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

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April 30, 2015

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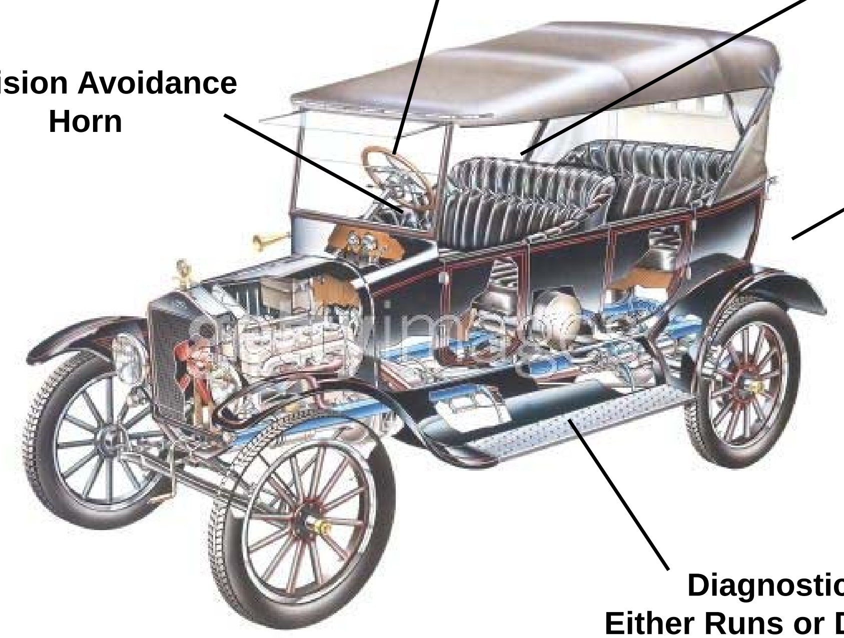
Additive Manufacturing Enabled Ubiquitous Sensing

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

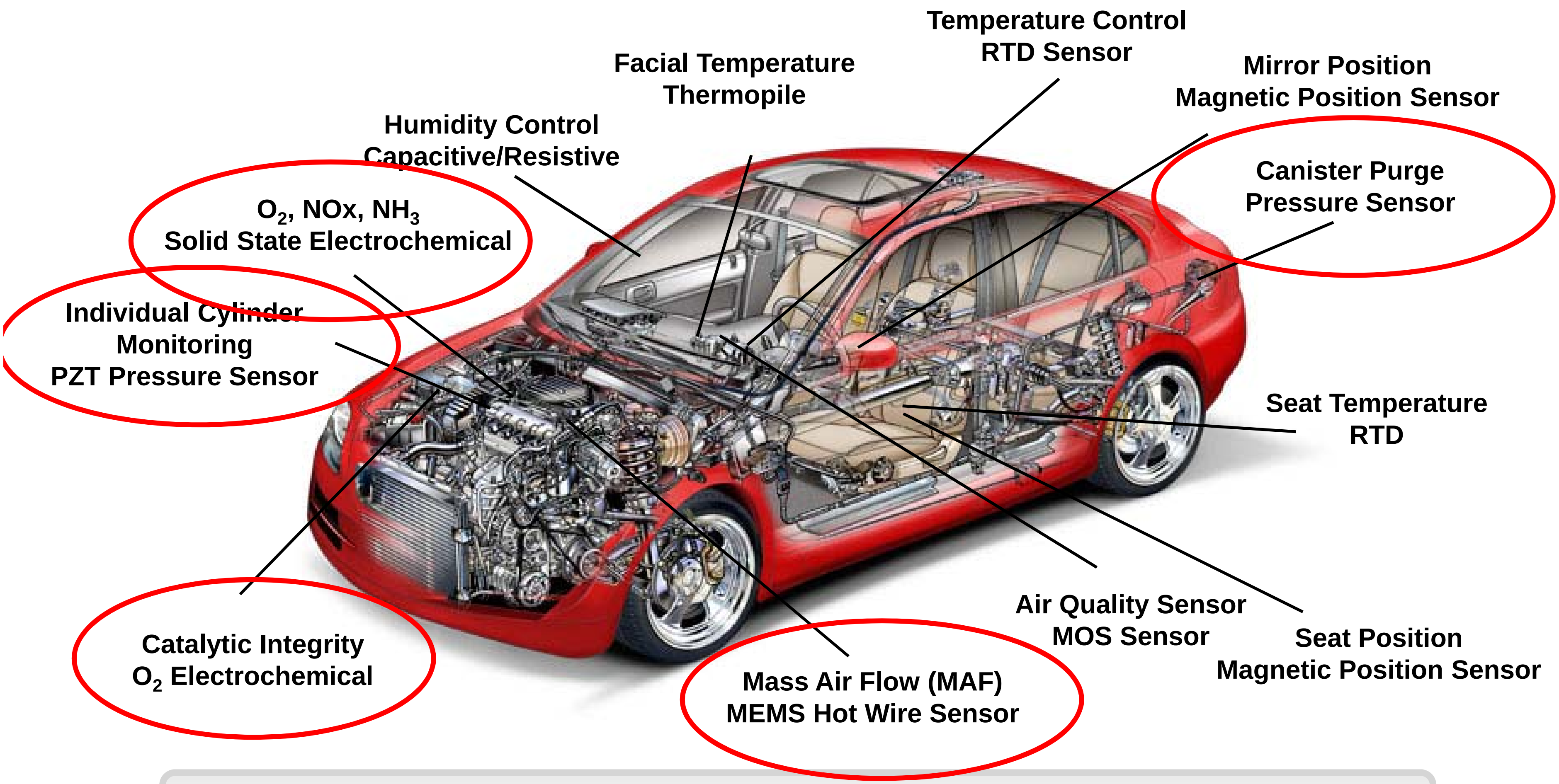
Minimalist Approach



Lots of Opportunity for Improvements

Automotive Sensing Systems

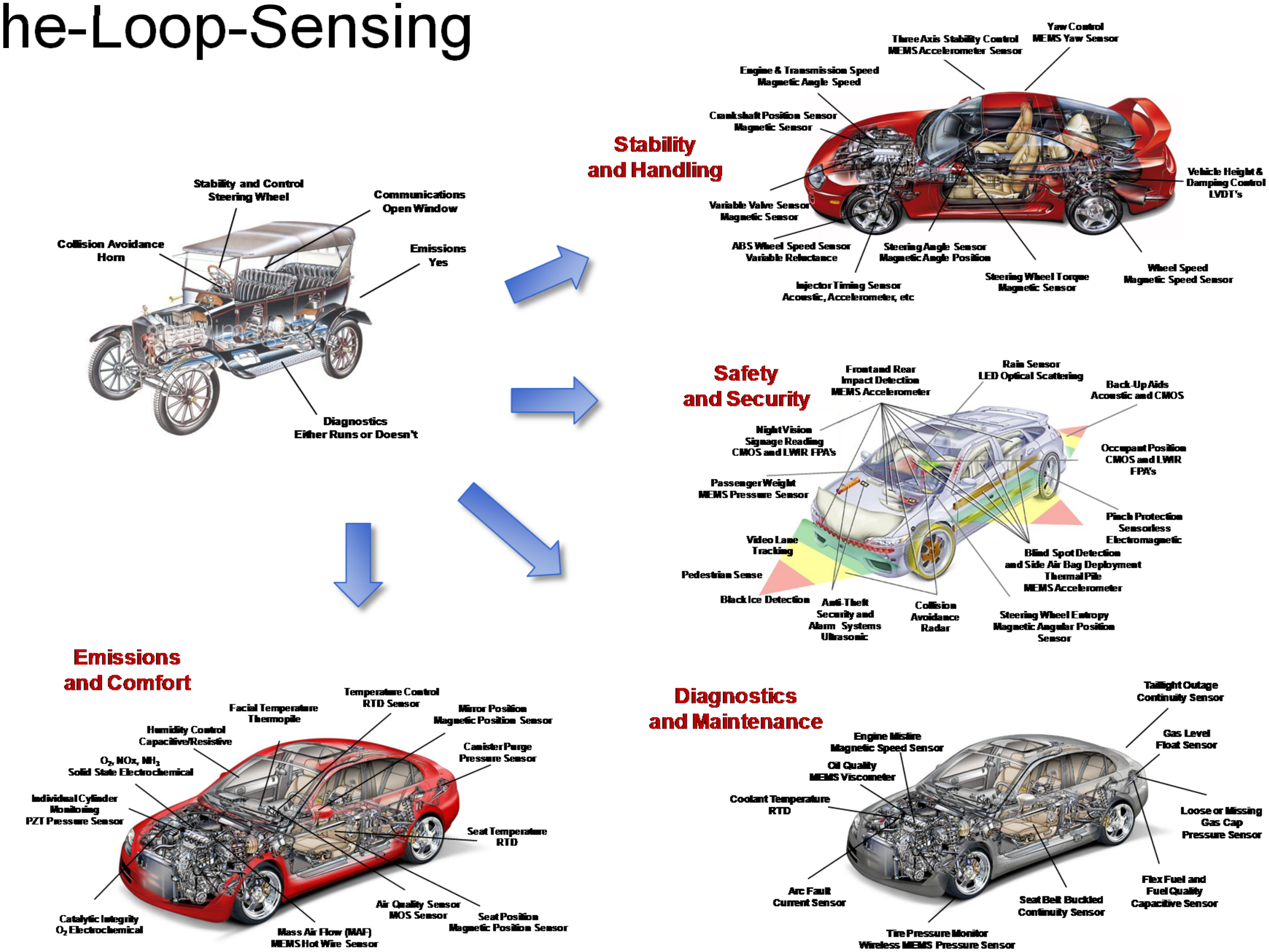
Emissions and Comfort Controls - Environment



