BIOINSPIRED APPROACHES TO DESIGN AND CONTROL OF MOBILE SOFT ROBOTS

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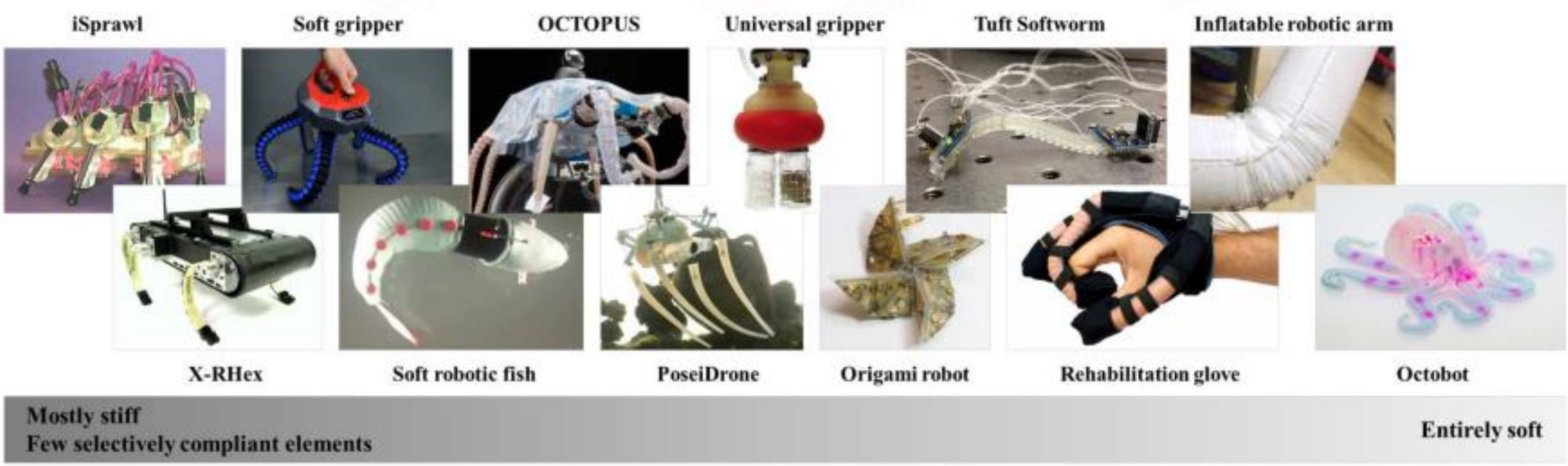
What's a soft robot?

"inherently compliant and exhibit large strains in normal operations"

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

"systems that are capable of autonomous behavior, and that are primarily composed of materials with moduli (i.e. Young module) *in the range of that of soft biological materials"*



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

Laschi C, Mazzolai B, Cianchetti M. 2016 Soft robotics: technologies and systems pushing theboundaries of robot abilities. Sci. Robot. 1

Push forward robots' capabilities

Where soft robots dare: «[…] capabilities for performing actions, such as squeezing, stretching, climbing and growing, that would not be possible with an approach to robot design based <u>on rigid links only</u>.»

[…] applications of an ability can eventually materialize in diverse fields.»

Very strong, forward looking statement, which is not completely satisfied by the current state of the art soft robots.

Laschi C, Mazzolai B, Cianchetti M. 2016 Soft robotics: technologies and systems pushing theboundaries of robot abilities. Sci. Robot. 1

Bio-inspiration for mobile soft robots

Having a compliant, deformable body

Conflictual goals

Exerting forces to the environment

Forces and deformations should be performed at the right time and with appropriate control law

By taking inspiration from soft animals

"We consider belonging to soft robotics field each robot for which ***locomotion is enabled*** *by deformable (due to inherent or structural compliance) components or which relies on such deformable components to* ***increase quantitative or qualitative performance****."*

Fundamentals of soft robot locomotion

Crawling
- Two anchor
- Peristaltic

Legged
- Running

Jumping
- Ballistic jump

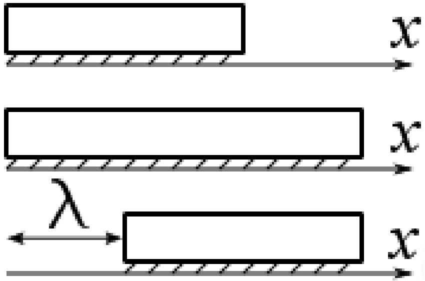
Flying
- Fixed wing
- Flapping wing

Swimming
- Jet propulsion

Not bioinspired
- Quasi-static rolling
- Vibration-based

Calisti, M., G. Picardi, and C. Laschi. "Fundamentals of soft robot locomotion." *Journal of The Royal Society Interface* 14.130 (2017): 20170101.

Biological model and locomotion principle: two-anchor crawl



M: mass of the animal

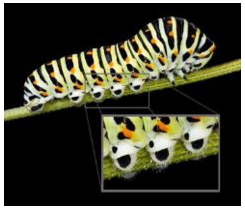
λ: elongation and shortening action

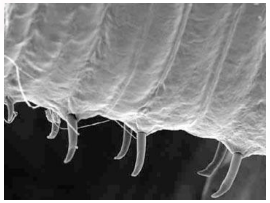
g: gravity acceleration

$$F_x = \mu_{-x} M g \qquad F_{-x} = -\mu_x M g \qquad R = \mu_{-x} M g - \mu_x M g$$

$$R > 0 \rightarrow \mu_{-x} M g > \mu_x M g \rightarrow \boldsymbol{\mu_{-x} > \mu_x}$$

