Graphene coated sensor yarn for composite preforms

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Textiles based composites

- **Textile based composite Structures:**

  A composite structure is a combination of two different materials;
  Reinforcement + Matrix.
  Reinforcement = Unidirectional, Bi-directional, Woven, knitted.
  Matrix= Resin = Thermoset or thermoplastic.

- **Structural properties:**

  Strong, light weight, high strength and stiffness.
  some applications, Aerospace, automobile & sports goods.

http://www.sciencedirect.com/science/article/pii/S0376042110000369

http://www.sciencedirect.com/science/article/pii/S0376042105000448

Limitations of composite structures

- Damage initiation and progression is a complex process.
- Delamination start at micro scale and can be remain hidden.
- **NDT methods**

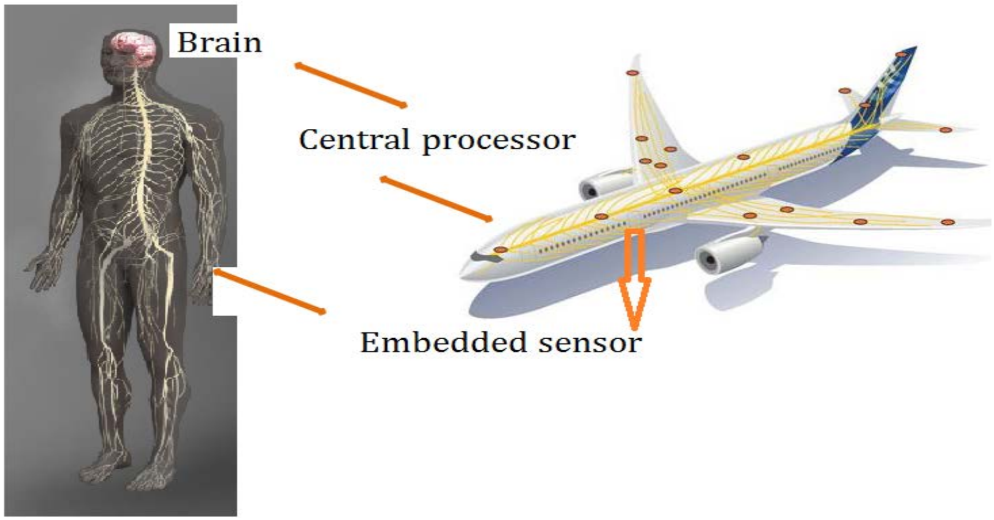
  Visual inspection, Acoustic emission, Ultrasonic , radiography, thermography.

  Limitations: performed at scheduled intervals,
  expensive (time consuming+ laborious).
  damage could remain hidden for some time.

- Prediction of damage is a challenge.
- Need to develop systems which can monitor the state of health.

Multifunctional structures

- Multi-functional composite structures offer multi-features and can perform more than one function.
- Smart structures act as an monitoring structure and can sense external stimuli, like pressure, temperature etc.
- Possible by integration of sensors.
- Synonymous to a human body.



Concept of health monitoring to a human nervous system

Part of picture taken from http://www.compositesworld.com/articles/structural-health-monitoring-composites-get-smart

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Literature gap

- **Sensors are added mostly within the rigid composite structure.**

  Thermoset and Thermoplastics resins used.

- **Similarly, little work is carried out in developing flexible smart composites.**

- **The aim of this research is to compare existing sensor material against graphene coated sensor yarn.**
- **Sensor type = *yarn based*.**

  share same geometrical makeup.
- **Textile technological process (*weft knitting*) is used for sensor integration).**
- **Focus on the how the sensor functions inside the composite.**
- **Characterisation =strain sensor/ pressure sensor.**

Types of sensors used for monitoring composites

- Optical fibres
- Preform as sensor.

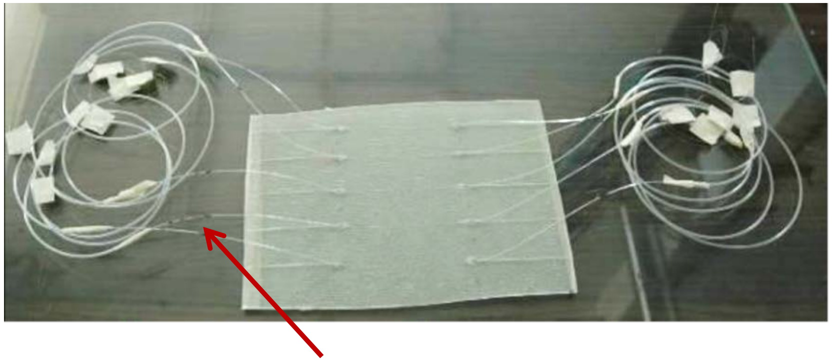
  Conductivity of carbon fibre
- Electro-conductive yarns.

  carbon fibre yarn, metal coated yarn, electro-conductive material coated yarn .
- Piezo electric/piezo ceramics sensors.

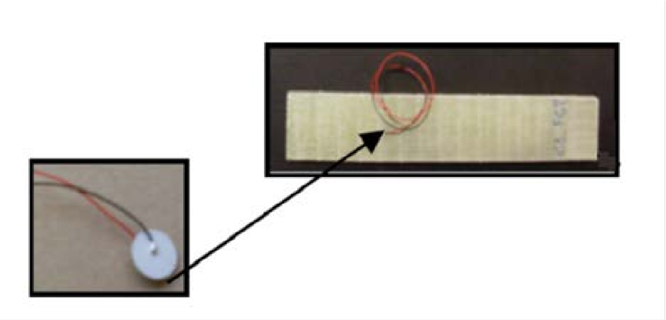
Synthetic: PZT (lead zirconate titanate), ($BaTiO_3$), PVDF etc.

Can be surface mounted or embedded.