Emissions Systems Imposed by Legislation Drove Sensor Needs

Automotive Sensing Systems

In-The-Loop-Sensing



United Technologies
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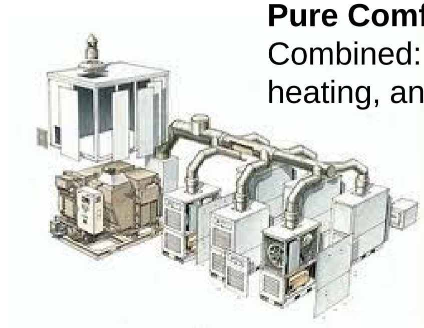
Building Sensing Systems

In-The-Loop-Sensing

HVAC System



Pure Comfort
Combined: cooling, heating, and power

Heat and Power System

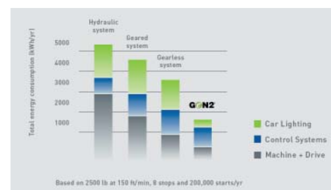
PureCell
Green power at 90% efficiency & 95% availability

Security System

OnGuard
Integrated people and building security

Transportation System

Otis Gen 2
Moving people with ReGen



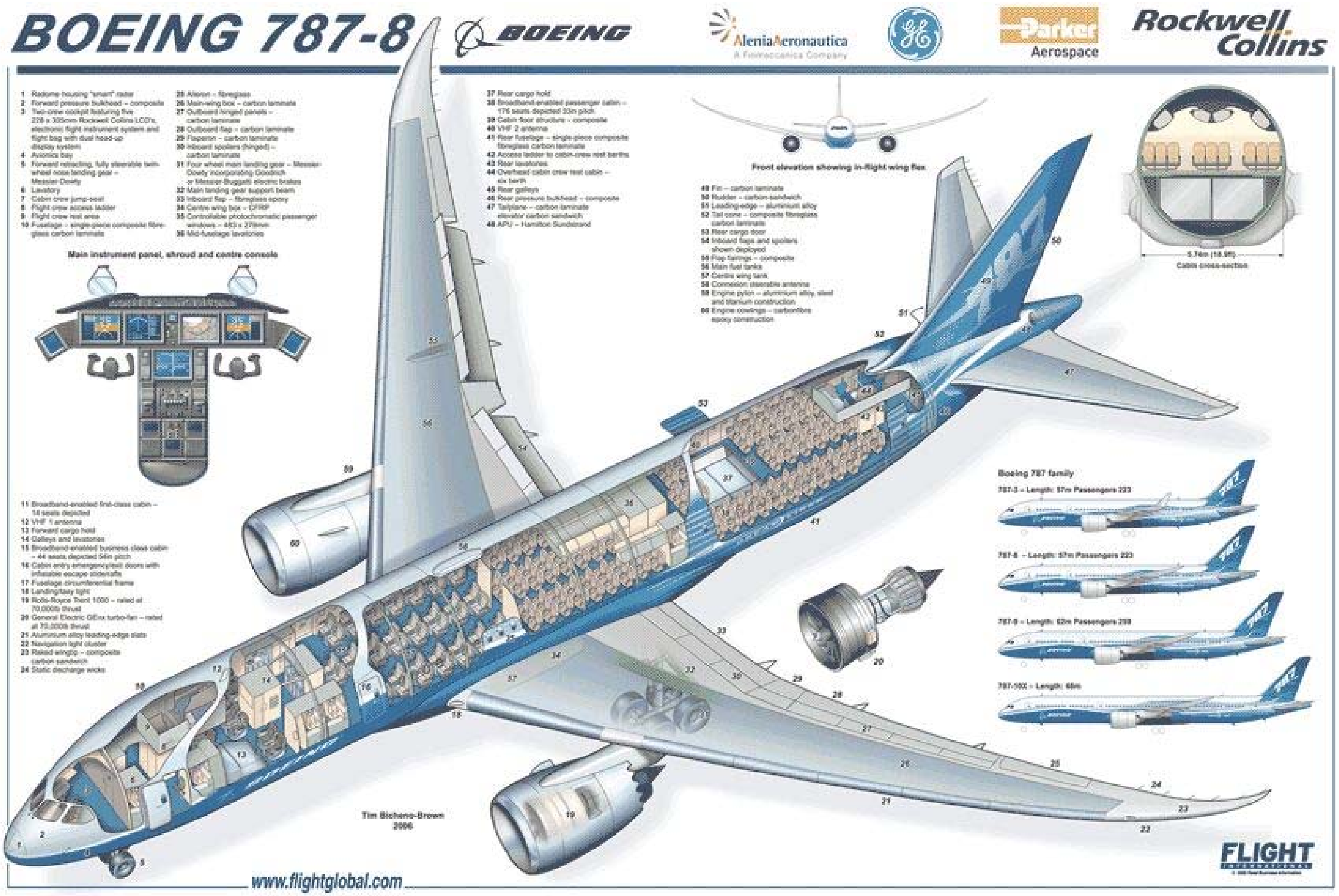
Communication System

EnergyWise
Integrated building IP and lighting

Lighting System

Aerospace In-the-Loop Sensing Systems

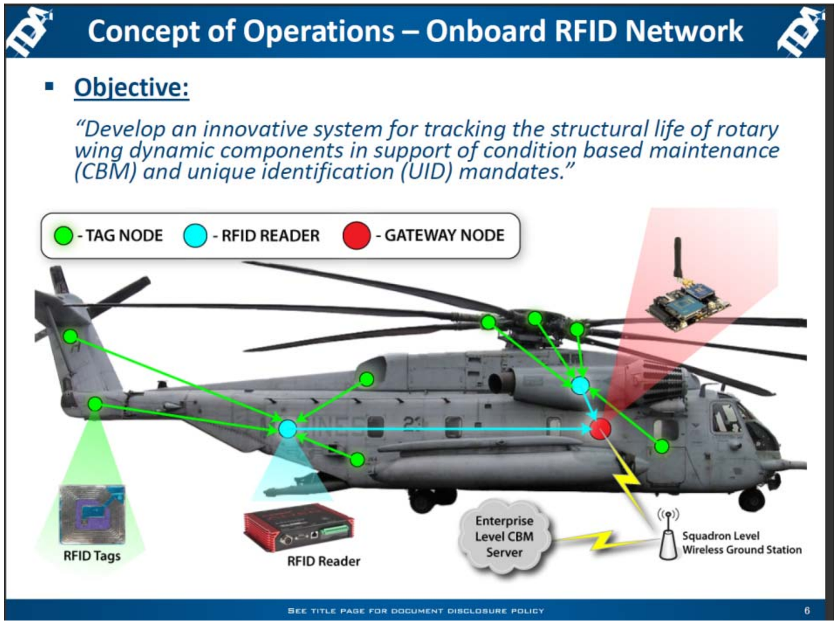
Integrated Sensing



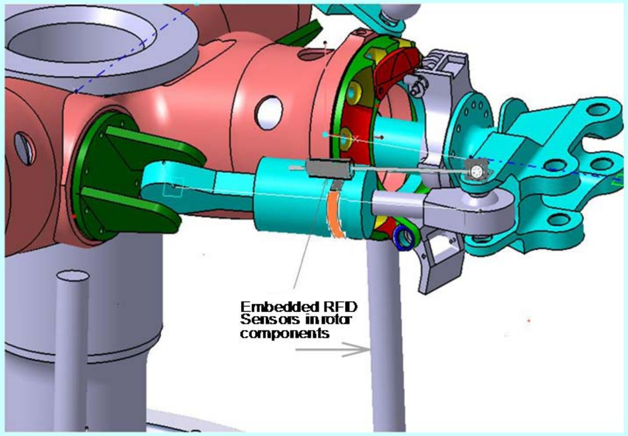
http://www.flightglobal.com/imagearchive/Image.aspx?GalleryName=Cutaways/Cutaway%20Posters/Microcutaways&Image=Boeing-787-8-microcutaway

UTC Opportunity Space

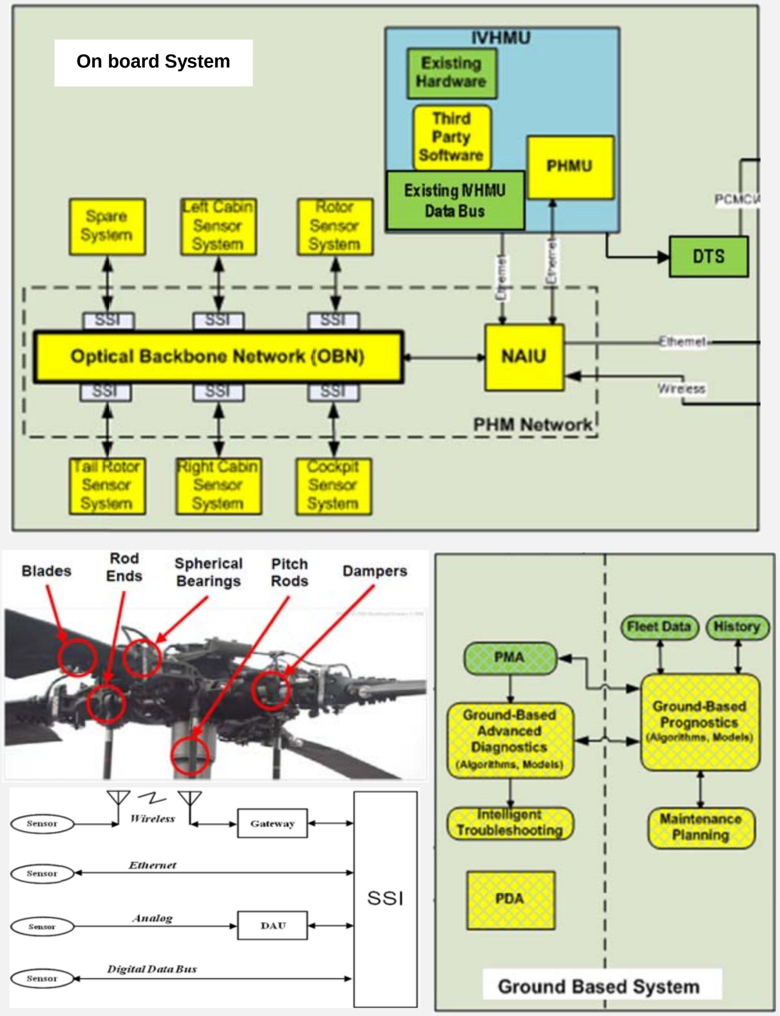
The Sikorsky Platform – Health and Utilization Monitoring System (HUMS)



