A Different Way to Look at Underactuated Mechanical Systems

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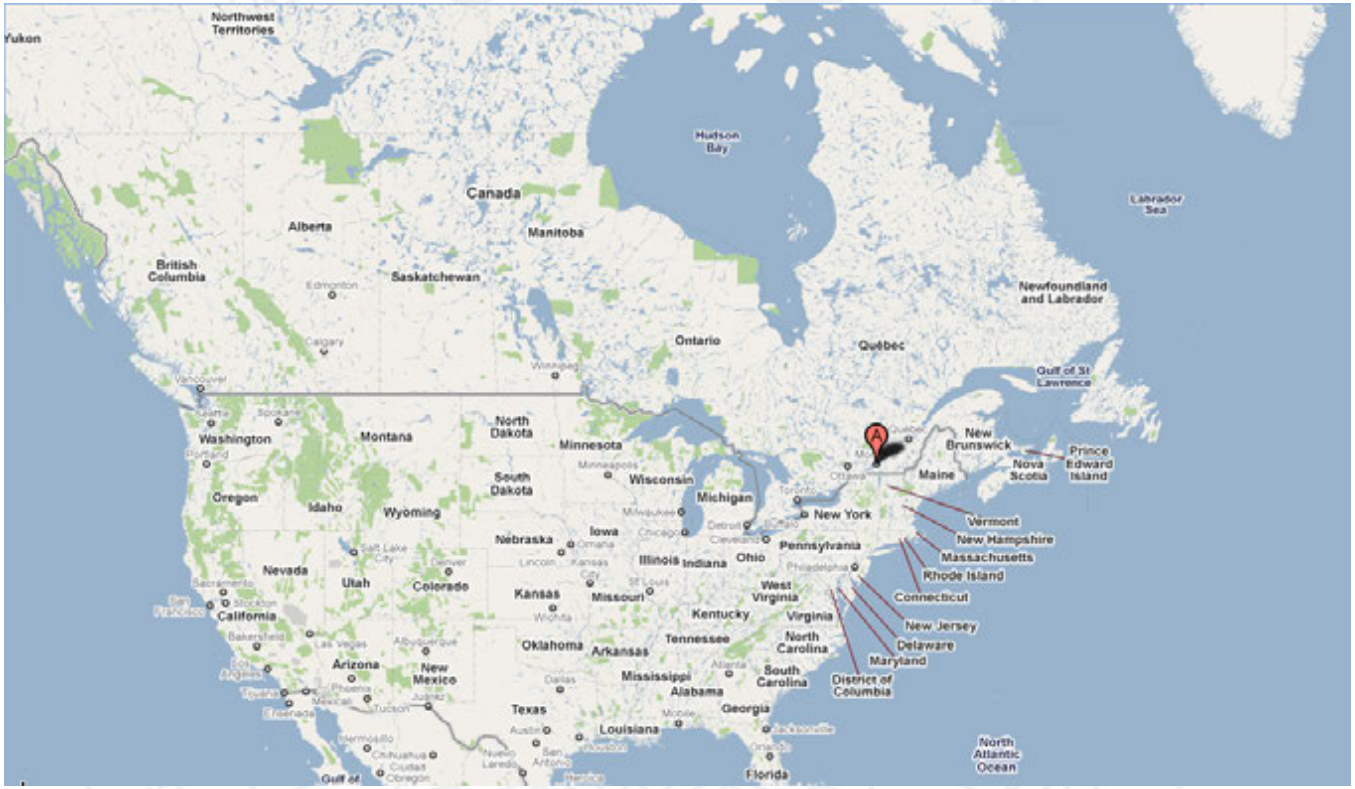
Based on a public seminar given at:
LIRMM, Montpellier, France
in Nov. 2018

Who Am I?

- Professor at Polytechnique Montréal, the metropolis of the French-speaking province of Canada, Québec.
- Founded in 1873, the largest French-speaking Engineering faculty in North America.



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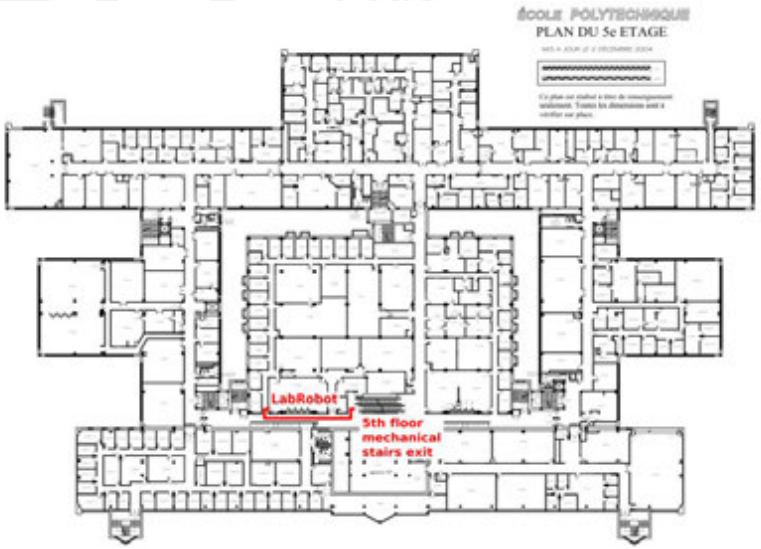
Introduction

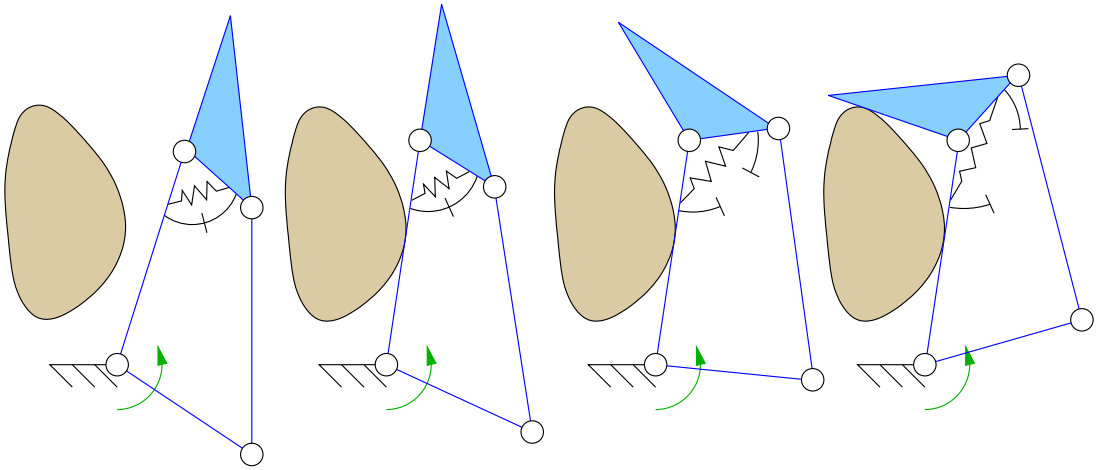
- My laboratory has been founded in 2006 using a Leaders Opportunity Grant by the Canadian Foundation for Innovation.
- To date, more than 100 students have been using this infrastructure. In average, 6 to 15 students/semester.

  `[Winter 2018]: 1 Postdoc - 5 Ph.D. - 0 M.Sc. - 7 B.Ing.`
- One main idea behind the lab: **rapid prototyping**.



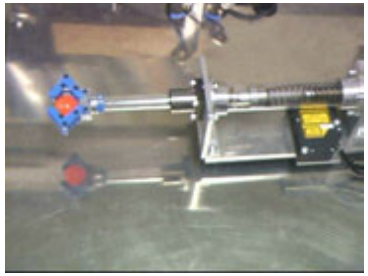
Research Activities

- Our main area of expertise lies with underactuated robotic hands.
- Usual fully actuated robotic hands vs. simple grippers are characterized by:
  - adaptability, enhanced dexterity,
  - but complex design and control.
- An intermediate solution is underactuation (= fewer actuators than DOF).
- which leads to shape adaptation:

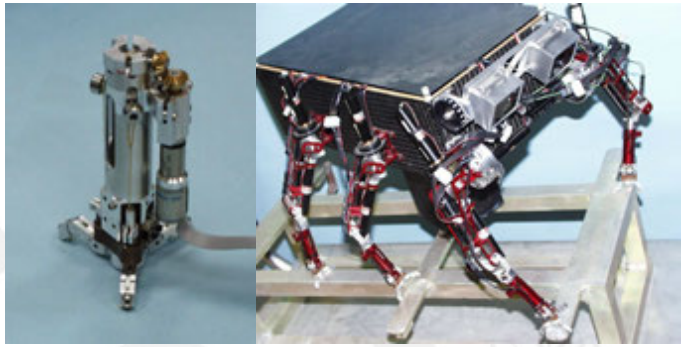


- This effect can be achieved using pulleys/tendons, linkages, pneumatic cylinders, etc. [Birglen et al. 2008]

A Brief *(but very incomplete and very obsolete)* Pictorial Review



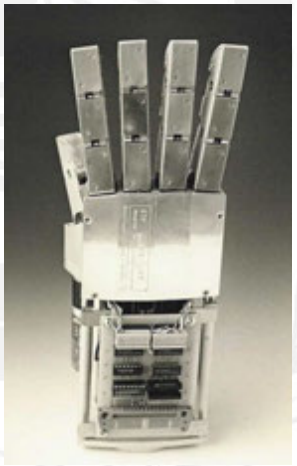
The 100G Hand, Hiroshima University [2003]



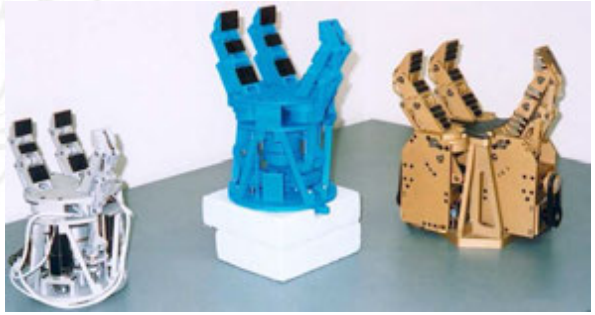
The LEMUR 1 Hand, JPL [2001]

The RTR Hand 2, Pisa University [2002]

The Soft Gripper, Tokyo Institute of Technology [1978]



The Belgrade/USC Hand [1999]

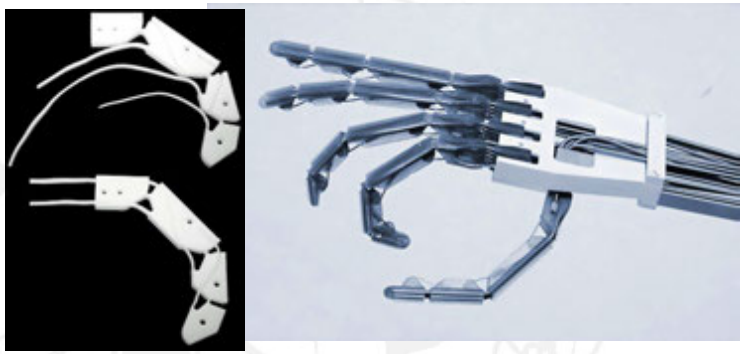


The SARAH and MARS Hands, Universite Laval [1998]

