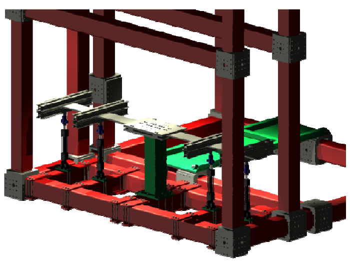
Sensor Applications to IVHM
in
Aerospace Systems





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National Research Council Canada
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Canada

Outline

- Introduction/General Remarks
- Roadmap for IVHM
- Structures HM
- SHM Test Platforms
- SHM and Load Monitoring
- Engine Health Management
- Sensors for Gas Turbines
- Energy Harvesting for Sensors
- Concluding Remarks

IVHM as a key enabler for the Digital Economy

- Integrated Vehicle Health Management is
  - An asset management strategy for cost and productivity
  - A multi-disciplinary capability covering many engineering fields, physics, materials science, information technology, sensors, life cycle management, integration and risk management
  - Applicable to complex machines and systems of machines: aircraft, ships, wind turbines, plant equipment, compressor stations,….
  - Integrates and exploits all information for decision support by fleet managers and operators and information
  - … a system level approach that can identify and transition new technologies into products and procedures that affect a fleet manager, operator of end user

Responding to Industry IVHM Needs with generalization to all vehicles

Objective

To develop and use a technology demonstration infrastructure to advance IVHM to clearly impact operational and support costs and safety of vehicles

Scope

To address barriers to technology transition to legacy and new vehicles through complementary technology demonstrators

- systems level: structures, propulsion, suspension gear, controls, power
- vehicle level: overall demonstrators that that show the synergy of incorporating appropriate technologies from the start of a design or operation
- technologies level: adapting/re-using existing technologies whenever possible and developing new ones when required

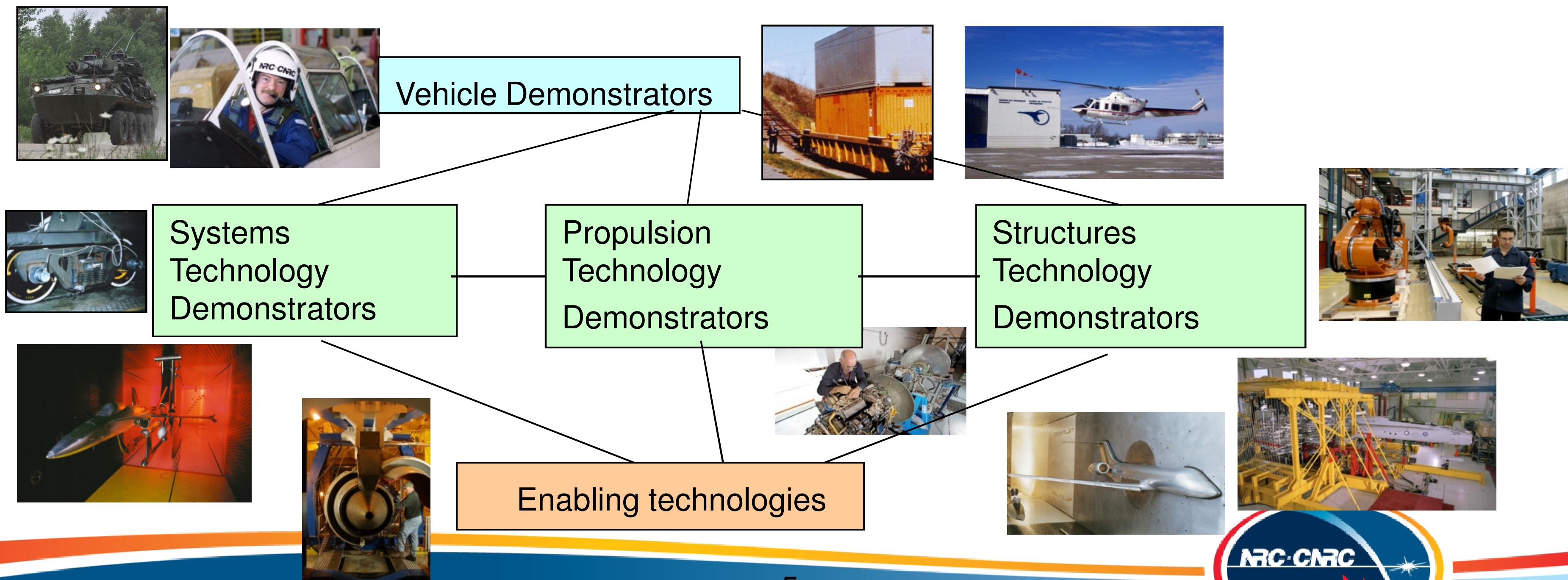
Program management

- Government leadership: NRC Aerospace plus other NRC Programs such as Surface Transportation and Industry Canada
- Industry involvement:
  - OEMs & TIER 1 Companies
  - TIER 2 Manufacturers
  - TIER 3 Suppliers

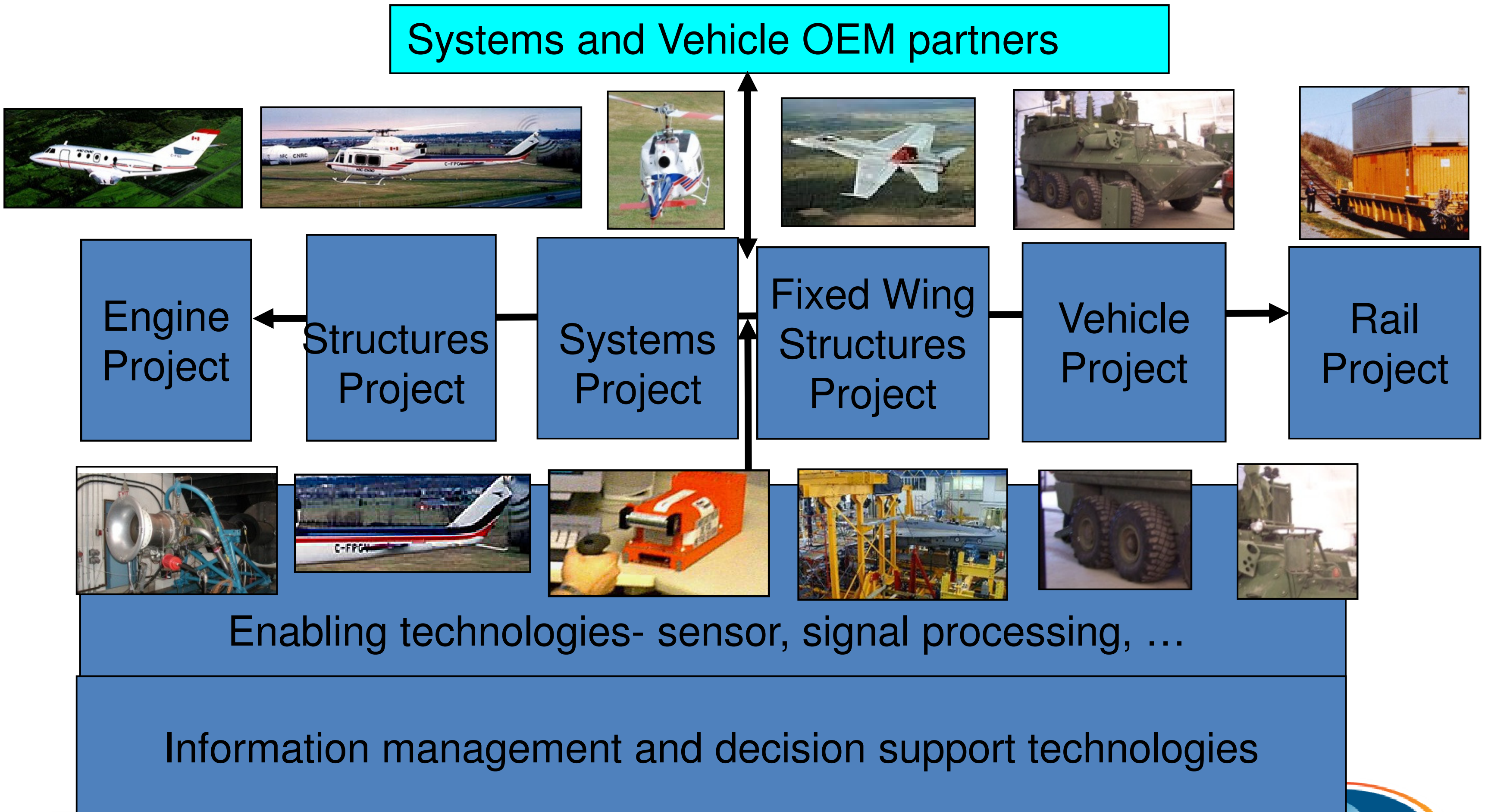
Potential Canadian IVHM Technology Demonstrator Program Concept

Approach

- Deliver an infrastructure for technology demonstration and transition of IVHM technologies
- Leverage Technology Insertion Road-mapping to promote R&D in Canadian companies
- Leverage Industrial Regional Benefits for increased R&D investment
- Coordinate Canadian activities and technology demonstration facilities
- Stimulate cooperation with Centres of Excellence, e.g. CANEUS,Cranfield, NASA and Universities nationally and internationally

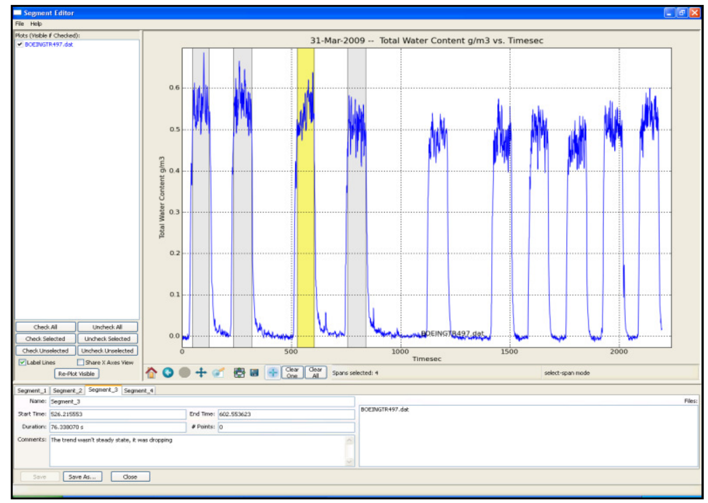


NRC Aerospace IVHM Program Components



Common program bases

- Technology demonstrators
  - Infrastructure of rigs, engines, aircraft, vehicles
  - Transition technology to industry
  - Identify industry needs and benchmarks
- Software Environment for Engineers and Technologists (NRC's SWEET)
  - Data sharing, visualization, provenance
- Environment for Building Maintenance Management Models (NRC's EBM3)
  - Rapid data exploitation
  - Basis for hybrid (data + physics) models
- Enabling technologies
  - Data mining and modeling
  - Sensors
  - Failure and life prediction models
  - Networks
  - Others?



