GRAPSS: Graphene-Polymeric Spray Sensor for Shape Recognition of Super-Deformable Structures

S. Ameduri, M. Ciminello, A. Concilio, L. Mazzola, O. Petrella, F. Piscitelli, R. Sorrentino, B. Tiseo, R. Volponi

MFMSiEM 2016, Texas A&M University, College Station, Texas, May 2-3 2016
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• Industrial requirements; initial and final TRL
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• Preliminary results
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GRAPSS Project – “Curiosity Driven” CIRA Action

Evaluating and proving the possibility of using graphene-based sensors for monitoring very large structural strains

Developing a prototype of a super-deformable graphene-based sensor system, specifically tied for non-conventional (morphing, deployable, compliant) structures

Budget: 200 kEu
Duration: 2 years
The sensor is made of a polymeric film filled with graphene particles (filler).

Over a certain concentration, the tunneling effect occurs so frequently that the polymeric nano-filled film becomes a conductive media.

An imposed deformation field causes the variation of the inter-particles distance, with a consequent global variation of the electrical resistance.
Some applications

- Shape reconstruction in presence of large deformations
- Morphing structures
- Deployable structures
- Structural Health Monitoring
- Sensor network

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R. Savino, IRENE programme: ground and flight test of hypersonic deployable re-entry heat shields, 8th European WS on Thermal Protection Systems & Hot Structures 2016
Scenario
Scenario

Graphene Nanoplateleles
0.01% to 2.5%

SWCNT
0.15% to 500%

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0.01% to 2.5%

Graphene-based polymer nanocomposites (2010), J. R. Potts et alii

SWCNT
0.15% to 500%

Graphene-based piezoresistive strain sensor for wireless SHM (2014), A. Rinaldi et alii

Wireless system integration for SHM purposes (2014), A. Rinaldi et alii


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Wireless system integration for SHM purposes (2014), A. Rinaldi et alii

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0.15% to 500%

Potential of Flexible Carbon Nanotube Films for High Performance Strain and Pressure Sensors (2014), O. Kanoun

Graphene-based polymer nanocomposites (2010), J. R. Potts et alii

Graphene-based piezoresistive strain sensor for wireless SHM (2014), A. Rinaldi et alii


Carbon Nanotube/Polymer Nanocomposites Flexible Stress and Strain Sensors (2008), J. H. Kang et alii


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Scenario

MWCNT
70 to 620%
Scenario

Simulation and experimental characterization of polymer/carbon nanotubes composites for strain sensor applications (2014) V. Tucci et alii

MWCNT 70 to 620%

Stretchable and Flexible High-Strain Sensors Made Using Carbon Nanotubes and Graphite Films on Natural Rubber (2014), S. Tadakaluru et alii

Electrical Properties of Graphene Polymer Nanocomposites (2015), P. N. Khanam et alii