Prosthetic Hand, Delft University of Technology [2000]

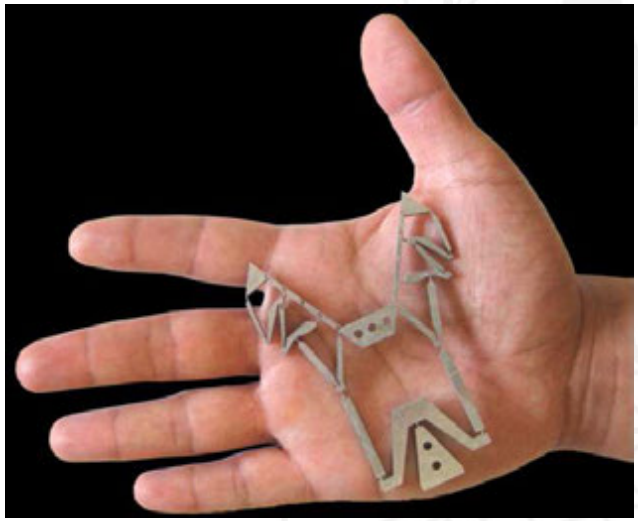
Prototypes Using Compliant Hinges *(same remark)*

Stanford University [1998]



Bologna University [2002]

Genova University [2004]



Polytechnique Montreal [2009]

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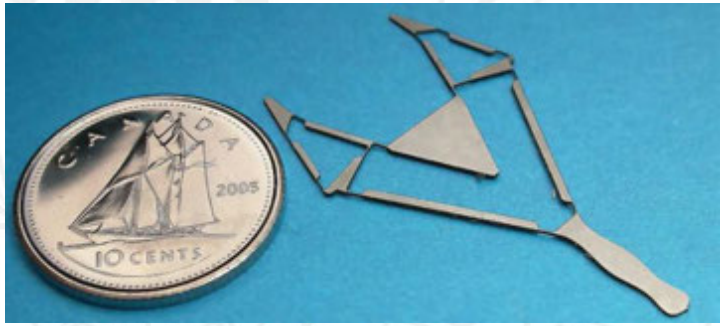
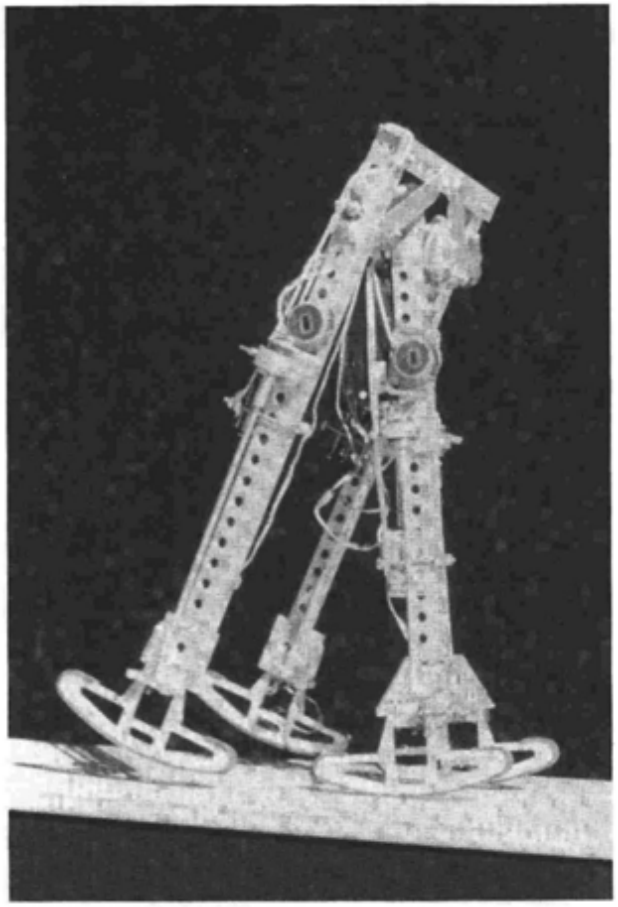


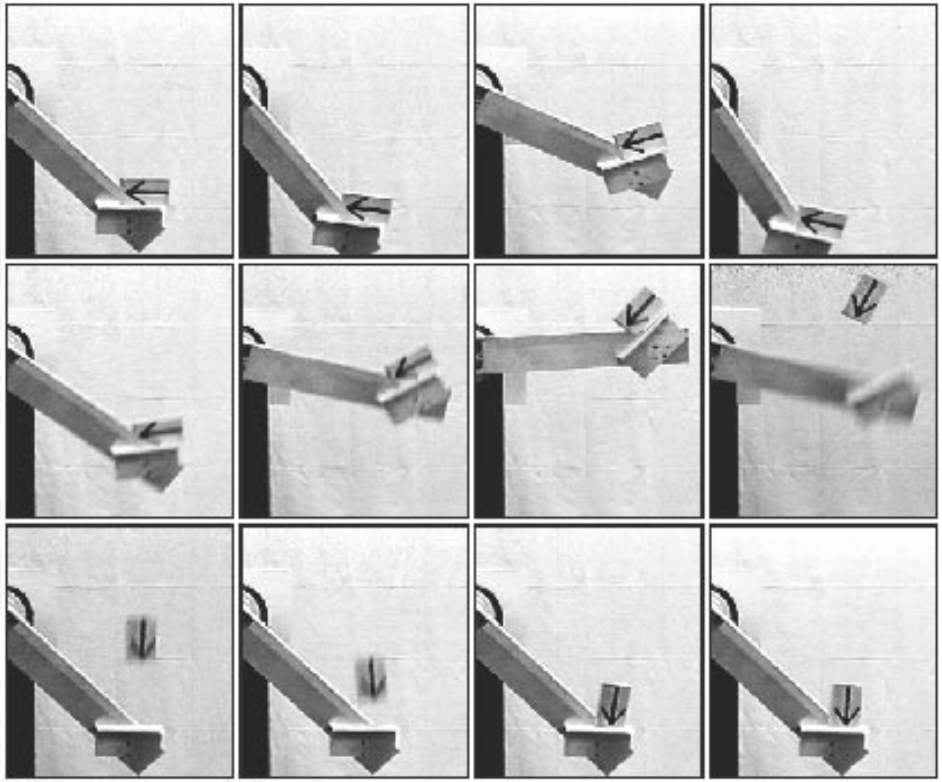
Underactuation in robotics

- Underactuation in robotics is ***ancient*** :



https://youtu.be/WOPED7I5Lac

McGeer passive walker [McGeer 1990]



Non prehensile manipulation
[Lynch and Mason 1999]

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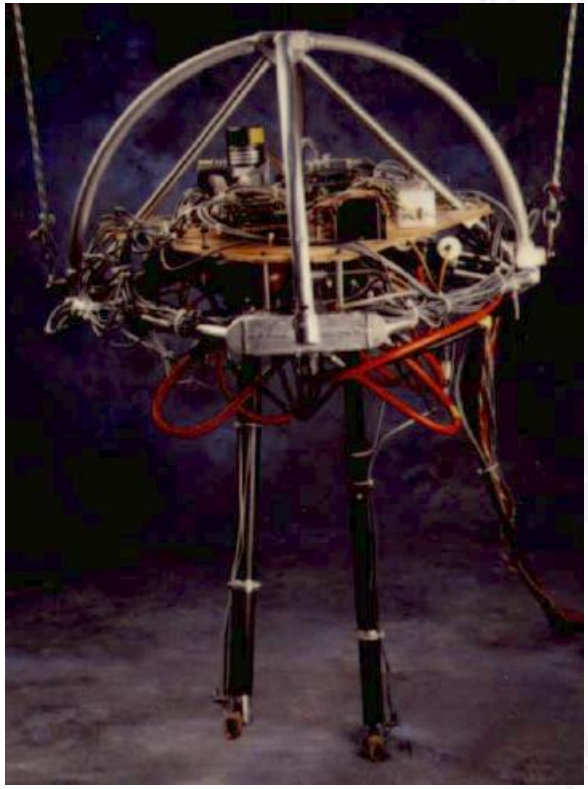

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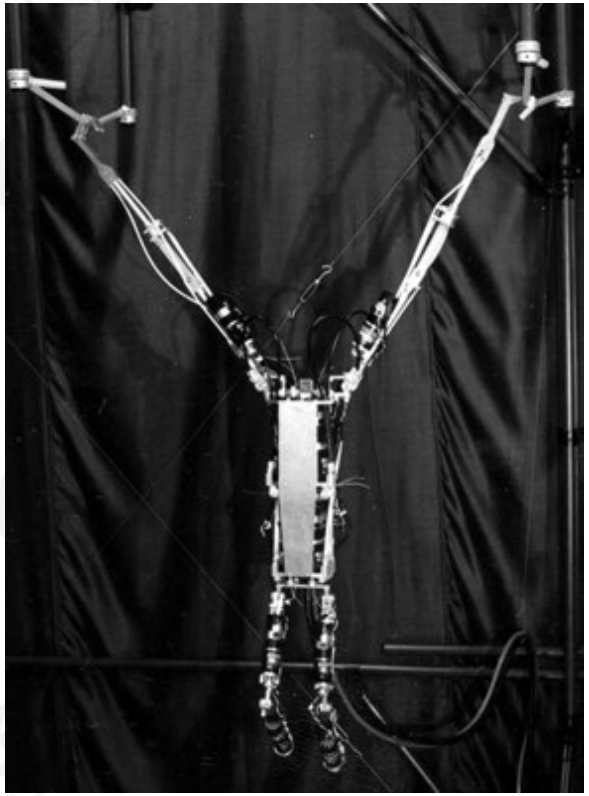
MIT 3D Hopper
[Raibert et al. 1993]



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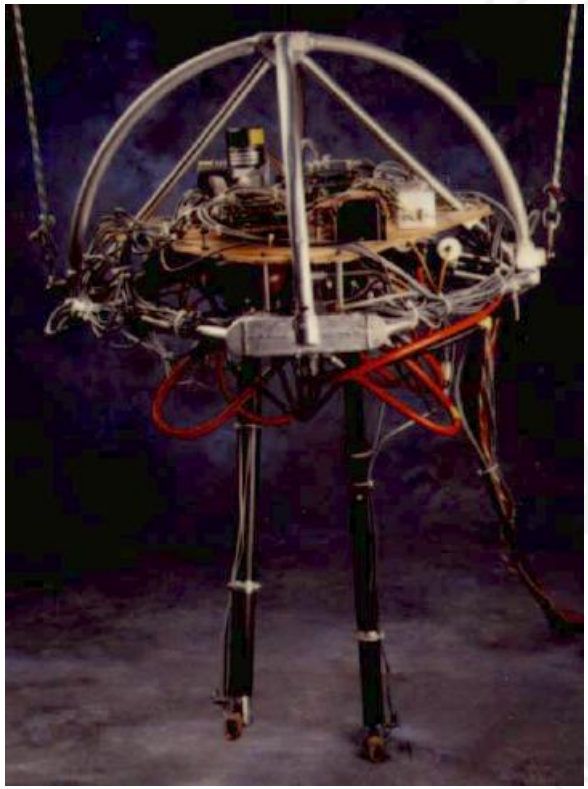