SWEET data visualization and exploitation

Common project approach

- Establish/develop a technology demonstrator in a key industry sector
  - Joint agreement and development of capable rigs and vehicles
- Enable simulated operations/mission tests
  - Characterize baseline and degraded states with extensive instrumentation
  - Share costs in adapting and or developing equipment and running tests
  - Demonstrate mid TRL technologies on relevant rig for relevant operations
- Both collaborative and proprietary projects
  - Address NRC and industry business models
- Access for advancing low TRL technologies
  - NRC, SME’s, universities
- Link demonstrator infrastructure to fleet applications
  - Transfer technologies to fleet installations
  - Flow down certification and procurement requirements

Way forward- underway!

- Develop project technical details and scope with industry technical action teams
- Develop project ways and means with the industry action teams with a multi-lateral NDA as a basis
- Establish the sector-wide program on IVHM program with strategic funding within NRC
- Develop targeted consortia as required to facilitate project and program development
  - With the TIER 1 Companies & Research Centres
  - With Industry Canada to exploit opportunities with the Industrial Regional Offsets programs that are aimed to encourage R&D in Canada

IVHM

Technologies & Infrastructure

Hosted

CANEUS-NRC Workshop in August 2012 in Ottawa

Focus on IVHM

Participation by Boeing, Airbus, Pratt & Whitney, NASA

Bell Helicoptor, Bombardier, Meggitt & Others

Visualizing the Problem Using Reverse Thinking

1. What decision do you need to make?
   - Individual aircraft - emergency (land the aircraft) / mission mix – availability / Op Tempo
   - Maintenance and inspections (scheduling / availability)
   - Fleet management (short term – missions; long term – LCMM, MRO, replacement)
2. What are the algorithms / predictive / prognostic capabilities enabling you to make that decision?
3. How robust are the systems?
   - What is the sensitivity / accuracy level required of the inputs?
4. What are the inputs into the system?
   - What are the characteristics of the parameter (sampling rates)?
   - What kind of data is required?
     - time history / peak - valley / other?
5. What types of sensors are capable of measuring the parameters you need as an input with the required accuracy and sampling rates?
6. What sensor is available or needs to be developed to meet the demand?

Recap on the Importance of Wireless SHM or EHM for Aircraft

- Damage tolerant design and SHM (i.e. inspection) to detect failure precursors are essential for mission reliability, safety, and efficient life cycle management. They are also mandatory for most civil and military aircraft for “Principal Structural Elements”.
- SHM, where necessary, should be done by the most cost-effective method and frequency for achieving the required reliability and safety. These means range from visual inspection to NDI to embedded wireless SHM.
- Wireless SHM offers the potential to reduce the weight and complexity of embedded sensor systems, and thereby overcome current limitations on the number of sensors that can be carried.
- Wireless SHM could also facilitate the integration of these embedded sensors into an airborne IVHM system where warranted.
- However, technical and regulatory (Certification)hurdles remain to be overcome, before wireless SHM can realize its full potential.

Example- Load Monitoring

- Requires correlation to flight parameters
  - Airspeed
  - Altitude
  - Acceleration (3D Gs)
  - Pitch / Roll / Yaw
  - Control surface settings
    - ailerons / elevators / rudders
  - Manoeuvres versus Gusts
    - Gusts < 2 seconds duration
    - Manoeuvres > 2 seconds duration
  - Strains
    - Far field
    - Hot spots
- Displacements / Loads
  - compare with certification tests

Sensor and System Challenges

- Weightless / miniature / self powered / inexpensive / compatible with aircraft environment
- Attachment – not always simple
  - Ex. Strain gauges require intimate bonding to structure
- Indestructible (no maintenance)
  - Ex. Strain gauges fatigue (+/- 1500 με only 1 million cycles)
    - » Fighter aircraft (8500 to -3500 με)
    - » Transport aircraft (3000 to -1500 με)
    - » Use pairs and test one against the other for deterioration / failure
- Data transmission
  - EMI/EMC effects / interference with other systems (i.e. avionics)
    - – Sampling rates (typical structural load fluctuations can be up to 4 Hz)
      - » 22x signal frequency for 1% accuracy

Additional Issues and Challenges

- Sensor / system desirable to be capable of interrogating large areas (fuselage / wing structures)
  - Require prior knowledge of the exact failure location
  - Able to detect a specific damage and monitor its changes (growth)
- Merging data from varying sources, sensors and acquisition systems
  - Sensor built-in tests for determining sensor integrity
  - Corroboration with other sensors / parameters
- Defining the algorithms that use the sensor information to make decisions
  - active - during flight / passive - post flight
- Individual Aircraft (short term impact)
  - On-board data storage and processing? Data download - in flight? - after landing?
  - On-board algorithms
    - Health of sensors and usage within expected ranges
    - Emergency / out of range condition recognition
- Aircraft Fleet (long term impact) – fleet management
  - Data processing centres
    - Algorithms for longer term impact (inspection, maintenance, CBM…)

Objectives

SHM Facilities

Design and development of four public accessible structural test beds for SHM system validation and verification

Representative aerospace structures of increasing complexity, well characterized for structured evaluation

Static and dynamic real scale loading conditions simulating flight loads

Structures can be undamaged or include damaged replaceable components – multiple site, multiple elements.

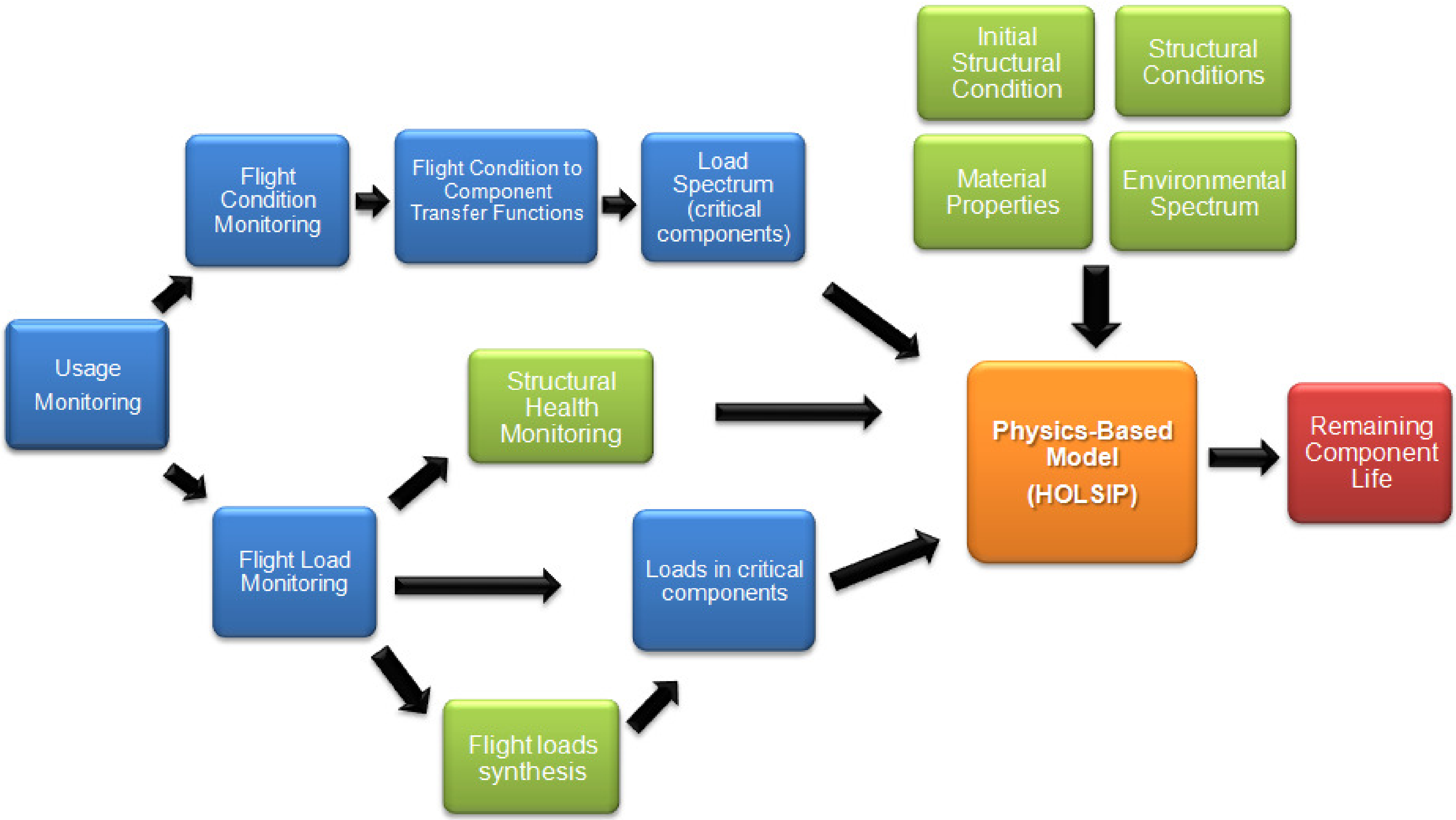
Advanced Loads Monitoring Development

Final objective of this task is to obtain sensor/system/technique able to accurately estimate bending, torsion and shear loading on an aircraft wing.

