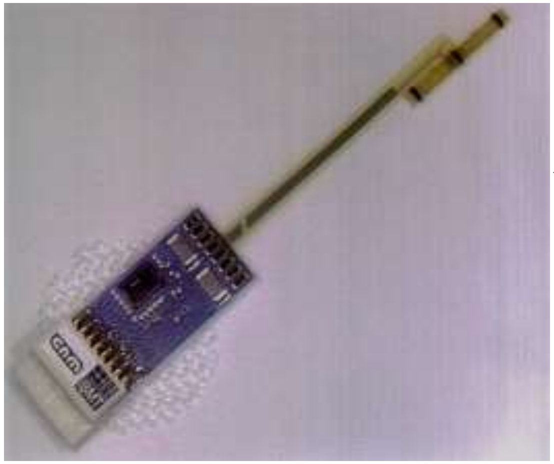


EU-FET “CYBERHAND” Project

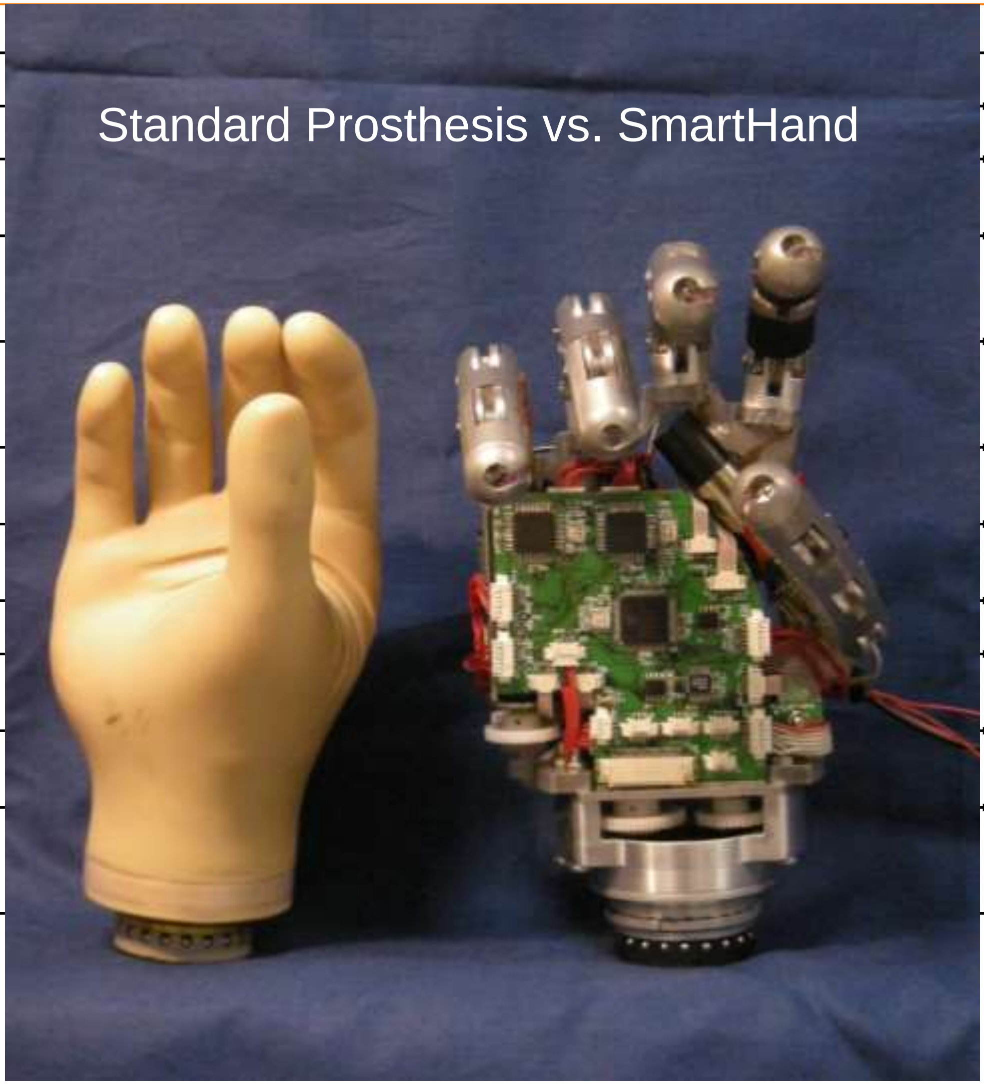
Cybernetic prosthesis controlled by the brain

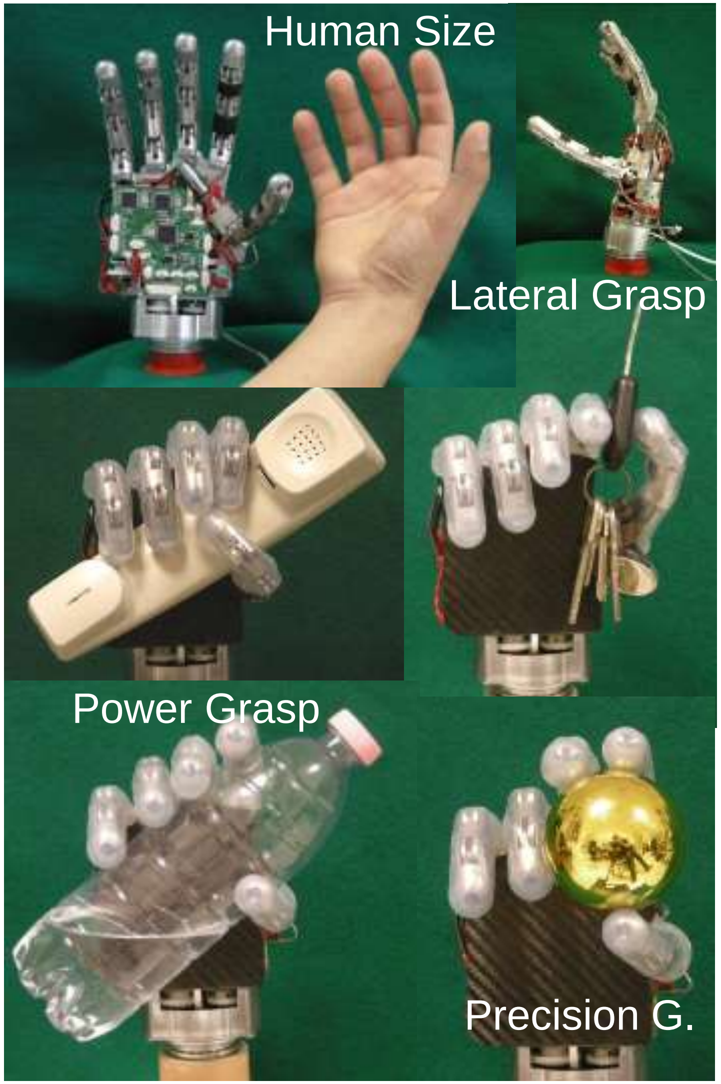






Brain-controlled hand prostheses





June 2010 Issue:

Rat, Monkey, and Man Control Robots with Their Minds

Neuroprosthetics research group

University of Florida

New class of software decoders to adaptively translate brain activity into control signals for prosthetic devices.

They show that a **rat could learn to control a robotic gripper** that bears no resemblance to its own limbs.

Rat

MotorLab

University of Pittsburgh

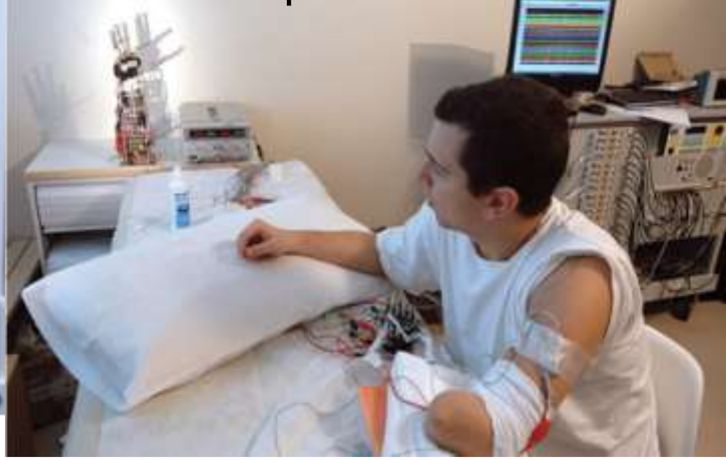
A monkey with two brain implants, one in the hand area and another in the arm area of its motor cortex to control a 7 DoF robotic arm.

The monkey is **able to maneuver with its thoughts alone the robotic arm** to grasp a knob, then to precisely turn the knob by controlling the arm's mechanical wrist.

Monkey

CyberHand Consortium

Scuola Superiore Sant'Anna



Scientists have demonstrated how an **amputee can control and perceive a robotic hand** after having electrodes surgically implanted on two different nerves of his arm.
The electrodes captured signals originating in the man's brain, allowing **bidirectional** flow of information.

