NIST Industry Forum: Monitoring, Diagnostics, and Prognostics for Large Manufacturing Operations

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Boeing Research & technology

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The Boeing Company

Boeing is the leading manufacturer of commercial jetliners and defense, space, and security systems.

A top U.S. exporter, the company supports airlines and U.S. and allied government customers in 150 countries.

Boeing employs more than 160,000 people across the United States and in more than 65 countries
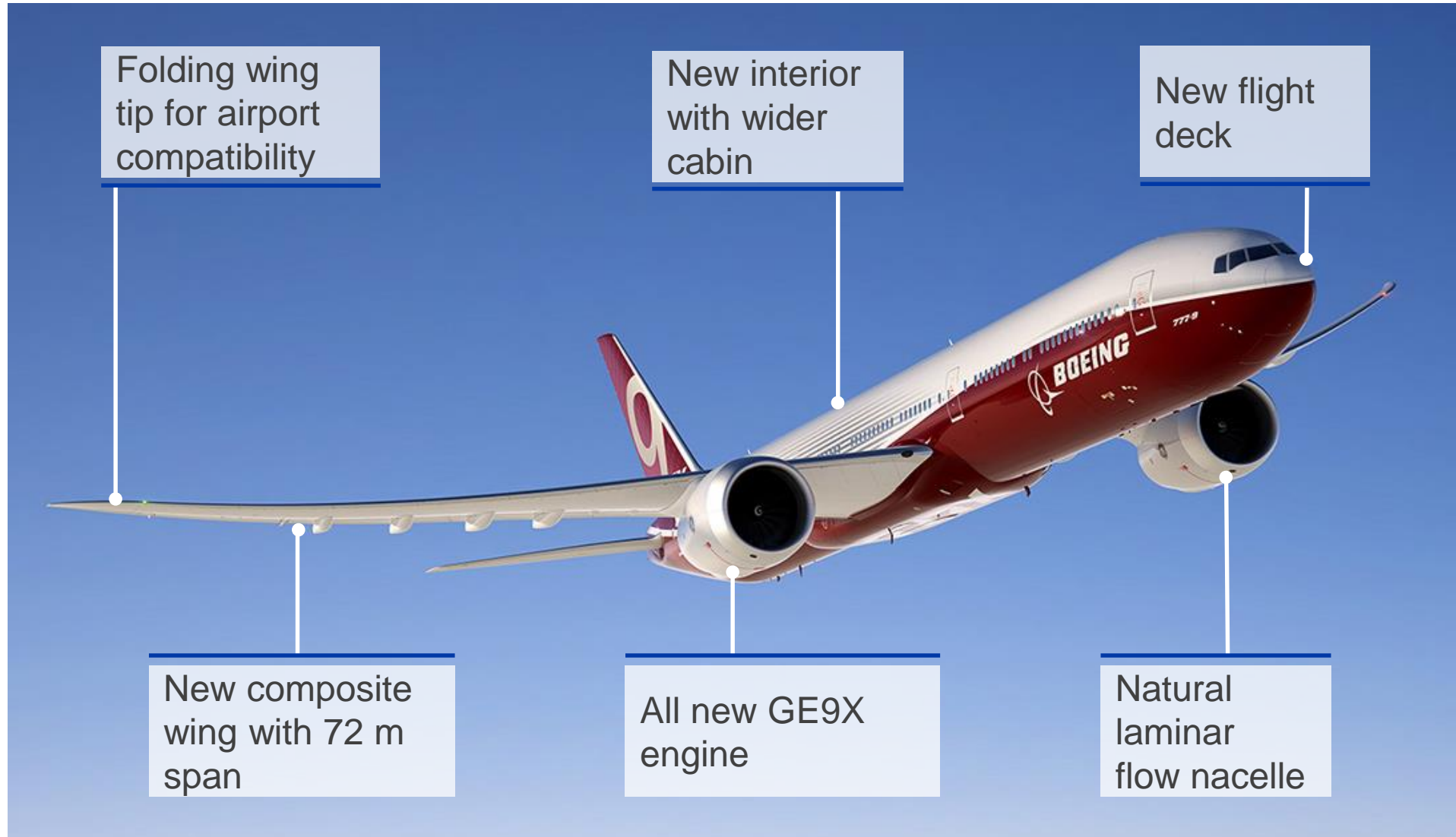

