Additive Manufacturing Enabled Ubiquitous Sensing in Integrated Aerospace and Ground Based Turbine Systems


Acknowledgements:
UTC Aerospace Systems: M. Lynch, M. Miller, C. Mueller, R. Poisson, B. Rhoden

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Additive Manufacturing Enabled Ubiquitous Sensing

Outline

• Compelling market and technology drivers for sensing – a historical perspective
• Why wireless signal/power and embedded sensing
• Additive manufacturing as a holistic approach
• Gaps and research opportunities
Historical Perspective of Automotive Sensing Systems

Minimalist Approach

- Collision Avoidance
- Stability and Control
- Steering Wheel
- Communications
- Open Window
- Emissions
  - Yes
- Diagnostics
  - Either Runs or Doesn’t

Lots of Opportunity for Improvements
Automotive Sensing Systems
Emissions and Comfort Controls - Environment

Emissions Systems Imposed by Legislation Drove Sensor Needs

- **O₂, NOx, NH₃**
  - Solid State Electrochemical
- **Humidity Control**
  - Capacitive/Resistive
- **Individual Cylinder Monitoring**
  - PZT Pressure Sensor
- **Catalytic Integrity**
  - O₂ Electrochemical
- **Mass Air Flow (MAF)**
  - MEMS Hot Wire Sensor
- **Temperature Control**
  - RTD Sensor
- **Facial Temperature**
  - Thermopile
- **Canister Purge**
  - Pressure Sensor
- **Seat Temperature**
  - RTD
- **Air Quality Sensor**
  - MOS Sensor
- **Seat Position**
  - Magnetic Position Sensor
- **Mirror Position**
  - Magnetic Position Sensor

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Building Sensing Systems
In-The-Loop-Sensing

HVAC System

Pure Comfort
Combined: cooling, heating, and power

Heat and Power System

PureCell
Green power at 90% efficiency & 95% availability

Security System

OnGuard
Integrated people and building security

Transportation System

Otis Gen 2
Moving people with ReGen

Lighting System

EnergyWise
Integrated building IP and lighting

Communication System

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Aerospace In-the-Loop Sensing Systems
Integrated Sensing

BOEING 787-8


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**Concept of Operations – Onboard RFID Network**

- **Objective:**
  
  "Develop an innovative system for tracking the structural life of rotary wing dynamic components in support of condition based maintenance (CBM) and unique identification (UID) mandates."

- **Example:** COST-A

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**Opportunity**

- **Source:** Bates, et. al. AHS Forum 68
UTC Opportunity Space
PW4000 112-Inch Fan Engine

- **High pressure spool** aerodynamically coupled to **Low Pressure**
- Inter-shaft bearing supports
- Variable pitch vanes in HPC only.
- Chemical Energy → Thrust

*Image publicly available on P&W external website*

**LPC** = Low Pressure Compressor
**HPC** = High Pressure Compressor
**HPT** = High Pressure Turbine
**LPT** = Low Pressure Turbine

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Pratt & Whitney currently captures about 100 parameters at multiple snapshots through a given flight, but that number will grow when the next generation of commercial engines enters service. The Geared Turbofan engine will collect 5,000 parameters continuously throughout a flight, generating massive amounts of data. The GTF family at maturity will have collected roughly 12 petabytes of data.

Matthew Bromberg, Pratt & Whitney President – Aftermarket MARKETS, April 1, 2015
Consequence of all Those Electrical Contacts
Failed Contacts are the Largest Source of Electrical Failures

43% of all Electrical Failures Due to Contacts


6% of Contact Failures Due to Corrosion Alone

(Based on U.S. Navy Safety Center Hazardous Incident Data for 1980-1999.)
UTC Opportunity Space

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UTC Opportunity Space

Additive Manufacturing as an Enabler

- Revolutionary designs
- Increased capacity
- High-performance Materials
- Design for Additive Manufacture
- Reduce lead-time, reduce cost

- Lower TSFC
- Enabling Designs
- Right-1st-Time Build

- Closed Loop Control
- In-Process Monitoring
- Detailed Empirical Understanding
- Prototyping / Tooling

Design for Additive Manufacture

• F-35 Growth (F135 upgrades)
• Next Generation Air Dominance (Next Gen engines)
• Advanced Subsonic (Derivative engines)

Photo credit: U. S. Air Force

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UTC Opportunity Space
Additive Manufacturing as an Enabler - In Process Prototype Development

Over 2,500 Prototypes
15 engine programs supported
ATOMeS:
Additive Topology Optimized Manufacturing with Embedded Sensing

This project aims to demonstrate an additive manufacturing process (guided by physics-based models) for seamlessly embedding a sensor suite into the airfoils of industrial natural gas turbines while maintaining their structural integrity and providing for wireless power, sensor interrogation, and real-time diagnostics through the employment of a health-utilization-monitoring system (HUMS).
Additive Topology Optimized Manufacturing

Design process...

