POTENTIAL MERITS FOR SPACE ROBOTICS FROM NOVEL SOFT ROBOTICS ACTUATION CONCEPTS

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European Research Council

Overview

"The main innovation is to propose two new categories of actuators: the <u>Series-Parallel Elastic Actuators (SPEA)</u> and the <u>Self Healing Actuators</u>"

- Traditional stiff actuators
- Compliant actuators: R&MM group experience
- Parallel Elastic Actuation
- Series-Parallel Elastic Actuation (SPEA)
- Innovative materials: Self-Healing Actuators

Stiff actuation

Stiff actuation
Excellent trajectory tracking

Suitable for static and known environments (often industrial settings)

Unsuitable for dynamic unknown environments (including humans)

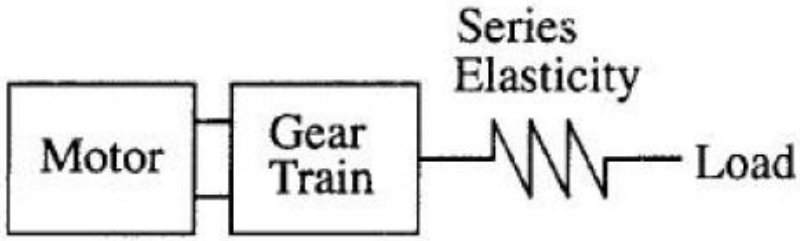
Stiff actuation

- No energy storage
  - (also recuperation in batteries in robotics not efficient)
- No shock absorption
  - Damage on harmonic drives
- Unsafe
  - Kept away from humans

Series Elastic Actuation
Variable Stiffness Actuation

Complaint actuators (SEA & VSA)

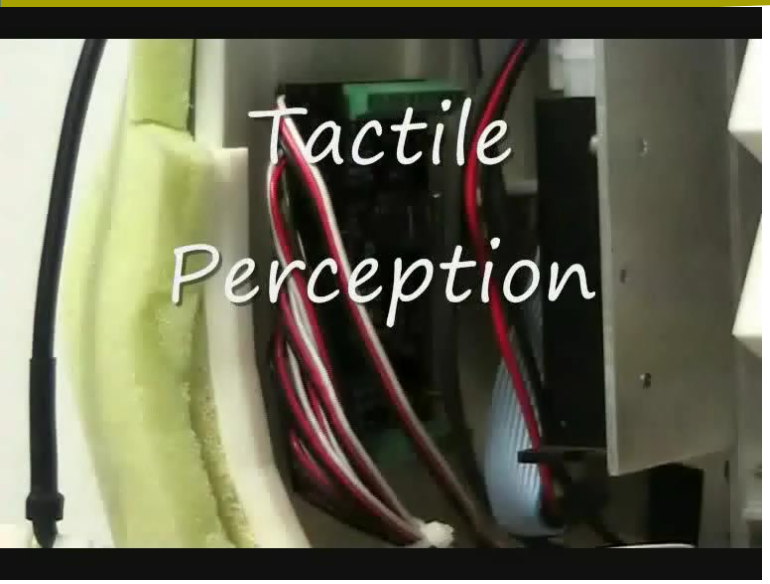
SEA
Pratt & Williamson
1995 - MIT



- Robustness – finite impedance
- Safety – human-robot interaction
- Reduce peak power & Increased energy efficiency
  - Power burst
  - Cyclic motions: store and release energy

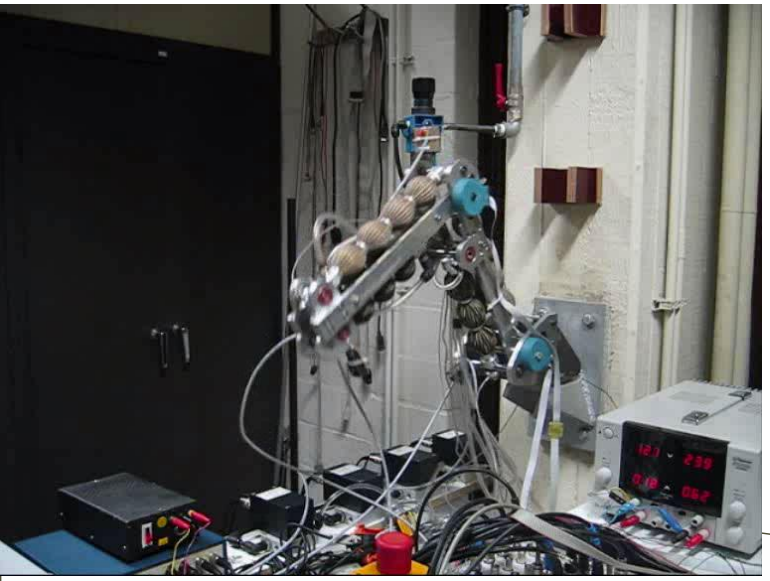
- VSA: Variable stiffness actuator
  - Tune natural frequency

Compliant Actuation



Probo social robot

Baxter



Soft Arm

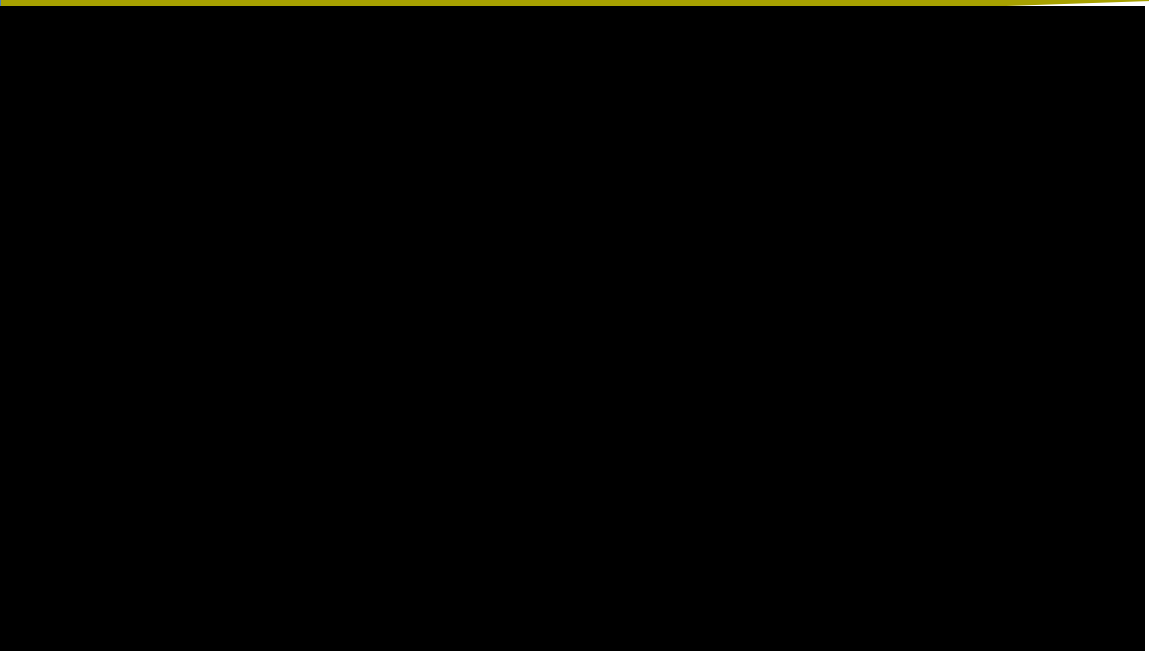
Compliant Actuation

Mirad, VUB

Altacro, VUB

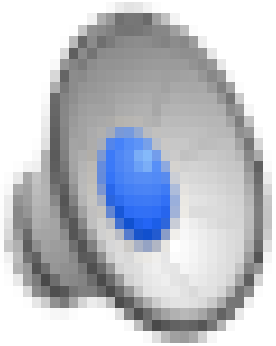
Vrije
Universiteit
Brussel

Compliant actuation

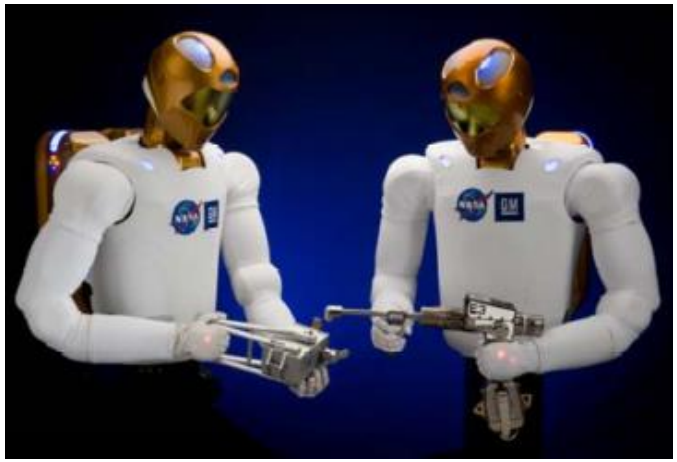


Cyberlegs, VUB

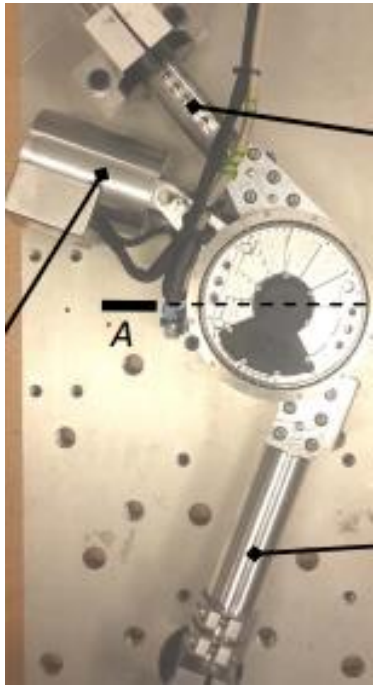
AMPfoot, VUB



Compliant Actuation



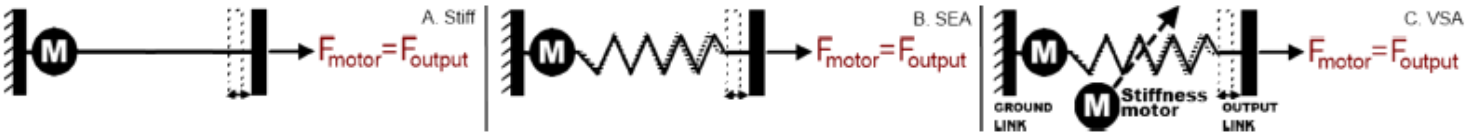
Robonaut 2: Diftler et al., 2011



Gancet et al., ASTRA 2011

Remaining problems

- All torque goes through motor



- When position/equilibrium position does not change
  - Mechanical power = 0
  - Electrical power != 0 (low energy efficiency)
- Size electric motor/gearbox is proportional to required torque, so still heavy motors.
- Copper losses in electric motor proportional to (torque ≈ current)^2.

Challenge

- Compliant actuators are able to reduce power requirements, but not torque
- Actuators are not yet able to
  - Work energy efficient
  - Provide enough torque
  - Different applications impossible
- Challenge is to improve torque/mass ratio and improve energy efficiency

Observation

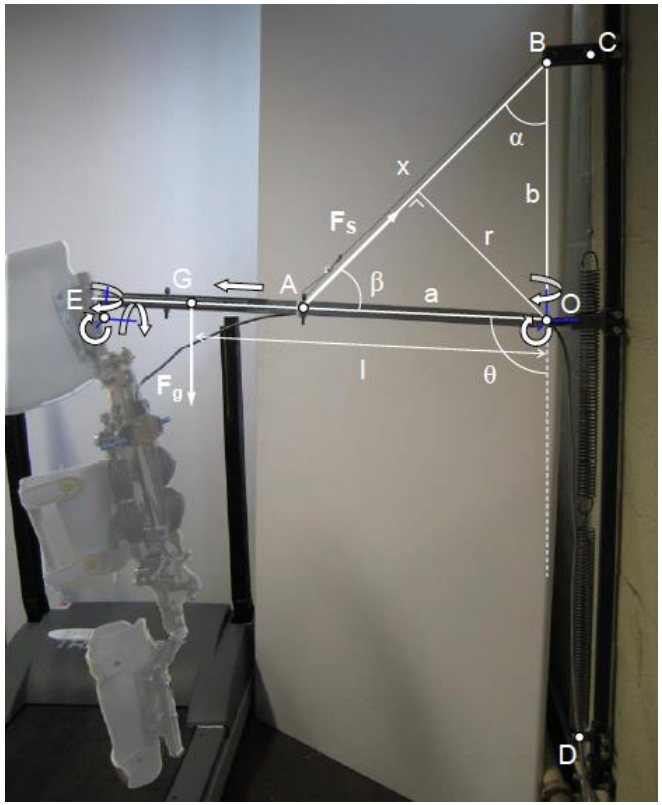
- Mammalian skeletal muscle
  - Average specific power density: 0.041W/g
  - Max efficiency: 20%

- Electric motor
  - Average specific power density: 0.5W/g
  - Max efficiency: 80%

Electric motor is not the problem.
The way transmissions and springs are used need drastic improvement, since all torques on the joint are maintained by the motor.

