Strain Sensor Survey for Parachute Canopy Load Measurements

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NASA Armstrong Flight Research Center

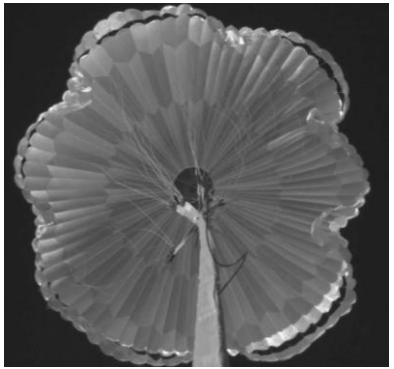
Aerodynamic Decelerator Systems Technology Conference and Seminar, May 14-19, 2022

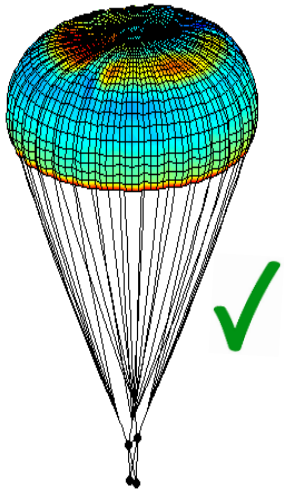
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WHY?

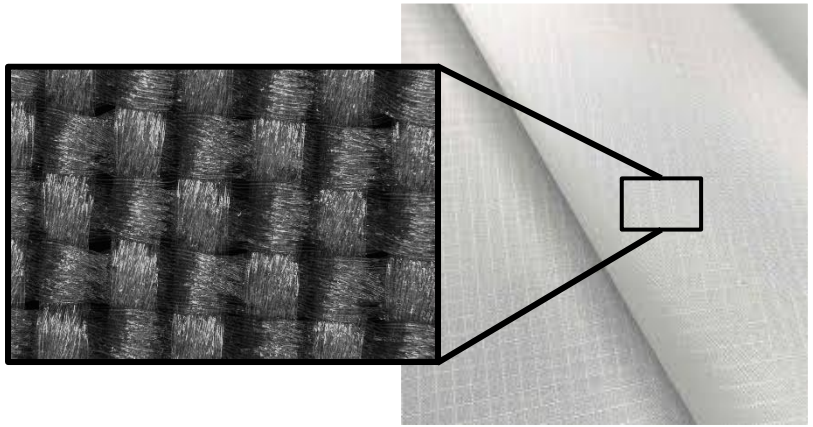
- Parachutes are at the edge of design limits (margins not well understood)
- Expensive & difficult to design and test parachutes
- Current models aren't validated
  - Modelers need real data to define the loading environment on the canopy

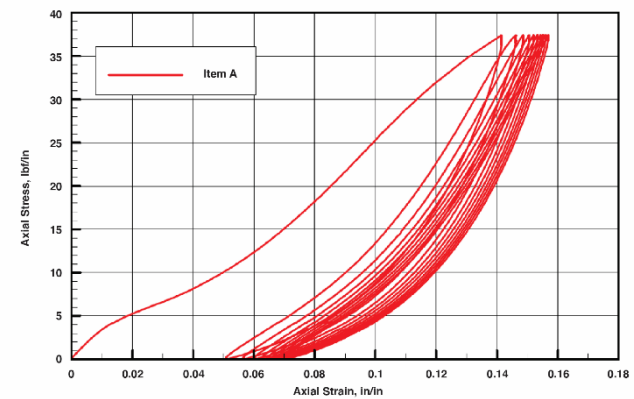




Instrumentation Challenges: Canopy Fabric

- Focus on canopy broadcloth
  - Ripstop Nylon
- Difficult to characterize mechanical response
- Sensing method cannot damage or modify parachute performance