A Review: Carbon Nanotube-Based Piezoresistive Strain Sensors (2012), W. Obitayo


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## Scenario

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type-Deposition</th>
<th>strain</th>
<th>Temp</th>
<th>Frequency</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Graphene Nanoplatelets - Spray</td>
<td>0.01% to 2.5%</td>
<td>RT</td>
<td>200KHz</td>
<td>Carboresin plate SHM</td>
</tr>
<tr>
<td>2</td>
<td>Graphene Nanoplatelets - Spray</td>
<td>0.01% to 2.5%</td>
<td>RT</td>
<td>200KHz</td>
<td>Carboresin plate SHM</td>
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<tr>
<td>3</td>
<td>Graphite Nanoplatelets vs. CNT</td>
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<td>.</td>
<td>Comparison</td>
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<td>4</td>
<td>Graphene Ink-jet printing</td>
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<td>Manufacturing</td>
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<tr>
<td>5</td>
<td>SWCNT/PMMA film</td>
<td>0.15%</td>
<td>RT</td>
<td>.</td>
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<tr>
<td>6</td>
<td>Graphene crumples</td>
<td>100%</td>
<td>RT</td>
<td>.</td>
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<tr>
<td>7</td>
<td>MWCNT sprayed</td>
<td>1%</td>
<td>RT</td>
<td>.</td>
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<tr>
<td>8</td>
<td>NW/PSNF</td>
<td>50%</td>
<td>RT</td>
<td>30Hz cycle</td>
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</tr>
<tr>
<td>9</td>
<td>Graphene sheets</td>
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<td>Comparison</td>
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<tr>
<td>10</td>
<td>MWCNT on silicon rubber</td>
<td>500%</td>
<td>19°C</td>
<td>.</td>
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<tr>
<td>11</td>
<td>SWNT/polymide</td>
<td>10%</td>
<td>RT</td>
<td>.</td>
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</tr>
<tr>
<td>12</td>
<td>PS/MWCNT/GNP</td>
<td>.</td>
<td>RT</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>13</td>
<td>Graphene</td>
<td>1.5%</td>
<td>RT</td>
<td>.</td>
<td>Quasi static</td>
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</tbody>
</table>
### Scenario

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>CB/CNT filler in conductive rubber</td>
<td>280%</td>
<td>RT</td>
<td>Quasi static</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>SW helical CNT yarns</td>
<td>500%</td>
<td>RT</td>
<td>600 cycles</td>
<td></td>
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<tr>
<td>16</td>
<td>Patterned graphene ripple</td>
<td>7%</td>
<td>RT</td>
<td>Quasi static</td>
<td></td>
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<tr>
<td>17</td>
<td>CB/TPE</td>
<td>50%</td>
<td>RT</td>
<td>Quasi static</td>
<td>3D printed</td>
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<tr>
<td>18</td>
<td>MWCNT/ poly(e-caprolactone)</td>
<td>70%</td>
<td>RT</td>
<td>Quasi static</td>
<td></td>
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<tr>
<td>19</td>
<td>Silver particles into PDMS or CNT into polymer-based pastes</td>
<td>15%</td>
<td>RT</td>
<td>Quasi static</td>
<td>flexible electrodes</td>
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<tr>
<td>20</td>
<td>Thermoplastic elastomer (Evoprene)/CB nanoparticle</td>
<td>0.1%</td>
<td>RT</td>
<td>Quasi static</td>
<td>Acrylic latex is used to make a protective film layer on the sensor</td>
</tr>
<tr>
<td>21</td>
<td>MWCNT/natural rubber</td>
<td>620%</td>
<td>RT</td>
<td>Quasi static</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Graphene woven fabrics GWFs</td>
<td>50%</td>
<td>RT</td>
<td>Quasi static</td>
<td>drying the GWF film on PDMS</td>
</tr>
<tr>
<td>23</td>
<td>CB based – ink jet printing</td>
<td>100%</td>
<td>RT</td>
<td>Quasi static</td>
<td>Hundreds of stretch-relaxation cycles</td>
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<tr>
<td>24</td>
<td>Micropattern of graphene oxide on PET</td>
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<td>RT</td>
<td>Quasi static</td>
<td>Ink jet</td>
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<tr>
<td>25</td>
<td>Graphene sheets rubber</td>
<td>800%</td>
<td>RT</td>
<td>Quasi static</td>
<td>infiltrate store-bought elastic bands</td>
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<tr>
<td>26</td>
<td>Graphene foam</td>
<td>50%</td>
<td>RT</td>
<td>Quasi static</td>
<td>CVD</td>
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</table>
## Industrial requirements