Parallel elastic actuation

Use of parallel springs

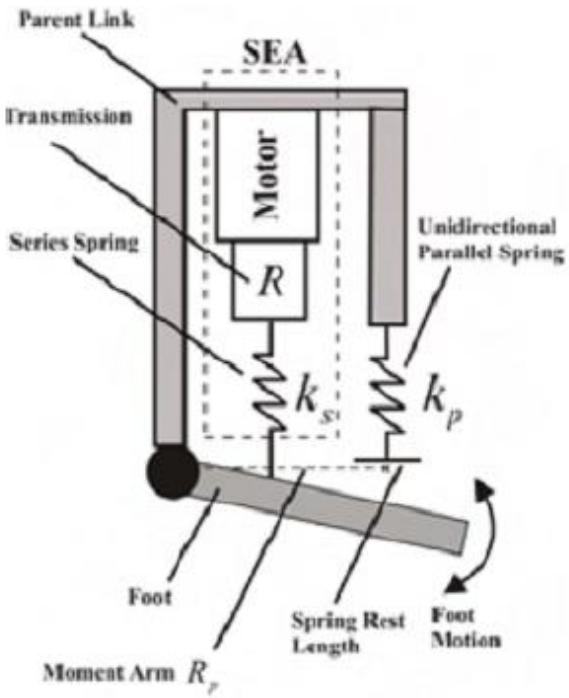


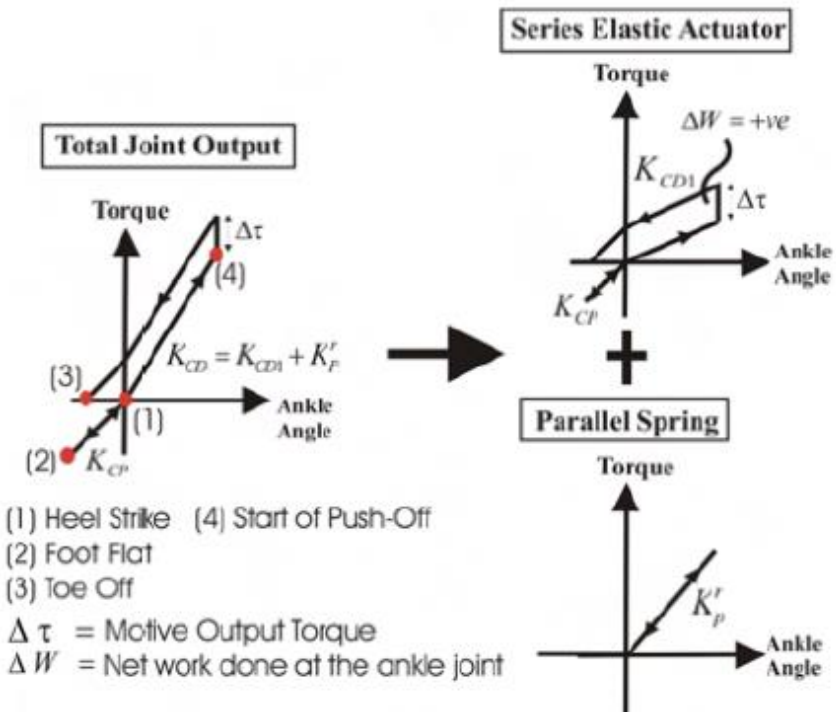
Fixed in the design phase

(for one load, or one torque profile)