Sensors in composites

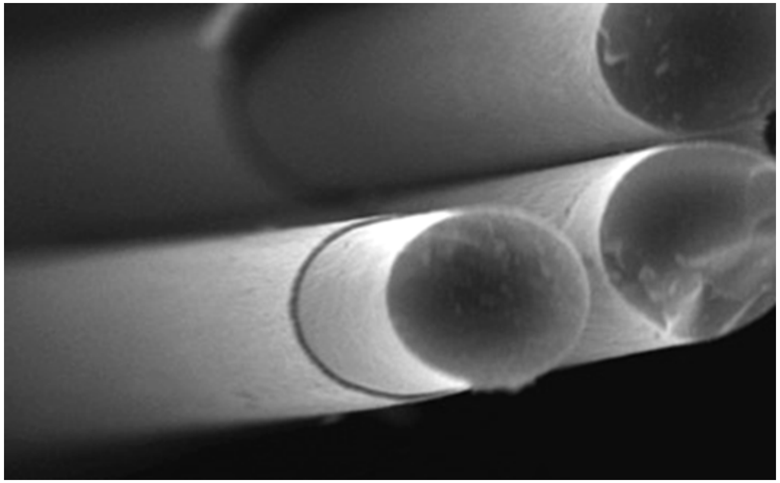


Glass Optical fibre



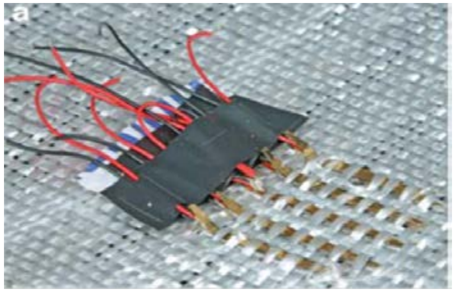
Piezo-electric based sensors

http://link.springer.com/chapter/10.1007/978-3-642-37143-1_37# cited on 12th June 2014



Aracon (Nickel coated by CVD on high performance fibres).

http://www.conductivecomposites.com/fibers.html



PVDF strips co-woven during preforming.

http://link.springer.com/chapter/10.1007/978-90-481-3771-8_25# cited on 12th June 2014

Sensor yarn materials

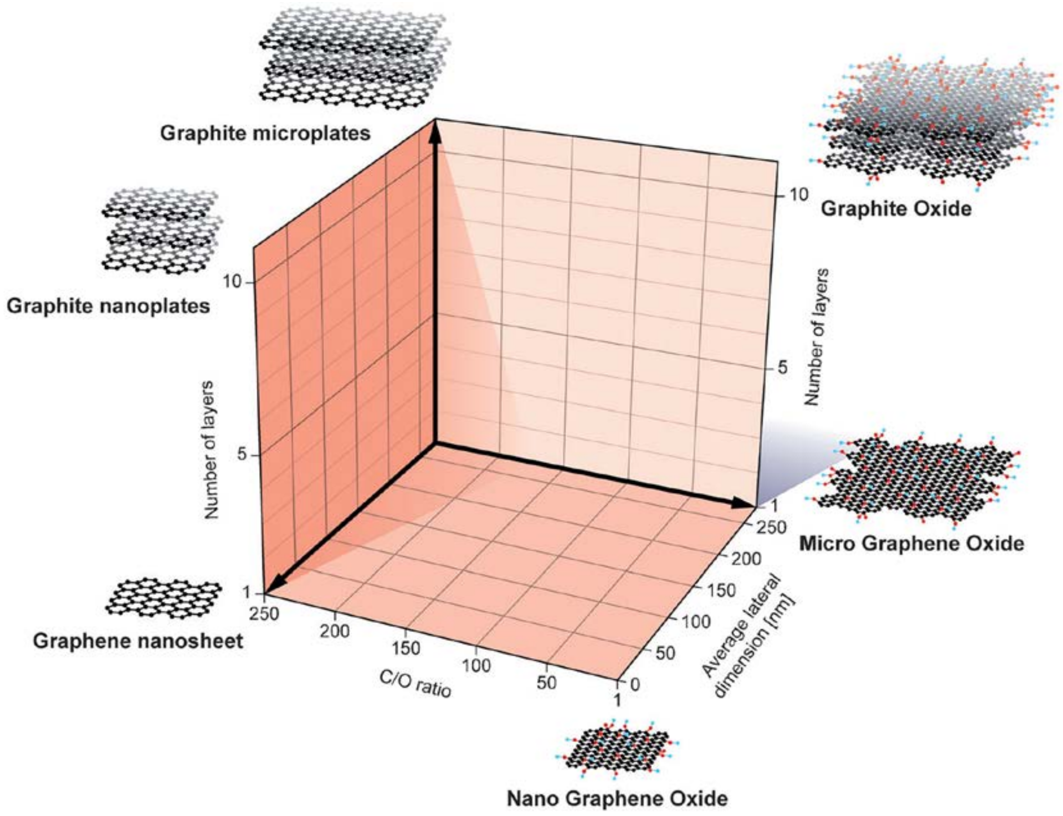
Continuous filament carbon fibre sewing threads (TIBTECH, Carbon Tenax)

Metallic coated sewing threads (TIBTECH, Silverpam 250)

