Application of SMA Actuators to Spacesuit Glove Mobility

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Overview

- Motivation
- SMA Actuator Design
- Design Iterations
- Conclusions
- Open Challenges
MOTIVATION
Motivation

- Current spacesuit gloves resist motion
- Astronaut complaints:
  - Finger fatigue
  - Lack of dexterity
  - Lack of tactile feedback
- Actuator assistance may reduce fatigue

Astronaut Greg Chamitoff during EVA
The Challenge

- Pressure vessel resists shape change
- Restoring force resists finger motion
- Actuator must be small, simple

Source: Main, Peterson, & Strauss (1994)
Approach

- Linear SMA actuator runs along palm side of finger
- Provides assist during finger deflection
- Gauntlet SMA extension considered

SMA with gauntlet extension
Membrane Deflection
Design Space

- Several variables
  - SMA material
  - System geometry
  - Actuator length
  - Actuator cross-section

- Several configurations evaluated during development

Table 1.1. Representative transformation temperatures for SMAs with different compositions and heat treatments.

<table>
<thead>
<tr>
<th>NiTi Based SMAs</th>
<th>$M_f$</th>
<th>$M_s$</th>
<th>$A_s$</th>
<th>$A_f$</th>
<th>Reference</th>
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<td>Ti$<em>{50}$Ni$</em>{50}$</td>
<td>15</td>
<td>55</td>
<td>80</td>
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<td>Ti$<em>{49.5}$Ni$</em>{50.5}$</td>
<td>−78</td>
<td>−19</td>
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<td>Ti$<em>{49}$Ni$</em>{51}$</td>
<td>−153</td>
<td>−114</td>
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<td>Ti$<em>{62}$Ni$</em>{38}$Cu$_{10}$</td>
<td>8</td>
<td>30</td>
<td>35</td>
<td>50</td>
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<td>Ti$<em>{50}$Ni$</em>{40}$Cu$_{10}$</td>
<td>21</td>
<td>41</td>
<td>53</td>
<td>67</td>
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<td>Ti$<em>{44}$Ni$</em>{47}$Nb$_{9}$</td>
<td>−175</td>
<td>−90</td>
<td>−85</td>
<td>−35</td>
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<td>Ti$<em>{42.2}$Ni$</em>{49.8}$Hf$_{8}$</td>
<td>50</td>
<td>69</td>
<td>111</td>
<td>142</td>
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<td>Ti$<em>{60.7}$Ni$</em>{39.8}$Hf$_{0.5}$</td>
<td>61</td>
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<td>619</td>
<td>626</td>
<td>702</td>
<td>[49]</td>
</tr>
</tbody>
</table>

Source: Lagoudas et. al. (2010)
SMA SPECIMEN DESIGN
SMA Specimen - Material

- Choose SMA composition
  - Ti$_{50}$Ni$_{40}$Cu$_{10}$
  - $M_f = 21^\circ C$, $M_s = 41^\circ C$, $A_s = 53^\circ C$, $A_f = 67^\circ C$
  - $E^A = 50$ GPa
  - $E^M = 25$ GPa
  - $\nu = 0.3$
  - $H_{\text{max}} = 5\%$
  - $\sigma^y = 600$ MPa

Source: Lagoudas et. al. (2010)
SMA Actuator – Geometry

- SMA cross-section 1
  - Round Wire
  - Diameter = 1 mm
- SMA cross-section 2
  - Rectangular Ribbon
  - Cross-section: 1 mm x 5 mm
- SMA cross-section 3
  - Rectangular Ribbon
  - Cross-section: 0.7 mm x 10 mm
SMA Actuator Simulation

- How to do M → A transformation in Abaqus?
- For purposes of computation speed, choose negative $\alpha$ such that $\varepsilon^{th} = H$ across $A_s$ to $A_f$.

