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Soft Robotic Modeling and Control: Bringing Together Articulated Soft Robots and Soft-Bodied Robots

Soft robot bodies: a control challenge or a solution for robot control?

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Abilities not yet reached by robots

Lessons from Nature

Lessons from Nature: simplifying principles

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Too complex?
Rather too simple?

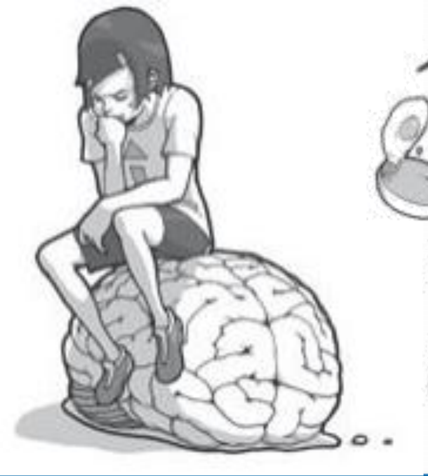
Studying living organisms and understanding what makes their behavior so smart and efficient

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

Embodied Intelligence & Morphological Computation

Classical approach

The focus is on the brain and central processing



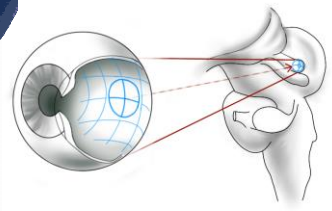
Modern approach

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

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

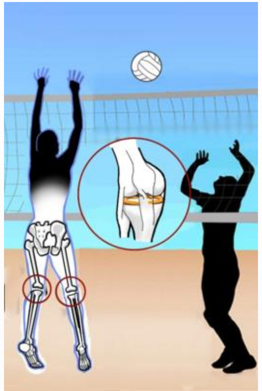
Shape

as body structure, specifies the behavioral response of the agent



Arrangement

of the motor, perceptive and processing units



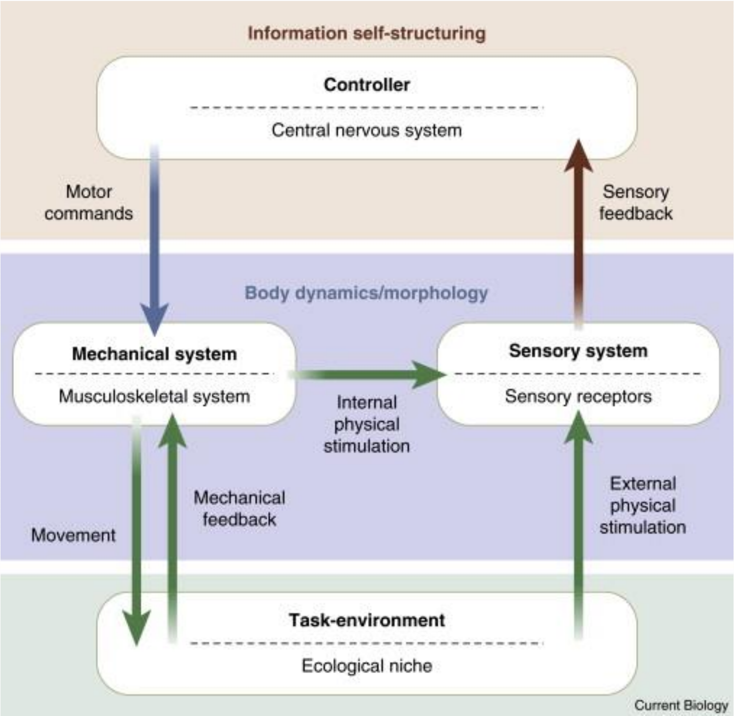
Mechanical properties

allow emergent behaviors and adaptive interaction with the environment

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

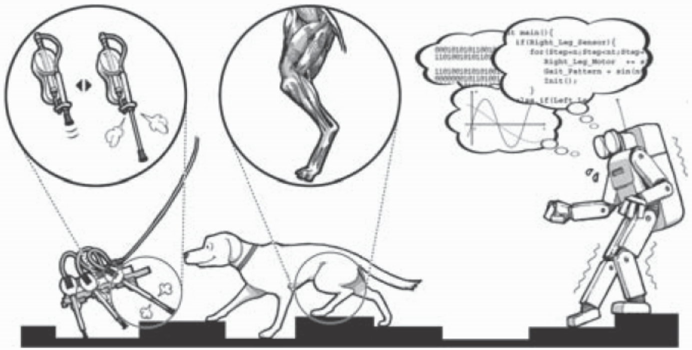
Zambrano D, Cianchetti M, Laschi C (2014) “The Morphological Computation Principles as a New Paradigm for Robotic Design” in *Opinions and Outlooks on Morphological Computation*, H. Hauser, R. M. Füchslin, R. Pfeifer (Ed.s), pp. 214-225.

Embodied Intelligence & Morphological Computation



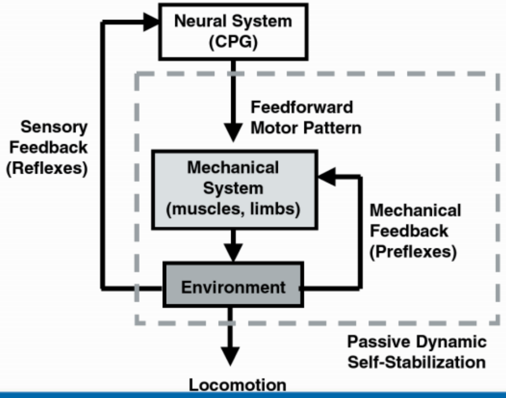
Adaptive behaviour emerges from the interaction between the morphology of the **body**, the **environment** and the **task.**

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



SPRAWL

Stanford Center for Design Research & UC Berkeley PolyPEDAL Lab



Open-loop/feedforward control

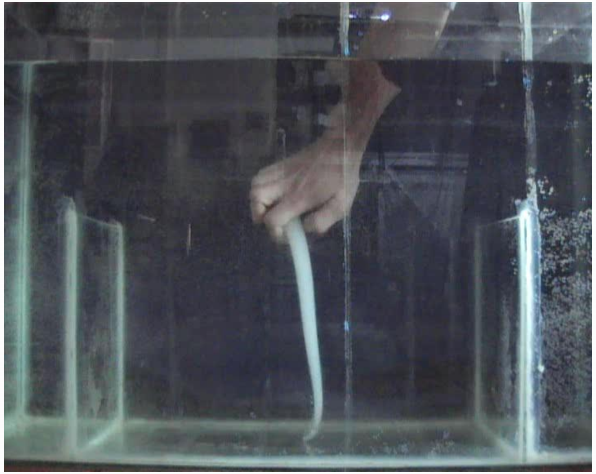
Passive viscoelastic structural elements

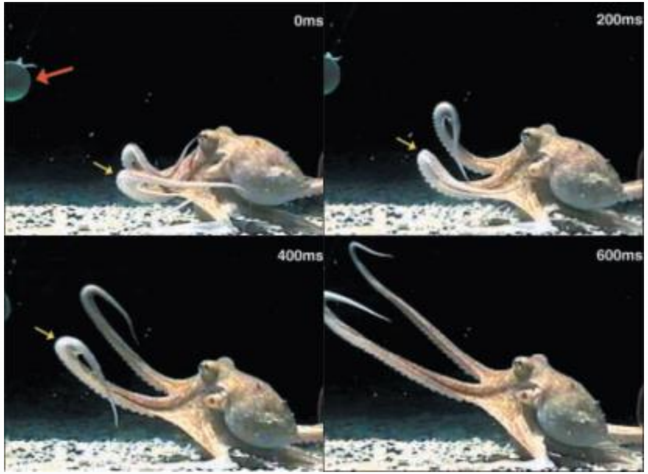
A new soft bodyware

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

JG Cham, SA Bailey, JE Clark, RJ Full and MR Cutkosky (2002). "Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing" *The International Journal of Robotics Research*, 21: 869

