
Dr. Gary W. Hunter, NASA Glenn Research Center at Lewis Field
Dr. Al Behbahani, AFRL
Presenter

• Dr. Gary W. Hunter
  – Intelligent Systems Hardware Lead, Sensors and Electronics Branch
  – Technical Lead, Chemical Sensors Team
  – Element Lead, High Temperature Propulsion Health, Vehicle Systems Safety Technologies Project

• Dr. Alireza (Al) R. Behbahani
  – Leader in Advanced Integrated Controls and prognostic/Diagnostic Systems @ AFRL
  – Senior Aerospace Engineer
  – Over 30 years experience in Aerospace, Nuclear, Mechanical, and Electronic control systems in University, Industry, and Government
OUTLINE

• INTRODUCTION

• MOTIVATION TOWARDS WIRELESS SMART SENSOR SYSTEMS

• PROPULSION SYSTEM APPLICATIONS

• ROLE OF WIRELESS SMART SENSOR SYSTEMS

• EXAMPLE SMART WIRELESS SENSOR SYSTEMS DEVELOPMENT

• SUMMARY AND FURTHER WORK
MOTIVATION TOWARDS WIRELESS SMART SENSOR SYSTEMS
SMART SENSOR SYSTEMS BASED ON MICROSYSTEMS TECHNOLOGY

- A RANGE OF SENSOR SYSTEMS ARE UNDER DEVELOPMENT BASED ON MICROFABRICATION TECHNIQUES AND SMART SENSOR TECHNOLOGY

- SMART SENSOR SYSTEMS APPROACH: STAND-ALONE, COMPLETE SYSTEMS INCLUDING SENSORS, POWER, COMMUNICATION, SIGNAL PROCESSING, AND ACTUATION

- BROAD RANGE OF APPLICATIONS

- MICROSYSTEMS TECHNOLOGY MOVING TOWARDS A RANGE OF APPLICATIONS

- ENABLE SYSTEM LEVEL INTELLIGENCE BY DRIVING CAPABILITIES TO THE LOCAL LEVEL USING DISTRIBUTED SMART SYSTEMS
“LICK AND STICK” TECHNOLOGY (EASE OF APPLICATION)
- Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology included.

RELIABILITY:
- Users must be able to believe the data reported by these systems and have trust in the ability of the system to respond to changing situations e.g. decreasing sensors should be viewed as decreasing the available information flow about a vehicle. Inclusion of intelligence more likely to occur if it can be trusted.

REDUNDANCY AND CROSS-CORRELATION:
- If the systems are easy to install, reliable, and do not increase weight/complexity, the application of a large number of them is not problematic allowing redundant systems, e.g. sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.

ORTHOGONALITY:
- Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to “see, feel, smell, hear” as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.
“LICK AND STICK” SENSOR SYSTEM AVAILABLE IN STANDARD SILICON TECHNOLOGY

- Sensors, power, and telemetry self-contained in a system near the surface area of a postage stamp
- Microprocessor included/smart sensor system
- Adaptable core system which can be used in a range of applications
- Built-in self check, internal data tables
- Multiple configurations available

**Input Data:**

- Oxygen 21%
- Hydrogen 0%
- RP-1 Vapor 0%
- 300 PPM
- 1000 PPM
- 2000 PPM
- 3000 PPM

**Output Data:**

- RAW SENSOR SIGNAL (mV)

**Basic Approach:** Meet the needs of multiple applications building from a core set of smart microsensor technology.

---

**Image Descriptions:**

- Hydrocarbon Sensor
- Oxygen Sensor
- Hydrogen Sensor

---

**Graph:**

- Time (sec) vs. RAW SENSOR SIGNAL (mV)
- Oxygen 21%
- Hydrogen 0%
- RP-1 Vapor 0%
- 300 PPM
- 1000 PPM
- 2000 PPM
- 3000 PPM

---

**Notes:**

- MEM (Makel Engineering Inc.)
PROPULSION APPLICATIONS
PROPULSION SYSTEM GOALS

Motivation / Goals

- Mitigate obsolescence
- Simplify Upgrades
- Improve Reliability
- Prognostic Capability
- Technology Push / Pull
- Add Customer Value
- Reduce Certification Cost/Time
- Capability Growth
- Improve Reliability
- Increase Availability
- Real-time Life Tracking
- Mission Success
- Prognostic Capability
- Lower Cost
- Add New Features
- Adaptive Control / Flow Control
- Reduce Weight
- Reduce Sustainment Costs
- Time to Adapt / Add New Features
- Performance, Time & Cost
ENGINE CONTROL ARCHITECTURES