Graphene-coated yarns

Bekinox® VN14/2x90/175S/316L
Stainless steel continuous filament yarn

Graphene

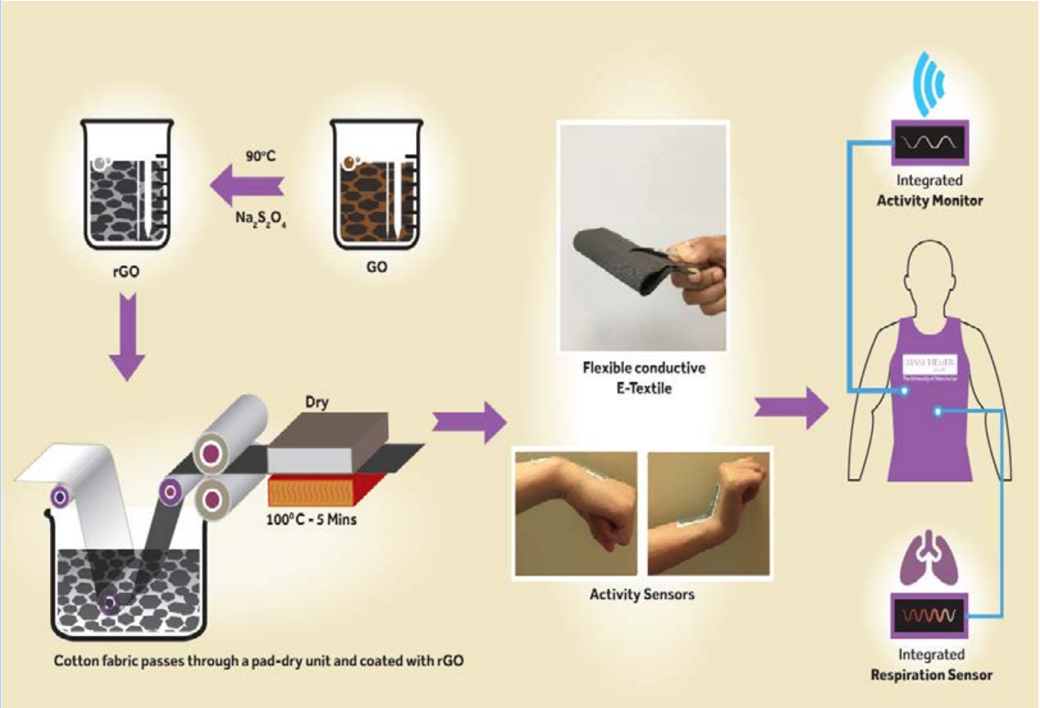


Classification for different graphene-type materials is based on the number of layers, the C/O ratio and the lateral dimensions, from Ref. [37].

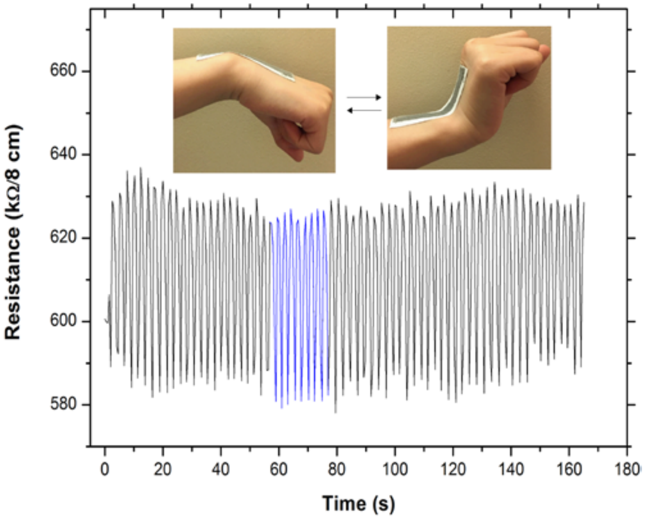
Graphene for wearable sensing

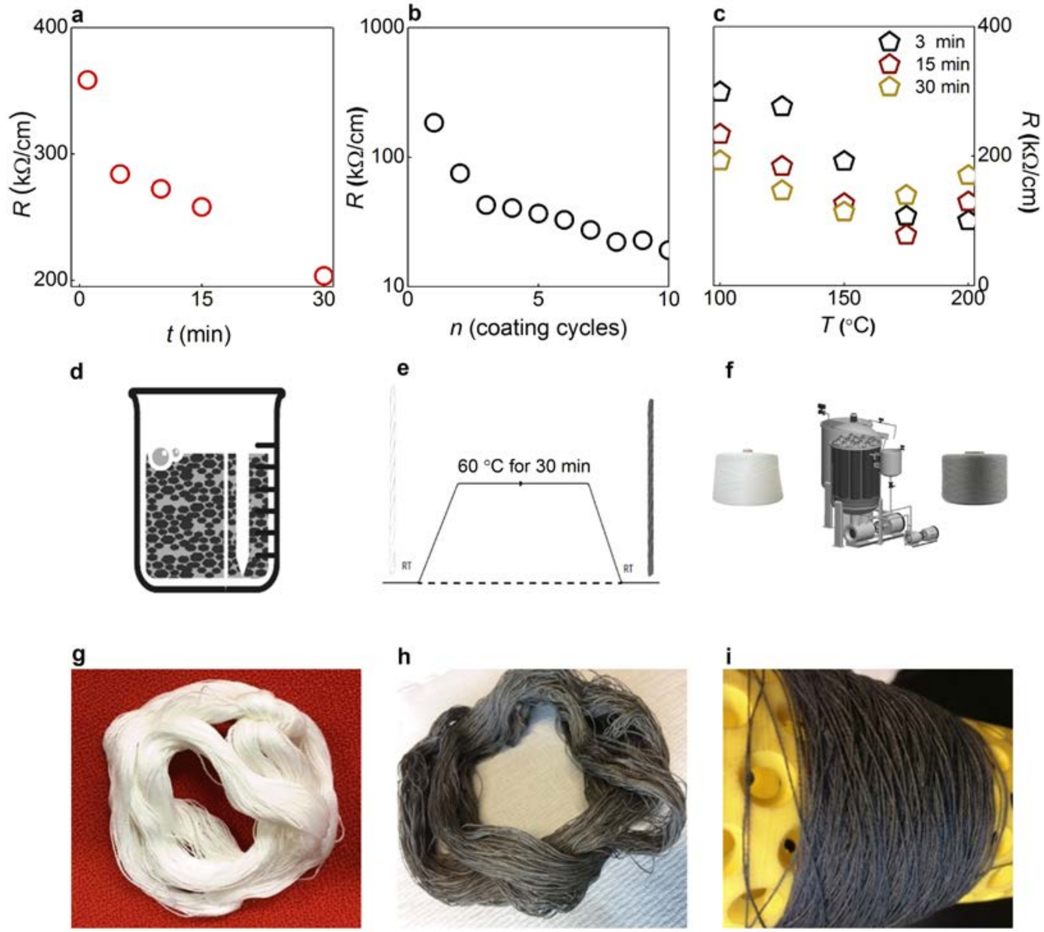
Wearable sensing research

- Material development
  - Metallic compound based textile sensing materials
  - 2D materials based textile sensing materials
- Technology development