Use of parallel springs

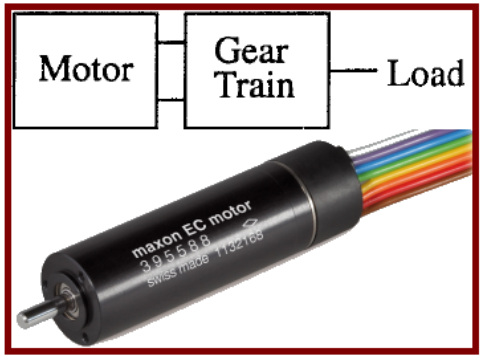

Source: H. Herr

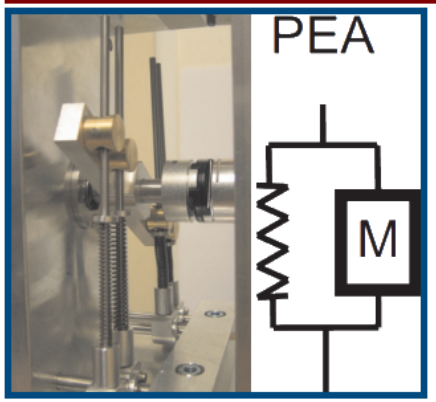




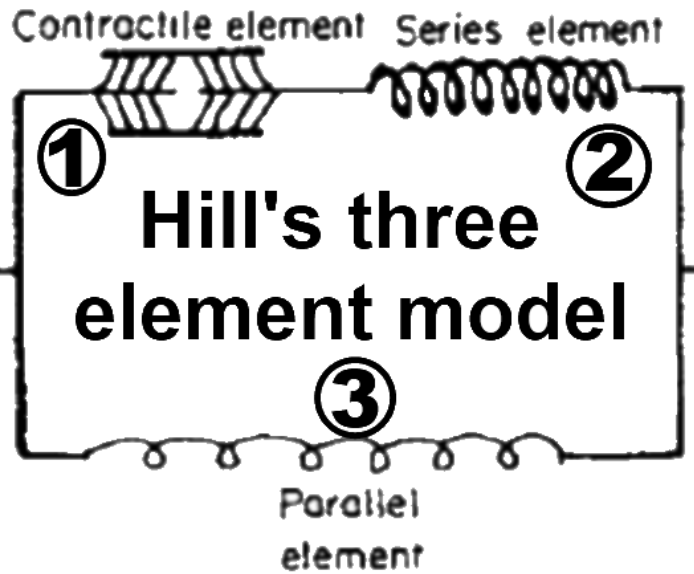
Biological muscle model

1 = STIFF



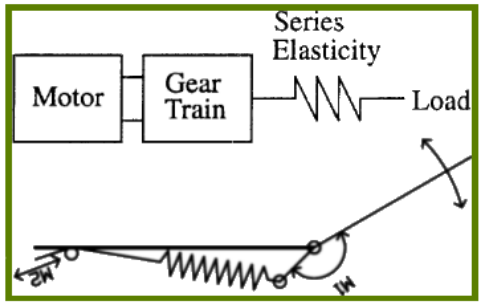


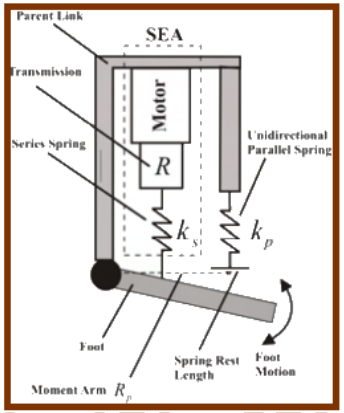
1+3 = PEA



A

1+2 = SEA

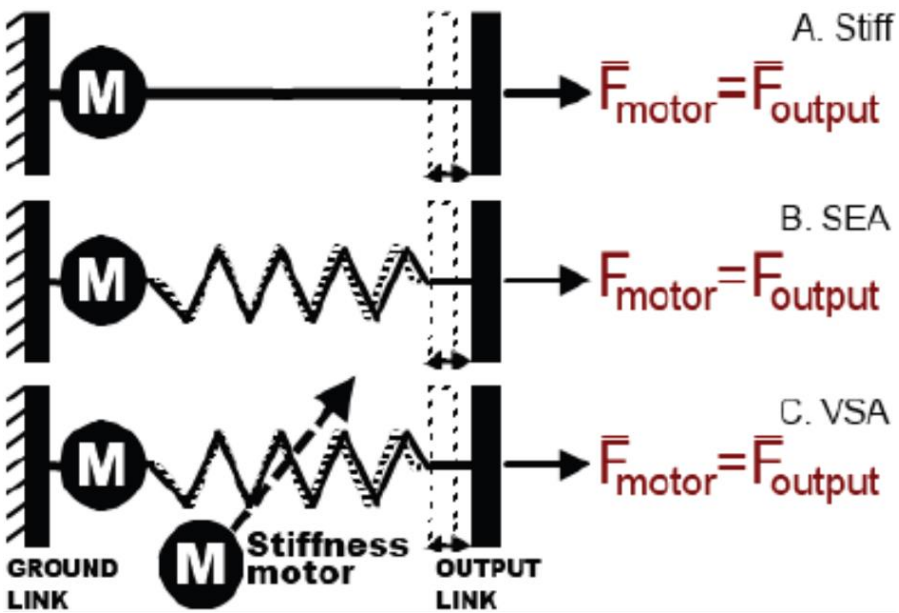


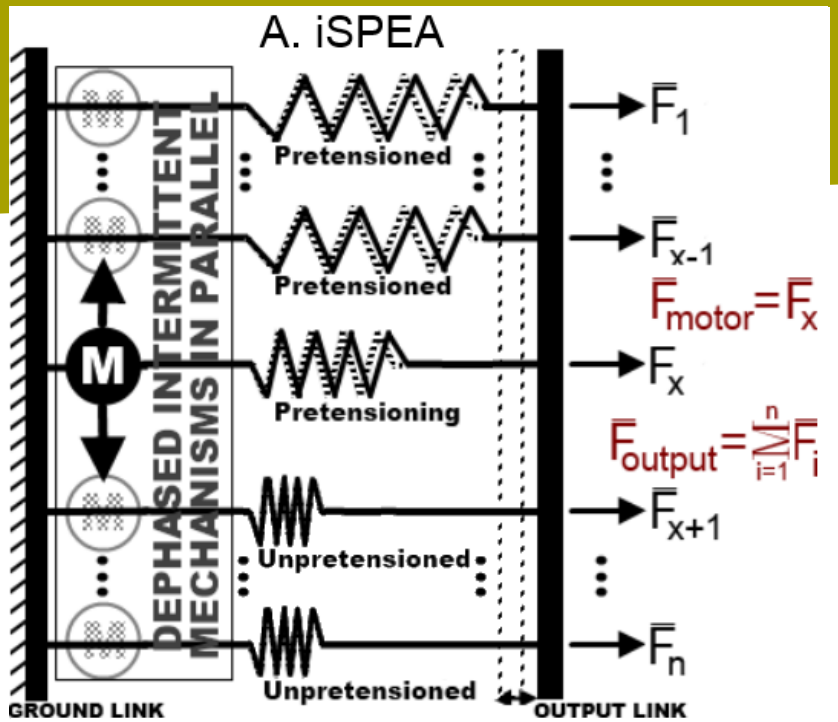


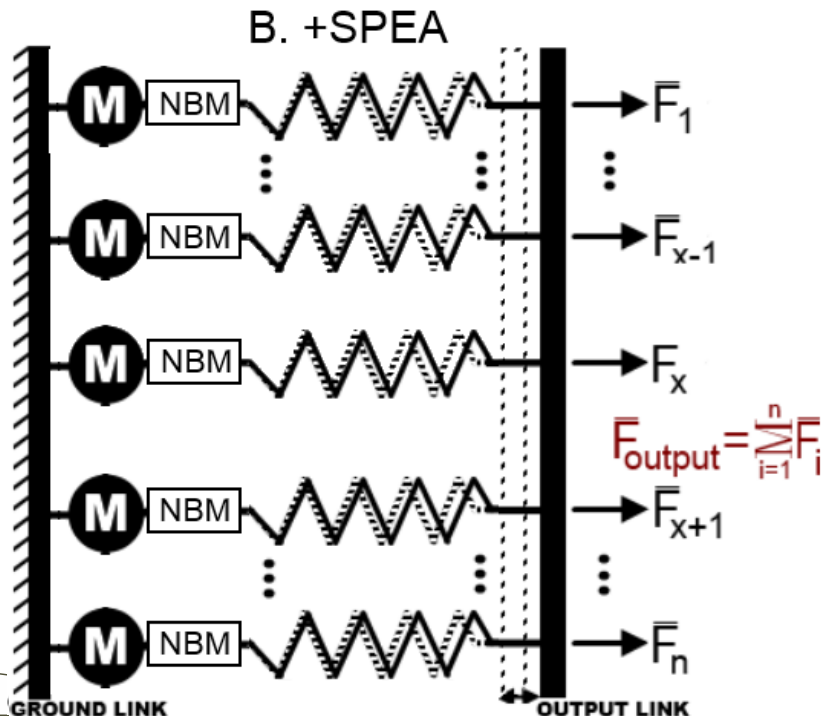
1+2+3 = SEA + PEA

Series-parallel elastic actuation

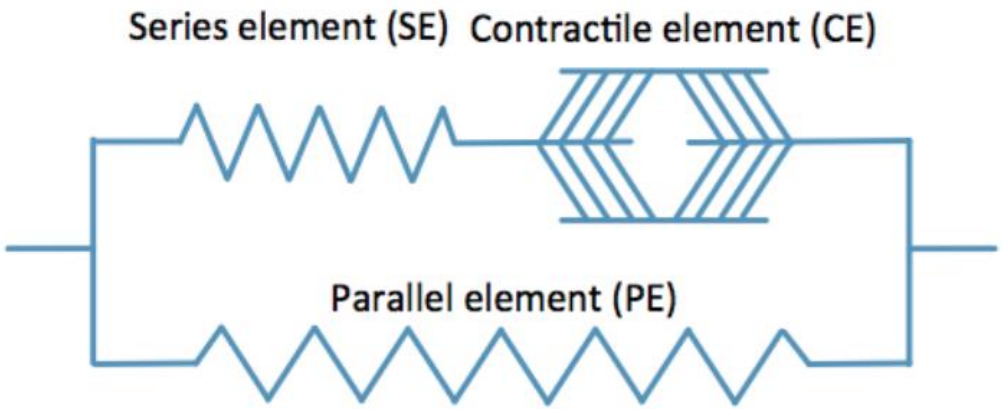
Problem stiff and VSA

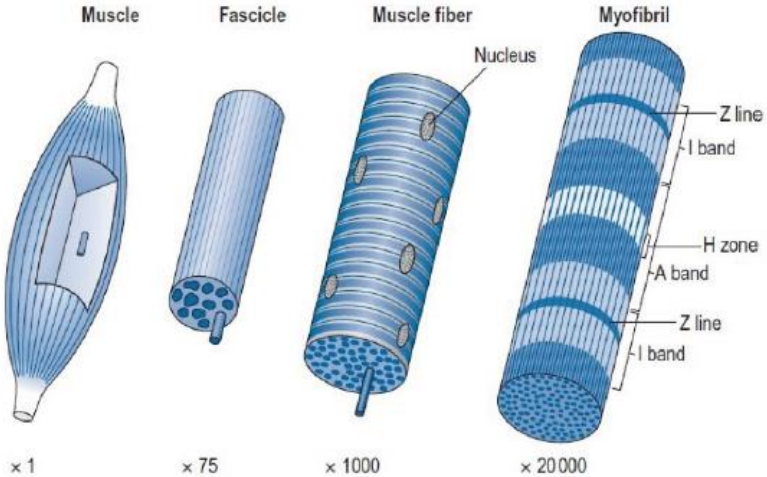






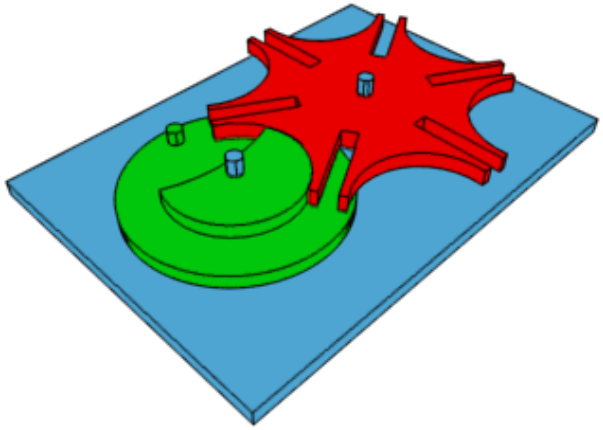
Biological evidence



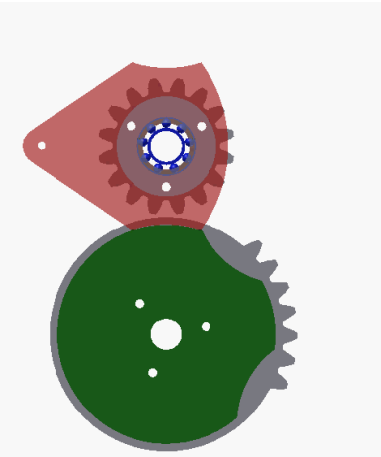


SPEA Proof of Concept

Challenge is the intermittent motion and locking



Geneva mechanism



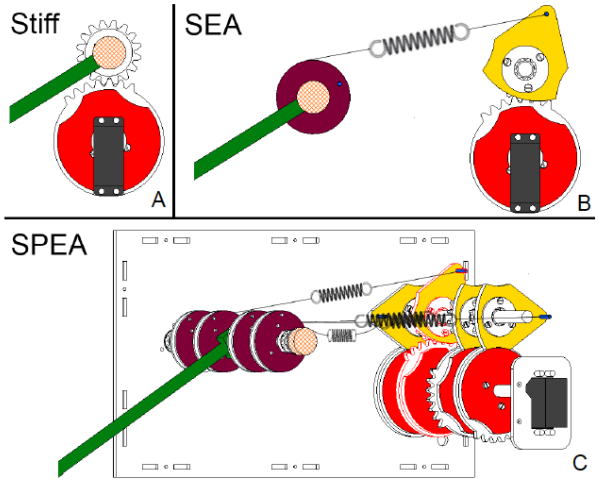
Mutilated gears

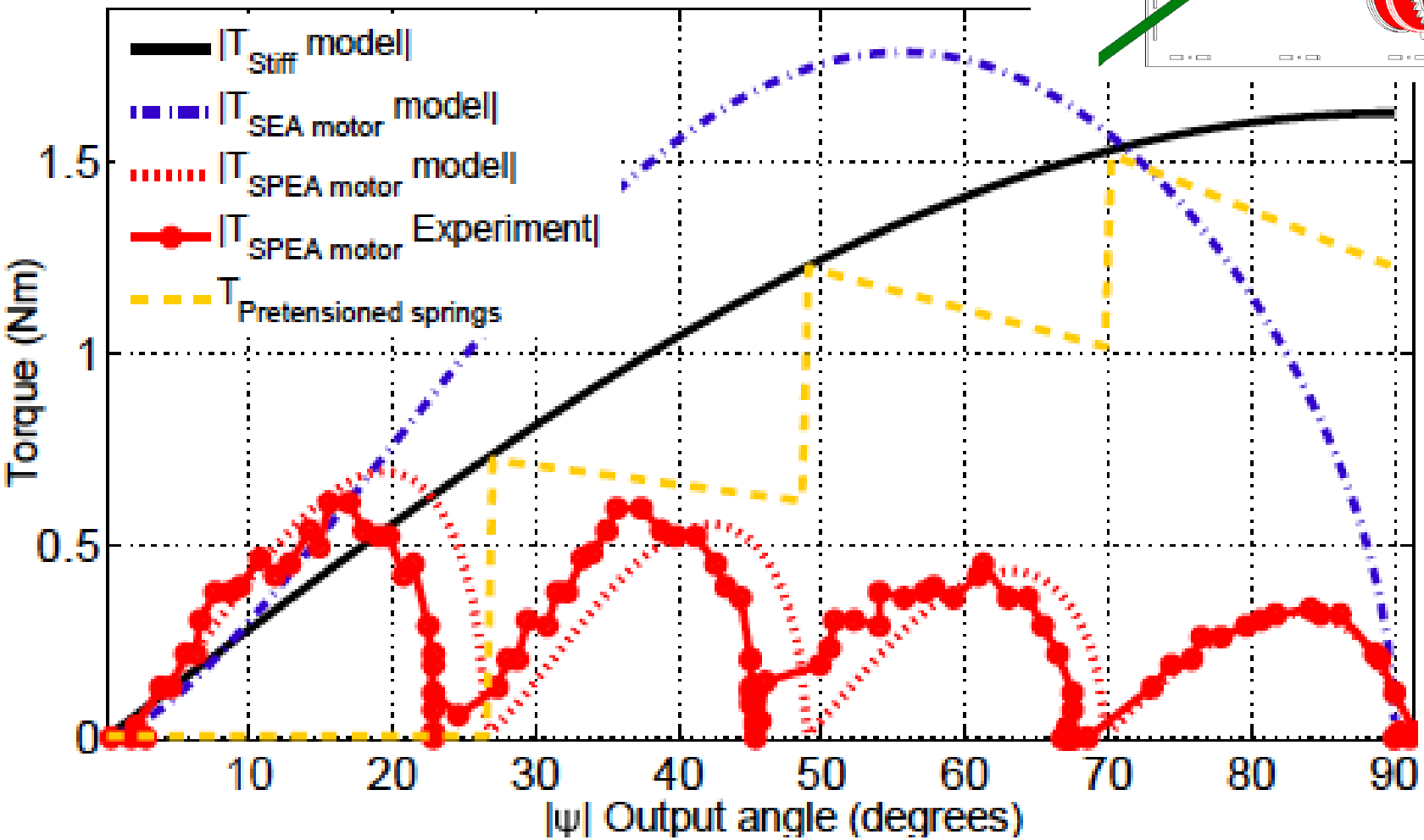
Lock Your Robot

A Review of Locking Devices in Robotics