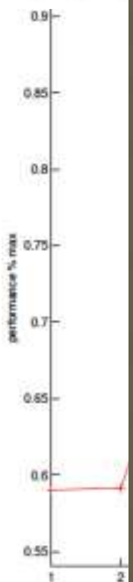
Human

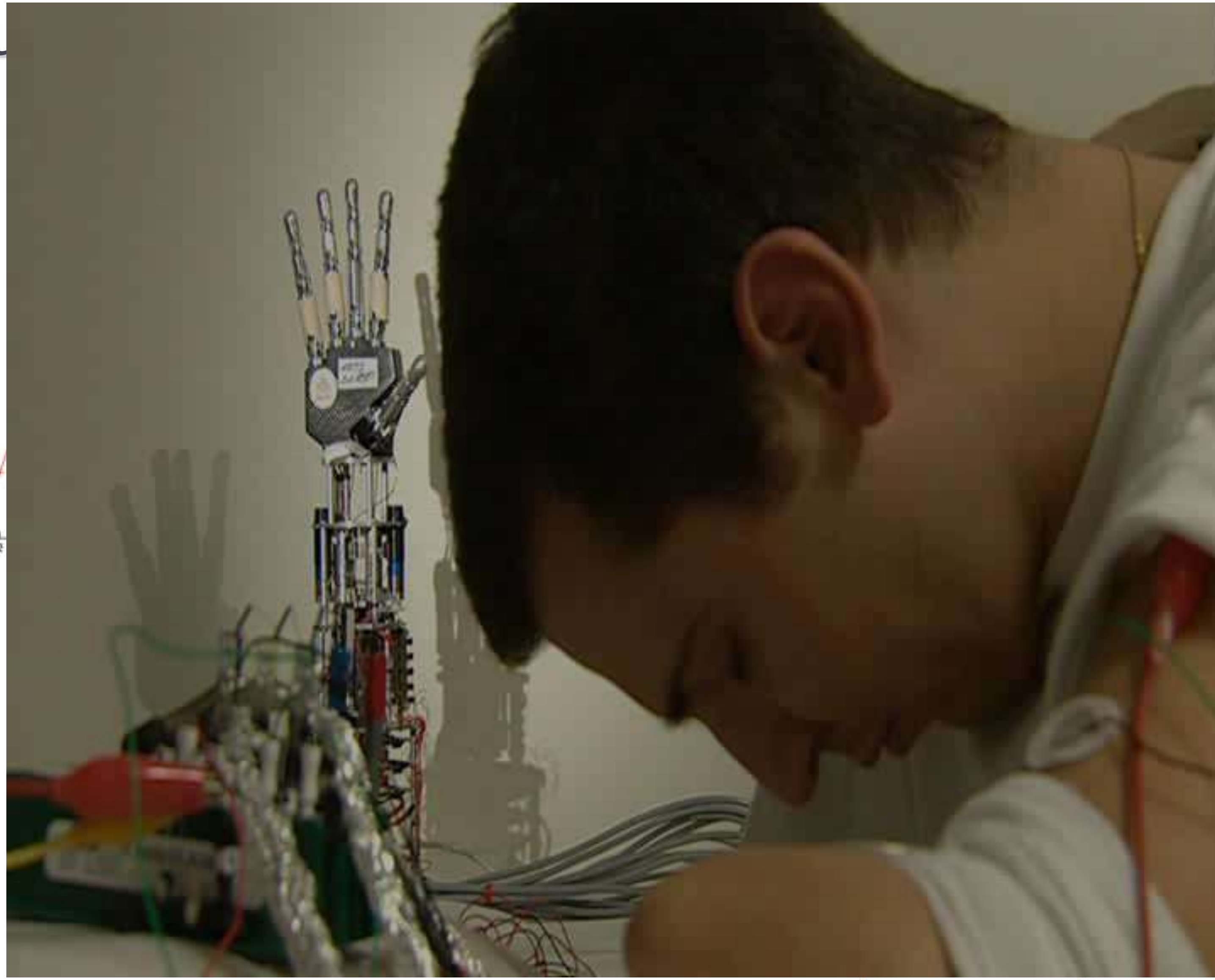
Decoding of motor information: resu

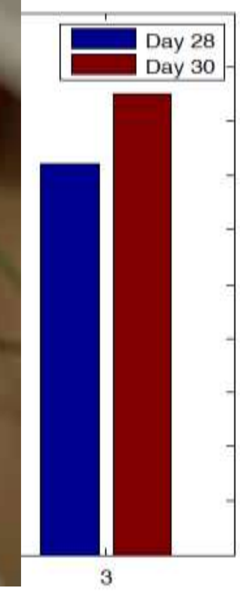
a

ossible

le







Micera, et al., Proc IEEE, 2010

Latest results

Silvestro Micera

Maria Chiara Carrozza

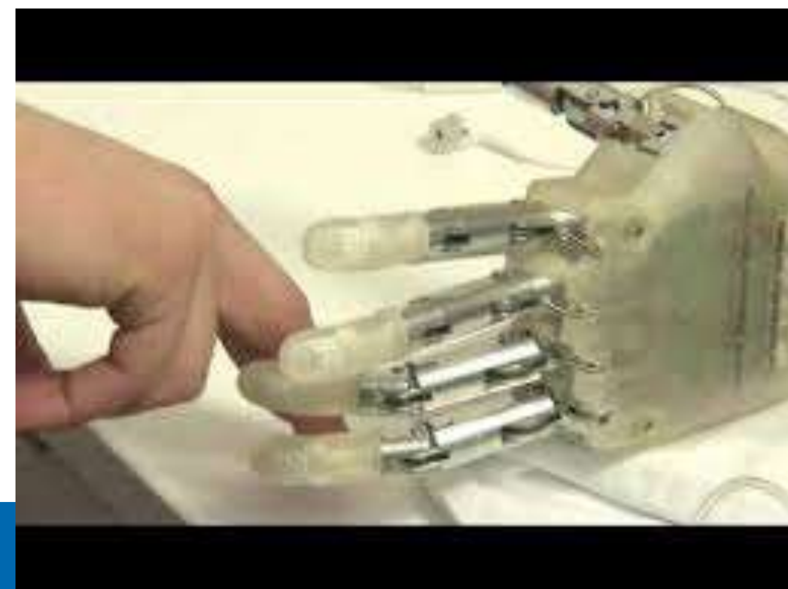
Christian Cipriani

Calogero Oddo

A new paradigm for prothesis and bionics

Amputee Feels in Real-Time with Bionic Hand

05.02.14 - Dennis Aabo Sørensen is the first amputee in the world to feel sensory rich information – in realtime – with a prosthetic hand wired to nerves in his upper arm. Sørensen could grasp objects intuitively and identify what he was touching while blindfolded.

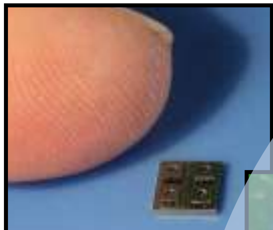


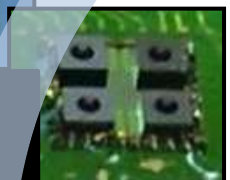
Raspopovic et al., 2014 Restoring Natural Sensory Feedback in Real-Time Bidirectional Hand Prostheses
Sci. Transl. Med. Vol. 6, Issue 222, p. 222ra19

Soft Fingertips and Artificial touch

2006
Single MicroTAF v1
Fingertip mock-up

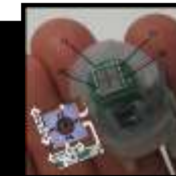
2007
Single MicroTAF v1
Antropomorphic fingertip





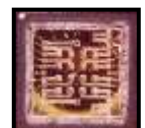
2007
Array of MicroTAF v1
Fingertip mock-up

2008
MicroTAF sensor v2



2009
Array of MicroTAF v2
Capacitive sensors v1
Antropomorphic fingertip with fingerprints
Passive-touch classification of textures