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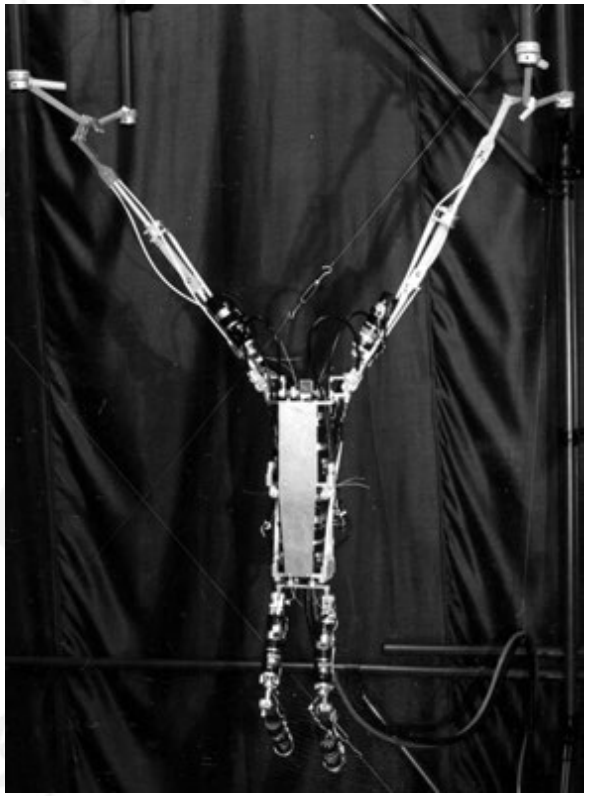

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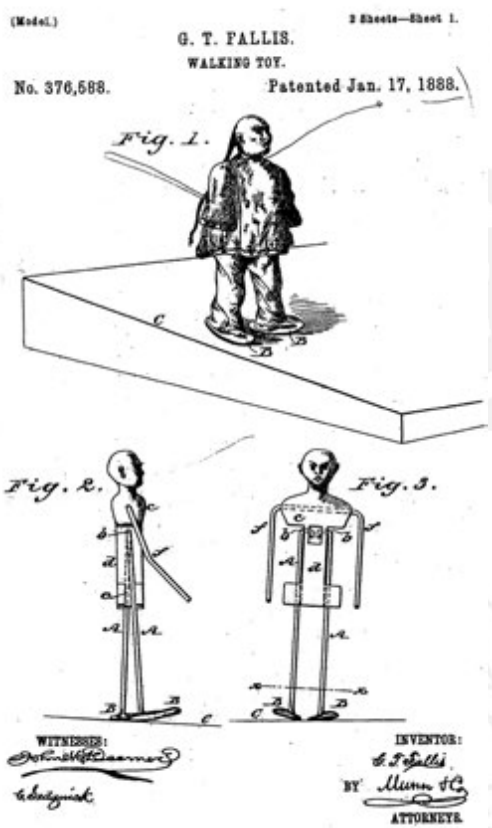
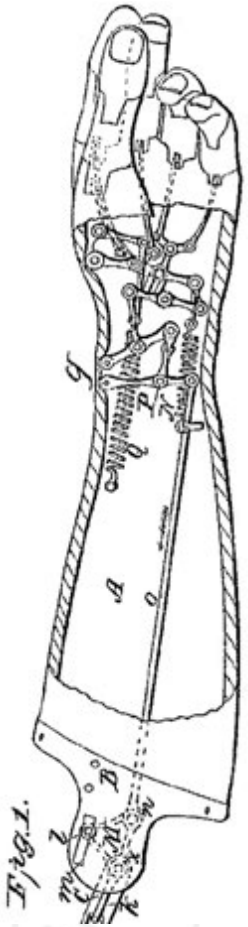


Walking toy, 1888



Spellerberg artificial arm, 1864

- and I do mean ***really ancient***: it predates robotics actually!

Analysis of Underactuated Robotic Hands

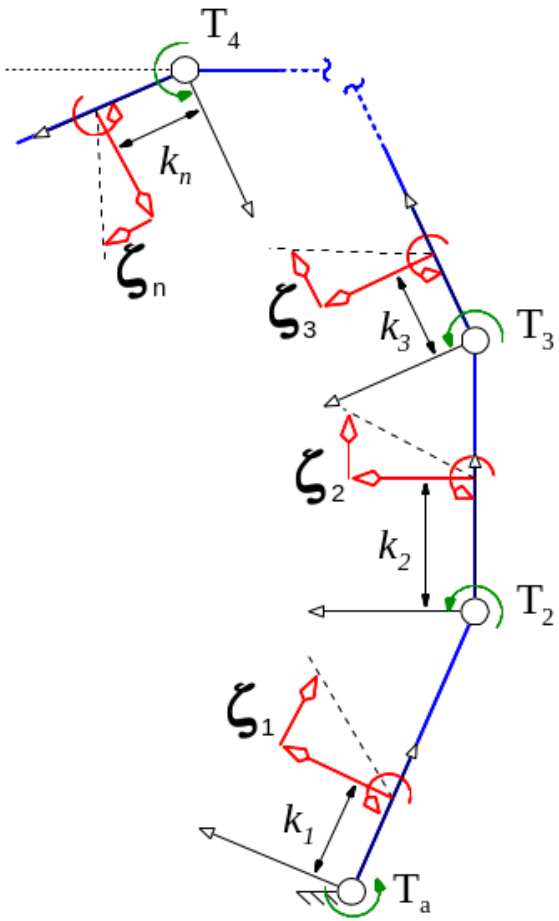
- Kinetostatic analysis of a finger:
- using virtual powers one can show that

$$\mathbf{t}^T \boldsymbol{\omega}_a = \sum_{i=1}^{n} \boldsymbol{\xi}_i \circ \boldsymbol{\zeta}_i \qquad (1)$$

- which can be expressed as

$$\mathbf{J}^\star \mathbf{f} = \mathbf{T}^\star \mathbf{t} \qquad (2)$$

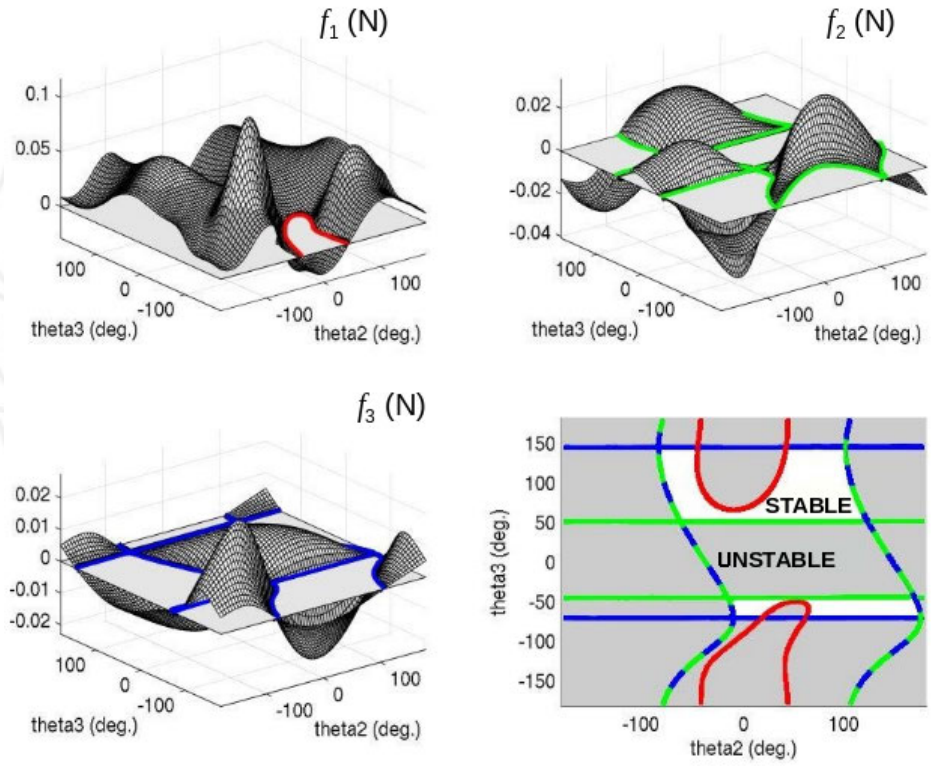
- where $\mathbf{J}^\star$ is a Jacobian matrix, $\mathbf{f}$ is the vector of the contact forces, $\mathbf{T}^\star$ is a Transmission matrix and $\mathbf{t}$ is an actuation vector.



The existence and general formulation of the Jacobian and Transmission matrices are probably the main contribution of my PhD thesis (2004).

Analysis of Underactuated Robotic Hands

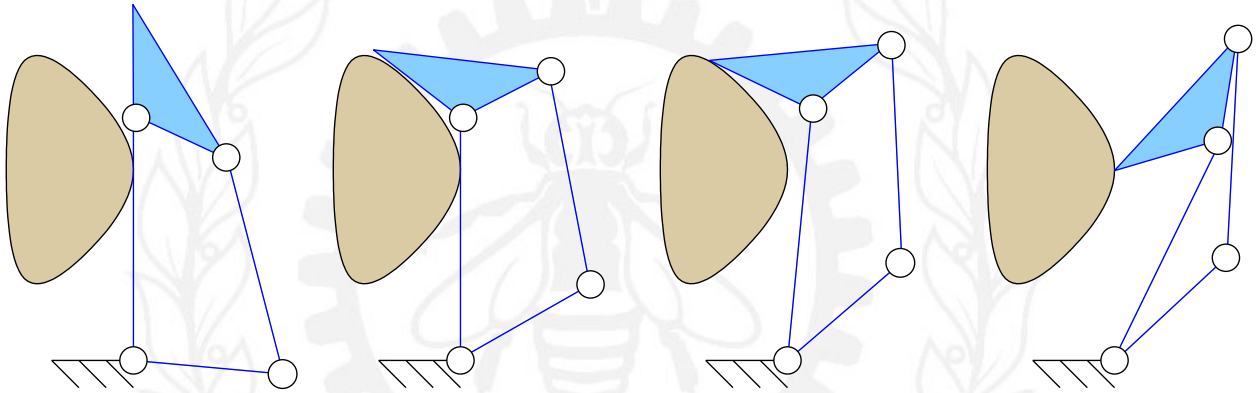
- Following this calculation one can obtain the expression of the contact forces:



- And if something can be calculated, it can then be *optimized*.
- But which optimization criteria should be used? See [Kragten and Herder 2010]

Analysis of Underactuated Robotic Hands

- Negative forces probably cannot be always eliminated (it yet remains to be proven...) and may lead to undesirable behaviours:



- These motions, similar to the *self-posture changeability* noticed by [Kaneko and Tanie 1994] can be studied in a *grasp-state space*.
- This work has been extended to two-finger grippers, mobile objects, and covering both precision and power grasps in [Kragten 2010] using a very clever energy-based approach.
- The stiffness of the (mostly pinch) grasps was also extensively studied by Prattichizzo and Bicchi [Prattichizzo et al. 2013]

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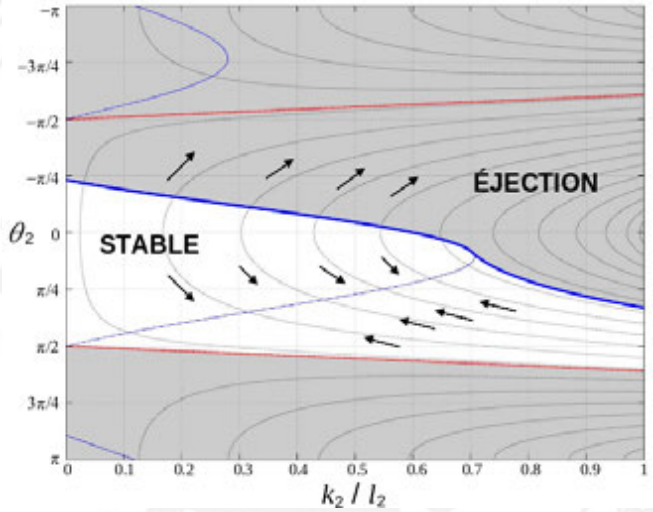

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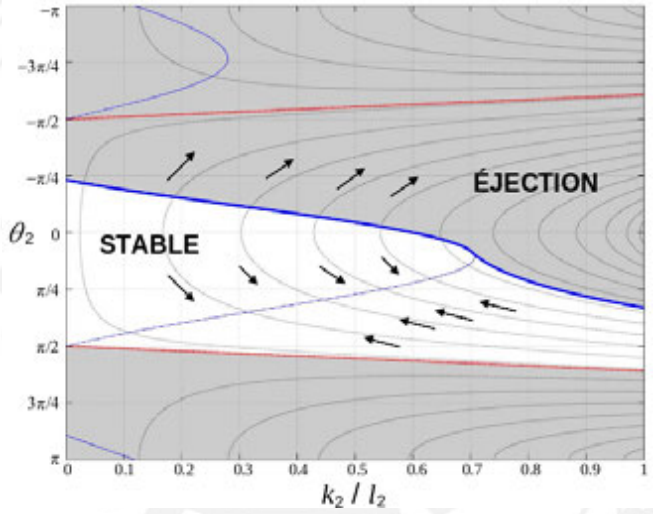

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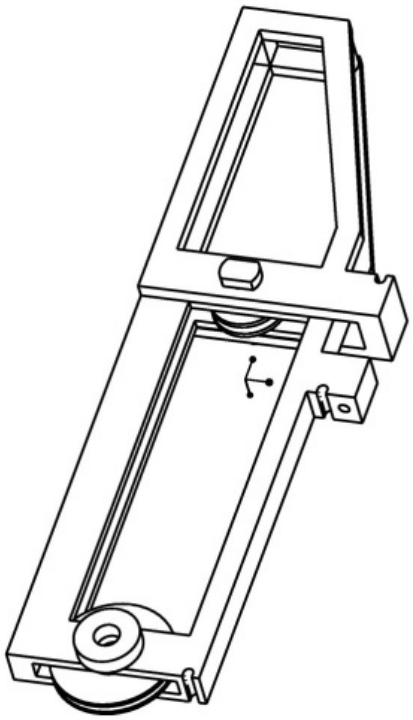
Synthesis of Underactuated Robotic Hands

- The development of these tools led to a better understanding of these mechanisms which itself led to their synthesis.
- First by playing with the Transmission matrix coefficients:



- If the transmission factor of the finger is sufficiently small (and negative), it is almost impossible to grasp an object [Birglen 2006].
- Synthesis of unstable grippers with applications...

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Skill Crane Machines

Children Toy

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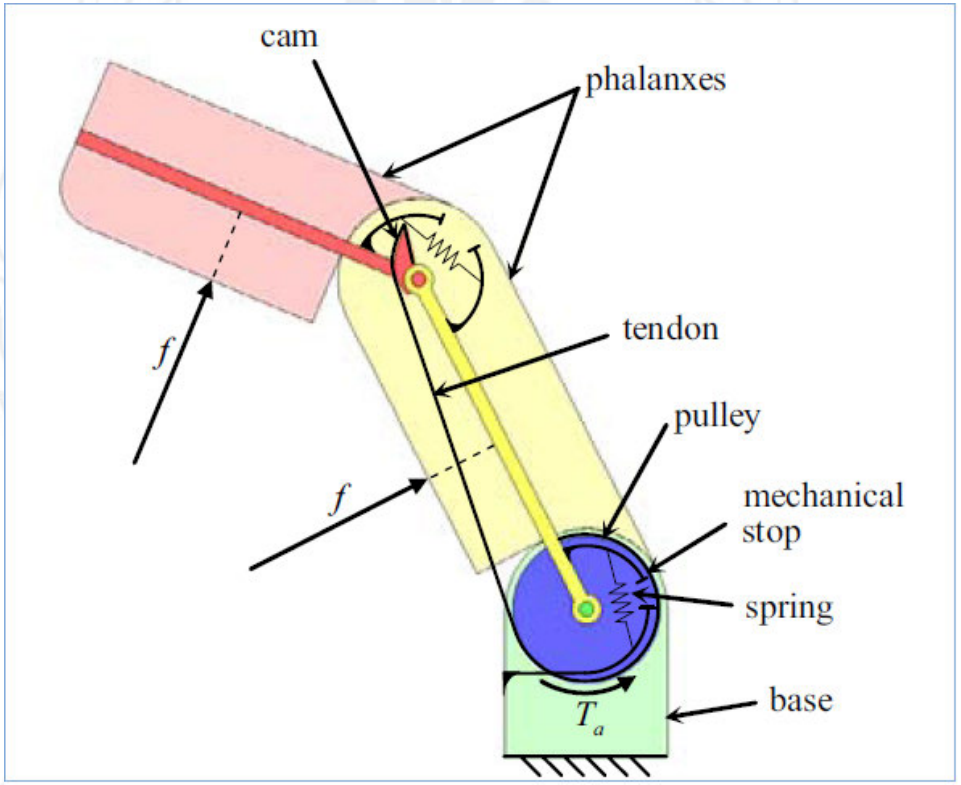
Synthesis of Underactuated Robotic Hands

- A much better and serious contribution was made using this technique by [Krut 2005] to generate a force-isotropic finger:



- And later by [Kragten et al. 2011] to maximize the range of graspable objects.

Synthesis of Underactuated Robotic Hands

- A broader challenge remained: the type synthesis of linkages for underactuated fingers.
- A dozen of architectures were known to work for two-phalanx fingers and only one for three-phalanx fingers.
- The underlying question to be answered was: *what linkages can be used to build underactuated fingers? How should it be connected?*
- The answer was deceivingly simple [Birglen 2009]: **almost all closed-loop linkage works!**
- Only three rules have to be respected:
  1. the transmission linkage should reach the distal phalanx;
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- Then, one has to place an actuator that affects all driven joints and as many passive elements as needed to statically constraint the linkage.

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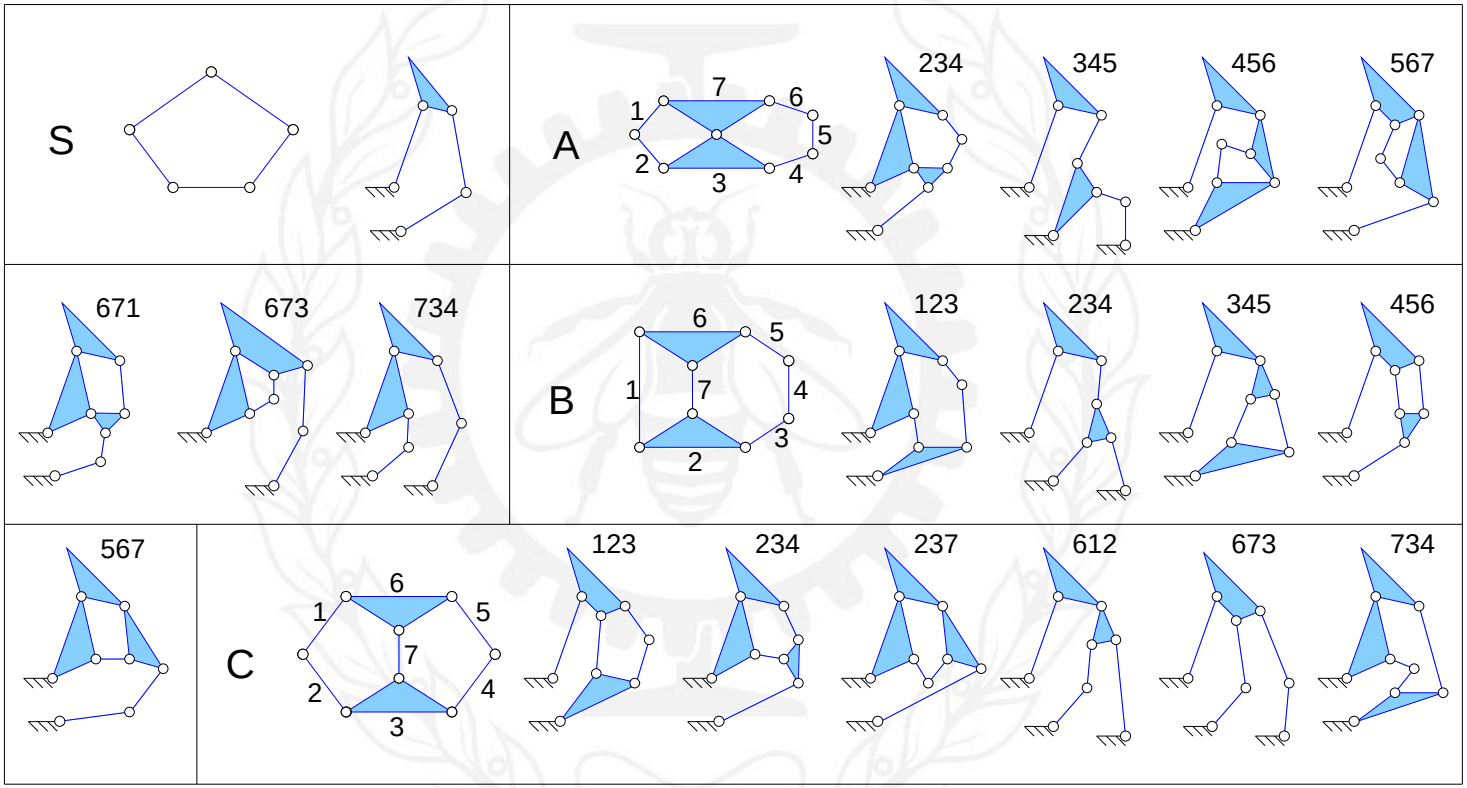