Opportunity



Example: COST-A



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

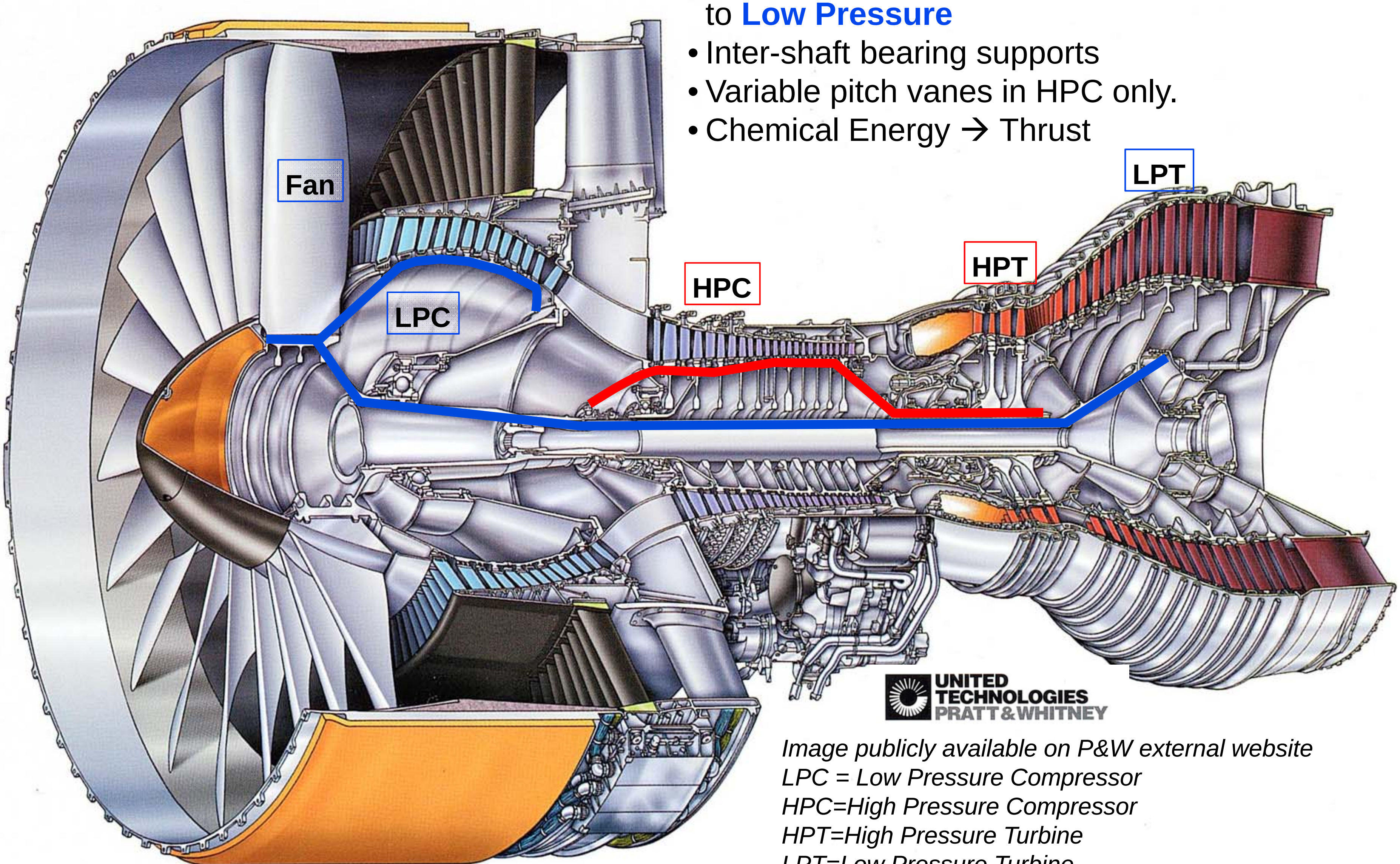


Image publicly available on P&W external website
LPC = Low Pressure Compressor
HPC=High Pressure Compressor
HPT=High Pressure Turbine
LPT=Low Pressure Turbine

UTC Opportunity Space

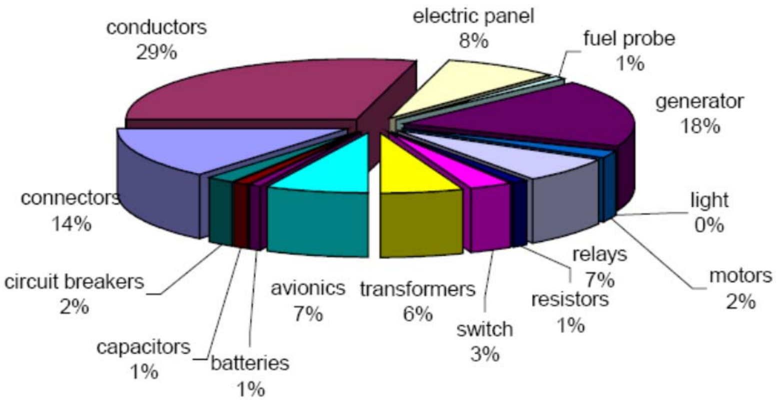
Pratt & Whitney Geared Turbofan Engine

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 <u>Geared Turbofan engine will collect 5,000 parameters</u> continuously throughout a flight, generating massive amounts of data. The <u>GTF family at maturity will have collected roughly 12 petabytes of data</u>.

Matthew Bromberg, Pratt & Whitney President – Aftermarket
MARKETS, April 1, 2015

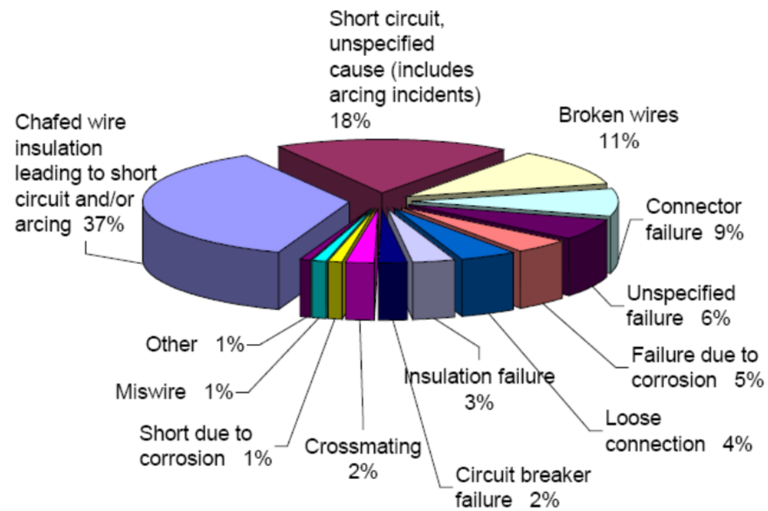
Consequence of all Those Electrical Contacts

