Enhancing In-Flight Structural Health Monitoring of Vertical Lift Vehicles Operating in an Urban Environment

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Outline

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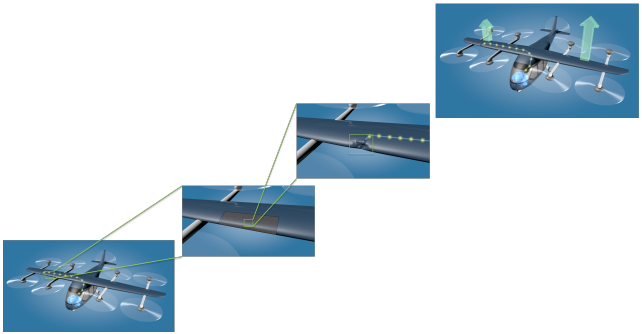
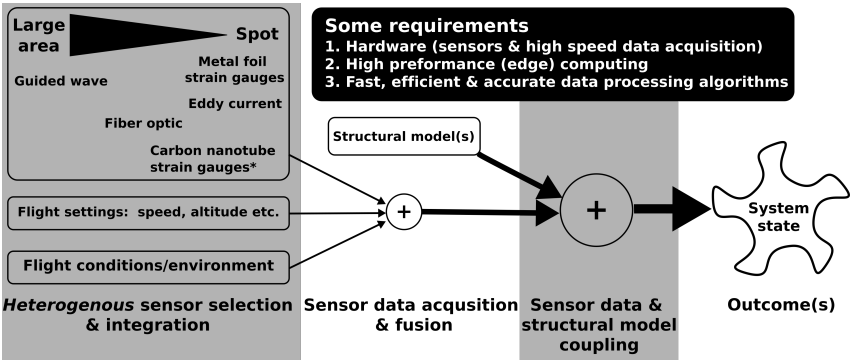
Why In-Flight Decision Making?



Adaptive "self-aware" vehicles that can mitigate the effects of in-flight damage events. This implies:

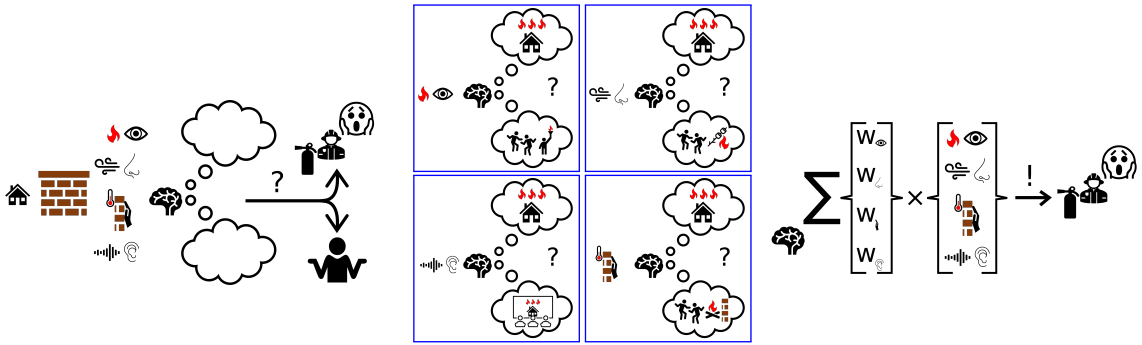
1. **Global** coverage of the **structure** with health monitoring sensors.
2. Making [continue to fly | ground] **decisions** based on the sensor data.
3. A **multidisciplinary** problem (Controls, Sensors, Structures, Materials...).

Sensor Data Fusion for Structural Health Monitoring (SHM)



Data from multiple-sensor types and modeling required.

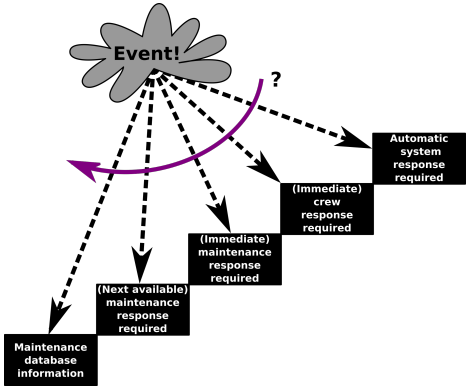
Why Multiple Sensor Types?