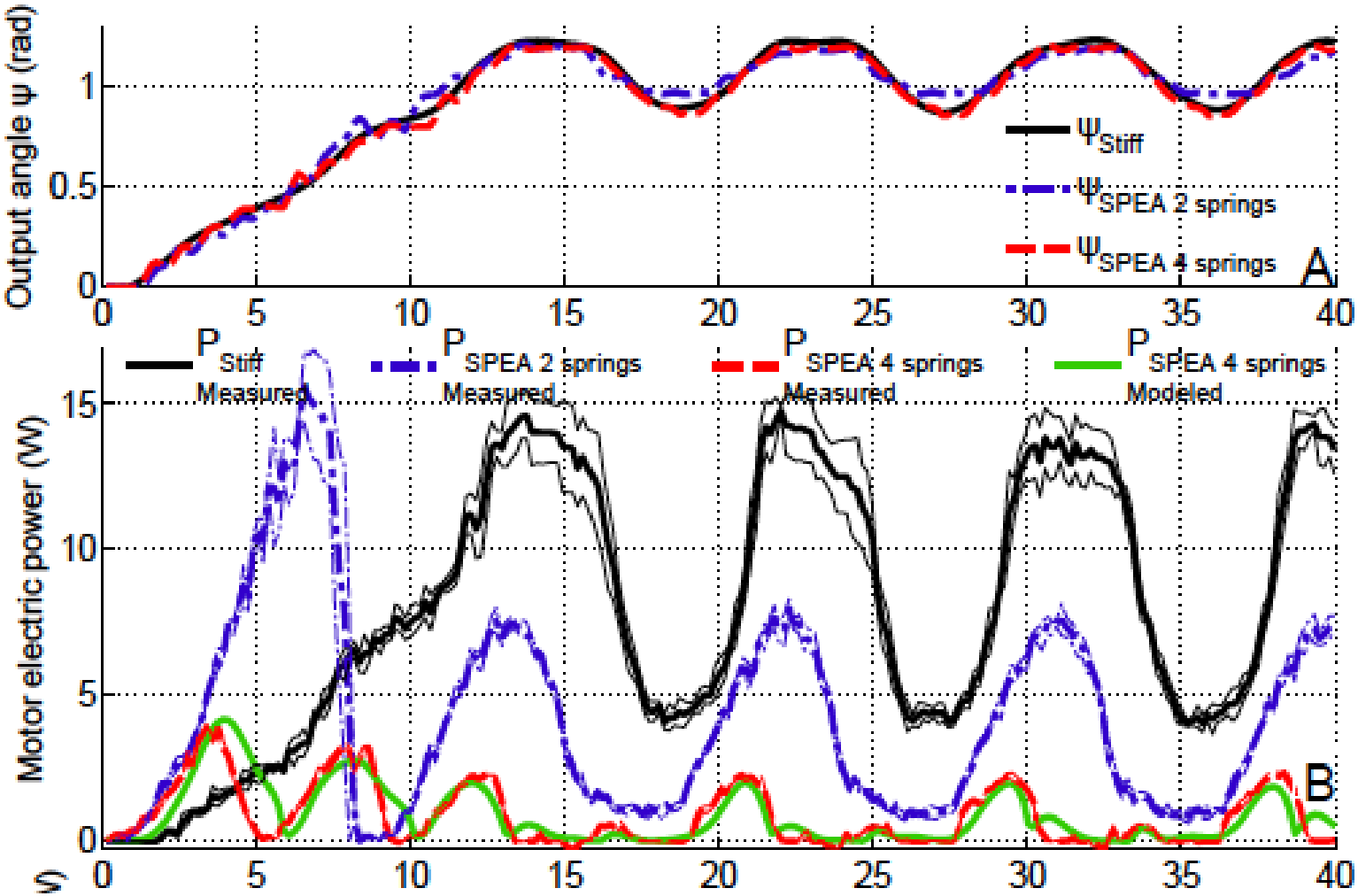
By Michiel Plooij, Glenn Mathijssen, Pierre Cherelle, Dirk Lefeber, and Bram Vanderborght

SPEA1: torque





SPEA1: power



$$P_{output} = T_{output} * v = (T_{springs} + T_{motor}) * v$$

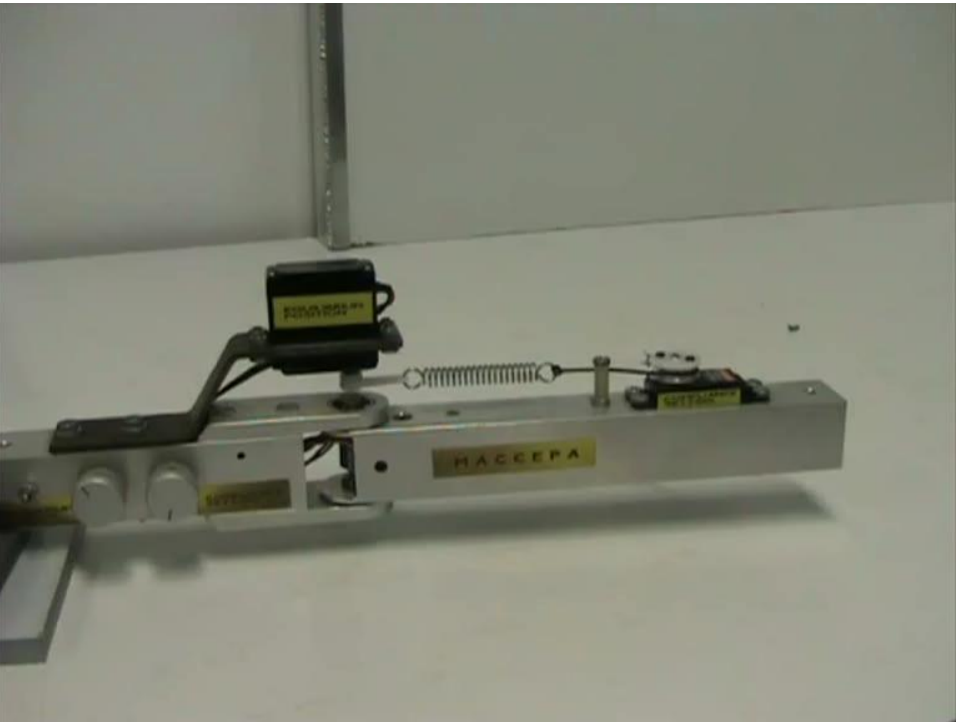
SPEA1 conclusion

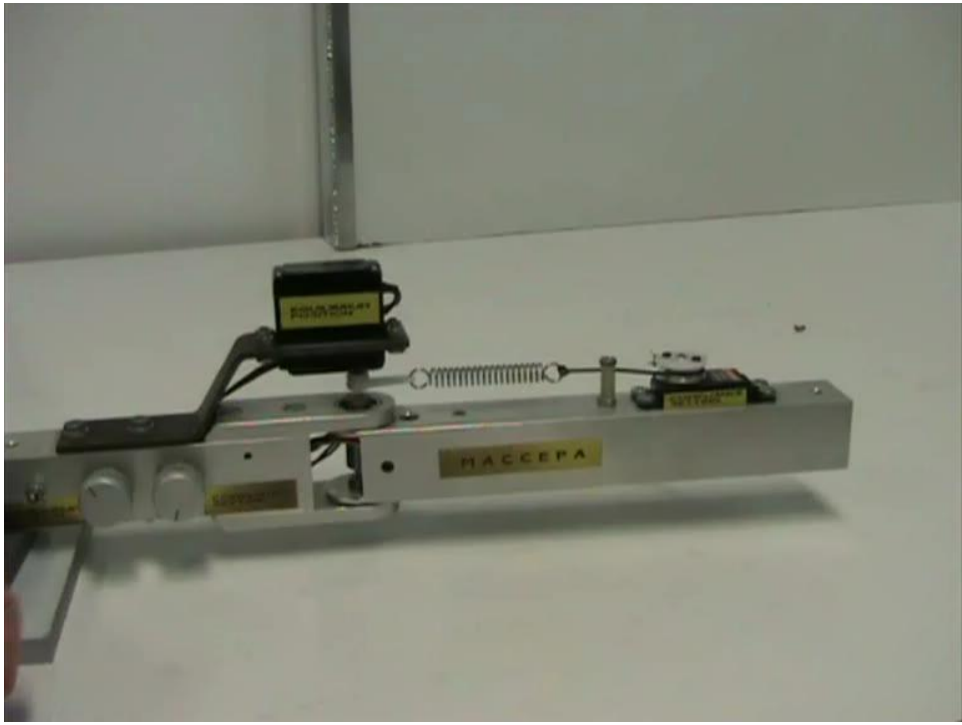
- Feasibility shown for reduce torque requirements electric motor and energy efficiency
- Kept compliance

- Points to improve
  - Increased mechanical complexity
  - Unidirectional torque
  - No variable stiffness

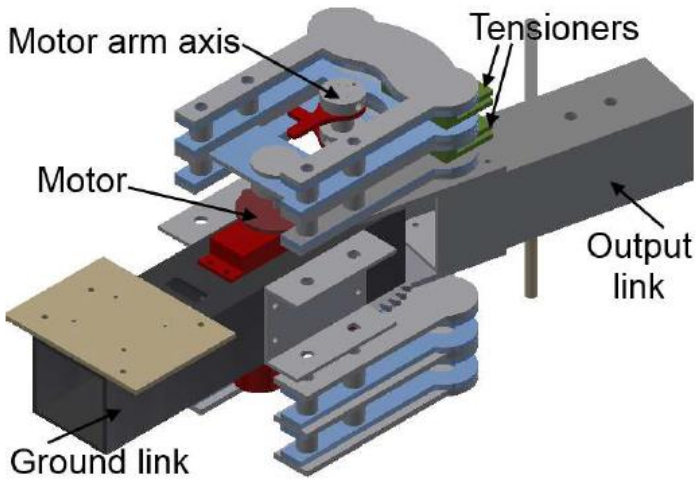
SPEA 2

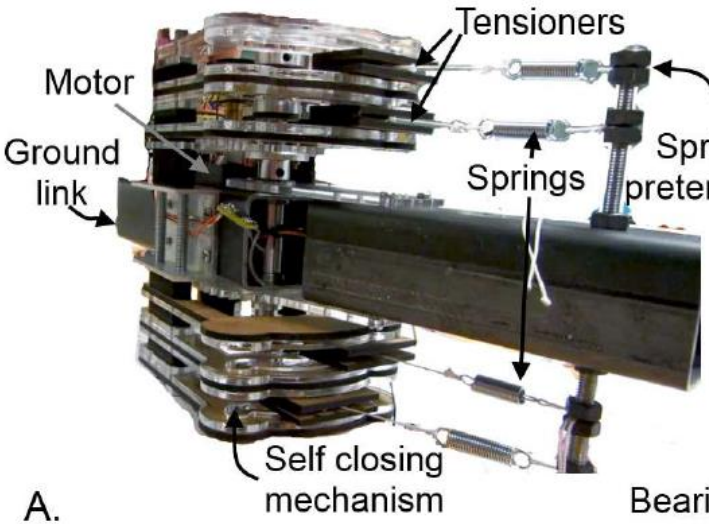
- Based on MACCEPA principle

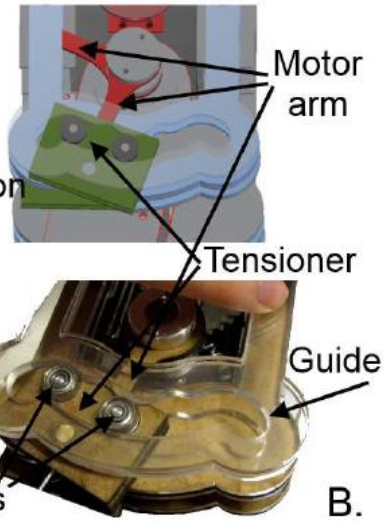


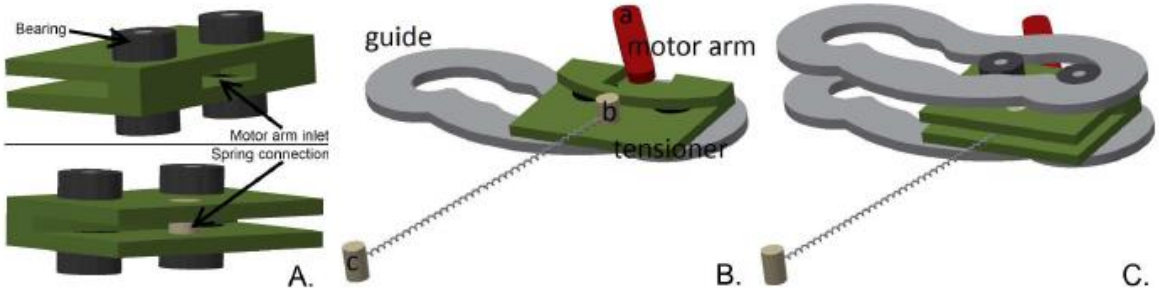


SPEA 2: design









SPEA 2

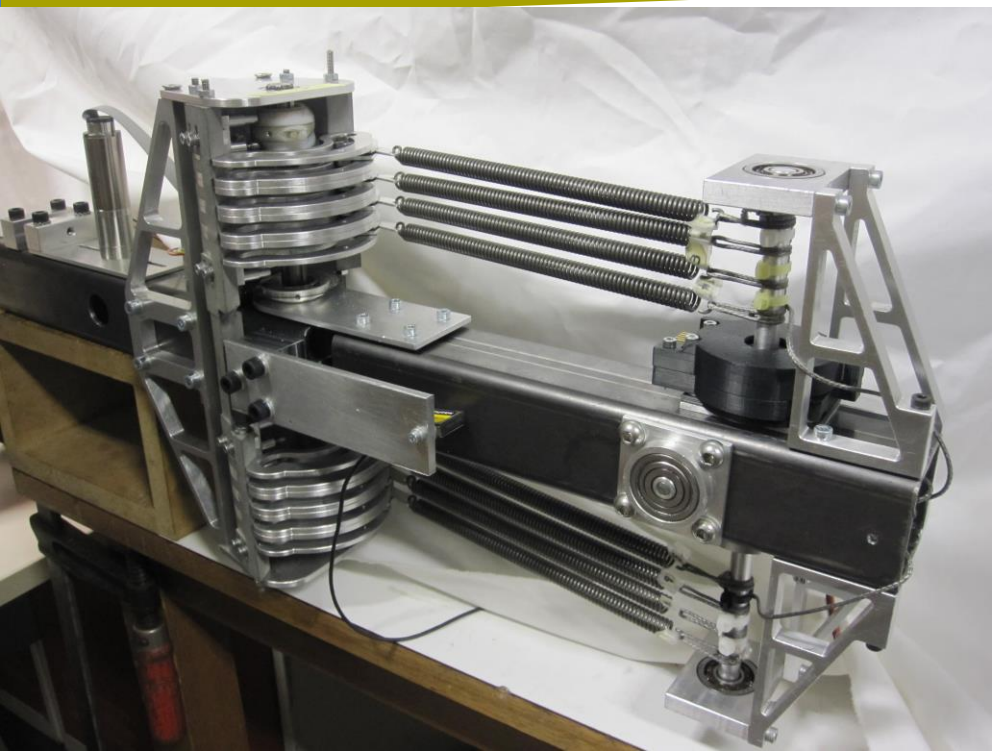
Design of a novel intermittent self-closing mechanism for a MACCEPA-based Series-Parallel Elastic Actuator (SPEA)