Failed Contacts are the Largest Source of Electrical Failures



43% of all Electrical Failures Due to Contacts

Based on U.S. Air Force Safety Center Electronics Failure Data for 1989-1999



6% of Contact Failures Due to Corrosion Alone

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

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

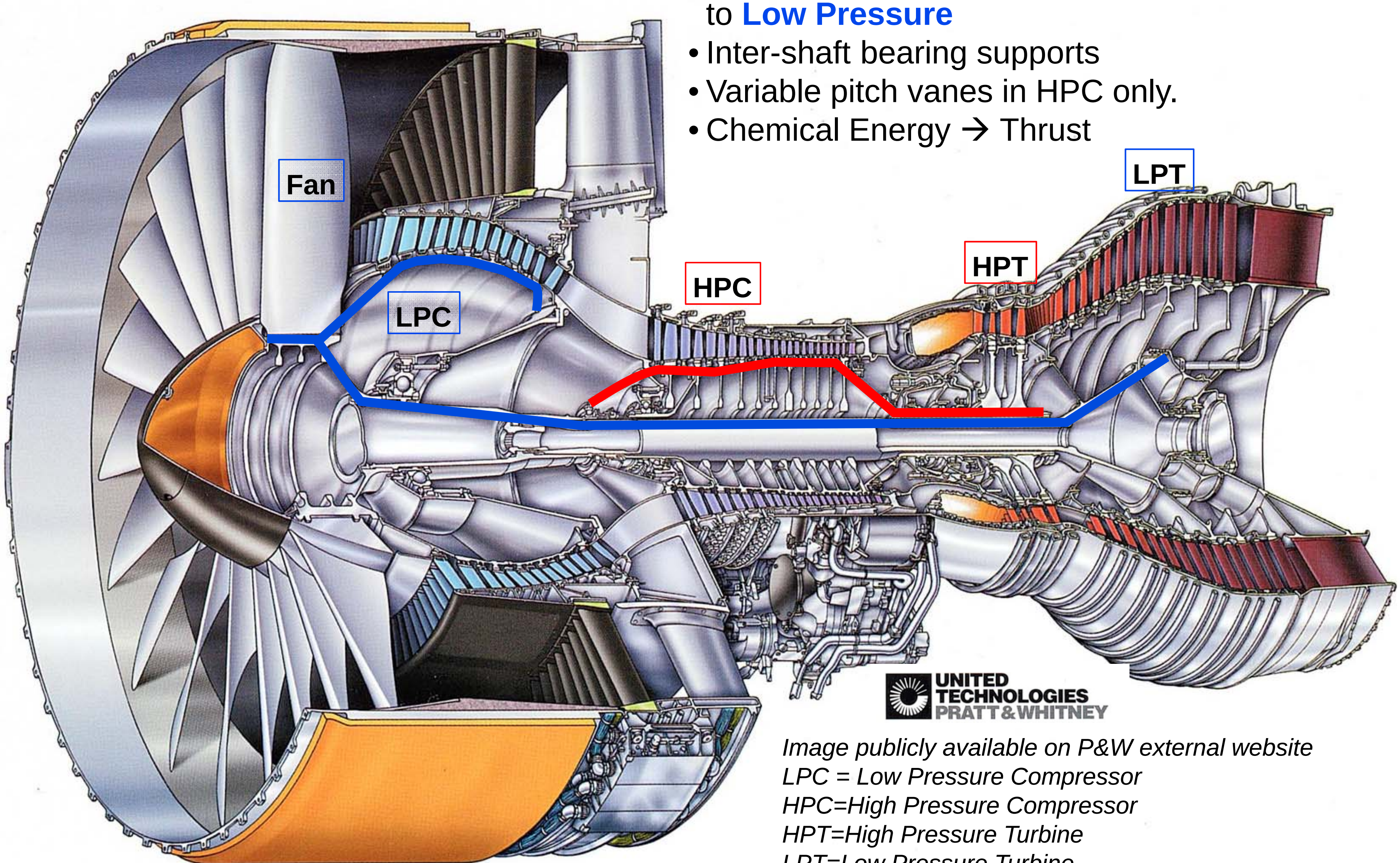


Image publicly available on P&W external website
LPC = Low Pressure Compressor
HPC=High Pressure Compressor
HPT=High Pressure Turbine
LPT=Low Pressure Turbine

UTC Opportunity Space

Additive Manufacturing as an Enabler

Revolutionary designs

Increased capacity

High-performance Materials

Design for Additive Manufacture

Reduce lead-time, reduce cost

Detailed Physic-Based Understanding

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

Closed Loop Control

In-Process Monitoring

Detailed Empirical Understanding

Prototyping / Tooling

Next Generation Air Dominance
(Next Gen engines)

Advanced Subsonic
(Derivative engines)

F-35 Growth
(F135 upgrades)

Photo credit: U. S. Air Force

UTC Opportunity Space

Additive Manufacturing as an Enabler - In Process Prototype Development

Visual

Rigs & Testing

Engine Development

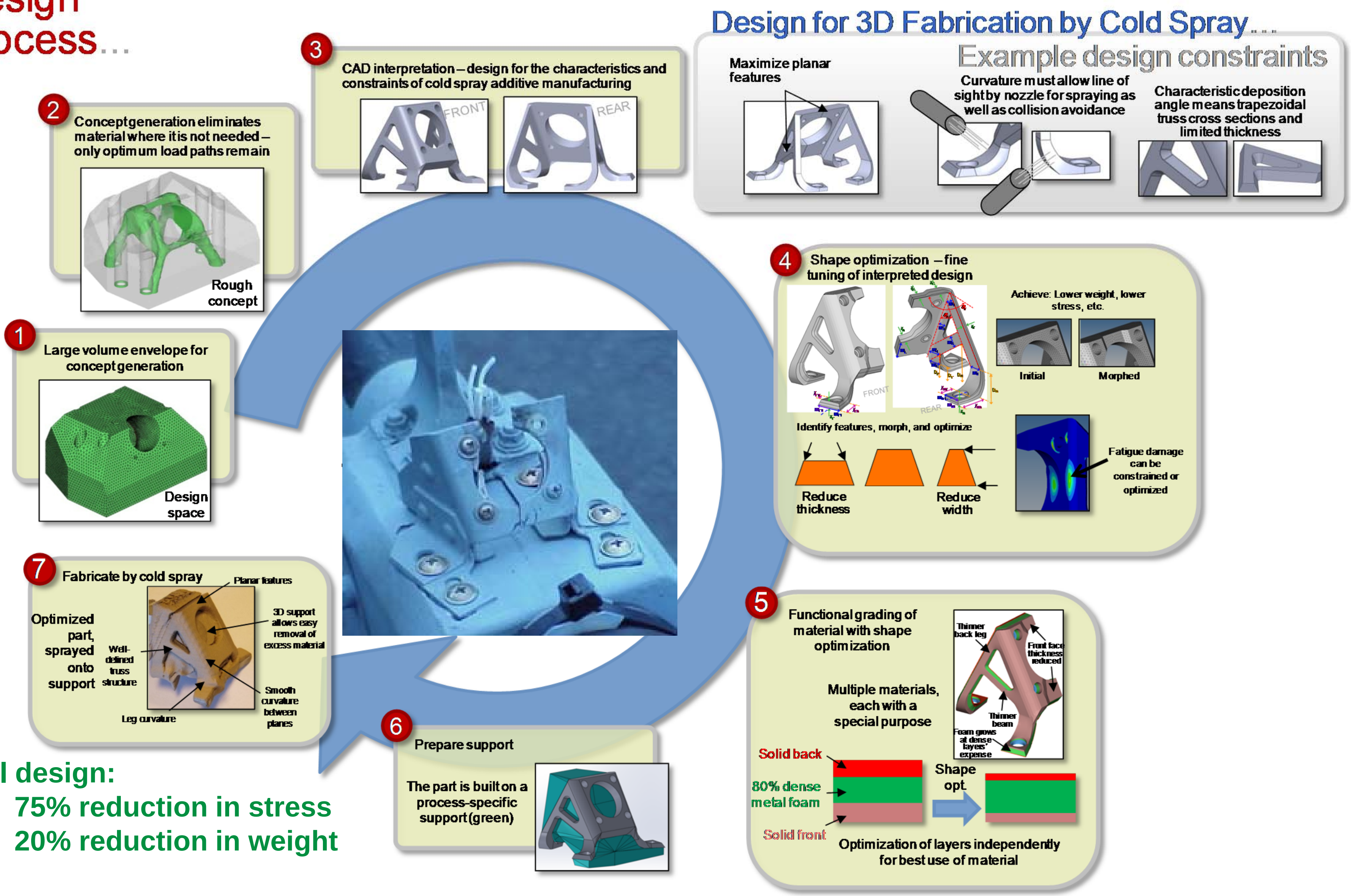
Over 2,500 Prototypes
15 engine programs supported

ATOM*e*S:
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…



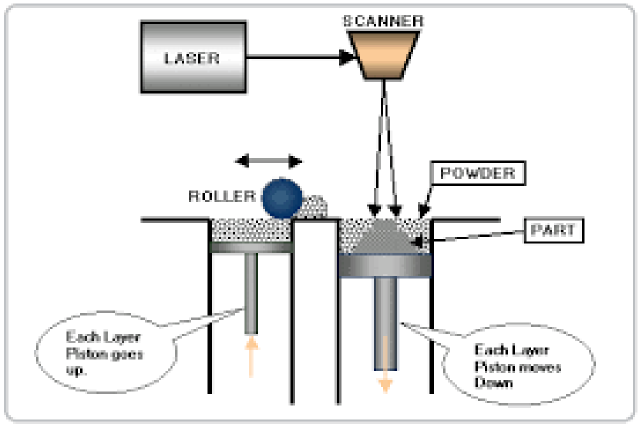
Final design:

1. 75% reduction in stress
2. 20% reduction in weight

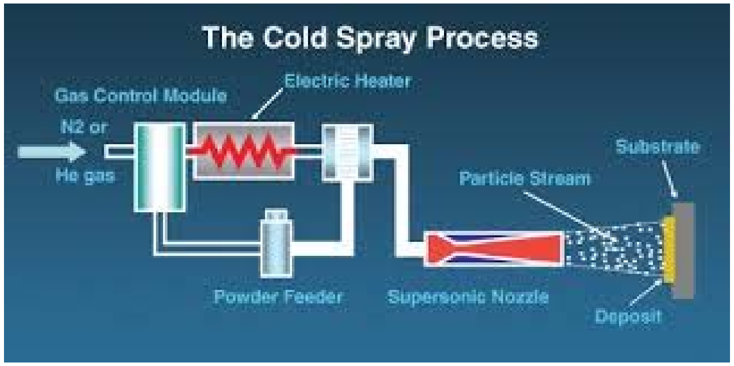
United Technologies Research Center

ATOM*e*S: Additive Topology Optimized Manufacturing with embedded Sensing

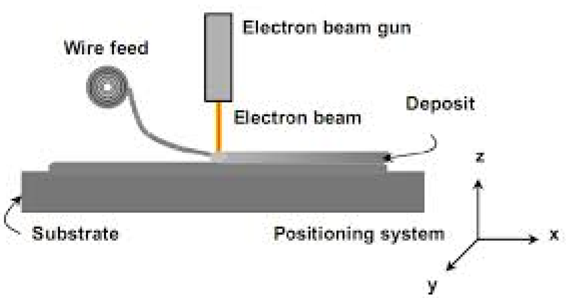
Additive Manufacturing Palette



DMLS: Direct Laser Metal Sintering



Cold Spray

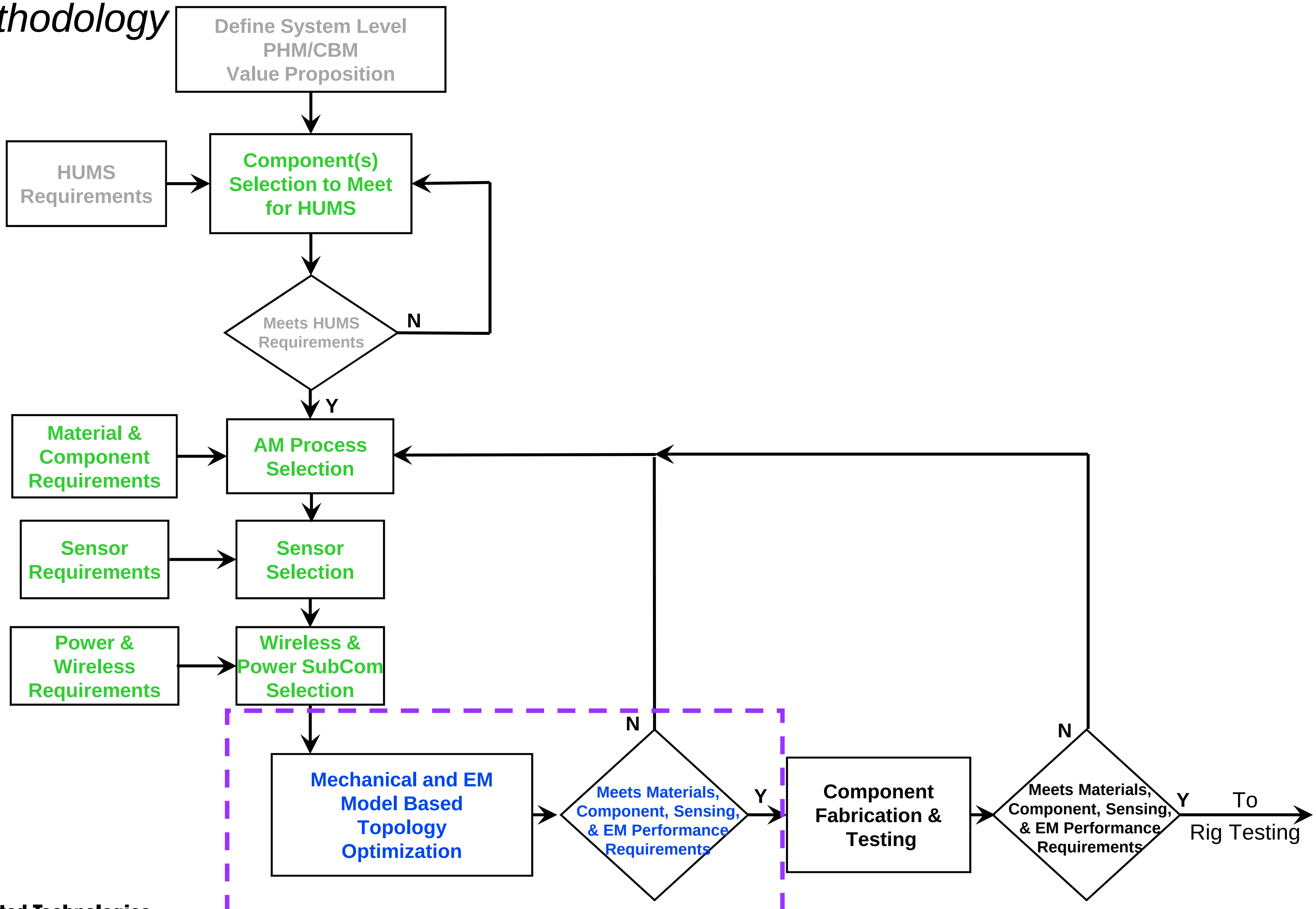


WASP:
Wire Arc Sintering Processing

LENS: Laser Engineered Net Shaping

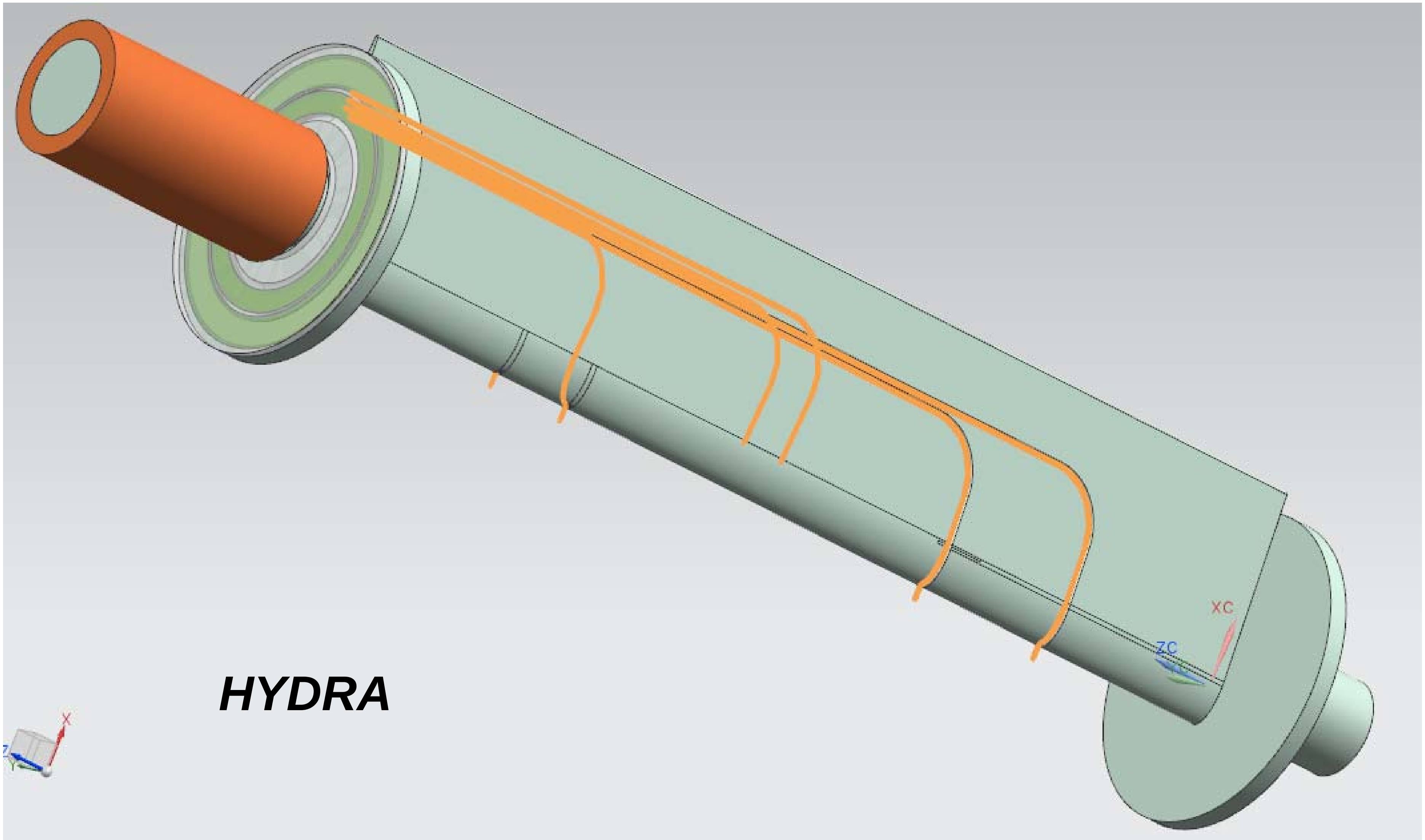
ATOMeS: Additive Topology Optimized Manufacturing with embedded Sensing

