Model-Based Orienteering:

(selected topics on)

Where To Go, Where Not To Go, and Imaginative Trails

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The ShanghAI Lectures 2018

Dec. 13, 2018

Outline

1. Where To Go — Get_Intelligence(natural_system);
{Soft Bioinspired Robotics}

2. Where Not To Go — Change_Game(artificial_system);
{Biomedical Robotics/Engineering}

3. Imaginative Trails — Set_Intelligence(artificial_system);
{Creative Engineering/Soft Robotics}

1. Where To Go

"Why do plants not have brains? The answer is actually quite simple - they don't have to move." (Lewis Wolpert)

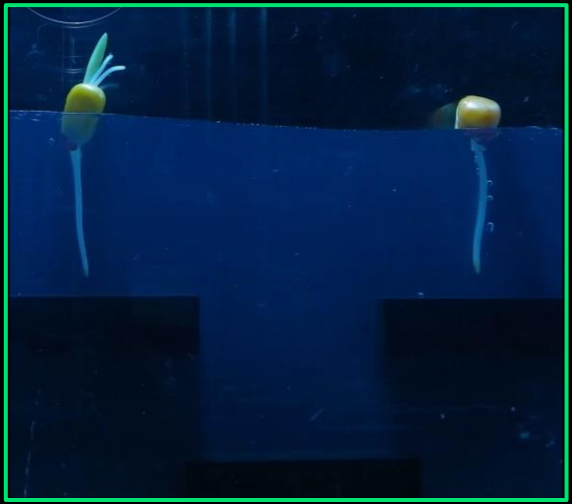
Ok, yet plants do move! ;-)

Plant-Inspired Osmotic Actuation

with B. Mazzolai (IIT)

Yes, plants do move. “Slow” Movements [Examples]

Stomata guard cells



Roots (irreversible)

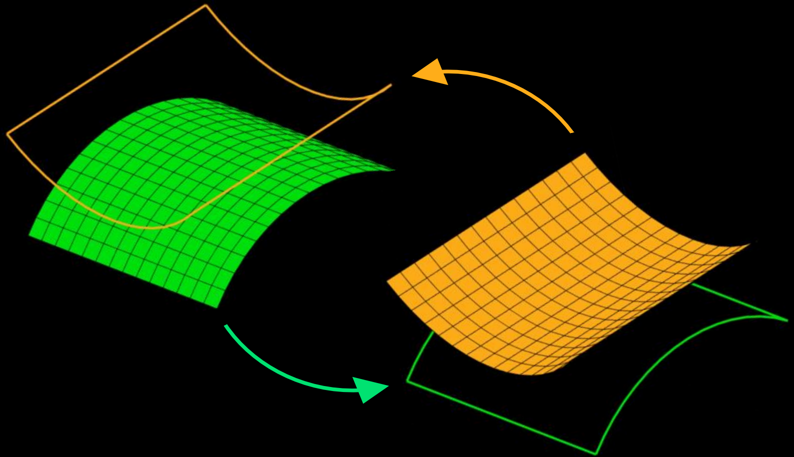
Mimosa pudica

Drosera

Yes, plants do move. “Fast” Movements [Examples]

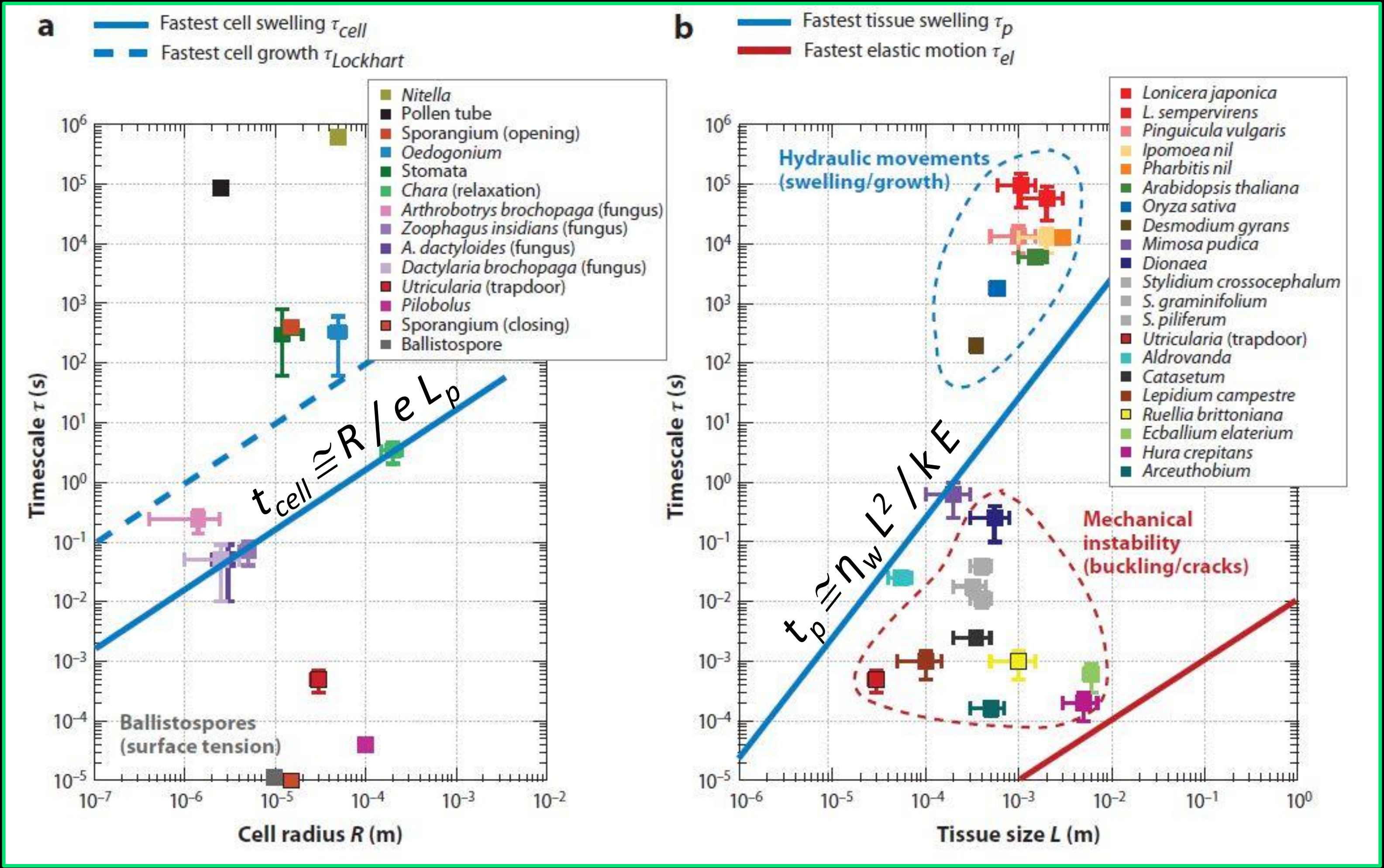
Venus flytrap

Stylidium debile



“snap” also involving biomechanical instabilities; “recharge” water-driven …

Physical Boundaries btw Fast/Slow Mov's



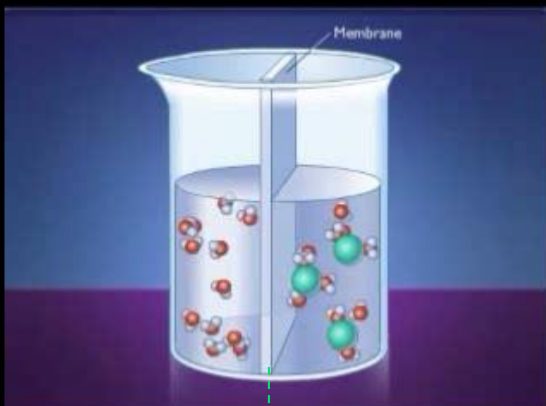
Forterre J., "Slow, fast and furious: understanding the physics of plant movements", J. Exp. Botany 64(15): 4745-60, 2013

Slow (low-power-consumption) movements: water-driven. Osmosis key player!

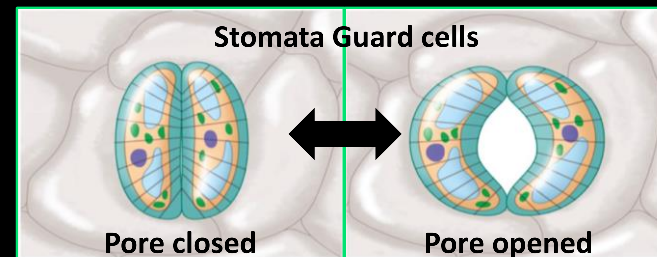
Osmotic Actuation: Basic Modelling

Slow (low-power-consumption) movements: water-driven.

Osmosis: ubiquitous key player!



cell turgor (sort of "natural hardness"): generated by water influx due to the osmolyte concentration gradient through the cell wall and the plasma membrane

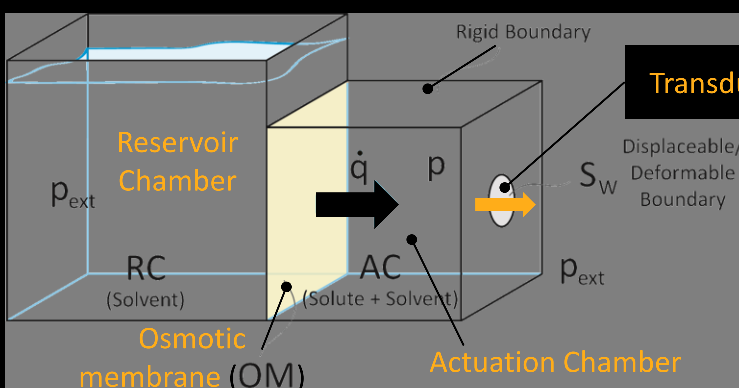


(Flaccid Cell: Water lost , vacuole shrinks, cell loses shape)

(Turgid Cell: Water enters, vacuole swells and pushes the wall)

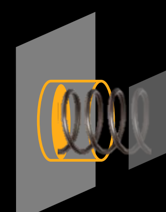
$\Pi_1 < \Pi_2$ — osmotic pressure

$\Pi = iRT\,M$ — molarity



$$\dot{q}_{1\rightarrow 2} = S_{OM}\,\alpha_{OM}\,[(\Pi_2 - \Pi_1) - (p_2 - p_1)]$$

osm. membrane surface & permeability



elastic external load

$$p - p_{ext} = (k_{EL}/S_p^2)\,(V - V_0)$$

bulging membrane

$$p - p_{ext} = k_{BD}\,(V - V_0)^3$$

$$\begin{cases} dV/dt = S_{OM}\,\alpha_{OM}\,[V_0\Pi_0 / V - (p - p_{ext})] \\ V(t=0) = V_0 \end{cases}$$

1st order O.D.E. w/ analytical solution

E. Sinibaldi

Osmotic Actuator 1/4

Model-Based Design

Targeted Performance Metrics:

- Characteristic actuation time
- Maximum force
- Peak power & Power density
- Actuation work & Energy density

Guidelines:

- Actuation times modulated by varying the surface area of osmotic and bulging membranes
- Power and energy density maximized by increasing the actuation chamber surface-to-volume ratio
- …