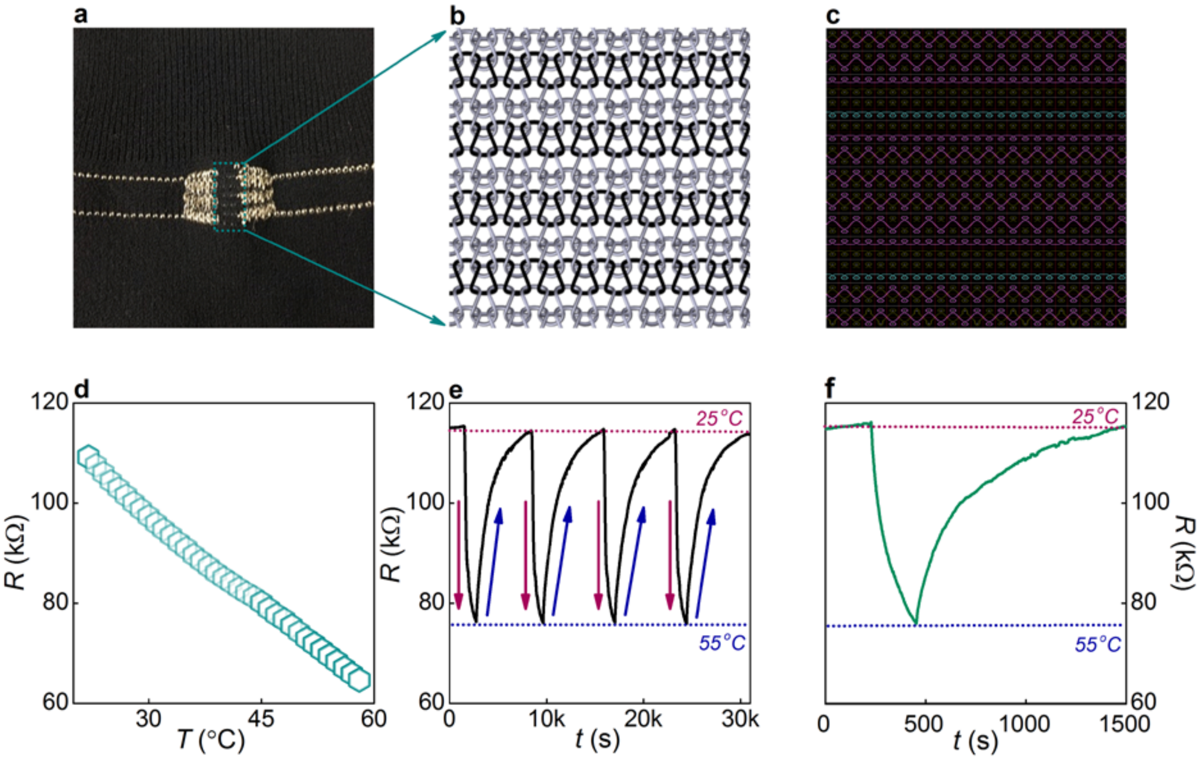
https://pubs.acs.org/doi/abs/10.1021/acsnano.7b05921





Optimisation of rGO coating. a) *The change of resistance of rGO (SH) yarn with coating time.* ***b)*** *The resistance of rGO (SH) coated and dried (at 100 °C) yarn Vs number of coating cycles.* ***c)*** *The change of rGO (SH) yarn resistance with curing time and temperature.* ***d)*** *Rapidly reduced graphene oxide rGO (SH) ink.* ***e)*** *A dyeing cycle diagram of textile yarn with rGO (SH) at 60 °C for 30 minutes.* ***f)*** *A commercial yarn dyeing machine which could potentially dye tonnes (~1,000 kg) of textile yarn (in packages).* ***g)*** *Undyed hank of scoured-bleached control cotton yarn.* ***h)*** *A hank of rGO dyed (coated) cotton yarn.* ***i)*** *Highly flexible graphene-coated yarn wrapped around a cone.*

https://www.researchgate.net/publication/331414209_Engineering_Graphene_Flakes_for_Wearable_Textile_Sensors_via_Highly_Scalable_and_Ultrafast_Yarn_Dyeing_Technique



Fabrication and characterisation of knitted graphene sensors a) *Knitted temperature sensor with graphene coated yarn.* ***b)*** *Knitted structure used as a scaffold for the placement of graphene yarn as temperature sensor.* ***c)*** *Yarn path notation diagram for knitted temperature sensors.* ***d)*** *Temperature dependence of the resistance of knitted sensor showing almost linear change with negative temperature co-efficient.* ***e)*** *Cyclic test of knitted sensor's temperature sensitivity between 25 and 55 °C shows excellent repeatability.* ***f)*** *Time response property of knitted temperature sensor.*

Theoretical aspects

Resistance of an electrical conductor is given by

$$R = \rho \frac{L}{A} \quad ------------- (1)$$

R = electrical resistance in the conductor

ρ = electrical resistivity of the material

L = length of the electrical conductor

A = electrical current carrying area

$$R_c = \frac{\rho_m}{2} \left(\frac{\pi \rho_f}{W} \right)^{\frac{1}{2}} \quad ------------- (2)$$