- Using only revolute and prismatic joints and designs with less than 8 links, there are up to 3,024 different valid fingers.
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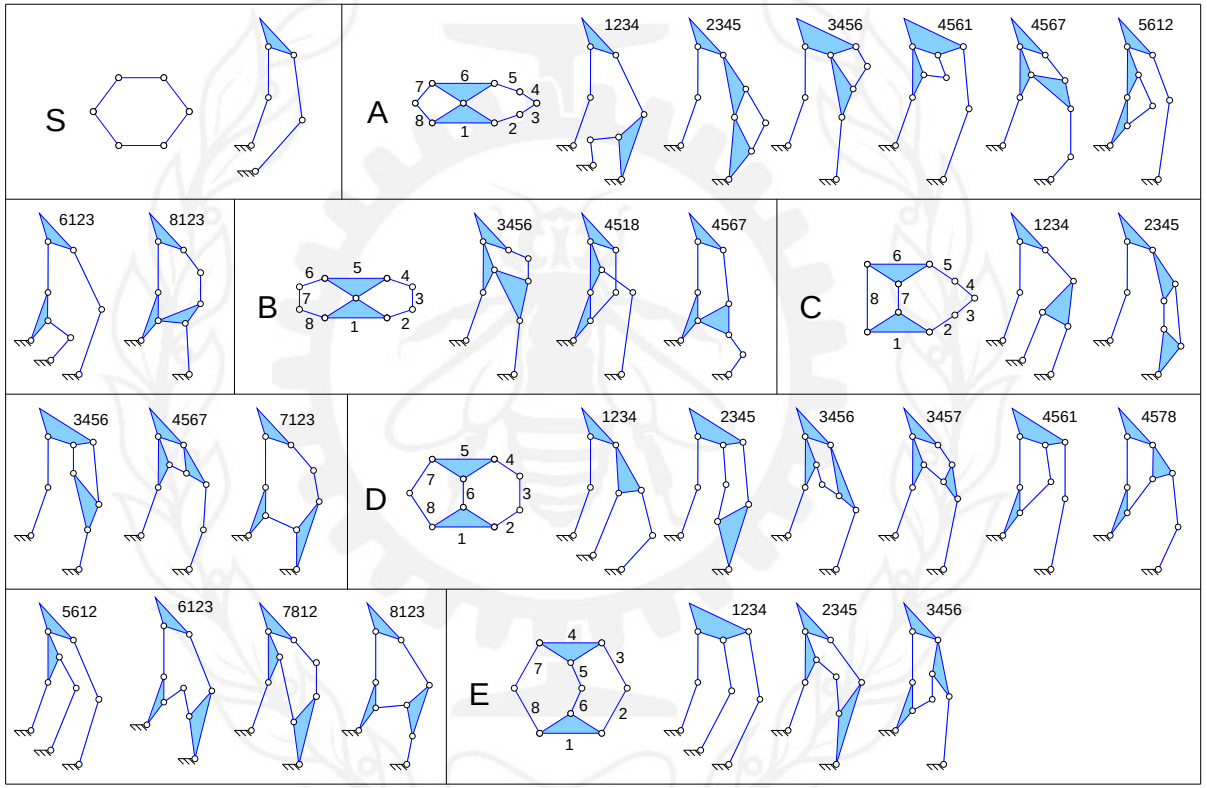

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Answer: ***I don't know!***

- We designed a software to help us explore this ocean of possibilities:
- Interestingly, some architectures do stand out but there doesn't seem to be a universal solution [Larouche and Birglen, 2012].

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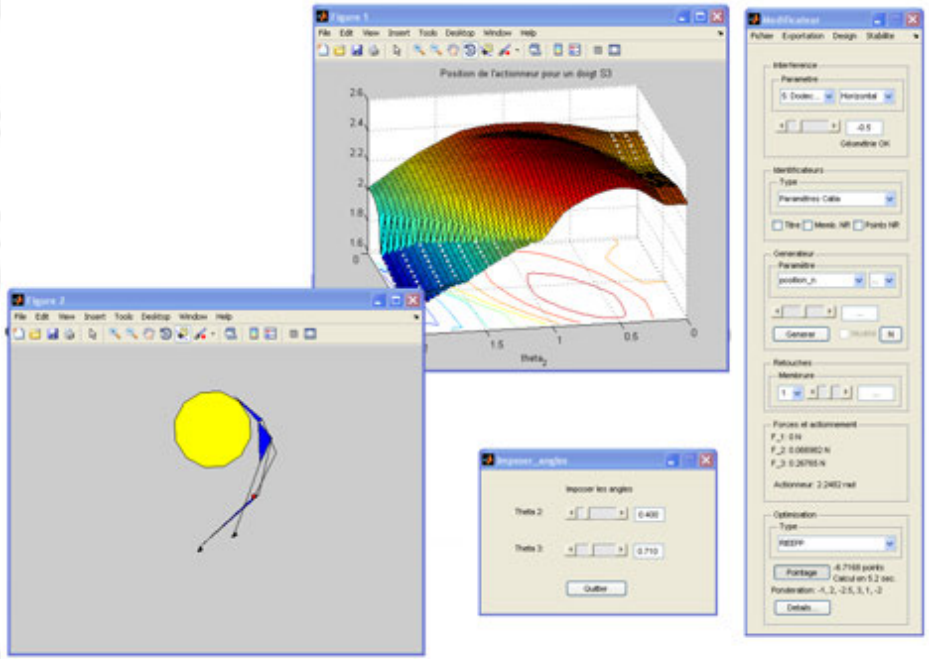

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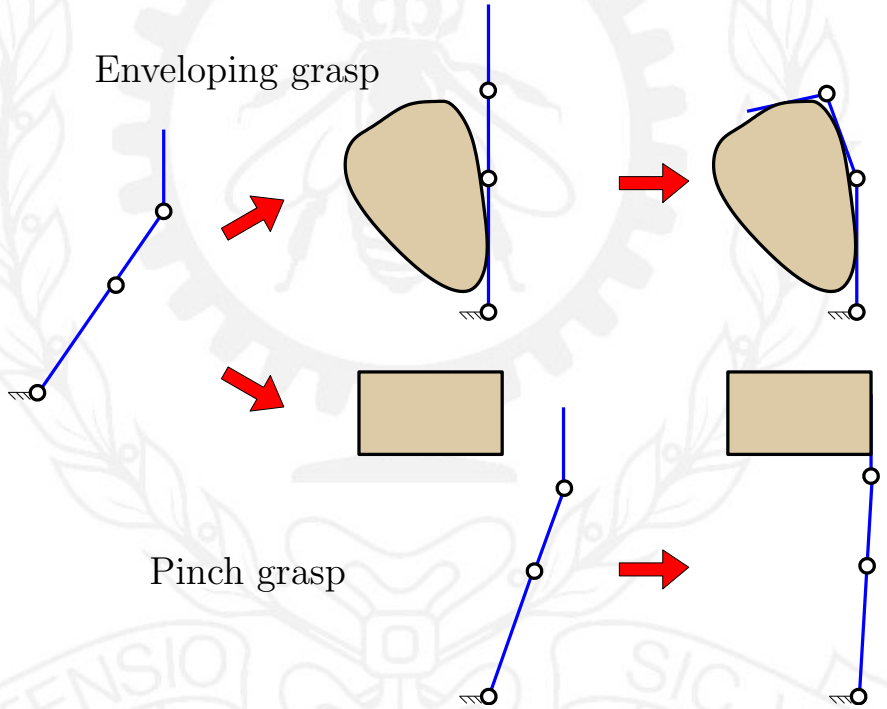
Synthesis of Underactuated Robotic Hands

- Careful selection of the geometric parameters of the finger and locations of actuation and passive elements allows for different kinematic preshaping [Birglen 2010] also referred to as synergies [Grioli et al. 2012].



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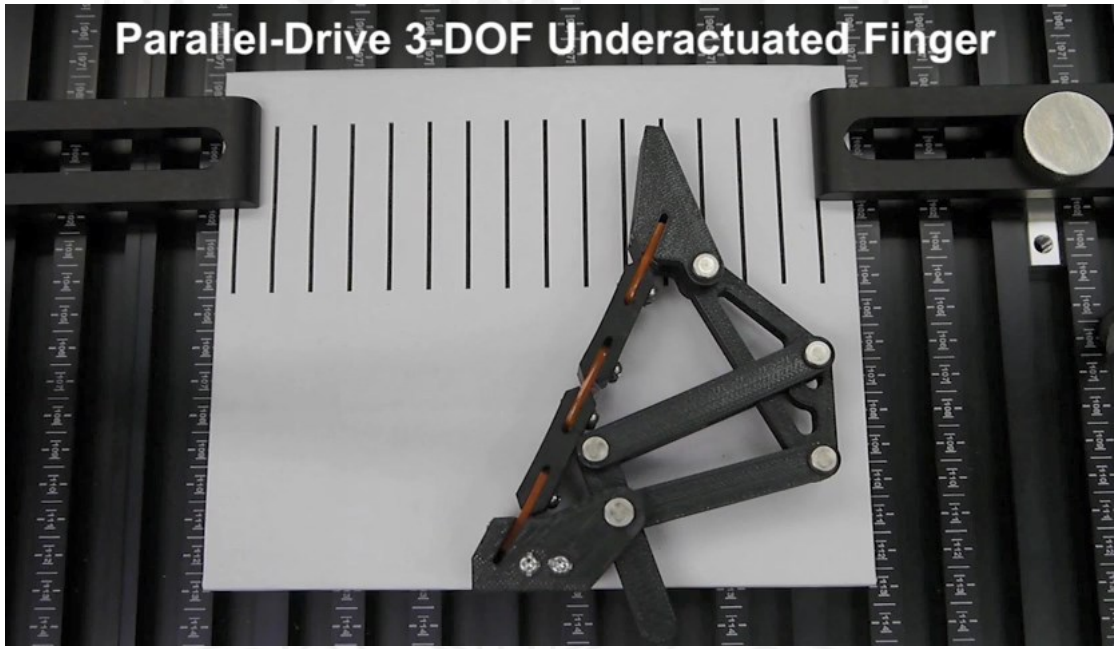

https://youtu.be/xMhQIqgqqCg

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Synthesis of Underactuated Robotic Hands

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  1.-2. can actually be circumvented [Birglen 2009]
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- Entirely passive finger, neither fully coupled nor fully adaptive motions: the *coupling* is adaptive.