Analytical expressions (bulging disk implementation) as a function of the design parameters

$$t_{c,\mathrm{BM}} \cong \frac{1}{3\alpha_{\mathrm{OM}} k_{\mathrm{BM}}^{1/3} \Pi_0^{2/3}} \beta^{5/3} L^{4/3}$$ characteristic time

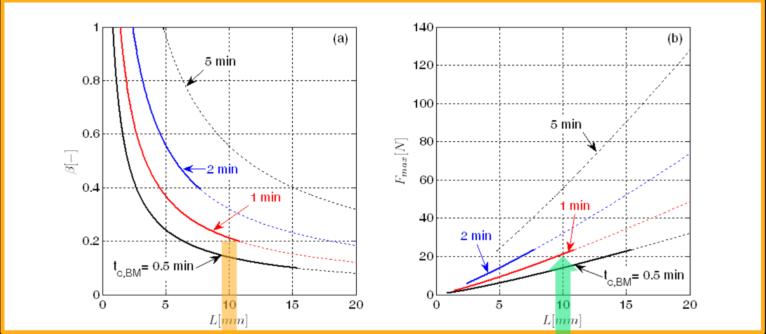
$$F_{\max} \cong \Pi_0 \beta L^2$$ maximum force

peak power $$P_{\max} \cong \frac{\Pi_0^2 \alpha_{\mathrm{OM}}}{4} L^2 \Rightarrow \mu_P \cong \frac{\Pi_0^2 \alpha_{\mathrm{OM}}}{4} \frac{1}{\lambda L}$$ power density

work $$W \cong \frac{\Pi_0^{4/3}}{4k_{\mathrm{BM}}^{1/3}} \beta^{5/3} L^{10/3} \Rightarrow \mu_W \cong \frac{\Pi_0^{4/3}}{4k_{\mathrm{BM}}^{1/3}} \frac{\beta^{5/3} L^{1/3}}{\lambda}$$ energy density

$\beta = S_w/S_{OM}$ (bulging disk surface / osmotic membrane surface)

Where to go, if we target O(1)min timescale?



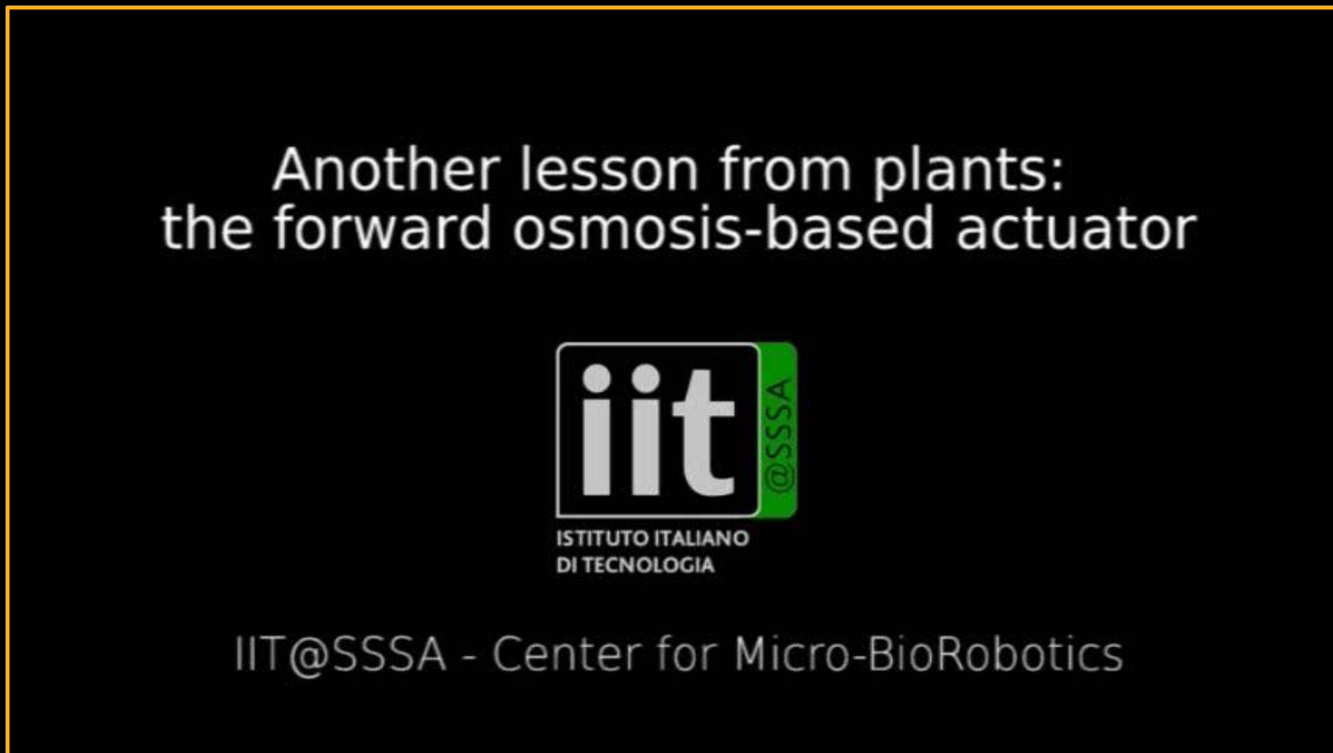
Lengthscale: 10mm

(w/ β=0.2) Max force ~20 N!

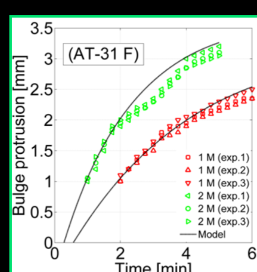
OK, let's go!

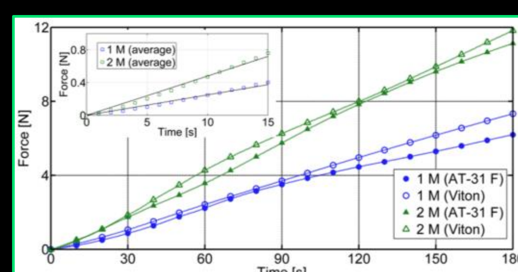
Osmotic Actuator 2/4

Implementation



Model accurately predicts actuation dynamics, force scaling w.r.t. molarity, …





Characteristic time ~2min

Maximum force ~20N

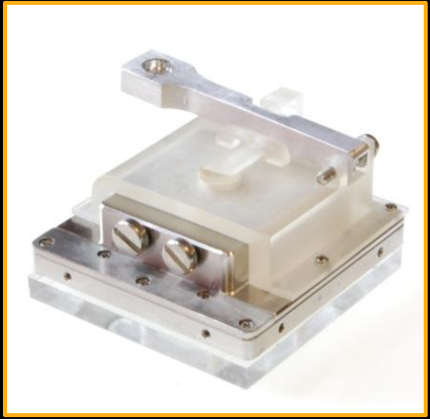
As predicted!

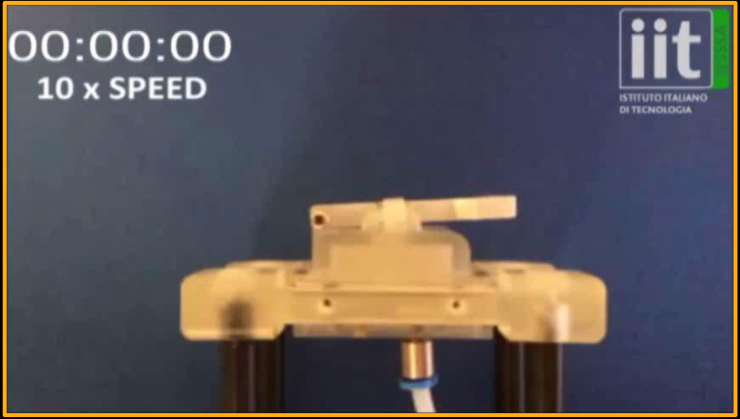
Osmotic Actuator 3/4

Illustrative Tasks

Remember "fast" movements!

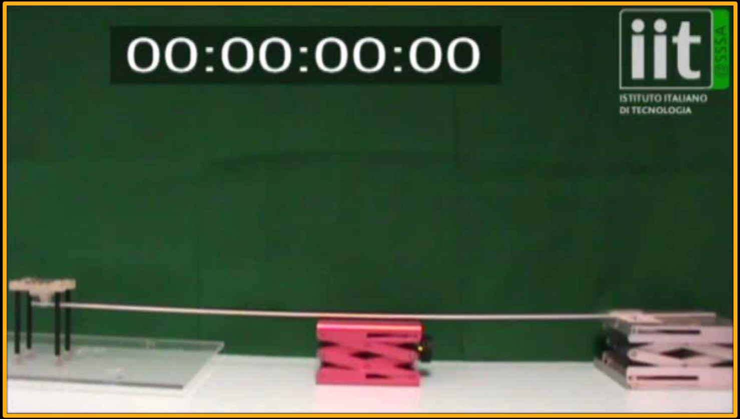
Trigger a preloaded mechanism





Remember "slow" movements!

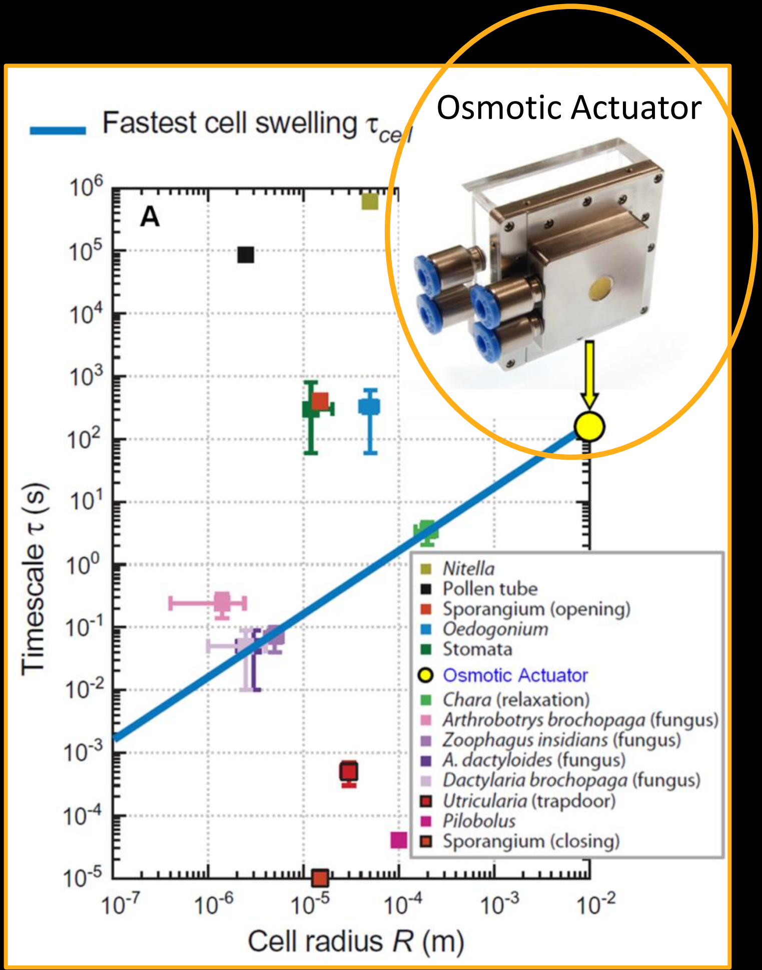
Raising a 2kg beam (using a ϕ5 mm bulging disk!)