R_c = contact electrical resistance between filaments

ρ_m = volume resistivity of the materials

ρ_f = hardness in the contact due to constrictive forces between conductors

W = contact force

Theoretical aspects

Relative resistance change per unit initial resistance $= \dfrac{\Delta R}{R_0}$

ΔR = change in resistance

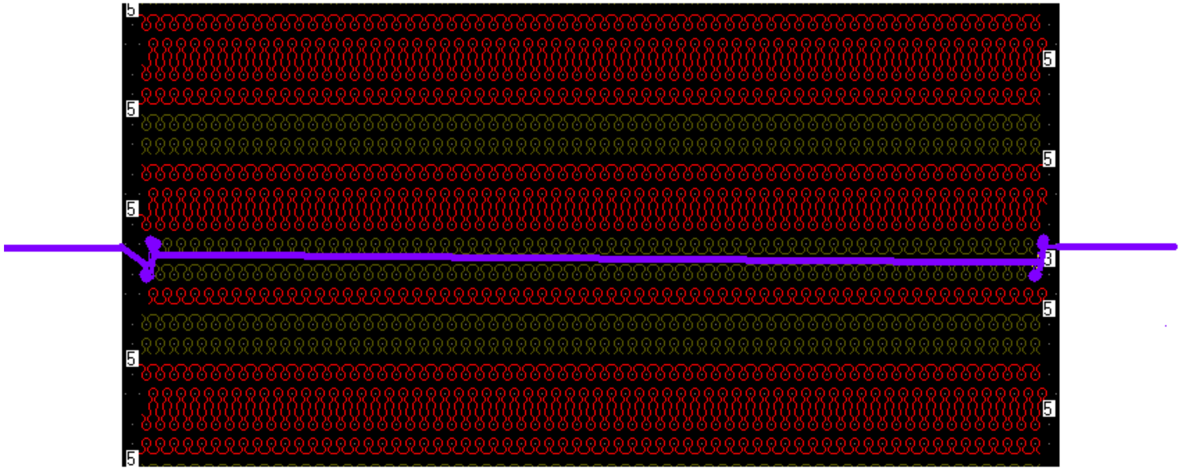
R_0 = initial resistance

$$GF = \frac{\Delta R}{R_0} \Big/ \varepsilon$$

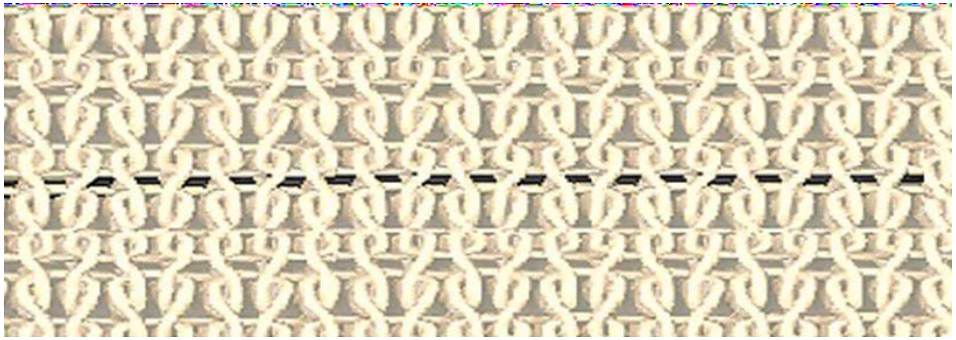
GF = gauge factor

ε = strain in the yarn

Experimental design

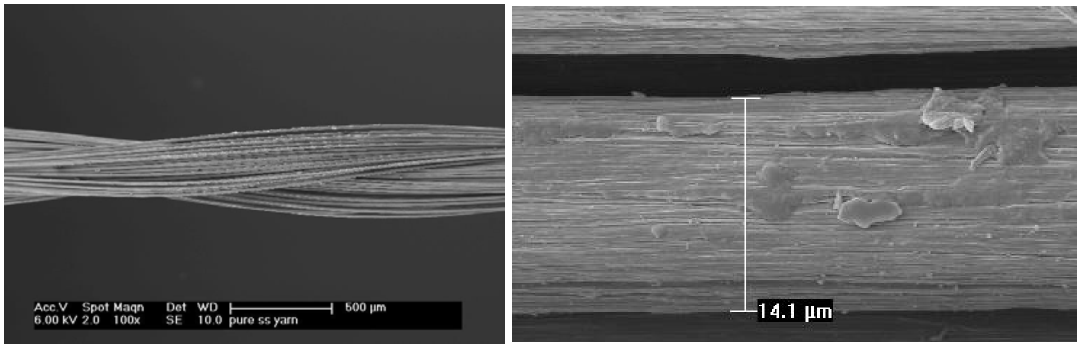


Yarn path notations for the sensor yarn integrated full Milano structure

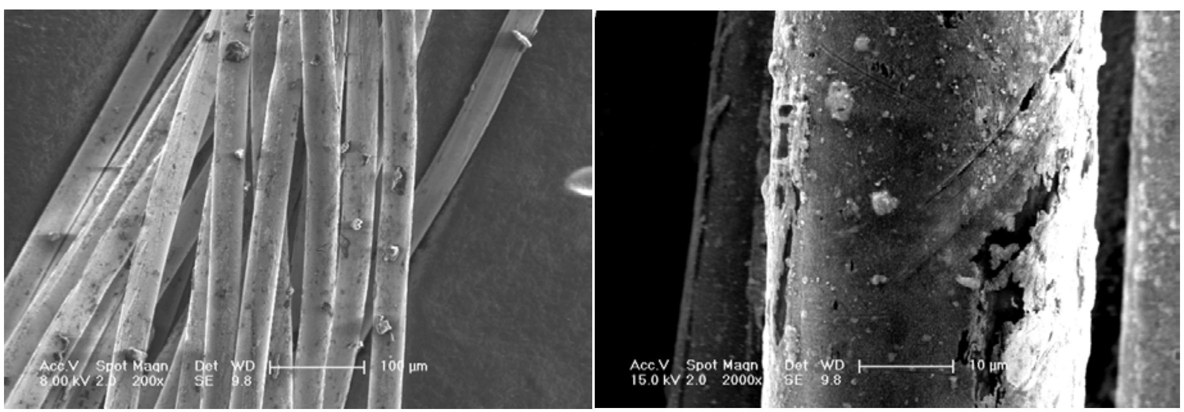


Full Milano structure with the single sensor yarn

Morphology of the sensor yarn

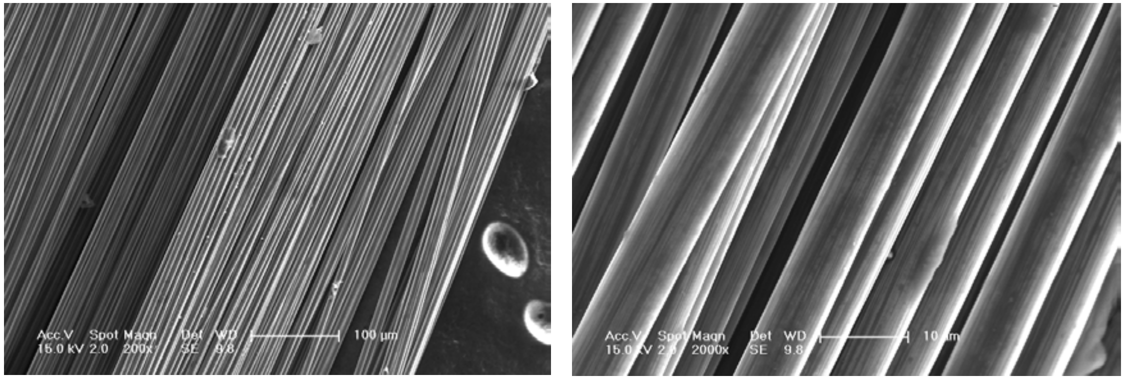


Two-ply continuous filament SS yarn (**a**) at 100x magnification; (**b**) at 4000x magnification

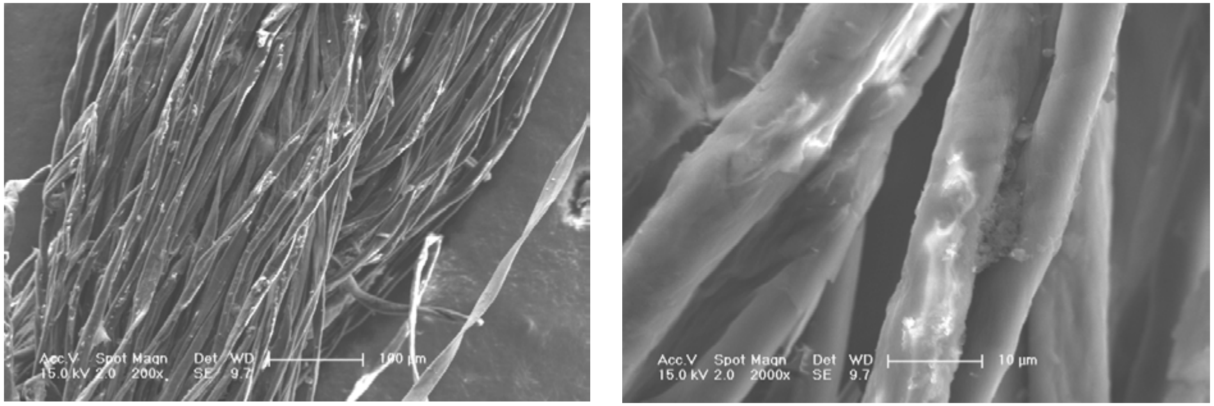


Continuous fibre silver coated polymeric yarn (**a**) at 200x magnification; (**b**) at 2000x magnification

