Nano-Engineered Distributed Strain Sensing Using Electrical Time Domain Reflectometry

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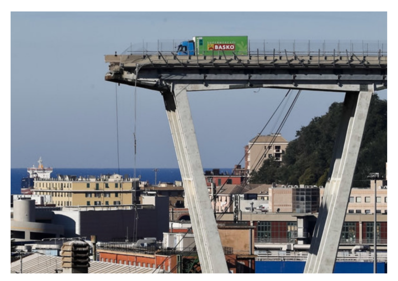
INTELLIGENT MULTIFUNCTIONAL MATERIALS AND SYSTEMS LABORATORY

Motivation

- Structured systems are subjected to various loads throughout entire service time

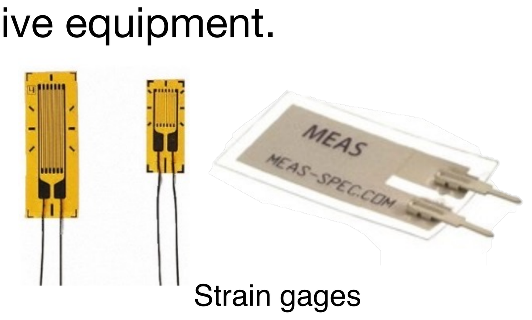
Airbus A319-132 (2009)



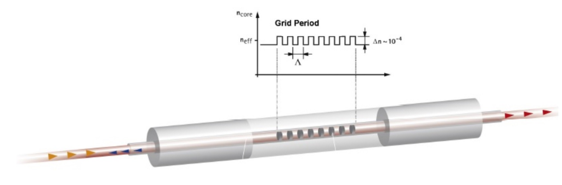
Geona bridge failure (2018)

Napoli ship failure (2007)

- Strain sensing is important to determine stress and potential residual stresses after fabrication, and to help estimate structure's integrity
- Conventional strain gages are discrete transducers that can only take measurements at their instrumental location
- Fiber optic sensors require high manufacturing cost and complex and expensive equipment.



Strain gages

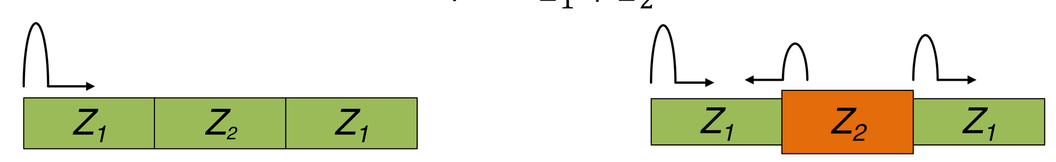


Fiber optic sensors

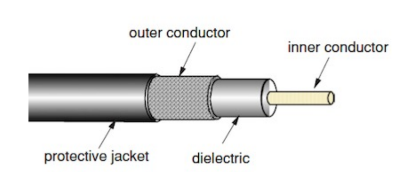
Electrical Time Domain Reflectometry

- Electrical time domain reflectometry (ETDR) is an electrical measurement technique that propagate EM waves in a transmission line and examines the reflected wave
- Electrical impedance discontinuity induces a reflected wave
- Reflection coefficient:

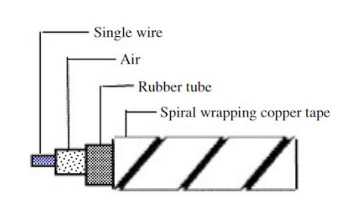
$$\Gamma = \frac{V^-}{V^+} = \frac{Z_2 - Z_1}{Z_1 + Z_2}$$



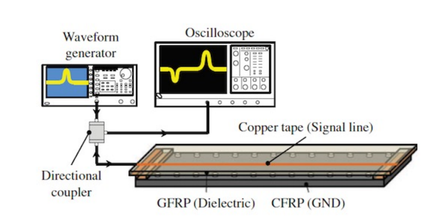
- ETDR sensors:
  - Limitations such as low sensitivity, recoverability, limited applications



Lin *et al.* (1999)