Methodology



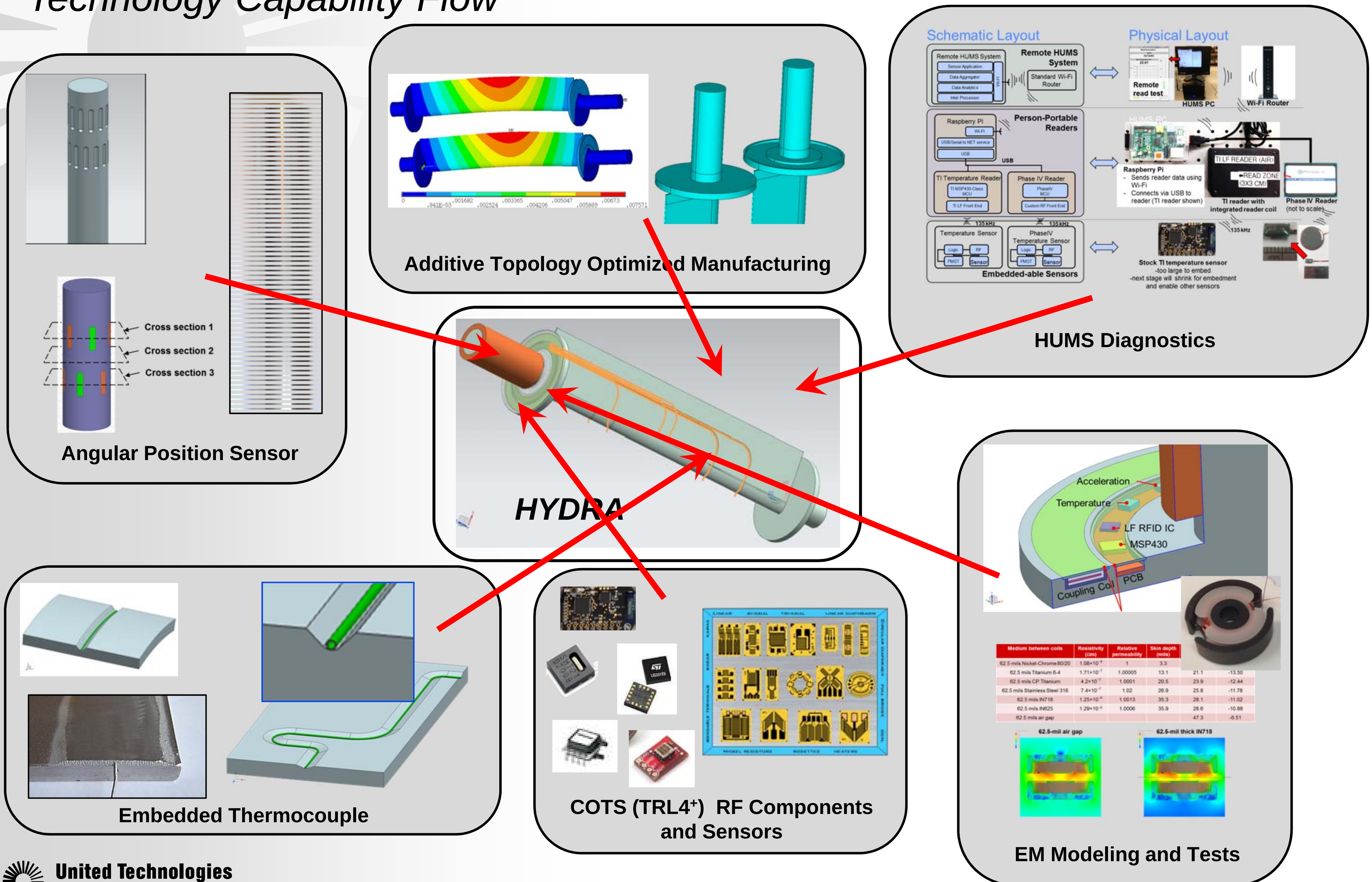
Hydra Concept – A Research and Development Platform

Integrated Inlet Guide Vane with Embedded Sensing



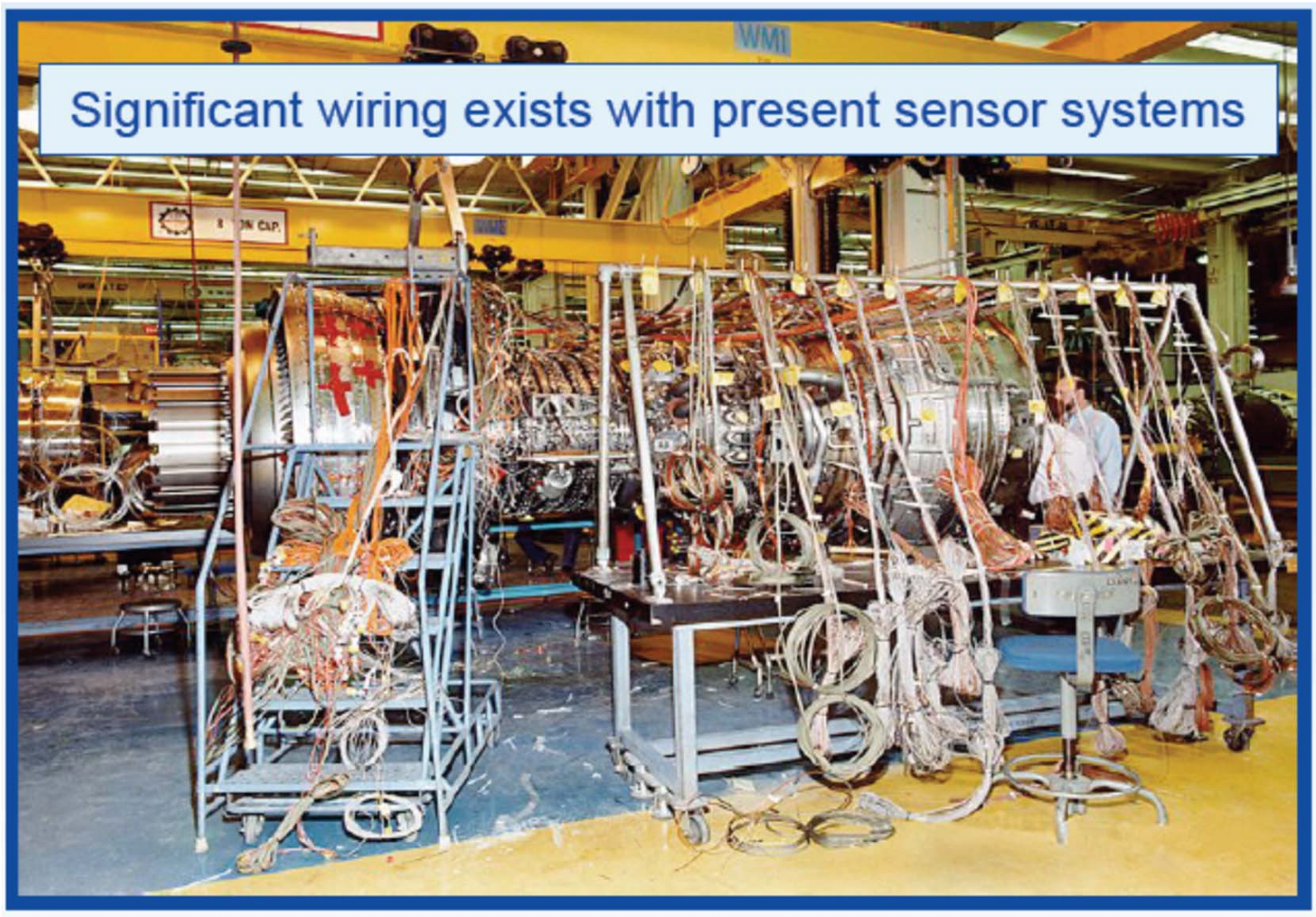
ATOMeS: Additive Topology Optimized Manufacturing with embedded Sensing

Technology Capability Flow



ATOM*e*S

TRL6 Hardware Test



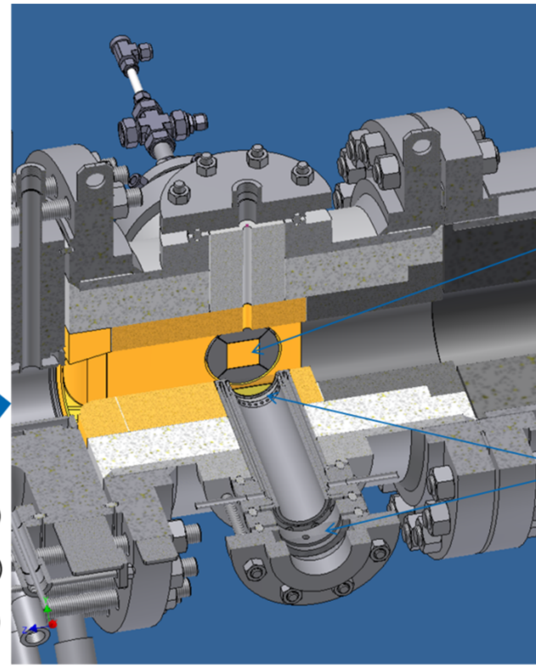
This page contains no technical data subject to the EAR or the ITAR.

TRL4+ Demonstrator

NETL Test Facility

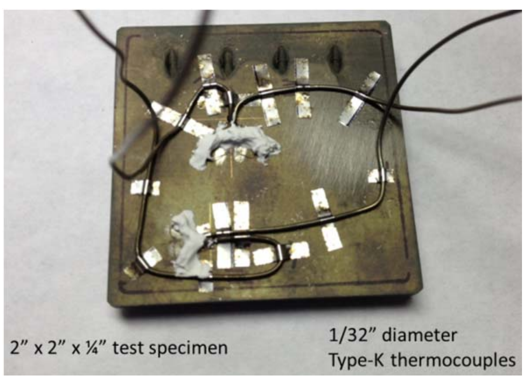
Flow from
swirl-stabilized
premixed NG
combustor