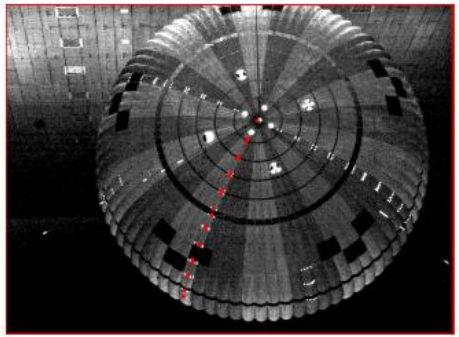




Ref.1

Latest Instrumentation and Testing

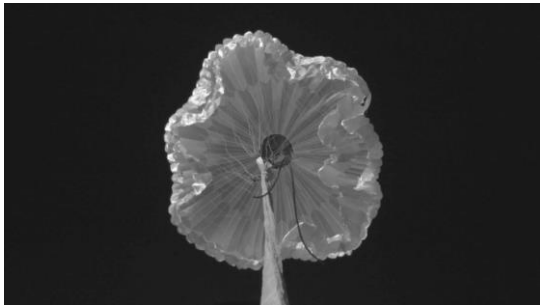
- Wind tunnel tests
  - Photogrammetry for shape, lines instrumented for load
- Drop Tests
  - Line data and image-based area & motion tracking
- Sounding rocket qualification tests
  - Limited suspension line data



https://arc.aiaa.org/doi/10.2514/6.2018-3802



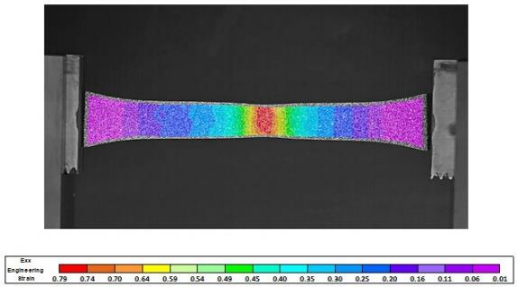




https://www.nasa.gov/feature/jpl/third-aspire-test-confirms-mars-2020-parachute-a-go

Current Technology and Vision Based Limitations

- Digital Image Correlation (DIC) and Photogrammetry
  - Requires line of sight, stationary cameras, and a zero-strain reference frame



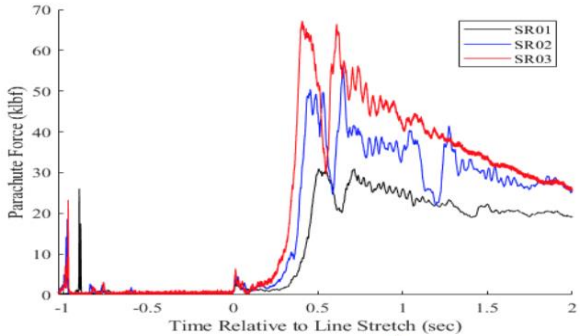
- **Need in-situ local strain measurements on canopy**

Sensor Requirements

- Up to 40% strain (conservative failure)
- High strain rate, inflation in < 0.5 sec
- Minimal hysteresis
- Minimal drift
- Pressure packed
- Data acquisition and wiring cannot interfere



NASA/JPL-Caltech



https://doi.org/10.2514/6.2019-3376

Ref. 2

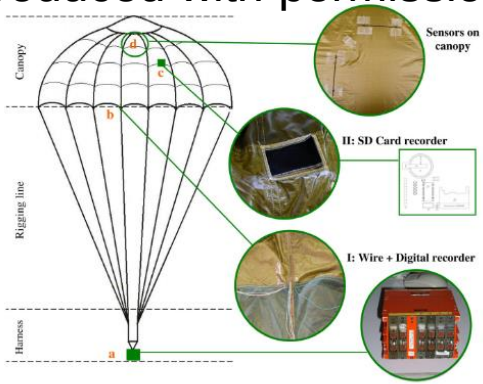
State of the Art Sensor Applications

- Emerging from combination of different application areas: medical and biomonitoring [12], soft robotics [13], flexible circuits [14], smart fabrics [15], and other soft goods industries [16] .