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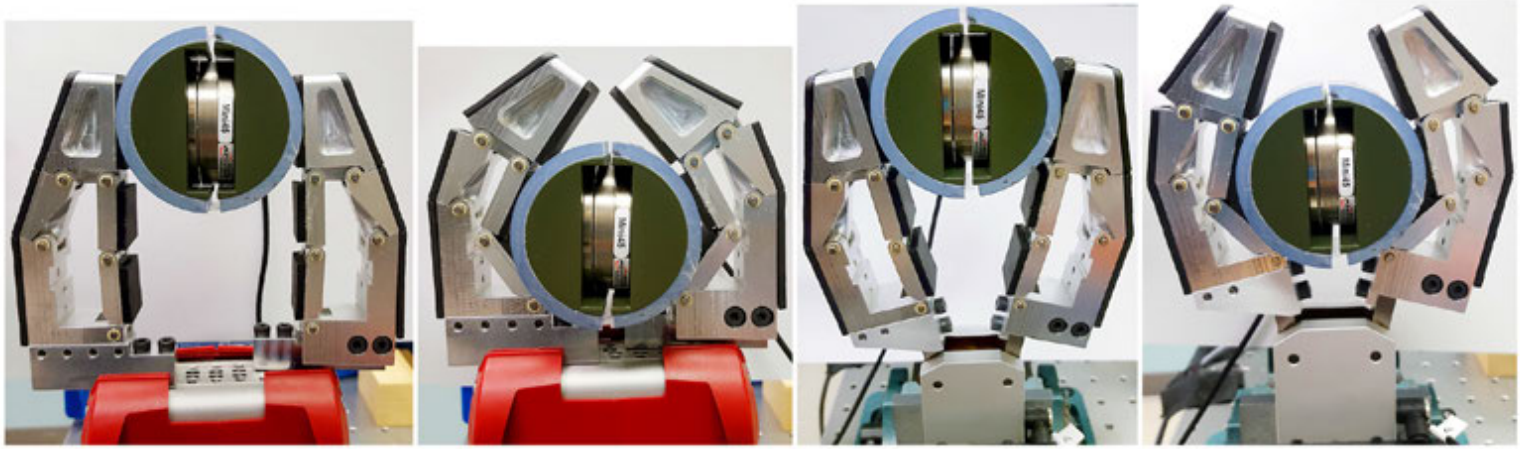

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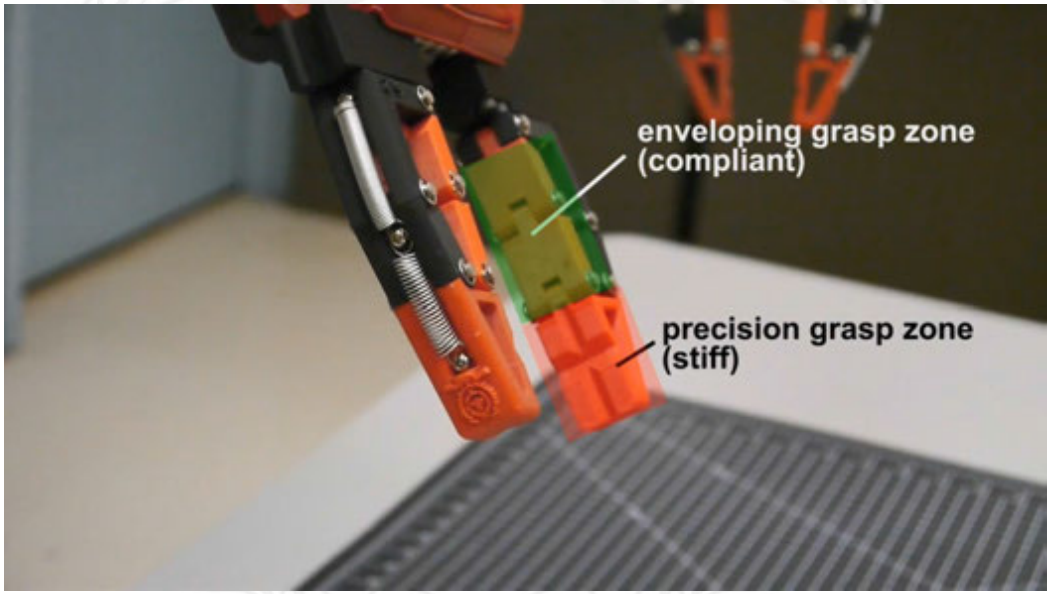

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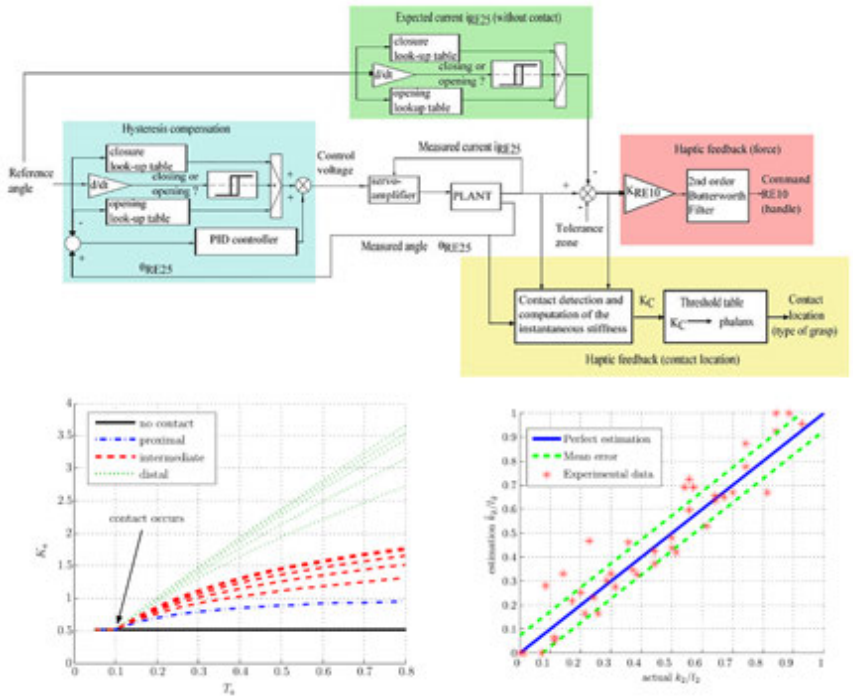
Control of Underactuated Robotic Hands

- The mechanical properties of these systems have also intringuing applications for control:

- *Tactile sensing without tactile sensors!*
- Using the variable stiffness created by the linkage to measure contact locations when placing local sensors is impossible or impractical.
- Virtual sensors providing haptic feedback [Belzile and Birglen 2014].

Control of Underactuated Robotic Hands

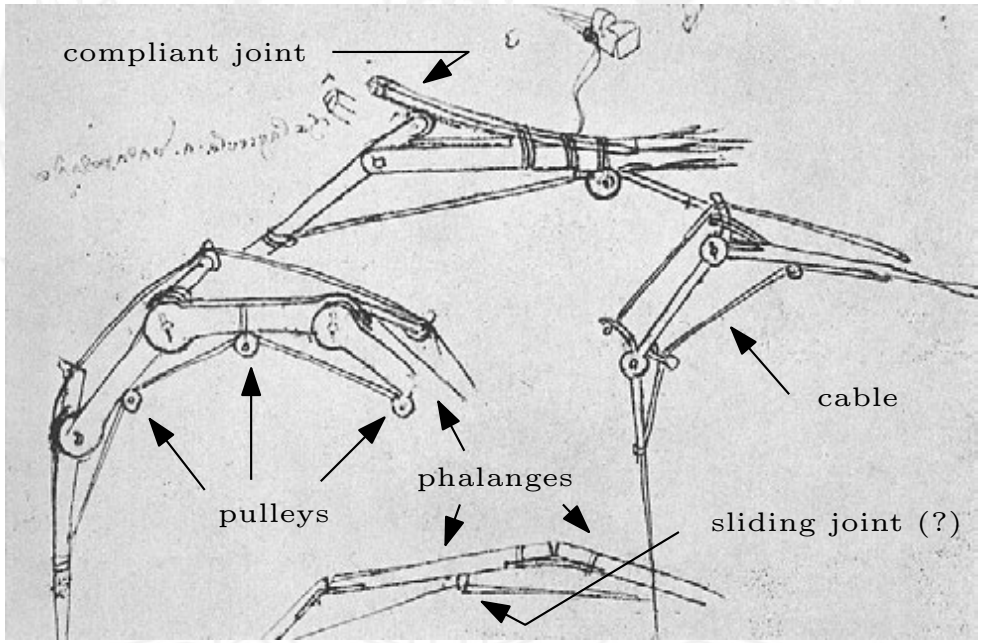
- The mechanical properties of these systems have also intringuing applications for control:



- *Tactile sensing without tactile sensors!*
- Using the variable stiffness created by the linkage to measure contact locations when placing local sensors is impossible or impractical.
- Virtual sensors providing haptic feedback [Belzile and Birglen 2014].

Beyond Underactuation in Grasping

- Underactuation in grasping is in my opinion only a subset of a much broader family of linkages which includes differentials.
- Marvellous mechanical devices were once created without any electronics, sensors or control schemes:

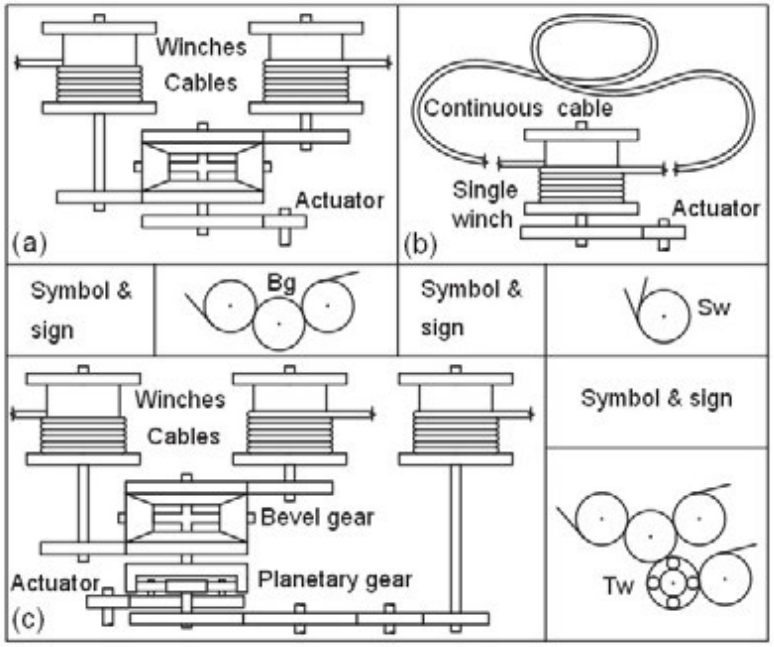


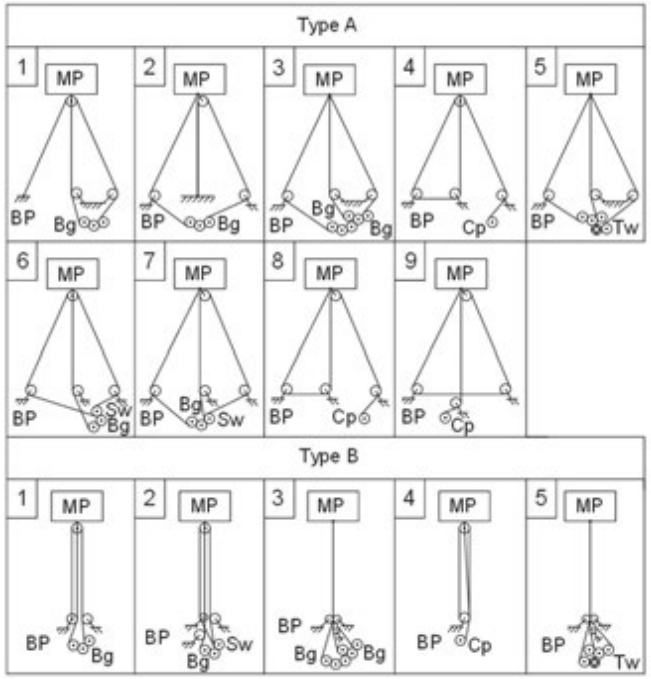
Da Vinci's Codex Atlanticus, ca. **1496**

- It hints that other applications are still yet possible, if one takes the time to investigate past knowledge (literature reviews are **essential**).