Centralized FADEC
- Analog Sensor
- Analog Power / Communication

Fully Distributed Control
- Low Temp Digital Control Module
- High Temp Digital Control Module

Aircraft Bus

~125°F
~450°F
Higher
Objective: Modular, Open, Distributed Engine Control

**Technology Benefits**

- **Increased Performance**
  - Reduction in engine weight due to digital signaling, lower wire/connector count, reduced cooling need
  - 5% increase in thrust-to-weight ratio

- **Improved Mission Success**
  - System availability improvement due to automated fault isolation, reduced maintenance time, modular LRU
  - 10% increase in system availability

- **Lower Life Cycle Cost**
  - Reduced cycle time for design, manufacture, V&V
  - Reduced component and maintenance costs via cross-platform commonality, obsolescence mitigation
  - Flexible upgrade path through open interface standards

**Capability Needs**

- **Open Systems Development, Modeling & Design**
  - Future systems requirements definition
  - Open industry interface standards definition
  - System modeling tools development
  - Modular system integration and test techniques

- **Hardware Systems Development**
  - High temperature integrated circuits and systems development
  - Improved electronic component availability

- **Software Systems Development**
  - Software system partitioning
  - Software design and modular test capability
  - Software distributed system V&V
Existing Aircraft
- Although aircraft propulsion systems are highly reliable, propulsion malfunctions contributing to aviation accidents and incidents do occur.
- Degradation and damage that develops over time in hot section components can lead to catastrophic failure.
- Ground-based testing may not identify problems occurring in-flight, or due to damage or degradation in harsh environment conditions during operation.
- Information related to the engine health state is limited due to the harsh environment operational conditions.
- Examples of malfunctions include uncontained rotor failures, in-flight engine shutdowns, and restricted thrust response.
- Examples of underlying causes include turbomachinery damage, controls and accessory faults, and environmental effects such as volcanic ash and ice ingestion.

Future Aircraft
- It is desired that new materials and capabilities be incorporated future aircraft to improve fuel efficiency and reduce noise and emissions while safety is maintained at existing levels. System-level effects of integration of new flight technologies is unclear.
- One way to incorporate these technologies and maintain safety is through health monitoring, but for an engine the operational environments mean limited information is available.
- One example is that changes in the operation of an engine system, for example by increased operating temperatures, may have long-term effect on engine conditions and safety. Knowing these problems as they develop, rather than when they manifest themselves in an accident, is desired.
Propulsion Health Management

Demonstrated Needs Include:

- Advances in algorithms and data analysis are necessary to keep pace with increased data acquisition capabilities.
- Sensor system integration improvements and new functionality can be a means to address existing safety issues and also facilitate the introduction of new flight technologies.
- One way to monitor engine systems, and mitigate potential issues is through small, low weight sensors, such as fiber optics or wireless, which can be integrated easily. An objective is to avoid costly retrofits while maintaining safety.
- Advances in sensors and electronics are critical for enhancing engine health assessments.
- Engine sensor reliability and limited measurement capability are major challenges to increased situational awareness.
- Very difficult to model some engine parameters, e.g., turbine blade temperatures, strains, heat fluxes; measurements are needed.
- Measurement and diagnostics of the engine should be viewed as a integrated, whole field problem and not a collection of individual technologies.
- Engine tests provide rare and much needed opportunities to demonstrate propulsion health management technology.
PROPULSION CONTROL AND HEALTH MONITORING TECHNOLOGIES ASSOCIATED SENSE PARAMETERS

- FOD and hot gas ingestion detection
- Ice accretion detection
- Inlet shock control

- Stability margin management
- Active stall control
- Active flow control
- Life management
- Clearance control
- High cycle fatigue detection

- Combustion instability control
- Emissions minimizing control
- Burner pattern factor control

- Active turbine tip clearance control
- Life management
- Active cooling control

- Domestic object damage detection
- Blade erosion and rub detection
- Afterburner light-off detection

Inlet debris
Inlet shock position
Pressure & temperature

- Stall precursors
- Flow separation
- Stress, strain
- Tip clearance
- Blade time of arrival, bending, flutter
- Vibration
- Pressure & temperature

- Combustion instabilities
- Emissions
- Burner pattern factor
- Pressure & temperature

- Blade tip to casing clearance
- Turbine inlet temperature
- Blade/vane temperature
- Vibration
- Stress/strain

- Exhaust debris
- Pressure & temperature
Technologies Associated with Both Distributed Engine Controls and Propulsion Health Management

The solution is not just software! New hardware capabilities are required!