1. Large volume envelope for concept generation
2. Concept generation eliminates material where it is not needed—only optimum load paths remain
3. CAD interpretation—design for the characteristics and constraints of cold spray additive manufacturing
4. Shape optimization—fine-tuning of interpreted design
5. Functional grading of material with shape optimization
6. Prepare support
7. Fabricate by cold spray

Final design:
1. 75% reduction in stress
2. 20% reduction in weight

Example design constraints:
- Curvature must allow line of sight by nozzle for spraying as well as collision avoidance
- Characteristic deposition angle means trapezoidal truss cross sections and limited thickness

Maximize planar features
- Achieve: Lower weight, lower stress, etc.
- Initial
- Morphed
- Identify features, morph, and optimize
- Reduce thickness
- Reduce width
- Fatigue damage can be constrained or optimized

Optimization of layers independently for best use of material
- Solid back
- 80% dense metal foam
- Solid front
- Shape opt
- Optimization

United Technologies Research Center

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ATOMeS: Additive Topology Optimized Manufacturing with embedded Sensing

Additive Manufacturing Palette

DMLS: Direct Laser Metal Sintering

WASP: Wire Arc Sintering Processing

LENS: Laser Engineered Net Shaping

Cold Spray
ATOMeS: Additive Topology Optimized Manufacturing with embedded Sensing

Methodology

- Define System Level PHM/CBM Value Proposition
- HUMS Requirements
- Component(s) Selection to Meet for HUMS
- Meets HUMS Requirements
- AM Process Selection
- Material & Component Requirements
- Sensor Requirements
- Power & Wireless Requirements
- Sensor Selection
- Wireless & Power SubCom Selection
- Meets Materials, Component, Sensing, & EM Performance Requirements
- Mechanical and EM Model Based Topology Optimization
- Component Fabrication & Testing
- Meets Materials, Component, Sensing, & EM Performance Requirements
- To Rig Testing

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Hydra Concept – A Research and Development Platform

Integrated Inlet Guide Vane with Embedded Sensing
ATOMeS: Additive Topology Optimized Manufacturing with embedded Sensing

Technology Capability Flow

Angular Position Sensor

Additive Topology Optimized Manufacturing

HUMS Diagnostics

Embedded Thermocouple

COTS (TRL4+) RF Components and Sensors

EM Modeling and Tests

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ATOMeS

TRL6 Hardware Test

Significant wiring exists with present sensor systems

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TRL4+ Demonstrator

NETL Test Facility

Flow from swirl-stabilized premixed NG combustor

Temperatures: 1000-1300°C
(typical 1175°C)
Pressure: 1 – 10 bar
(typical 2 – 5 bar)
Velocities: 30 – 80 m/s
(typical 70 m/s)

Test specimen platform (2” x 2”)

Viewport (fused silica windows)

2” x 2” x ¾” test specimen
1/32” diameter Type-K thermocouples

UTRC / NETL Development Probe

HYDRA

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Design Philosophy: Use Non-Proprietary COTS Components to Allow User Community Access
ATOMeS

Angular Position Sensor Sensitivity Analysis

- Resolution of <0.5 angular degree can be achieved
- Magnet material should be selected in conjunction with sensor IC specifications to achieve desired resolution without saturation

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Magnet Material</th>
<th>Simulation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{sat}</td>
<td>Sensitivity</td>
<td>B_r</td>
</tr>
<tr>
<td>73.3mT</td>
<td>3mV/mT</td>
<td>1050mT</td>
</tr>
</tbody>
</table>

- Flux contained in the VR structure

Flux lines of the VR sensing assembly

Magnetic field density variation

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Additive Manufacture offers tremendous potential for reducing cost in prototyping, engine development programs, and production.

UTC has AM applications in all of these categories, including productionization of components.

Significant work is still necessary bring AM processes to the point of rapid, part specific development and validation.

UTC has worked with and is working with a number of partners to rapidly develop this technology.
ATOMeS

Technology Opportunity Space

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Supply Chain Hardware Integrity for Extended Defense

The Counterfeit Parts & Materials Challenge
15th Annual CQSDI
Cape Canaveral, FL
March 26-27, 2008
Lloyd Condra, Boeing Phx
Tony Marino, Boeing Integrated Def
tArt Mester, Boeing Integrated Def
tBill Procarione, Boeing Integrated Def
tBill Sotfield, Boeing Phx

Scope of the Problem
Engineering, Operations & Technology | Phantom Works

Almost anything can be counterfeited:
- Fasteners (bolts, nuts, rivets, fluid bolts)
- Electronics (capacitor, resistor, integrated Circuits)
- Materials (titanium, composite chemicals)
- Anything else (Electronic Assemblies, Pumps, Actuators, Batteries, etc.)

Counterfeiters are very creative:
- Darwin rules
- There is no “final” solution

There are many sources of counterfeit parts and materials:
- The supply chain is large and complex
- Aerospace has limited control

Impact of using counterfeit parts or materials:
- Potential loss of life
- Monetary loss
- Liability
- Lack of availability of our products for customer use
- Loss of customer/public trust and image
- Brand damage

Counterfeiting accounts for more than 8% of global merchandise trade and is equivalent to lost sales of as much as $600B and will grow to $1.2T by 2009.
Ref: Dept of Commerce

Counterfeit parts are usually ½ or less of the street price for genuine goods. The intense pressure on cost adds to the attractiveness of counterfeit parts.

The true numbers are not known. Industry is attempting to quantify the costs.
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