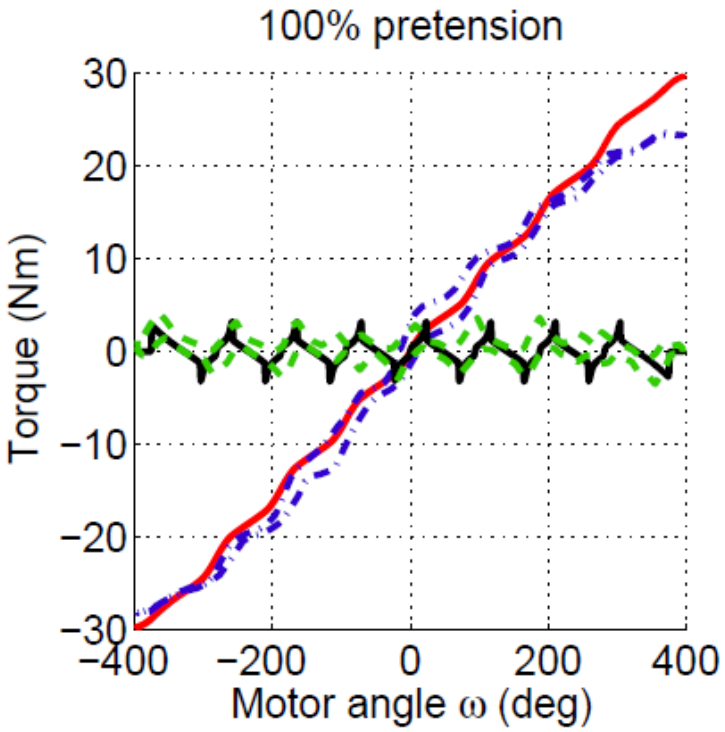
Glenn Mathijssen, Raphaël Furnémont,
Branko Brackx, Ronald Van Ham,
Dirk Lefeber and Bram Vanderborght

IROS 2014 • CHICAGO

Vrije Universiteit Brussel

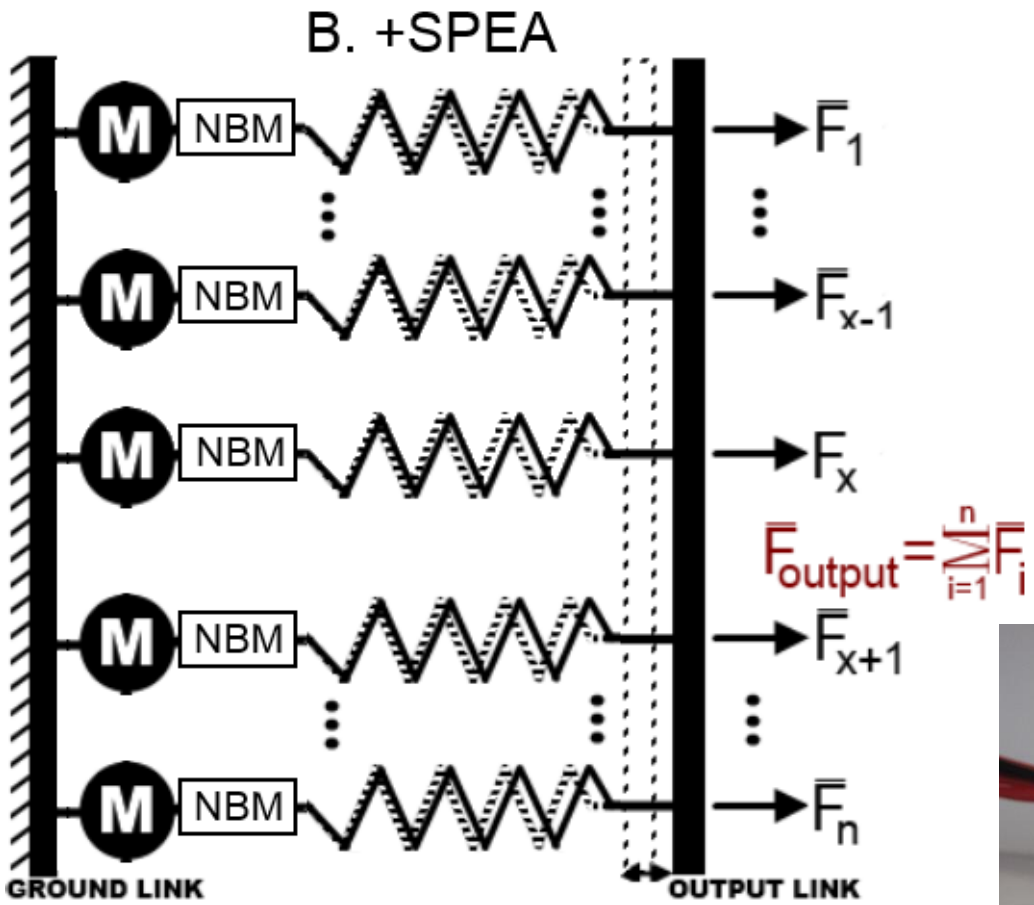
SPEA 3: MACCEPA-based with cylindrical cam mechanism



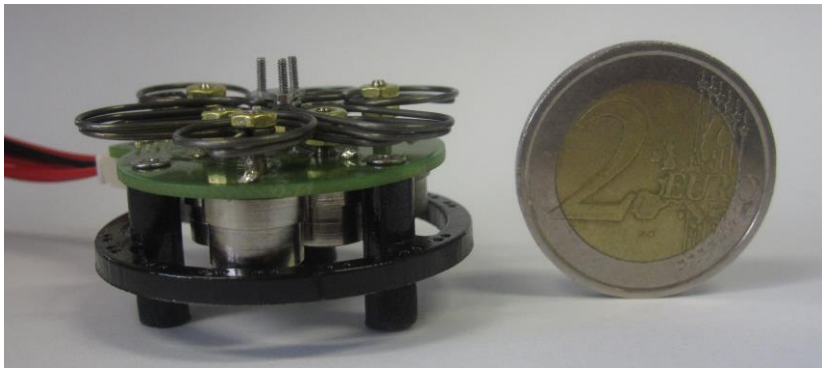


SPEA 3: MACCEPA-based with cylindrical cam mechanism

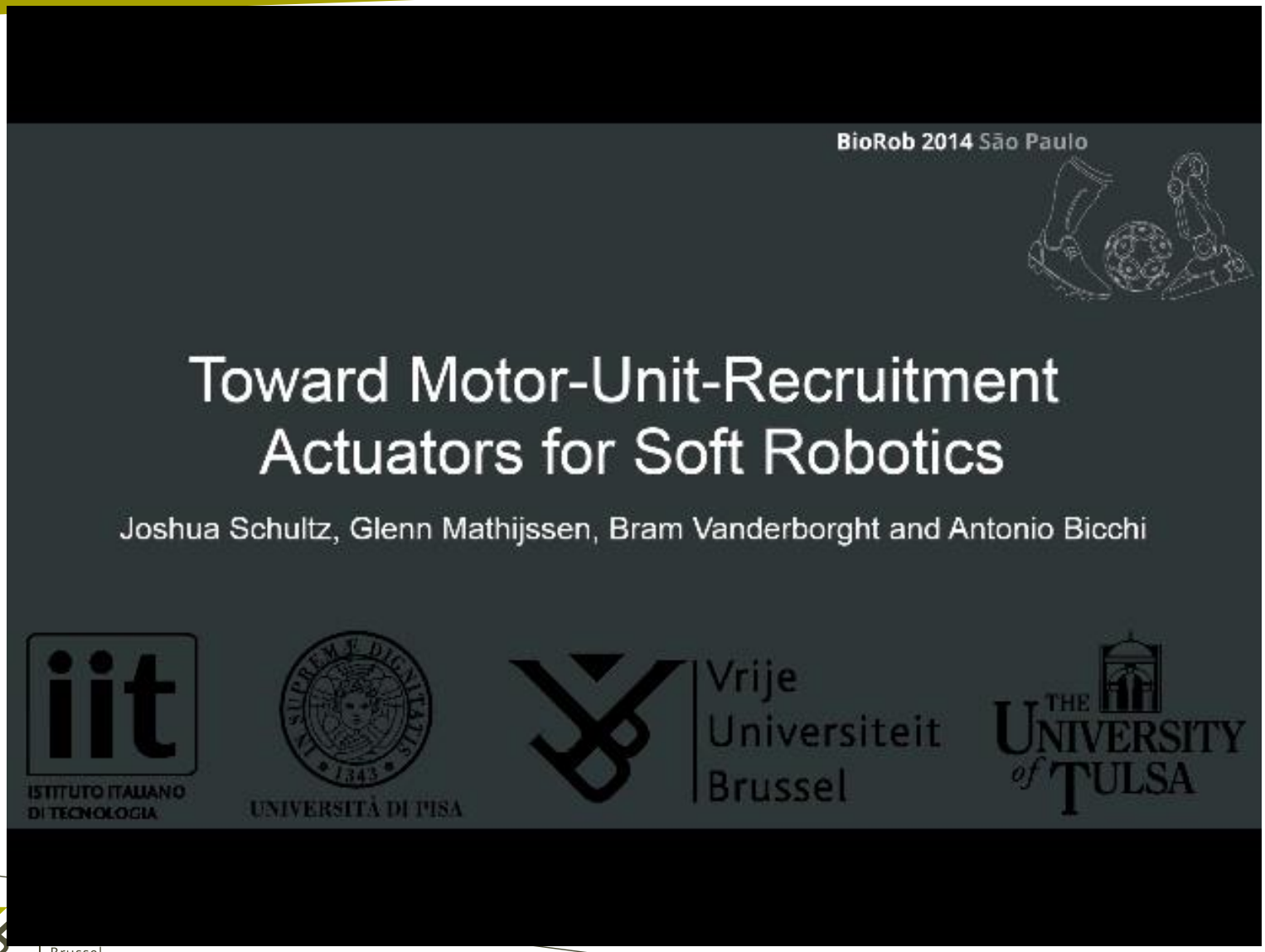
SPEA+ 1: Muscle-like Actuator



Collaborations with Prof. Antonio Bicchi and Prof. J. Schutlz on the ERC grant 'Soft Hands'