Osmotic Actuator 4/4

Comparative Performance and … Biomimicry!

Actuator Category	Actuator Subcategory	Output Power [mW]	Max. Force [N]	Energy Efficiency [%]	Energy Density [J cm^{-3}]
Osmotic	Osmotic (Forward Osmosis)	0.18[a]	> 10[b]	11[a,c]	3.3[a]
Fluid-based	Hydraulic	10^2	10^3	90 – 99	10
	Pneumatic	10^{-1}–10^2	10	30 – 40	10^{-1}
Piezoelectric	Piezoelectric Ceramic	10 – 10^3	10	30	10^{-1}
Shape Memory Alloys (SMA)	Thermally Activated SMA	10^{-2}	10^{-1}	0.01	> 1^2
	Ferromagnetic SMA	10^2	10^2	10	10^{-3} –10^{-1}
Magnetostrictive	Magnetostrictive	10^2	10^2 – 10^3	80 – 99	10^{-2}
Nanostructures-based	Carbon Nanotubes aerogel	10	10^{-3}	40	10^{-2} – 10^{-3}
Electroactive polymers	Dielectric Elastomers	1	1	50[c]	10^{-1} – 1
	Electrostrictive Polymers	10	10^{-1}	30 – 50	10^{-1} – 1
	Conducting Polymers	10^{-2} – 1	1	0.25	10^{-1} – 1
	Ionic Polymer Metal Composites	10^2–10^3	10^{-1}	2 – 3[c]	10^{-3}–10^{-2}
	Piezoelectric polymers	10	10^{-2}	90 – 95	10^{-3}
	Liquid Crystal Elastomers	10^2	10	<5	10^{-3}–10^{-1}
	Shape Memory Polymers	10 – 10^2	10	2 – 8	1



competing with low-power-consumption technologies (pneumatic, SMA, conductive polymers):

osmotic actuation gets high forces like pneumatic actuation; pneumatic can be more efficient, osmotic more energy-dense

matching the characteristic time of an ideal, giant plant cell with the same typical size (10 mm). So …

Elucidating Osmosis-Driven Turgor Dynamics 1/2

Using our Biomimetic Device to Investigate Plant Osmolytes

The KCl conundrum: KCl considered as the main player in turgor dynamics, yet:

- KCl (potassium chloride) is not efficiently retained within the cell wall (rejection coefficient ~0.5-0.7)
- KCl creates a non-physiological environment for the cell
- KCl has a Stokes radius (0.25nm) sensibly smaller than plant cell pore size (1-10nm). Hence, retaining KCl is expensive for the plant cell

Cytosol Osmolytes ([1M] for generic cells, [1.5M] for motor cells)	
KCl	[0.25M] – [0.75M]
D-Glucose	[0.6M]
L-Glutamine	[0.15M]
other small biomol. (proteins, nucleic acids, polysaccharides)	<[1mM]

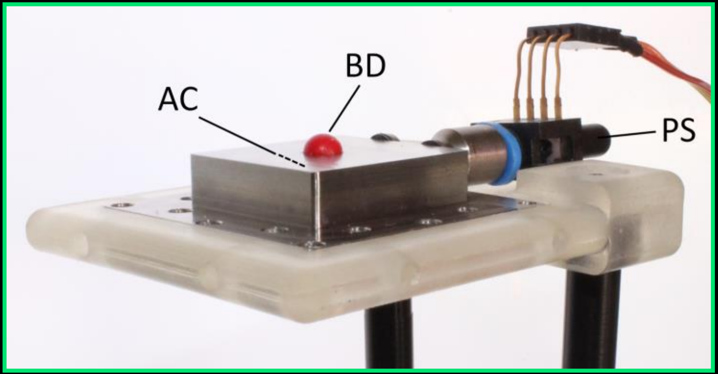
Other small molecules such as D-Glc and L-Gln are detected at high levels in plant cytosol: their effect must be elucidated

We considered 5 model cytosols:

- Generic (plant) cell cytosol (M1, [1M])
- Motor (plant) cell cytosol (M2, [1.5M])
- KCl alone ([1.5M])
- Five modified mixtures (by changing the [KCl]:[D-Glc]:[L-Gln] composition)

Elucidating Osmosis-Driven Turgor Dynamics 2/2

Supramolecular structures sustain turgor formation better than KCl alone!



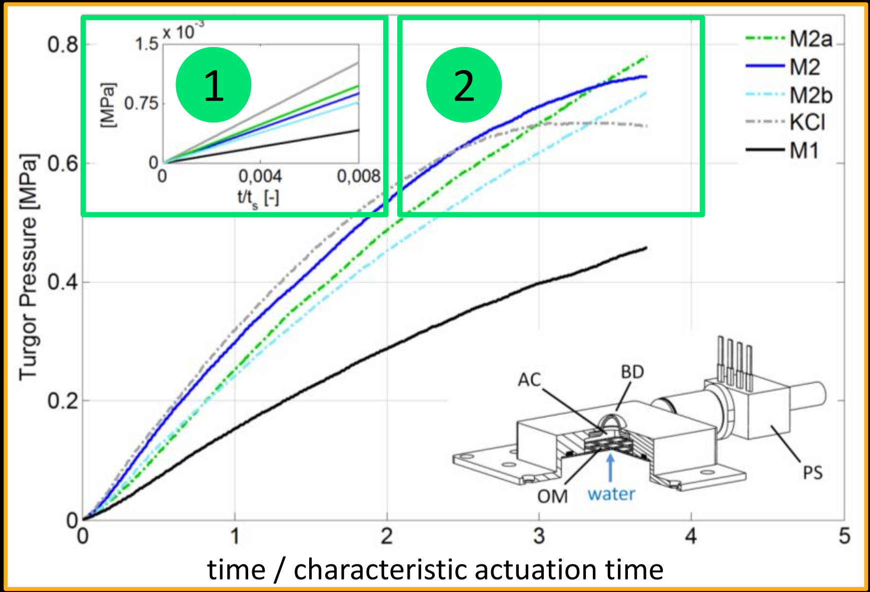
osmotic actuator + pressure sensor

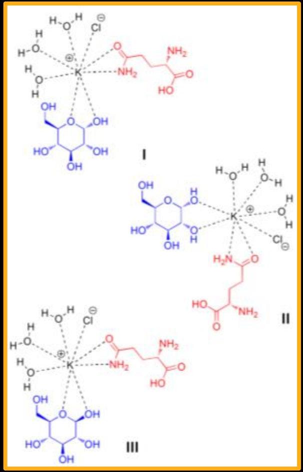
1

At the beginning, turgor formation rate is dictated by the initial osmotic potential (KCl fastest, ranking consistent with the osmometry measures,), yet …

2

Over longer times the osmolyte mixtures (in particular the plant motor cell model cytosol M2) outperform KCl



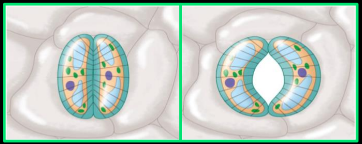


Can be explained in terms of the cooperative effect of osmolyte association, which can decrease osmolyte backflow through the (pressurized) osmotic membrane thanks to the larger size of complexes (derived from NMR)

Biorobotics Science and Technology

Closing the Loop! (Nice to be here, starting from a simple model …)

Technology



Science

Biological System

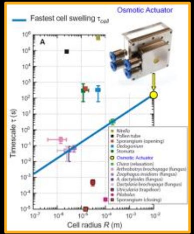
New Technology
New Applications

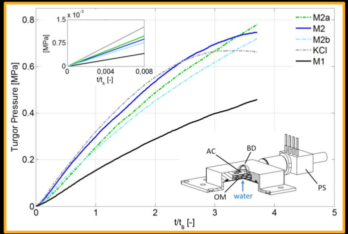
New Scientific Knowledge

Bioinspired Artificial System

Biomimetic Artificial System

Reversible osmotic actuation:
to appear
(application to Soft Robotics)





2. Where Not To Go

reducing complexity by keeping vision (vs dream visions ;-))

Magnetic Retrieval from the Bloodstream

with L.C. Berselli (U. Pisa) and A. Menciassi (SSSA)

The Game

A proposed Pathway for Targeted Therapy: Magnetic Targeting

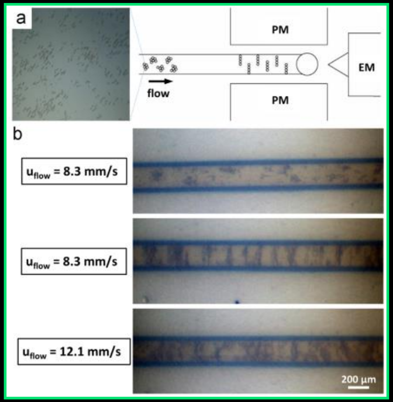
A strong motivation

- Magnetoresponsive (super paramagnetic, e.g., Fe_3O_4) carriers (loaded with drug …) could be accumulated at the target site using external fields (by, e.g., high-field rare earth magnets) > lower drug dose (> lower systemic drug-induced toxicity)
- Intrinsically theranostic: also act as contrast agents in MRI

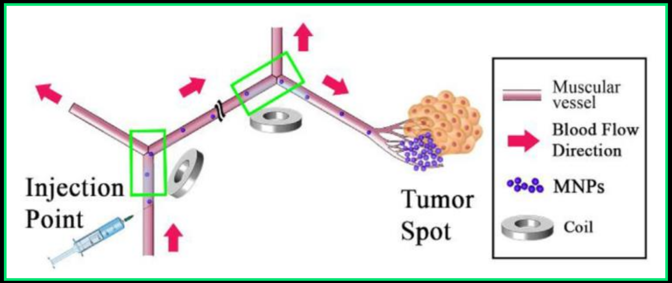
(deliberately neglect complementary nanomedicine issues such as: loading efficiency, on-command release, surface functionalization to maximize targeting while minimizing sequestration by the immune system)

… whence many studies … well, mostly in controlled lab setups …

- small vessels (capillary flows)
- relatively close magnetic sources
- source distribution not necessarily consistent with clinical constraints



J. Mag. Mag. Mat. 401: 956–964 (2016)



J. Mag. Mag. Mat. 438: 173–180 (2017)

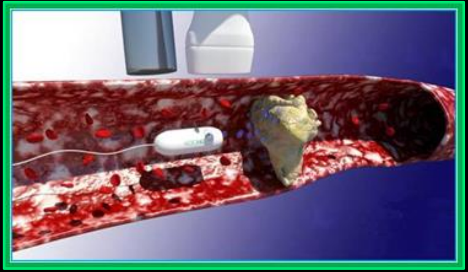
… are we sure that's The Way to go? 1/2

Framing the game (by embarking more physical/clinical aspects):

…Yet release will likely occur in larger vessels!