Katabasis Aerospace (AIAA 10.2514/6.2019-3146)

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Cochrane et al 2010
http://www.mdpi.com/1424-8220/10/9/8291

Sensor Survey

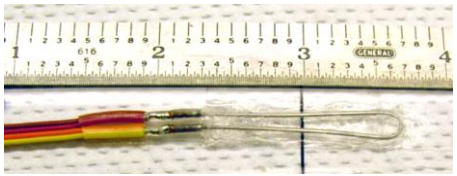
Transition slide

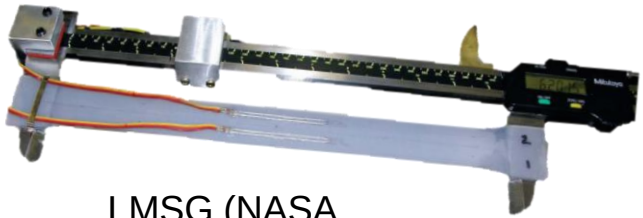
Resistive Based Sensors

- Elastic Strain Gauges
  - Create conductive elastomer: embed conductive particles, gels, or liquids

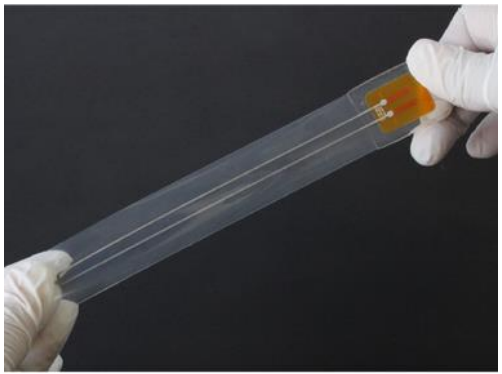
$$GF = \frac{\Delta R}{R\epsilon}$$

- Liquid and Ionic metal strain gauges





LMSG (NASA AFRC)



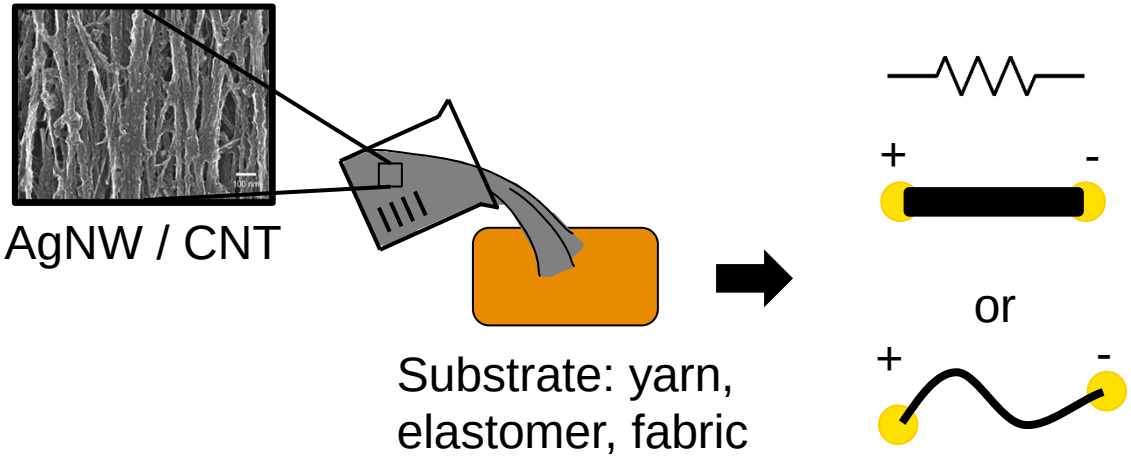
https://www.liquidwire.com/

Resistive Based Sensors

- Conductive inks and coatings: silver nanowires (AgNW), and carbon nanotubes (CNT) / graphene / carbon black

Generalized process

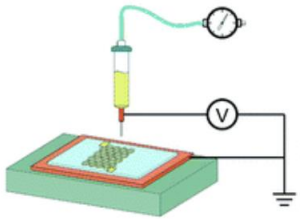
https://technology.nasa.gov/patent/LAR-TOPS-292