The octopus arm embodied intelligence



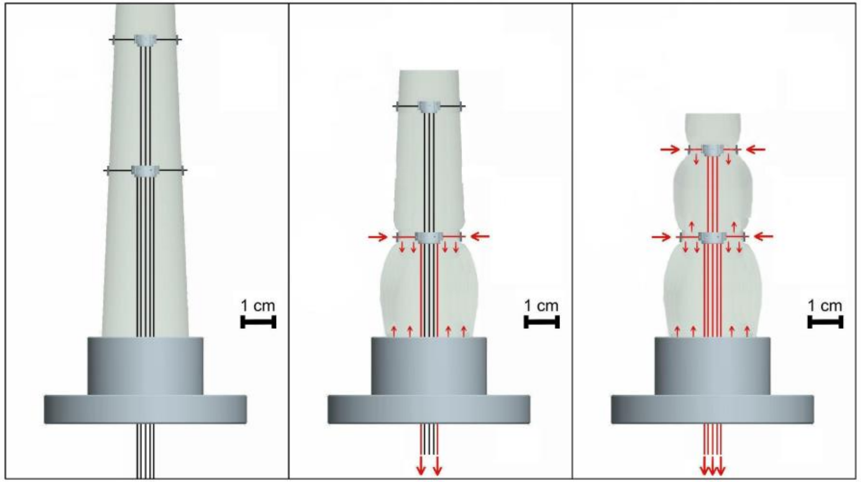


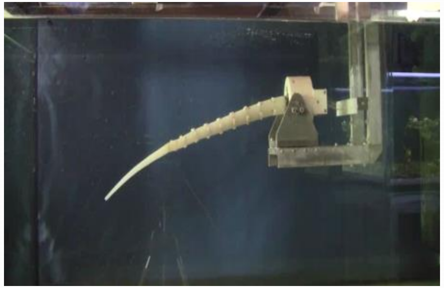
- stiffening wave from base to distal part, that can start from any part of the arm;
- movement executed in about 1 second, velocities in the range of 20–60 cm/s;
- control divided between central and peripheral: from brain: **3 parameters** (yaw and pitch of arm base and peak velocity of bend-point);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

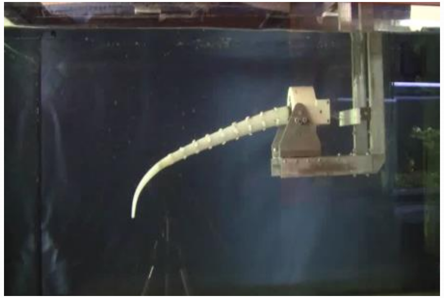
I. Zelman, M. Galun, A. Akselrod-Ballin, Y. Yekutieli, B. Hochner, and T. Flash (2009) Nearly automatic motion capture system for tracking octopus arm movements in 3D space, *Journal of Neuroscience Methods, Volume 182: 97-109*

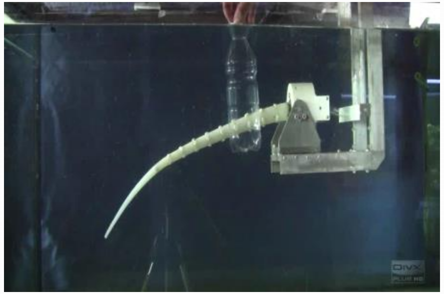
L. Zullo, G. Sumbre, C. Agnisola, T. Flash, B. Hochner (2009) Nonsomatotopic Organization of the Higher Motor Centers in Octopus, *Current Biology, 19:1632-1636.*

Simplifying principles in reaching









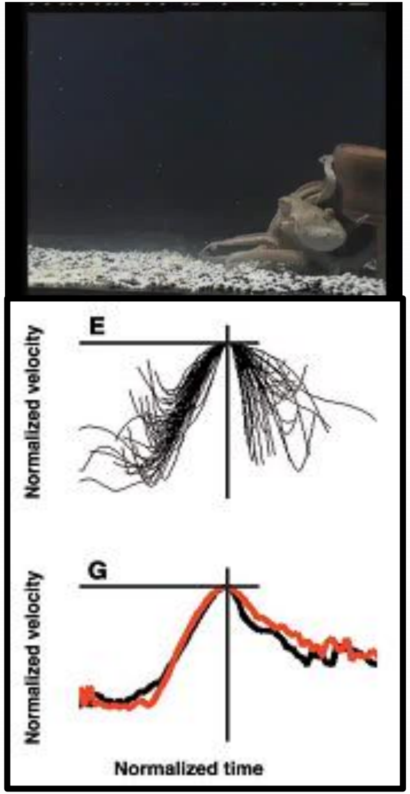
- Silicone
- 9 sections of transverse and longitudinal cables (coupled)
- Simple activation pattern: sequential activation of sections, with equal activation of 4 longi-transverse cables per section

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

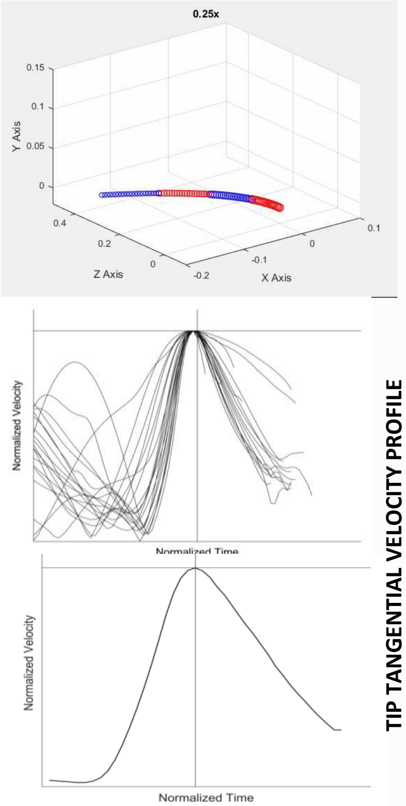
Simplifying principles in reaching

***morphological and environmental properties** are the factors that affects the invariant velocity profile observed*

Biological behaviour



Robot behaviour



TIP TANGENTIAL VELOCITY PROFILE

- 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

Sumbre, G., Gutfreund, Y., Fiorito, G., Flash, T., & Hochner, B. (2001). "Control of octopus arm extension by a peripheral motor program", *Science*, *293*(5536), 1845-1848.

T. George Thuruthel, Falotico E., Renda F., Flash T., Laschi C., "Emergence of Behavior through Morphology: A Case study on an Octopus Inspired Manipulator", *Bioinspiration and Biomimetics*, under review.