737

CH-47 Chinook

The 787 Dreamliner family

- **Innovative and efficient airplane family**
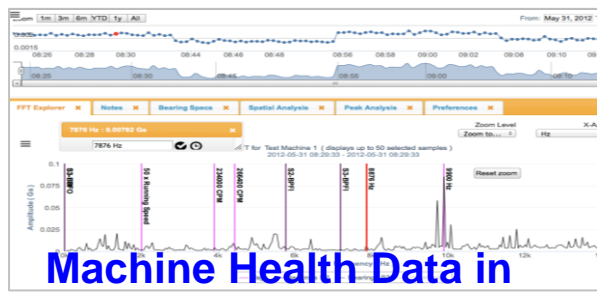- **Offers 20-25 percent better fuel per seat and emissions than the airplanes it replaces**

- **Comfort and convenience for passengers**
- **Profitability and flexibility for airlines**
- **Exceptional environmental performance for everyone**

Al Salour, 5/21/2018, Filename.ppt | 3

777X benefits from key technologies

Folding wing tip for airport compatibility

New interior with wider cabin

New flight deck

New composite wing with 72 m span

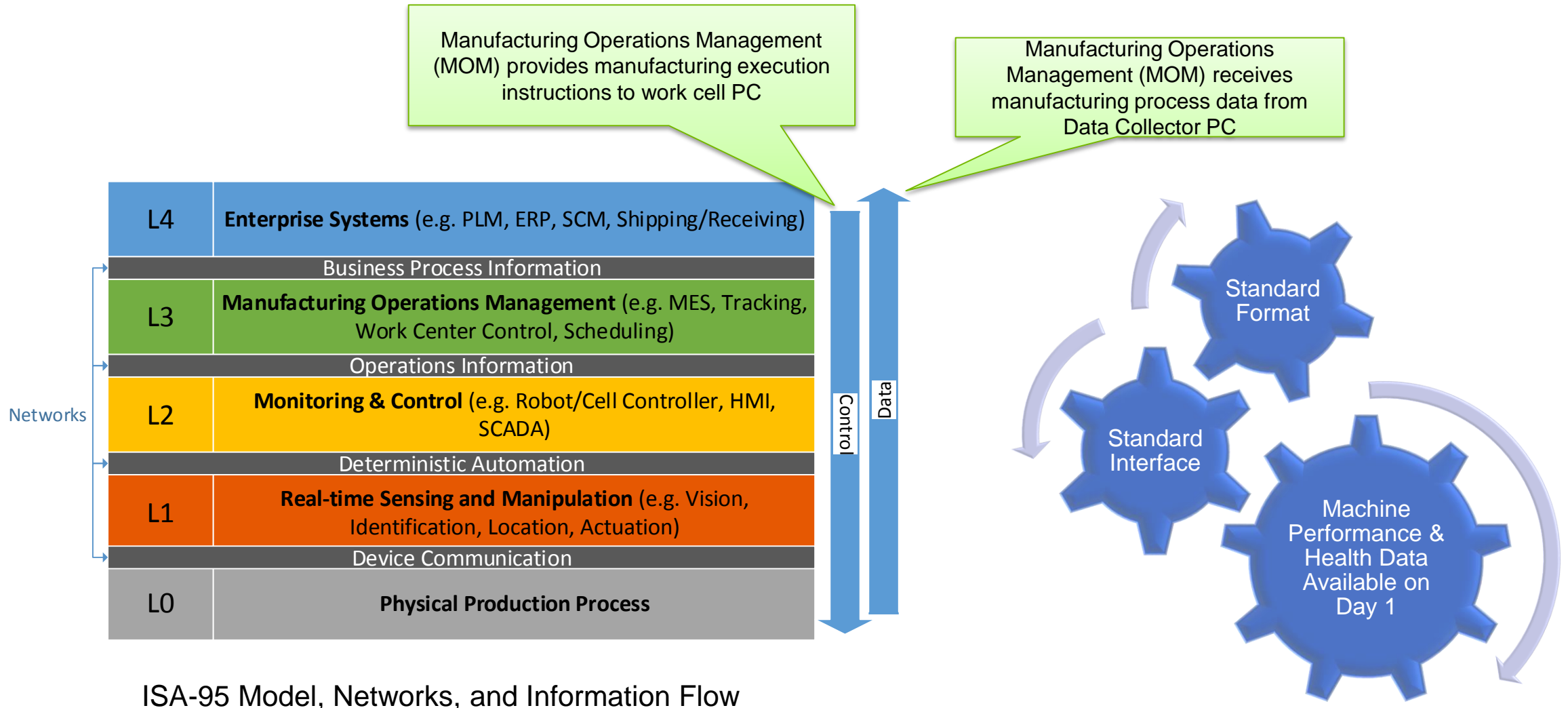All new GE9X engine

Natural laminar flow nacelle

Network Data Model for Manufacturing

1. Data Acquisition Framework – Sensors & DAQ Modules

2. Communication system

3. Data Analytics
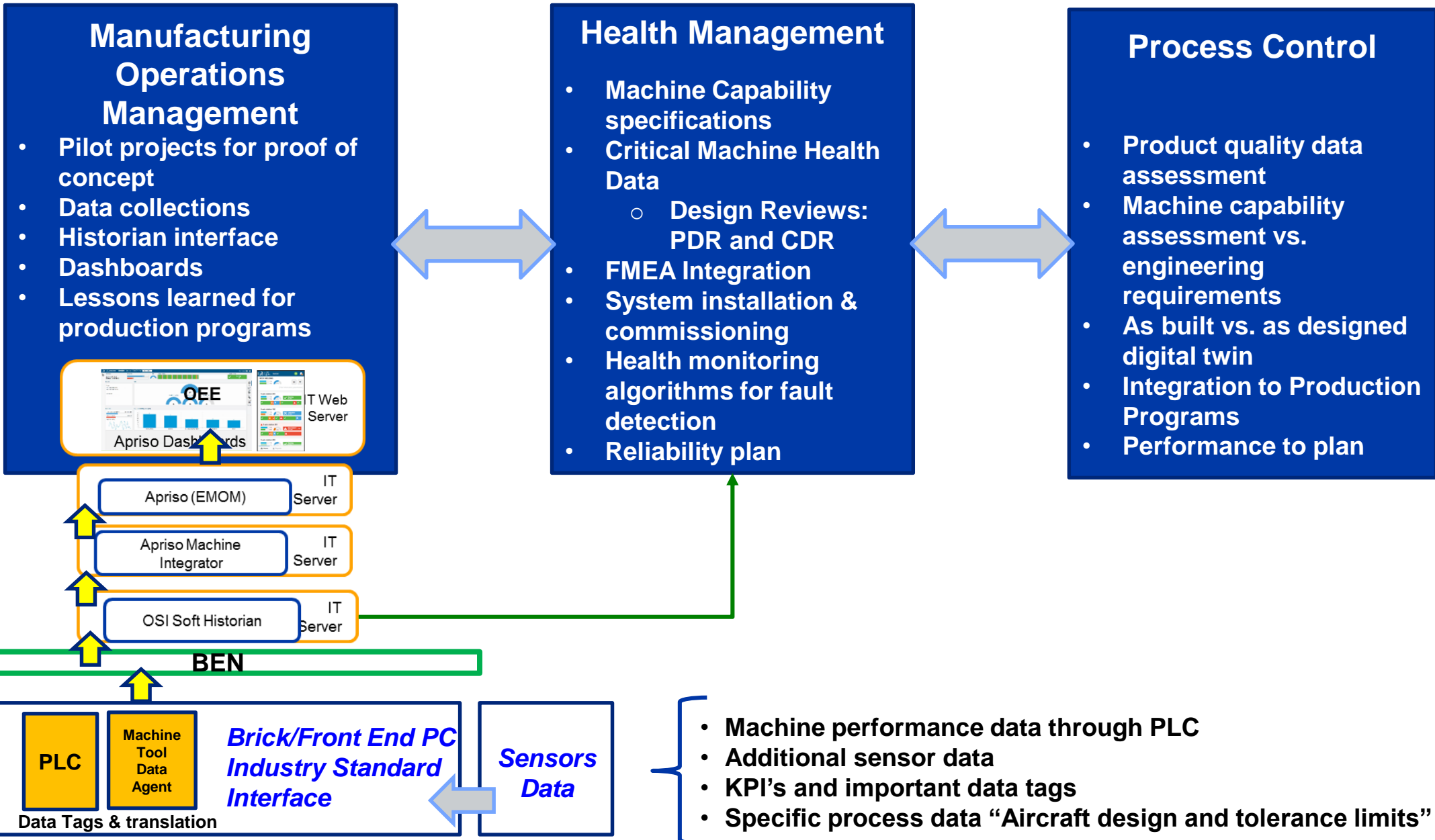
4. Interface to backend systems & portal visibility

Machine Health Data in Digital Format

Strategy: Data Collection and Interface between ISA-95 Levels 0 to 4

Manufacturing Operations Management (MOM) provides manufacturing execution instructions to work cell PC