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Preliminary release</th>
<th>Advanced release (feasibility study)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical materials</td>
<td>Graphene or CNT, Polymer matrix</td>
<td>Spray (on pre-shaped elastomer)</td>
</tr>
<tr>
<td>Deposition technique</td>
<td>Spray (directly on the coupon)</td>
<td></td>
</tr>
<tr>
<td>Deformation range</td>
<td>Tens %</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>Space conditions</td>
<td></td>
</tr>
<tr>
<td>Temperature range</td>
<td>-50°C to +80°C</td>
<td>Space conditions</td>
</tr>
<tr>
<td>Humidity range</td>
<td>up to 100%</td>
<td>Space conditions</td>
</tr>
<tr>
<td>Frequency range</td>
<td>Low-Medium Range</td>
<td>Complex geometry (distributed)</td>
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<tr>
<td>Mask shape</td>
<td>Simple geometry</td>
<td></td>
</tr>
<tr>
<td>Fatigue (if applicable)</td>
<td>Hundreds cycles</td>
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<tr>
<td>Calibration</td>
<td>TBD</td>
<td>TBD</td>
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<tr>
<td>Sensitivity</td>
<td>TBD</td>
<td>TBD</td>
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<tr>
<td>Repeatability</td>
<td>Statistical evaluation</td>
<td>Statistical evaluation</td>
</tr>
<tr>
<td>Accuracy</td>
<td>TBD</td>
<td>TBD</td>
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</table>
Initial and final Technology Readiness Levels

**ELEMENT**

**Material:**
Graphene-polymeric matrix

**Integrated structure:**
Sprayed graphene-based deposition

**Sensor system:**
Operating sensor

**Working sensor:**
Within the specs
<table>
<thead>
<tr>
<th>INITIAL AND FINAL TECHNOLOGY READINESS LEVELS</th>
</tr>
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<tbody>
<tr>
<td><strong>ELEMENT</strong></td>
</tr>
<tr>
<td><strong>Material:</strong> Graphene-polymeric matrix</td>
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<tr>
<td><strong>Integrated structure:</strong> Sprayed graphene-based deposition</td>
</tr>
<tr>
<td><strong>Sensor system:</strong> Operating sensor</td>
</tr>
<tr>
<td><strong>Working sensor:</strong> Within the specs</td>
</tr>
</tbody>
</table>

**REFERENCE TRL (US DOD):**

- **3**: Graphene and polymeric matrixes do exist and have been proved.
- **2**: The specific graphene-polymeric concentration will be the object of the current research.
- **2**: Sensor functionality will be investigated in the current research.
- **1**: There is no guarantee the envisaged development will work within the operating specifications.


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## Initial and final Technology Readiness Levels

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>REFERENCE TRL (US DOD)</th>
<th>FINAL TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material:</strong></td>
<td>3 Graphene and polymeric matrixes do exist and have been proved</td>
<td>4 Graphene and polymeric matrix will be proved to work together into lab test specimens</td>
</tr>
<tr>
<td>Graphene-polymeric matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Integrated structure:</strong></td>
<td>2 The specific graphene-polymeric concentration will be the object of the current research</td>
<td>4 The graphene and polymeric matrix compound will be released together with the spray process</td>
</tr>
<tr>
<td>Sprayed graphene-based deposition</td>
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<td></td>
</tr>
<tr>
<td><strong>Sensor system:</strong></td>
<td>2 Sensor functionality will be investigated in the current research</td>
<td>4 The proof they are able to work together will be obtained by dedicated experiments</td>
</tr>
<tr>
<td>Operating sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Working sensor:</strong></td>
<td>1 There is no guarantee the envisaged development will work within the operating specifications</td>
<td>5 The sensor is tested proving functionality within environmental parameters and preliminary space qualification processes</td>
</tr>
<tr>
<td>Within the specs</td>
<td></td>
<td></td>
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**REFERENCE TRL (US DOD)**

- **3**: Graphene and polymeric matrixes do exist and have been proved
- **2**: The specific graphene-polymeric concentration will be the object of the current research
- **2**: Sensor functionality will be investigated in the current research
- **1**: There is no guarantee the envisaged development will work within the operating specifications
- **4**: Graphene and polymeric matrix will be proved to work together into lab test specimens
- **4**: The graphene and polymeric matrix compound will be released together with the spray process
- **4**: The proof they are able to work together will be obtained by dedicated experiments
- **5**: The sensor is tested proving functionality within environmental parameters and preliminary space qualification processes
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GANTT