Simplifying principles in elongation and stiffening

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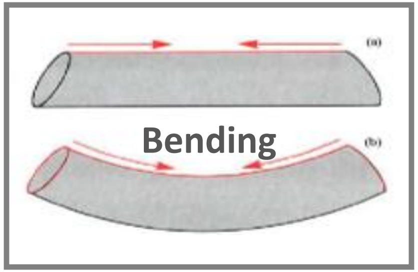
The octopus arm muscular hydrostat



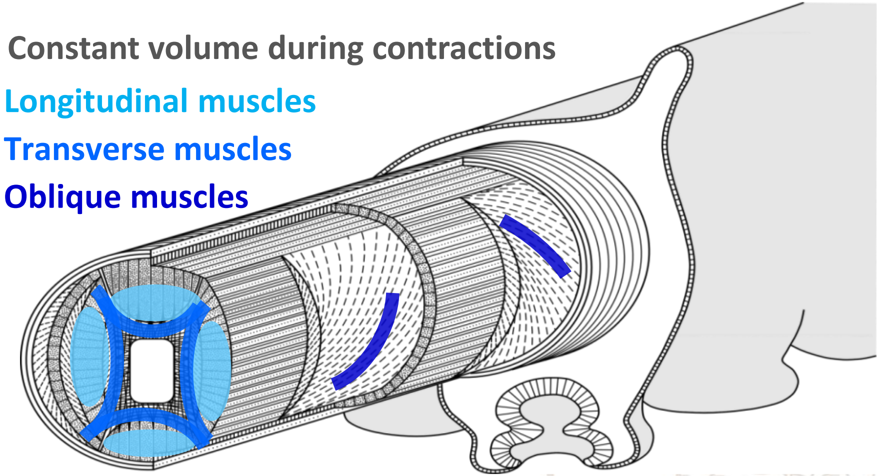
Stiffening (co-contractions)

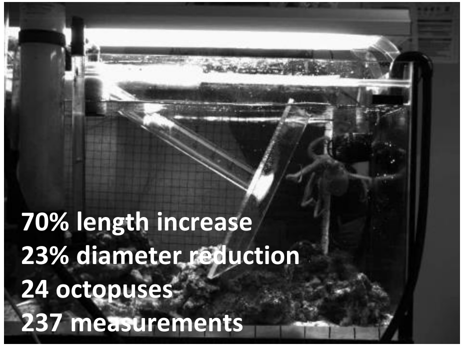
Constant volume during contractions

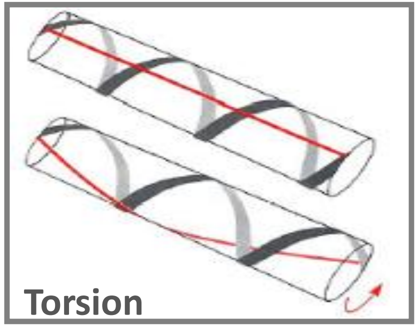
Longitudinal muscles

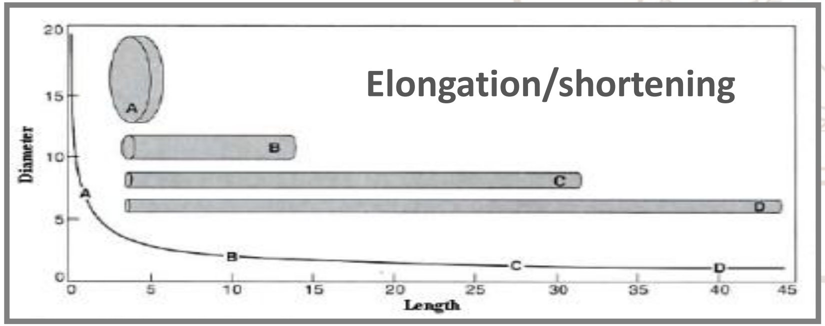
Transverse muscles

Oblique muscles







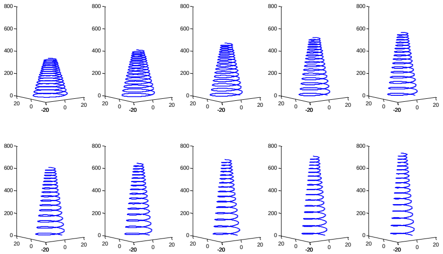


Muscular structure working as a modifiable skeleton

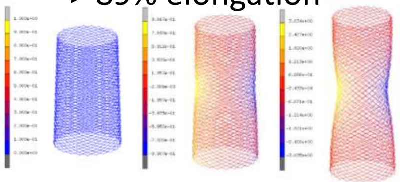
Kier W. "The arrangement and function of Molluscan muscle", *The Mollusca*, Vol. II, 1988

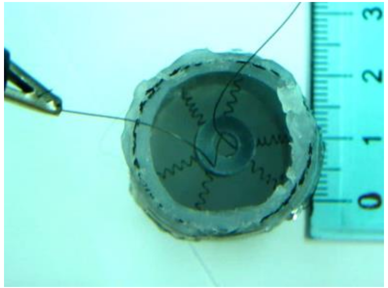
Simplifying principles in elongation and stiffening

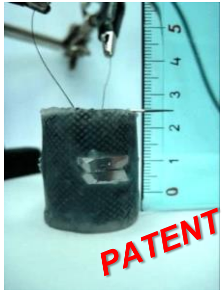
Octopus-like muscular hydrostat



20% diameter reduction
=> 89% elongation



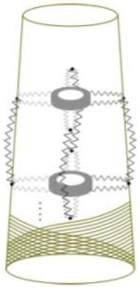




1 second of 600 mA direct current and then 50% duty cycle pulse current

6 SMA springs:
- 0.2 mm Flexinol® wire diameter
- <D>/d = 6 (cycle life parameter)
- Spring internal diameter = 1 mm

Silicone / braided sleeve:
- External diameter = 28mm
- Internal diameter = 20mm



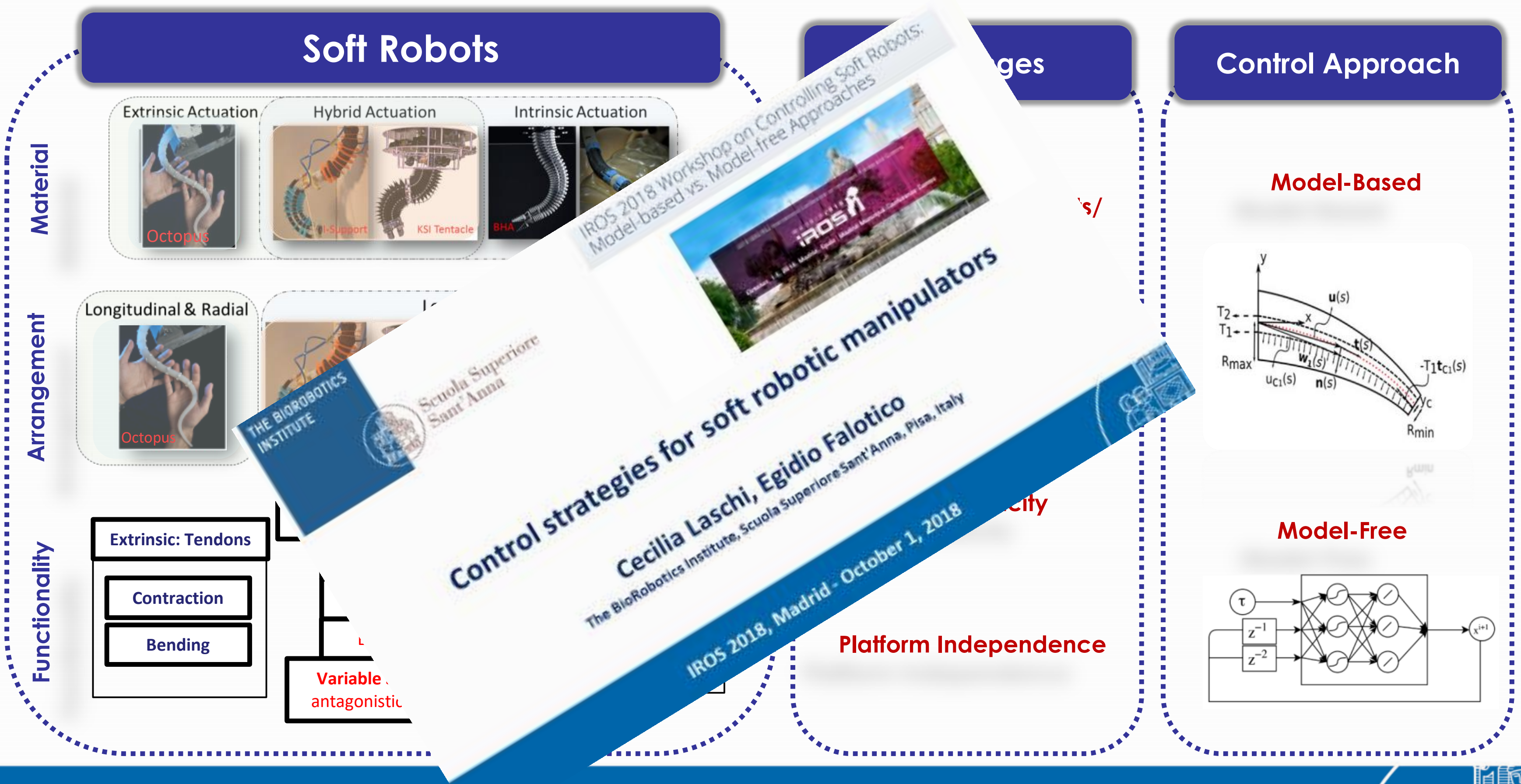
Diameter reduction by 25%, elongation by 41.3%