2010
Active-touch classification of textures



2011
Artificial curiosity

2012
Capacitive sensors v2
Neuromorphic coding

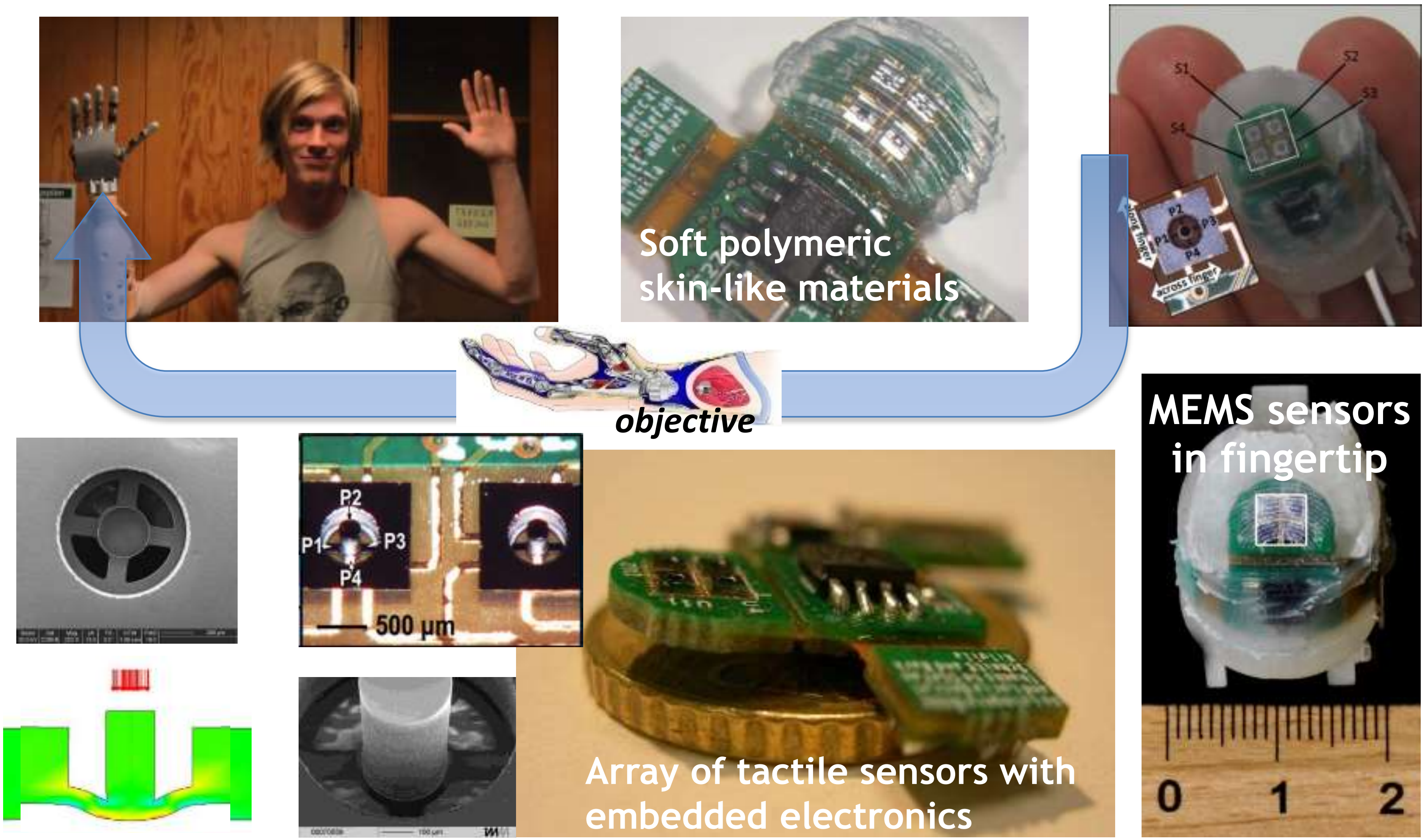
2013+
Implants for amputees

2005
MicroTAF Sensor v1

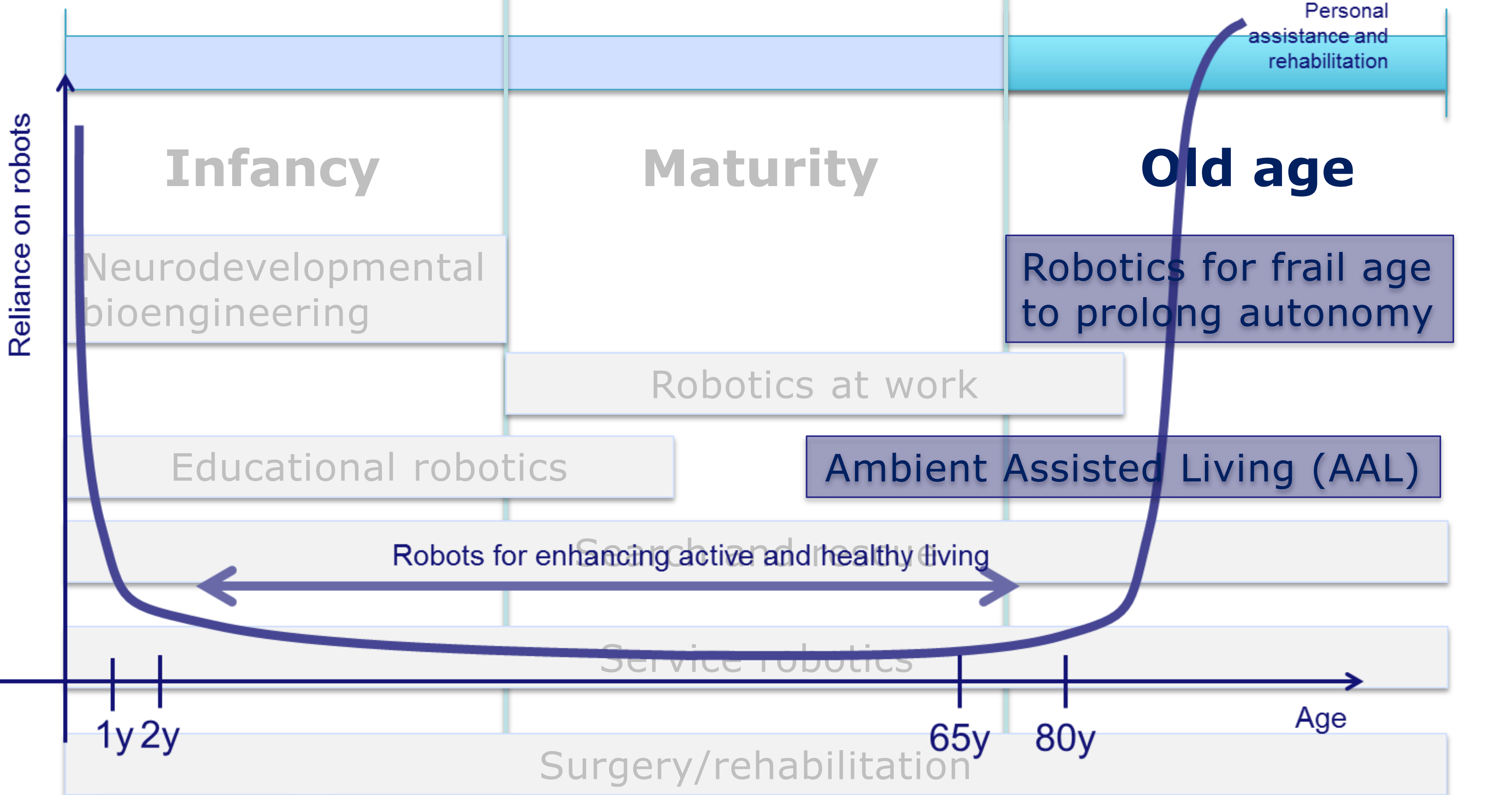
- *L. Beccai et al., Sensors and Actuators A, 120(2), 2005, pp. 370-382.*
- *C.M. Oddo et al., Measurement Science and Technology, 18, 2007, pp. 623–631.*
- *L. Beccai et al., IEEE/ASME Transactions on Mechatronics, 13(2), 2008, pp. 158-168.*
- *C.M.Oddo et al., Sensors 2009, 9(5), pp. 3161-3183.*

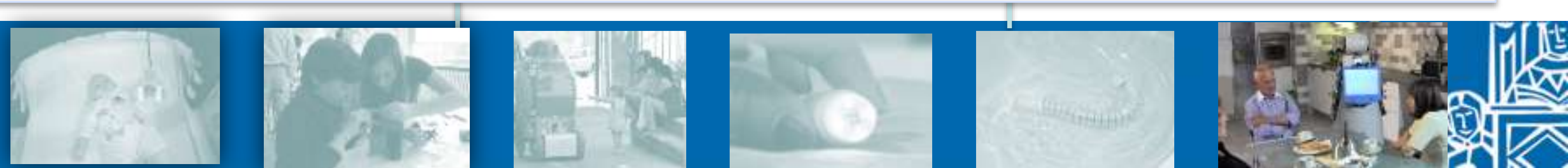
- *C.M.Oddo et al., Sensors 2011, 9(5), pp. 3161-3183.*
- *C.M.Oddo et al., IEEE Transactions on Robotics 2011, 27(3), pp. 522-533.*
- *G. Spigler et al., IEEE BioRob 2012.*
- *L. Pape et al., Frontiers in Neurorobotics 2012*
- *S. Raspopovich et al., Science Translational Medicine 2014*