- Larger flow rates (particle dragging)
- Pulsatility (unsteady) effects

(either by standard injection or by miniature intravascular devices)



Model-based reconstruction of blood velocity profile in pulsatile flows >

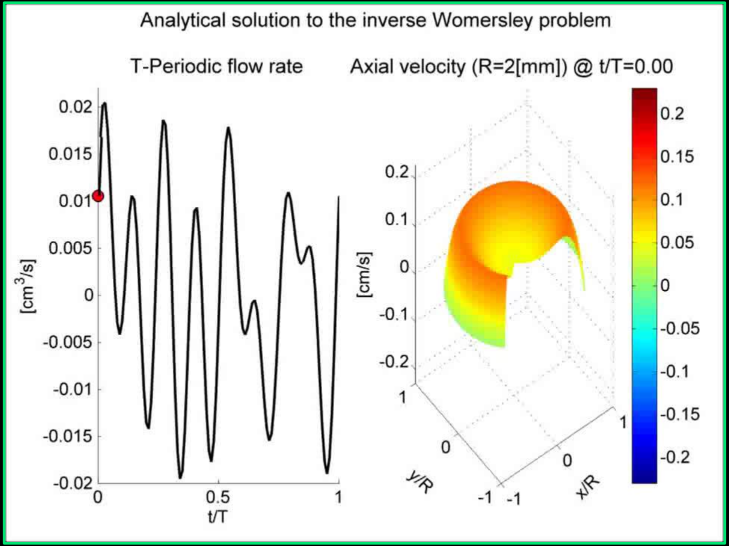
- Starting from the flow rate (inverse problem), which is measurable in clinics
- Aiming at a benchmark (analytical) solution, for cheap *in silico* exploration of particle transport

flow rate

$$\frac{q_n}{\pi R^2} = \left[1 - \frac{{}_0\widetilde{F}_1\left(;2;j\mathrm{Wo}_{R,n}^2/4\right)}{{}_0\widetilde{F}_1\left(;1;j\mathrm{Wo}_{R,n}^2/4\right)}\right]\frac{\sigma_n}{j\omega_n}$$

axial speed

$$v_n = \left\{1 - \frac{J_0\left[(-1)^{3/4}\,\mathrm{Wo}_{r,n}\right]}{J_0\left[(-1)^{3/4}\,\mathrm{Wo}_{R,n}\right]}\right\}\frac{\sigma_n}{j\omega_n}$$



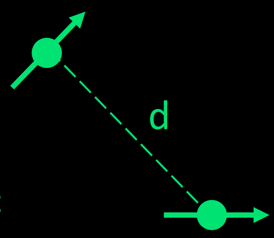
… are we sure that's The Way to go? 2/2

Framing the game (by embarking more physical/clinical aspects):

> (Classical) Models for magnetics > Integration >

- (NeFeB) cylindrical magnet with axial magnetization (equivalent currents models w/ classical complete elliptic integrals)
- Point-dipole model (w/ saturation) for The particles
- Trajectory integration: fluidic and magnetic actions, using physically representative parameter values (fictitious time-reversal also useful)

F ~1/(d^4)



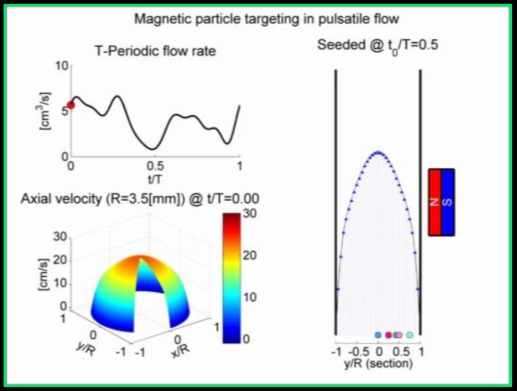
$$\mathbf{H} = \frac{M_m^s}{2\pi} \int_{\xi=0}^{l_m} \left[h_\rho(\rho, z+\xi)\hat{\mathbf{e}}_\rho + h_z(\rho, z+\xi)\hat{\mathbf{e}}_z \right] \mathrm{d}\xi,$$

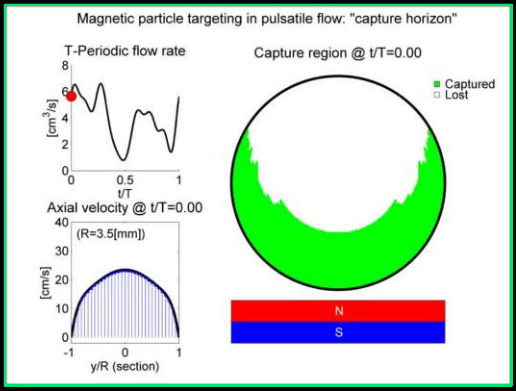
$$h_\rho(\rho,z) := \frac{1}{\sqrt{Q}} \frac{z}{\rho} \left[\frac{2-k^2}{2\left(1-k^2\right)} E(k) - K(k) \right],$$

$$h_z(\rho,z) := \frac{1}{\sqrt{Q}} \left[\frac{P}{Q} \frac{1}{1-k^2} E(k) + K(k) \right],$$

> clearly see

- Strong unsteady effects (dynamic capture horizon, …)
- Strongly adverse scaling effects: <u>hard to efficiently capture in clinically representative conditions > challenging to control/track carrier biodistribution</u>!





> whence, provocatively, "Where Not To Go"

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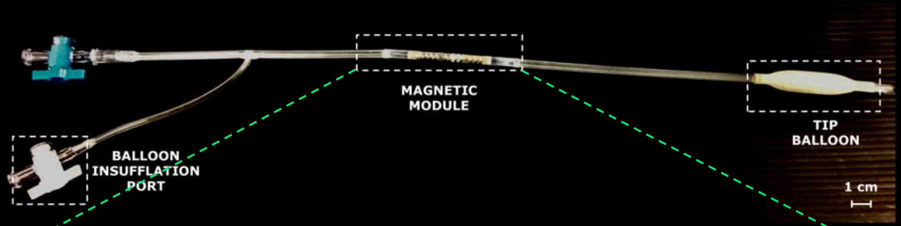
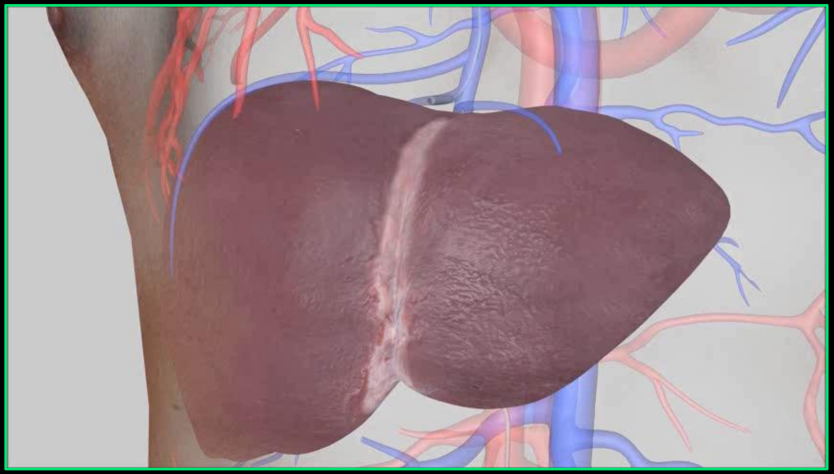
Game Change!

Magnetic Retrieval

A New Clinical Perspective

- With medical doctors: 2-catheter procedure for organs featuring terminal circulation (one main inlet, one main outlet), e.g., liver, pancreas, lung, and kidney





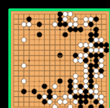
- Integration of a miniature module into a clinically used 12 French catheter
- Capture efficiency: ≈94% (500 nm SPIONs) and 78% (250 nm SPIONs)
- No blood alterations (hemolysis, platelet degradation). Could outperform current chemoembolization procedures (same application frequency, less invasiveness) and enable higher doses and/or new "high-risk/high-gain" drug formulations

Evolutionary (Co-)Design

Intertwining Models and Tools: A Growing Quest for Converging Development!

+ computational models,
model-based tool design,
prototyping & exp. validation

Particle Targeting



AI (also) here?

theoretical model

$$\frac{q_n}{\pi R^2} = \left[1 - \frac{{}_0\tilde{F}_1\left(;2;j\mathrm{Wo}_{R,n}^2/4\right)}{{}_0\tilde{F}_1\left(;1;j\mathrm{Wo}_{R,n}^2/4\right)}\right]\frac{\sigma_n}{j\omega_n}$$

Particle Retrieval

novel tool & procedure

Also intercepting some coming trends by the FDA

Virtual testing & computer modes to be integrated into the FDA regulatory process: "... use of in silico tools in clinical trials for improving drug development and making regulation more efficient." (07/07/2017)

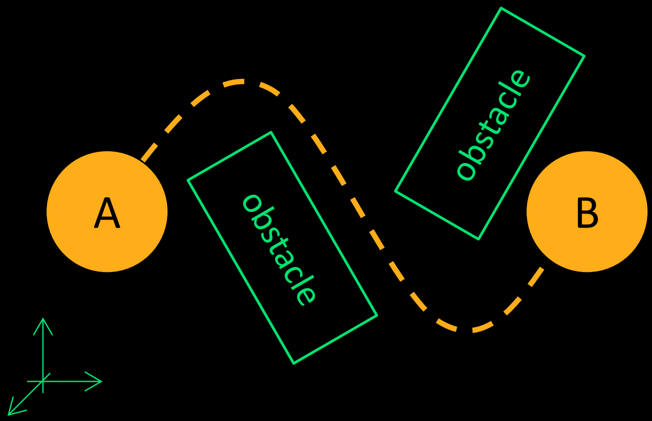
3. Imaginative Trails

a musical offering to flexible robotics

The Interlaced Continuum Probe

… well, in a sense, with J.S. Bach ;-) (Bach is Bach. Is Bach!)

The Follow-The-Leader Challenge



To go from A to B along a chosen path, with the entire tool shaft following the chosen curve (contactless: no supports)

Open problem for a flexible tool!