Manufacturing Operations Management (MOM) receives manufacturing process data from Data Collector PC

L4 — **Enterprise Systems** (e.g. PLM, ERP, SCM, Shipping/Receiving)

Business Process Information

L3 — **Manufacturing Operations Management** (e.g. MES, Tracking, Work Center Control, Scheduling)

Operations Information

L2 — **Monitoring & Control** (e.g. Robot/Cell Controller, HMI, SCADA)

Deterministic Automation

L1 — **Real-time Sensing and Manipulation** (e.g. Vision, Identification, Location, Actuation)

Device Communication

L0 — **Physical Production Process**

Networks

Control   Data

ISA-95 Model, Networks, and Information Flow

Standard Format

Standard Interface

Machine Performance & Health Data Available on Day 1

Equipment Data Flow Architecture "Boeing Model"

Manufacturing Operations Management

- Pilot projects for proof of concept
- Data collections
- Historian interface
- Dashboards
- Lessons learned for production programs

OEE
Apriso Dashboards
T Web Server

Apriso (EMOM)	IT Server
Apriso Machine Integrator	IT Server
OSI Soft Historian	IT Server

BEN

Health Management

- Machine Capability specifications
- Critical Machine Health Data
  - Design Reviews: PDR and CDR
- FMEA Integration
- System installation & commissioning
- Health monitoring algorithms for fault detection
- Reliability plan

Process Control

- Product quality data assessment
- Machine capability assessment vs. engineering requirements
- As built vs. as designed digital twin
- Integration to Production Programs
- Performance to plan

Factory Floor

PLC	Machine Tool Data Agent

Brick/Front End PC Industry Standard Interface

Data Tags & translation

Sensors Data

- Machine performance data through PLC
- Additional sensor data
- KPI's and important data tags
- Specific process data "Aircraft design and tolerance limits"

Machine Performance & Health Monitoring
"Closed Loop Connected Factory"

Enterprise Systems

PLM MOM/MES ERP

Part Geometry   Work Instructions & IT Reporting Platforms   Schedule vs. Actual

Machine Health & Maintenance

Digital Twin Characteristics Control

- *Program vs. Actual Machine Attributes*
- *Machine Electrical & Mechanical Systems Functionality vs. Actual Performance*
- *Machine Calibration, Set-up, N/C Program vs. Actual Recorded Capability & Part Condition*
- *Simulated vs. Actual Conditions (N/C machining, cutters, kinematics, instrumentation) Context-Based Smart Manufacturing*

Dashboard & Visualization

Historian   *Boeing App Store & Data Analytics*

Machine Learning Intelligence

Performance Dashboards on Enterprise Network

OEE, KPI Status, Material Planning & Usage, Schedule Status, Quality Non-Conformances

Component Health Monitoring: Vibration Analysis, FMEA, Fault Detection

Management Reports

Business Outcome

- Predictability
- Reliability
- Quality
- Delivery

Data Acquisition Hardware & Firmware

OPC-UA; MQTT MT-Connect

Data Tags

PLC

Production Application Integration

Sensors

Mechanics interface

Maintenance Ticketing

Machine Health Monitoring Approach – Boeing Model

Composite Laminating Machines Health Management

Automated Fiber Placement for Composite Structures

- Machine coordinate relationship to airplane coordinate
- Capability to trace back error to cause (example: missing tow, gaps, or laps)
- Location of the error in 3D map
- Part centric approach and focus on machine reliability
- Monitoring movements of machine from course, sequence, and layer
- Interface for operator to enter downtime
- Monitoring both multiple parts over one machine or one machine over multiple parts
- Standard time to actual time comparison and % completions (performance to plan)
- Forecasting completions based on past performance data

FMEA Classification

Item Number	Category	Process Step or Variable or Key Input - System	Potential Failure Mode	Potential Effect(s) of Failure	SEV (1-10)	Potential Cause(s) of Failure	OCC (1-10)	Current Process Control (Prevention)	DET (1-10)	RPN (SxOxD)
		What is the process step?	The ways or "modes" in which something might fail. In other words, in what ways can the Process Step, Variable, or Key Input go wrong?	What happens when the failure occurs? In other words, what is the impact on the Key Output Variables (customer requirements) or internal requirements?	How serious is the affect of the failure?	What causes the Key Input to go wrong? (How could the failure mode occur?)	How frequently does the failure occur?	What are the existing controls that either prevent the failure mode from occurring?	How probable is Detection of cause?	#VALUE!

