POTENTIAL MERITS FOR SPACE ROBOTICS FROM NOVEL SOFT ROBOTICS ACTUATION CONCEPTS

Glenn Mathijssen (1,2), Seppe Terryn (1), Raphaël Furnémont (1)  
Manolo Garabini (2), Manuel Catalano (2), Giorgio Grioli (2)  
Dirk Lefeber (1), Antonio Bicchi (2) and Bram Vanderborght (1)

(1) Vrije Universiteit Brussel  
(2) University of Pisa
Overview

“The main innovation is to propose two new categories of actuators: the **Series-Parallel Elastic Actuators (SPEA)** and the **Self Healing Actuators**”

- 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

Tactile Perception

Probo social robot

Soft Arm
Compliant Actuation

Altacro, VUB

Mirad, VUB
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

Motor → Gear Train → Load

Hill's three element model

1

Contractile element

Series element

2

Parallel element

3

1+2 = SEA

Motor → Gear Train → Series Elasticity → Load

1+3 = PEA

1+2+3 = SEA + PEA
Series-parallel elastic actuation
Problem stiff and VSA
Biological evidence
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

\[ P_{\text{output}} = T_{\text{output}} \times \nu = (T_{\text{springs}} + T_{\text{motor}}) \times \nu \]
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
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 Lefebre and Bram Vanderborght
SPEA 3: MACCEPA-based with cylindrical cam mechanism

6.6 kg
22 Nm
SPEA 3: MACCEPA-based with cylindrical cam mechanism

Cylindrical cam mechanism for unlimited subsequent spring recruitment in Series-Parallel Elastic Actuators

Glenn Mathijssen, Raphaël Furnémont, Simon Beckers, Tom Verstraten, Dirk Lefeber, and Bram Vanderborght

ICRA 2015

Vrije Universiteit Brussel
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

Toward Motor-Unit-Recruitment Actuators for Soft Robotics

Joshua Schultz, Glenn Mathijssen, Bram Vanderborght and Antonio Bicchi
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

Sharp objects
Impacts
Overloads

Protection

Cuts
Bone fracture or torn muscle
torn muscle

Self-healing mechanism

Compliant Robots

Cuts, scratch and perforations
Damage of the compliant element
Damage of the compliant element or overheating motor

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 $\rightarrow$ Requires heating

- Heating ↔ mobility
- Recovery properties ↔ Cooling

Fast forward: x520
Diels-Alder Polymers DA-series

4 different DA-polymer materials: **DPBM-FGE-J…**

- **Furan spacer length:** length of polymer chains

<table>
<thead>
<tr>
<th>Glassy Thermoset</th>
<th>J230</th>
<th>Very brittle glassy Thermoset</th>
<th>/</th>
</tr>
</thead>
<tbody>
<tr>
<td>J400</td>
<td>Brittle glassy Thermoset</td>
<td>1,24±0,69</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elastomers</th>
<th>J2000</th>
<th>Elastic Elastomer</th>
<th>131±39</th>
</tr>
</thead>
<tbody>
<tr>
<td>J4000</td>
<td>Very Elastic Elastomer</td>
<td>450±130</td>
<td></td>
</tr>
</tbody>
</table>

(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, ...

![Diagram showing the concept of self-healing mechanical fuse](image)
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 fracture

---

**DPBM-FGE-J400: 1 and 2 SH-cycles**

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>1 SH-Cycle</th>
<th>2 SH-Cycles</th>
<th>3 SH-Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91</td>
<td>72</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>44</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>99</td>
<td>100</td>
</tr>
</tbody>
</table>

Fracture Force (N)

3 Samples

- SH-process
- Stress/strain test
- Fracture

x3
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

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softness</td>
<td>Controlled actuation: position control</td>
</tr>
<tr>
<td>Simple, easy to fabricate</td>
<td>Function(ΔP)</td>
</tr>
<tr>
<td>light</td>
<td>Speed of actuation and deformation</td>
</tr>
<tr>
<td></td>
<td>Dependent of the mass flow rate of air</td>
</tr>
<tr>
<td></td>
<td>Pressure system</td>
</tr>
</tbody>
</table>

 Sofﬁe 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 1 (< 78 °C)

Self-healing process 2 (< 98.5 °C)

Self-healing process 3 (< 90 °C)
## Soft Pneumatic actuators
### Experiments

#### Experiment 1:

<table>
<thead>
<tr>
<th>Over pressures</th>
<th>0 bar</th>
<th>0.16 bar</th>
<th>0.17 bar</th>
<th>0.25 bar</th>
<th>0.30 bar</th>
<th>0.36 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,36 bar</td>
<td>0.04 N</td>
<td>0.12 N</td>
<td>0.60 N</td>
<td>1.05 N</td>
<td>1.48 N</td>
<td>2.21 N</td>
</tr>
</tbody>
</table>

#### Experiment 2:

- A: 16.5 mm
- B: 3.3 mm
Experiment 3: Healing of a controlled incision in the SPC

- 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

Small perforation at an overpressure of 0.46 bar
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
References