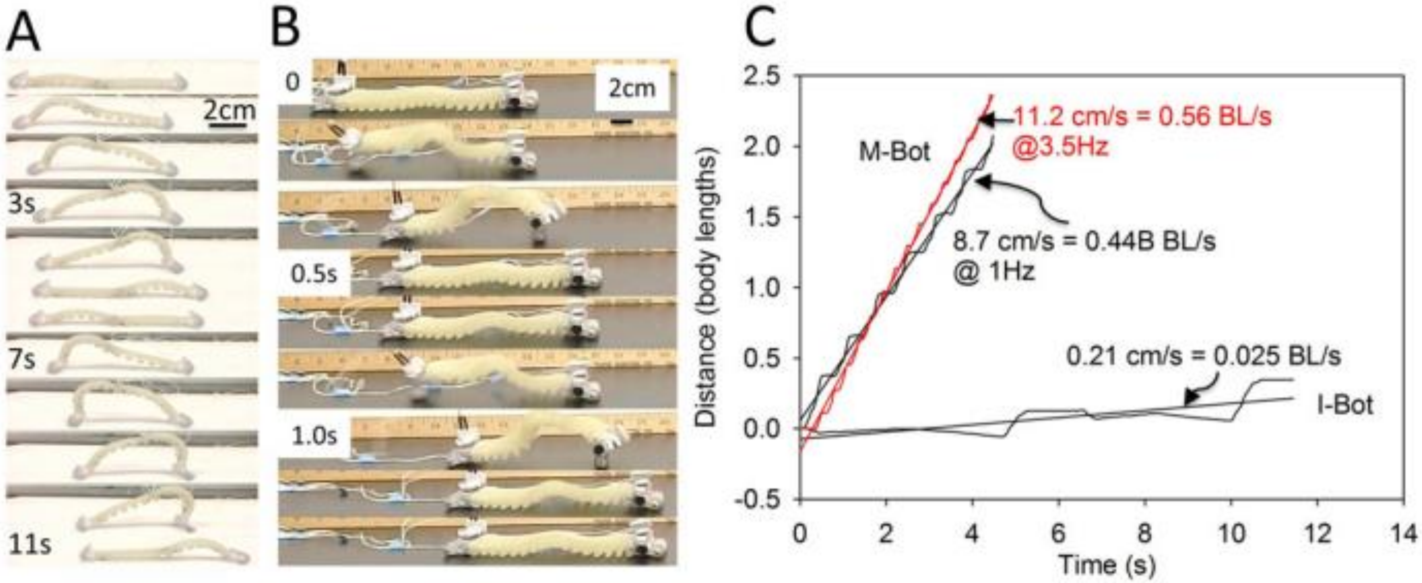
Adhesion mechanism

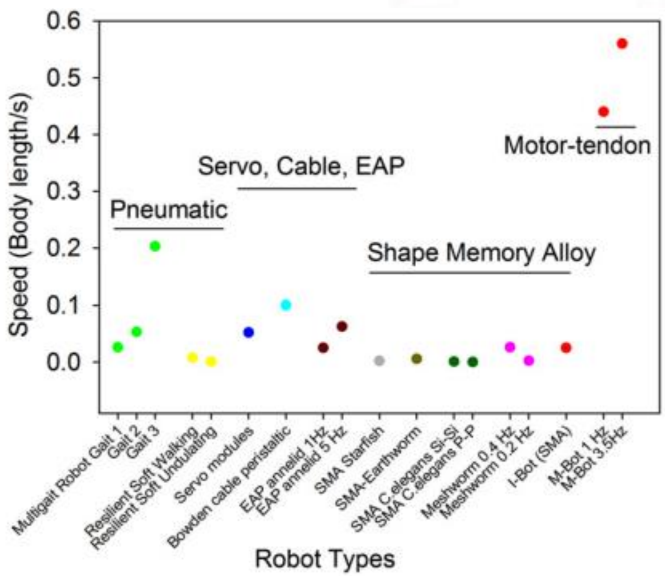




Elongation (shortening) mechanism

Elongation mechanism: tendons / motors

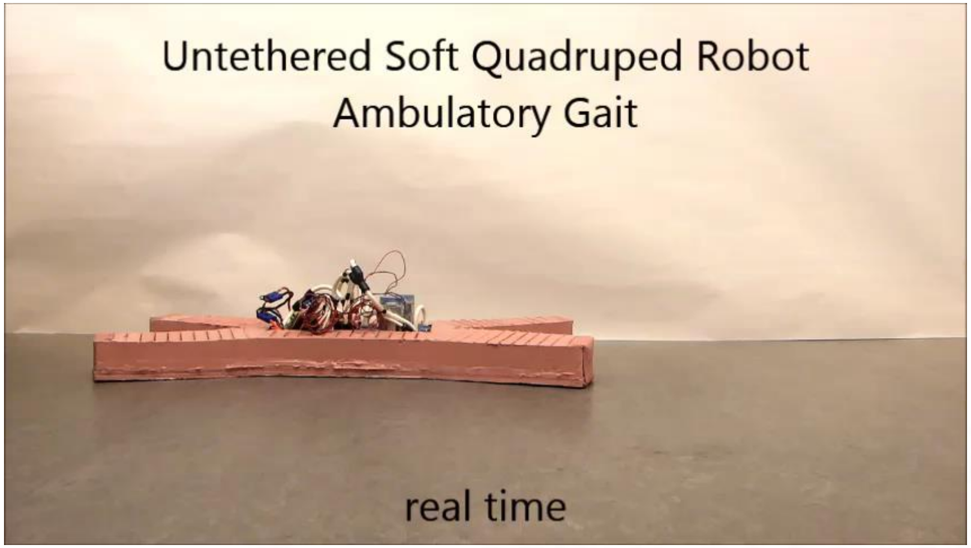


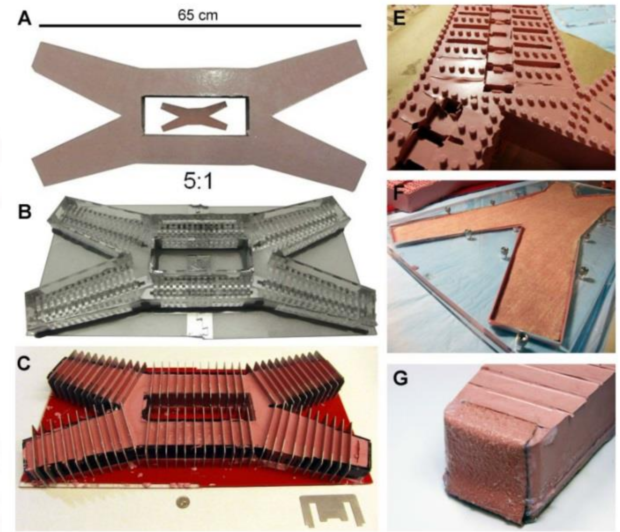


Student challenge: SoftRobotics Week 2015

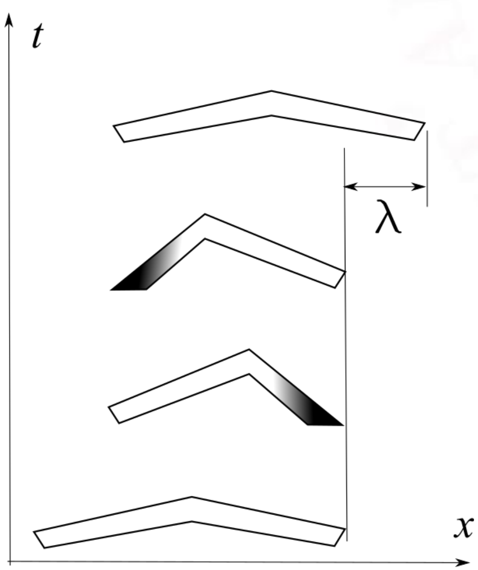
Umedachi T, Vikas V, Trimmer BA. 2016 Softworms: the design and control of non-pneumatic, 3D-printed, deformable robots. Bioinspir. Biomim. 11, 25001. (doi:10.1088/1748-3190/11/2/025001)

Legged crawler





Crawling gait (not walking)



End pose

Sliding of the frontal part of the robot

Change of the anchor (no locomotion)

Sliding of the rear part of the robot

Initial pose

Why legged?

Multi-gait locomotion

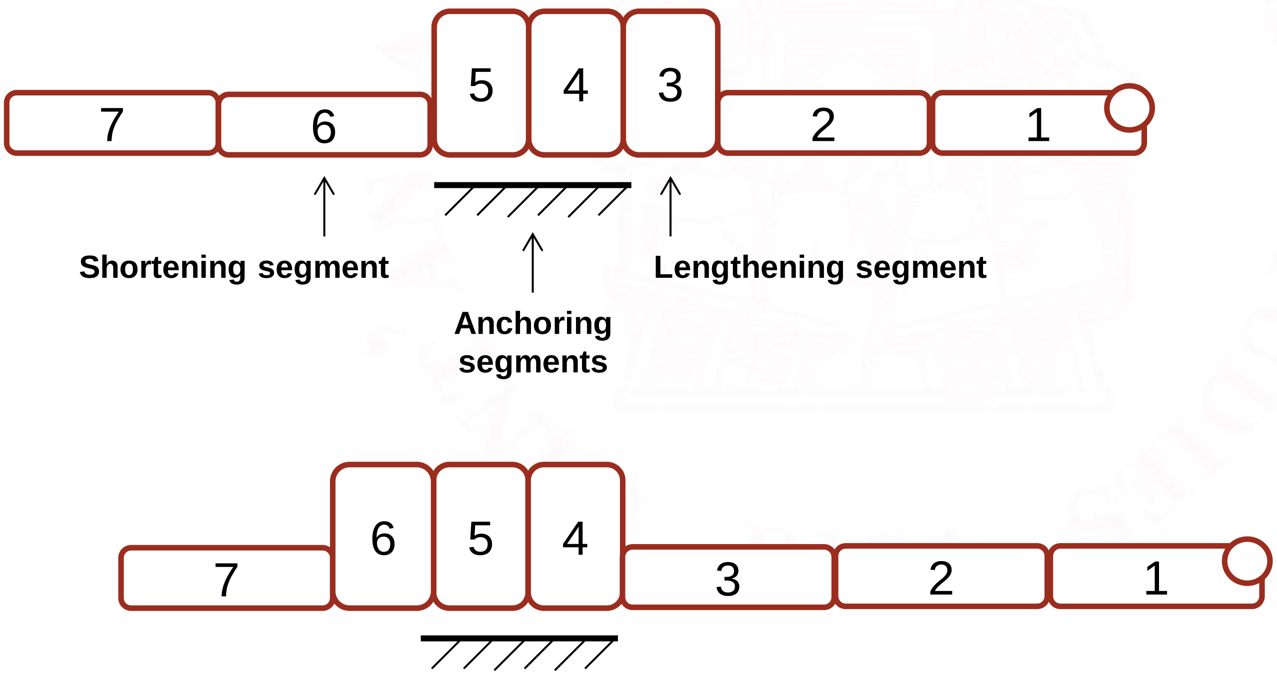
Tolley, Michael T., et al. "A resilient, untethered soft robot." *Soft Robotics* 1.3 (2014): 213-223.

Shepherd RF, Ilievski F, Choi W, Morin SA, Stokes AA, Mazzeo AD, Chen X, Wang M, Whitesides GM. 2011 Multigait soft robot. Proc. Natl Acad. Sci. USA 111, 20 400–20 403. (doi:10.1073/pnas.1116564108)

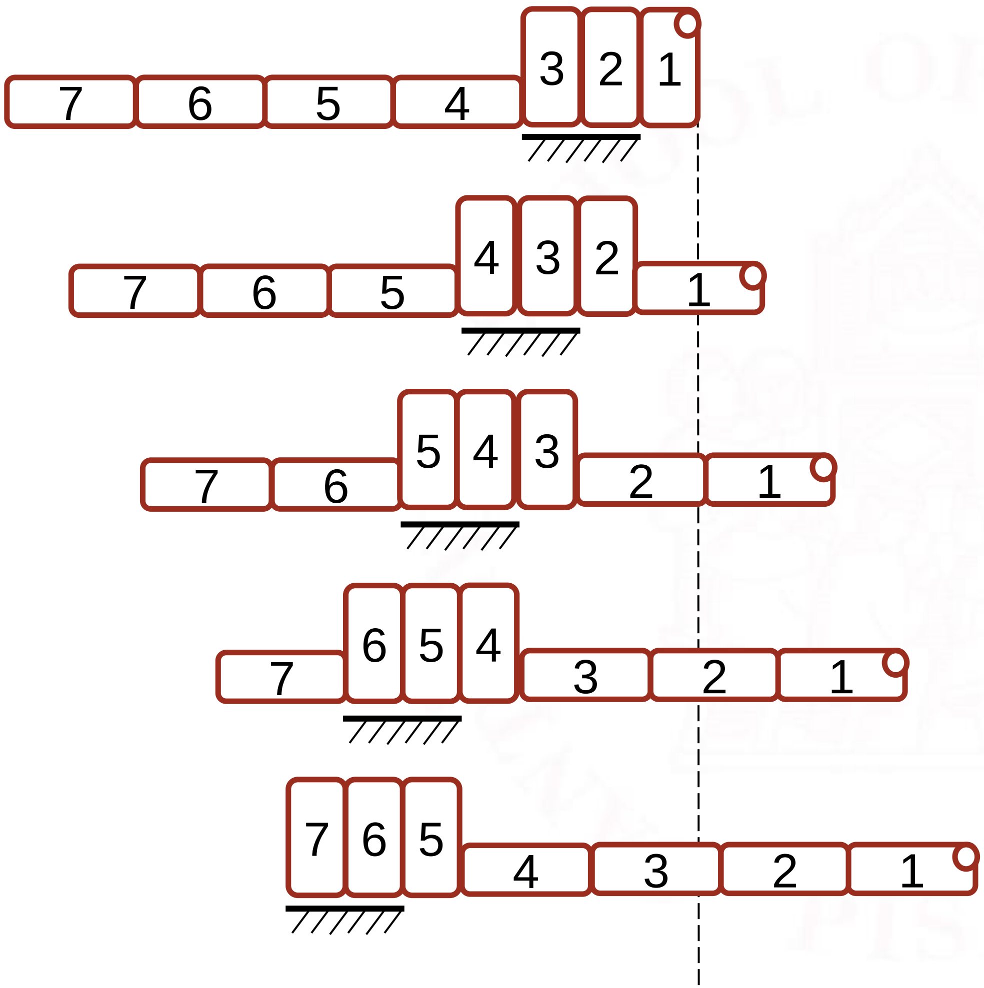
Biological model and locomotion principle: peristaltic crawl

Fundamental element is still the **Hydrostatic skeletons**, but in peristaltic locomotion the actuation pattern is the key to obtain locomotion