What to do? The dilemma A solution

It's not about how good each of the sensors is, it's the complexity of the sensed environment!

What To Do With The Sensor Information?

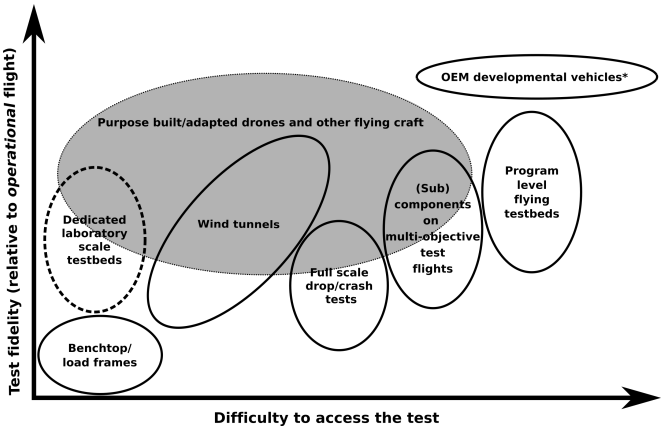


There is a hierarchy of responses/respondents for which SHM system requirements are **not** the same.

Challenges for Deployment of Large Networks of In-Situ Sensors

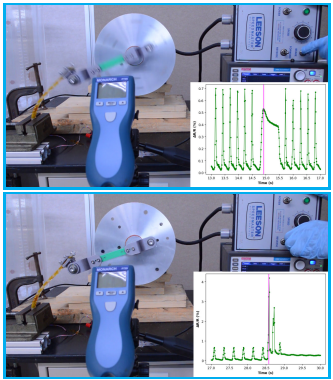
- Sensors
  - Types
  - Relationship of sensor output to structural state
  - Number of sensors
  - Location of sensors
  - Response rate
- Data Acquisition
  - Required reading rate
  - Data processing rate to translate data into structural information
- Decision Making
  - Translation of sensor data to actionable response
  - Threshold of signal for taking action
  - Reliability under operational conditions
  - Handling false positives/false negatives
- Operational Use
  - Reliability over sensor lifetime
  - Sensor maintenance and redundancy
  - Cost of sensor deployment

Different Ways to Evaluate Potential Technologies



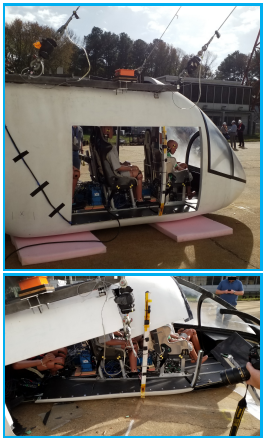
*Original Equipment Manufacturer. **Axes on arbitrary scales.

Examples of Tests We Have Run



Benchtop

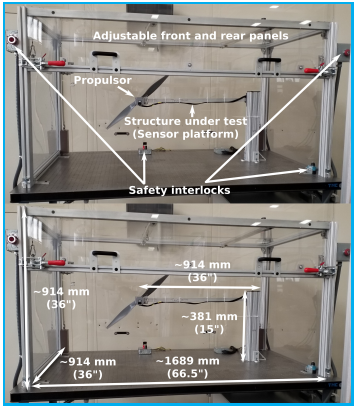
Load frame



Drop test

Sensor Integration Testbed

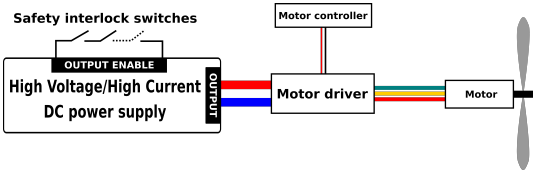
Overview



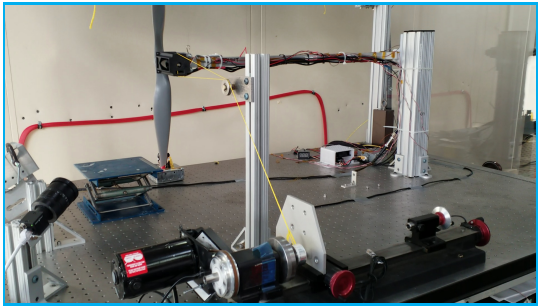
Labels and dimensions

A dedicated facility for multi-sensor testing.