<table>
<thead>
<tr>
<th>WP Id</th>
<th>WP Title</th>
<th>Task Id</th>
<th>Task title</th>
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<tbody>
<tr>
<td>WP0</td>
<td>Management</td>
<td>0.1</td>
<td>Technical Management</td>
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<td></td>
<td>0.2</td>
<td>Financial and Administrative Management</td>
</tr>
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<td>0.3</td>
<td>Dissemination &amp; Exploitation</td>
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<td>0.4</td>
<td>Value and Risk, CCR</td>
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<tr>
<td>WP1</td>
<td>Specifications</td>
<td>1.1</td>
<td>Critical bibliographic survey</td>
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<tr>
<td></td>
<td></td>
<td>1.2</td>
<td>Specifications</td>
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<td>1.3</td>
<td>Test matrix release and instrumentation identification</td>
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<tr>
<td>WP2</td>
<td>Materials and Processes</td>
<td>2.1</td>
<td>Graphene-polymeric matrix composition assessment</td>
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<td>2.2</td>
<td>Dispersion conditions definition</td>
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<td>2.3</td>
<td>Controlled deposition process assessment</td>
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<tr>
<td>WP3</td>
<td>Design and optimization</td>
<td>3.1</td>
<td>Sensor layout definition</td>
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<td>3.2</td>
<td>Coupled system modeling</td>
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<td>3.3</td>
<td>Optimization</td>
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<td>WP4</td>
<td>Manufacture and integration</td>
<td>4.1</td>
<td>Graphene manufacturing and deposition</td>
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<td>4.2</td>
<td>Sensor electrical integration and signal conditioning</td>
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<td>4.3</td>
<td>Morphological and functionality tests</td>
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<td>WP5</td>
<td>Experimental Charact.</td>
<td>5.1</td>
<td>Setup realization</td>
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<td>Calibration tests</td>
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<td>Electromechanical tests</td>
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<td>5.4</td>
<td>Environmental tests</td>
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<td>WP6</td>
<td>Conclusions</td>
<td>6.1</td>
<td>Final review on the attained results</td>
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## Test matrix for the 1st release of the sensor

<table>
<thead>
<tr>
<th>ID</th>
<th>Coupon/Constraint</th>
<th>Electro-Quasi Static</th>
<th>Electro-Dynamic</th>
<th>Environmental</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>- 3 point bending (strain gauge limit) (tension and compression)</td>
<td>Sine excitation (via pzt) at resonances (0-500Hz)</td>
<td>@RT,H,P</td>
</tr>
<tr>
<td>2</td>
<td>#3 - Alu beam</td>
<td></td>
<td>Sine excitation (via pzt) at resonances (0-500Hz)</td>
<td>-T:-50°C to +80°C with 10°C incremental step</td>
</tr>
<tr>
<td>3</td>
<td>clamped-clamped and clamped-free</td>
<td></td>
<td>Sine excitation (via pzt) at resonances (0-500Hz)</td>
<td>-T:-50°C to +80°C with 10°C incremental step -H: 50% to 100% with 10% incremental step.</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>- 3 point bending (strain gauge limit) (tension and compression)</td>
<td></td>
<td></td>
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</table>
### Test matrix for the 1st release of the sensor

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<tr>
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<th>Electro-Dynamic</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td>- 3 point bending (strain gauge limit) (tension and compression)</td>
<td>Sine excitation (via pzt) at resonances (0-500Hz)</td>
<td>@RT,H,P</td>
</tr>
<tr>
<td>6</td>
<td>#3 - CF beam</td>
<td></td>
<td>Sine excitation (via pzt) at resonances (0-500Hz)</td>
<td>-T:-50°C to +80°C with 10°C incremental step</td>
</tr>
<tr>
<td>7</td>
<td>clamped-clamped and clamped-free</td>
<td></td>
<td>Sine excitation (via pzt) at resonances (0-500Hz)</td>
<td>-T:-50°C to +80°C with 10°C incremental step -H: 50% to 100% with 10% incremental step.</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>- 3 point bending (strain gauge limit) (tension and compression)</td>
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</table>
## Test matrix for the 2nd release of the sensor