Artificial Touch for Hand Neuroprostheses



Robot Companions for all ages





Demographic Ageing

Social Necessity

Dependency Ratio

- From 1:4 to 1:2
- 80+ doubles by 2025

Cost of Care

- Up by 4-8 % of GDP by 2025

Human Resources

- Shrinking work force
- Lacking 20 million carers by 2020

Major Opportunity

Empowerment

- Active Ageing

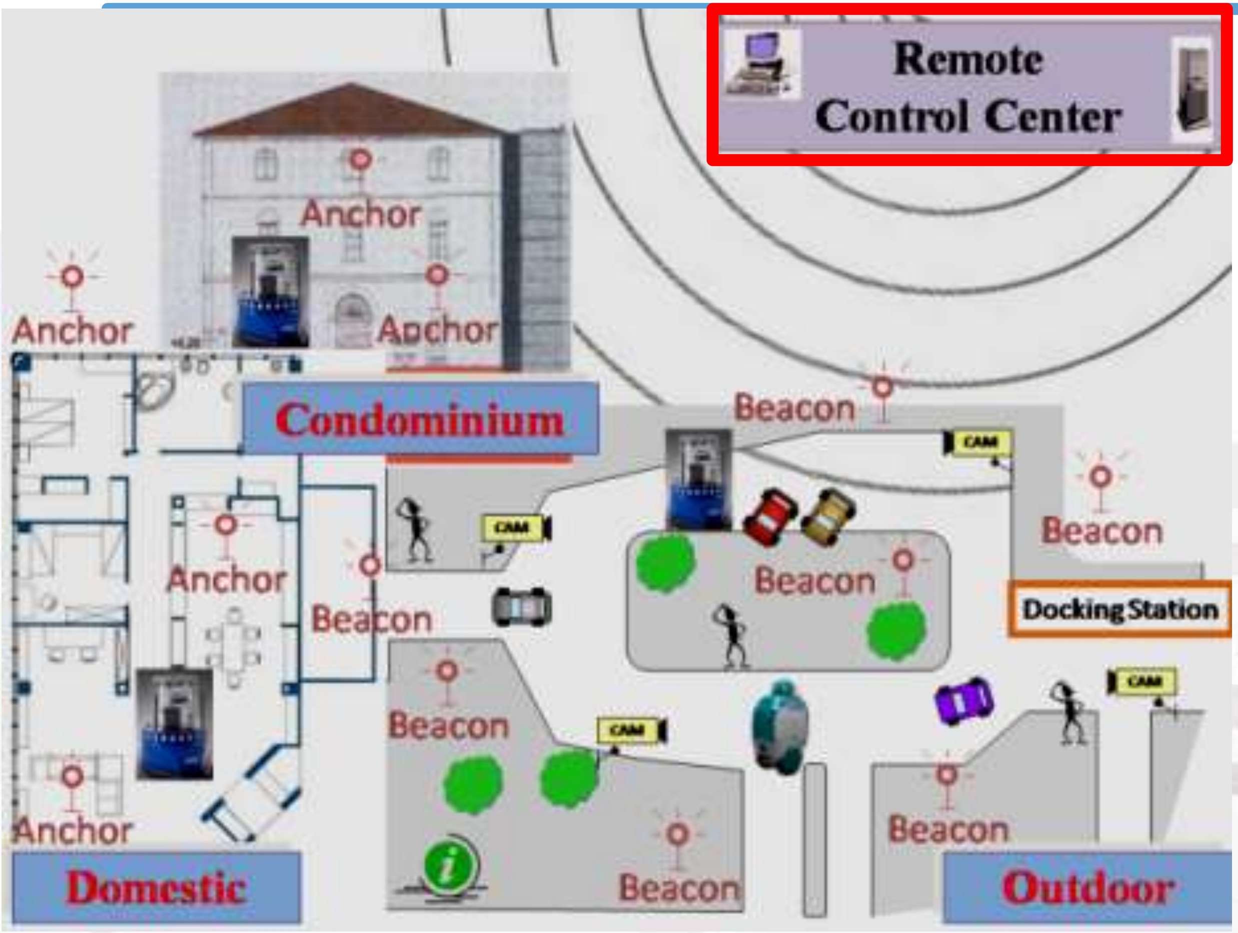
New Care Models

- Integrated care
- Large Efficiency gains

Growth and Markets

- 3000 B€ Wealth
- 85 Million Consumers and growing

The "living lab" concept, and the emergence of AAL-Robotics CONVERGENCE



Control Center able to supervise and guarantee safety and security for people, robots and public spaces

The Robot-Era Project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement num. 288899

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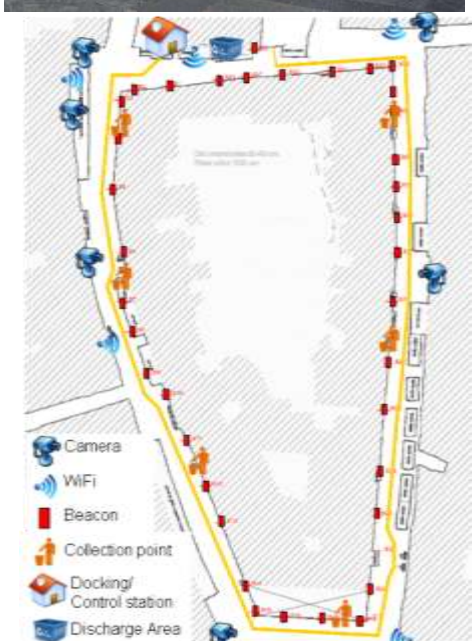
SERVICE ROBOT
for garbage collection
DustBot
Networked and Cooperating Robots
for Urban Hygiene
EU-IST Project no. FP6-045299
www.dustbot.org

Service Robots in an AAL context in the RoboTown



The EU DustBot campaign in Peccioli, Pisa, Tuscany

- from June 15 to August 7, 2010-
- in the very heart of the town
- with real users: 24 families and 10 business activities
- 95% of users declaring satisfaction and ease of use

ROBOT-ERA Services

Realistic Indoor and Outdoor Environments

- Communication
- Indoor escort at night
- Reminding
- Objects transportation and manipulation

