An introduction to rate-independent soft crawlers

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An illustrated introduction to rate-independent soft crawlers

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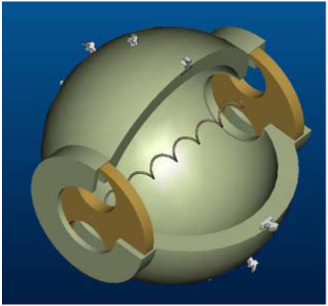
Crawlers in Nature

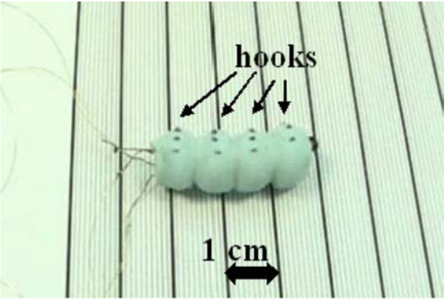
Soft robotics

Elastic materials

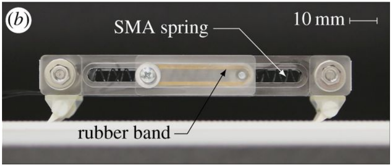
Large deformations

Compliance and morphological computation



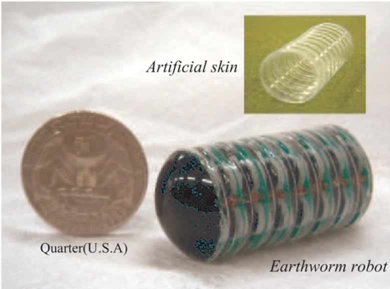


Menciassi et al., 2006

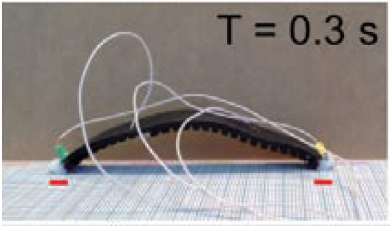


Noselli& DeSimone, 2014

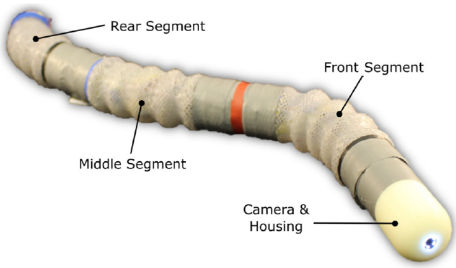
Seok et al., 2013

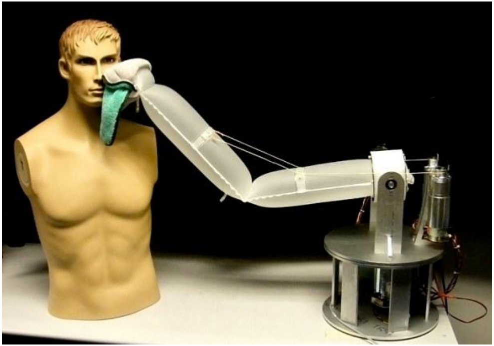


Jung et al., 2007



Umedachi et al., 2013





Application fields

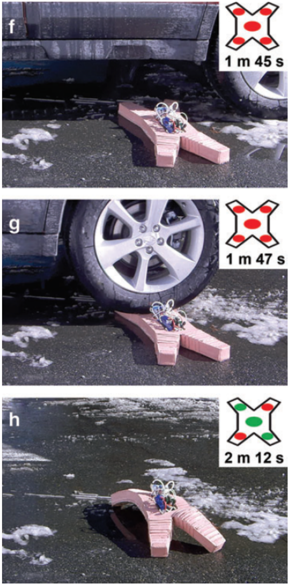
Interaction with fragile objects

Activity in unknown/uncertain environment

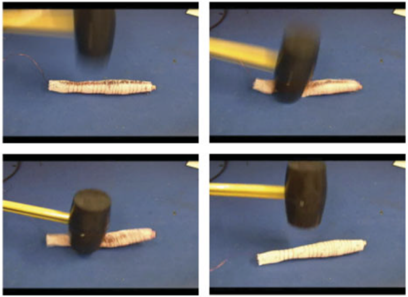
Medical intervention

Bernth et al., 2017
Sanan et al., 2011

Soft robots, are also tough!