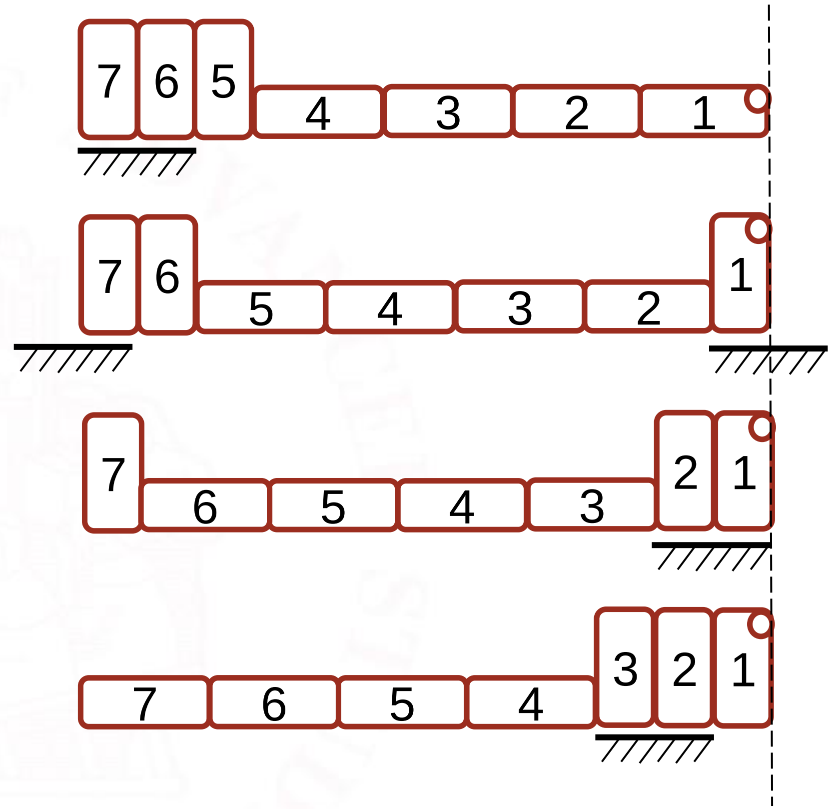
Waves of contraction move backward (or forward in some cases) along the body, and segments of the body lengthen and shorten in turn



Biological model and locomotion principle



Propulsive actions



Changing anchors

Biological model and locomotion principle

$$\mu_x \delta m g < \mu_{-x} \delta m g$$

δm : a small portion of the body mass
g: gravity acceleration
μ_x: static friction coefficient (forward direction)
μ_{-x}: dynamic friction coefficient (backward direction)

(1-n)

n

Coupled contraction/ elongation

No anisotropic friction required

$$\mu_x \delta m g n < \mu_{-x} \delta m g (1 - n)$$

$$\mu_x n < \mu_{-x} \, (1 - n)$$

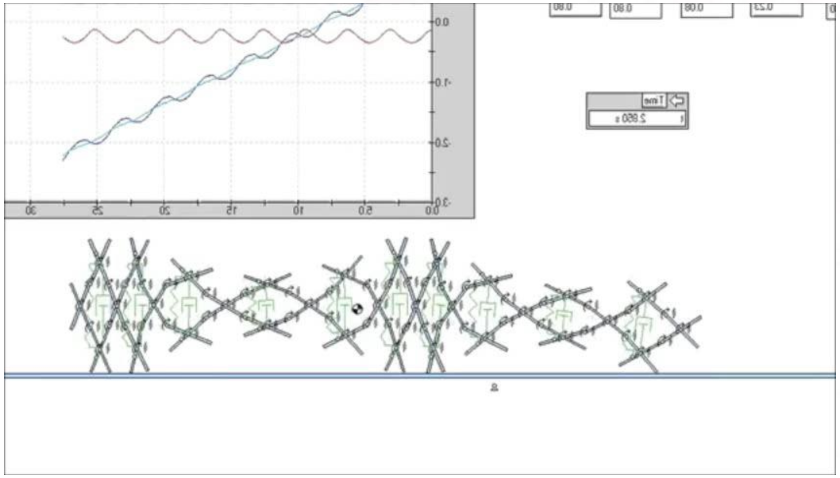
$$n < \frac{\mu_{-x}}{\mu_x + \mu_{-x}}$$

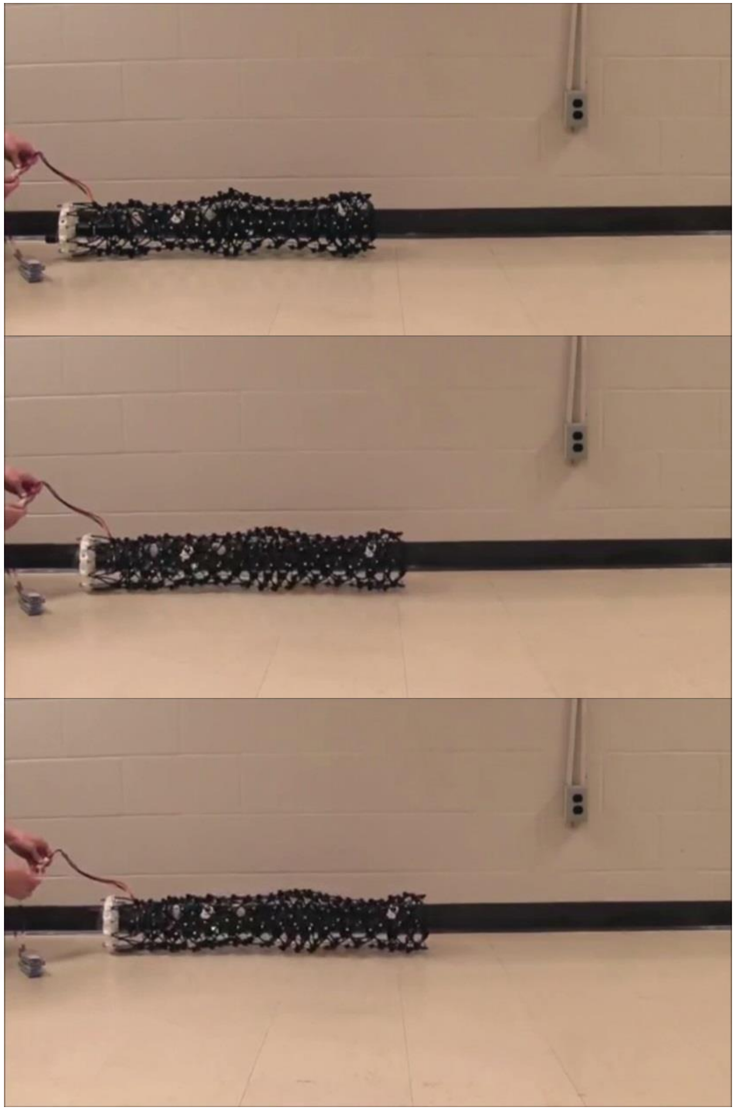
Reference	Segments	Non-anchoring segments	Speed slip efficiency
Vaidyanathan *et al* (2000)	Three spikes on foam, underwater	33–66%	≪50%
Mangan *et al* (2002)	Three inflatable meshes in tube	66–100%	18%
Menciassi *et al* (2004)	Four wire legs on velvet	0%	10%
Omori *et al* (2009))	Four expandable segments in soil or pipe	50%	vertical climbs
Seok *et al* (2010)	Four constrictions of mesh on floor	0–25%	87%
Boxerbaum *et al* (2010)	12 tensioned radii mesh thus . . . 27 rubber tips on floor	81–85%	91%

Note: This table only includes robots in which radial and longitudinal expansions are coupled for each segment so that the term ‘segment’ is consistent. Speed slip efficiencies are based on our best understanding of the cited authors’ measured speed over expected top speed, not on duplication of experiments.

Daltorio KA, Boxerbaum AS, Horchler AD, Shaw KM, Chiel HJ, Quinn RD. 2013 Efficient worm-like locomotion: slip and control of soft-bodied peristaltic robots. Bioinspir. Biomim. 8, 35003.

Robotic model: focus on anchors and elongations

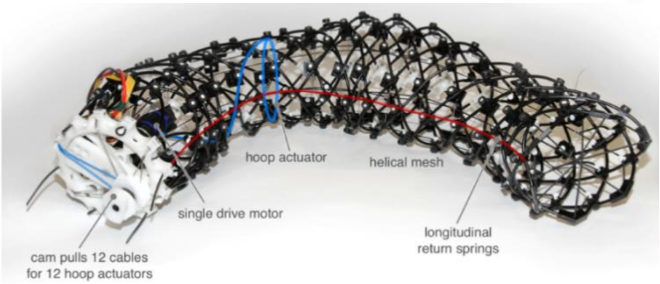




Daltorio KA, Boxerbaum AS, Horchler AD, Shaw KM, Chiel HJ, Quinn RD. 2013 Efficient worm-like locomotion: slip and control of soft-bodied peristaltic robots. Bioinspir. Biomim. 8, 35003.(doi:10.1088/1748-3182/8/3/035003)

Soft components exploitation

Underactuation



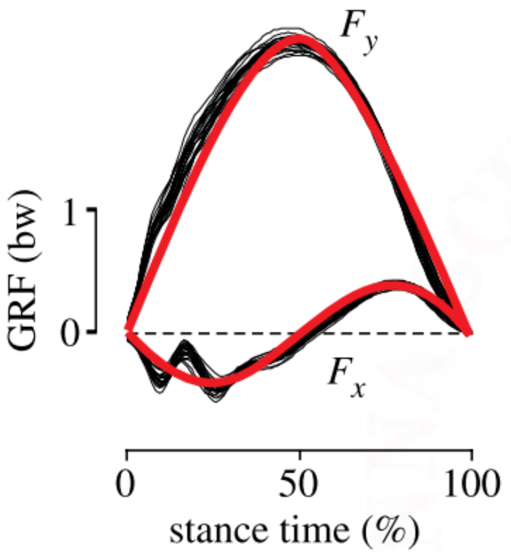
Material or structures distribute the action of the actuator, so that the need of several actuations is not needed. Moreover, underactuation could be exploited to embed control in the mechanisms.

Work in harsh conditions

Resilience to damages

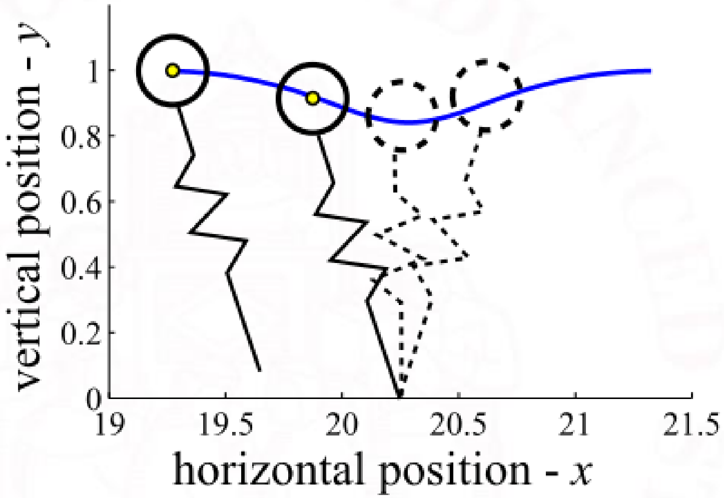
Adaptability to the environment

Biological model and locomotion principle: running/hopping



Geyer, Hartmut, Andre Seyfarth, and Reinhard Blickhan. "Compliant leg behaviour explains basic dynamics of walking and running." *Proceedings of the Royal Society of London B: Biological Sciences* 273.1603 (2006): 2861-2867.