SMA- & cables-based version (18 transverse SMA springs and 12 longitudinal cables)

SMA-based version (22 SMA springs)

Follador M., Cianchetti M., Arienti A., Laschi C., "A general method for the design and fabrication of shape memory alloy active spring actuators", *Smart Materials and Structures* 21(1), 2012
Follador M, Cianchetti M, Laschi C (2012) "Development of the functional unit of a completely soft oc-topus-like robotic arm", *IEEE Int. Conf. on Biomedical Robotics and Biomechatronics – BioRob 2012*, 640-645.
Cianchetti M, Licofonte A, Follador M, Rogai F, Laschi C (2014) "Bioinspired Soft Actuation System using Shape Memory Alloys" *Actuators* 3(3), 226-244.

Approaches for control of soft robots



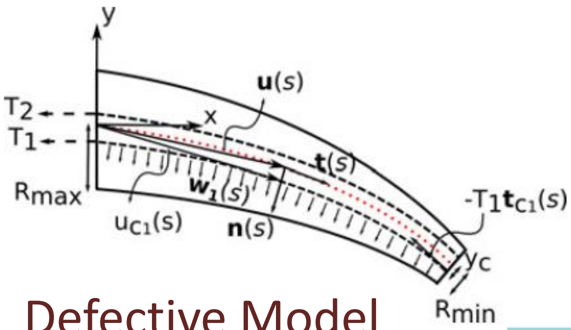
T. George Thuruthel, Y. Ansari, E. Falo... , C. Laschi (2018) "Control Strategies for soft robotic manipulators: a survey", *Soft Robotics* 5(2)

Comparison of model-based and model-free approaches

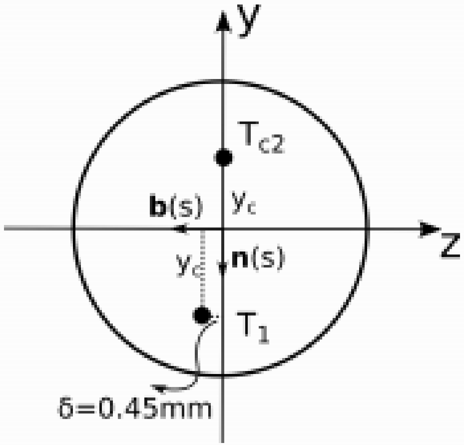
1. Jacobian-based Inverse Static Controller
2. Learning-based Control, by learning the inverse model.

   Learning by collecting points and exploiting the approximation capability of a FNN, as for rigid robots

control the end effector position through the cable tension



Defective Model



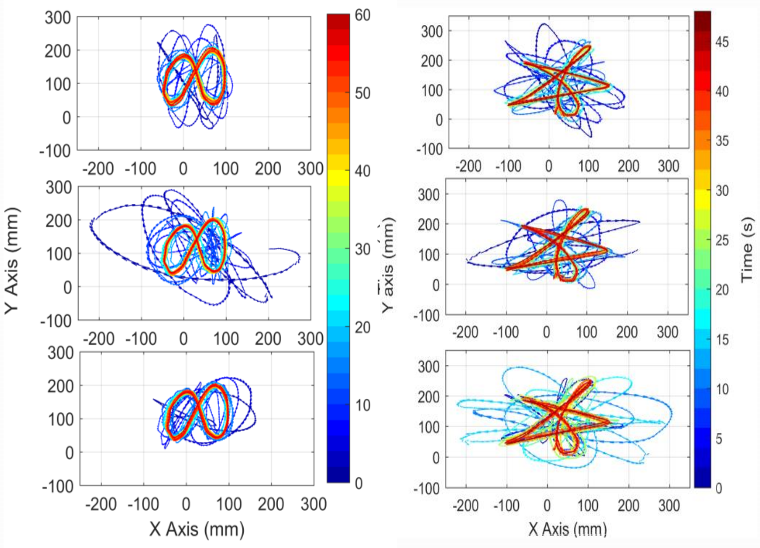
Method (Cost)	Statistics Index	ERR/L [%]
JM (351ms)	Mean	0.27
	Std	0.03
	Max	0.32
NN (0.125ms)	Mean	0.73
	Std	0.55
	Max	3.1

Method (Cost)	Statistics Index	ERR/L [%]
JM (351ms)	Mean	1.30
	Std	0.55
	Max	2.62
NN (0.125ms)	Mean	0.75
	Std	0.68
	Max	3.51

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

Self-Stabilizing Trajectories

The unique dynamics of a soft manipulator exhibits larger number of dynamic attractors that can be used for stable open loop control



The stable trajectories can be observed using the learned forward model

Thuruthel T. G., Falotico E., Manti M., Laschi C. (2018). Stable Open Loop Control of Soft Robotic Manipulators. *IEEE Robotics and Automation Letters*, *3*(2), 1292-1298.

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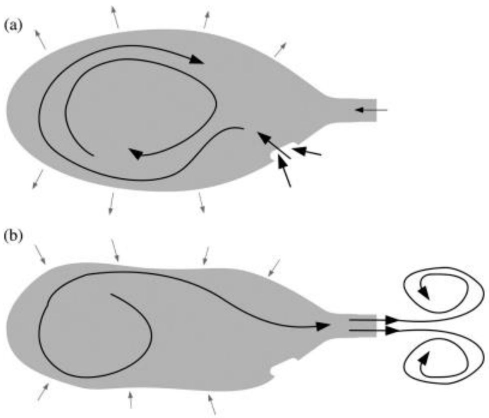
Pulsed-jet swimming in cephalopods