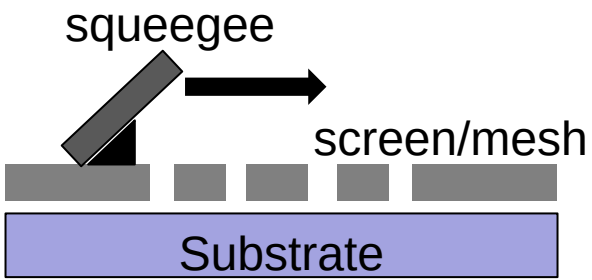


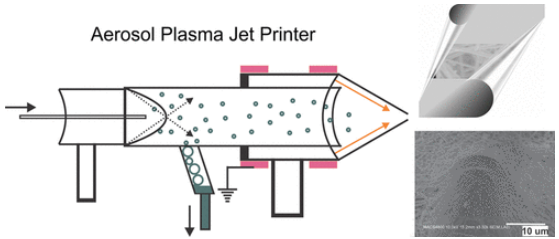
Resistive Based Sensors

- Conductive inks printing methods
  - Screen printing
  - 3D: Electrohydrodynamic, fused deposition modeling
  - Inkjet
  - Cold Plasma-jet

https://pubs.rsc.org/en/content/articlelanding/2018/nr/c7nr09570h



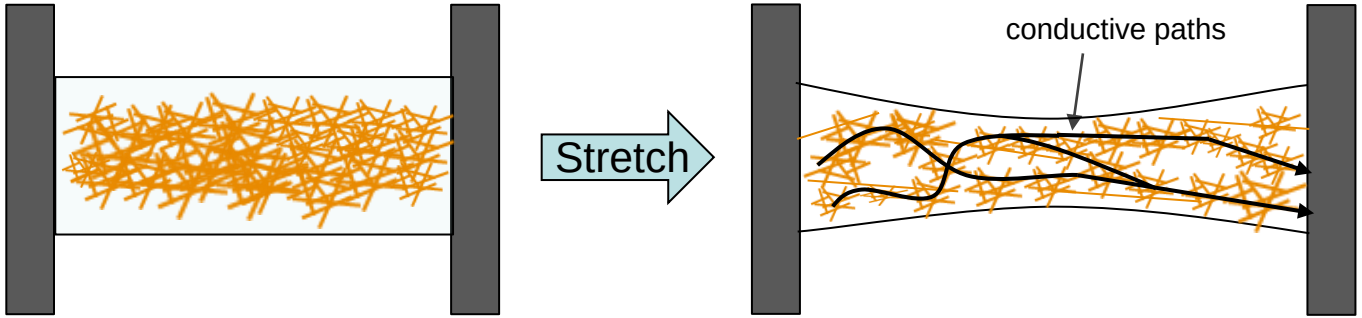




https://pubs.acs.org/doi/10.1021/am505325y
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Resistive Based Sensors

- Conductive Polymer Composites
  - CNT's or AgNW in PDMS, Silicone, TPU, etc.



- Elongation creates reduced conductive paths → ΔR

Resistive Based Sensors

- Ohmic contact and embroidered e-textiles
  - Varying yarn types, plies, and coatings
  - ISO standard stitch patterns that change resistance when stretched
- Ohmic contact not limited to thread



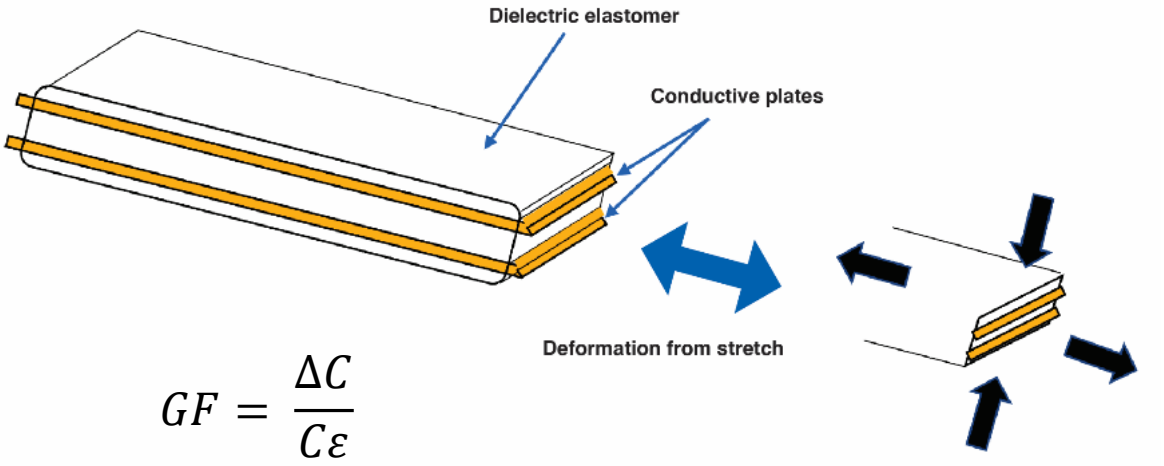
Heriot Watt University, (10.3390/ma12091469)