- Continuous Life Tracking
- Compactness
- Advanced Damage/Life Models
- Nonlinear Methods
- Robust, Multivariable Methods
- Logic for Active Control
- Model-Based
- Robust, Fail-safe Sensors

- Unique Sensing
- MEMS
- MOMS
- Specialized Act.
- Active "Component" Control Hardware
- Continuous Life Tracking
- Compactness

- Advanced Control Logic & Design Methods
- Real-Time Engine Models
- Accuracy
- Compactness
- Adaptive

- Distributed Control Architecture
- Integration Technologies
- Flight Control
- Thermal Management
- Low Observables
- Advanced Fuel Systems
- Health Management
- Power

- High Temp Electronics
- High Speed Data Bus
- Fiber Optics
- Electro-Optics
- Power Distribution
- Electronic Packaging
- High Temp Power Conversion
ROLE OF WIRELESS SMART SENSOR SYSTEMS
High Temperature Wireless Smart Sensor Systems

- Sensors should go where they are needed, even in the harshest of environments.
- Wires add weight, complexity, and are one of the main causes of sensor failure.
- Future implementation of sensor technology can be significantly enhanced by:
  - Improving the ease of integration.
  - Decreasing the burden on the vehicle by decreasing the wire count.
  - Improving reliability by minimizing one of the major causes of sensor failure.
- Processing at the source can significantly enhance resulting information:
  - Improve the fidelity of the information (e.g. signal amplification).
  - Select information to be transmitted/Decrease the amount of information that needs to be sent routinely.
- Drive intelligence to the local level:
  - Local processing to allow component level diagnostics.
  - Decrease burden on the FADEC.
- Objective: High temperature Smart Sensor Systems with wireless telemetry and distributed electronics operable over the broad operating temperature range and conditions of the engine.
Implementation of Distributed Engine Controls with Smart Wireless Sensors

Supervisory FADEC

Selected Information Flow to FADEC

Nodes (or Other Smart Sensors)

Smart Sensors

Processed Information
Sensors and their functions in Turbine Engine Controls and PHM

Dual Purposes/Wide Application Environment Range

- Inlet
  - FOD Detection
  - Stall/ Surge Avoidance
  - Tip Clearance Control
  - Life Management
  - HCF Detection & Ctrl.

- Fan
  - Disk Crack Sensor
  - Tip Clearance
  - Adv. Press. Sensor
  - Vibration

- Comp.
  - Vibration
  - T41 Sensor
  - Erosion Detection
  - Corrosion Detection

- Combustor
  - Life Management
  - Tip Clearance Control

- Turbine
  - Disk Crack Sensor
  - Tip Clearance
  - Vibration
  - T41 Sensor
  - TBC Spalling Detection
  - Corrosion Detection

- Nozzle
  - Exhaust Debris Monitoring System (EDMS)
  - Acoustic Sensor
  - Emissions Sensor

Black: Real Time Diagnostics
Green: Both Real Time Diagnostic and Advanced On-Wing Inspection
Blue: New Real Time Performance Measurement Required
Red: Advanced On-Wing Inspection Technique
CORRELATION OF POSITION WITHIN THE ENGINE TO TEMPERATURE LIMITATION ON ELECTRONIC MATERIALS

Inlet Compressor Turbine Exhaust

Duct boundary layer
Flow instability
Airfoil boundary layer
Tip clearance

Boundary layer
Pattern Factor
Emission
Combustor instability
Tip clearance

Flow mixing

Electronic Materials Operation Range
Silicon Carbide
Silicon

Supreme Challenge Measurements at combustor exit

Gas Path Temperature, °F

Temperatures:
- 3000° F
- 1500° F
- 400° F

Electronic Materials Operation Range

Silicon Carbide
Silicon
Technical Requirements for Smart Sensors in Distributed Controls and Propulsion Health Management

**Major Drivers**
- Suitable security of the information exchange is critical for their use, especially in control systems.
- Reliability of the radio connection is fundamental for control purposes
- Operation in Engine Environments

**Related Drivers:**

**Physical Drivers for Smart Sensors/Distributed Control System Designs**
- Thermal Environment
- Externals Packaging
- Rapid Reconfiguration / Upgradability
- Generic Physical/Functional Interface
- Environmental Requirements
- Certification Impact
- Integration Testing
- Need to integrate electronics onto or within existing hardware

**Environmental Requirements**
- Design for existing ambient temperatures and vibration environments
- Don’t drive cost/complexity into the DCM to withstand unrealistic margins
- Design electronics to withstand existing hardware thermal conditions
- Recognize limitations of typical industry materials
EXAMPLE HIGH TEMPERATURE SMART