Beyond Underactuation in Grasping

- We can use the same idea (differential mech.) to drive cable robots:





- The synthesis and kinematics are challenging [Khakpour and Birglen 2014] but worth investigating.
- One prototype has been built [Fedorov and Birglen 2018] and another is coming soon *(crossing fingers really hard)*.
- Hold on is this thing still underactuated? Well..... not really to be honest....

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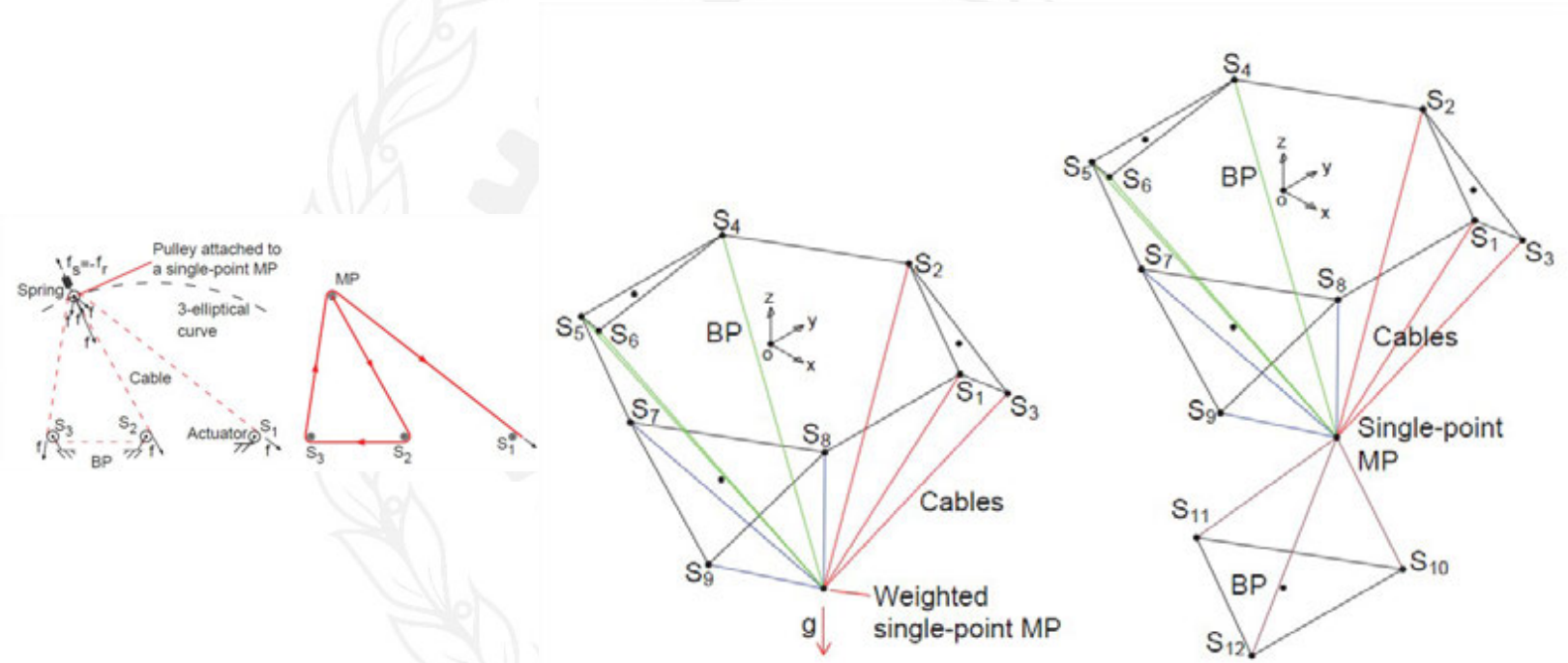

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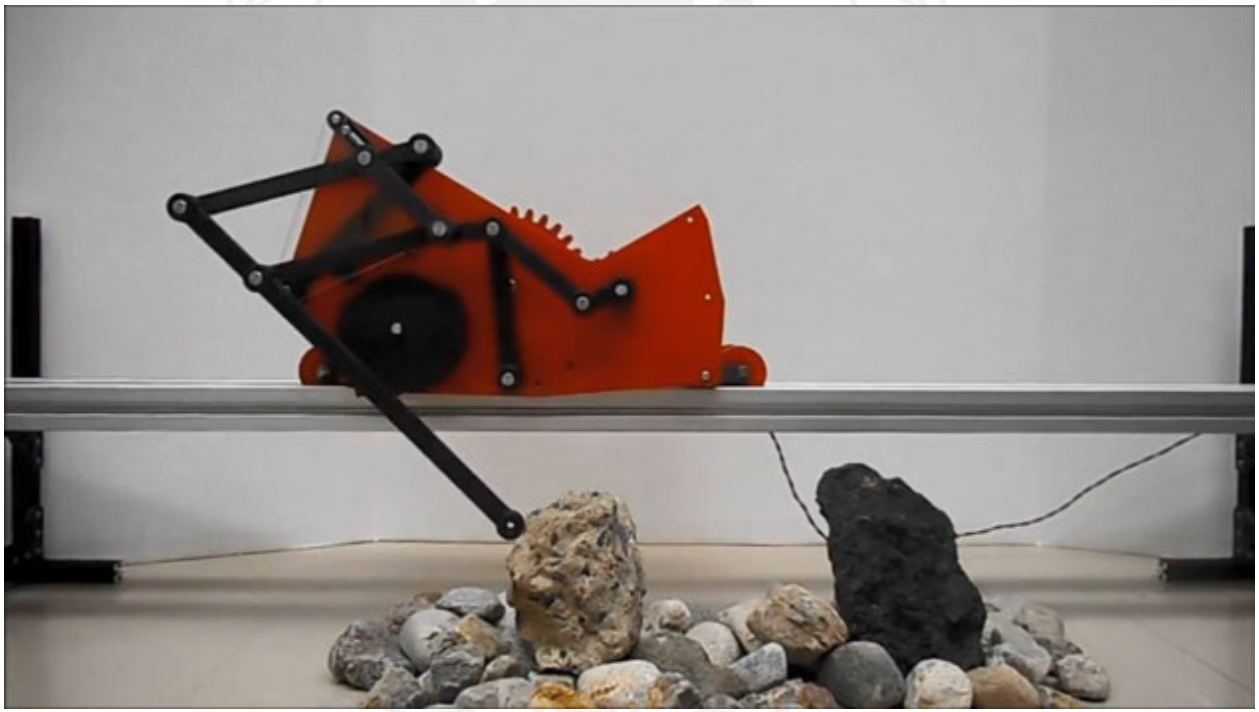
- We also worked on a walking robot application and redesigned a leg from scratch. Not using the same linkage as in the hands but applying the same design principles [Fedorov and Birglen 2017]:



- The leg mechanically reacts to a collision and generates a trajectory overcoming the obstacle, mimicking a *mechanical reflex*.
- and after all this... we're back to "underactuated" walking!

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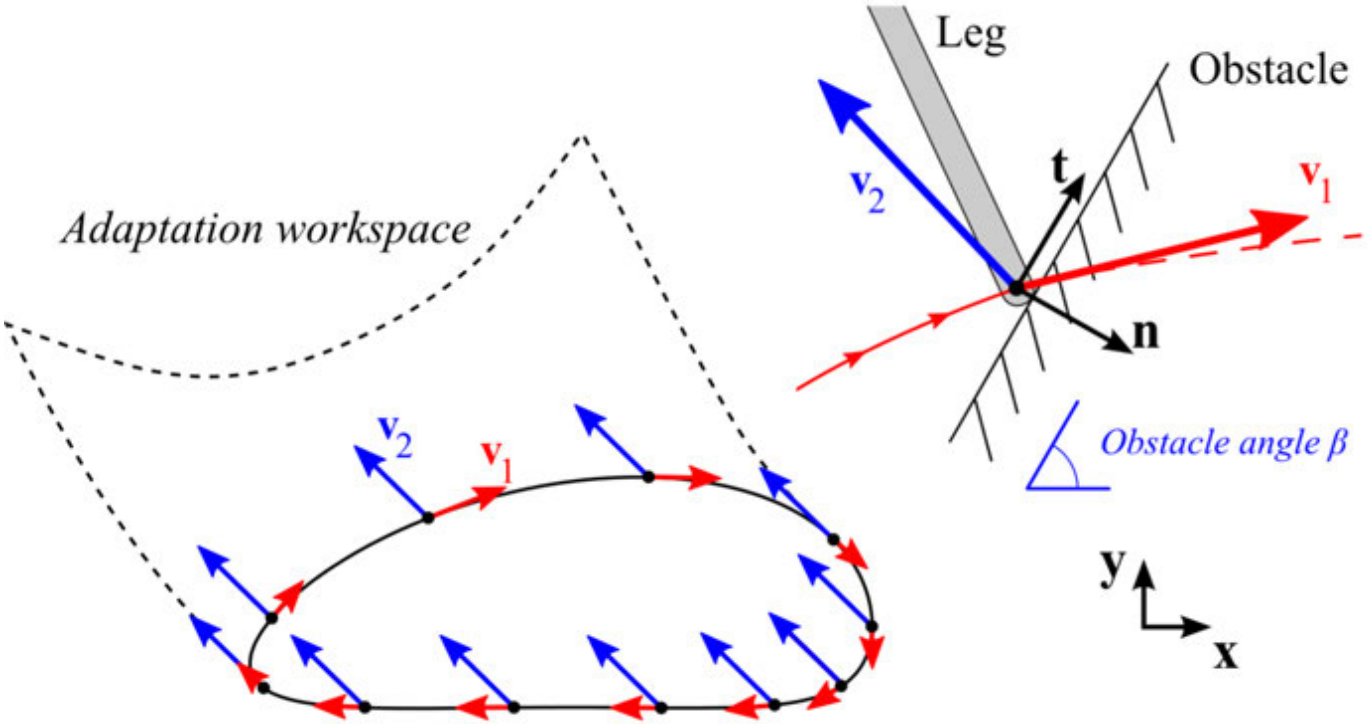