Ohmic contact of a sensor electrodes in relaxed position (shorted); (b) stretched position (open)

Capacitive Based Sensors

- Flex and stretch sensors configured as capacitors
  - Can be conductive polymer composites, or e-textile based



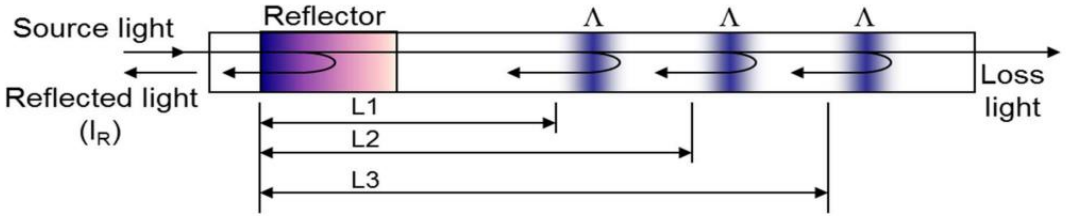
$$GF = \frac{\Delta C}{C\varepsilon}$$



Bando C-STRETCH

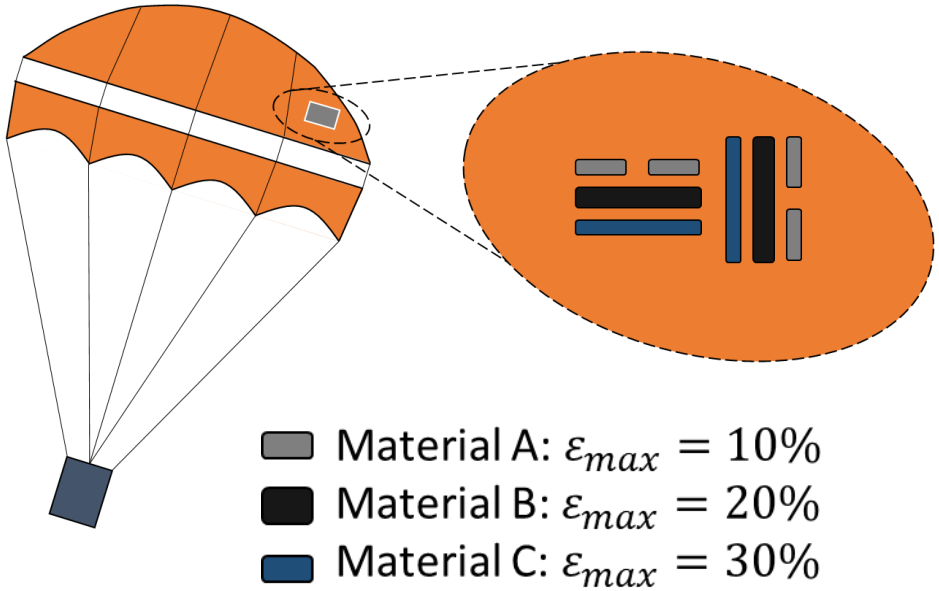
Optical

- Plastic Fiber Optics
  - Fiber Bragg grating or light intensity bend effect (Redondo, OFSETH)
  - Large hysteresis, difficult to achieve elongation (cite Redondo)



Passive Sensors

- Materials with discrete breaking strains placed at location
- Inspect post test, broken materials give max elongation that occured