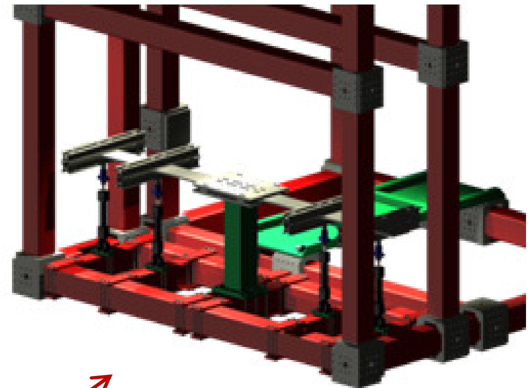
Objective

Increase Technology Readiness Level (TRL) of SHM and Load Monitoring Systems

Roadmap for Health Usage Monitoring



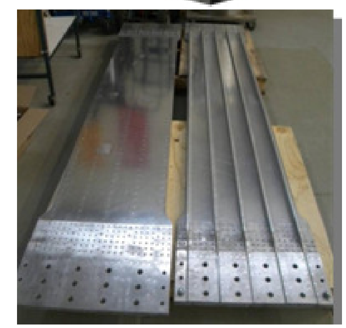
SHM Test Platforms



- Static, quasi-static and low frequency bending torsion and coupled loading conditions (up to 3 Hz). Max. displacement amplitude approx. 25 cm (10 in).
- Baseline sensors: LVDTs and strain gauges.
- Structures can be damage free or have damaged components, skins, etc, to assess:
  - SHM systems to locate and characterize damage in composite and metallic structures.
  - Load monitoring systems on more complex, full scale aircraft structures.

Increasing Complexity

1(a) Cantilever aluminium beam with rectangular cross section – 2.44 m (8 ft) in length x 2 – to simulate simple aircraft spar, or as a simple representation of aircraft wings.



1(b) Cantilever wing planks simulating aircraft wing skin reinforced with riveted stringers – 2.74 m (9 ft) long per side x 2.

2 Wing box scenario – aluminium inner structure (ribs and spars) and composite/aluminium skins.

3 Full scale test of a fighter aircraft wing (CF188) subjected to realistic load spectra and loading configurations.

SHM and Load Monitoring

Sensors:

- Capacitance Disbonding Detection Technique (CDDT)
- Surface Mountable Crack Sensor (SMCS)
- Acellent (PZT)
- Ultrasound
- MEMS (Gyroscope, Accelerometers, etc)
- Fibre Optics
- Carbon nano tubes
- Etc.

NDE:

- Thermography
- Eddy Current
- Ultrasound

Experimental Mechanics:

- Thermoelastic Stress Analysis (TSA)
- Digital Image Correlation (DIC)

Validation

Communication:

- Wireless
- Wired
- Optics

Power:

- Energy Harvesting (Piezoelectric, etc)
- Miniaturized Batteries

Diagnosis: Current condition!

Prognostics: Prediction of what is going to happen!

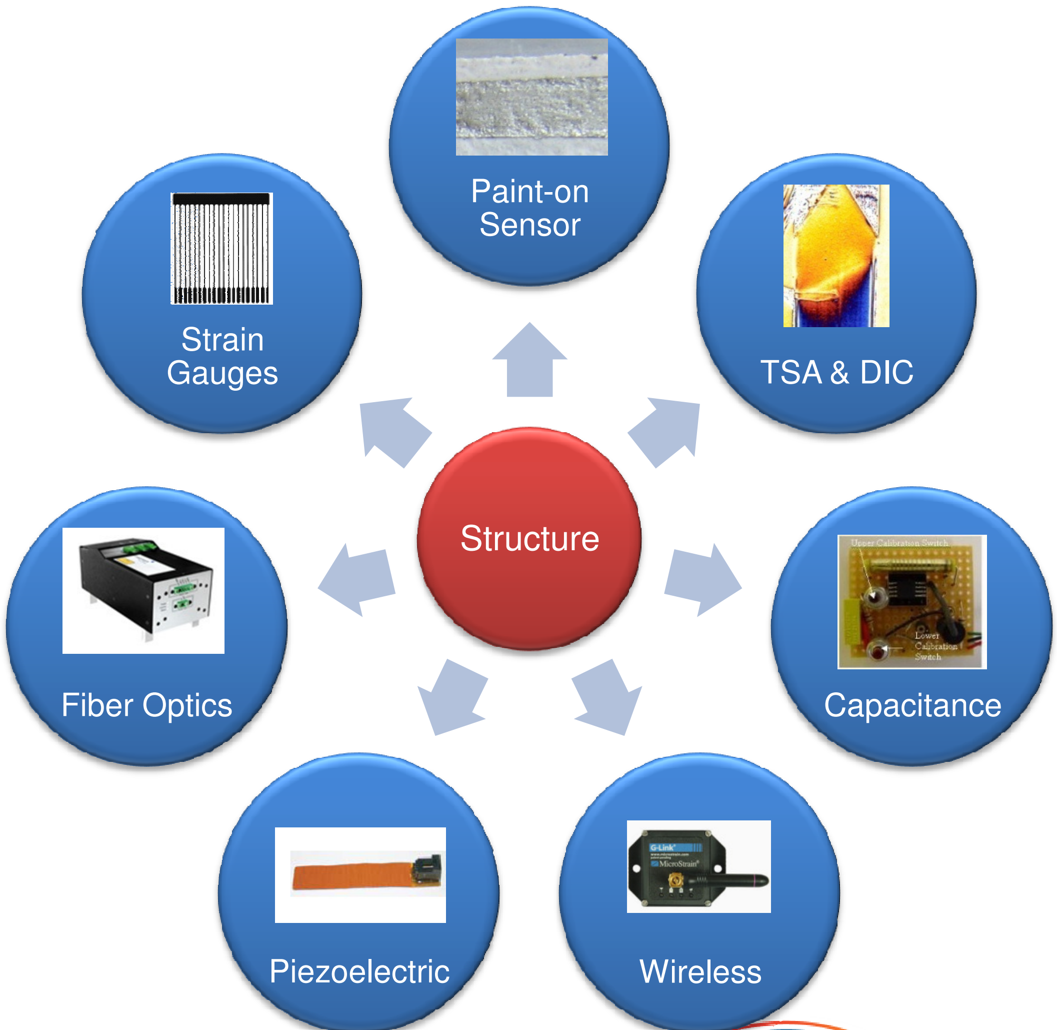
Decision Making

GOAL:

Life Assessment
Condition Based Maintenance (CBM) of Structure

Damage Monitoring Technologies used by NRC

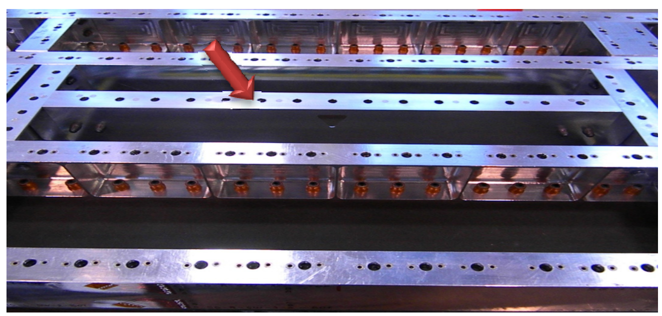
- Several sensors are being evaluated for damage detection on the different SHM platforms.
- There is a need to relate the parameters that are monitored by a particular sensor type to the life of the component.
- This may include the development of algorithms to relate the measured parameters to the actual damage that is present on the component.

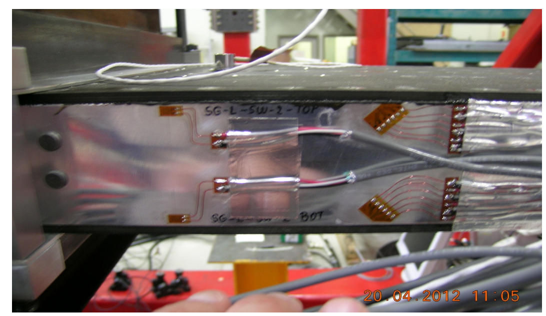


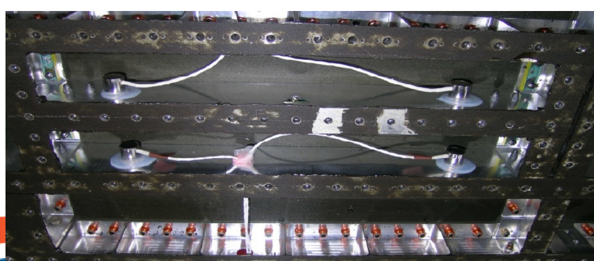
Acoustic Emission with Cranfield

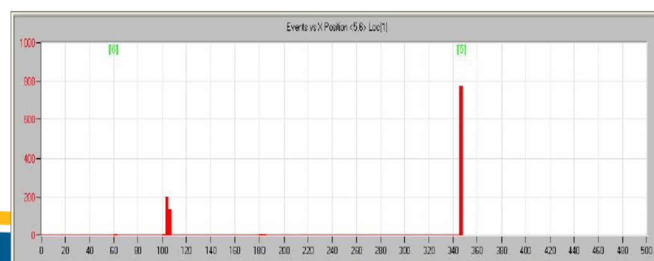
- Fatigue cycling in bending loading conditions (up to 1 Hz). Max. displacement amplitude approx. 5 cm (2 in). Loads ranging up to 6.7 kN (500 lbf), more than 60k cycles – local stress at crack location 69 MPa (10 ksi)
- Baseline sensors: strain gauges.
- Structural damaged components: internal C-channel spar and/or metallic interchangeable skins; to verify systems capability to identify damage in composite and metallic structures.
- Sampling frequency: 2 to 5 MHz