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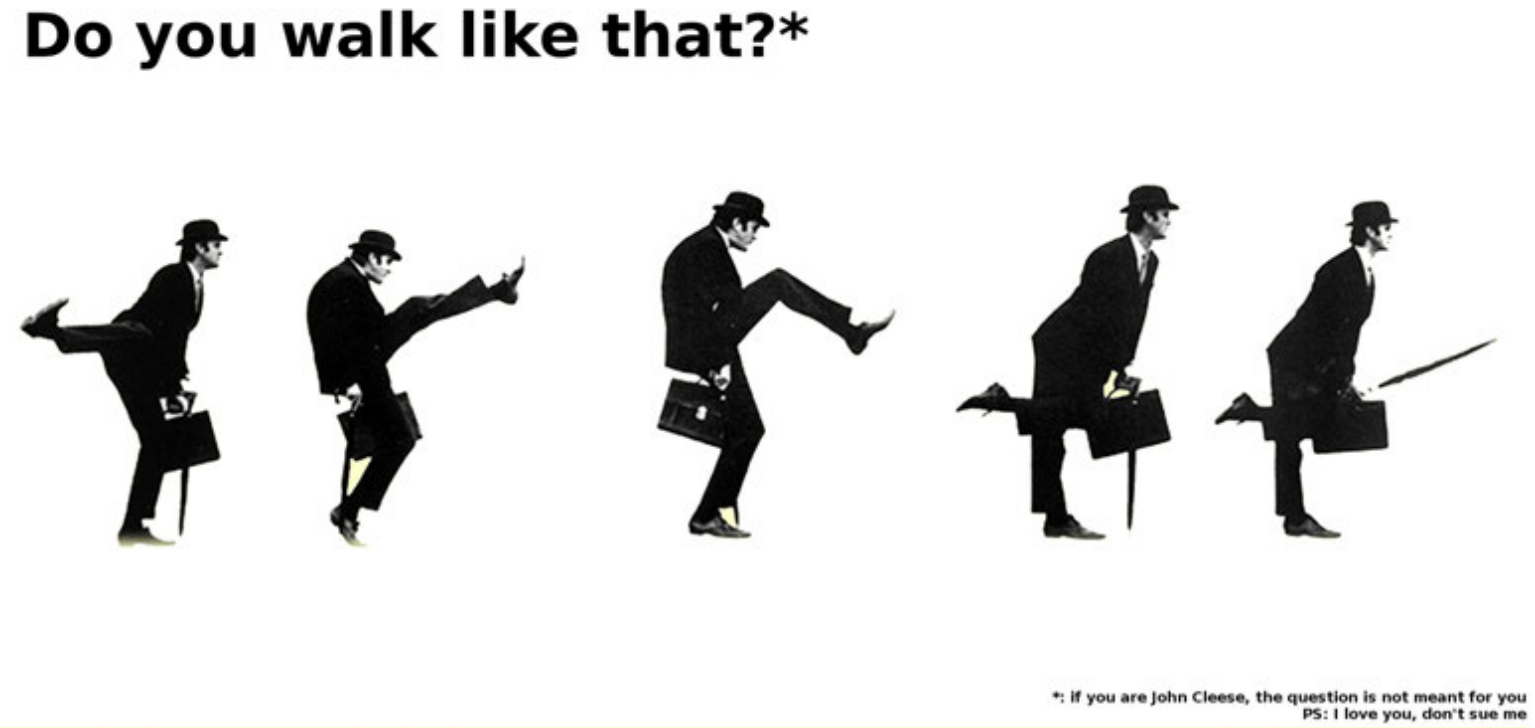

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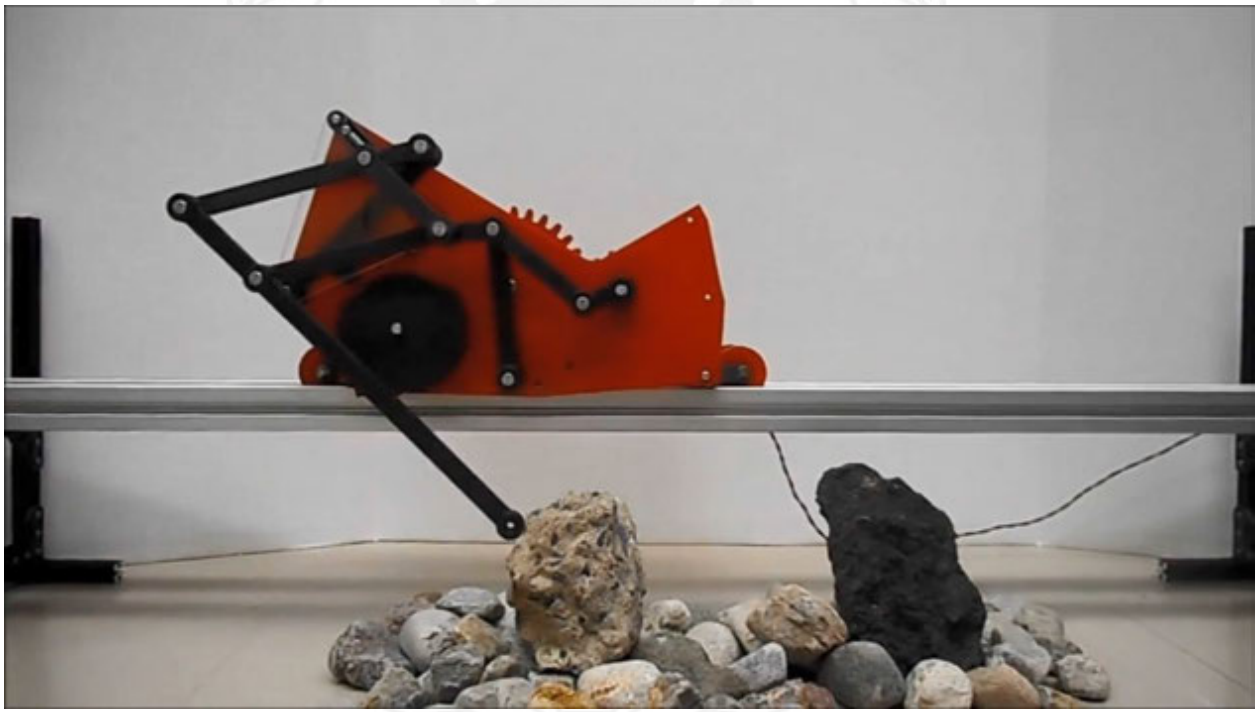

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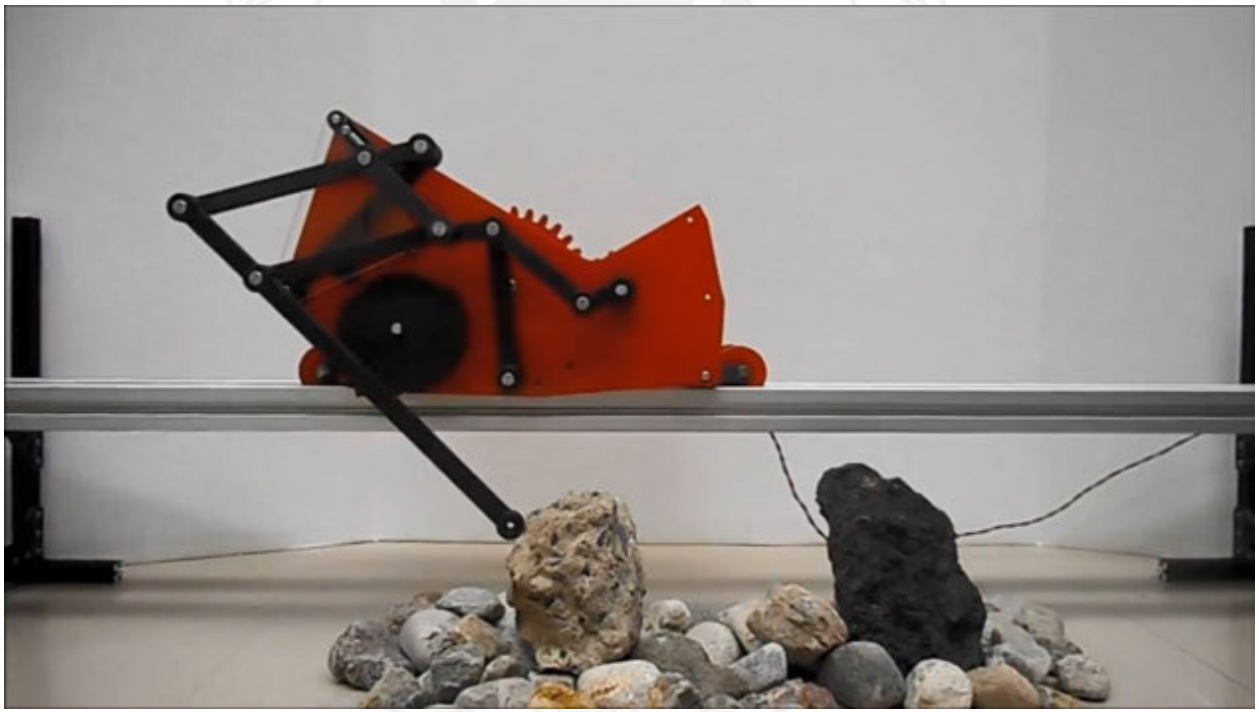

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Conclusions

- Underactuation can have many meanings, many practical implementations, many theoretical foundations.
- To me it is a means of getting the maximum out of a minimal number of actuators by combining them with mechanisms.
- To avoid confusion with well-established terminology *(and people with large H-index)* I often refer to these devices as self-adaptive or differential.
- They are a way to embed some "intelligence" in the mechanical design of machines.
- Why combine smart electronics and advanced control or even A.I. to dumb mechanics?
- I have one message I'm passionate about and would like to share:

if we want to create the best mechatronic and robotic devices possible we must combine the best of mechanical science to the best of electronics and control.

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- Keeping in touch:

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http://twitter.com/LionelBirglen

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Reference List I

Forewords: since the objective of this seminar is essentially to present my work, this reference list is heavily biased toward citing my own papers. This is by no means representative of the field and many related important works from other people exist and should be consulted.

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