<table>
<thead>
<tr>
<th>ID</th>
<th>Coupon</th>
<th>Shape</th>
<th>Electro-Q Static</th>
<th>Environment</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>Traction – Ultimate load</td>
<td>@RT,H,P</td>
</tr>
<tr>
<td>2</td>
<td>#3 – Rubber</td>
<td>simple</td>
<td>Static traction: 0% Static traction: 25% Static traction: 50%</td>
<td>-T: -50°C to +80°C with 10°C step -H: 50% to 100% with 10% step -P: Space pressure condition</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>Static traction: 0% Static traction: 25% Static traction: 50%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>#3 – Foam</td>
<td>simple</td>
<td>Traction: Ultimate load</td>
<td>@RT,H,P</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>Static traction: 0% Static traction: 25% Static traction: 50%</td>
<td>-T: -50°C to +80°C with 10°C step -H: 50% to 100% with 10% step -P: Space pressure condition</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>Static traction: 0% Static traction: 25% Static traction: 50%</td>
<td></td>
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</table>
## Test matrix for the 2nd release of the sensor

<table>
<thead>
<tr>
<th>ID</th>
<th>Coupon</th>
<th>Shape</th>
<th>Electro-Q Static</th>
<th>Electro-Dyn</th>
<th>Environment</th>
</tr>
</thead>
</table>
| 7  | #3 - SMP | simple | Pred shape (flat)  
Recov shape (ring) | -Thermal Cycle (Tg) |             |
| 8  | #3 - SMP | simple | Pred shape (flat)  
Recov shape (ring) | -Thermal Cycle  
-H: 50% to 100% with 10% step |             |
| 9  | #3 - SMP | simple | Pred shape (flat)  
Recov shape (ring) | -Thermal Cycle  
-H: 50% to 100% with 10% step  
-P: Space pressure condition |             |
| 10 | #3 – SMA | simple | Pred shape (stretched)  
Recov shape (short) | -Thermal Cycle (Tg) |             |
| 11 | #3 – SMA | simple | Pred shape (stretched)  
Recov shape (short) | -Thermal Cycle  
-H: 50% to 100% with 10% step |             |
| 12 | #3 – SMA | simple | Pred shape (stretched)  
Recov shape (short) | -Thermal Cycle  
-H: 50% to 100% with 10% step  
-P: Space pressure condition |             |
| 13 | #1 - Alu | complex | Sine excitation (via pzt) at resonances | -T: -50°C to +80°C with 10°C step  
-H: 50% to 100% with 10% step  
-P: Space pressure condition |             |
| 14 | #1 - Alu | complex | Sine excitation (via pzt) at resonances | -T: -50°C to +80°C with 10°C step  
-H: 50% to 100% with 10% step  
-P: Space pressure condition |             |
| 15 | #1 - CF | complex | Sine excitation (via pzt) at resonances | -T: -50°C to +80°C with 10°C step  
-H: 50% to 100% with 10% step  
-P: Space pressure condition |             |
Preliminary results: modeling of the dispersion conditions

- Simulation of particle morphology
- Modeling of particle interaction
- Estimate of local electrical resistance
- Estimate of the global resistance
- Global resistance vs applied strain
Simulation of particle morphology

Random generation of the 1st point of the CNT, inside the volume fraction

Random generation of the next 4 points by spherical coordinate

Computation of curvature and torsion and related stress condition

Estimate of point distance wrt previous ones

no satisfaction of constraints

Random generation of the next point

Type of particle: MW CNT
Aspect ratio 1: 500
Length: 1000 nm
Simulation of particle morphology
Modeling of particle interaction