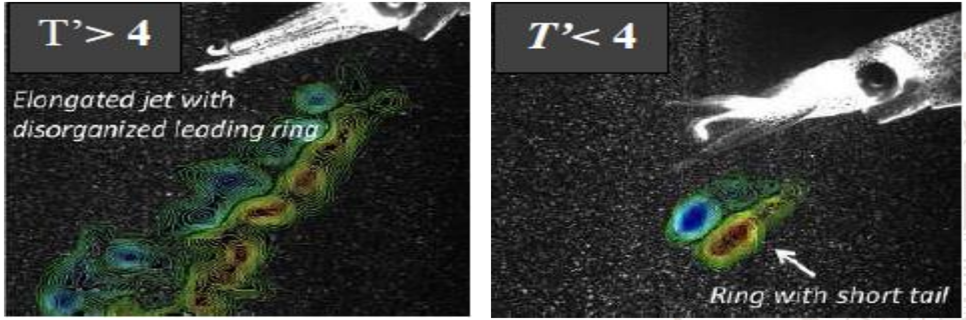


REFILL PHASE

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

JET PHASE

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

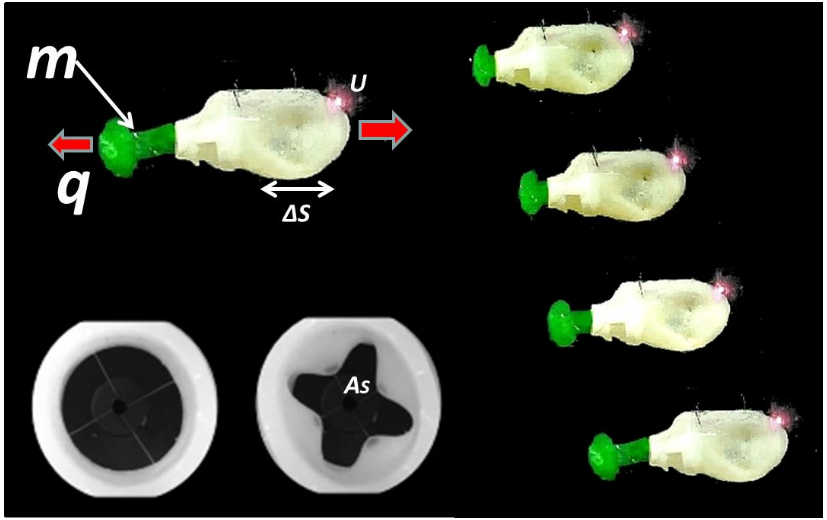


Ejection of a discontinuos stream of fluid through a nozzle that produces **ring vortexes**.
The generation of ring vortexes provides an additional thrust to the one generated by a continuous jet, by generating an additional pressure at the nozzle orifice

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



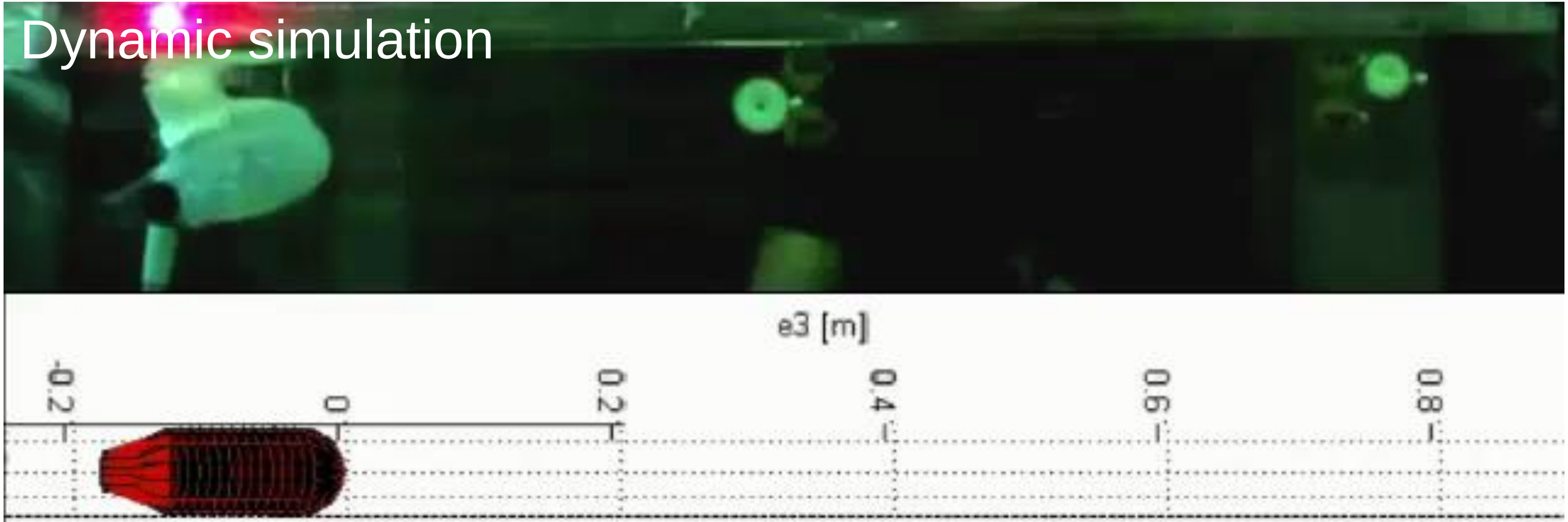
Silicone and cables, 1 DOF

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

Pulsed-jet swimming soft robot

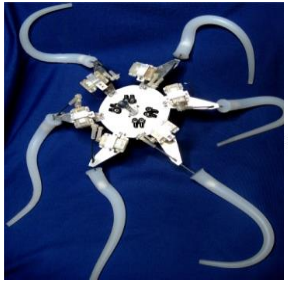


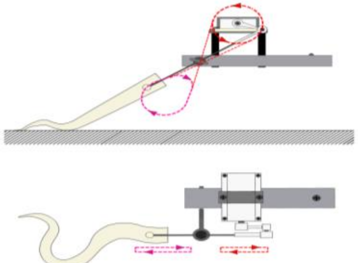
The external loads considered are: gravity, buoyancy, added mass, drag load (coming from the interaction with the fluid) and cable load (input)

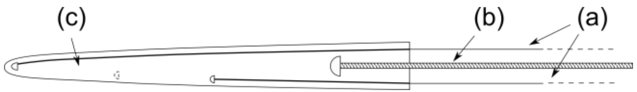
Renda F., Giorgio Serchi F., Boyer F. and Laschi C. (2015), "Modelling Cephalopod-inspired pulsed-jet locomotion for underwater soft robots", Bioinspiration & Biomimetics, (10), 055005, doi:10.1088/1748-3190/10/5/055005.
Renda F., Giorgio Serchi F., Boyer F. and Laschi C. (2015), "Structural Dynamics of a Pulsed-Jet Propulsion System for Underwater Soft Robot", International Journal of Advanced Robotics System, 12:68, 2015, doi: 10.5772/60143.

Simplifying principles in underwater locomotion

Octopus crawling







(a) Nylon cables for grasping
(b) Flexible steel cable
(c) Silicone cone

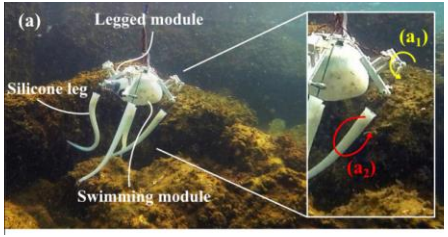
Octopus recorded through a transparent bottom and a mirror. Locomotion is based on **cyclic** control of **two** back arms, while the body is raised thanks to **neutral buoyance**. Locomotion consists of 4 phases:

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

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.

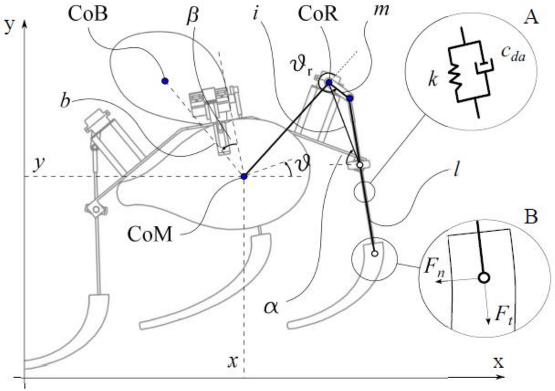
Evolutionary algorithms to design soft bodies with underwater self-stabilized locomotion

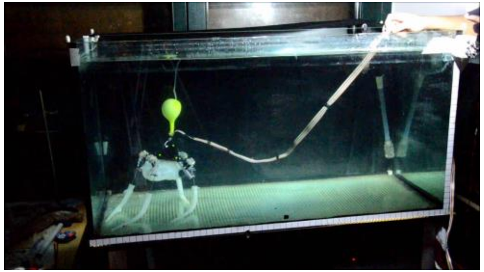
How to design the morphology of a soft robot with octopus-like pushing-based locomotion strategy?