- Drug and shopping delivery
- Garbage collection

- Surveillance,
- Outdoor-Indoor link

...with soft companions

What is next? New frontiers for BioRobotics and Robot Companions

1973


WABOT-1


P2


KOBIAN


DB


CB


iCub


HRP-4C


WABIAN


ASIMO


HRP-2


ARMAR-III


Partner Robot


Hubo


ARMAR-IV

NAO


Justin


Lola

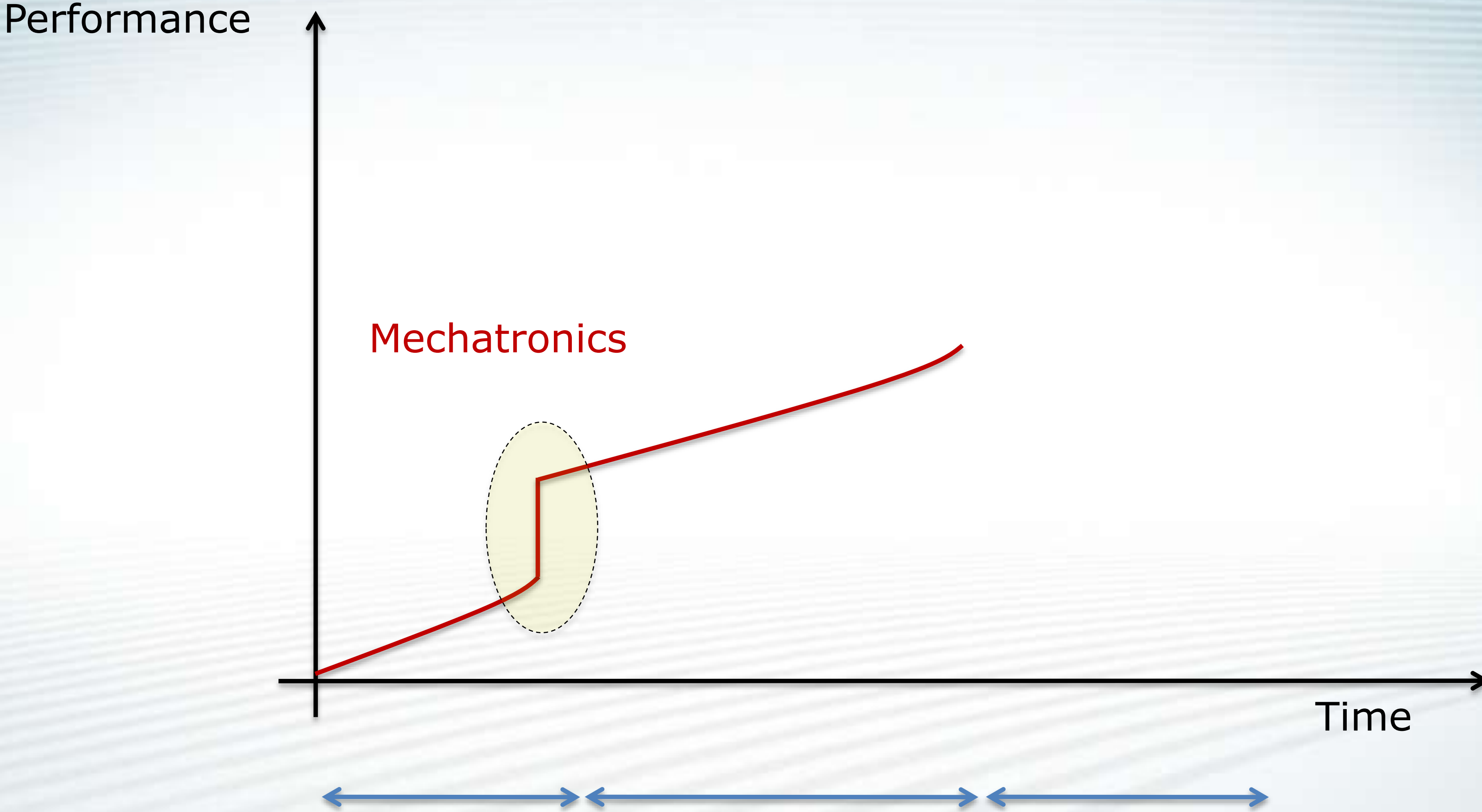

Robonaut


Twendy-one


Petman

Today

The Quest for new generations of robot companions



Pre-mechatronics

Mechatronics and Supermechatronics

Evolution of robot arms

PUMA arm

Dexter arm (S.M.)

Low size and mass, thanks to cable transmission

WAM arm (Barrett Technologies)

High speed: 20 m/s

DLR lightweight arm

Payload/mass ratio = 1

'70s

'90s

today

Weight: 54 kg
Payload: 2 kg

Weight: 40 kg
Payload: 2 kg

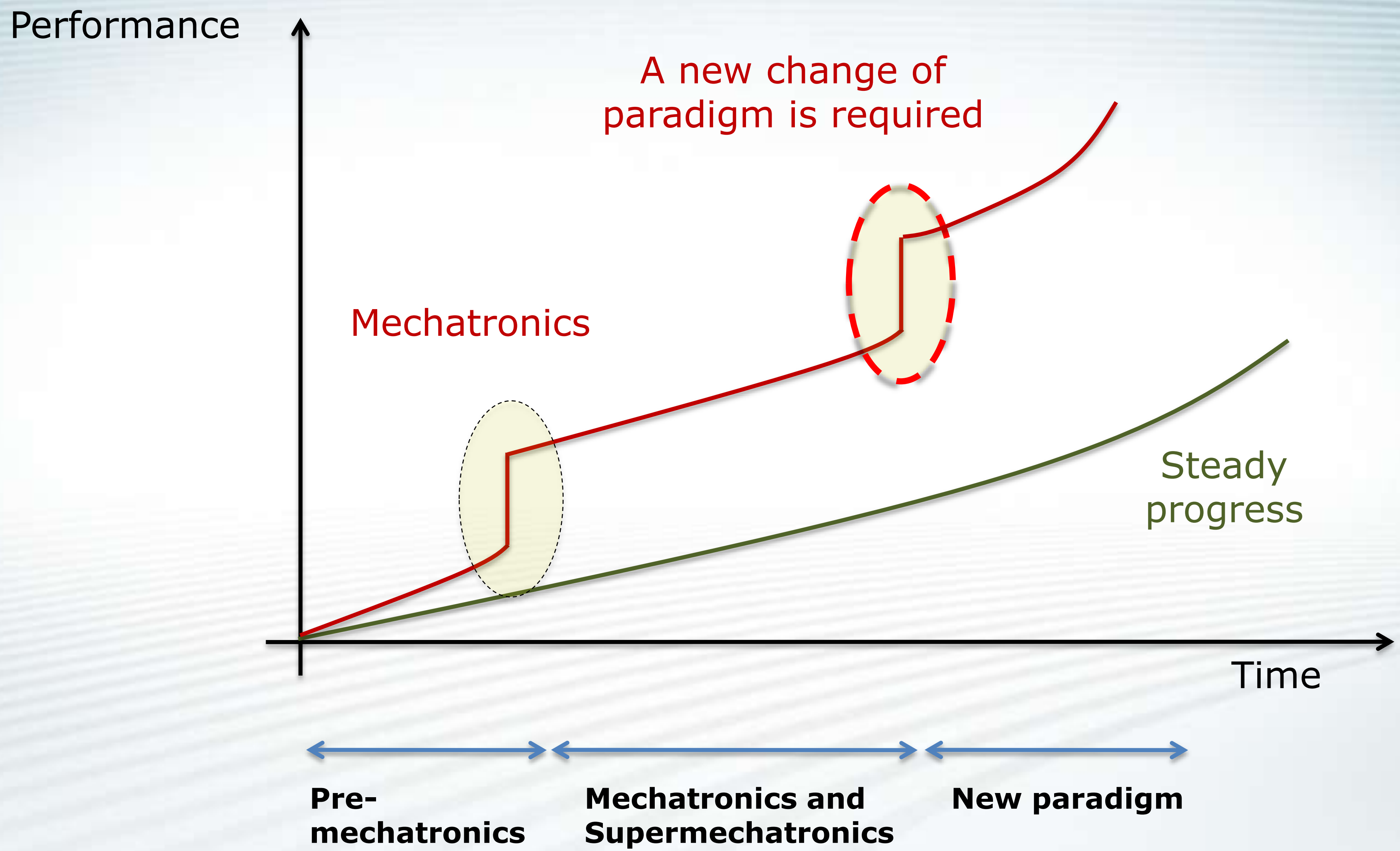
Weight: 25 kg
Payload: 4 kg

Weight: 14 kg
Payload: 15 kg

The robotics bottleneck

Today, more functionality means
more complexity, energy, computation, cost
less controllability, efficiency, robustness, safety

The Quest for new generations of robot companions



A whole new Robotics

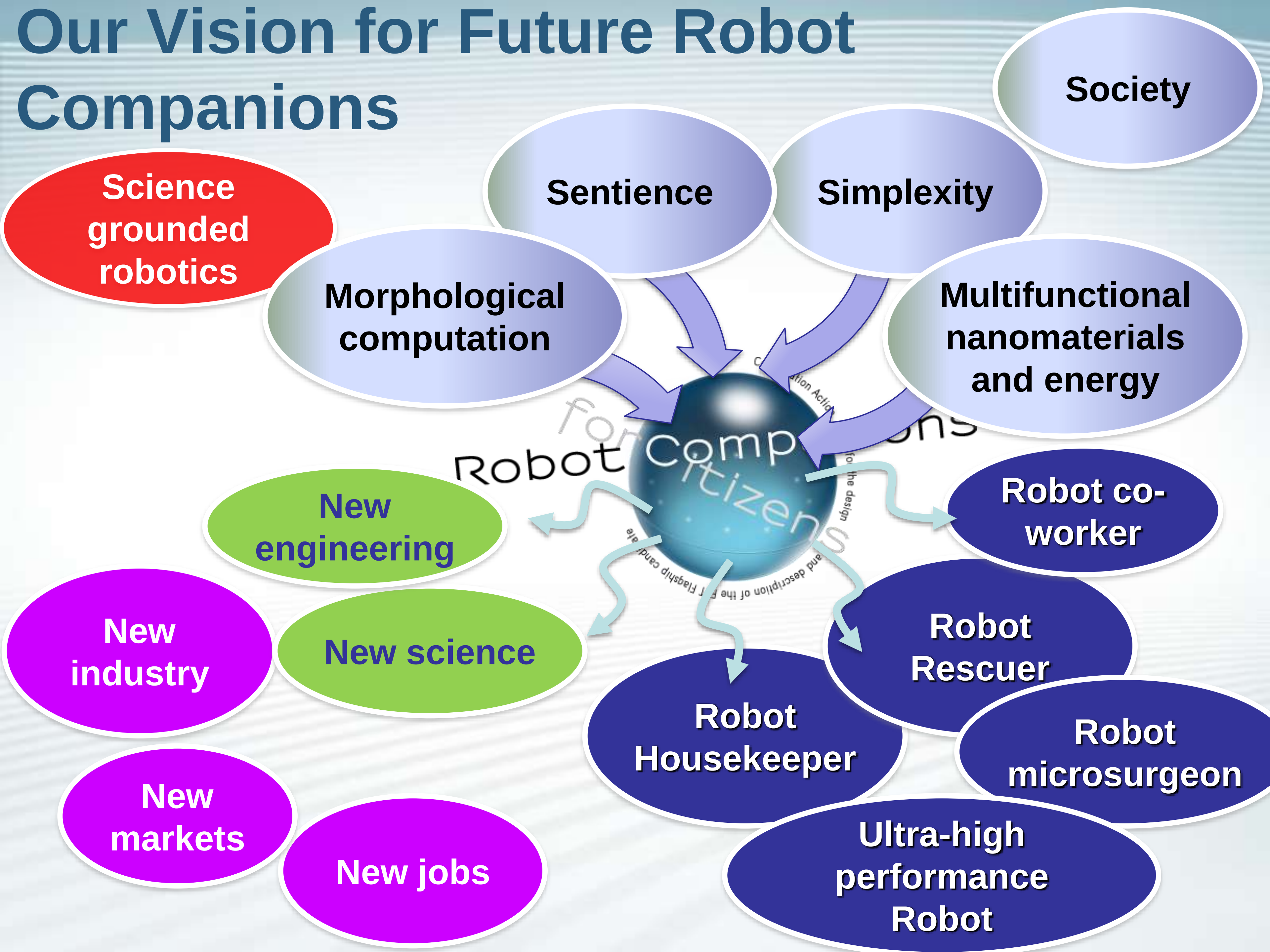
We need *simplification mechanisms and new materials*, *fabrication technologies* and *energy forms*