Spring-loaded inverted pendulum (SLIP)



m: point mass of the system

l_0: rest lenght of the leg

(x, y): position of the mass

x_t: foot position at touchdown

g: gravity acceleration

Stance phase:

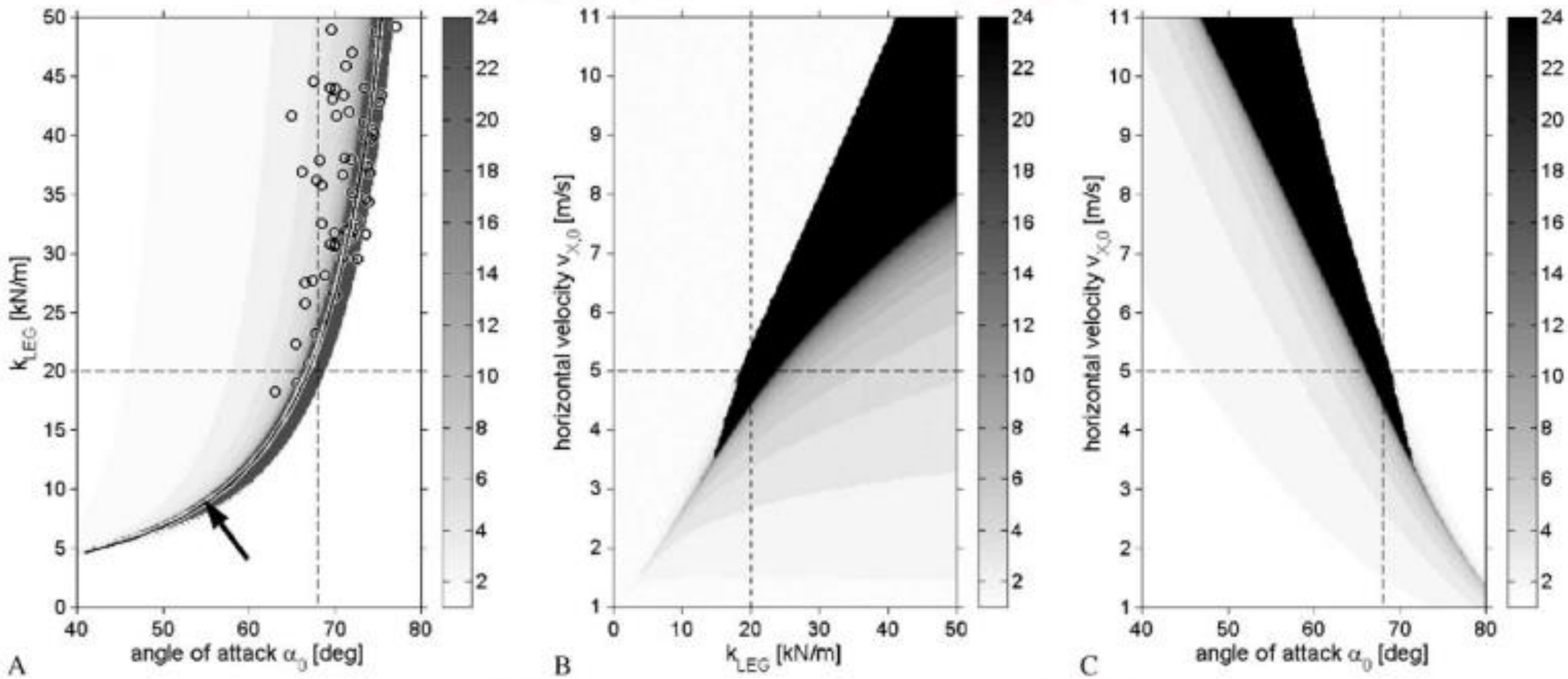
$$m\ddot{x} = k\left(l_0 - \sqrt{(x - x_t)^2 + y^2}\right)\frac{(x - x_t)}{\sqrt{(x - x_t)^2 + y^2}} = k(x - x_t)\left(\frac{l_0}{\sqrt{(x - x_t)^2 + y^2}} - 1\right)$$

$$m\ddot{y} = ky\left(\frac{l_0}{\sqrt{(x - x_t)^2 + y^2}} - 1\right) - g$$

Elastic leg

Biological model and locomotion principle

Parameters which guarantee stable locomotion in humans:



Self-stabilization of running

Seyfarth, Andre, et al. "A movement criterion for running." *Journal of biomechanics* 35.5 (2002): 649-655.

Soft components exploitation: energy efficiency

Compliance on leg → **Compliance on body**

Rigidly attached load

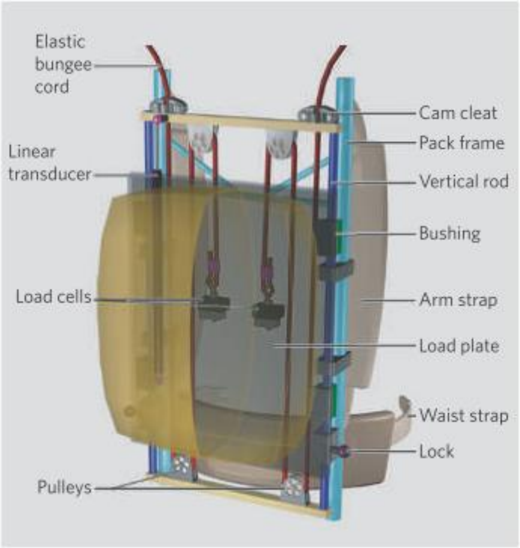
The load (backpack) and the carrier oscillate of the same amplitude.

Elastically attached load

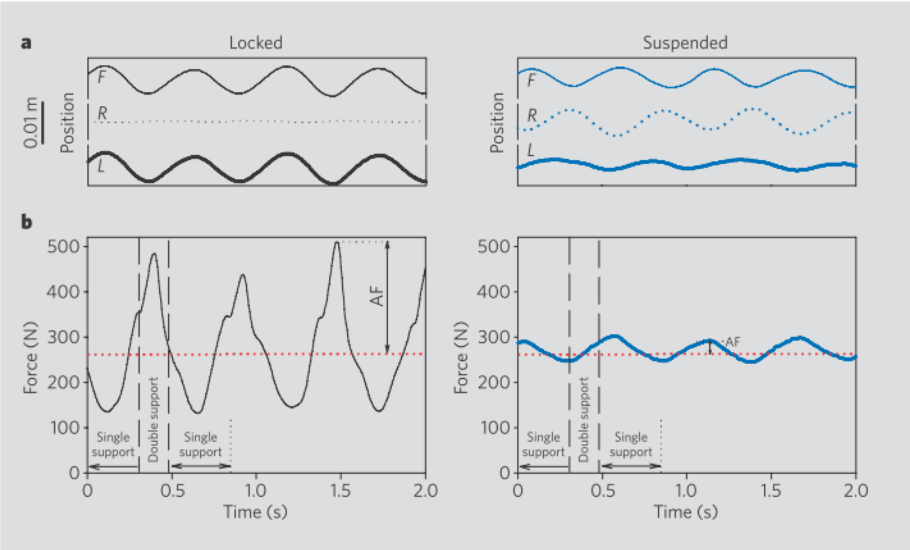
Decoupling the oscillation of the load with the oscillation of the carrier.

Rome, Lawrence C., Louis Flynn, and Taeseung D. Yoo. "Biomechanics: Rubber bands reduce the cost of carrying loads." *Nature* 444.7122 (2006): 1023.

Soft components exploitation: energy efficiency



27Kg: fixed or suspended

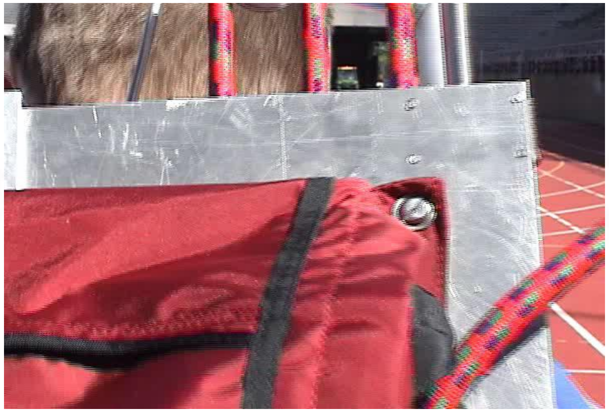


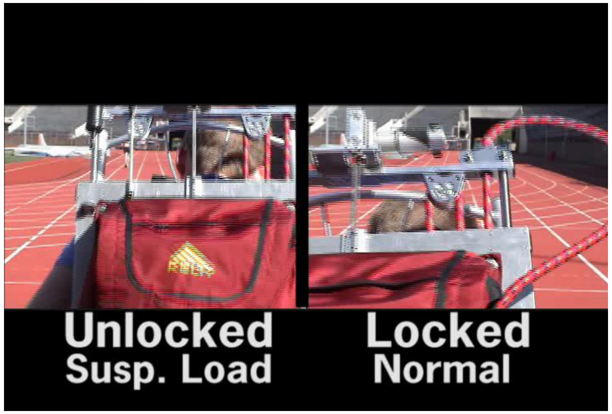
Metabolic cost:

640 W→ 600 W

Equivalent weight carried:

27 kg→ 21.7 kg





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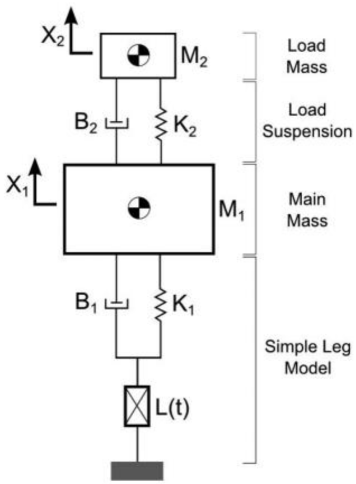
Soft components exploitation: energy efficiency



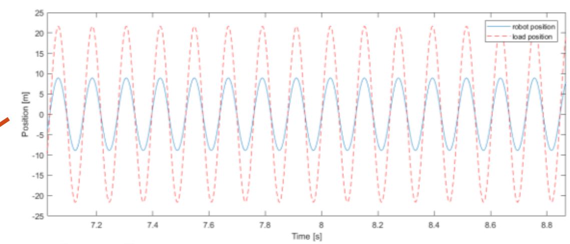
Double-mass coupled-oscillator

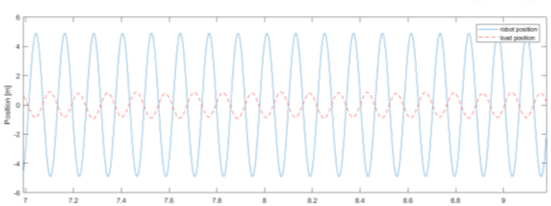
$$\ddot{X}_1 = \frac{1}{M_1}\left(-(B_1 + B_2)\dot{X}_1 - (K_1 + K_2)X_1 + B_2\dot{X}_2 + K_2X_2 + B_1\dot{L}(t) + K_1L(t)\right) - g$$

