The Art and Artillery of Artificial Muscles

By Jack Forman
Research Interests:
Morphing fabrics, Computational design of textiles, Fiber Synthesis, Smart Materials, Metamaterials

Bachelors
Carnegie Mellon University
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Tangible Media Group
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Overview

• Passive Fiber Actuation
• Pneumatic Actuation
• Dielectric Fibers
• Thermal Actuation
  • Shape Memory Alloy
  • Twisted Then Coiled Polymer Muscles
• LCE fibers
What is an artificial muscles?

“Artificial muscles, also known as muscle-like actuators, are materials or devices that mimic natural muscle and can change their stiffness, reversibly contract, expand, or rotate within one component due to an external stimulus (such as voltage, current, pressure or temperature).

The three basic actuation responses– contraction, expansion, and rotation can be combined within a single component to produce other types of motions (e.g. bending, by contracting one side of the material while expanding the other side). Conventional motors and pneumatic linear or rotary actuators do not qualify as artificial muscles, because there is more than one component involved in the actuation.” https://en.wikipedia.org/wiki/Artificial_muscle
Overview


Basic Tendon Actuation

• Passive fiber pulled with a motor

• Pros
  • Extremely accessible

• Cons
  • External motors+electronics are bulky
  • Uneven actuation due to friction

McKibben Actuator Background

• Composed of elastomeric tubing surrounded by a constraining braid

• Inflating the tubing causes the muscle to expand (or contract)

• Control of braiding angle and pattern can determine actuation displacement and behavior

• Hydraulic actuation fixes lag associated with pneumatic actuation
McKibben Actuator Background

• Pros
  • Fast, powerful actuation
  • Cheap and accessible to produce
  • Hold actuated state unpowered

• Cons
  • Requires pump (noisy + bulky)
McKibben Actuator Applications

Dielectric Elastomer Background

- Composed of a elastomer (often silicone) layer sandwich by two conductive electrodes (often carbon grease)
- Voltage-induced charge on plates cause attractive force
- Removing voltage removes attraction and allows elastomer to restore original shape

Dielectric Elastomers Background

• Pros
  • Fast actuation speed
  • Lightweight
  • Power efficient

• Cons
  • High voltages needed
  • Constant power needed to maintain actuation

Rapid oscillation of 3D printed Dielectric fibers

Shape-Memory Alloy Actuator

• One of the most popular shape memory materials

• Nickel Titanium Alloy

• A wire-like material that exhibits super elasticity at elevated temperatures

Phases of SMA in response to temperature and loading cycles

Source: https://www.skyfi.com/project-ideas/shape-memory-intelligent-alloys
Jie Qi Self Flapping Crane

• https://fab.cba.mit.edu/classes/863.10/people/jie.qi/jieweek10.html

• https://www.youtube.com/watch?v=ARMepo5nY1Q&ab_channel=JieQi
Shape-Memory Alloy Actuator

• Pros
  • Well-commercialized
  • Range of actuation temps and diameters

• Cons
  • Actuation displacement is small ~5% and not self-reversing
  • High hysteresis
  • Pain to work with and stiff

Fishing Line Actuators Background

• Hanes et. al found that over-twisting fishing line produced actuators 100x more powerful than human muscle

Material Mechanisms

Polymer Behavior

Cold

Normal

Hot
Fishing Line Actuators Background

• Pros
  • Extremely accessible to fabricate with low cost material
  • Powerful actuators with no hysteresis (>1 million cycles)

• Cons
  • Constraining twist is challenging
  • Non-self reversing
Fabrication

Step 1: Coiling
Fabrication

Step 2: Plying
Fabrication

Step 3: Training
Fabrication

Step 4: Coating

Coils are coated with silicone
But what about much longer fibers?
Fabrication

Semiautomated Coiling
Fabrication

Semiautomated Coiling
ModiFiber

• TCP actuators coated in Silicone
• The compression of the silicone after actuation restores the
• By using silver-coated fishing line, the heating element is embedded and sensing is possible

Actuation

Motion Types

(a) 1-Ply Twisting
(b) 1-Ply Shrinking
(c) 2-Ply Shrinking
Applications
Porosity
Changing
Dress
Explorations

Fabric-Embedded Haptic Feedback

Constriction becomes noticeable after 5 minutes
Application:
Non-invasive Haptics
2-Ply Shrinking Actuator