Tolley et al., 2014



Seok et al., 2013

Why rate-independent systems (or SP)?

$\rightarrow$ Dry friction

$\rightarrow$ Elasticity

$\rightarrow$ No inertial effects

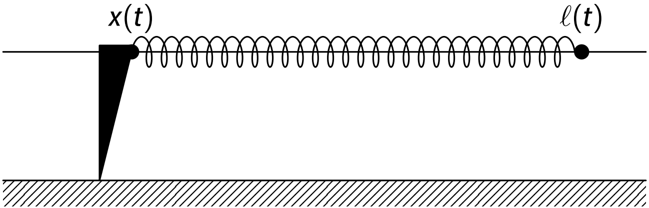
Why crawlers?

$\rightarrow$ Simple enough for analytical approach

$\rightarrow$ Complex enough to be meaningful

$\rightarrow$ Simplexity

A classical system with friction

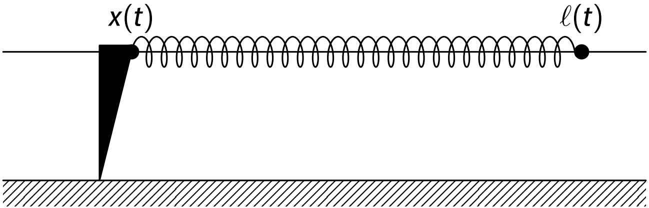


Dry friction on the contact point $z(t)$

Force balance on the point $\ell(t)$

Neglect inertia

A classical system with friction



Energy $\mathcal{E}(t,x) = \frac{k}{2}(\ell(t) - x - L^{\mathrm{rest}})^2$

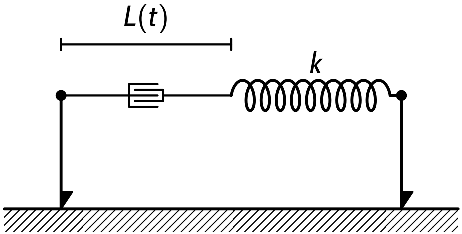
Dissipation potential $\mathcal{R}(\dot{x}) = \mu\,|\dot{x}|$

Force balance: $0 \in \partial_{\dot{z}}\mathcal{R}(\dot{z}) + D_z\mathcal{E}(t,z)$

Play operator

Sweeping process on $\mathbb{R}$ with $C(t) = [-a, a] + b(t)$

A minimal model of crawler



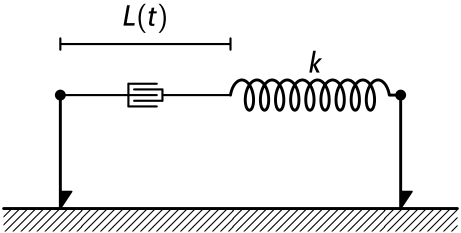
Energy $\mathcal{E}(t,x) = \frac{k}{2}(x_2 - x_1 - L^{\mathrm{rest}} - L(t))^2 \approx \langle \mathbb{A}x, x\rangle - \langle \ell(t), x\rangle$

Dissipation potential $\mathcal{R}(\dot{x}) = \mu\,|\dot{x}_1| + \mu\,|\dot{x}_2|$

Energy is invariant for translation

Our system has dimension 2, our control has dimension 1.

A minimal model of crawler?

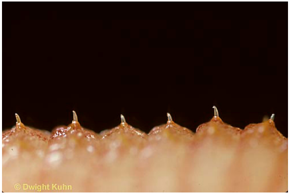


Multiple solutions

It is symmetric, so we do not expect it to go anywhere

BAD EXAMPLE! What are we missing?