Fatigue crack grown from jeweller saw cut notch in hole

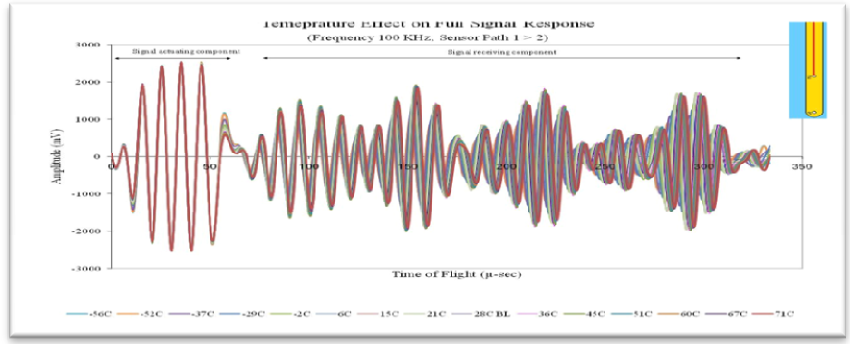


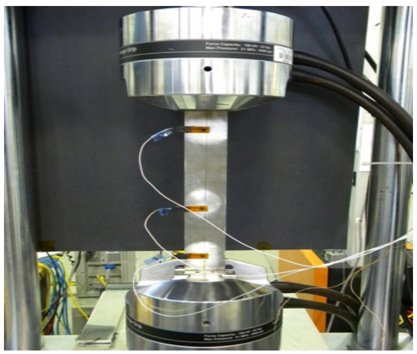


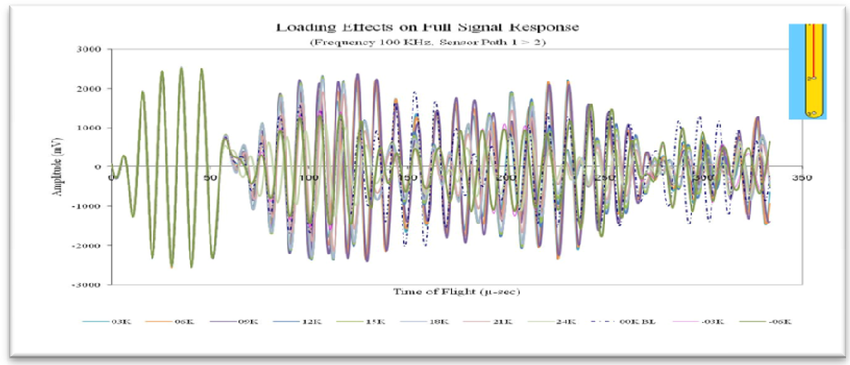


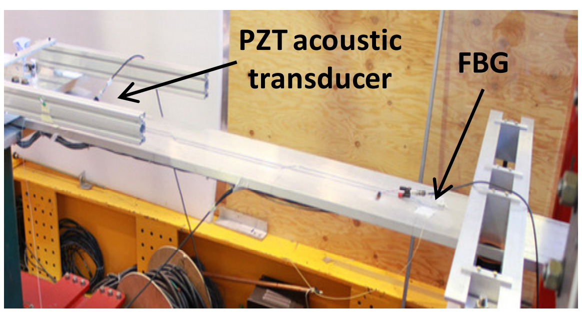


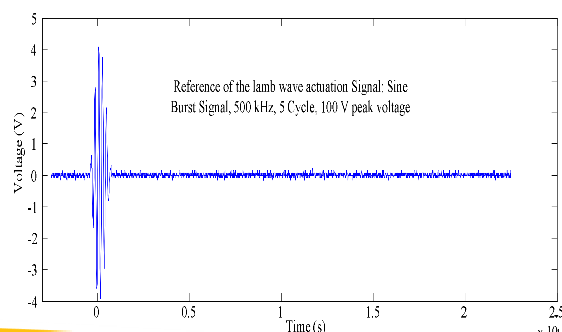
Acoustic Ultrasonic
Piezo (Acellent) and Hybrid Piezo/Optical

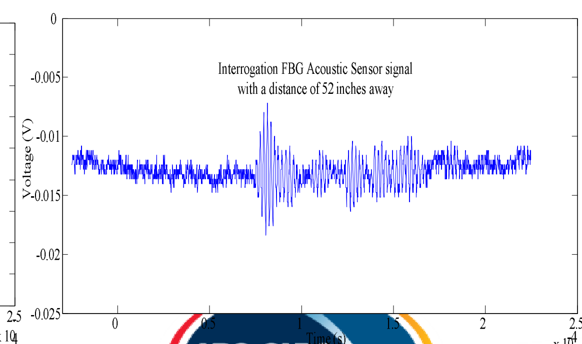






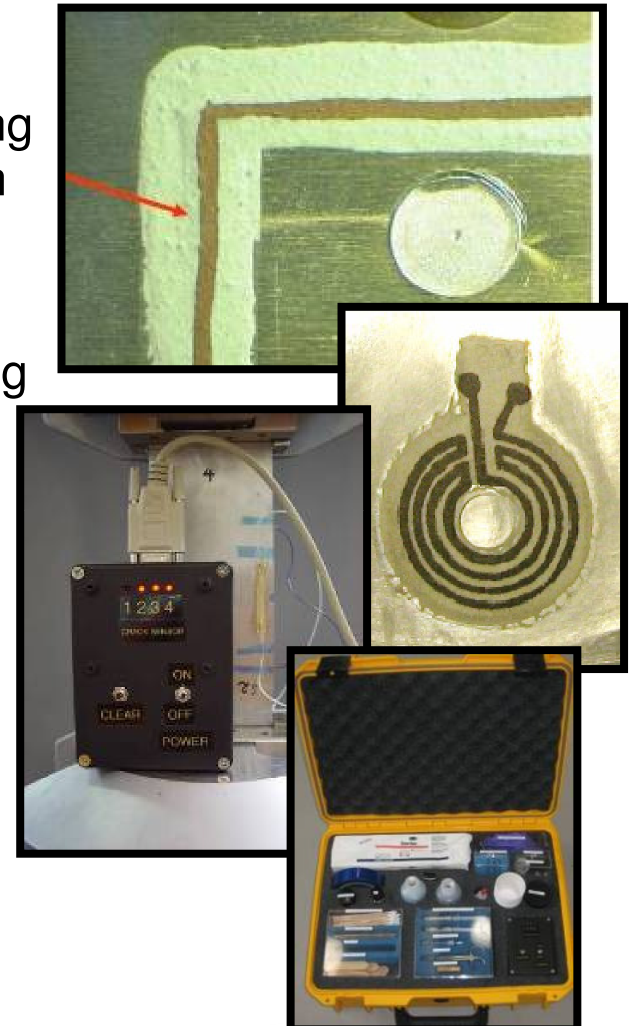






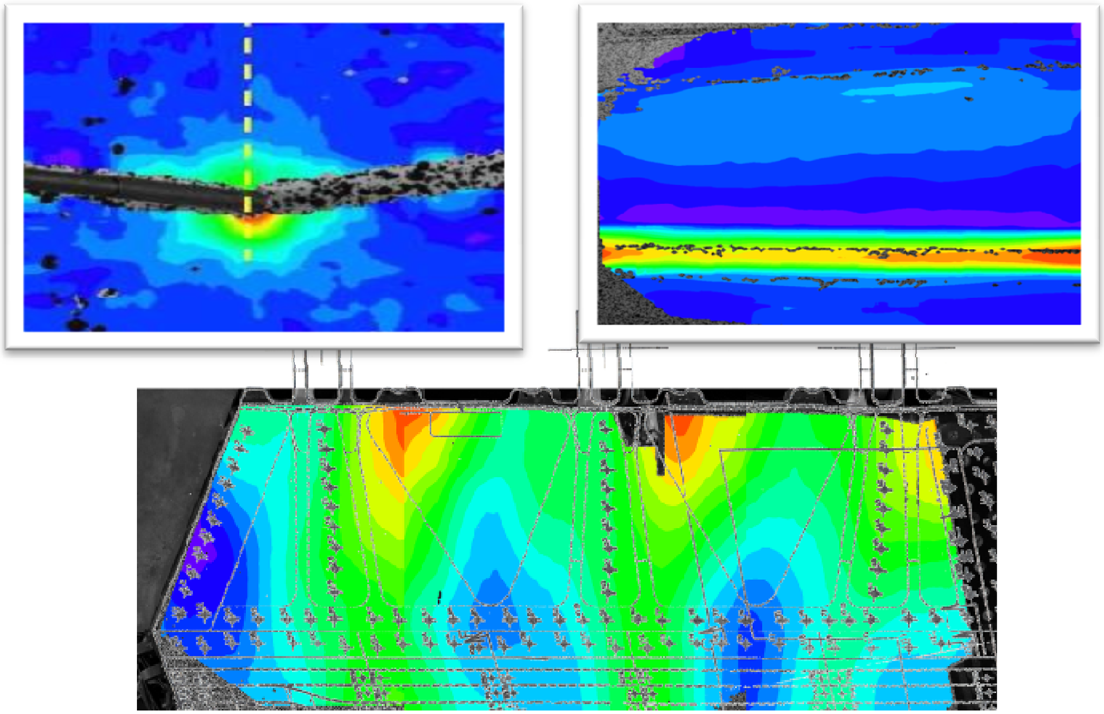
Surface Mountable Crack Detection

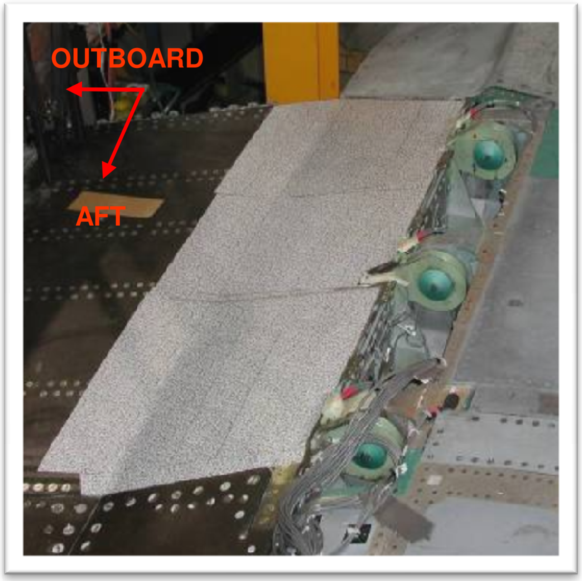
- The sensor consists of a conductive paint and an insulating substrate used to isolate the electrical sensing circuit from the base material
- As a crack passes through the conductive paint it causes the circuit to break, thus interrupting a signal and indicating the occurrence of a crack.
- Crack remains detected even after crack closure
- The shape and geometry can be customized to fit the needs of the region being monitored.
- A kit that includes all the necessary procedures and equipment has been developed, including a stand alone interrogator unit that monitors up to 4 channels