We want to tap
the biggest and most advanced treasure
of engineering solutions

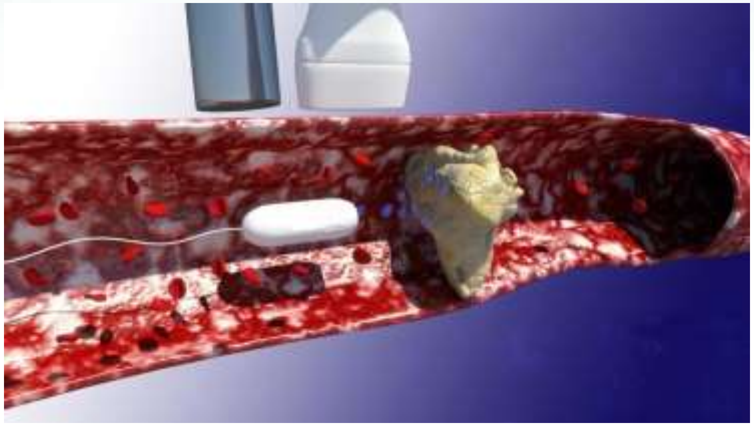
- Studying natural organisms and understanding what makes them so smart and efficient
- Studying things only living organisms can do, and how they do it

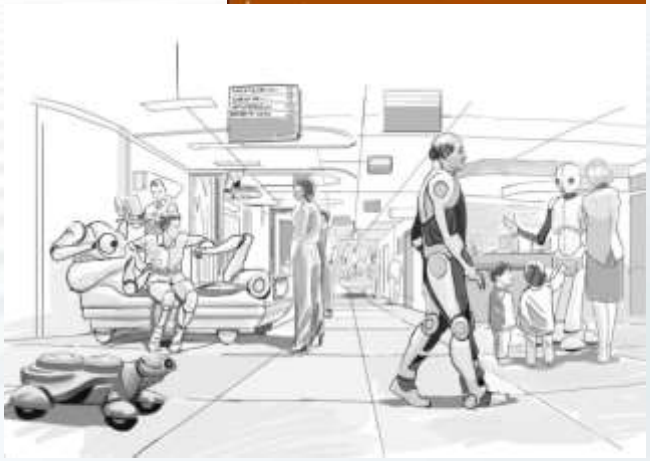
(Super)mechatronics

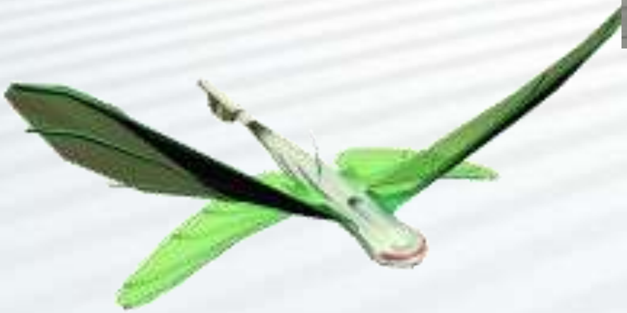
(Super)mechatronics Vs. a new paradigm


Our Vision for Future Robot Companions
Society
Sentience
Simplexity
Science grounded robotics
Morphological computation
Multifunctional nanomaterials and energy
Robot
Robot co-worker
New engineering
New industry
New science
Robot Rescuer
Robot Housekeeper
Robot microsurgeon
New markets
New jobs
Ultra-high performance Robot

Concepts of Robot Companions

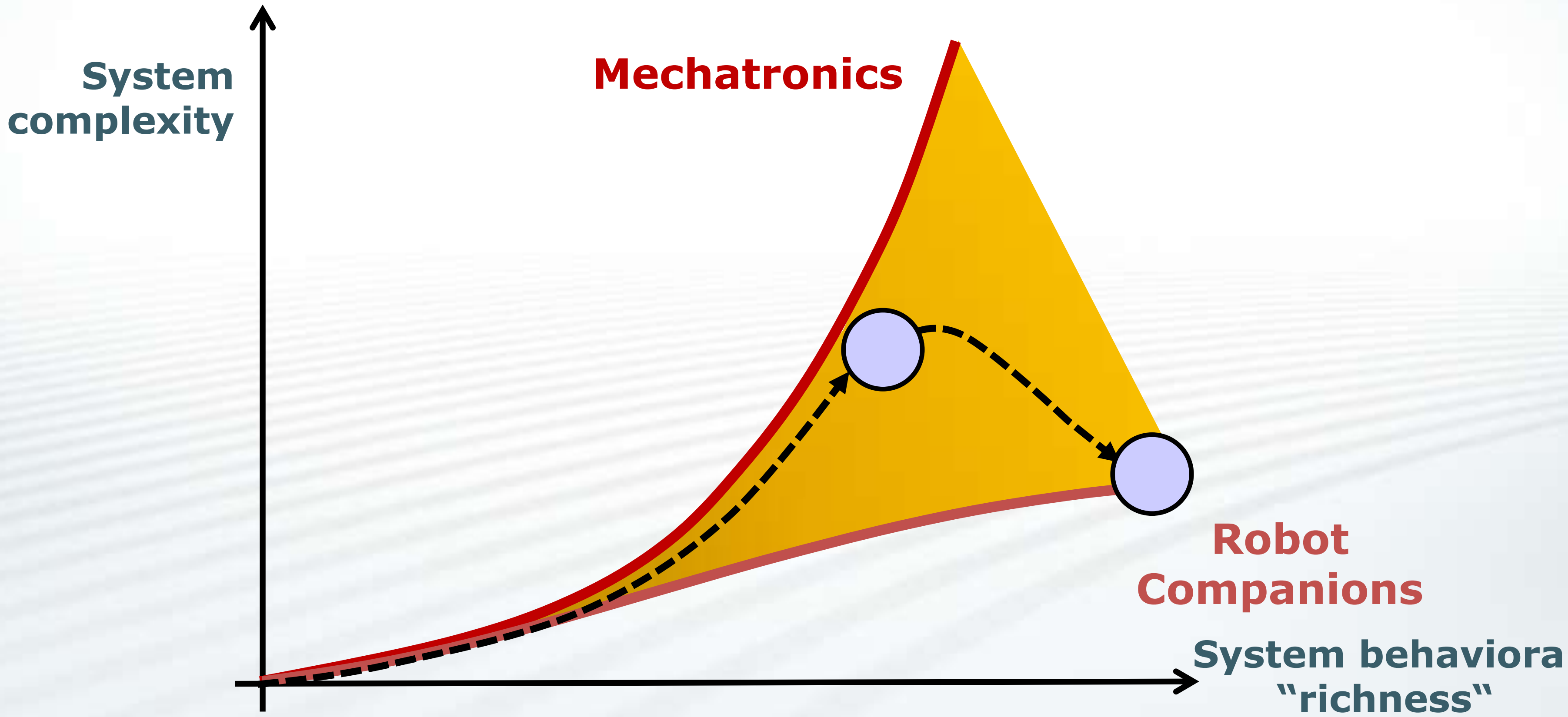






“More than Mechatronics”: enablers

- New pervasive/portable/interactive IT
- Morphological computation
- New fabrication approaches



The MEMS (silent) revolution

The future of human-machine interfaces is now!