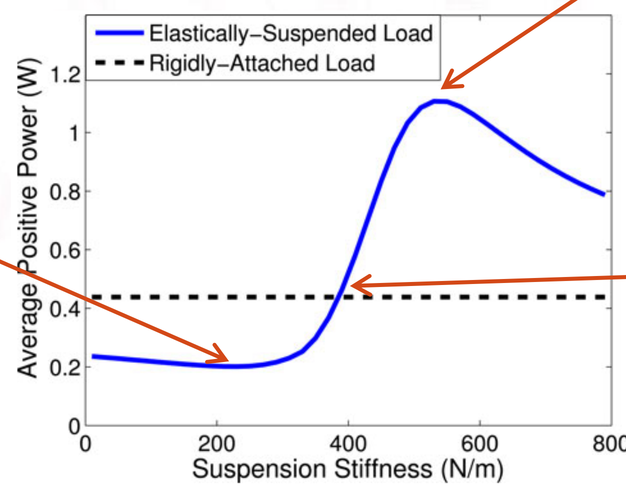
$$\ddot{X}_2 = \frac{1}{M_2}\left(-B_2\dot{X}_2 - K_2X_2 + B_2\dot{X}_1 + K_1X_1\right) - g$$

$$L(t) = Asin(\omega t)$$

Model Parameters	
Robot Mass M_1	274 g
Load Mass M_2	125 g
Effective Leg Stiffness K_1	1500 N/m
Effective Leg Damping B_1	10 Ns/m
Effective Suspension Damping B_2	0.1 Ns/m
Center of Mass Amplitude A	3 mm
Locomotion Frequency ω	52 rad/s





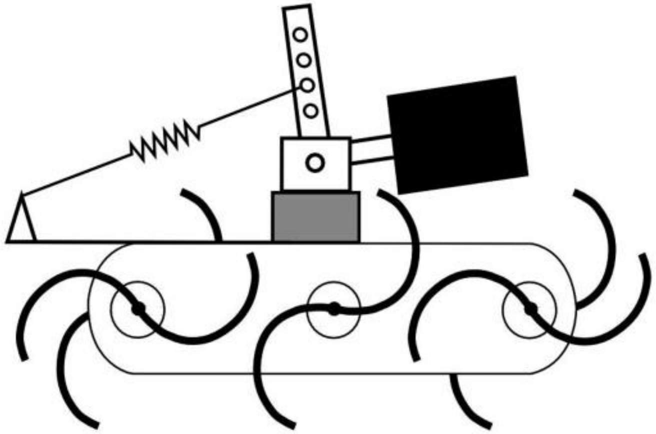


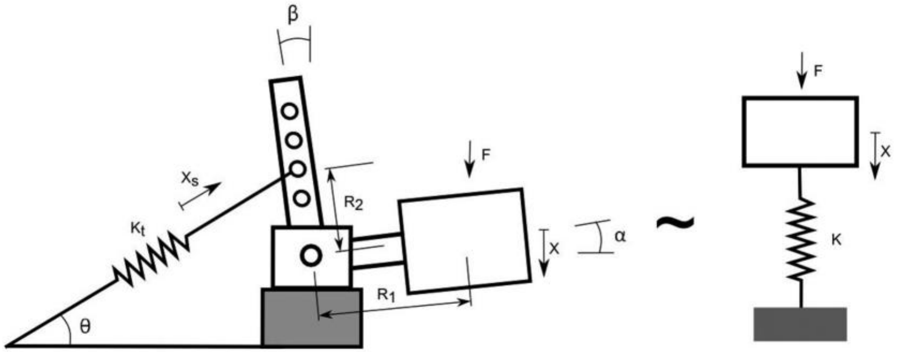
average positive power of locomotion

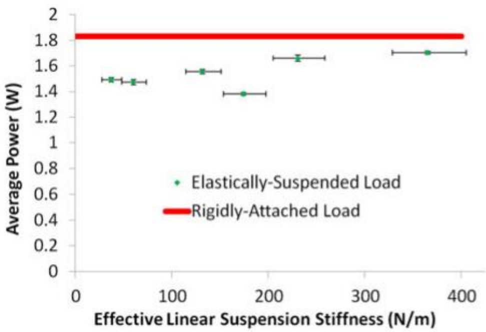
$$K_2 = \omega^2 M_2$$

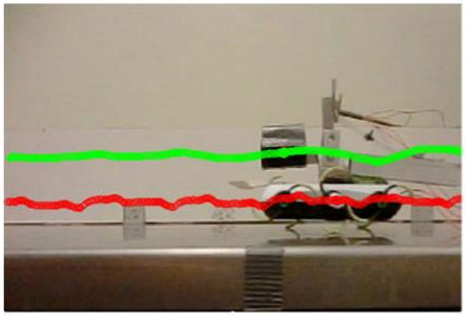
Ackerman, Jeffrey, and Justin Seipel. "Energy efficiency of legged robot locomotion with elastically suspended loads." *IEEE Transactions on Robotics* 29.2 (2013): 321-330.

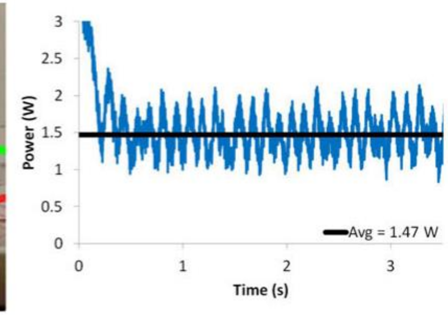
Soft components exploitation: energy efficiency

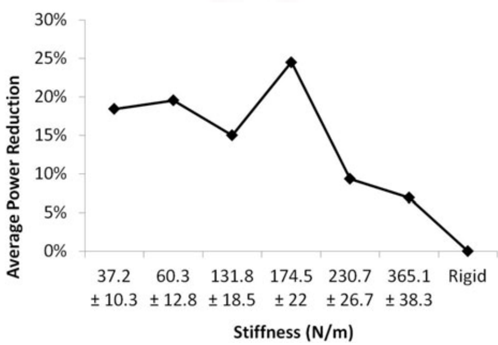


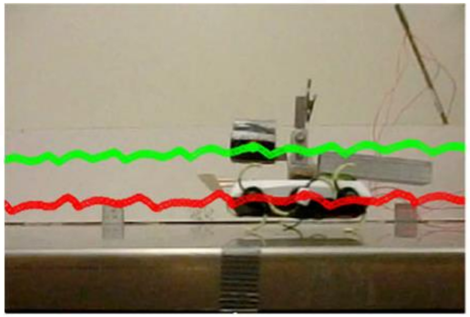


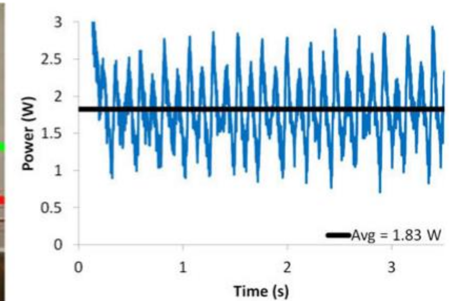






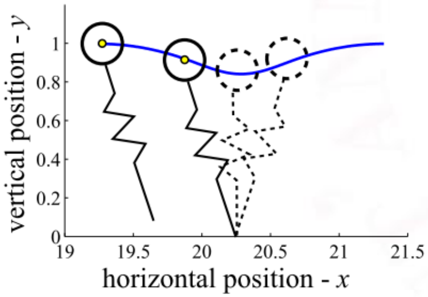


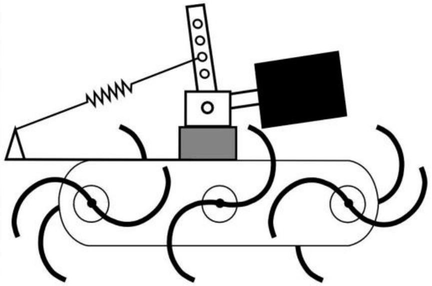




Soft components exploitation: behavioral diversity

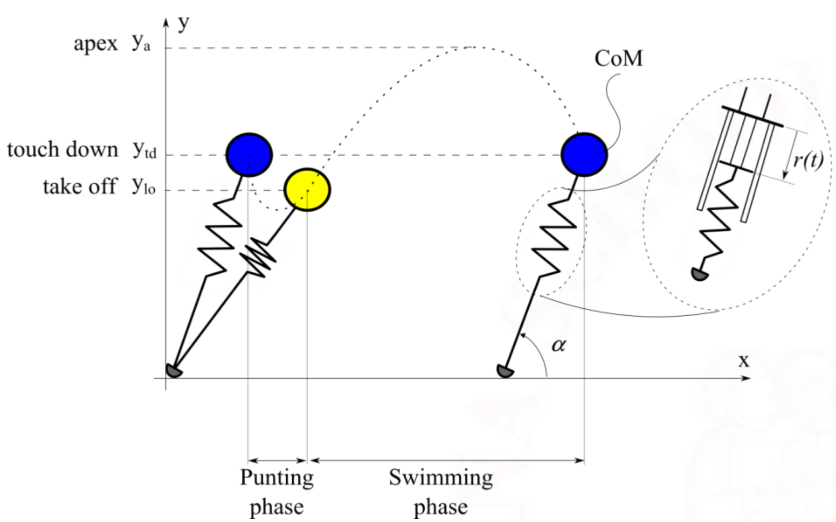
Compliance on leg → Compliance on body → Shape-changing body

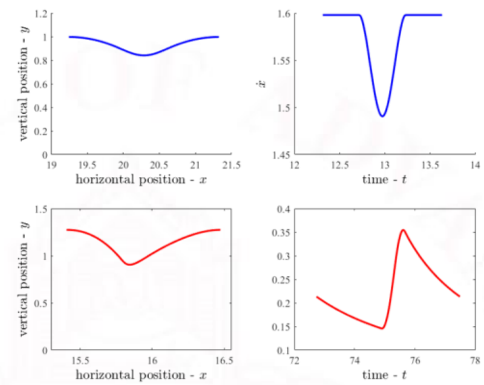


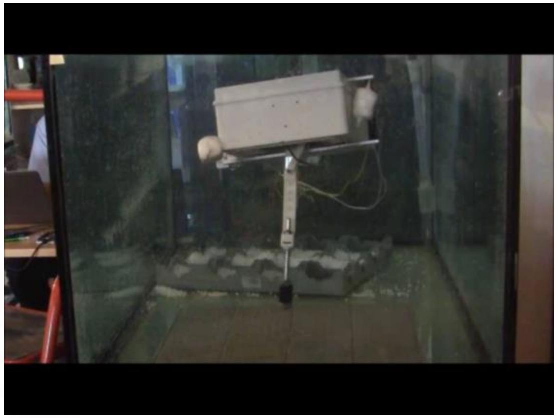


Punting gait model: the U-SLIP model

Punting gait model







- Pushing-based locomotion
- Springy leg

We added to SLIP water drag dampings, added mass, buoyancy and pushing propulsion:

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

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

Where:	
m	Model mass
M	Model added mass
V	Model volume
g	Grativational acceleration
r0	Leg rest length
k	Leg stiffness
ρ	Water density
r	Elongation law
l	Current leg length (w elo/comp)

Swimming to punting condition: $\tilde{y} = r_{(}$ sin α

Punting to swimming condition: $\tilde{l} \geq 1.25 r_0$

M. Calisti and C. Laschi (2015)Underwater running on uneven terrain, Proceedings of the 2015 MTS/IEEE OCEAN Conference, pp. 1-5

The U-SLIP model: Limit cycle and basin of attraction

Dimensionless equations

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

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

With:

$A = Xr_0/(m+M)$

$B = Yr_0/(m+M)$

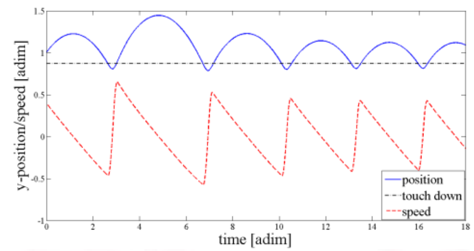
$C = (m - \rho_w V)/(m+M)$

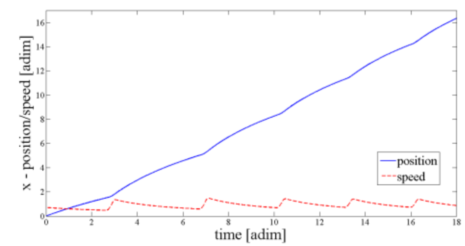
$D = kr_0/(mg+Mg)$

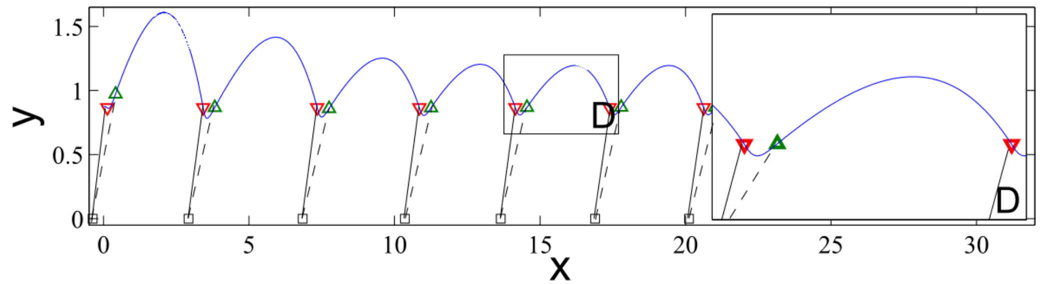
$r = r_s t \qquad y = r_0 \sin \alpha$

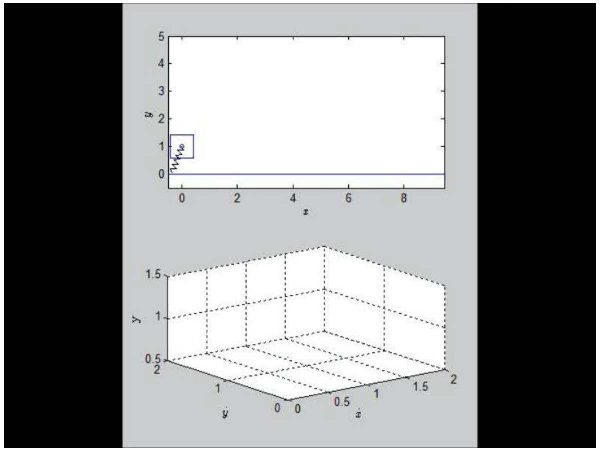
2 control parameters

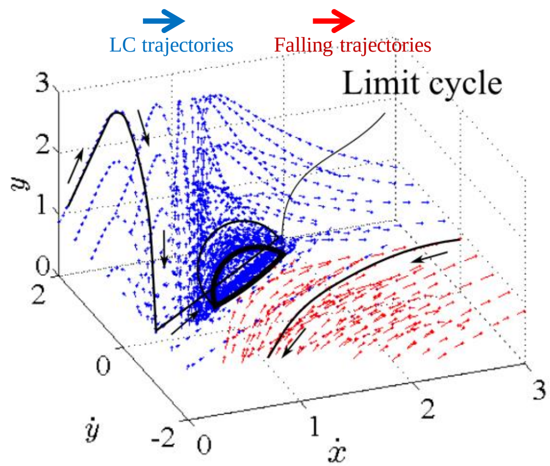
4 design parameters



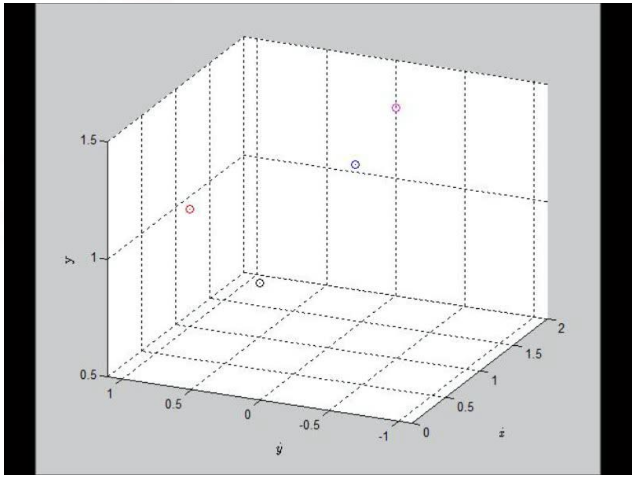




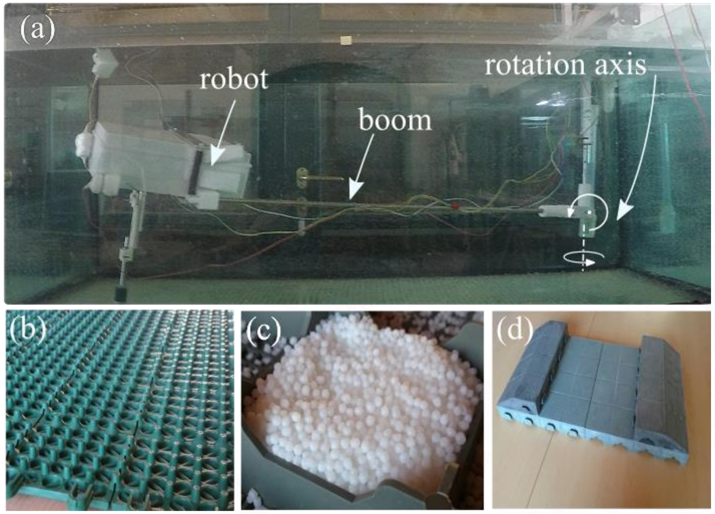


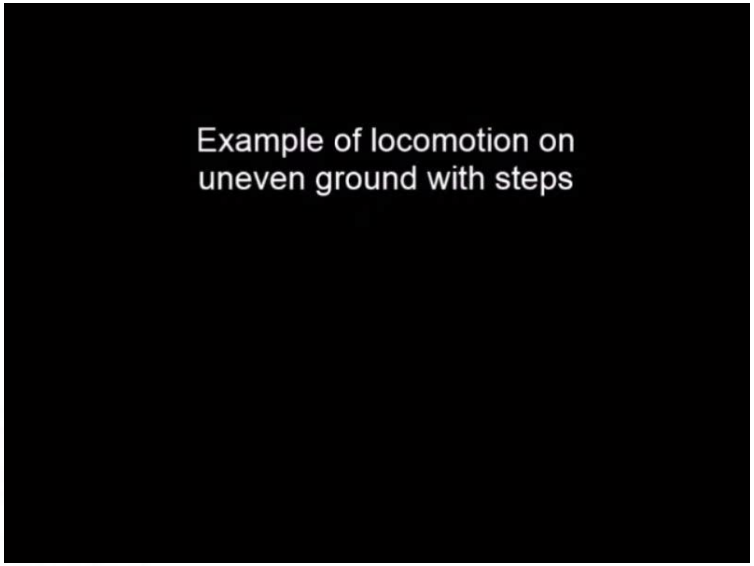


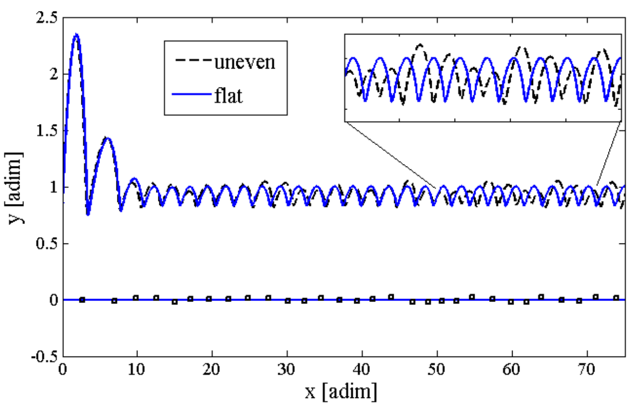
Basin of attraction



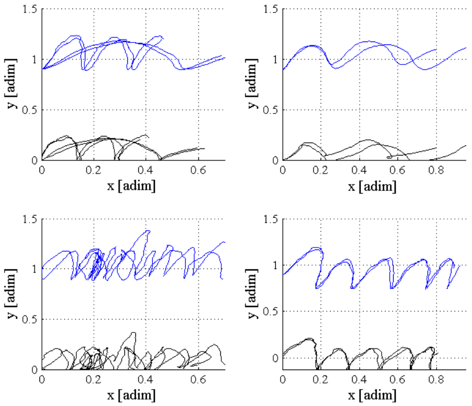
Experimental trials on uneven grounds



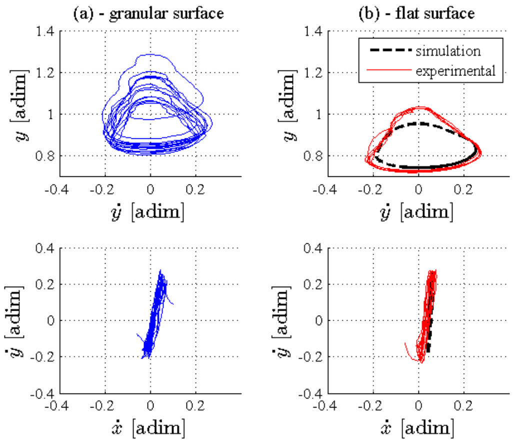




Simulations with flat or uneven terrain



Motion on different grounds



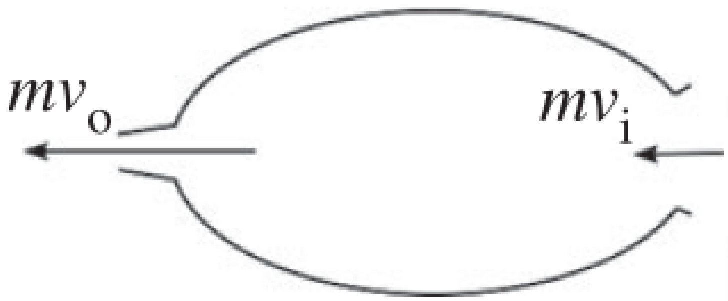
Limit cycles from experimental trials

M. Calisti, E. Falotico and C. Laschi, "Hopping on Uneven Terrains With an Underwater One-Legged Robot," in IEEE Robotics and Automation Letters, vol. 1, no. 1, pp. 461-468, Jan. 2016.