Digital Image Correlation Technique for Photogrammetry

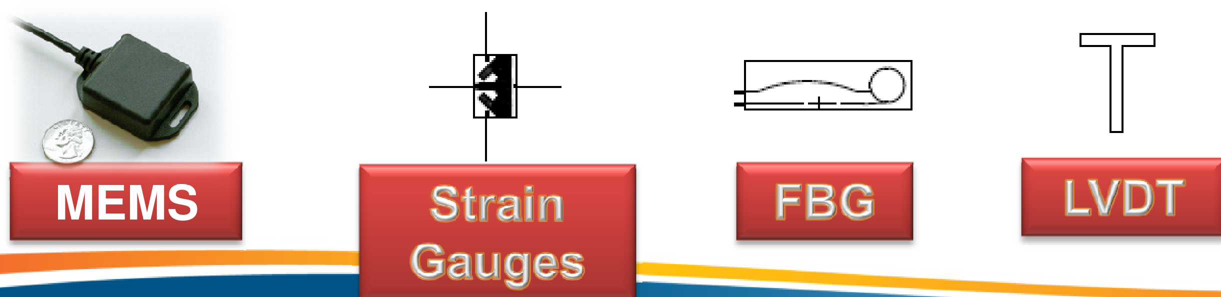
- This technique can be considered for load monitoring on all test rigs – full scale testing, both static and dynamic, low frequency loading conditions.



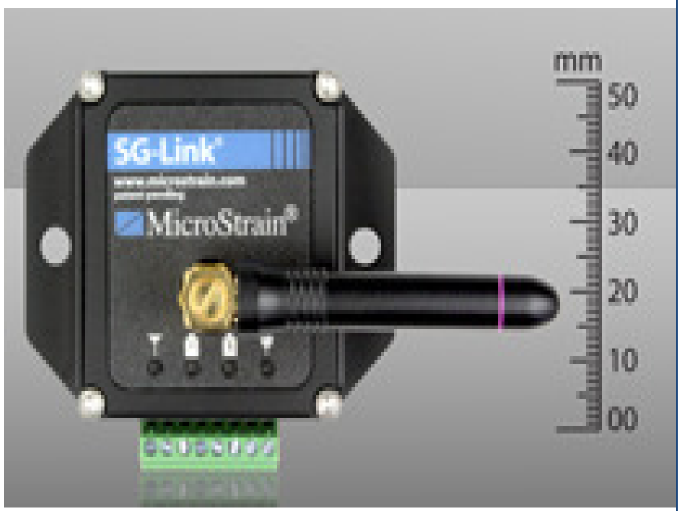


Load Monitoring Technologies

- **Strain Gauges**: Baseline technology to which all other technologies are compared. This technology was used extensively during the CF188 full scale test (FST).
- **Fibre Optics:**
  - **Fiber Bragg Grating** from Insensys Inc.
  - **Distributed Sensing** from Luna Technologies Inc.
- **MEMS**: Micro Electro-Mechanical Systems, are small miniaturized sensors with embedded accelerometers, gyroscopes, magnetometer and temperature sensors. These small micro devices are also being considered for load monitoring.
- **Photogrammetry**: This technologies utilizes optical cameras for displacement measurements, from which loads can be estimated.
- **MTS LVDTs**: MTS is interested in evaluating the performance of their LVDTs for real time load monitoring in full scale tests applications.
- **Eddy Current:** Being evaluated for load and damage detection FST applications.



Wireless Transmission Capabilities / Expertise



Direct strain gauge input data logging transceiver for use in high speed wireless sensor networks.

Features and Benefits
2.4 GHz direct sequence spread spectrum radio is license free worldwide
IEEE 802.15.4 open communication architecture
Supports simultaneous streaming from multiple nodes to PC
Data logging rates up to 2048 Hz, storing up to 1,000,000 measurements
Real-time streaming rates up to 4 kHz
Communication range up to 70 m line-of-sight, 300 m with high gain antennas
Regulated 3 volt sensor excitation supports most analog sensors
On-board bridge completion resistors
Includes internal resistor for wireless shunt calibration
Low power consumption for extended use
Internal rechargeable battery

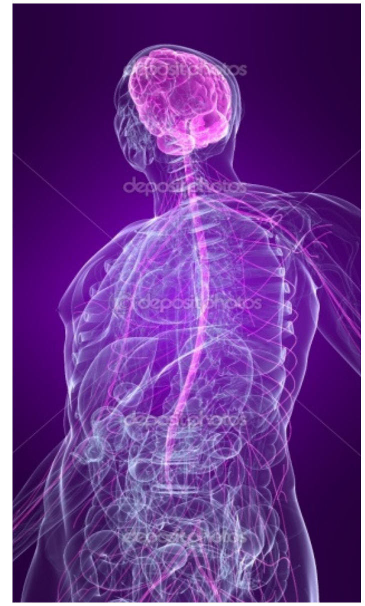
The **SG-LINK®** wireless strain node is compatible with a wide range of Wheatstone bridge strain gauges, displacement sensors, load cells, torque transducers, pressure sensors, accelerometers, geophones, temperature sensors, inclinometers, and others.

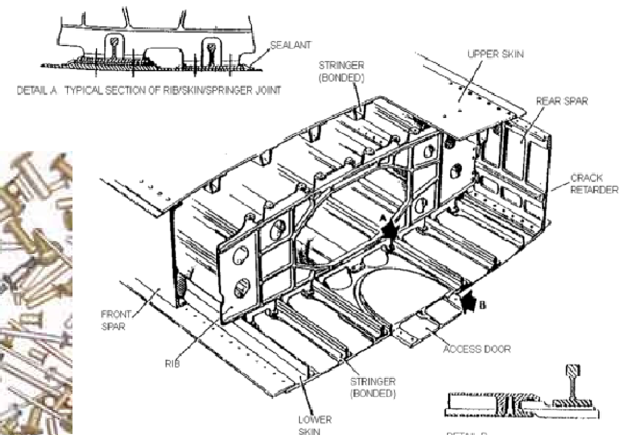
Future Endeavours

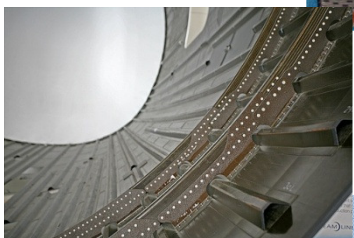
- There is a need to increase the TRL (to a maximum of 6) of several of the systems/sensors that NRC has examined on SHM platforms.
- Capability is being developed to evaluate the performance of the sensor systems to determine their reliability, endurance and resilience, while facing environmental conditions (i.e. temperature and humidity, and vibration). The platforms offer easy access for sensor / structural element replacement.
- The evaluation of the SHM systems will be carried out not only on the sensor but also the DAQ side.
- Data analysis from the SHM systems will be integrated into crack growth prediction and risk assessment software for determining the useful life of aerospace structures (HOLSIP).
- Collaboration with commercial and military entities to develop policies on the requirements for the use of SHM systems within their aircraft fleets.

Future Endeavours

- Structures in the concept of a biological system, with SHM being one of the main aspects of the integrated structure, which will contribute also to its performance and self-healing capabilities.
- Integrate:
    - Sensors into the materials, structures and joints - nano-particles, fibre optics, piezoelectrics, etc.
    - Data transmission and processing – wireless, fibre optics.
- Determine and influence SHM capabilities and requirements, and their inclusion in structural design, testing, regulations and certification.







Materials:
Carbon and Glass Fiber laminates;
Aluminium;
Nomex…

Analytical methods;
Numerical simulations (Finite Element Methods, etc);
Experimental work dedicated to structural elements, with well characterized testing conditions - new designs.

Quality of the composite;
Usage and fatigue monitoring;
SHM applied to common composite damage mechanisms, types and locations

Support HOLSIP:
For new materials & designs;
To monitor usage;
Support a safe life;
Extended life;
Condition Based Maintenance.

Ageing and new aircraft …
… from the beginning.

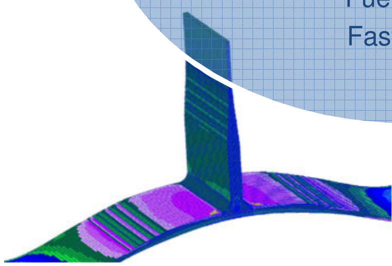
Design detail / geometric features:
Plate-beam configurations;
Honeycomb-Al-Composite interface;
Spar-web-stringer details:
Web to wedge;
π, T, Z and Ω;
Fuel holes;
Fasteners.

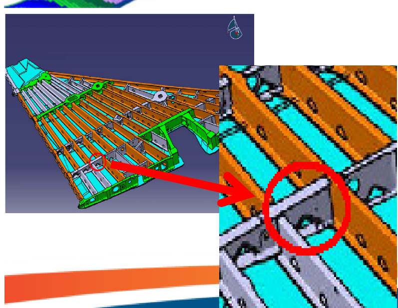
Static, quasi-static, or very low frequency cyclic loading monitoring;
Vibration based SHM (natural frequencies, modes, curvature, global and local changes, orthogonality, etc);
Wave based SHM (Lamb and Rayleigh waves and impedance methods).

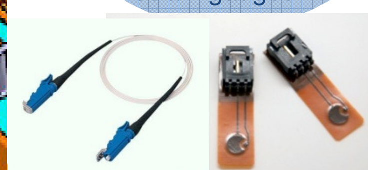
Sensors:
Carbon nano tubes;
PZTs;
Optical fibers;
MEMS;
Local GPS;
Strain gauges…

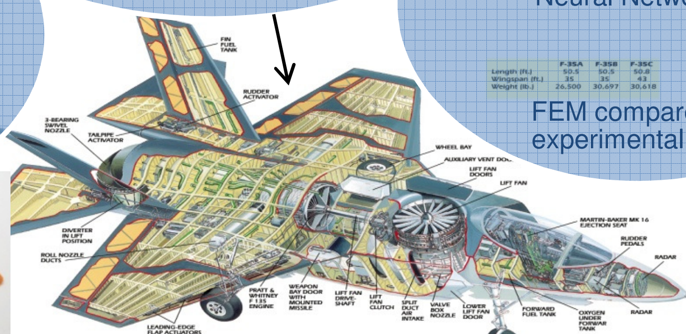
Data post processing:
Statistical methods;
Genetic Algorithms;
Neural Networks.