Xbox – Kinect 2

Siri

Google Glass

Pebble smartwatch

Fingerprint readers

Focusing on the **BODY** of future robots and exploring a different paradigm: **SIMPLIFICATION** and **INTEGRATION**

less **components**
higher **rubustness**
lower **computation load**
higher **energy efficiency**
higher **adaptivity**
higher **dependability**

Ultimately, acceptable, affordable, dependable and sustainable new robots

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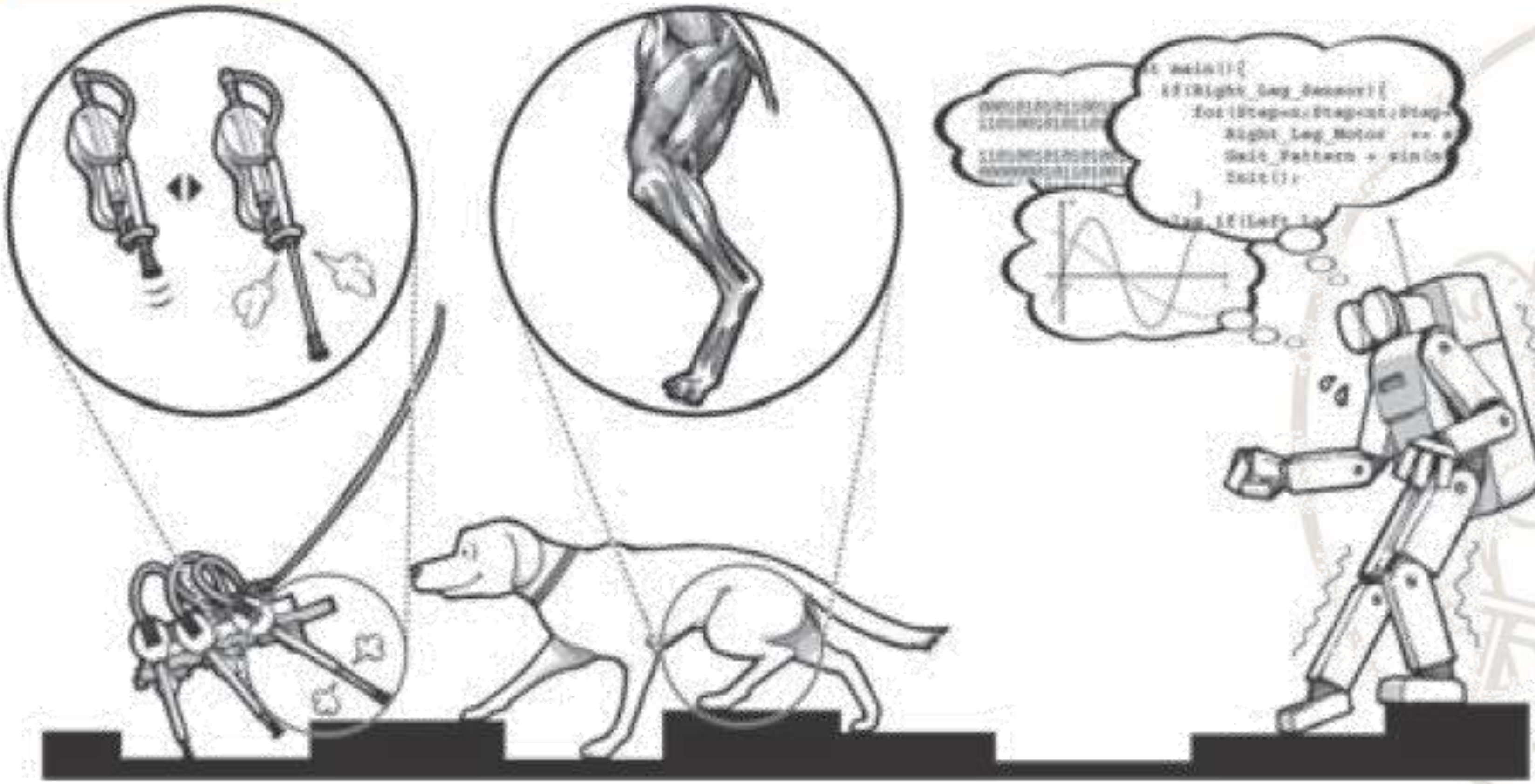
Morphological computation

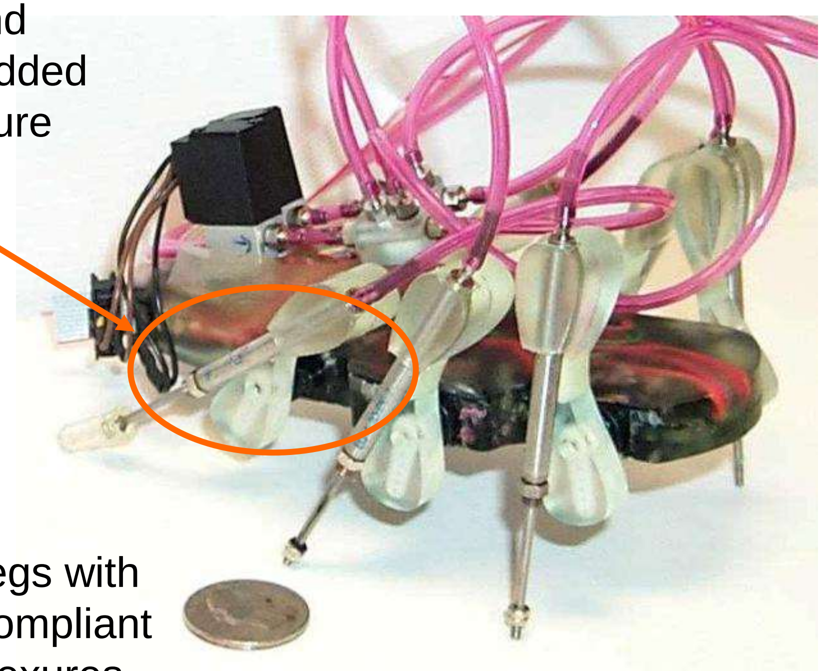


Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

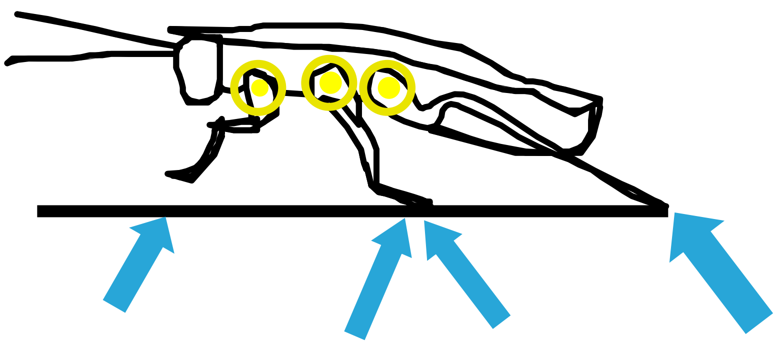
Dynamical properties and mechanical feedbacks lead to stable emergent behaviors: Adaptation in small biomimetic robots

Actuators and wiring embedded inside structure

Deflection Passive joint



Legs with Compliant Flexures



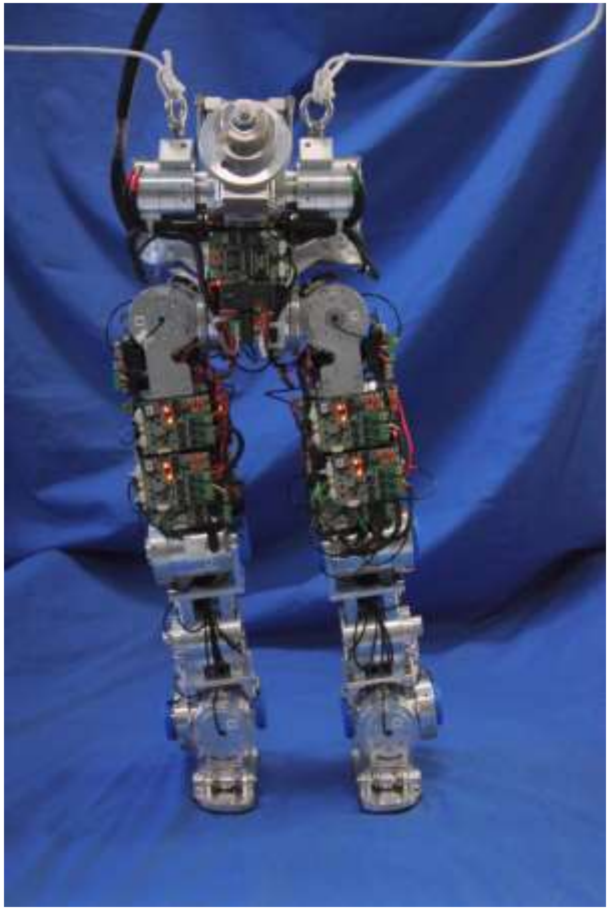
ground reaction forces

Kim S., Clark J. E. & Cutkosky M.R. 2006 iSprawl: Design and Tuning for High-speed Autonomous Open-loop Running. ***The International Journal of Robotics Research***. **25**:903-912.