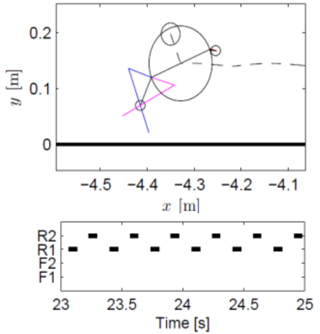


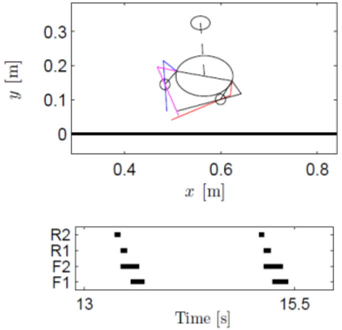
Resulting octopus-like two-pushing leg strategy

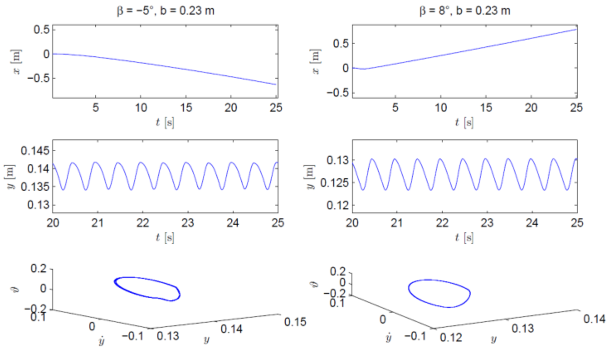
Novel quadruped strategy, with long flight phases

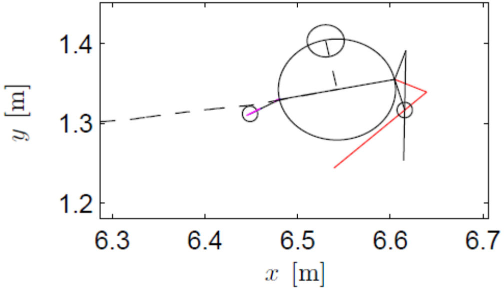












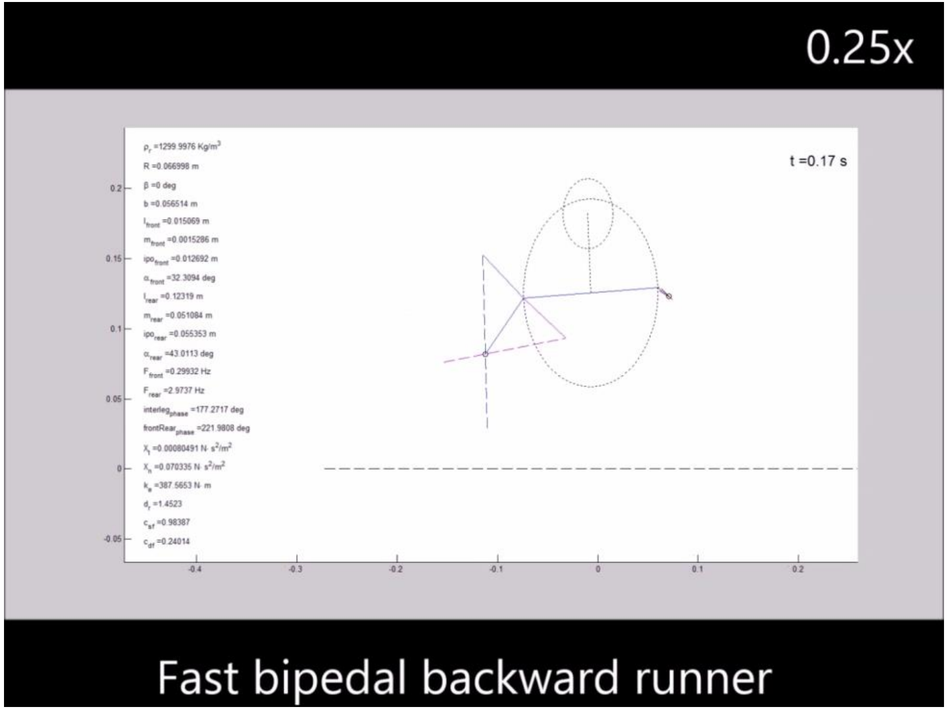
Calisti M., Corucci F., Arienti A., Laschi C. 2015. "Dynamics of underwater legged locomotion: Modeling and experiments on an octopus-inspired robot", *Bioinspiration & Biomimetics* 10(1),.

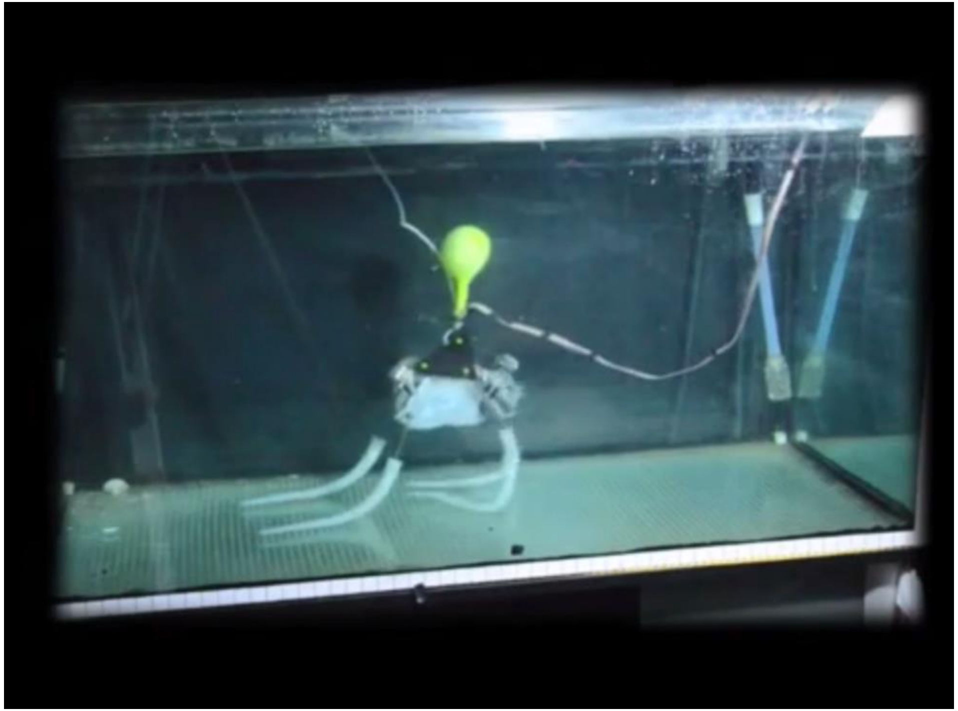
F. Corucci, M. Calisti, H. Hauser, C. Laschi "Shaping the body to shape the behavior: a more active role of the morphology in the brain-body trade-off", 13th European Conference on Artificial Life (ECAL 2015) in York, United Kingdom, 20-24 July 2015

F. Corucci, M. Calisti, H. Hauser, C. Laschi, "Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot", *ICAR2015*, July 27-31, Istanbul, Turkey

F. Corucci, M. Calisti, H. Hauser, C. Laschi, "Novelty-based evolutionary design of morphing underwater robots", Genetic and Evolutionary Computation Conference (GECCO), July 11-15 2015, Madrid, Spain

Evolutionary algorithms to design soft bodies with underwater self-stabilized locomotion





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(1),.