Strain Sensor Performance Comparison

Sensor	Max Elongation	GF	Hysteresis %	Meas. Type	TRL	Ref
OFSETH	3%	na	na	Optical	8	Narbonneau et al 2010
Plastic Optical Fiber	35%	na	Severe	Optical	6	Bazin et al 2019
Conductive Thread 602 Coverstitch	19%	0.4*	10.6*	Resistance	7	Gioberto et al 2012
Conductive Thread 304 Zig Zag	50%	1.6	6.3	Resistance	7	Tangsirinaruenart et al 2019
Ionic Liquid Strain Gauge,	100%	0.97	na	Resistance	5	Chossat et al 2013
Artificial Skin liquid conductor microchannels	250%	3.93	negligble	Resistance	5	Yong-Lae et al 2012
Printed Liquid Metal Strain Gauge	350%	na	na	Resistance	6	Kim et al 2015
AgNW EHD Printing	30%	na	na	Resistance	5	Cui et al 2018
AgNW on Hydrogel	59%	na	na	Resistance	4	Ko et al 2017
AgNP Ink	400%	na	na	Resistance	4	Liang et al 2017
VAgNPN on Silicon	460%	NonLin	na	Resistance	5	Lee et al 2012
TPE Carbon Black	80%	20	7	Resistance	5	Mattmann et al 2008
SWCNT Film	280%	NonLin	12*	Resistance	7	Yamada et al 2011
Piezoresistive Fabric Sensor	65%	0.3* course NonLin. Wale	na	Piezoresistive	7	Paradiso et al 2005
MWCNT in PDMS	70%	56	na	Piezoresistive	5	Oh et al 2018
TPU/MWCNT	120%	8.6 - 176	Significant	Piezoresistive	4	Christ et al 2017
CNT-Elastomer Capacitor	130%, 300%	~1	Base RΔ, None	Capacitance	5	Cai et al 2013
Silicon-Textile Composite	125%	1.23	None	Capacitance	7	Atalay et al 2017
Bend Labs	75%	na	None	Capacitance	9	Bendlabs.com
StretchSense	100%	na	None	Capacitance	9	Stretchsense.com

*, approximated from source graph or data table

Sensor Survey Takeaways

- Bonding without hysteresis is a challenge
  - Sensor must move with material, NOT stiffen material
  - Cannot allow for relative motion between sensor and fabric

- Using sensor substrates or adhesives (epoxy, silicone) with dissimilar stiffnesses causes peeling / debonding at high strains

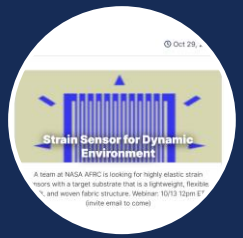
- Soft sensors need a reliable soft to hard transition for reliable instrumentation

Sensor Survey Takeaways

- Polymer composites have gauge drift, hysteresis, or degradation from cycling and high strain
  - Fundamental structure has cracks and voids upon stretch → change in base resistance etc.
  - Reduced/eliminated with reconfiguring as capacitive sensor
- Coated parachute fabrics can have reduced ultimate strength
- Calibration challenges with clamping effects on fabric

Next steps/ Future work

- EPIC sensor test campaign.



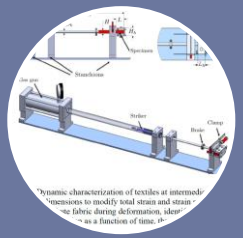
Identify candidate sensors capable of measuring canopy strain and strain rate for supersonic deployment



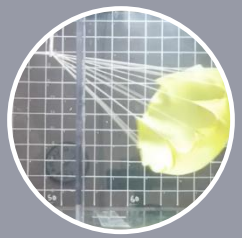
Identify bonding method for each sensor



Test candidate sensors via static strain tests (uniaxial and biaxial) on a coupon of parachute fabric



Test candidate sensors via dynamic strain tests on a coupon of parachute fabric



Test candidate sensors via simulated relevant environment test.

TRL 2 TRL 3 TRL 4 TRL 5

Bibliography

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- Suman Muppidi, Clara O'Farrell, John W. Van Norman and Ian G. Clark. "ASPIRE Aerodynamic Models and Flight Performance," AIAA 2019-3376. AIAA Aviation 2019 Forum. June 2019.



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