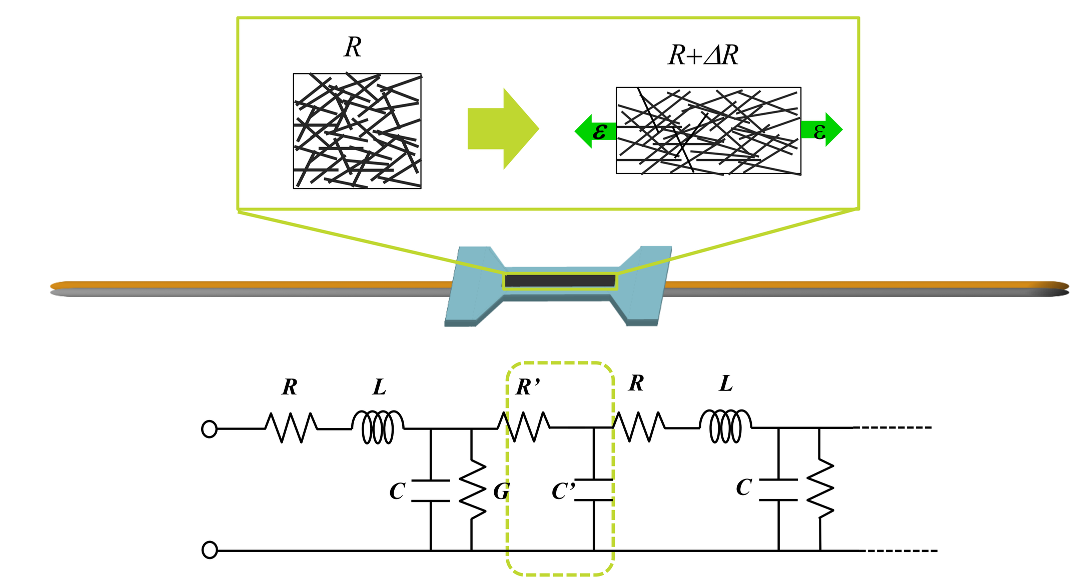
Chen *et al.* (2005)



Todoroki *et al.* (2016)

Research Objective

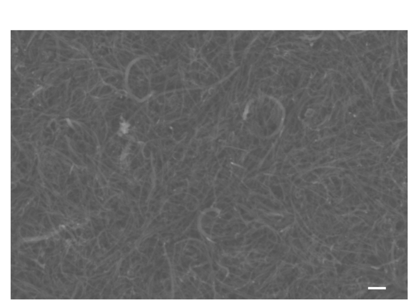
- Devise low-cost distributed ETDR strain sensors by integrating piezoresistive multi-walled carbon nanotube (MWCNT)-based sensing elements
  - Parallel plate type transmission line: uniform EM field penetration
  - MWCNT-based element: intrinsic piezoresistivity can be tuned



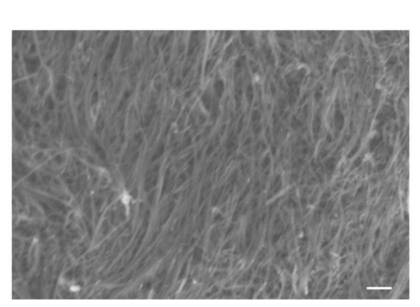
Sensing element

MWCNT-based ETDR Sensor Fabrication

- MWCNT-Pluronic thin films were fabricated by vacuum filtration of 1 mg/mL MWCTN-Pluronic dispersion
  - MWCNT thin film #1: random dispersion
  - MWCNT thin film #2: AC voltage (2.8 kVp-p at 30 kHz) for 10 min

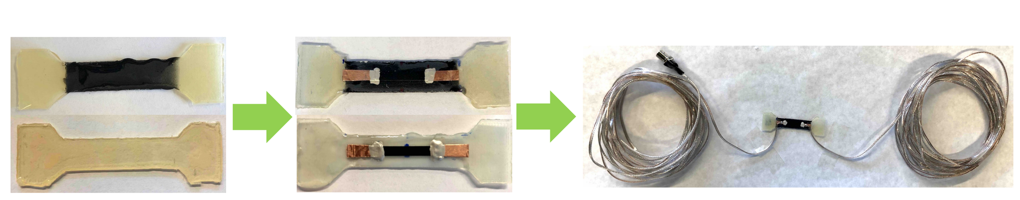


MWCNT thin film #1



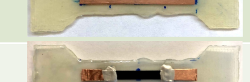
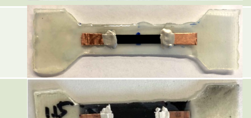
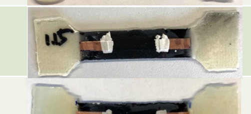
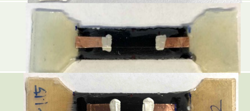
MWCNT thin film #2