Morphology of the sensor yarn



Continuous fibre carbon yarn (**a**) at 200x magnification; (**b**) at 2000x magnification



Graphene coated cotton yarn (**a**) at 200x magnification; (**b**) at 2000xmagnification

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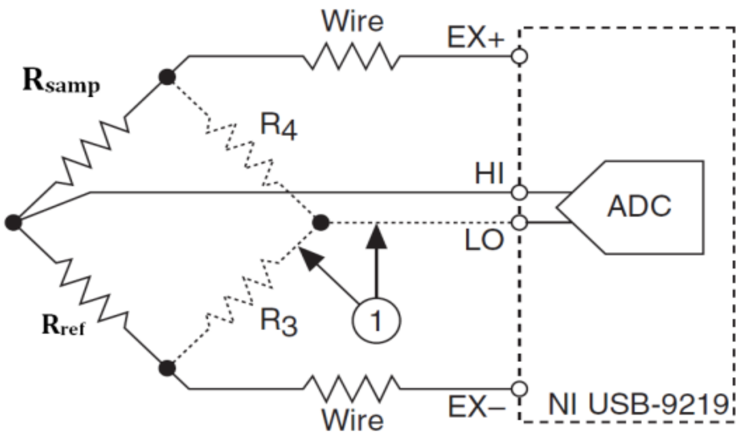
Comparison of the sensor yarns

For the stainless steel yarn, the tenacity was 18cN/Tex where the fineness of the Stainless Steel yarn was 250Tex

Mechanical properties for the electro-conductive sewing threads

Sensor yarn	Young's modulus (pa)	Break point (N)	Elastic limit (%)
Graphene	1692.31	2.8	0.52
Carbon	26800	52.4	1
Silver	190	7.6	10

Electromechanical Characterisation



$R_1 = \mathbf{R_{samp}}$ & $R_2 = \mathbf{R_{ref}}$

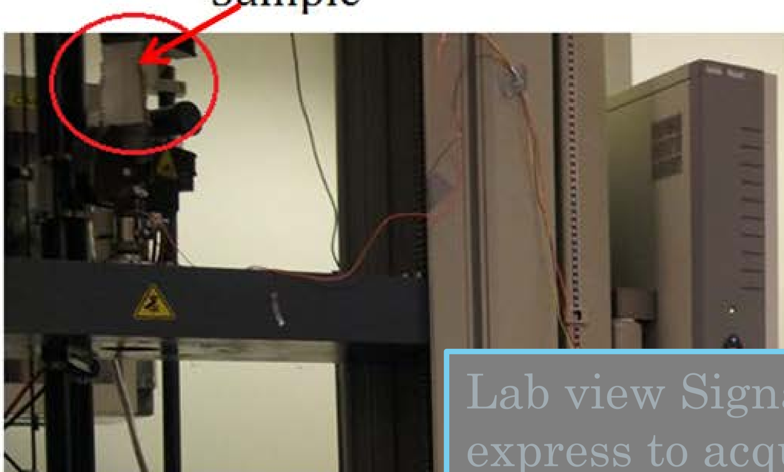
Half-bridge circuit diagram with NI-9219,Full- lines representing external circuit while (1)- dotted lines represent the circuitry connected inside the 9219-module, source from National instruments (Instruments, 2011)

