Sensors for Intelligent Engines

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OUTLINE

• INTRODUCTION
• PRESSURE SENSORS
• HIGH TEMPERATURE ELECTRONICS
• COMBUSTION CONTROL APPLICATION
• HARSH ENVIRONMENT SMART SENSOR SYSTEMS
• SUMMARY
Sensors and Electronics Branch:
Scope of Work

High Temperature SiC Electronics
Micro-Electro-Mechanical Systems (MEMS)
Nanotechnology SiC Nanotubes

Chemical Sensors
Thin Film Sensors
A RANGE OF SENSOR AND SENSOR SYSTEM DEVELOPMENT

HARSH ENVIRONMENT SENSORS AND ELECTRONICS

NASA GRC/CWRU O2 MICROSENSOR
MICROSYSTEMS TECHNOLOGY

- A RANGE OF SENSOR SYSTEMS ARE UNDER DEVELOPMENT BASED ON MICROFABRICATION TECHNIQUES AND SMART SENSOR TECHNOLOGY
- MICROSYSTEMS APPROACH: STAND-ALONE, COMPLETE SYSTEMS INCLUDING SENSORS, POWER, COMMUNICATION, SIGNAL PROCESSING, AND ACTUATION
- ENABLE SYSTEM LEVEL INTELLIGENCE BY DRIVING CAPABILITIES TO THE LOCAL LEVEL USING DISTRIBUTED SMART SYSTEMS
- BROAD RANGE OF APPLICATIONS
- MICROSYSTEMS TECHNOLOGY MOVING TOWARDS A RANGE OF APPLICATIONS

Microsystem Block Diagram
SENSOR SYSTEM IMPLEMENTATION

- **OBJECTIVE:** A SELF-AWARE INTELLIGENT SYSTEM COMPOSED OF SMART COMPONENTS MADE POSSIBLE BY SMART SENSOR SYSTEMS

- SENSOR SYSTEMS ARE NECESSARY AND ARE NOT JUST GOING TO SHOW UP WHEN NEEDED/TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER

- SENSOR SYSTEM IMPLEMENTATION OFTEN PROBLEMATIC
  - LEGACY SYSTEMS
  - CUSTOMER ACCEPTANCE
  - LONG-TERM VS SHORT-TERM CONSIDERATIONS
  - SENSORS NEED TO BUY THEIR WAY INTO AN APPLICATION

- SENSOR DIRECTIONS INCLUDE:
  - INCREASE MINIATURIZATION/INTEGRATED INTELLIGENCE
  - MULTIFUNCTIONALITY/MULTIPARAMETER MEASUREMENTS/ORTHOGONALITY
  - INCREASED ADAPTABILITY
  - COMPLETE STAND-ALONE SYSTEMS (“LICK AND STICK” SYSTEMS)

- POSSIBLE LESSONS LEARNED
  - SENSOR SYSTEM NEEDS TO BE TAILORED FOR THE APPLICATION
  - MICROFABRICATION IS NOT JUST MAKING SOMETHING SMALLER
  - ONE SENSOR OR EVEN ONE TYPE OF SENSOR OFTEN WILL NOT SOLVE THE PROBLEM: THE NEED FOR SENSOR ARRAYS
  - SUPPORTING TECHNOLOGIES OFTEN DETERMINE SUCCESS OF A SYSTEM
BASIC APPROACH:
MAKE AN INTELLIGENT SYSTEM FROM SMART COMPONENTS
POSSIBLE STEPS TO REACH INTELLIGENT 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.
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
SiC-BASED PRESSURE SENSORS

• SiC HAS EXCELLENT MECHANICAL PROPERTIES FOR USE AS A HARSH ENVIRONMENT PRESSURE SENSOR (T > 500°C, SILICON UNDERGOES PLASTIC DEFORMATION)

• FORM DIAPHRAM OF SiC AND INTEGRATE WITH ELECTRONICS

• WIDE RANGE OF APPLICATIONS
  ➢ AERONAUTIC ENGINE APPLICATIONS
  ➢ AUTOMOTIVE APPLICATIONS
  ➢ MATERIAL PROCESSING

• ENGINE OPERATION DEMONSTRATED AT 500°C

• CAN BE INTEGRATED WITH FLOW VELOCITY AND TEMPERATURE

SiC High Operating Temp. Probe (HOTProbe): SiC chip to simultaneously measure flow velocity, pressure, and temperature;

500°C SiC pressure sensor

Real World Application: Pressure Sensor Installed in Engine Test
Progress Timeline

Thermally stable ohmic contact to n-type SiC at 600 °C in air for over 1000 hours.

2nd generation manufacturable MEMS-DCA SiC pressure transducer. Patent applied.

Technology Transfer

1999 (TRL-1) ➔ 2000 ➔ 2002 (TRL-3) ➔ 2007 (TRL-4) ➔ 2010 (TRL-5)

1st generation MEMS-DCA SiC pressure Transducer demonstrated.

MEMS-DCA Pressure transducer patent 6,845,664 awarded
Licensing applications in process

High Temperature Pressure Concept Funded by GMI. (Spring 99)

Field Application

www.nasa.gov
High Temperature SiC Pressure Sensor Development

Objective:
• Develop high temperature (500 to 600°C) SiC pressure sensors for:
  ➢ Active combustion control.
  ➢ Engine health monitoring with wireless data transmission.