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

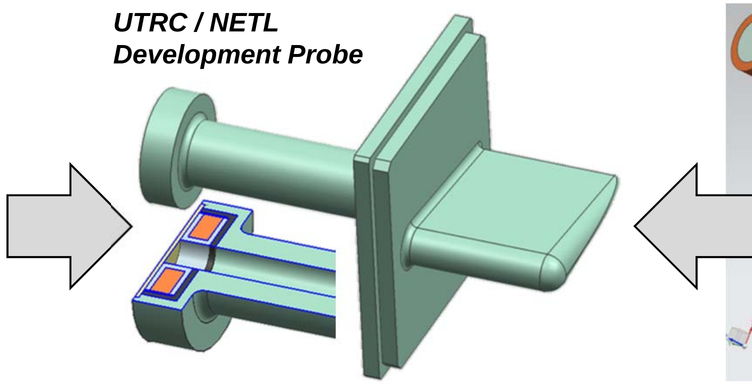


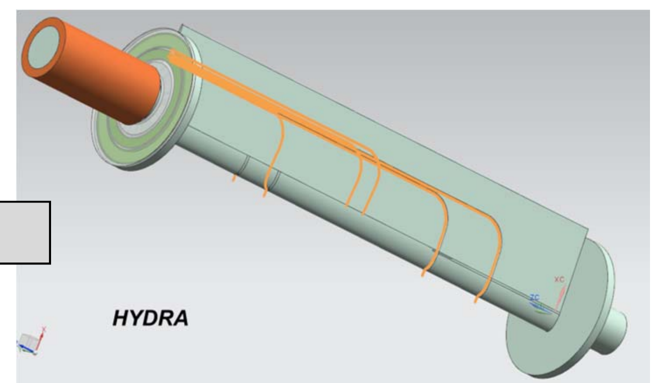
Test specimen platform
(2” x 2”)

Viewport
(fused silica windows)



UTRC / NETL
Development Probe





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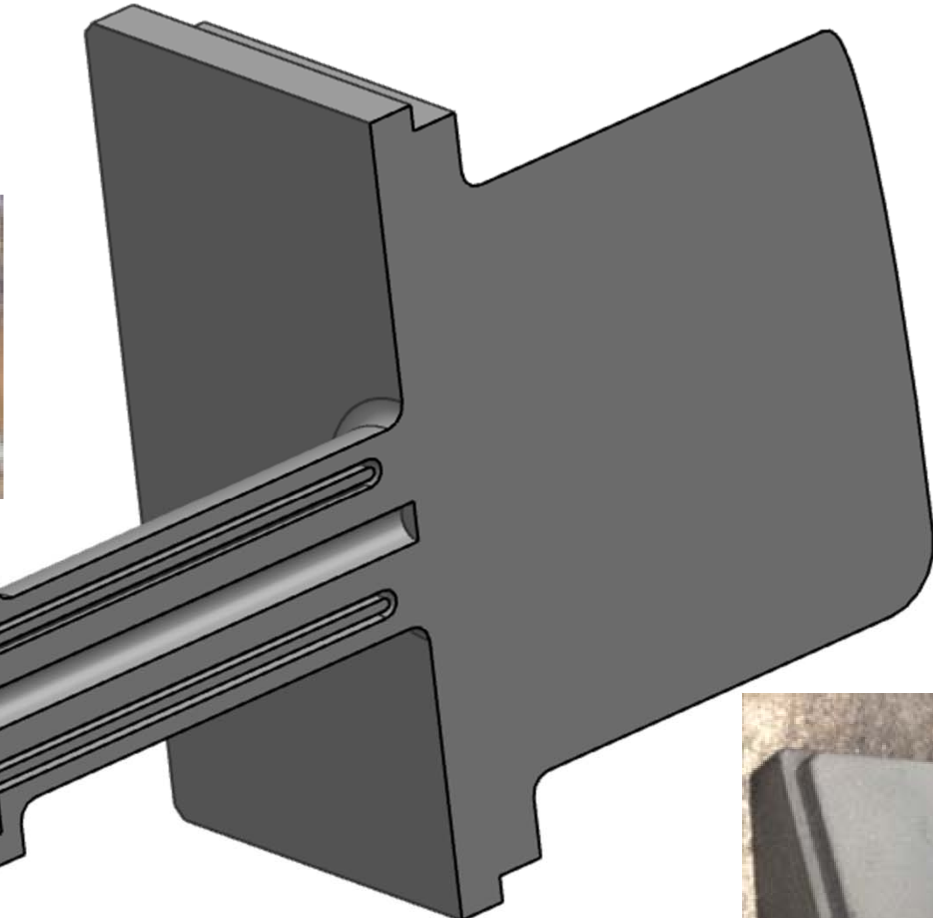
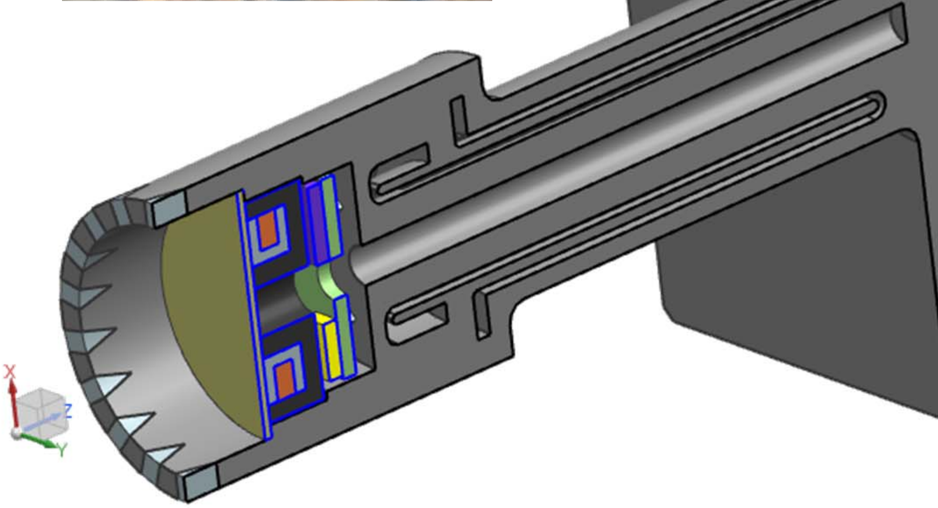
Section View of UTRC / NETL Stub Vane Development Probe Concept

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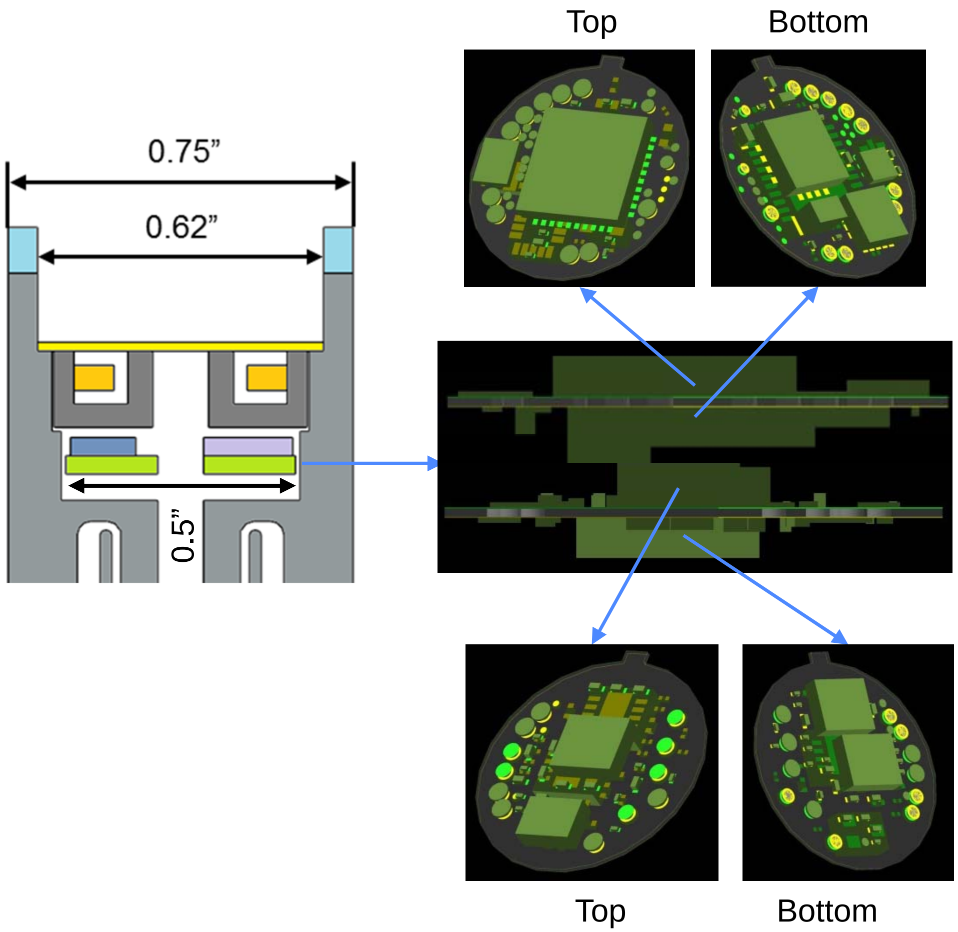
Tag Board Layout and COTS BOM



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

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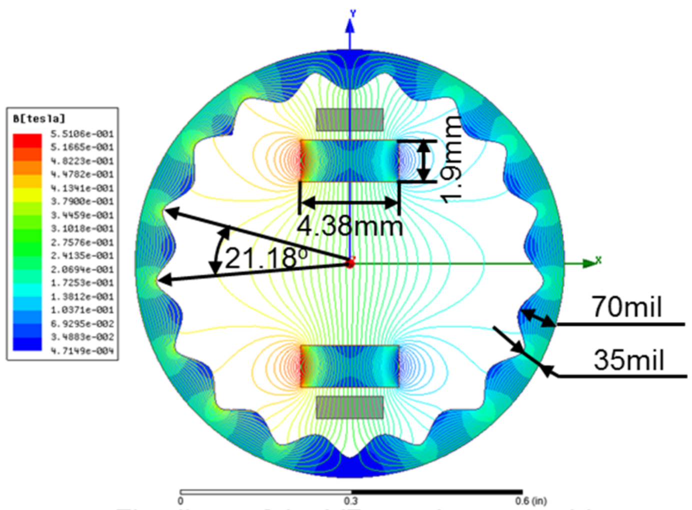
Angular Position Sensor Sensitivity Analysis