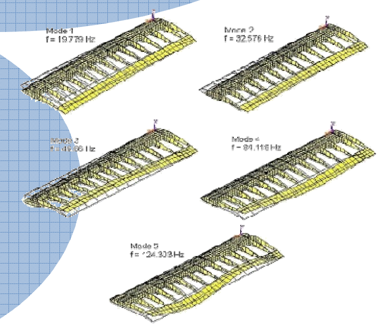
FEM compared to experimental data











Aerospace Research

Engine Performance Prognosis and Health Management

National Research Council Canada
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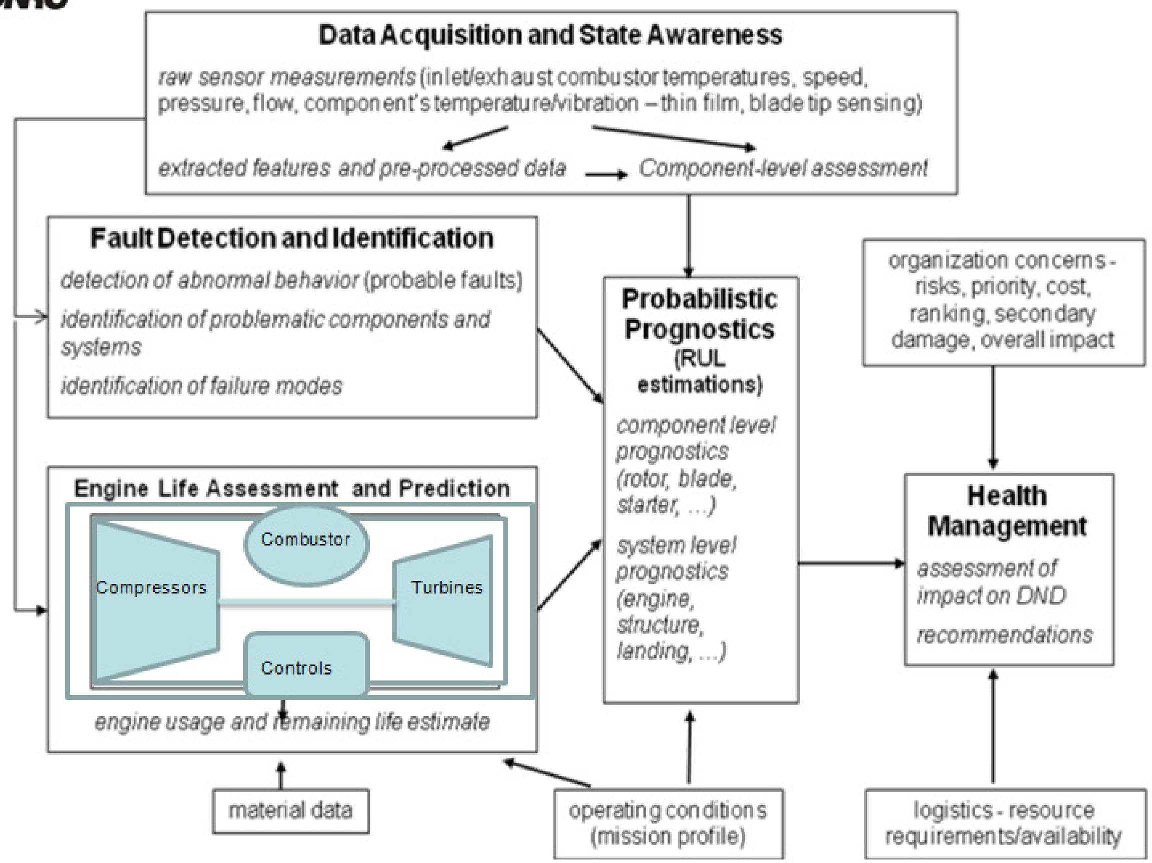
The PHM Framework

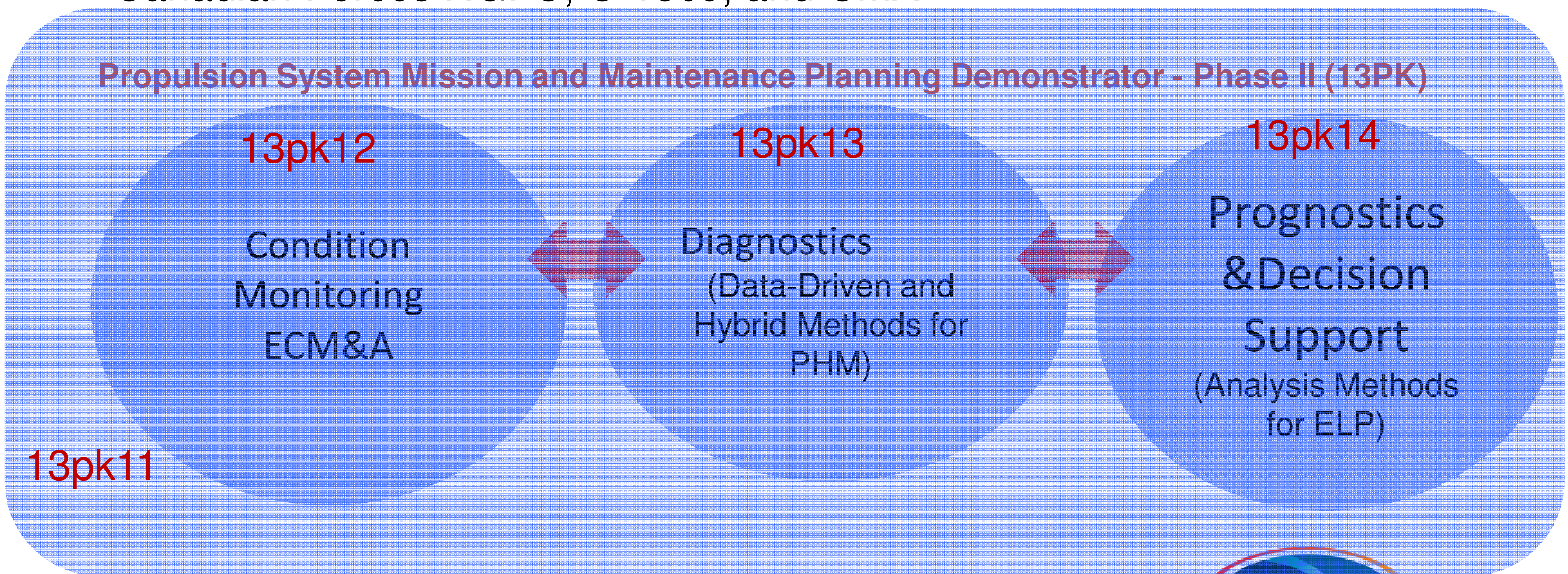
Propulsion System Mission and Maintenance Planning Requirements

NRC·CNRC



13PK Objectives Functional Blocks

Improved capability to certify and support advanced diagnostic and prognostic systems for future weapon systems to be acquired by Canadian Forces NGFC, C-130J, and CMA

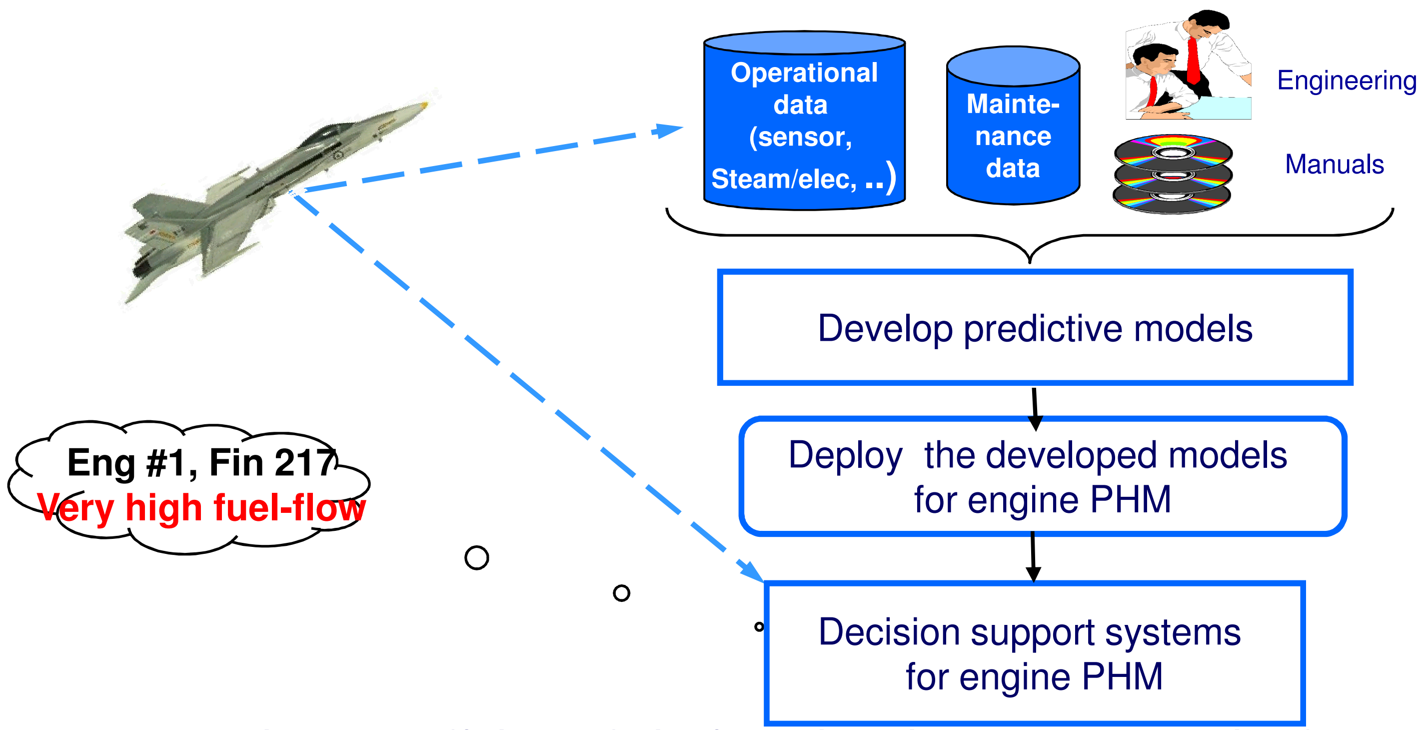


Engine Condition Monitoring and Assessment

Technologies developed/evaluated

Task	Description	Performer
C1	Electrostatic Condition Assessment	GTL
C2	Spectroscopic Fault Assessment	GTL, SMPL
C3	Performance Analysis	IIT, GTL, SMPL
C4	Eddy Current Blade Condition Assessment	SMPL, DRDC
C5	High Temperature Blade Assessment	SMPL,DRDC
C6	Engine Oil Condition Assessment	IMI, GTL, DRDC
C7	Fluid Leak Detection	IMI, GTL, DRDC
C8	IUT for monitoring of bearing conditions	IMI, GTL, DRDC
C9	Integrated Operating Environment Assessment	DRDC, GTL
C10	Wireless and MEMS Sensors	DRDC, GTL
C11	Virtual Sensors and Sensor Data Fusion	DRDC, GTL