65 km on one battery charge! With only 1800 kJ in 2.7 kg batteries and 10 kg total weight

- “Passive Dynamic Walker” “Ranger”, “IIT Legs”

Morphological computation and energy efficiency



A reference: energy in Humans

Energy for basic functions: circa 1300 kcal (5.4 MJ) / day

Energy for physical activity: circa 800 kcal (3.3 MJ) / day

Energy expenditure breakdown	
liver	27%
brain	19%
heart	7%
kidneys	10%
skeletal muscle	18%
other organs	19%

Human daily steps: 900 to 3000.
Average daily distance: 2 km
Weight: 70 kg
PERFORMANCE: 24 kJ/(kg*km)

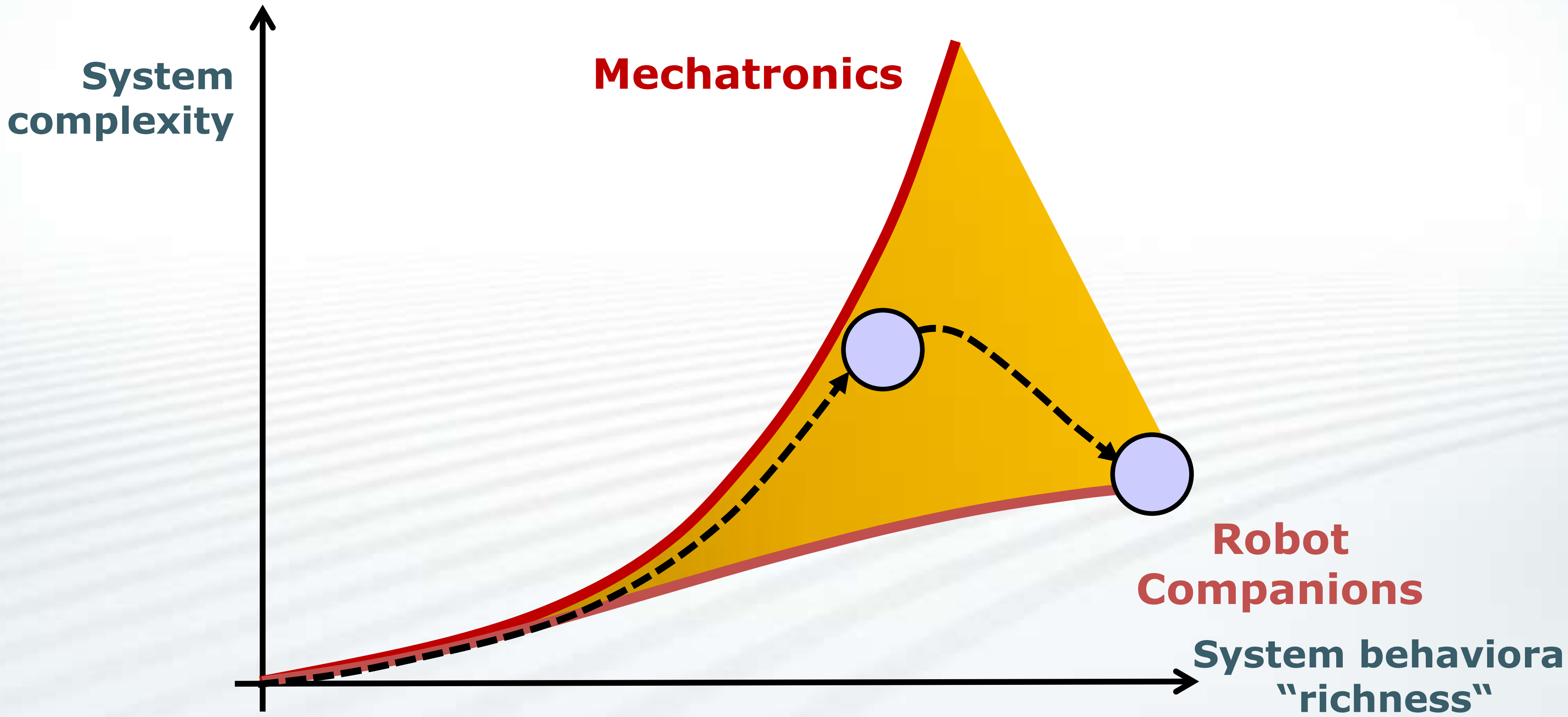
Passive walker range: 65 km
Weight: 10 kg
PERFORMANCE: 2.8 kJ/(kg*km)

References:

1. Starner T., Paradiso J.A., Human generated power for mobile electronics, In *Low-power electronics design*, Piguet, C. CRC Press, Boca Raton, 2005.
2. Powers S.K., Howley E.T., *Exercise physiology: Theory and application to fitness and performance.* McGraw Hill Companies, New York, 2004.

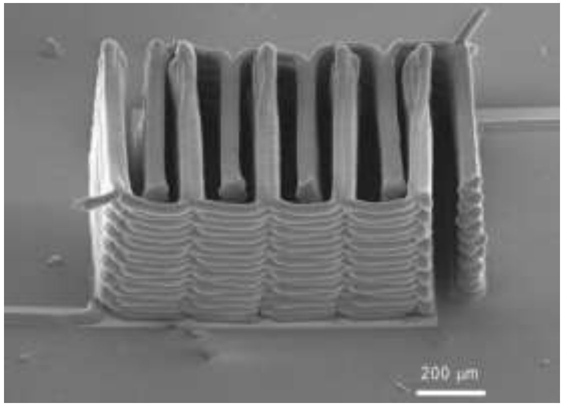
"More than Mechatronics": enablers

- New pervasive/portable/interactive IT
- Morphological computation
- **New fabrication approaches**



The Digital Revolution: the approach

Digital manufacturing and Fab Labs



Crowd funding

Social Innovation

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FabLab: a space where to make ideas real (physical)

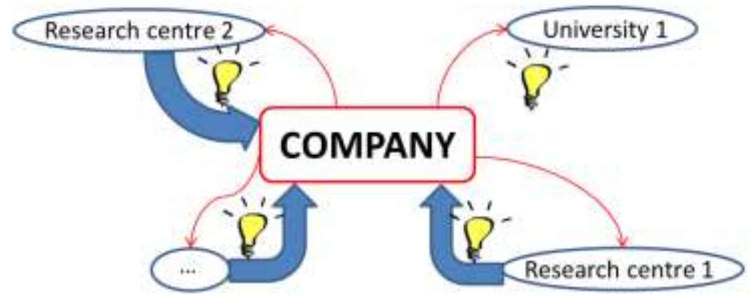
«A place to learn, collaborate, innovate and create just about anything you can imagine»

Social Innovation: the evolution from tradional innovation

Traditional (in-house) innovation

- Internal IP

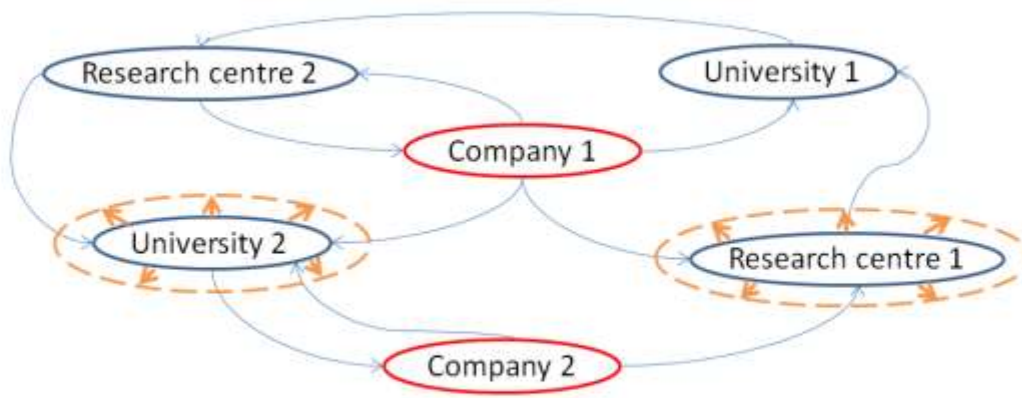
Open innovation



- NDA
- Mail
- Workshops with invited players
- Joint initiatives

Social innovation

More than Open innovation



- Open Network

Conclusions

- Robotics is a well established, successful, and promising field (**one of the 12 potentially economically disruptive technologies, McKinsey Report, 2013**)
- BioRobotics is **science** and **engineering**
  - BioRobotics addresses need-driven solutions
  - BioRobotics is a discovery engine for new science and to **nurture innovators**
- BioRobotics and the concept of Robot Companions mean:
  - Convergence, Traslation, Real world, High impact trans-disciplinary research
  - BioRobotics aims at advancing the (bio)mechatronics paradigm
- **The progress and deployment of companion robots can be accelerated by rethinking the way robots are designed, also using methods and technologies developed by the emerging community of *Soft Robotics***

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Acknowledgments

Many colleagues, many PhD students, many funding agencies (mostly the *European Commission*)