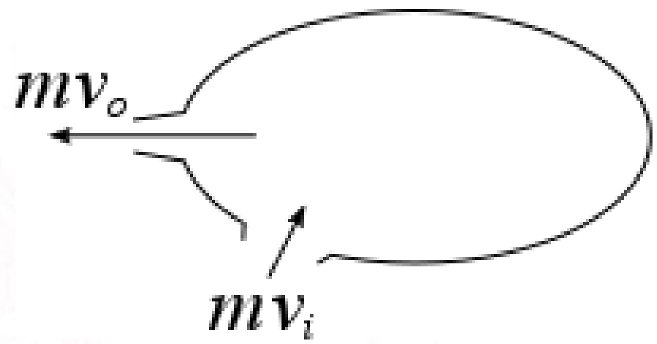
Jet-propulsion swimming

Animal example

Biological model and locomotion principle



Salp mechanism



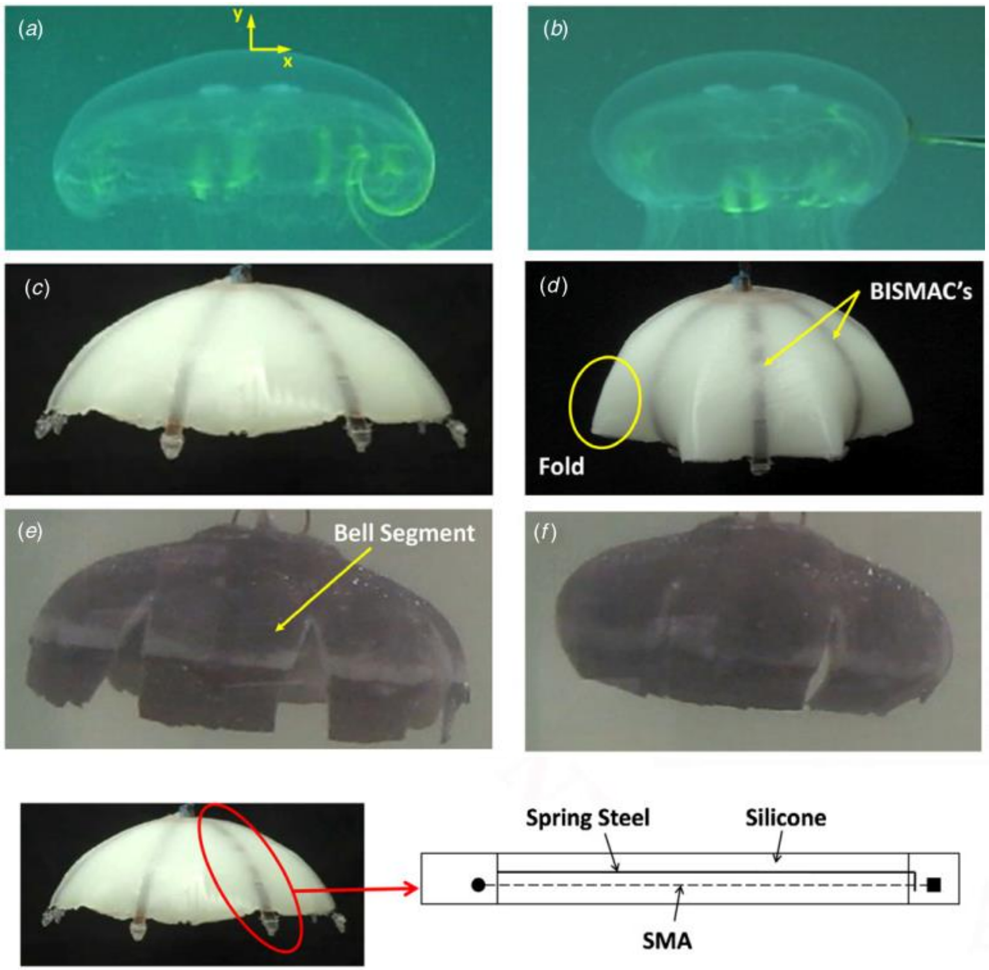
Cephalopod mechanism

$$F_i = \frac{d(mv_i)}{dt}$$

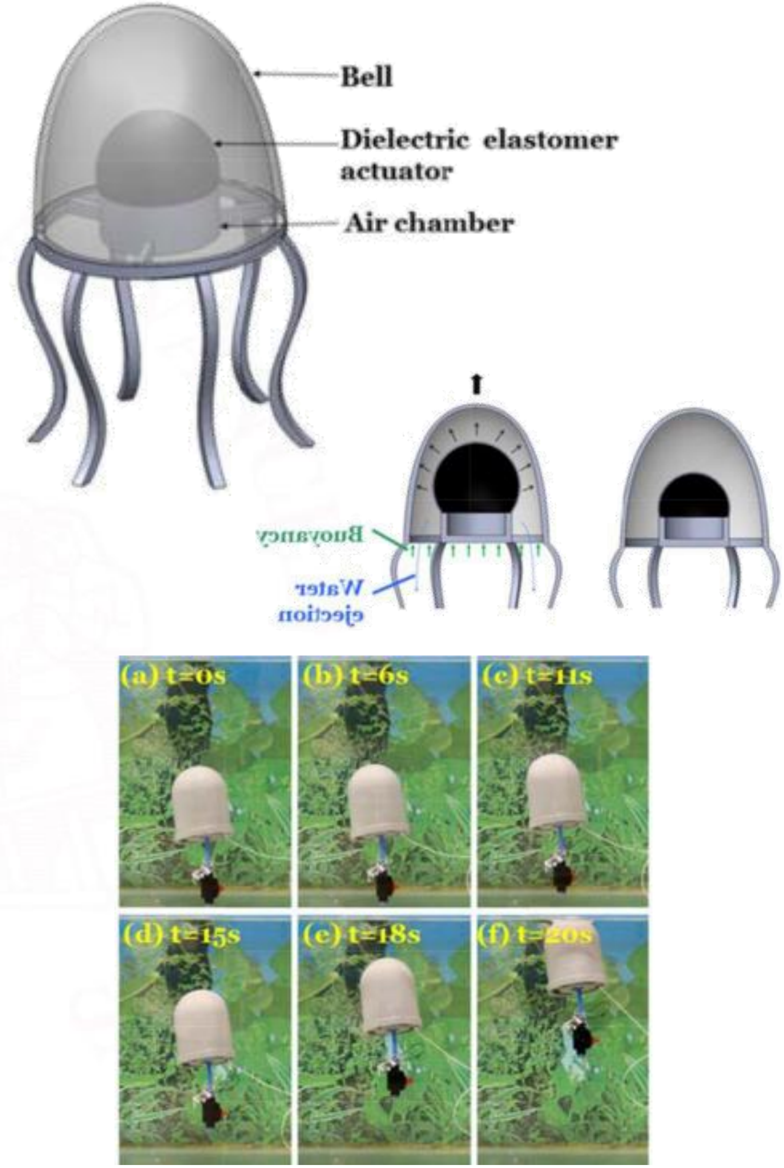
$$F_o = \frac{d(mv_o)}{dt}$$

The variation of linear momentum of the mass of water during ingestion and ejection propels the body

Jellyfish-inspired

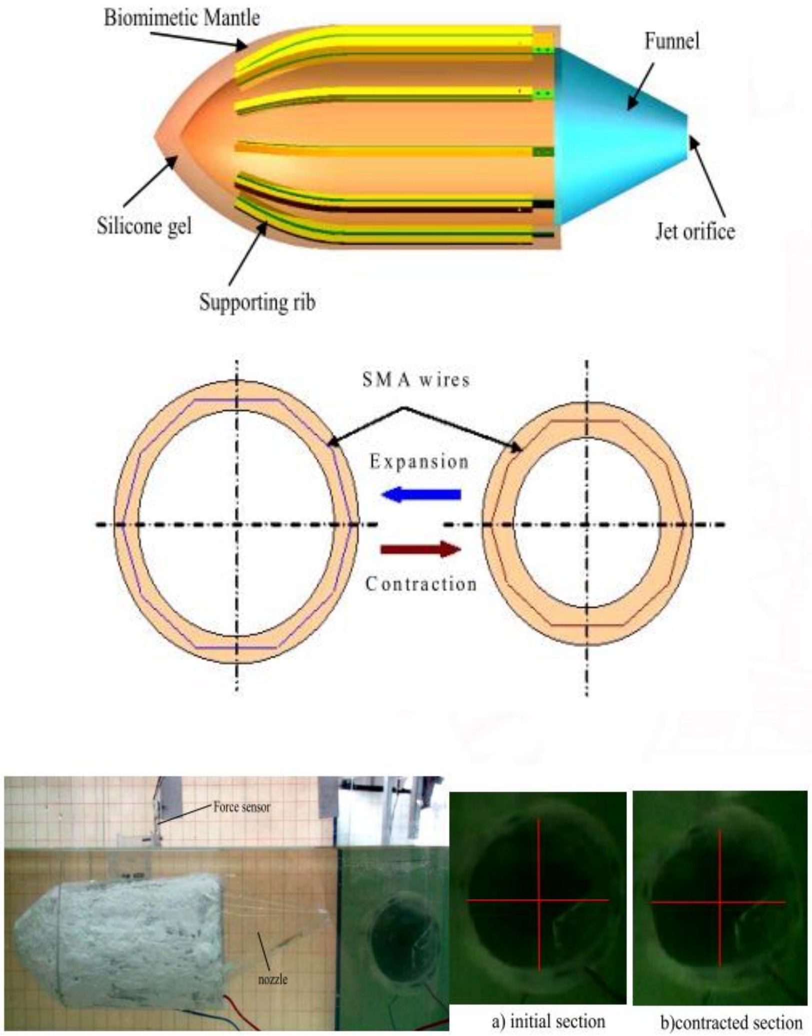


Villanueva A, Smith C, Priya S. 2011 A biomimetic robotic jellyfish (Robojelly) actuated by shape memory alloy composite actuators. Bioinspir. Biomim. 6, 36004.