The Potential

Key applications: contactless inspection (at large), medical robotics (tool guide)

The First Move 1/2

A base constraint (so evident that it might be paradoxically overlooked):
Beyond the reach of a single tool: we need <u>two mutually supporting tools</u>

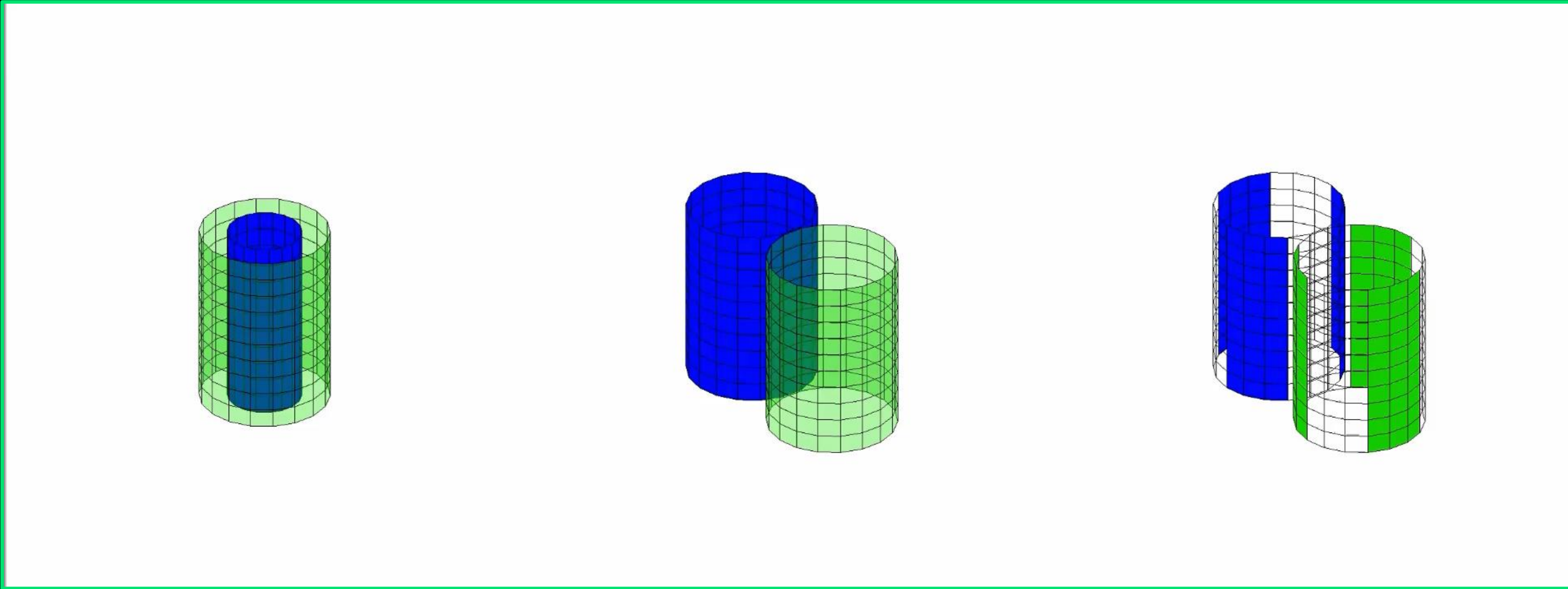
Ant bridges (stiffening by limbs interlocking): ex-post analogy, since we did not pursue bioinspiration!

We started from (and only leveraged) symmetry: that's it!

https://www.pinterest.com/mavissullivan16/world-of-ants/

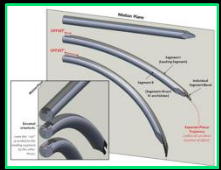
The First Move 2/2

Concentric?	Interlocked?	Interlaced??
Hard to achieve a symmetrical behavior	Better, yet still symmetry-breaking	Stronger symmetry, yet: feasible?



Articulated system: Cardioarm → Flex (H. Choset, CMU & MedRobotics) Great!

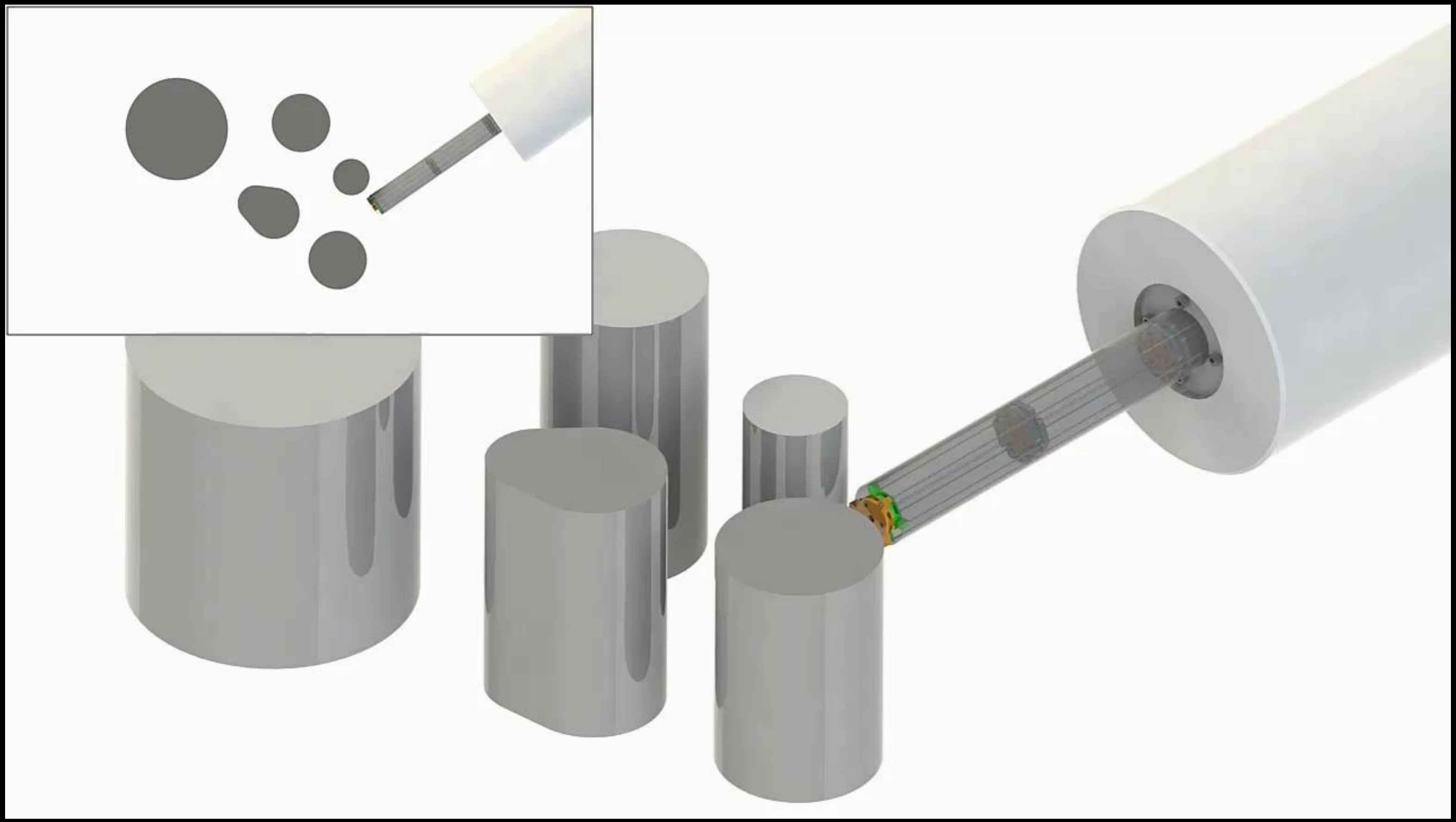
Needle-like probe: Sting (F. Rodriguez Y Baena, ICL). Needs tissue support. No stiffening



No prior art, not even concepts

Our Vision 1/2

A follow-the-leader interlaced continuum robot



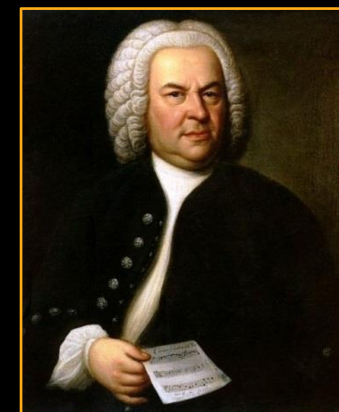
Leader/Follower (←deployment) become Follower/Leader (→retrieval)
Stronger symmetry: best if the two flexible robots are identical!

Our Vision 2/2

OK, yet how to make a leader and a follower identical? Of course: back to Bach!

A simple idea while listening to the Musical Offering (Musicalisches Opfer, BWV 1079c; 1747): it should be a kind-of canon!

J.S. Bach (1685-1750)



http://www.jsbach.net/bass/elements/bach-hausmann.jpg

[Wikipedia] Canon (music):
In music, a canon is a contrapuntal (counterpoint-based) compositional technique that employs a melody with one or more imitations of the melody played after a given duration (e.g., quarter rest, one measure, etc.). The initial melody is called the leader (or dux), while the imitative melody, which is played in a different voice, is called the follower (or comes). …

Leader L

Follower F(=L)

Frère Jacques canon (just to illustrate)

time-translation (in the simplest case)

L•g(L) (= g(L)•L) → "sounds pleasantly"

"simultaneously played with"

Canon

space-translation (angular shift)

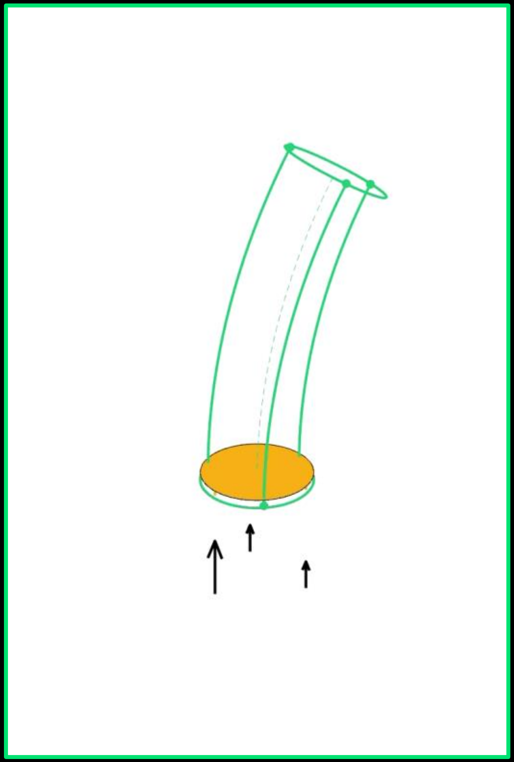
L•g(L) (= g(L)•L) → " builds the track"

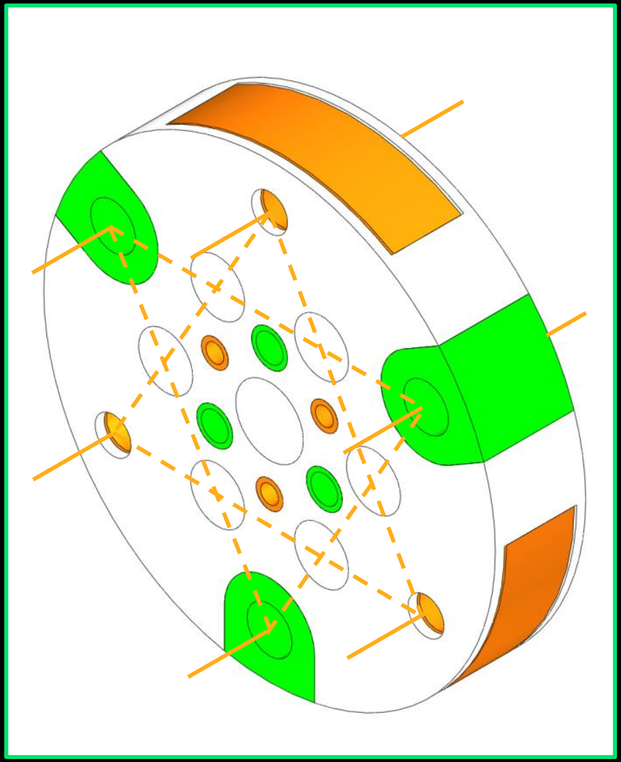
"deployed along"