Applying Load to The Test Article



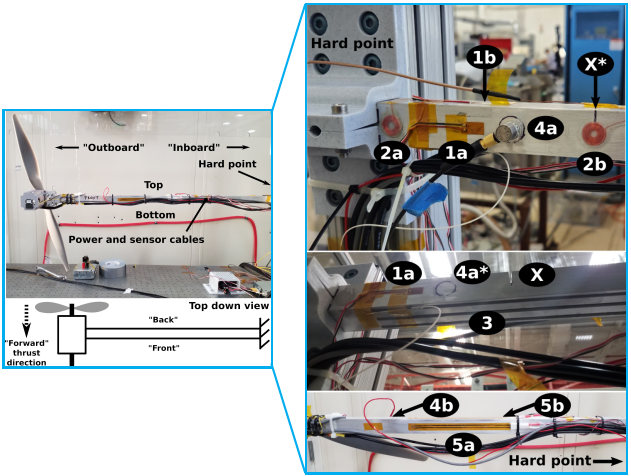
Motor & Propellor "Flight-Like"



Cam (Accelerated Fatigue)

Flexibility to use two methods of loading for crack initiation and "Flight-Like" testing.

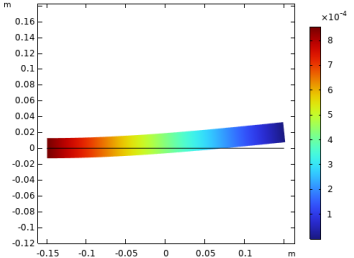
The Suite of Sensors Tested



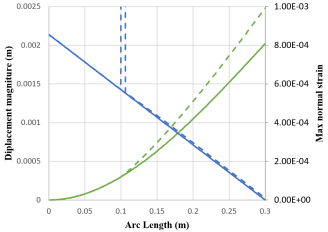
Sensor Location Identification

- 1a and 1b: Metal foil strain gauges
- 2a and 2b: Eddy current coils
- 3: Fiber optic sensors
- 4a/4a* and 4b: Acoustic emission sensors
- 5a, 5b and 5c: Carbon nanotube roving sensors

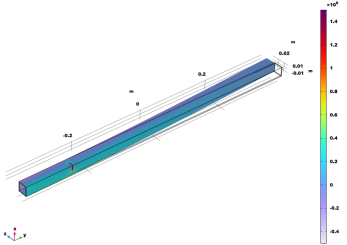
Preparation for the Run: Modeling



Strain Map



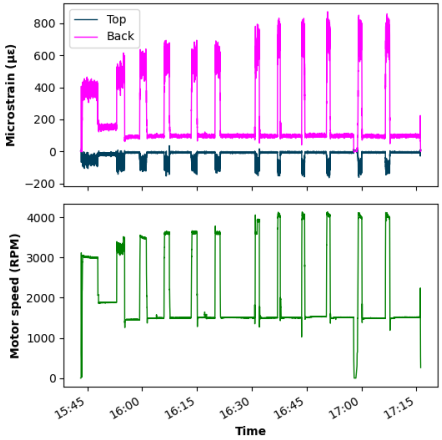
Maximum Strain



Finite Element Analysis

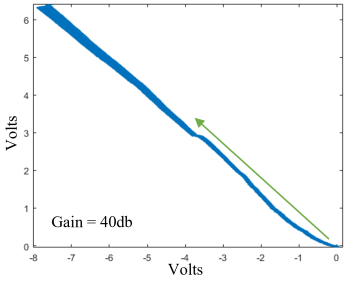
The modeling informed the positioning of a defect on the test beam.

Metal Foil Strain Gauges and Motor Speed Controller

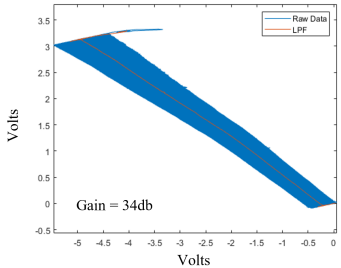


The metal foil gauges very accurately reflect instantaneous propulsor speed cycling.