F. Corucci, M. Calisti, H. Hauser, C. Laschi "Shaping the body to shape the behavior: a more active role of the morphology in the brain-body trade-off", 13th European Conference on Artificial Life (ECAL 2015) in York, United Kingdom, 20-24 July 2015

F. Corucci, M. Calisti, H. Hauser, C. Laschi, "Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot", *ICAR2015*, July 27-31, Istanbul, Turkey

F. Corucci, M. Calisti, H. Hauser, C. Laschi, "Novelty-based evolutionary design of morphing underwater robots", Genetic and Evolutionary Computation Conference (GECCO), July 11-15 2015, Madrid, Spain

PoseiDRONE: a soft underwater robot

Simplifying principles in underwater locomotion
U-SLIP model

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

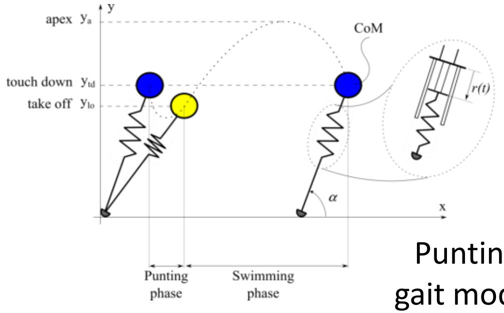
Water drag, added mass, buoyancy and pushing propulsion have been added to the SLIP model

$$\ddot{\tilde{x}} = -\frac{X}{(m+M)}\dot{\tilde{x}}|\dot{\tilde{x}}| + \frac{k(\tilde{x}-x_t)}{m+M}\left(\frac{(r_0+\tilde{r})-\tilde{l}}{\tilde{l}}\right)$$

$$\ddot{\tilde{y}} = -\frac{Y}{(m+M)}\dot{\tilde{y}}|\dot{\tilde{y}}| + \underbrace{\frac{k\tilde{y}}{m+M}\left(\frac{(r_0+\tilde{r})-\tilde{l}}{\tilde{l}}\right)}_{\text{null during swimming}} - \frac{mg}{m+M} + \frac{\rho_w V g}{m+M}$$

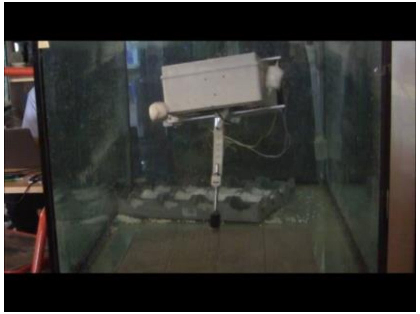
Swimming to punting condition: $\tilde{y} = r_0 \sin\alpha$

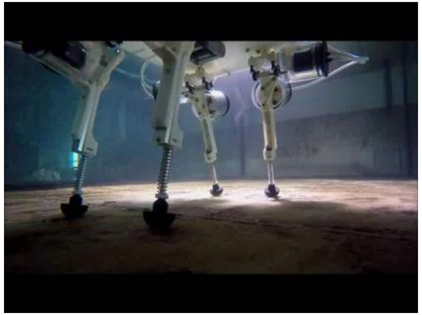
Punting to swimming condition: *Spring at rest length*



Punting gait model

Underwater hopping (bouncing) like a monopode





Dimensionless equations

$$\ddot{x} = -A\dot{x}|\dot{x}| + D\left(x - \frac{x_t}{r_0}\right)\left(\frac{1+r}{l} - 1\right) \qquad r = \boxed{r_s}t$$

$$\ddot{y} = -B\dot{y}|\dot{y}| + Dy\left(\frac{1+r}{l} - 1\right) - C \qquad y = r_0 \sin\boxed{\alpha}$$

With:

$\boxed{A} = Xr_0/(m+M)$

$\boxed{B} = Yr_0/(m+M)$

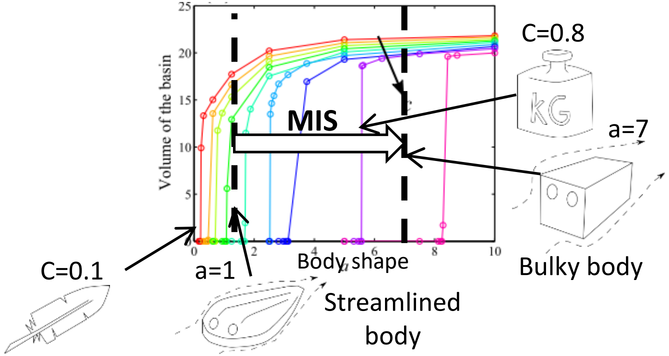
$\boxed{C} = (m-\rho_w V)/(m+M)$

$\boxed{D} = kr_0/(mg+Mg)$

2 control parameters

4 design parameters

Morphology-Induced Stability



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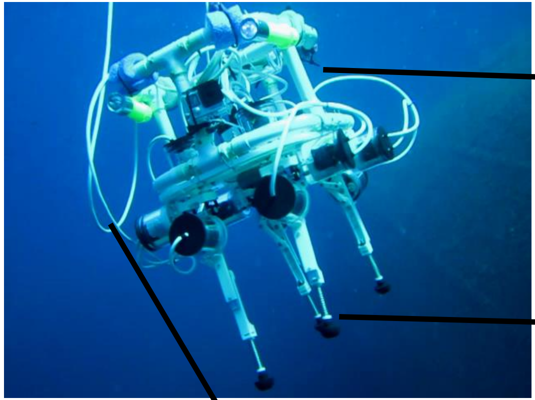
Seabed Interaction Legged Vehicle for Exploration and Research (SILVER)

Innovative underwater robot intended to became a common tool when accurate exploration, monitoring, and interaction with the benthic environment is required.

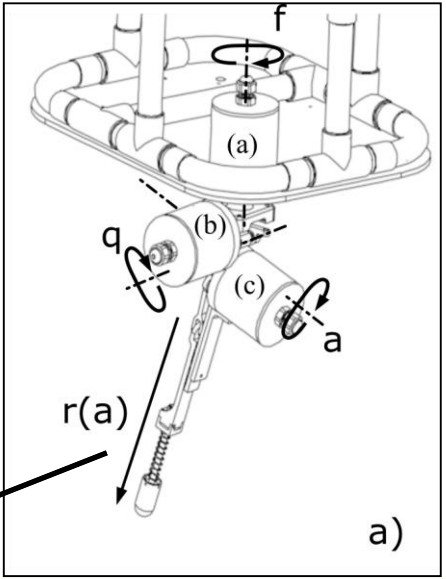


Open frame structure

Four legs with 3 DOFs.
Two rotational DOFs (f,q) and one prismatic DOF (r)

Remotely operated via a tether

Each leg features a linear spring

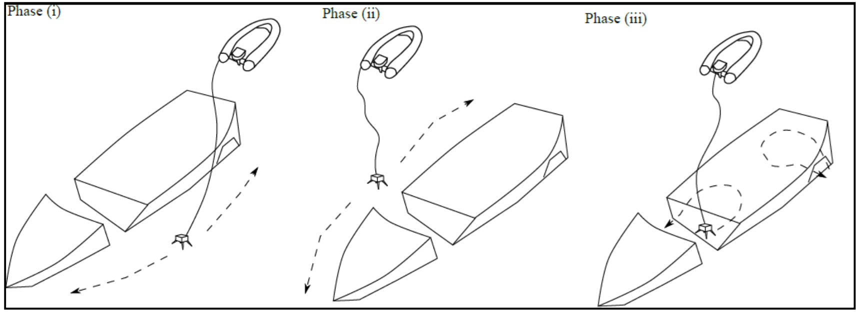


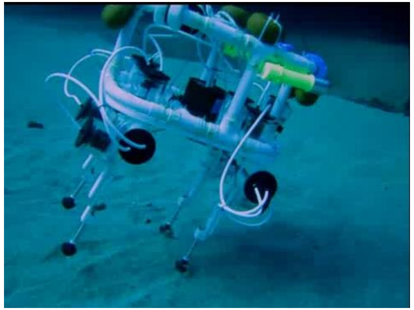
1. Design and Development of a remotely operated vehicle on four legs
2. Exploration of the wreck of the Elviscot, Pomonte, Elba Island
3. During the exploration the robot will collect pictures, long-exposure pictures, and videos.