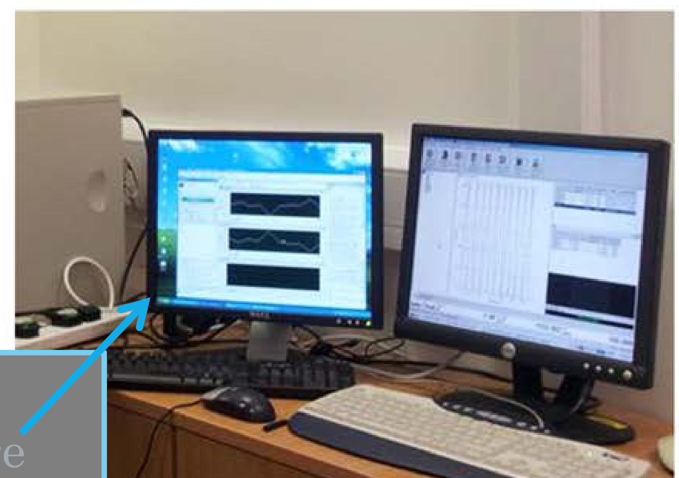
$$R_{ref} = \sqrt[2]{R_{samp_@}minvalue * R_{samp_@}maxvalue}$$

R_{sample} =With an accuracy of ±0.5 Ωs

$$R_{sample} = \frac{R_{ref} - 2 * NI_{9219reading} * R_{ref}}{2 * NI_{9219reading} + 1}$$