MEMS- Direct Chip Attach (DCA) Sensor Attributes:
• Eliminates failures associated with wire bonds at high temperature.
• Reduces thermomechanical stress by decoupling sensor from package.
High Temperature SiC Pressure Sensor Development

COMMERCIAL APPLICATIONS

- Aeronautical and automobile combustion engine pressure monitoring (temperature > 500°C)
- Pressure monitoring in deep-well drilling (temperature ~300°C)
- Pressure monitoring in industrial processes (temperature > 500°C)
- Licensed three patents related to the SiC pressure sensors to Endevco Corp.

Field Testing in Combustor Rig

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation (V)</td>
<td>5-10 V DC</td>
</tr>
<tr>
<td>Pressure Range (psi)</td>
<td>0.5-1000</td>
</tr>
<tr>
<td>Max. Rated Temp. (°C)</td>
<td>600</td>
</tr>
<tr>
<td>Pressure Sensitivity (μV/V/psi)</td>
<td>9.14@ 600 °C, 6.21@ 300 °C, 13.08@ 25 °C</td>
</tr>
<tr>
<td>Linearity (%FSO)</td>
<td>-0.46 @ 600 °C; 0.36@ 300 °C, 0.56@ 25 °C</td>
</tr>
<tr>
<td>Input/Output impedance (kΩ)</td>
<td>0.8@ 25 °C; 1.2@600 °C</td>
</tr>
<tr>
<td>Wiring</td>
<td>4-wire terminal: Two for excitation, two for output.</td>
</tr>
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Performance Parameters

Pressure Output vs Pressure and Temperature
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.

Less than 5% change in operating characteristics during 4000 hours of 500°C operation.
NASA GRC High Temperature Electronics

World Record Operation at 500°C, A NASA Top Discovery Story of 2007

- Components available at 500°C for a range of basic electronic circuits
- High Temperature Wireless at 500°C planned in 2012
- Next Generation Circuits in development

a) Differential Amplifier IC output/5000 hours and 500°C
b) Picture of Differential Amplifier IC/schematic,
c) High temperature packaging for SiC electronics,
d) Inverting Amplifier IC output,
e) NOR logic gate output,
f) NOT logic gate output.
Active Combustion Instability Control Via Fuel Modulation

High-frequency fuel delivery system and models

Advanced control methods

Physics-based instability models

High-temperature sensors and electronics

Realistic combustors, rigs for research
ERA SiC Pressure Sensor Development

*Amplify Data at the Source*

- Pressure Sensor Measurements Inherently Improved By In-Situ Processing
  - Small Signals May Be Interfered with By Noise Transferred Through the Wire
  - Amplify for Improved Signal Quality
- Integration of the Combined System Planned
- First Round Characterization of the Pressure Sensor System in Burner Rig Environments Completed
- Significant Part of the Overall Development of High Temperature Smart Sensor Systems

High Temperature Pressure Sensor

Smart Sensor System for Active Combustion Control

High Temperature Electronics
High Temperature Wireless
Parallel RF sensor data signal transmission at 500°C

- 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

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](image1)

![World Record High Temperature Electronics Device Operation](image2)

![High Temperature RF Components](image3)

![Energy Harvesting Thin Film Thermoelectrics](image4)
C-17 T1 Engine Testing

Ground Based Engine Test Challenge:
Currently it is difficult to conduct Engine Health Management system tests where it is possible to incorporate new sensors and also seed faults during operation. Engine testing is a necessary and challenging component of IVHM technology development. New detection and diagnostic technologies need an intermediate development step between lab testing and flight testing. The C 17 Engine test is an excellent opportunity to meet that need for several IVHM technologies.

Objective:
Demonstrate multiple structural and gas path health management sensors in an operating engine environment. Integrate sensor / detection technologies with Structural Health Management and Gas Path Health Management diagnostics.

Approach:
Perform engine ground tests using commercial derivative engine. Conduct normal engine operations and also operations that have seeded mechanical and gas path faults (simulated).


SUMMARY

- AEROSPACE APPLICATIONS REQUIRE A RANGE OF SENSING TECHNOLOGIES
- NASA GRC IS A WORLD LEADER IN AEROSPACE SENSOR TECHNOLOGY WITH A BROAD RANGE OF DEVELOPMENT AND APPLICATION EXPERIENCE
- A RANGE OF SENSOR AND SENSOR SYSTEM TECHNOLOGIES BEING DEVELOPED USING MICROFABRICATION AND MICROMACHINING TECHNOLOGY TO FORM SMART SENSOR SYSTEMS
- DRIVE SYSTEM INTELLIGENCE TO THE LOCAL (SENSOR) LEVEL
  - DISTRIBUTED SMART SENSOR SYSTEMS
- SENSOR AND SENSOR SYSTEM DEVELOPMENT EXAMPLES
  - HIGH TEMPERATURE PRESSURE SENSOR
  - HIGH TEMPERATURE ELECTRONICS
  - INTEGRATED SYSTEM: SMARTER SENSORS FOR IMPROVED MEASUREMENTS
- ON-ENGINE TESTS IN AVIATION SAFETY PROGRAM TENATIVLEY PLANNED
- CORE MICROSYSTEMS TECHNOLOGY APPLICABLE TO A RANGE OF APPLICATION ENVIRONMENTS