Interlaced Cont. Probe

Model-Based Design: Symmetry (&) Constraints 1/6

For each flexible device: 3 push/pull rods (3D steering) + 1 thin flexible backbone (retraction/continuity) + rigid disks ("vertebras")



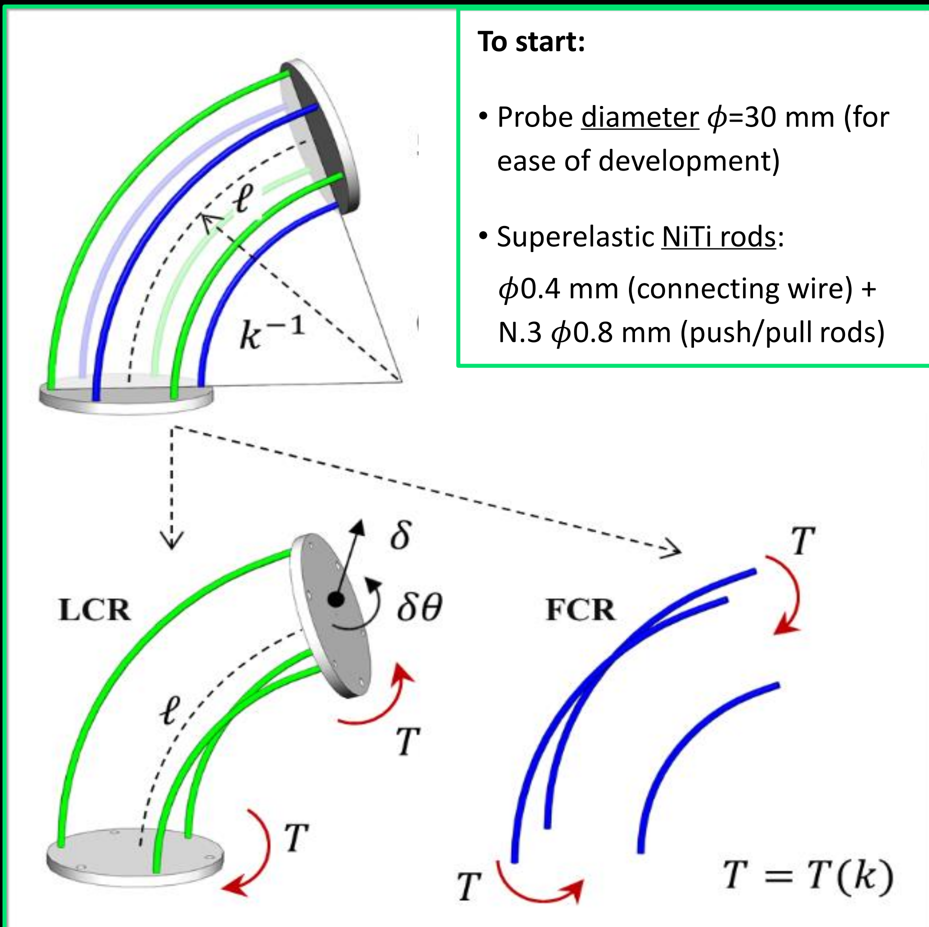


This robot is almost empty! Stiffening through the disks (= shape-lockers)

The disks must comply with a sort of hexagonal symmetry

Model-Based Design: Symmetry (&) Constraints 2/6

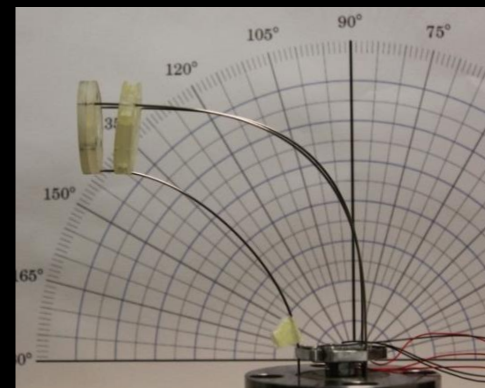
This is the core: Hacking design complexity by symmetry
Span between adjacent disks: Given the diameter, how long can it be?



To start:

- Probe diameter ϕ=30 mm (for ease of development)
- Superelastic NiTi rods: ϕ0.4 mm (connecting wire) + N.3 ϕ0.8 mm (push/pull rods)

LCR: leader continuum robot; FCR: follower continuum robot



rod mechanical instability

Idea (design ice-breaking):

- given a target curvature (K),
- for any fixed segment span (ℓ):

> get LCR pose (w/o FCR, unloaded) by IK
> add FCR (as torque) and update pose by FK

- assess deviation from the target pose

Model-Based Design: Symmetry (&) Constraints 3/6

Parallel continuum robot modelling: Formulation (Boundary-Value Problem)

1

Governing eq's: Rod equilibrium (Cosserat)

$$p_i' = R_i v_i,$$

$$R_i' = R_i (u_i)^\wedge,$$

$$n_i' = 0,$$

$$m_i' = n_i \times (R_i v_i),$$

2

Boundary cond's (distal disk equilibrium)

$$\sum_{i=1}^{3} n_i = 0,$$

$$\sum_{i=1}^{3} \big(p_i(\ell_i) \times n_i + m_i(\ell_i)\big) - m_f = 0,$$

(p/R: position/rotation; n/m: internal force/torque)

Constitutive relations (locally elastic, Kirchoff rod)

3

$$n_i = R_i K^{se} (v_i - v_i^*),$$

$$m_i = R_i K^{bt} (u_i - u_i^*),$$

Geometric compatibility constraints

4

$$p_{pd} + R_{pd}\, r_i - p_i(0) = 0,$$

$$\left(log\big(R_i^T(0)\ R_{pd}\big)\right)^\vee = 0.$$

$$p_{dd} + R_{dd}\, r_i - p_i(\ell_i) = 0,$$

$$\left(log\big(R_i^T(\ell_i)\ R_{dd}\big)\right)^\vee = 0.$$

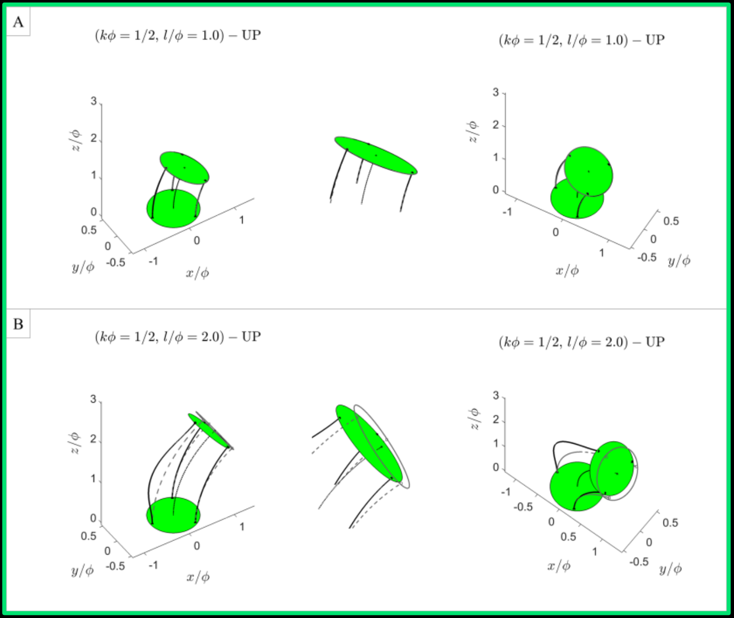
Step#1: also determine the rod lengths (besides internal actions and distal disk angular deviation)

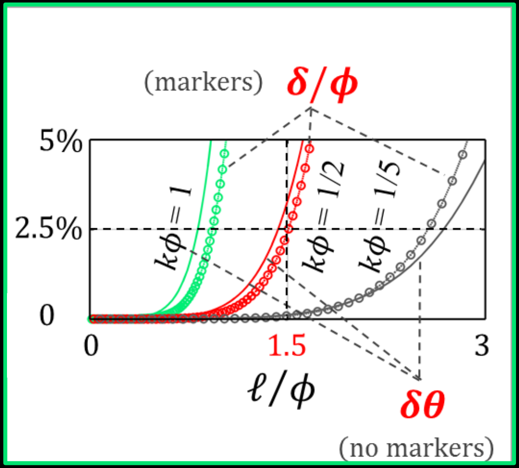
Step#2: using the previous lengths, compute internal actions and distal disk deviations (linear/angular)

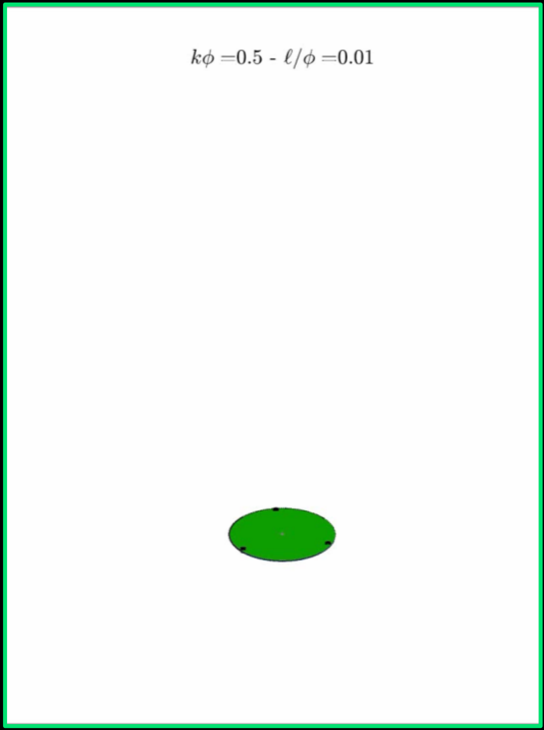
Simplified formulation (by symmetry); design methodology can be extended

Model-Based Design: Symmetry (&) Constraints 4/6

Parallel continuum robot modelling: Results







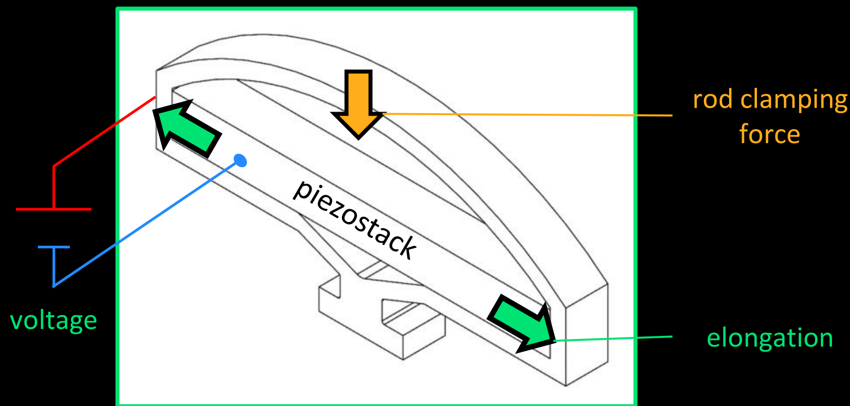
For ℓ/ϕ above 1.5 the track cannot be accurately built (error > 5%) due to mechanical instabilities

Targeted radius of curvature: 2ϕ (small, challenging!)