Data-driven Engine PHM

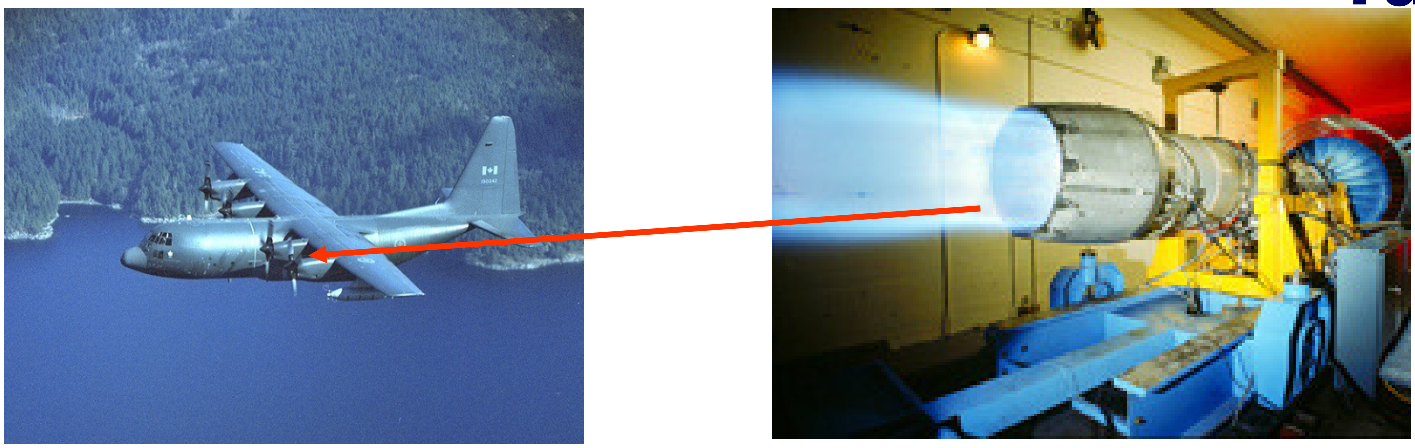


- predict unexpected events (failures) before they interrupt operation/generate impacts
- increase availability and reduces costs by maximizing the usage of systems/components and minimizing unexpected expanses

Developing Data-Driven Models for Engine PHM

- **Data management**
  - cleansing of data
  - storing data into data bases and data warehouses
  - providing secure and convenient access to the data
- **Data-driven modeling, reasoning, and simulation**
  - summarizing raw data into manageable information through statistics
  - extracting useful insights /developing predictive models through data mining, statistics, machine learning,…
  - using learned models to enhance simulation and background knowledge
  - fusing information and automate or support decision making
- **Computing**
  - developing high performance computing platforms and tools to perform required computations
- **Software tools**
  - developing tools that integrate and streamline the data analysis process
  - developing software to deploy the learned models in real-world application

Sensors for Gas Turbines

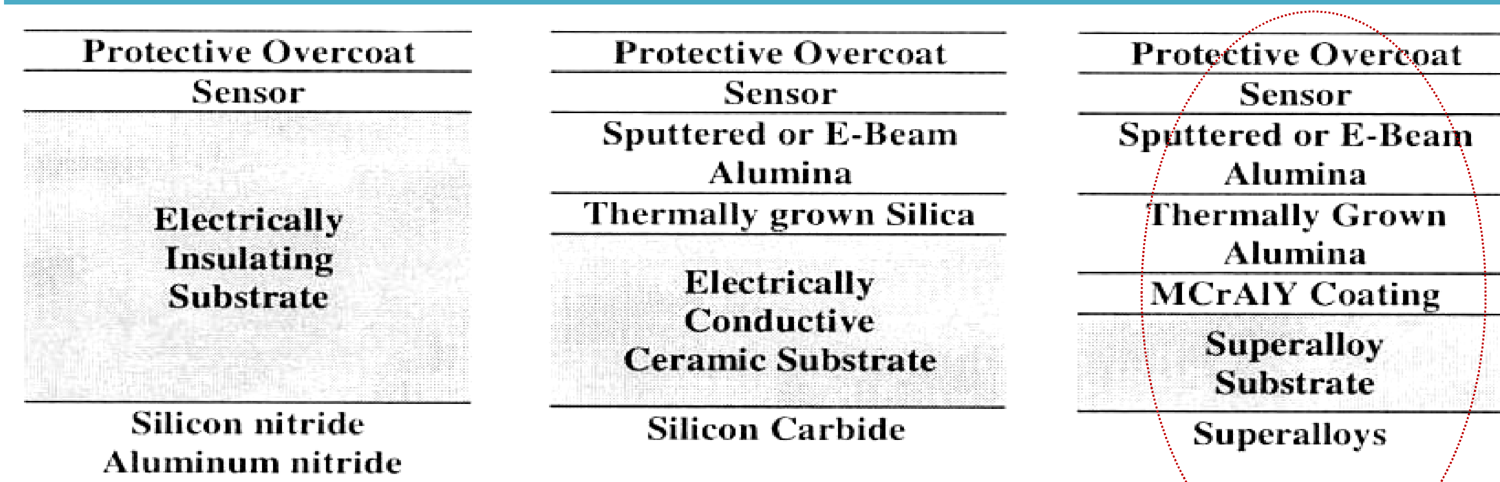


Sensors are needed for real-time monitoring of temperature, stress, fuel blow out, combustion instabilities, noise and NO_x emission etc.

- *Development of new laser fabrication technologies to produce reliable thin film thermocouple (TFTC) and thin film strain gauge (TFSG) sensors for gas turbine application*
- *Evaluation of durability and performance of the thin film sensors in cyclic furnace and burner rig testing*

Sensors for Gas Turbines
Why Thin Films ?

- Owing to small sizes, thin film sensors respond faster to thermal and strain changes than conventional wire sensors and offer superior spatial resolution
- Remains within the aerodynamic layer without any intrusive effects and contributing minimal effects on the modes of vibration of rotating parts
- The response time of thin film sensor becomes shorter as the thickness of sensing layer decreases
- Implication of temperature on lifing calculation +/- 50 degree to +/-2 degree



Thin Film Sensors for Gas Turbines

- Multilayer TFTC and TFSG sensors consisting of an EB- PVD MCrAlY coating, a TGO layer, a PLD Al_2O_3 layer, PLD sensing (Pt and Pt-13Rh; Pd-13Cr) layers and a PLD protective Al_2O_3 layer have been successfully fabricated on a Ni-base superalloy substrate using a combination of electron beam physical vapor deposition, pulsed laser deposition and laser micromachining techniques.
- The sensors have good electrical properties.
- This research has demonstrated that it is feasible to fabricate high quality thin film sensors on metallic substrates using the EB-PVD and laser fabrication technologies.
- Pushing the application limit of these sensors to higher temperatures.