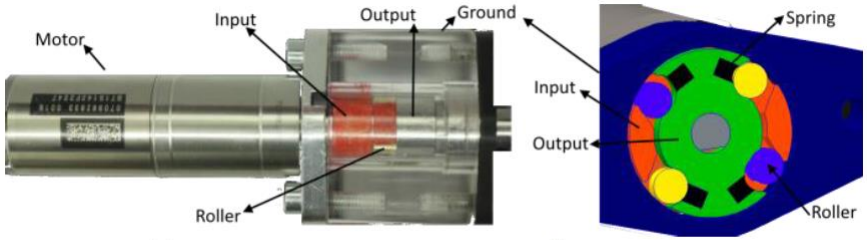


SPEA+ 1: Muscle-like Actuator

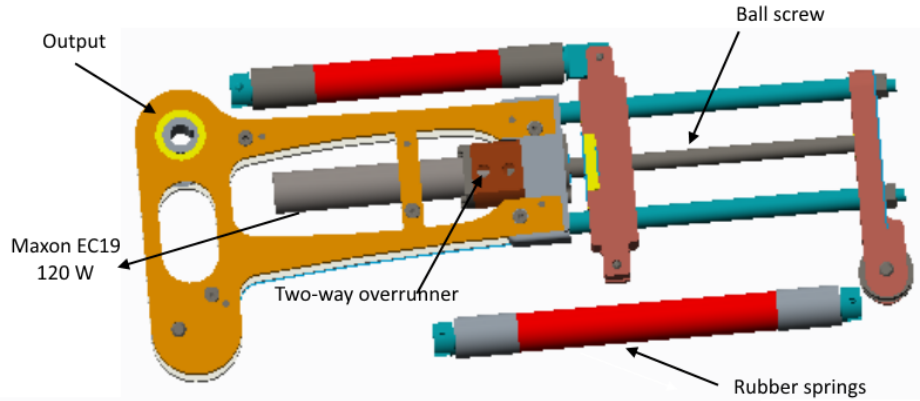


Modular +SPEA

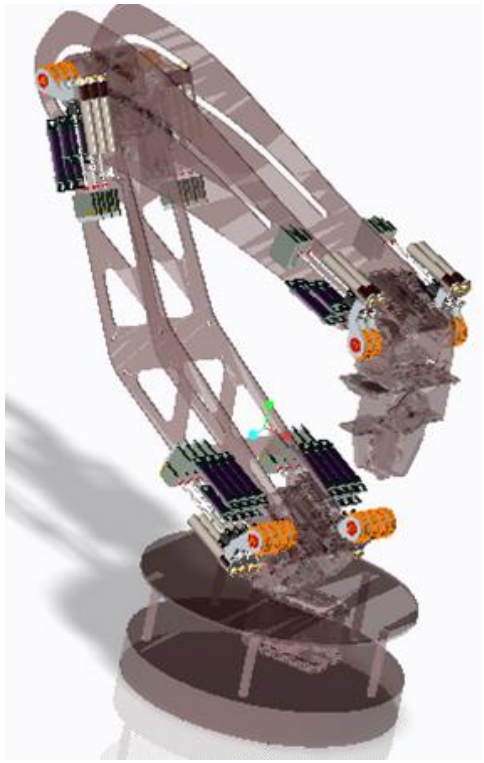
- Max. Weight: 1 kg.
- Layer thickness: 20mm.
- Min. continuous torque: 20 Nm.
- Min. torque bandwidth: 1 Hz.
- High efficient drive.
- Integrated passive non-backdrivable locker.
- Min. output angle range: 180°.
- Integrated electronics with ethercat communication.



Two-way overrunning mechanism



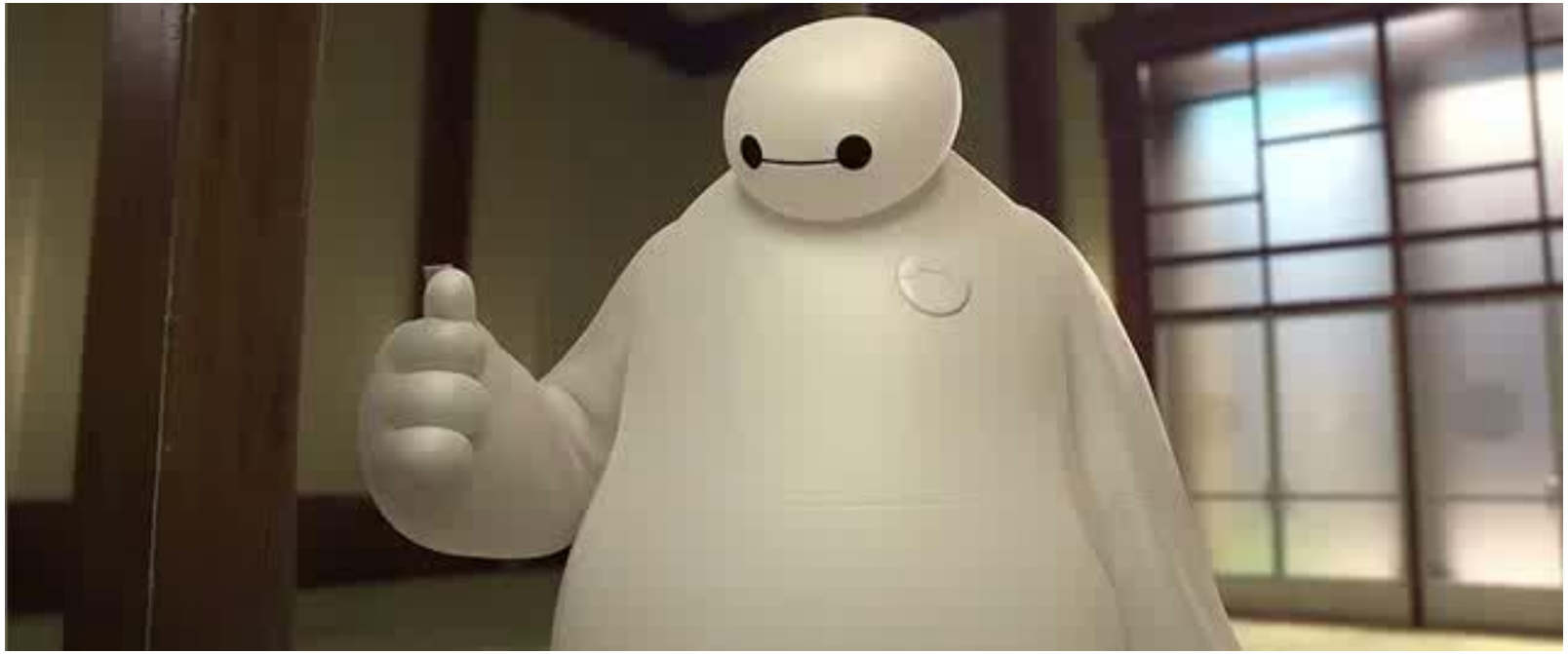
Modular +SPEA



Modularity on actuator level

- Versatile use of layers
- Robustness due to redundancy
- Potential low cost since 1 design and mass fabrication

Self-healing actuators



Big Hero 6

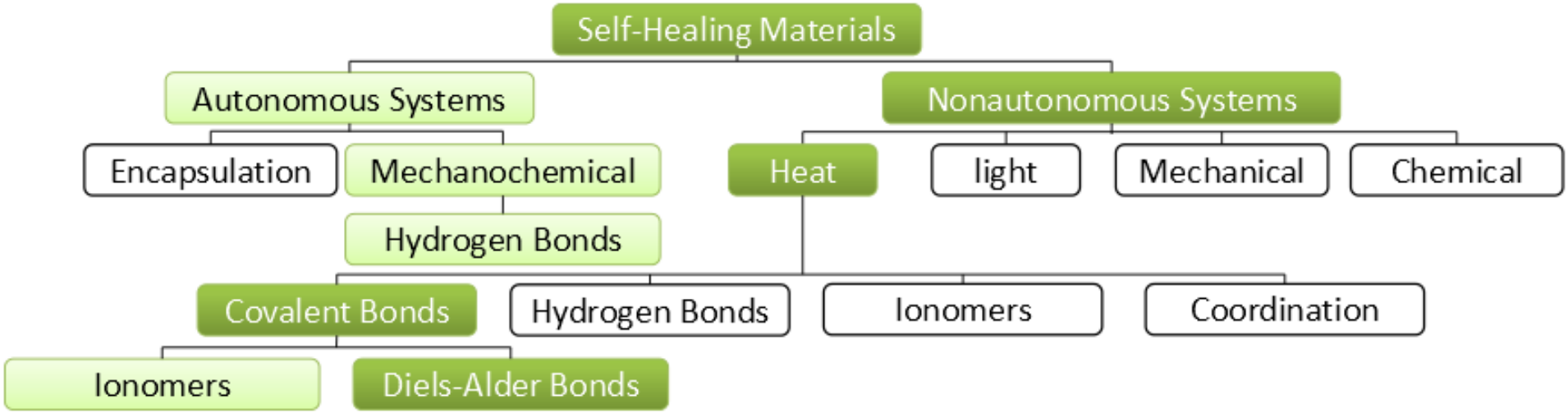
Self-healing Robotics

Reducing dimensions of the SPEA prototype → Polymers

Robotics + **Self-Healing Materials** → **Self-Healing Robotics**

	Organisms	Compliant Robots
Sharp objects	Cuts	Cuts, scratch and perforations
Impacts	Bone fracture or torn muscle	Damage of the compliant element
Overloads	torn muscle	Damage of the compliant element or overheating motor
Protection	**Self-healing mechanism**	**Overdimensioning** ✗
		Self-healing mechanism ✓

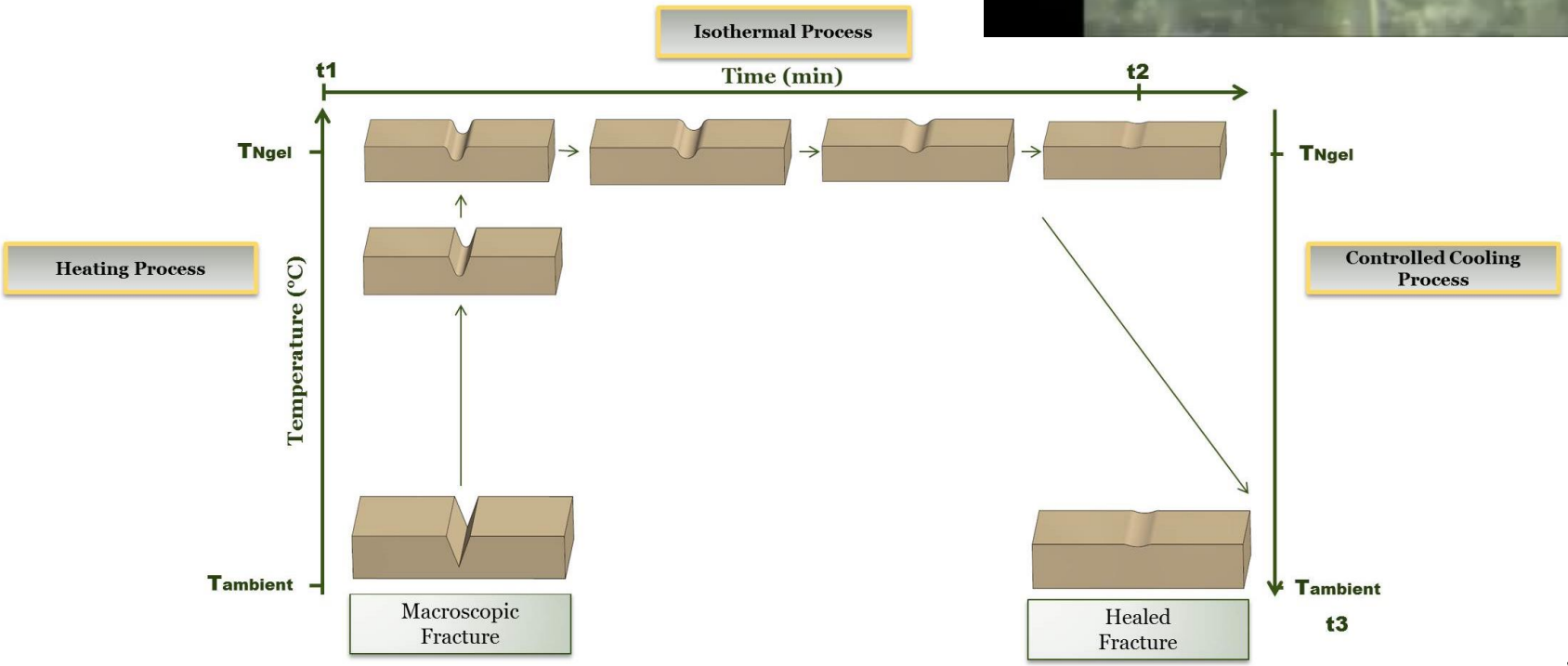
Selection of SH-polymer



- Diels-Alder Polymers
  - Self-healing based on thermo-reversible covalent bonds
    - Adequate mechanical properties
  - Recovery of initial mechanical properties after self-healing
    - SH-cycles are not limited
  - Non-Autonomous: require a heat stimulus
    - 70-120 °C