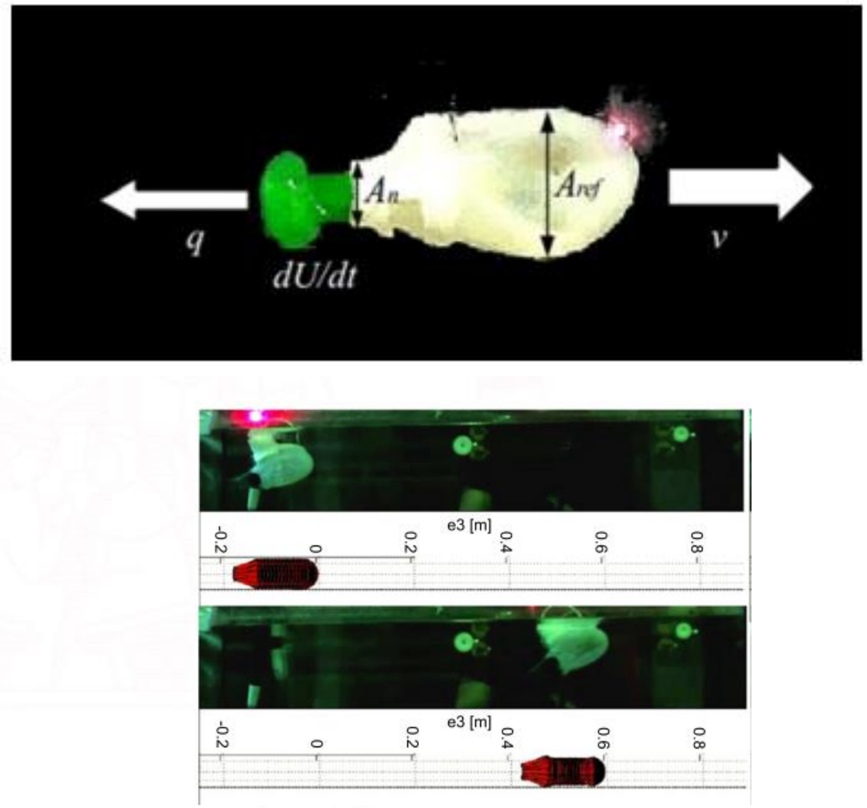


Godaba H, Li J, Wang Y, Zhu J. 2016 A soft jellyfish robot driven by a dielectric elastomer actuator. IEEE Robot. Autom. Lett. 1, 624–631

Cephalopod-inspired



Jian L, Jianing Z, Zhenlong W. 2016 CFD simulation of effect of vortex ring for squid jet propulsion and experiments on a bionic jet propulsor. Int. J. u- and e-Service Sci. Technol. 9, 211–226

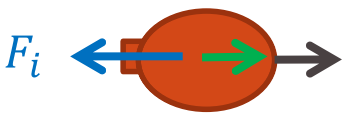


Renda F, Giorgio-Serchi F, Boyer F, Laschi C. 2015 Modelling cephalopod-inspired pulsed-jet locomotion for underwater soft robots. Bioinspir. Biomim. 10, 55005

Exploitation of soft components

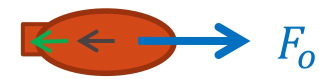
Frontal area change

Ingestion phase



$$M\frac{dv}{dt} = -\frac{1}{2}\rho C_d A_r v|v| - M_{add}\frac{dv}{dt} + F_i$$

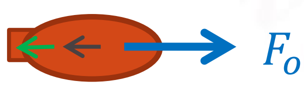
Expulsion phase



$$M\frac{dv}{dt} = -\frac{1}{2}\rho C_d A_r v|v| - M_{add}\frac{dv}{dt} + F_o$$

Added mass pumping

Expulsion phase



$$M\frac{dv}{dt} = -\frac{1}{2}\rho C_d A_r v|v| - \frac{d(M_{add}v)}{dt} + F_o$$

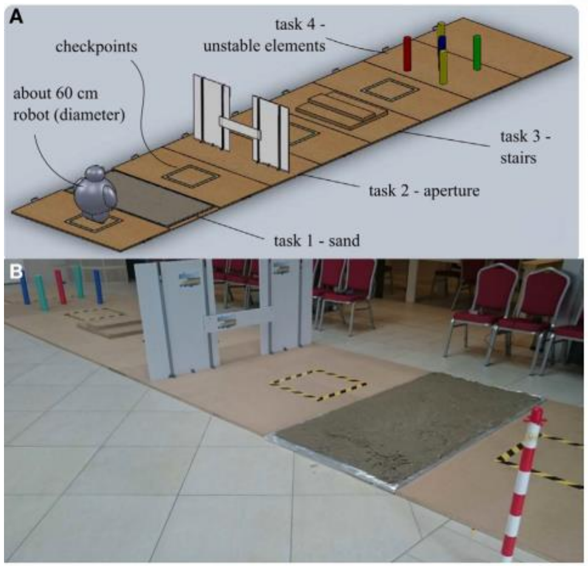
$$\boxed{\frac{dM_{add}}{dt} < 0}$$

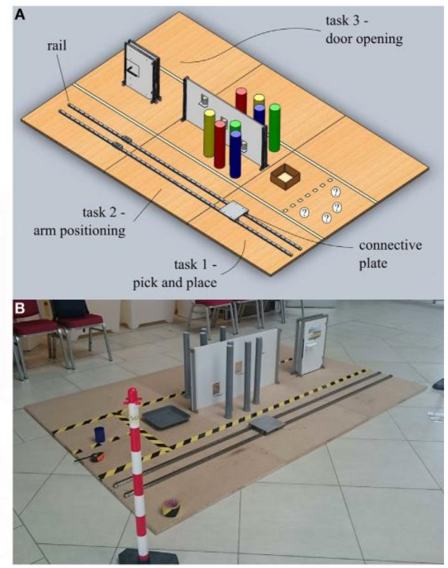
Additional thrust!

Giorgio-Serchi, Francesco, Andrea Arienti, and Cecilia Laschi. "Underwater soft-bodied pulsed-jet thrusters: Actuator modeling and performance profiling." *The International Journal of Robotics Research* 35.11 (2016): 1308-1329.

Giorgio-Serchi, Francesco, and G. D. Weymouth. "Drag cancellation by added-mass pumping." *Journal of Fluid Mechanics* 798 (2016): R3.

The RoboSoft Grand Challenge!





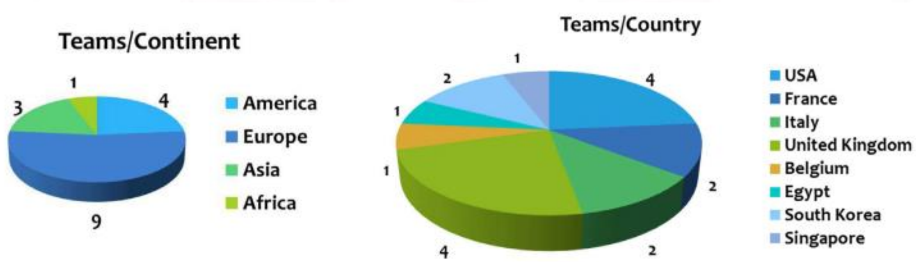


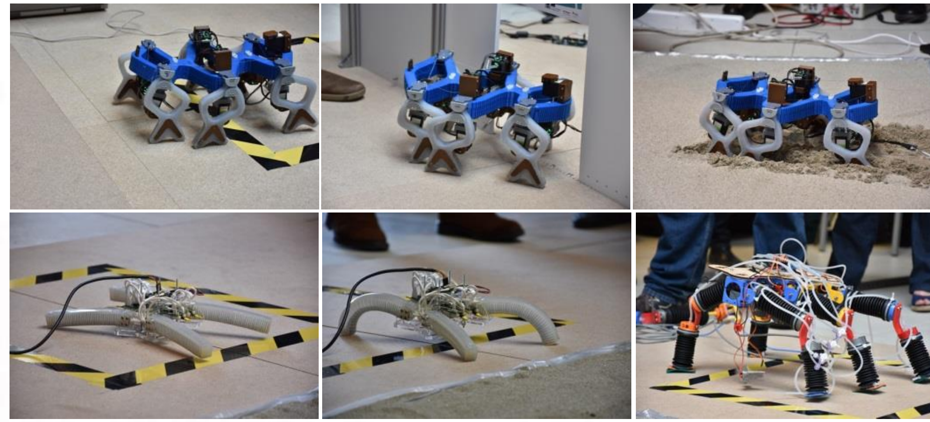
FIGURE 6 | **The RSGC raised worldwide interest, with 17 teams participating from 4 different continents which proposed 19 robots**. Financial support was provided to selected teams for traveling, accommodation and meals, for a maximum of two members for each selected team.

Calisti, Marcello, et al. "Contest-driven soft-robotics boost: the robosoft grand challenge." *Frontiers in Robotics and AI* 3 (2016): 55.

Robots participating

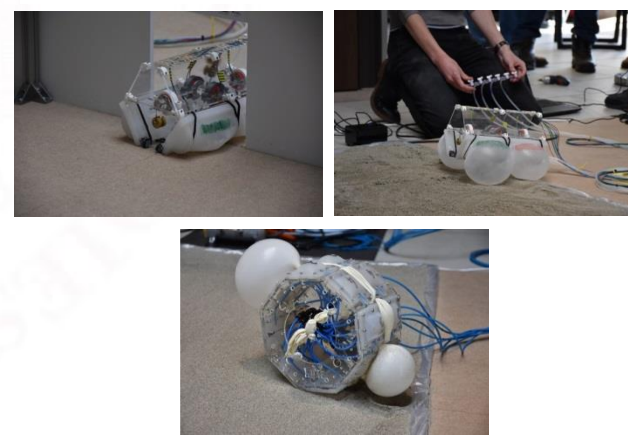
Deformable wheels

Legged



Crawling

Vibrational and shape morphing



Aftermovie - locomotion

https://www.youtube.com/watch?v=4BO_fxSsuo4

The RoboSoft Competition: 2018 edition!

RoboSoft
The first IEEE-RAS International Conference on
Soft Robotics
LIVORNO 2018

April 24-28, 2018

Conclusions on mobile soft robots

Locomotion → Interaction with the surroundings

- Continuous
- Periodic
- Discrete time (not periodic)

Approaches

«Whole» body is soft

Specific parts are compliant

The soft body «enables» locomotion

Trade-off

The soft parts «enhance» performance