SYSTEM DEVELOPMENT
HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

• NEEDS:
   OPERATION IN HARSH ENVIRONMENTS
   RANGE OF PHYSICAL AND CHEMICAL MEASUREMENTS
   INCREASE DURABILITY, DECREASE THERMAL SHIELDING, IMPROVE IN-SITU OPERATION

• RESPONSE: UNIQUE RANGE OF HARSH ENVIRONMENT TECHNOLOGY AND CAPABILITIES
   STANDARD 500°C OPERATION BY MULTIPLE SYSTEMS
   TEMPERATURE, PRESSURE, CHEMICAL SPECIES, WIND FLOW AVAILABLE
   HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS

• ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS

• LONG LIVED HIGH TEMPERATURE ELECTRONICS AT 500°C: TOP DISCOVERY STORY IN 2007

Range of Physical and Chemical Sensors for Harsh Environments
Harsh Environment Packaging (10,000 hours at 500°C)
High Temperature Signal Processing and Wireless
Long Term: High Temperature “Lick and Stick” Systems
Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500°C.

Optical micrograph of demonstration amplifier circuit before packaging.

2 transistors and 3 resistors integrated into less than half a square millimeter.

Single-metal level interconnect.

Test waveforms at 500 °C

Input (1 V P-P Sinewave)
Output 1 hr. @ 500°C
Output 4000 hr. @ 500°C

Less than 5% change in operating characteristics during 4000 hours of 500°C operation.
Based On NASA SiC Components Previously Demonstrated For Long-life Operation

Modulation Of Oscillator Output Frequency As A Function Of Applied Pressure At 500°C

Sensor Data Transmission Across A Power Wire Of A Complete System At 500°C Has Been Demonstrated For 1 Hour

Demonstration Of Wireless Sensor Transmission At 500 °C At A Distance Of 30 cm Has Been Achieved With An External Antenna

Both Are Considered World Firsts And Building Blocks For Future Technology Demonstrations

SiC Ring oscillator stack and capacitive pressure sensor system components in oven for 500°C testing

Transmission through power wire at 500°C over more than 1m

Wireless Transmission at 500°C with external antenna at 30 cm
OBJECTIVE:
MOVE TOWARD HIGHER DEGREES OF COMPLEXITY
ALLOWING HARSH ENVIRONMENT SMART SENSOR SYSTEMS

NASA AVIATION SAFETY PROGRAM: FULL SYSTEM APPROACH
TOWARD HARSH ENVIRONMENT SMART SENSOR SYSTEMS

Milestone: Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management FY2013

Metric: Demonstrate integrated self powered wireless sensor system at 500 °C with data transmission with operational life of at least 1 hr

Significant wiring exists with present sensor systems

Allow Sensor Implementation by Eliminating Wires

High Temperature Sensor Systems
World Record High Temperature Electronics Device Operation
High Temperature RF Components
Energy Harvesting Thin Film Thermoelectrics
SUMMARY

• SMART SENSOR SYSTEMS HAVE A RANGE OF APPLICATIONS
  – INTEGRATED SYSTEM OF PROCESSING, COMMUNICATIONS, SENSORS, AND POWER
  – SMART TECHNOLOGY IS BECOMING INCREASING DOMINANT IN COMMERCIAL APPLICATIONS
  – APPLICATIONS FOR PROPULSION SYSTEMS

• DISTRIBUTED ENGINE CONTROL APPLICATION INCLUDES:
  – PERFORMANCE, TIME, COSTS
  – OPTIMIZED SYSTEMS ENGINEERING APPROACHES, AND IS MORE POWERFUL, FLEXIBLE, AND SCALEABLE

• PROPULSION HEALTH MANAGEMENT MOTIVATION INCLUDES:
  – RELIABILITY OF SENSOR SYSTEMS, INCREASED SENSOR COVERAGE, IMPROVED ABILITY TO UNDERSTAND VEHICLE HEALTH (LOCAL PROCESSING)

• BOTH APPLICATION AREAS SHARE COMMON TECHNOLOGY NEEDS
  – SECURITY
  – RELIABILITY
  – OPERATION IN ENGINE ENVIRONMENTS

• EXAMPLE OF HIGH TEMPERATURE DEVELOPMENT: SiC BASED INTEGRATED SYSTEM

• IMPLEMENTATION WILL LIKELY BE BASED FIRST ON MORE MATURE TECHNOLOGY MORE BENIGN ENVIRONMENTS, FOLLOWED BY SELECTED IMPLEMENTATION IN HARSH ENVIRONMENTS FOR MORE CRITICAL APPLICATIONS

• THIS IS A CORE TECHNOLOGY OF WIDE AND SIGNIFICANT IMPACT THAT NEEDS FURTHER DEVELOPMENT