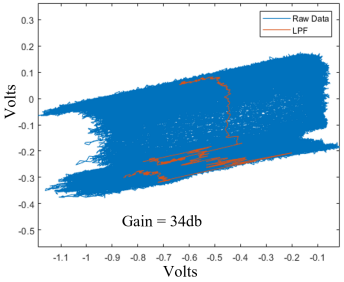
Eddy Current Coils Real Time Response



Initial Cam Loading



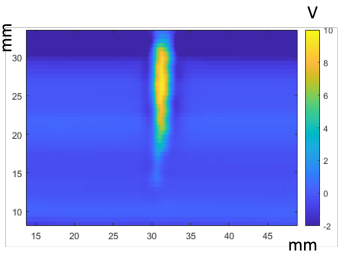
Final Cam Loading



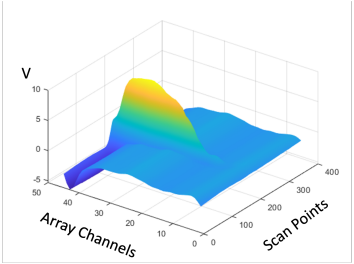
"Flight-Like"

Lift-off of the coils as bending occurs seen in large horizontal response. A clear propagation of the signal in the crack-like direction was recorded in the filtered data.

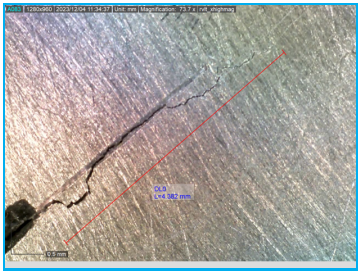
Eddy Current Coils Damage Site Scan



Eddy Current C-Scan



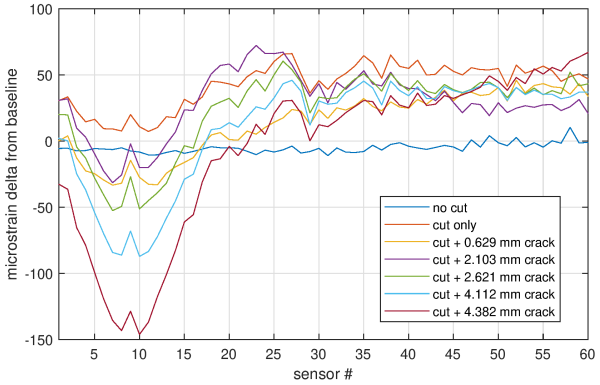
3D View of C-Scan



Micrograph

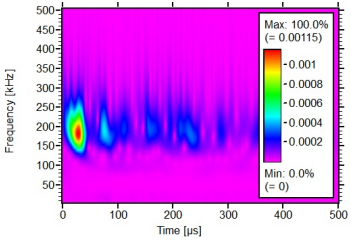
C-scan with eddy current array able to monitor the progression of the damage once crack started.

Fiber Optic Sensors

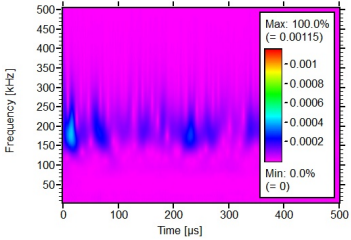


Clear progression from the baseline test (no cut) to when the crack is growing.Temperature changes and any shift in the propulsor power cables are expected to also affect the sensor data.

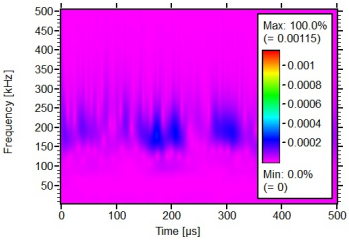
Guided Wave Sensor: Ultrasonic Transmission (UT)



Before Notch



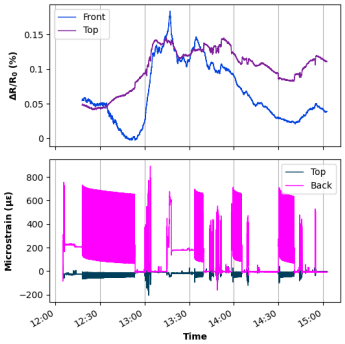
After Notch



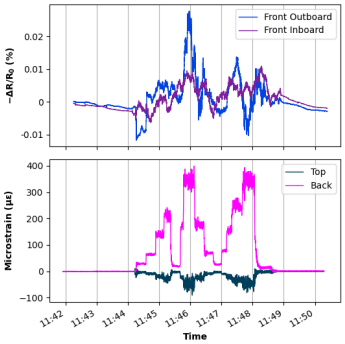
After Cam Loading

Wavelet transform of UT pulse after mechanical fatigue shows significant reduction in wave propagation throughout the capture time window.