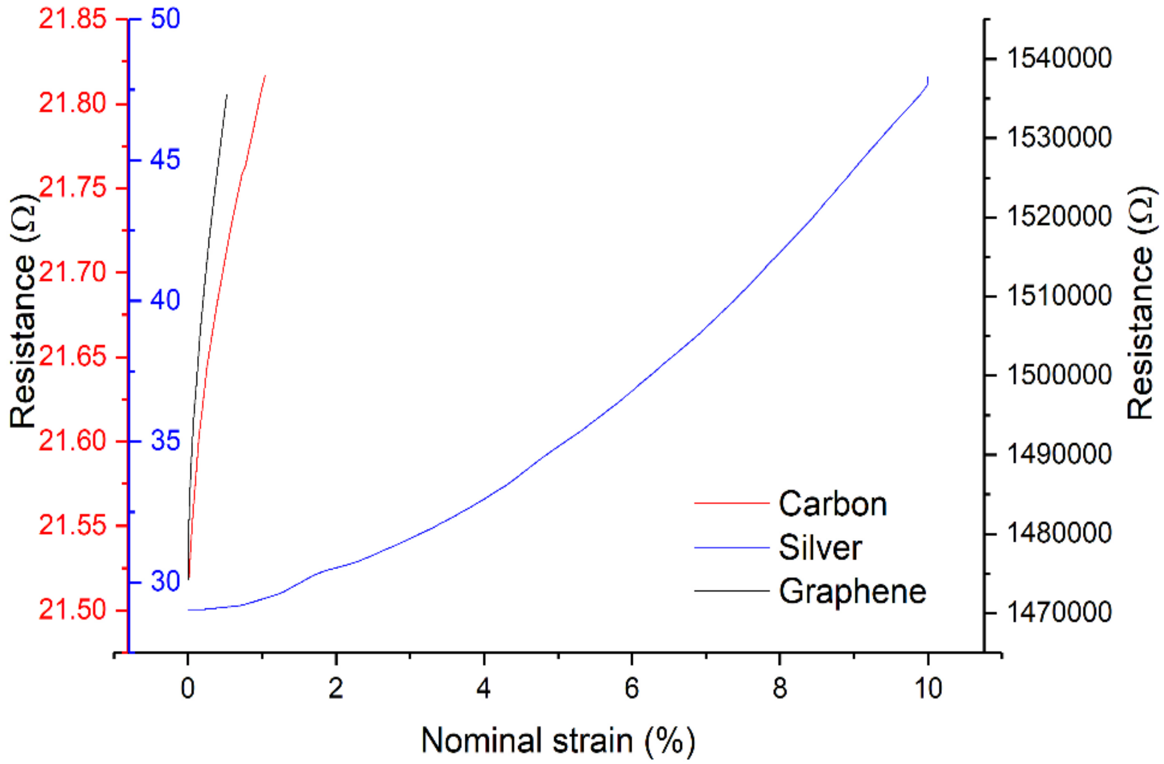
Sample





Lab view Signal express to acquire the data

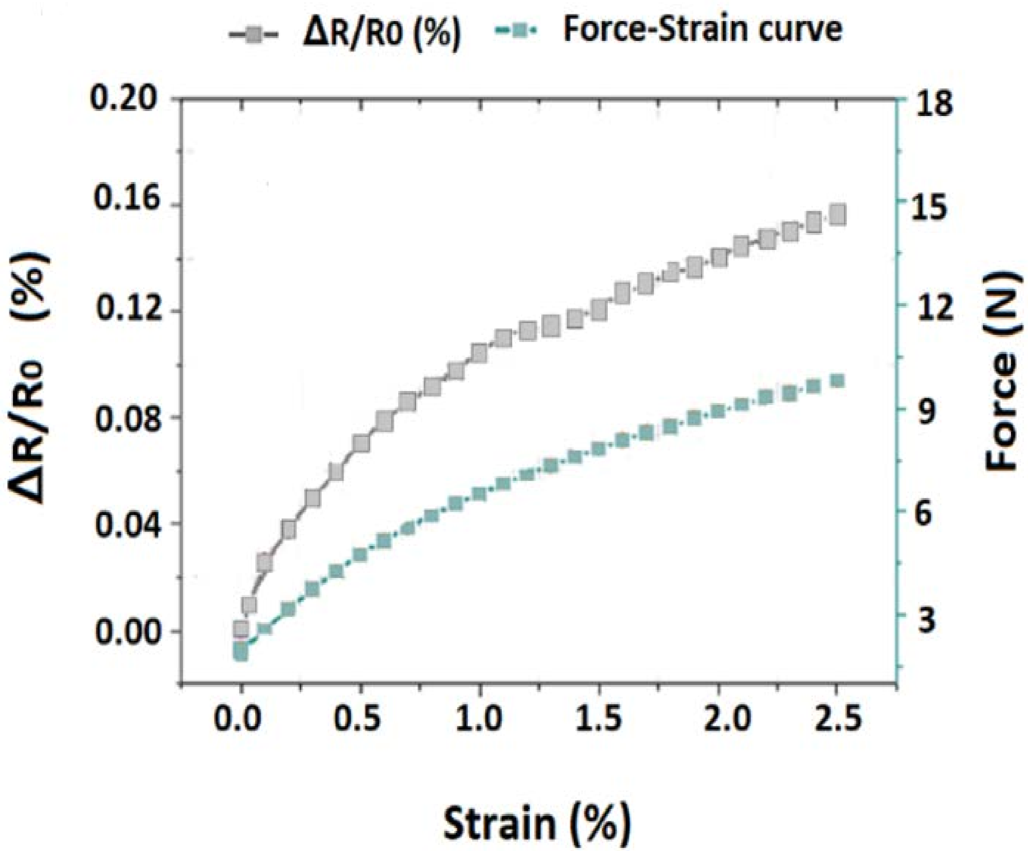
Comparison of sensor yarn



Electrical resistance of silver, carbon and graphene sensor yarn against strain experienced

Results and conclusions

Stainless steel yarn integrated composite testing



- Electro-mechanical testing
- Zwick Roell Z050 tensile machine. 10KN load cell.
- Rate = 2 mm/min.
- Gauge length = 100 mm.
- Number of samples= 6

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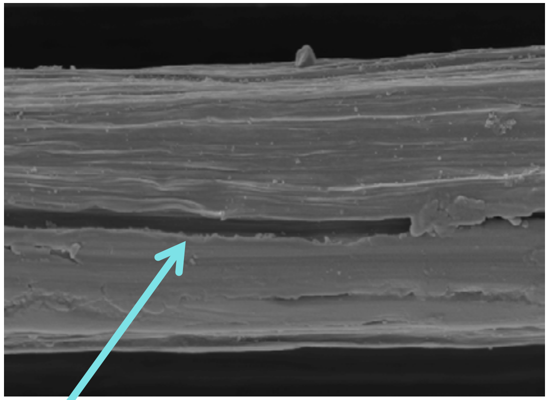
Conclusions

Results showed that instead of tensile loading of the sensor yarn, using compressive loading to measure the tensile stain gives better results for graphene coated yarn.

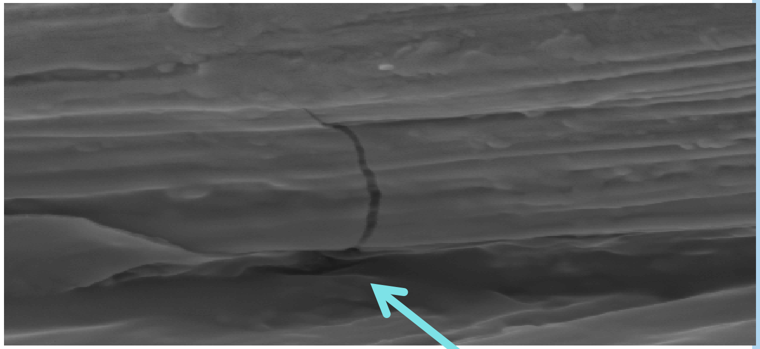
These results show that by designing the graphene coated sensor in a more efficient way, higher sensor sensitivities and gauge factors could be achieved.

Under compressive loading mechanism, the sensitivity of the graphene coated sensor yarn are far better than the other yarn tested.

Damage at microscopic level for the stainless steel yarn

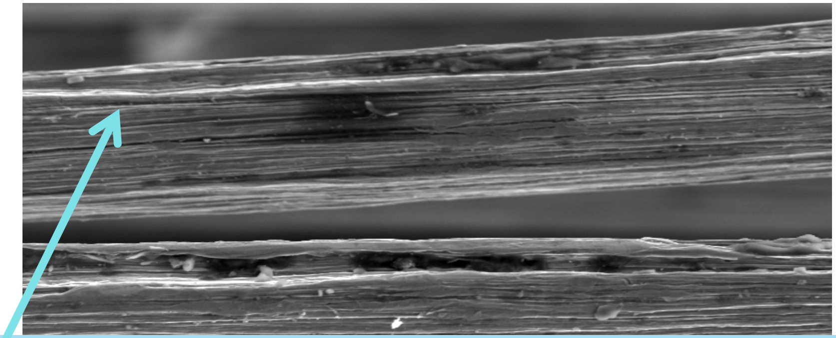


Sensor Design One Sample showing exfoliation within single filament, image taken at 8000X magnification



Sensor design One –

Crack within single filament, picture taken at 16000x.



Sensor design1 stretched till 7% strain showing progressive exfoliation within each strand (SEM Image taken at 4000x Magnification)

Possible improvements

- Gauge factor improvement by changing design of sensing preform.
- Increase of flexibility range without avoiding permanent deformation.
- Use of fine Tex Glass yarn.
- Development of composite structure.
- Electromechanical characterisation.
- Further studies to evaluate the reliability of the sensing yarn.

End of presentation

Thank you!