- Computation of the minimum distance among one CNT and the others
  - Contact
  - Out of tunnelling range
  - Within tunnelling range
  - Tunnel resistance estimate

\[ R_{\text{tun}} = \frac{h^2 d}{Ae^{2\sqrt{2m\lambda}}} \exp\left(\frac{4\pi d}{h}\sqrt{2m\lambda}\right) \]


MFMSiEM 2016, Texas A&M University, College Station, Texas, May 2-3 2016
Estimate of the local resistance

- Similitude with the heat transfer

\[ q = k \downarrow T \cdot \Delta T \]
\[ l = k \downarrow R \cdot \Delta V \]

CNT center of gravity
BC on the volume faces
Equivalent thermal links
Estimate of the local resistance

- Similitude with the heat transfer

\[ q = k \downarrow T \cdot \Delta T \]
\[ I = k \downarrow R \cdot \Delta V \]

CNT center of gravity
BC on the volume faces
Equivalent thermal links
Estimate of the local resistance

- Similitude with the heat transfer

\[ q = k \downarrow T \cdot \Delta T \]
\[ I = k \downarrow R \cdot \Delta V \]

CNT center of gravity
BC on the volume faces
Equivalent thermal links
Estimate of the local resistance

- Similitude with the heat transfer

\[ q = k_{\downarrow} T \cdot \Delta T \]
\[ l = k_{\downarrow} R \cdot \Delta V \]

\[ k_{\downarrow} T = k A/d \]
\[ k_{\downarrow} R = k' A/d \]

\[ k' : k' A/d = 1/R \]

CNT center of gravity
BC on the volume faces
Equivalent thermal links
Estimate of the local resistance

- Similitude with the heat transfer

\[ q = k_{\downarrow} T \cdot \Delta T \]

\[ l = k_{\downarrow} R \cdot \Delta V \]

\[ k_{\downarrow} T = k A/d \]

\[ k_{\downarrow} R = k' A/d \]

\[ k' : k' A/d = 1/R \]

- CNT center of gravity
- BC on the volume faces
- Equivalent thermal links
Estimate of the global resistance

• Steady heat transfer FE analysis

Single FE

\[
k \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}
\]

- CNT center of gravity
- BC on the volume faces
- Equivalent thermal links
Estimate of the global resistance

- Steady heat transfer FE analysis

\[ \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} \]

Single FE nodal temperatures

CNT center of gravity
BC on the volume faces
Equivalent thermal links
Estimate of the global resistance

- Steady heat transfer FE analysis

\[
k \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}
\]

- Single FE
- CNT center of gravity
- BC on the volume faces
- Equivalent thermal links

nodal heat power
Estimate of the global resistance

- Steady heat transfer FE analysis

\[ k \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} \]

- CNT center of gravity
- BC on the volume faces
- Equivalent thermal links

Limitations:
- Steady approach (no current displacement considered)
- Only tunneling resistance included in the model
- Applicable to a small volume (2000 x 2000 x 2000 \( \text{vm} \))
Conclusions

• The GRAPSS Project was presented in terms of scope, available sources, background, strategy and planning

• The first activities were described:
  • SoA on similar applications
  • Test matrix identified on the basis of aerospace industrial requirements
  • Modeling approach to relate sensor electrical resistance to the applied strain
Further steps

- Modeling approach assessment (reduction of computational efforts)
- Database / lookup table preparation to drive the identification of the key parameters for the dispersion procedure: particle morphology and concentration
- Material and Processes assessment
- Test specimen preparation
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MANY THANKS
FOR YOUR KIND ATTENTION!

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GRAPSS: Graphene-Polymeric Spray Sensor for Shape Recognition of Super-Deformable Structures,
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MFMSiEM 2016, Texas A&M University, College Station, Texas, May 2-3 2016