- MWCNT-based ETDR sensor assembly:



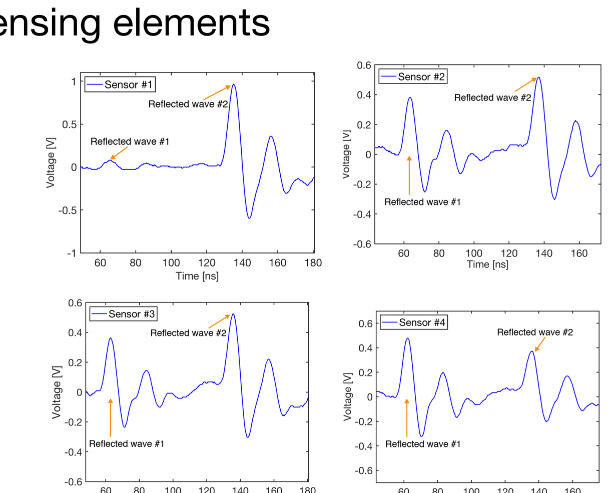
Dielectric thick film → MWCNT-based sensing element → MWCNT-based ETDR sensor

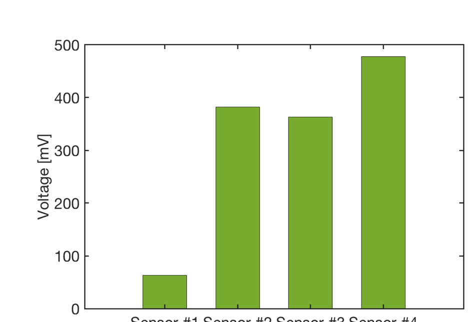
- Sensor #1 - #4: the effects of R & C properties on strain sensing behavior
- Sensor #5: incorporate 3 sensing elements for distributed strain sensing validation

	Conductor	Dielectric	Sensing element
Sensor #1 (control case)	Copper tape	Epoxy	
Sensor #2	MWCNT thin film #1	Epoxy	
Sensor #3	MWCNT thin film #1	MWCNT-epoxy	
Sensor #4	MWCNT thin film #2	MWCNT-epoxy	
Sensor #5	MWCNT thin film #1	MWCNT-epoxy	

Unstrained ETDR Sensor Response

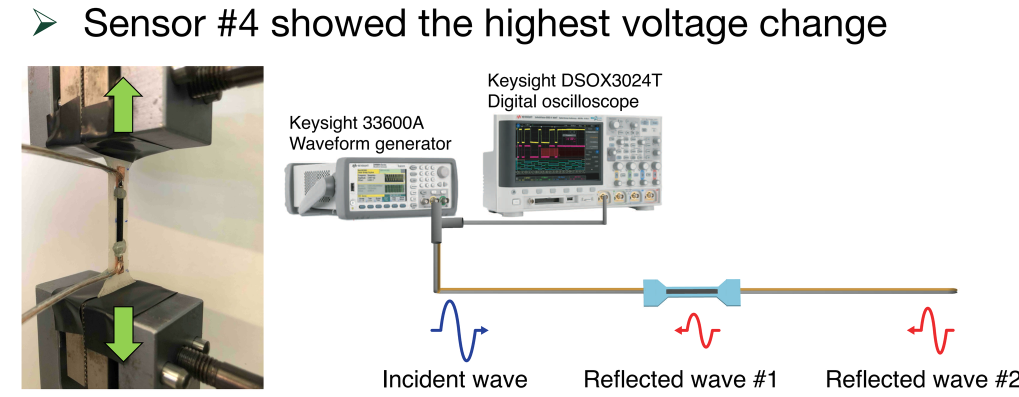
- ETDR measurements:
  - Reflected wave #1: impedance mismatch between the sensing element and the parallel wire
  - Reflected wave #2: at the end of the ETDR sensor due to open-circuit condition
  - Different reflected waves' voltage due to impedance difference among four sensing elements