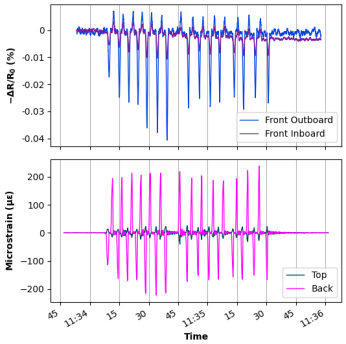
Carbon Nanotube (CNT) Roving Sensors: Test of Experimental Sensor Device Fabrication



Cam Loading



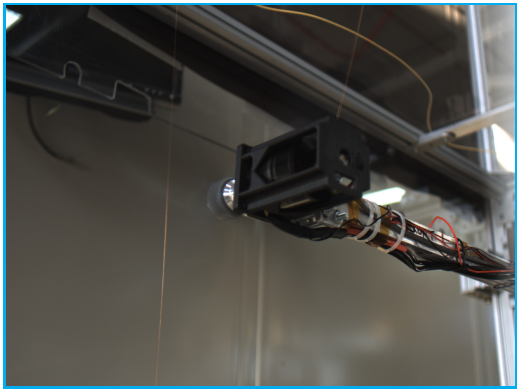
"Flight-Like" Thrust Steps



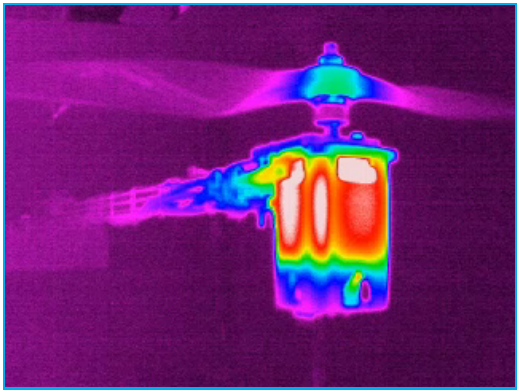
Load Spikes

CNT roving sensor data noisier than the metal foil gauges. Temperature, electrical interference, the effectiveness of strain transfer between packaging and sensing CNT are all contributors.

Auxiliary Sensors



Video Frame from Optical Camera

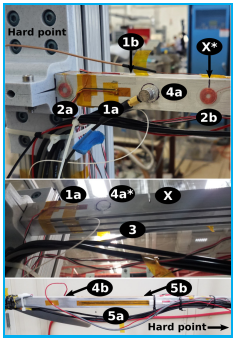


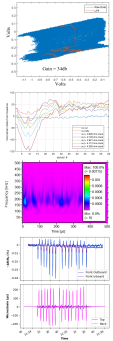
Thermograph of the Running Motor

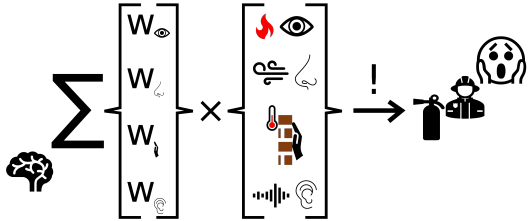
Sensors for motor temperature were the only ones that provided immediately actionable data.

Observations/Discussion

The sensors are able to pick up simulated damage with varying degrees of success however ...







Physical integration of sensors on its own is not enough for realizing “self-aware” vehicles!

Concluding Remarks

- Challenges in structural health sensor-based decision making:
  - While sensors currently play critical roles in many structures and systems, global coverage and reliability required for self-aware vehicles is non-trivial.
  - Where sensor-based health monitoring is pursued, practical deployment in specific applications need to address the following:
    - Size of sensors
    - Associated data acquisition hardware and wiring harnesses
    - Ambiguity of signals
    - Sensor reliability
    - Redundancy
    - Maintenance
    - Additional system complexity from use of the sensors
    - Cost – both upfront and lifetime
- Overcoming structural health monitoring-based decision making will require addressing above issues.
  - Requires repeated test campaigns with the full range of sensors.
  - Dedicated testbeds can allow investigation of multiple sensor types in a relevant configuration.
  - Testing needs to include data fusion.
  - Testing must account for all the key requirements for deployment in a product right from the start.

Acknowledgements

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