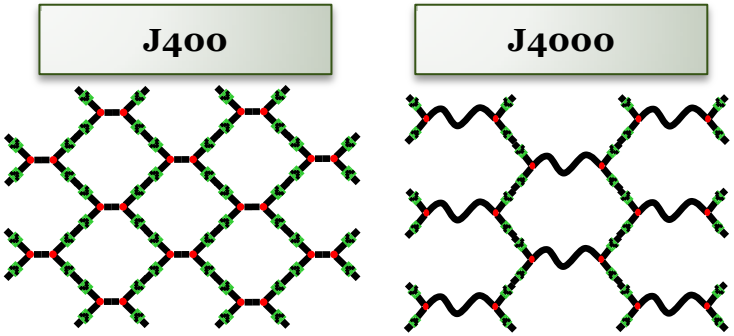
Diels-Alder Polymers
Non Autonomous SH-process
→ Requires heating

Fast forward: x520



Diels-Alder Polymers
DA-series

4 different DA-polymers: **DPBM-FGE-J…**
Furan spacer length: length polymer chains



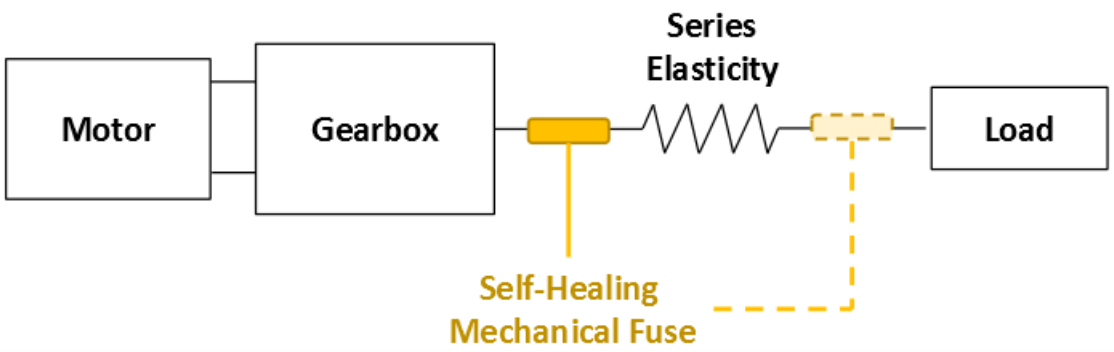
		Behavior at ambient temperature	Strain at fracture %
Glassy Thermoset	J230	Very brittle glassy Thermoset	/
	J400	Brittle glassy Thermoset	1,24±0,69
Elastomers	J2000	Elastic Elastomer	131±39
	J4000	Very Elastic Elastomer	450±130

(Thermo-) mechanical properties were analyzed

Concept 1 :Self-Healing Mechanical Fuse Conceptual design: Implementation in a SEA

Protection of actuator components against damage caused by overloads (impacts and collision)

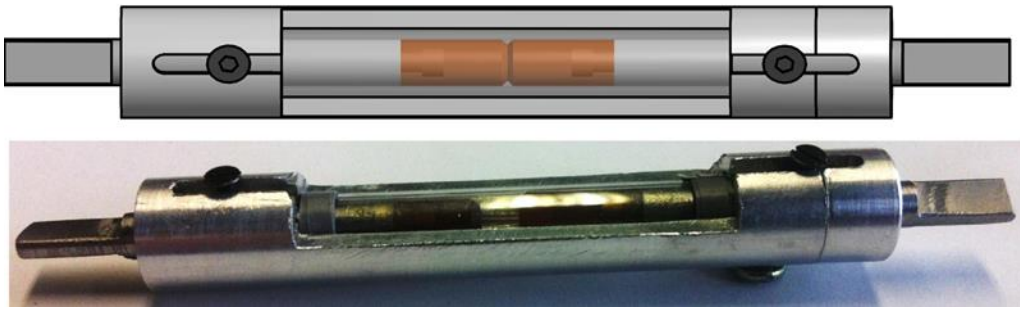
- Protect expensive components: Motor, Gearbox and series compliant element
  - Self-healing material which is weakest component

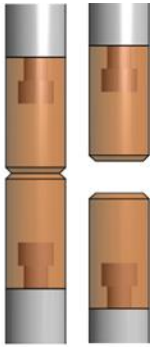


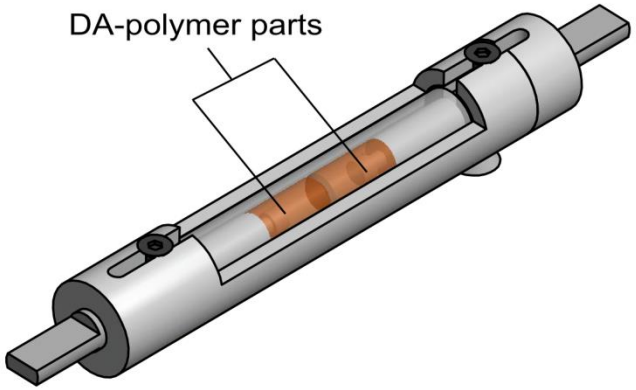
- **SH-mechanical fuse concept**
  - Sacrificial SH fuse in series with initial compliant element
  - Minimal mechanical contribution
  - Uniform (even for stiff actuators): MACCEPA, SPEA, …

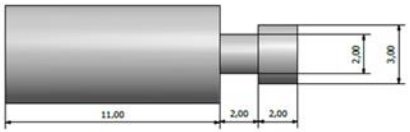
SH-Mechanical Fuse Prototype: Implementation in a SEA

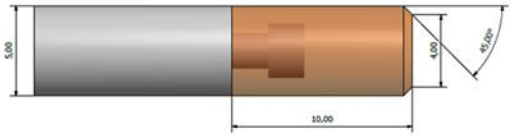
- Diels-Alder Polymer: DPBM-FGE-J400







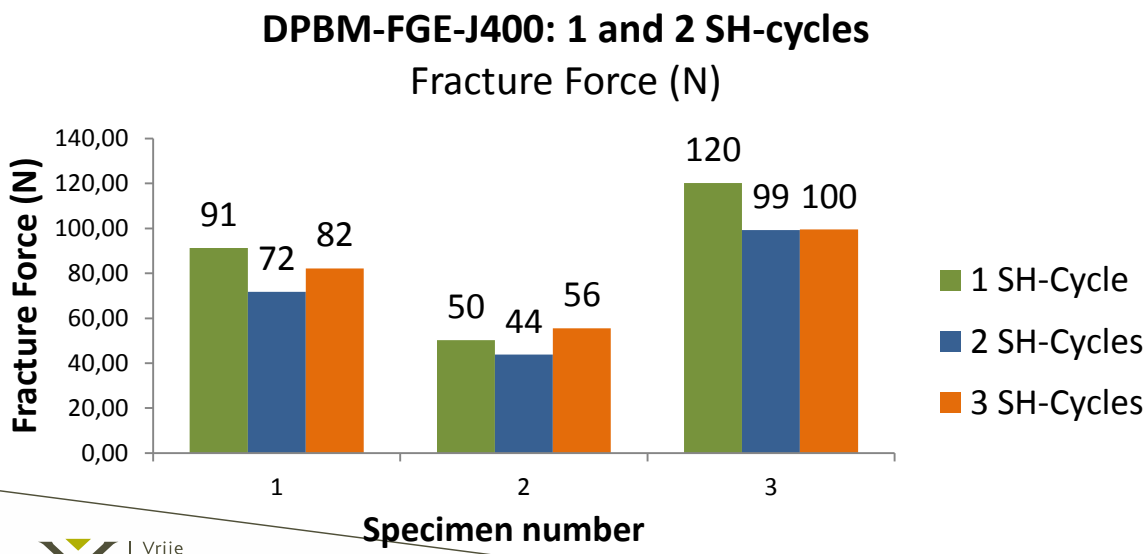




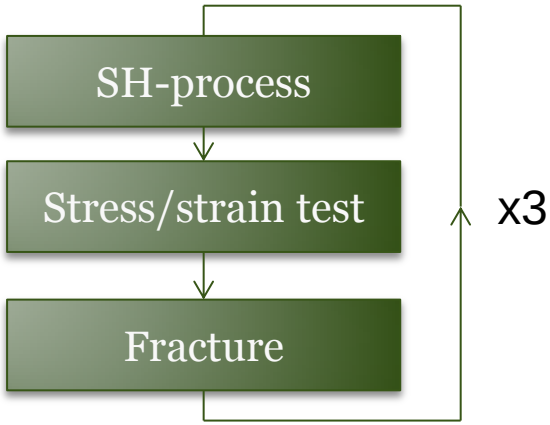
SH-Mechanical Fuse
Experiments

- SH-process: T-profile derived from the Kinetics/Equilibrium simulation
  - Duration: 2 h 50 min
  - Max T: 119,5 °C
  - → external heating: placed in furnace

- Universal Testing Machine (UTM)
  - Stress/strain test until fraction

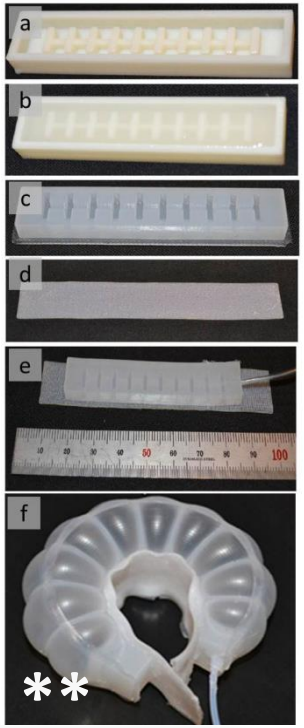


3 Samples

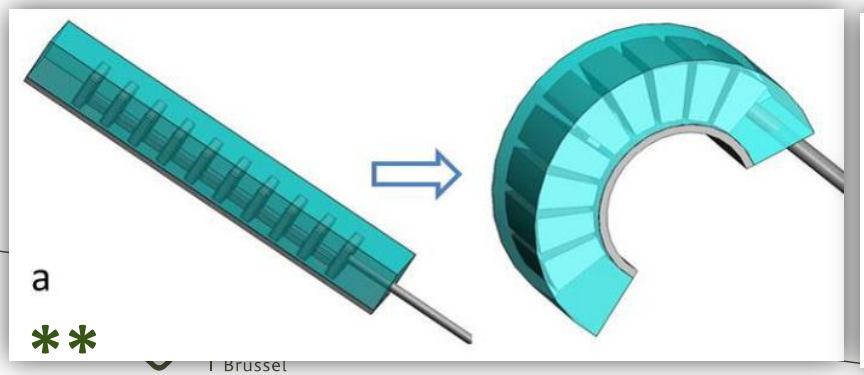


Soft Pneumatic actuators

- Actuated by compressed air
- Working principle:
  - (Multi-) air chamber(s)
  - Introduce anisotropy in response
    - Limitation of the strain in one plane/direction
- Materials: Hyper elastic polymer



Advantages	Disadvantages
• Softness • Simple, easy to fabricate • light	• Controlled actuation: position control • Function(ΔP) • Speed of actuation and deformation • Dependent of the mass flow rate of air • Pressure system



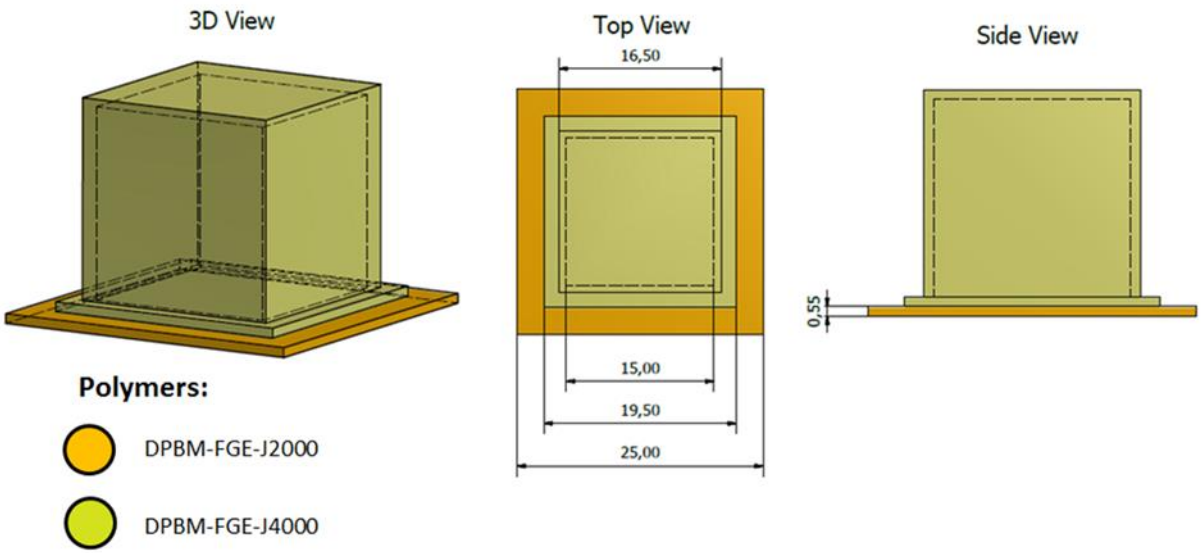
(*) P. Polygerinos et. al., in Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), November 2013.