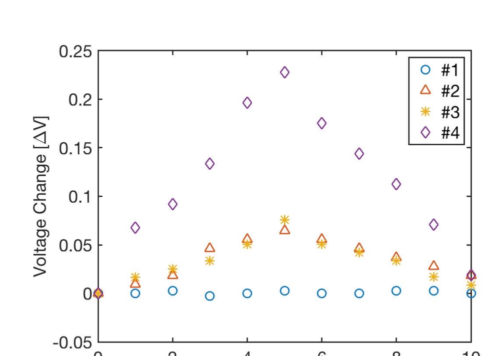




ETDR Strain Sensing Results

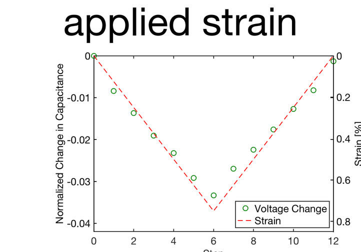
- Uniaxial tensile loading and unloading
- The voltage peak of Reflected wave #1 increased in tension
- Sensor #4 showed the highest voltage change



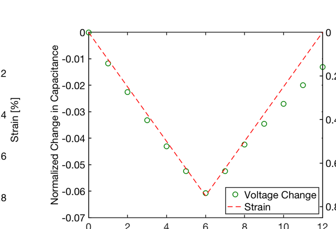


Strain Sensing Response of Dielectric and Conductor

- C component:
  - MWCNT-epoxy was more sensitive to applied strain

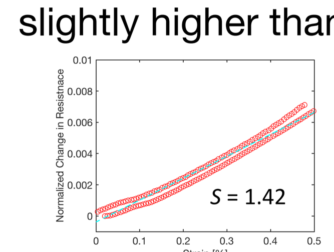


Epoxy

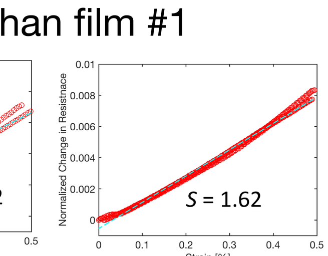


MWCNT-epoxy

- R component:
  - Strain sensitivity of MWCNT film #2 was slightly higher than film #1



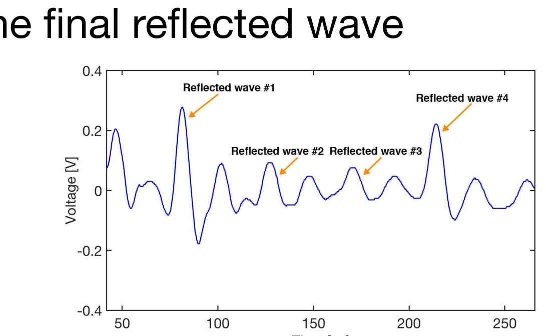
MWCNT film #1



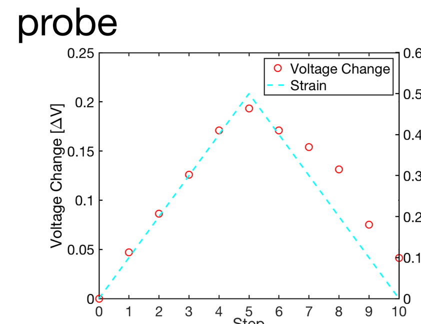
MWCNT film #1

Distributed ETDR Sensor Response

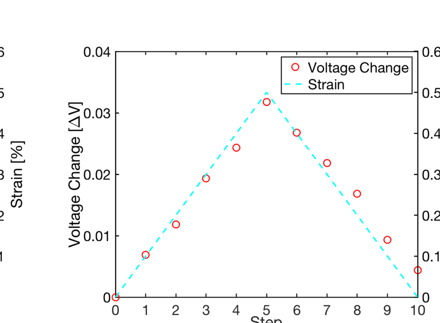
- The location of reflected waves were identified using the location of the incident wave and the final reflected wave



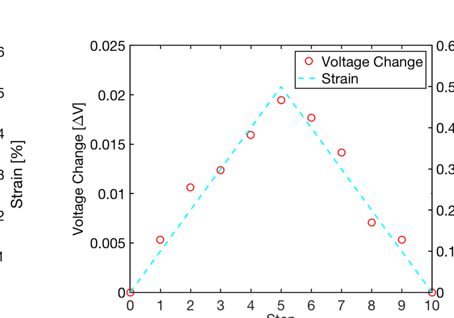
- Strain sensing results:
  - Sensing elements #1 to #3 showed strain sensing behavior
  - The voltage change degraded as the sensing element was farther from the probe



Sensing element #1



Sensing element #2



Sensing element #3