(Don't worry, it is a pathological example)



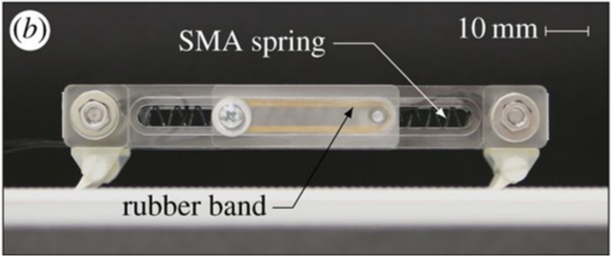
Three ways to asymmetry

Anisotropic friction

Complex shape change

Friction manipulation

Anisotropic friction

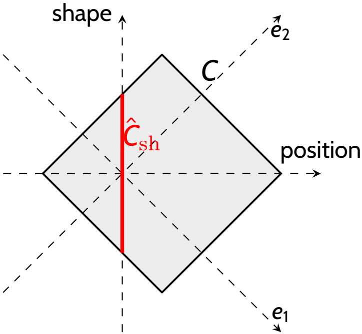


Noselli & DeSimone, 2014

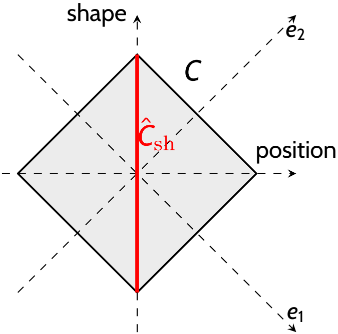
It moves and the solution is unique!

Bonus question: How do slanted bristles produce anisotropy?
[G.& DeSimone, 2017]

Stasis domains



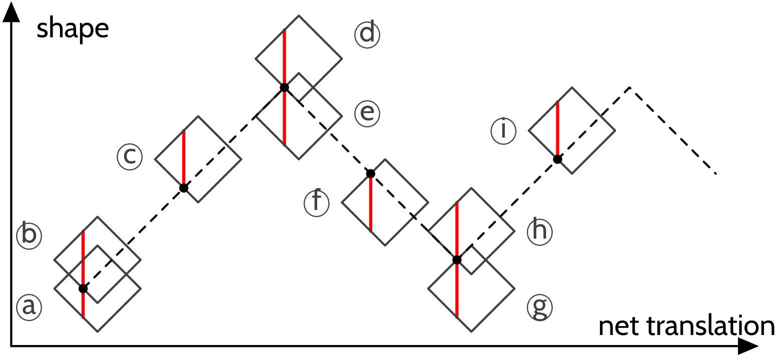
Case $2\mu_- = \mu_+$



Bad case $\mu_- = \mu_+$

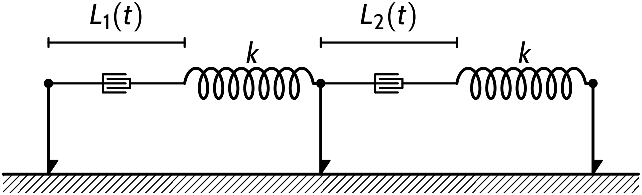
In general, for RIS, we have $-D_x\mathcal{E}(t,x) \in C := \partial\mathcal{R}(0)$

In our case we get more: $-D_x\mathcal{E}(t,x) \in \hat{C}_{\mathrm{sh}}$



$$-\dot{u}(t) \in \mathcal{N}_{\tilde{C}(t,u)}(u) \qquad \tilde{C}(t,u) = C - \ell(t) + \hat{\pi}(u)$$

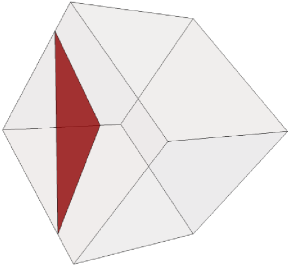
Complex shape change



G. & DeSimone, 2016

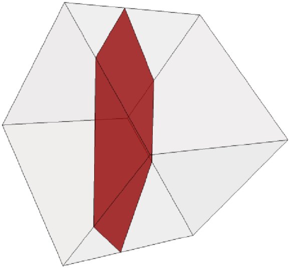
Uniqueness fails only for $\mu_+ = 2\mu_-$ and $\mu_- = 2\mu_+$.