Model result: a span $\ell/\phi = 1.5$ should enable track-building

Model-Based Design: Symmetry (&) Constraints 5/6

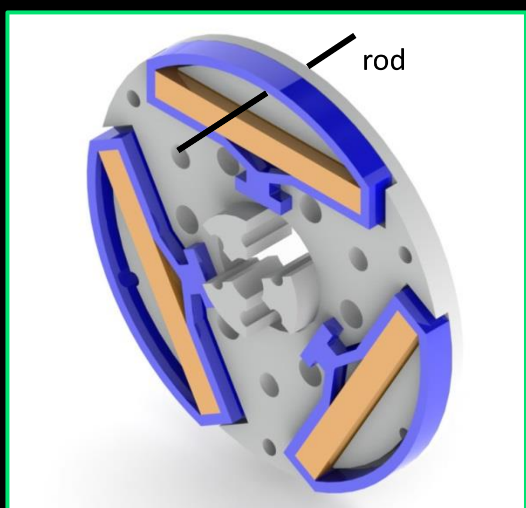
Stiffening by rod clamping, through piezoelectric brakes



Initial design

Targeted clamping force on each rod: 10 N (obtained from the parallel Cosserat model)

Powering: Full series for each CR (simultaneous clamping on all of the shape-lockers) → just a couple of wires!



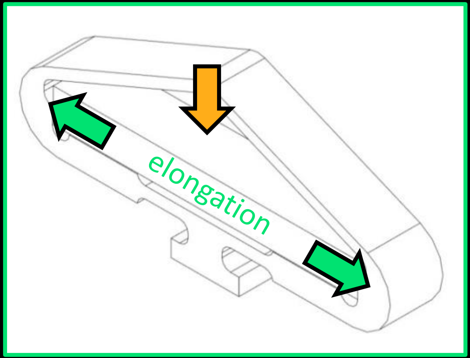
(half-disk + piezo brakes)

Miniature piezo actuators

- P-882.51 PICMA Stack Multilayer by PI
- size: 3 x 2 x 18 mm
- load-free expansion: 18 µm
- maximum blocking force: 210 N @125 V

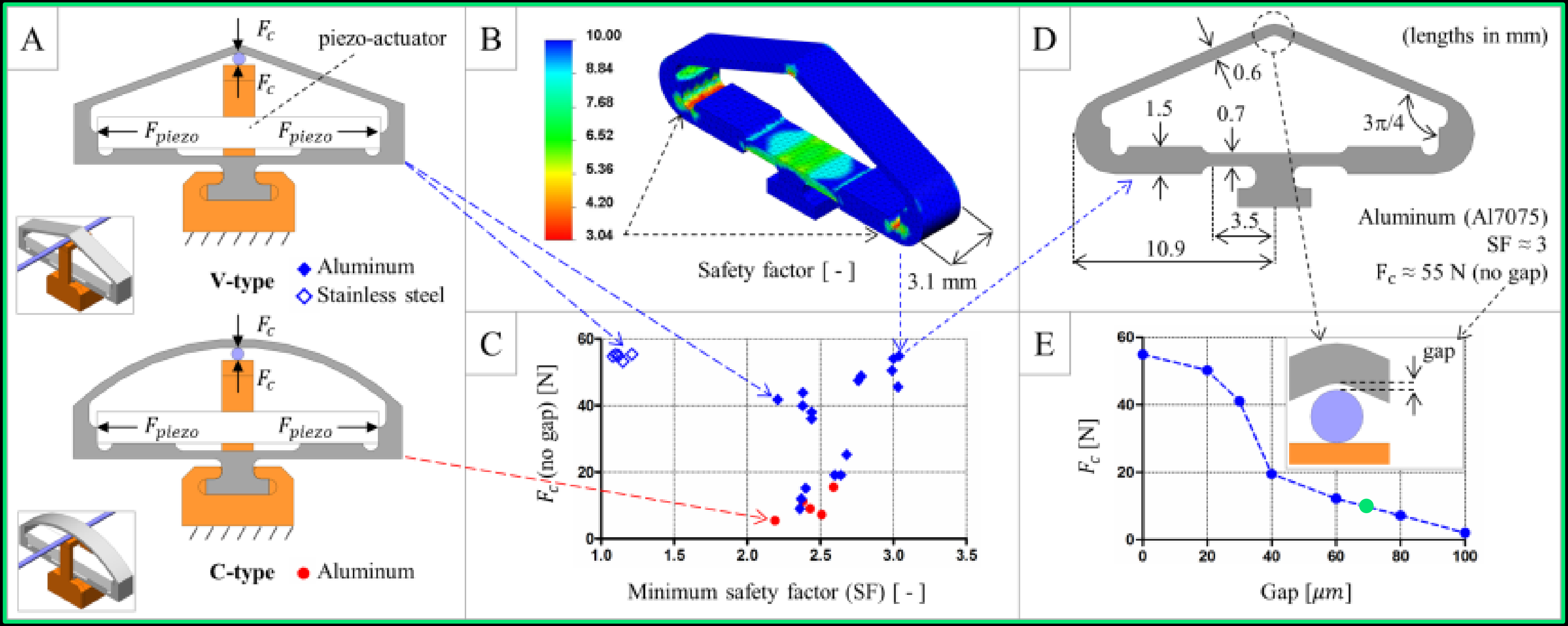
Model-Based Design: Symmetry (&) Constraints 6/6

Piezoelectric brakes (cages): Design optimization



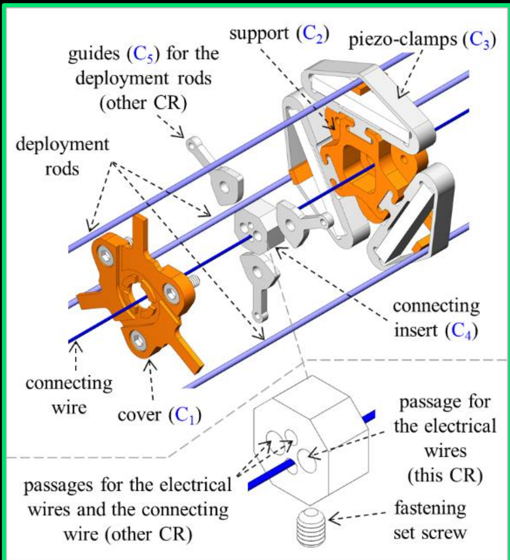
Final design

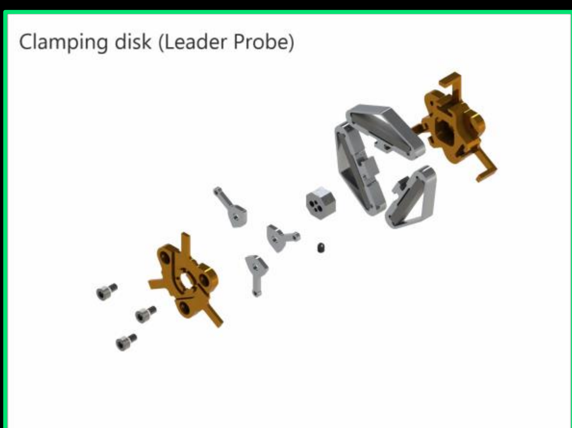
(disk w/o cover
+ piezo brakes)



[Complexity Reduced by Design] Components 1/2

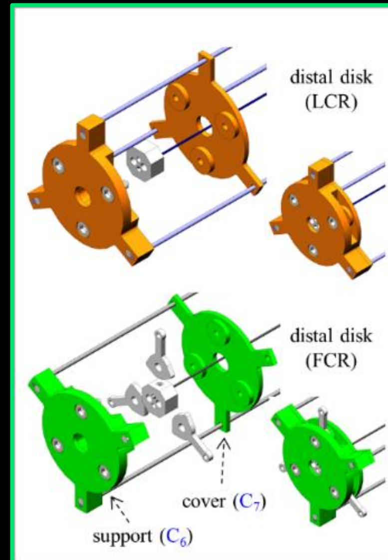
Shape-locker

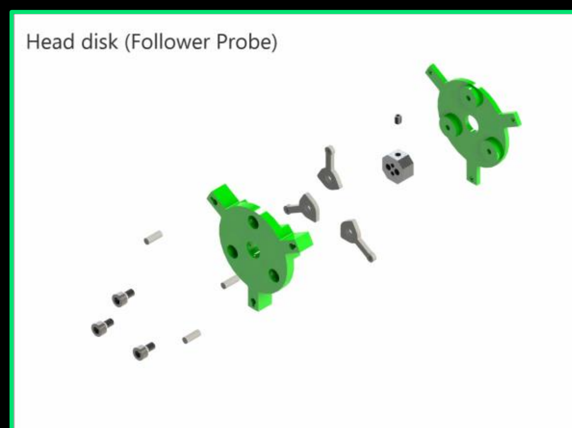




Clamping disk (Leader Probe)

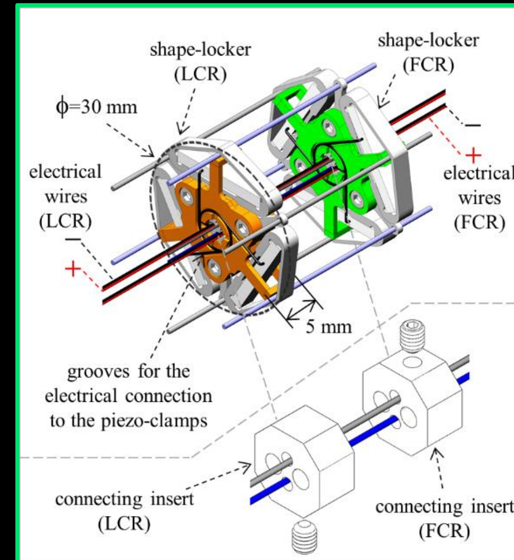
Distal disks





Head disk (Follower Probe)

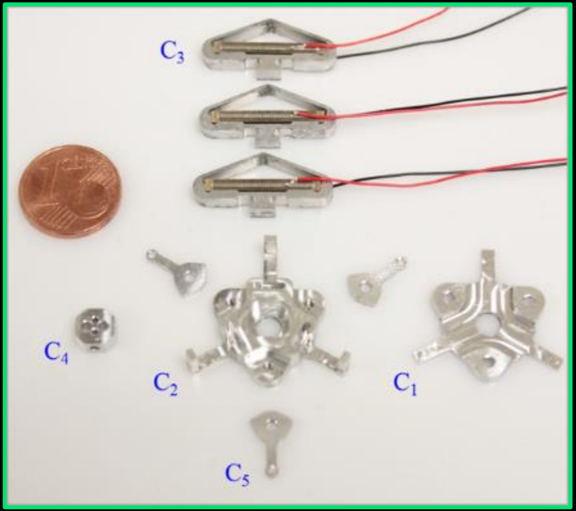
Adjacent shape-lockers

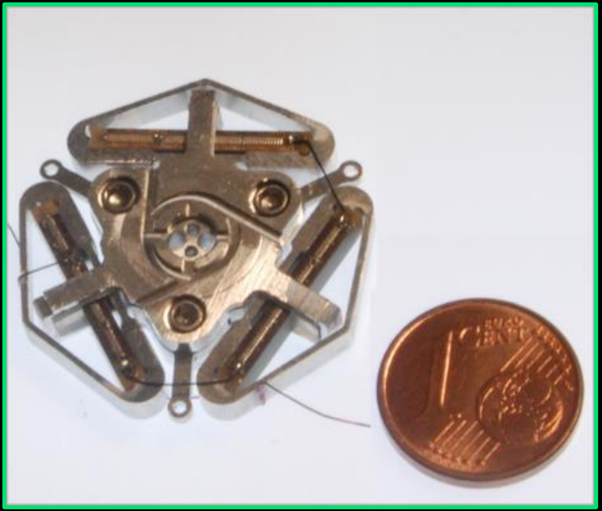


Symmetry permits to assemble both flexible devices "within each other"!