(**) Y. Sun et. al., in Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 4446 - 4453, November 2013.

Soft Pneumatic actuators
Conceptual design

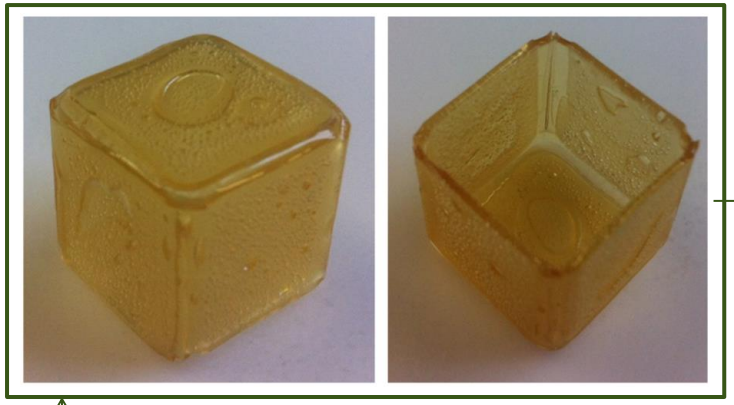
- Study the potential of DA-polymers for Bending SPA
  - Single cell prototype: Soft Pneumatic Cell (SPC)
  - → creating multi-cell actuator is straight forward
- Introduce anisotropy
  - Use 2 different DA-polymer series
    - DPBM-FGE-J2000 and J4000

→ Result: a SPA made **entirely** out of SH material

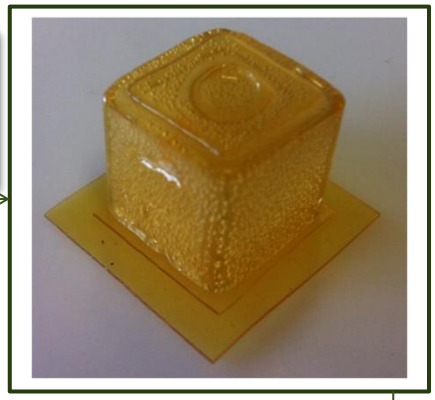


Soft Pneumatic actuators

Shaping process: Shaping through folding and self-healing



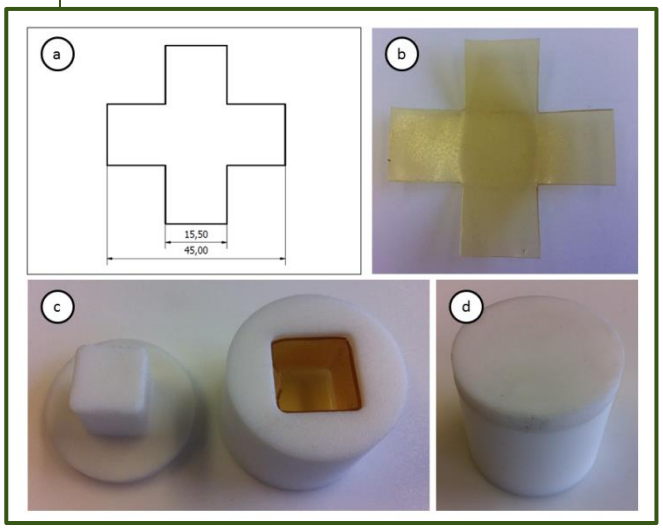
Self-healing process 2 (< 98.5 °C)



< 98,5 °C

Self-healing process 1 (< 78 °C)

Self-healing process 3 (< 90 °C)



Soft Pneumatic actuators
Experiments

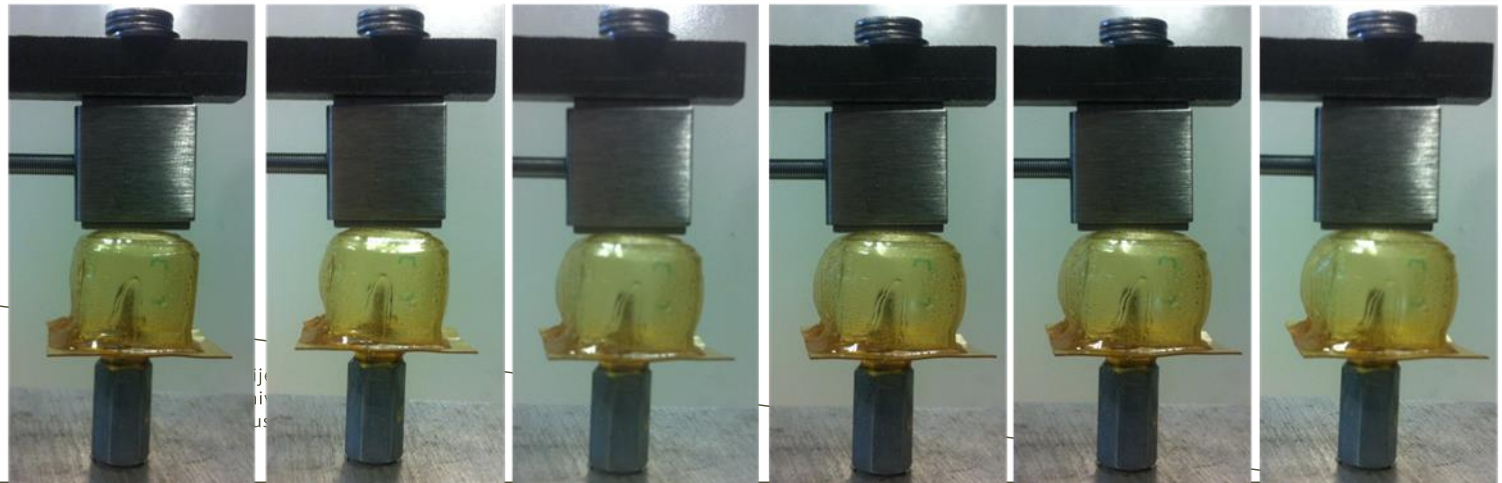
Experiment 1:

Over pressures

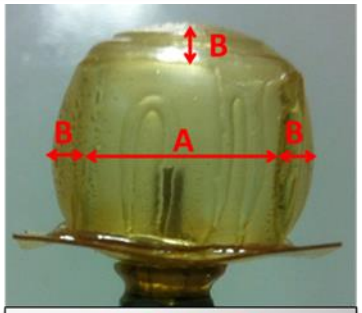
0 bar	0,16 bar	0,17 bar	0,25 bar	0,30 bar	0,36 bar

Experiment 2:

0,15 bar	0,17 bar	0,26 bar	0,31 bar	0,36 bar	0,42 bar
0,04 N	0,12 N	0,60 N	1,05 N	1,48 N	2,21 N



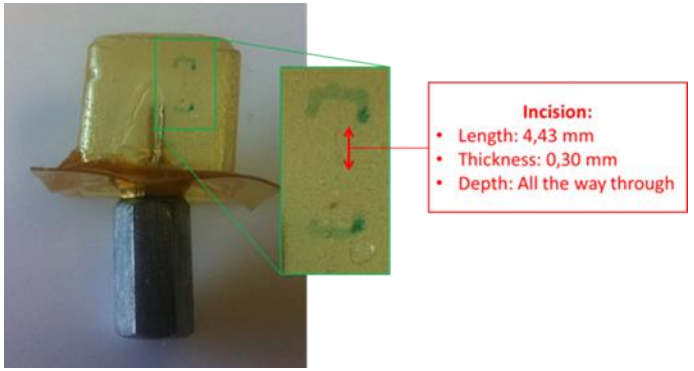
0,36 bar



- A: 16,5 mm
- B: 3,3 mm

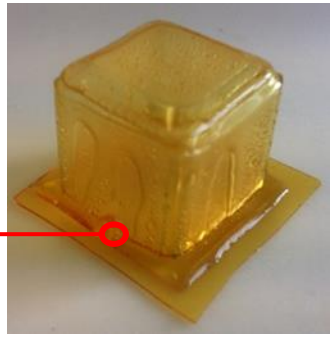
Soft Pneumatic actuators
Experiments

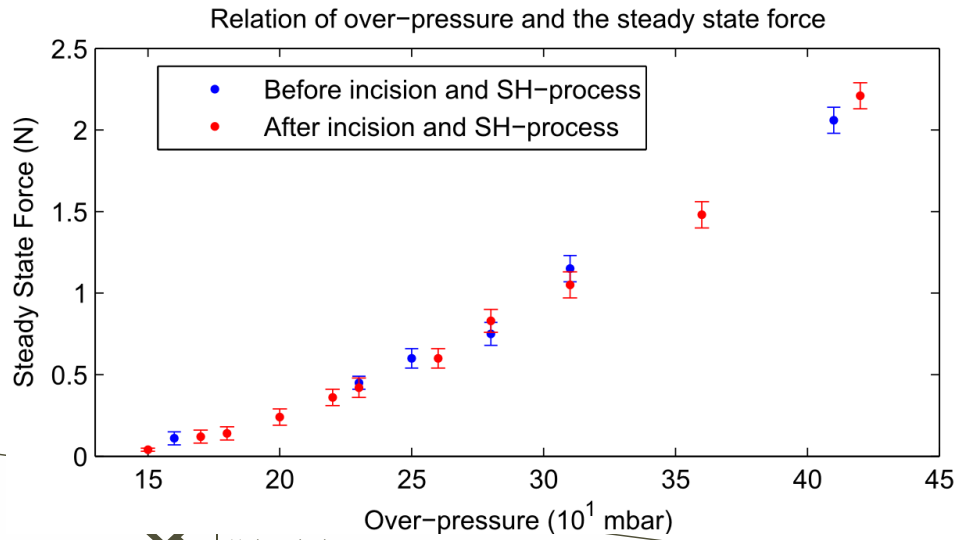
Experiment 3: Healing of a controlled incision in the SPC



Incision:
- Length: 4,43 mm
- Thickness: 0,30 mm
- Depth: All the way through

Small perforation at an overpressure of 0,46 bar





- SH-process: T-profile derived from the Kinetics/Equilibrium simulation
  - Duration: 30 hours
  - Max T: 70 °C
- Fail over-pressure before SH-process:
  - 0,46 bar
- Fail over-pressure before SH-process:
  - 0,48 bar
- At the same location

Conclusion

- Compliant actuators investigated for safety, energy efficiency, robustness, explosive motions
- Requirements for torque/mass and efficiency not yet reached for different applications (power augmentation, running robots, manipulators...)
- Use of switchable parallel and serial elastic elements
- PoC showed feasibility for improved torque and efficiency
- Preliminary idea that needs (lot of) further development and research (over ERC grant)
  - Complex mechanical model
    - Brain: 85 billion neurons– PC: 2,6 billion transistors
    - Body: 800 muscles and much more muscle fibers – Robot: 50-70 actuators.
  - Reduced forces through the parts, redundant
  - Additive manufacturing techniques to build it (not any more with nuts and bolts).
- Preliminary idea of self healing robotics

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