Three contact points, two scenarios



$\mu_+ > 2\mu_-$

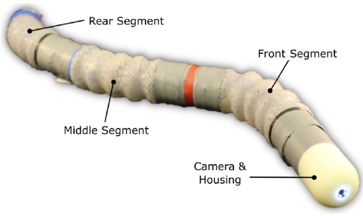
(only backwards locomotion)



$\mu_- < \mu_+ < 2\mu_-$

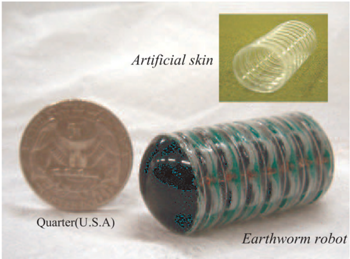
(locomotion achievable in both directions)

Complex shape change

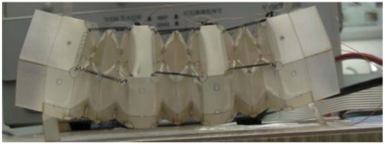


Bernth et al., 2017

Seok et al., 2013

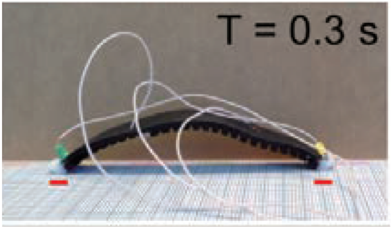


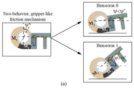
Jung et al., 2007



Onal et al., 2013

Friction manipulation



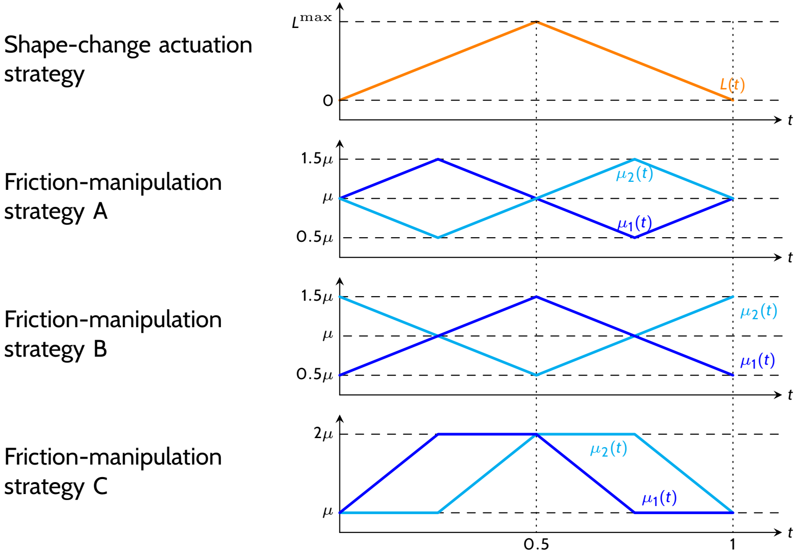


Umedachi et al., 2013,
Vikas et al. 2016

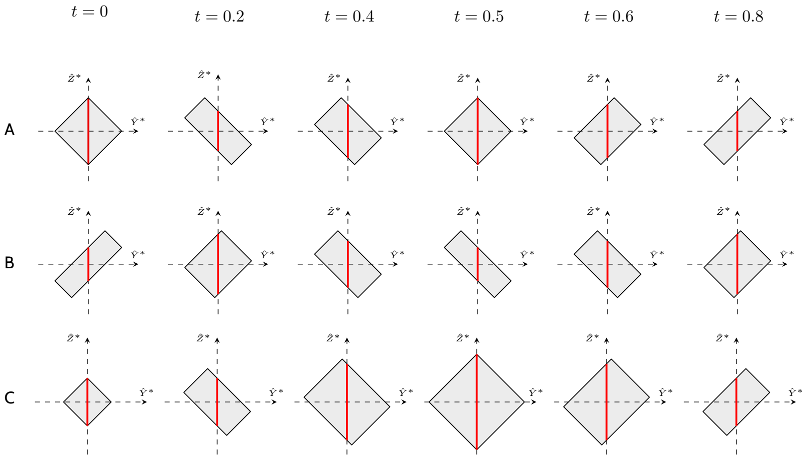
We control friction coefficients

The dissipation potential $\mathcal{R}$ depends on time

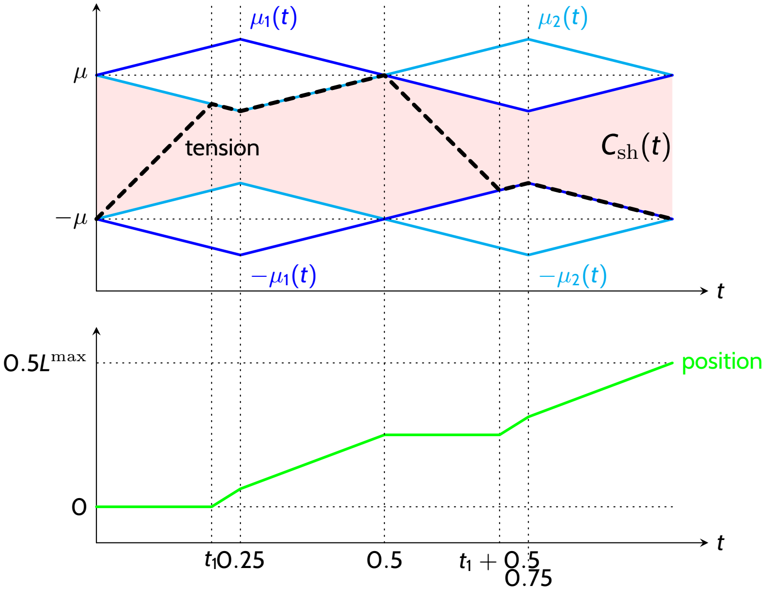
An extreme example is two-anchor crawling



Shape-change actuation strategy
Friction-manipulation strategy A
Friction-manipulation strategy B
Friction-manipulation strategy C
$L^{\max}$
0
$L(t)$
t
1.5μ
μ
0.5μ
$\mu_2(t)$
$\mu_1(t)$
2μ
0.5
1



$t=0$
$t=0.2$
$t=0.4$
$t=0.5$
$t=0.6$
$t=0.8$
A
B
C
$\hat{Z}^*$
$\hat{Y}^*$



$\mu_1(t)$
$\mu_2(t)$
μ
$-\mu$
tension
$C_{\mathrm{sh}}(t)$
$-\mu_1(t)$
$-\mu_2(t)$
t
$0.5L^{\max}$
position
0
t
t_1
0.25
0.5
$t_1 + 0.5$
0.75

What we know

Well-posedness of the approach (existence and uniqueness)

$\rightarrow$ Coercivity and uniqueness of minimum in the "shape-sections" of $\mathcal{R}$

$\rightarrow$ Lipschitz continuity in time

$\rightarrow$ Bounds and coercivity conditions uniform in time on $\mathcal{R}$

Abstract theorems on Hilbert spaces

$\rightarrow$ Discrete and continuous crawlers

$\rightarrow$ Planar crawlers (with modelling issues)

Motility analysis

$\rightarrow$ Does the crawler move? Can it move in both directions?

$\rightarrow$ Common sense optimization

(DeSimone, G. & Noselli, 2015; G. & DeSimone, 2016; G., *prep.*)

Some open problems

Optimal control

$\to$ Control on actuation or friction

$\to$ We want to move (fast)

$\to$ Constraints on control parameters

Compliance

$\to$ Everything

Dynamical properties

Problems with variational taste

$\to$ State-dependent dissipation (Anisotropic friction for planar crawlers, obstacles)

$\to$ Rate-dependent dissipation (mucus of the snail, biological fluids)

Thank you for your attention

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