[Complexity Reduced by Design] Components 2/2

A "minimal" set of different components: still thanks to symmetry!



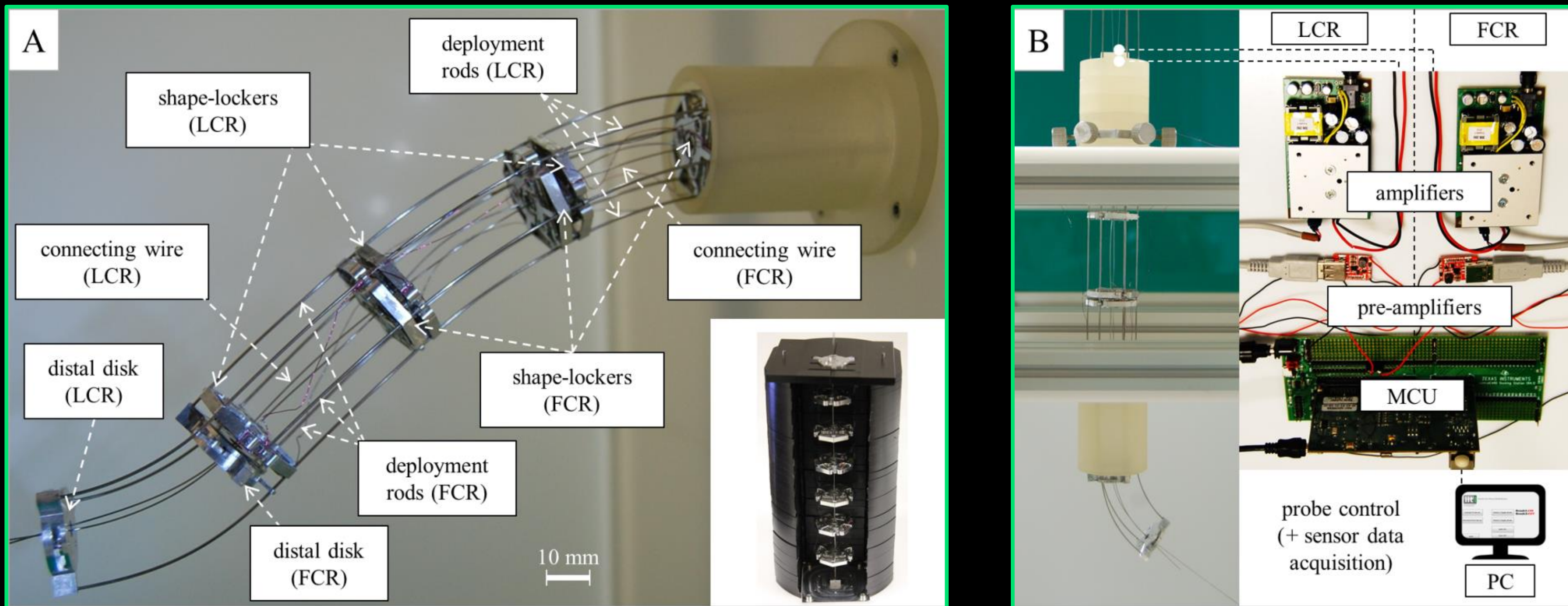


Number of components for a probe with n active segments (*)

Component	No. of instances
C_1: Shape-locker cover	$2n$
C_2: Shape-locker support	$2n$
C_3: Piezo-clamp	$6n$
C_4: Connecting insert	$2n + 2$
C_5: Guides for the deployment rods	$6n + 3$
C_6: Distal disk support	2
C_7: Distal disk cover	2

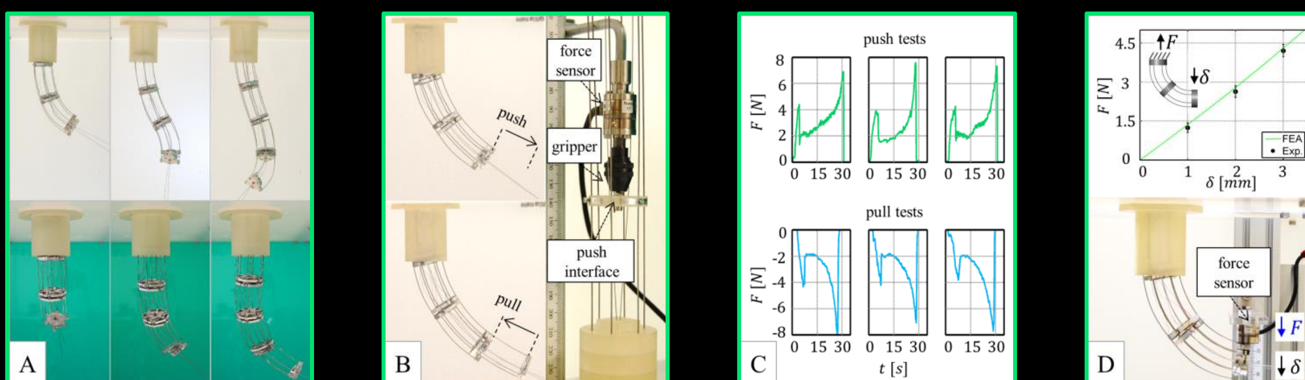
(*) Additional commercial items:
6+2 NiTi rods;
$2n$+2 set screws;
$6n$+3 screws;
$6n$ piezo-stacks;
4 electrical wires
(driving electronics excluded)

The Interlaced Continuum Probe 1/2



The robot (+ assembly stack and driving electronics)

- Actuation (push/pull) force: ~4 N (peak: 8 N)

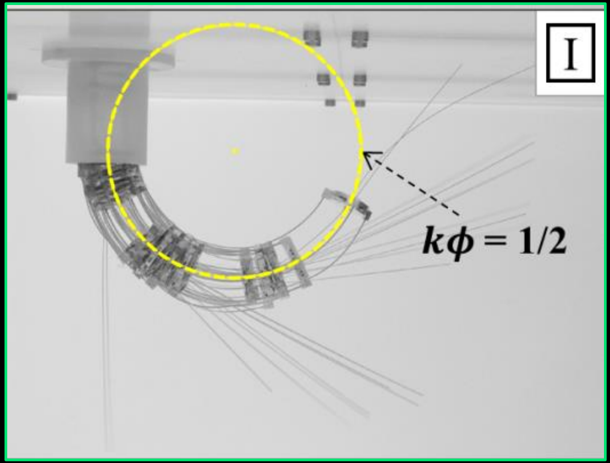


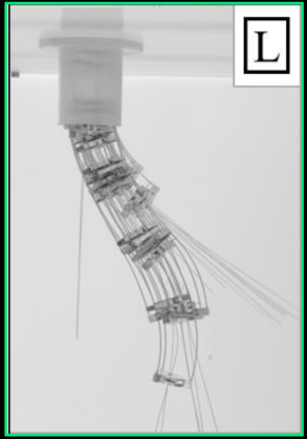
- Stiffness (locked-configuration) : ~1.5 N/mm

3D Poses + Push/pull and stiffness tests

The Interlaced Continuum Probe 2/2

It "grows" by physically building its track, without any supports!





High-curvature & double-curvature paths (more challenging)

(2X)

30 mm

(patented)

… mechanical intelligence embodied owing to … Bach-inspiration! ;-)

Keen on More Details?

1. Where To Go

- E. Sinibaldi, G.L. Puleo, F. Mattioli, et al., “Osmotic actuation modelling for innovative biorobotic solutions inspired by the plant kingdom”. Bioinspiration & Biomimetics, 8(2), 025002 (12 pages), 2013 [DOI: 10.1088/1748-3182/8/2/025002]
- E. Sinibaldi*, A. Argiolas, G.L. Puleo and B. Mazzolai*, “Another lesson from plants: the forward osmosis-based actuator”. PLoS ONE, 9(7), e102461 (12 pages), 2014 [DOI: 10.1371/journal.pone.0102461]
- A. Argiolas, G.L. Puleo, E. Sinibaldi* and B. Mazzolai*, “Osmolyte cooperation affects turgor dynamics in plants”. Scientific Reports (Nature Publishing Group), 6, 30139 (8 pages), 2016 [DOI: 10.1038/srep30139]
- I. Must, E. Sinibaldi* and B. Mazzolai*, [paper on reversible osmotic actuation for soft robotics to appear]

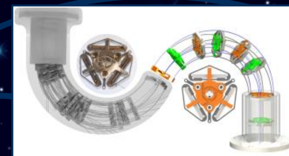
2. Where Not To Go

- L.C. Berselli, P. Miloro, A. Menciassi and E. Sinibaldi*, “Exact solution to the inverse Womersley problem for pulsatile flows in cylindrical vessels, with application to magnetic particle targeting”. Applied Mathematics and Computation, 219, pp. 5717-5729, 2013 [DOI: 10.1016/j.amc.2012.11.071]
- V. Iacovacci*, L. Ricotti, E. Sinibaldi*, et al., “An intravascular magnetic catheter enables the retrieval of nanoagents from the bloodstream”. Advanced Science, 5, 1800807 (8 pages), 2018 [DOI: 10.1002/advs.201800807]

3. Imaginative Trails

- B. Kang, R. Kojcev and E. Sinibaldi*, “The first interlaced continuum robot, devised to intrinsically follow the leader”. PLoS ONE, 11(2), e0150278 (16 pages), 2016 [DOI: 10.1371/journal.pone.0150278]

Connecting the Dots 1/2



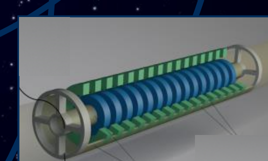
Imaginative Trails

Given a behavior of interest, how does it come about?
How to implement it?

Things can be seen differently.
See different: simplify, change, create

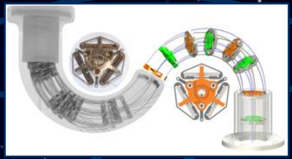
Where To Go

Where Not To Go



Opportunity to connect (natural/artificial, close the loop) and innovate

Connecting the Dots 2/2



Imaginative Trails

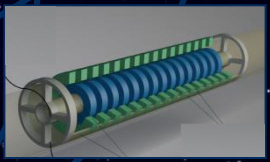
Embodied Intelligence

AI-based
Generative Design

人工智能 上海授课 The ShanghAI Lectures

Where To Go

Where Not To Go



Bridging across disciplines.
"Nemo solus satis sapit"

"No man is sufficiently wise of himself" (from Miles Gloriosus by Latin poet T. M. Plautus, c.250–184 BC)

Thank You!

Edoardo Sinibaldi

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