SILVER: Seabed-interaction legged vehicle for exploration and research, Early Career Grant of the National Geographic Society, **Marcello Calisti**

NATIONAL GEOGRAPHIC

SILVER: Seabed-interaction legged vehicle for exploration and research





Self-Stabilizing on uneven ground

No induced disturbances

Static gaits

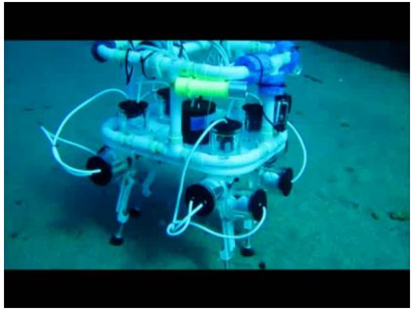
- Walking
- Crawling
- On spot rotation

Precise foot placement is allowed by the rigid structure of the leg. Nothing new, just implemented as in literature.

Dynamic gaits

- Forward hopping
- Rotation hopping

Enabled by compliancy. Disturbance rejection (self stabilization). Based on reduced order model for underwater dynamic legged locomotion.



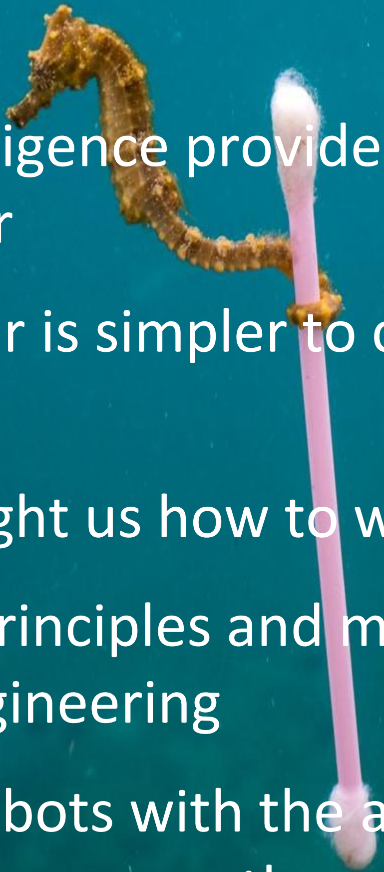
Close inspection

Station keeping (long exposures)

Picardi G., Laschi C., Calisti M. (2018) "Model based Open Loop Controller of a Multigait Legged Underwater Robot", *Journal of Mechatronics* 55:162-170.

Exploration of the wreck of the Elviscot, Pomonte, Elba Island

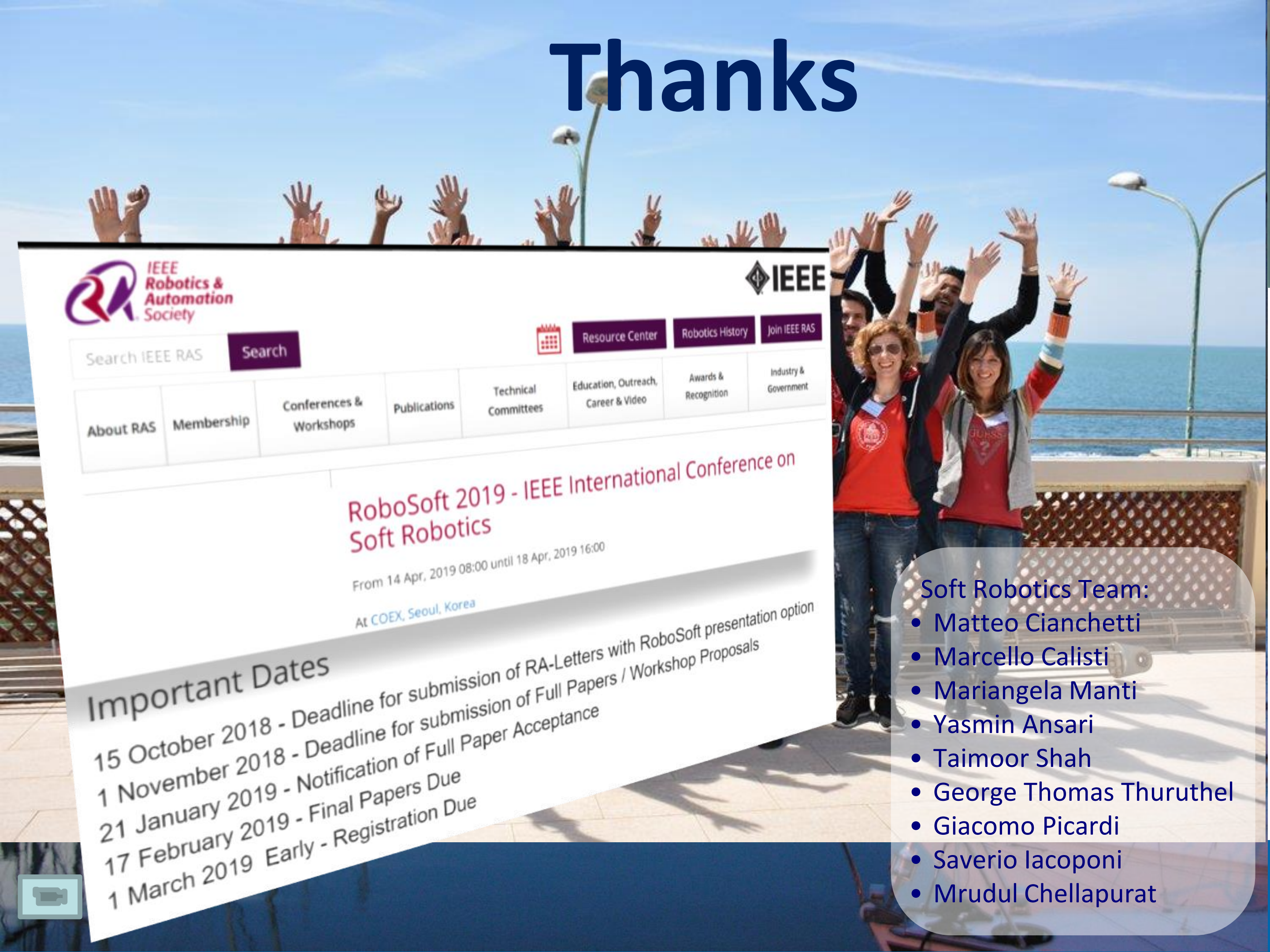
Summary



- Embodied intelligence provides simplifying principles for robot behaviour
- Robot behaviour is simpler to control, but design becomes more complex
- An octopus taught us how to walk underwater
- By identifying principles and modeling them, we can translate biology into engineering
- We can build robots with the ability of walking underwater, to monitor and preserve the oceans

A soft benthonic robot searching for plastic on the seafloor

Thanks



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Soft Robotics Area

- Blue Resolution - ARBI
- Silver – National Geographic
- RoboCom++, EU
- I-Support, EU PHC
- PoseiDRONE, Fondazione Livorno
- RoboSoft CA, EU ICT FET-Open
- Smart-e, EU Marie Curie ITN
- OCTOPUS, EU ICT FET
- OCTO-Prop, EU Marie Curie Grant