$$H = \alpha \left( A_s - A_f \right)$$

$$\implies \alpha = \frac{0.05}{53 - 67} = -0.00357$$
DESIGN ITERATIONS
Model 1

- High-density polyethylene (HDPE) tube and knuckle joints ($E = 700$ MPa)
- Radius = 10mm
- Thickness = 0.5mm
- Joint thickness = 0.1mm
- Tube length = 90mm
- 2mm long steel attachment point ($E = 200$ GPa)
- NiTiCu wire extending past tube into gauntlet ($L = 150$ mm)
Model 1

Suit Pressure: 1/3 atm
Model 1
Model 2

- HDPE rectangular pad and knuckle joints (E = 700 MPa)
- Width = 10mm
- Thickness = 1mm solid
- Joint thickness = 0.1mm shell
- Pad length = 90mm
- 2mm long steel attachment point (E = 200 GPa)
- NiTiCu wire extending past pad into gauntlet (L = 150 mm)
Model 2
Model 2
Model 2

U, U2

+8.142e+00
+7.464e+00
+6.785e+00
+6.107e+00
+5.428e+00
+4.750e+00
+4.071e+00
+3.393e+00
+2.714e+00
+2.036e+00
+1.357e+00
+6.785e-01
-5.226e-05
Model 3-A

- 3 steel rectangular pads (E = 200 GPa)
- 2 nylon circular joints (E = 4 GPa)
- Width = 10mm
- Thickness = 1mm solid
- NiTiCu wire attached at base of finger (L = 90 mm)
Model 3-A
Model 3-A

1.15 GPa >> \( \sigma^y \)
Model 3-B

- Same passive structure model as model 3-A
- Active structure changed to NiTiCu ribbon attached at base of finger (90 mm x 5 mm x 1 mm)
Model 3-B

570 MPa < σ\text{y}
Model 3-B
Model 3-B

Tip deflection: 1.98 cm
Full Hand Visualization
Design 5

- Finger model width increased to 15 mm
- 1/3 atm pressure distributed along palm-side surface of finger
- NiTiCu ribbon attached at base of finger (90 mm x 10 mm x 0.7 mm)
Design 5

$S_y$, Max. Principal
Multiple section points
(Avg: 75%) [MPa]

+1.088e+03
+9.976e+02
+9.069e+02
+8.162e+02
+7.255e+02
+6.348e+02
+5.441e+02
+4.535e+02
+3.628e+02
+2.721e+02
+1.814e+02
+9.069e+01
+0.000e+00

590 MPa < $\sigma_y$
Design 5

Tip deflection: 8.43 mm
Power Analysis

- Estimates and Assumptions:
  - 1.7 W/cm heating rate
  - 1.63 J/cm activation energy

- Results:
  - <1 s actuation time
  - ~1 kW power per hand
Energy Analysis

- Estimates and Assumptions:
  - 245 J per finger per cycle
  - 10 gripping actions per minute
  - 8 hour total EVA time
  - 0.252 MJ/kg battery energy density

- Result:
  - 18.7 kg battery mass required
CONCLUSIONS & OPEN CHALLENGES
Conclusions

- SMA-based thermal actuator is capable of providing assistance in hand gripping motion.
  - Example tested gives 2 cm tip deflection for the configuration modelled
  - Total finger angle decreased by 40 degrees

- SMA ribbon is more feasible than a wire.
  - Increased practical cross-sectional area
  - Reduced actuation stress
Conclusions

- Ti$_{50}$Ni$_{40}$Cu$_{10}$ SMA is promising for space suit applications.
  - Reasonable temperature ranges for suit glove (No cooling below ambient required)
  - High transformation strain
  - Reasonably high yield stress

- Structural analysis of buckled pressure vessels presents a challenge for future work.
Open Challenges

- Incorporate true suit stiffness into model
  - Glove stiffness
  - Pressurization
- Build and test in hardware experiment
  - Create attachment for interior of glove finger
  - Test with suit cooling system
  - Validate FEA model
Questions?