Functional Garment

Notification triggers actuators embedded in sleeve
ModiFiber

• Pros
  • Cheap to produce
  • Self-reversing

• Cons
  • Slow actuation speed (~5 minutes)
  • High temperatures needed

Liquid Crystal Elastomer Fibers

- Soft rubbery material
- Massive strains of 40-60%
- Self-reversing
- 1 Hz actuation speed
- Actuation temperatures from 15-60°C

FibeRobo:
Fabricating 4D Fiber Interfaces by Continuous Drawing of Temperature Tunable Liquid Crystal Elastomers

Jack Forman, Ozgun Kilic Afsar, Sarah Nicita, Rosalie Lin, Liu Yang, Megan Hofmann, Akshay Kothakonda, Zachary Gordon, Cedric Honnet, Kristen Dorsey, Neil Gershenfeld, Hiroshi Ishii
Overview

- Why Fabricate FibeRobo
- Fabricating FibeRobo
- Fabricating with FibeRobo
  - Knitting
  - Weaving
  - Embroidery
Related Work: Shape Shifting Fabric Interfaces


Kim et al. KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting. DIS 2021
Guiding Principles

• **Process Compatibility**
  • Work with, not against, standard textile machinery

• **Modifiable Materiality**
  • Enable fiber tunability for a specific application

• **Integrated Interactivity**
  • Embed dynamic digital interaction within a fabric form factor
Key Features

- 42% contraction at ~60°C
- Self-reversing without hysteresis
- Can be triggered by heat or electricity
- Soft and safe to the touch
- Compatible with industrial knitting, weaving, sewing, etc.
- 30-60X cheaper to produce than purchasing SMA, with 10x more stroke

Actuation of fiber sample with heat gun (real time)
Fabrication Overview

Step 1: Wet Extrusion
- LCE resin
- Heating jacket
- UV light
- Cured & aligned
- Unaligned & partially cured

Step 2: Tensioning & partial curing
- Pulling the fiber, stretching it, weakly crosslinking, then coating with mineral oil

Step 3: Full curing under tension

Step 4: Collection
- Fully cured and spun fiber
UV fiber spinning using custom desktop setup
Fabrication Overview

- Actuation temperature changes with LC mesogen
- Carbon Black dyeing affords resistive sensing
- Thicker fibers generate more force but slower actuation
Braiding with litz wire enables integrated heating.
Embroidery

- **a. Stroke width**
- **b. Stitch Spacing**
- **c. Double-sided threading**
- **d. Stitch staggering**

**LCE Fiber**
- Conductive thread
  - silver-plated nylon
- Silk, cotton thread
- Substrate fabric
Embroidered blooming lampshade
EiheRoho Knitting
FurbeRobo
Future Works

• Fabricating complex textile closed loop interfaces with weaving and knitting machines

• Reformulation of resin to make recyclable or compostable

• Making fibers even more accessible

• Understanding needs of textile designers and craftspeople
Fibero: Fabricating 4D Fiber Interfaces by Continuous Drawing of Temperature Tunable Liquid Crystal Elastomers

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<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Actuation Strain</th>
<th>Max Cycle Speed</th>
<th>Hysteresis</th>
<th>Self Reversing</th>
<th>Accessibility</th>
<th>Notes</th>
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<tbody>
<tr>
<td>McKibben</td>
<td>Pneumatic/Hydraulic</td>
<td>~66%</td>
<td>40 Hz</td>
<td>Negligible</td>
<td>Yes</td>
<td>Commercially Available</td>
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<tr>
<td>Dielectric Elastomer</td>
<td>Voltage (kV)</td>
<td>~10%</td>
<td>700 Hz</td>
<td>Negligible</td>
<td>Yes</td>
<td>Early Laboratory Material</td>
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<td>Shape-Memory Alloy</td>
<td>Thermal</td>
<td>~5%</td>
<td></td>
<td>Significant</td>
<td>No</td>
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<td>Fishing Line Actuators</td>
<td>Thermal</td>
<td>~10-30%</td>
<td>~2 Hz</td>
<td>Negligible</td>
<td>No</td>
<td>Easy and Cheap to produce</td>
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<tr>
<td>Liquid Crystal Elastomers</td>
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<td>~40-60%</td>
<td>~1 Hz</td>
<td>Negligible</td>
<td>Yes</td>
<td>Early Laboratory Material</td>
</tr>
</tbody>
</table>
Wildcard Week?!
Thank you! AnyQuestions?
Wanna work on artificial muscles? Reach out!

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Forman’s Four F’s of Fabric Formation

Fiber
Fabrication
Form
Function