- 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

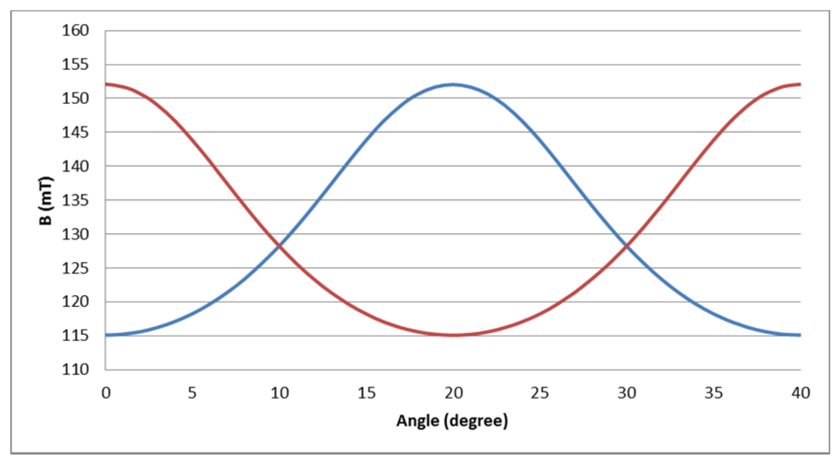
Table 1. Sensor and magnet design example

Sensor		Magnet Material		Simulation results		
B_{sat}	Sensitivity	B_r	H_b	B_{max}	$\Delta B_{min}/0.5$	V_{min}
73.3mT	3mV/mT	1050mT	119.4kA/m	51.7mT	20.4μT	0.61mV

- Flux contained in the VR structure



Flux lines of the VR sensing assembly



Magnetic field density variation

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Technology Opportunity Space

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

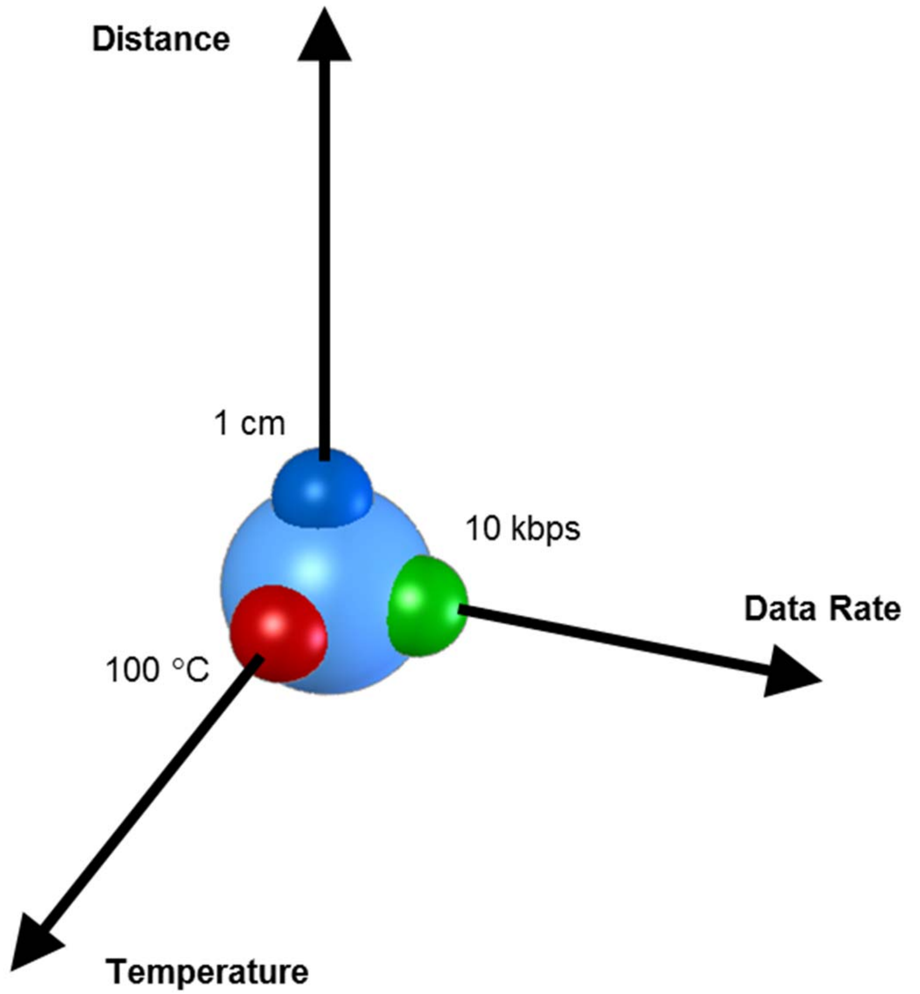
UTC has AM applications in all of these categories, including productionization of components

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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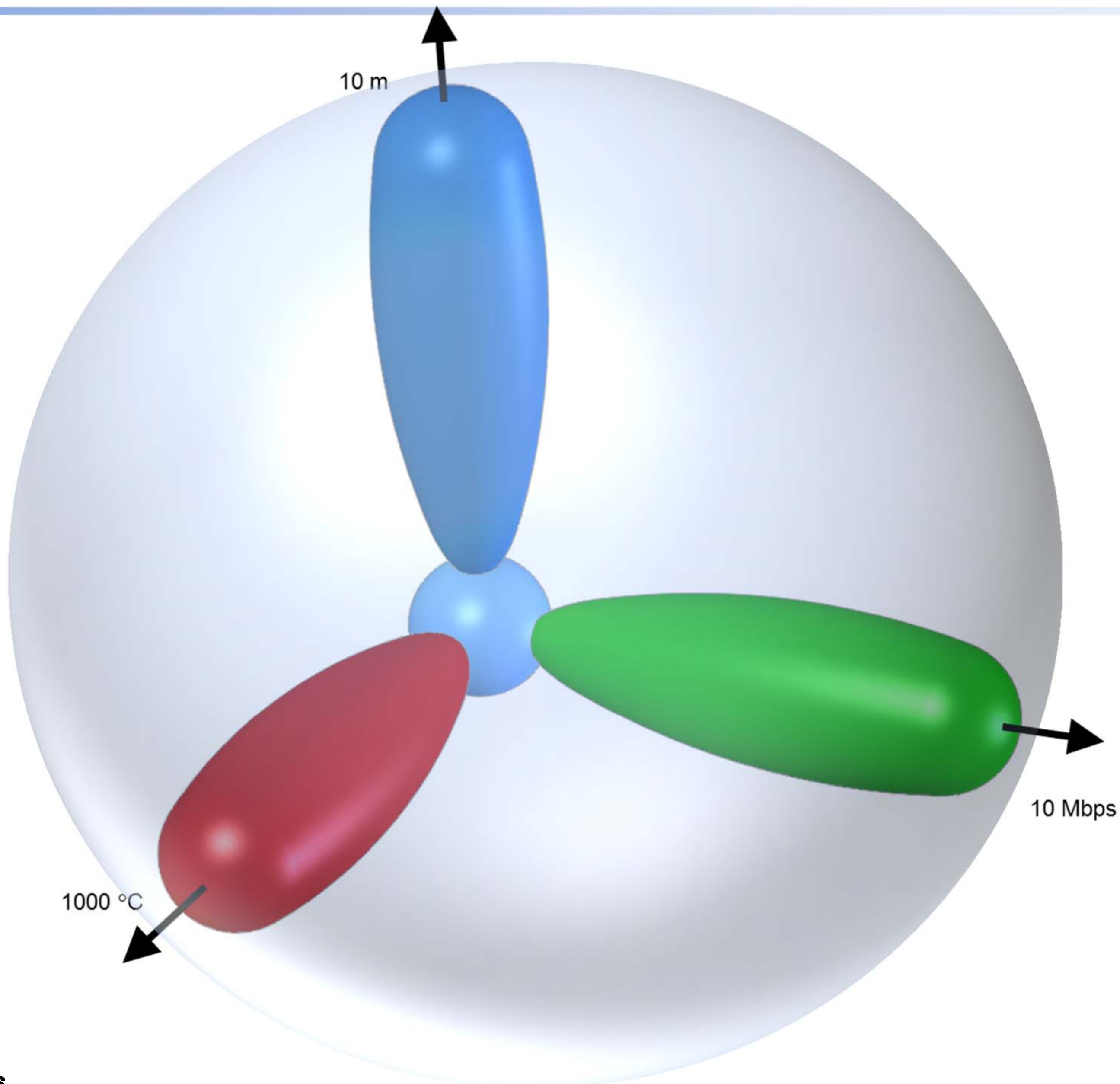

Supply Chain Hardware Integrity for Extended Defense

BOEING
Engineering, Operations & Technology
Phantom Works

Phantom

The Counterfeit Parts & Materials Challenge

15th Annual CQSDI
Cape Canaveral, FL
March 26-27, 2008

Lloyd Condra, Boeing Pha
Tony Marino, Boeing Integrated Defer
Art Mester, Boeing Integrated Defer
Bill Procarione, Boeing Integrated Defer
Bill Scofield, Boeing Pha

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

Scope of the Problem

Engineering, Operations & Technology | Phantom Works

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.

The Counterfeit Parts & Materials Challenge
Boeing, March 26-27, 2008

ATOM*e*S

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