Thin Film Sensor Fabrication Process

Sensor Design

LMM Shadow Mask Fabrication

EB-PVD MCrAlY Layer

Thermally Grown Oxide Layer

PLD Insulating Al_2O_3 Layer

TFTC

PLD Pt Layer

PLD Pt13Rh Layer

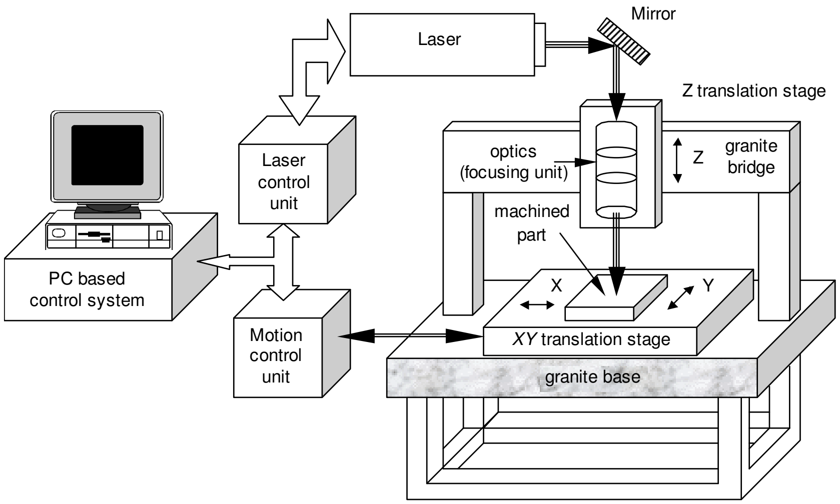
TFSG

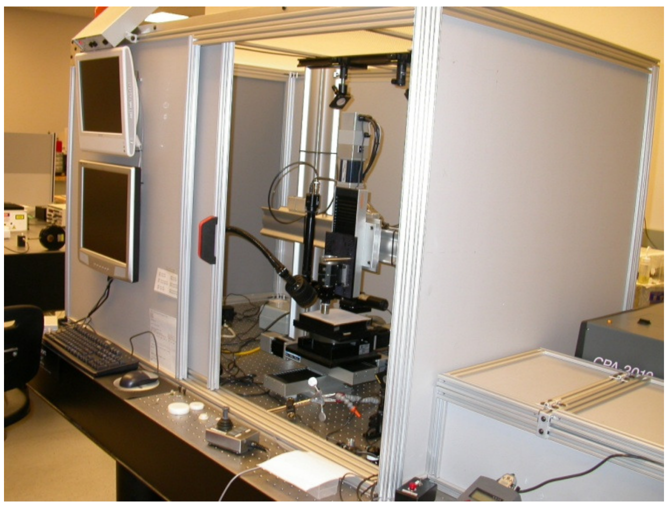
PLD Pd13Cr Layer

PLD Protective Al_2O_3 Layer

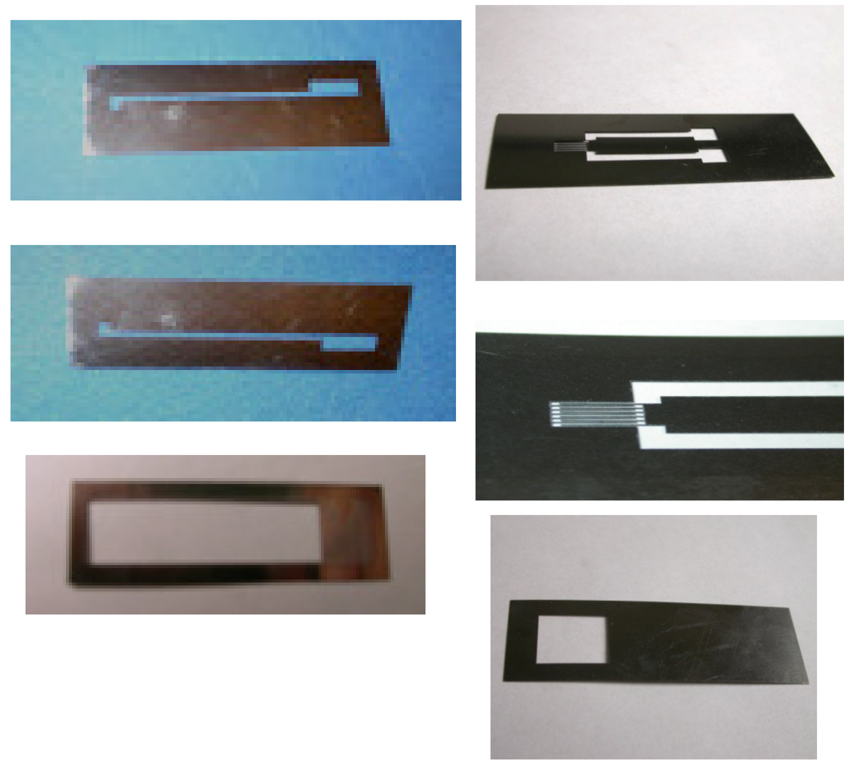
Testing

Shadow Mask Fabrication



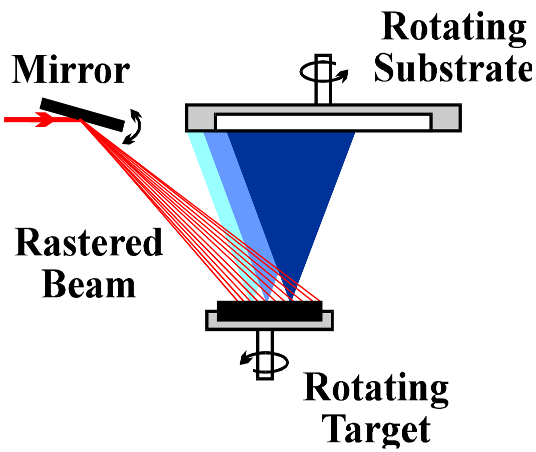


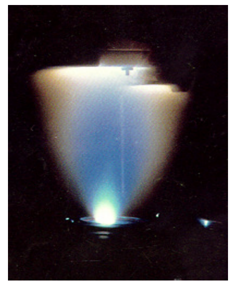
NRC state-of-the-art laser micromachining system

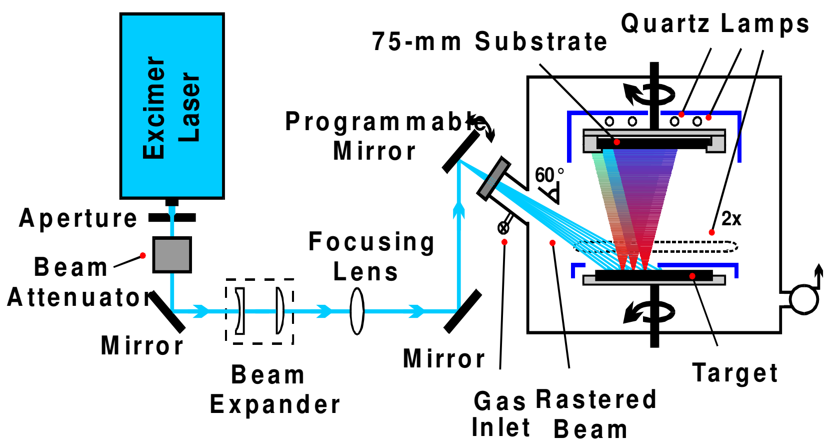


Shadow mask fabricated with UV Nd:YAG laser on stainless steel 0.2mm-thick foil

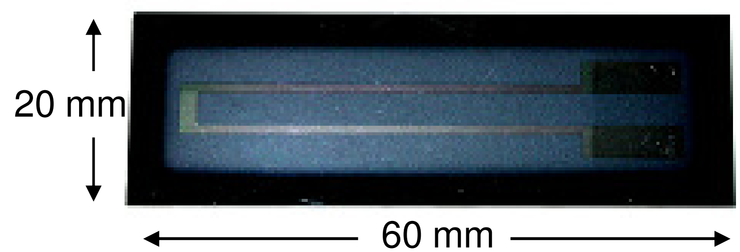
Large-area Pulsed Laser Deposition







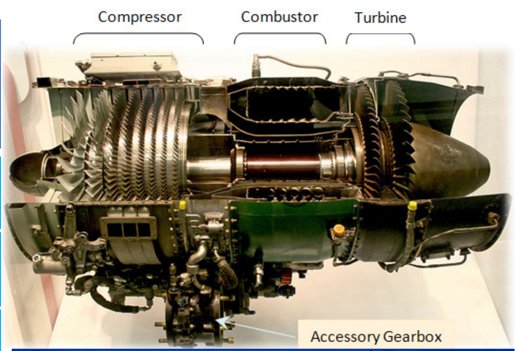
Large-area PLD system

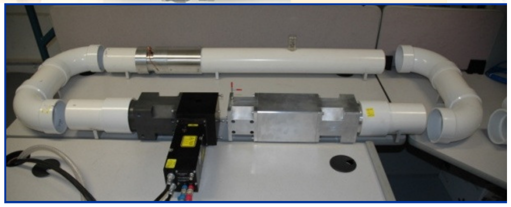


PLD fabricated thin film thermocouple

Next-Phase Transition--Integration

Task	Technology	Init. TRL	End TRL
I-1	Propulsion CBM specifications		
I-2	PHM technology integration	5	6/7
I-3	Evaluation of PHM systems	5	6/7
SA-1	Transition of thermal fluid dynamics analysis	5	6
SA2	Transition of engine oil condition monitoring	6	8
SA3	Degradation sensor system	5	

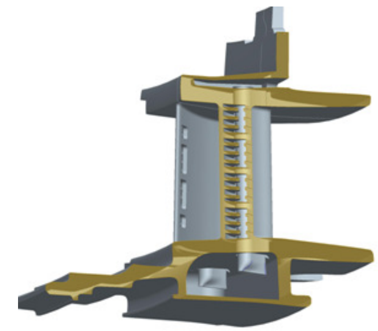


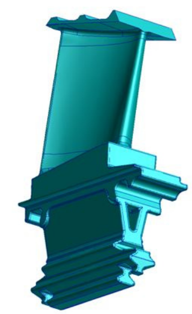


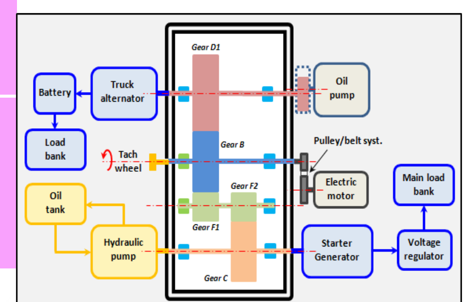
I—Integration
SA—State Awareness

Next-Phase Transition—Cont'd

Task	Technology	Init. TRL	End TRL
D1	Transition of diagnostics technologies	6	7
D2	Fuel control diagnostics and prognostics	5	
P-1	Transition of hot section material modeling	5	6
P-2	Transition of hot section component lifing	5	6
P-3	Mechanical Components Life prediction	5	6







D—Diagnosis
P—Prognosis

Our Aircraft Fleet

Energy Harvesting

Energy sources available for harvesting the operation of Sensors

- **Light**
- **Radio-frequency**
- **Motion**
- **Thermal gradients**

Energy Sources for Harvesting

Light
Most mature and high power under the daylight,
But not available at dark place

Radio-frequency
Can be used everywhere
But usually very small power

Motion
Versatile

Thermal gradients
Very effective if temperature difference is large
(ex. hot exhaust pipe)

Concluding Remarks

NRC has been working on the IVHM of Aerospace Vehicles for last 4 years.

The IVHM concept have been divided into several tasks/modules addressing various issues dealing with sensors, SHM and PHM for components and modules.

NRC has developed several platforms for testing and certification of sensors for both aerostructures and propulsion systems. These platforms are available to the sensor developers for certification/demonstration in realistic operating environments.

Prognosis of sensors are important particularly for those which are utilised in harsh aircraft operating environment.

Thank You for your Attention!