Current process control (Detection)	Recommended Action	Responsibility	Actions Taken	Target Completion Date	Action Complete Date	SEV (1-10)	OCC (1-10)	DET (1-10)	RPN (SxOxD)
What are the existing controls that detect the potential failure?	What are the actions for reducing the Occurrence of the cause, or improving Detection? Should have actions on high RPN's or Severity of 9 or 10.	Who's Responsible for the recommended action?	What were the actions implemented? Include completion month/year. (Then recalculate resulting RPN.)	What is the target completion date?		Frequency or Occurrence of Potential Failure?	How frequent is cause likely to Occur?	How probable is Detection of cause?	

Machine Learning – Metal Fabrication Center

Automated Lubrication Sensor

- ❖ Network Drop
- ❖ Data Acquisition Modules
- ❖ OEE Calculations
- ❖ CBM Investigations
  - Trend Analysis & Comparisons with the Past History
  - Spectrum Analysis:
    - FFT, Time Domain, Frequency Domain, and Peak Rate Analysis
- ❖ Machine Problems
  - Spindle Faults
  - Axes Motors
  - Sub-Components Mechanical or Electrical Systems Failures

- ❖ Corrective Actions

Raw Data vs. Expected Data

Spindle Monitoring

Key Objectives

- Understand and determine what data to collect
- Signals representing functional degradations
- Software application and intelligence to detect faults before they occur
- Actions to mitigate failures
- Fault history and best practices plans

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Machine Monitoring – Assembly Automation Systems
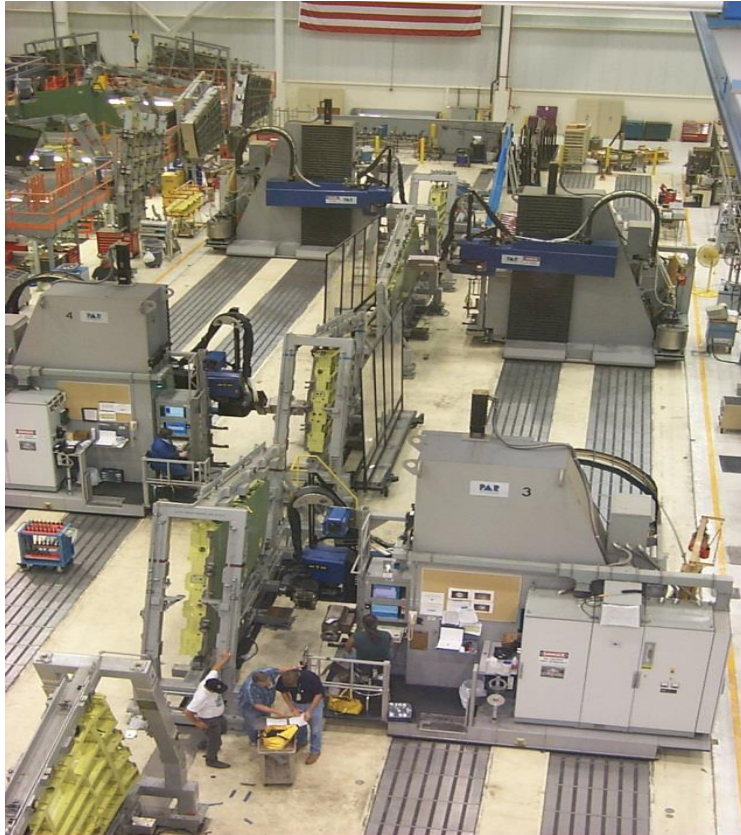
❖ Network drops & connectivity

❖ Data Collections & Quality Status
- Hole or fastener data
- OEE

❖ Machine Health Data
- Tool Tip & Spindle Monitoring
- Motion System
- Tools & Holding Fixtures
- Mechanical Components

❖ Data Analytics
- CBM
- Calibration
- Part Quality
- Throughput

❖ Non Conformance & Corrective Actions
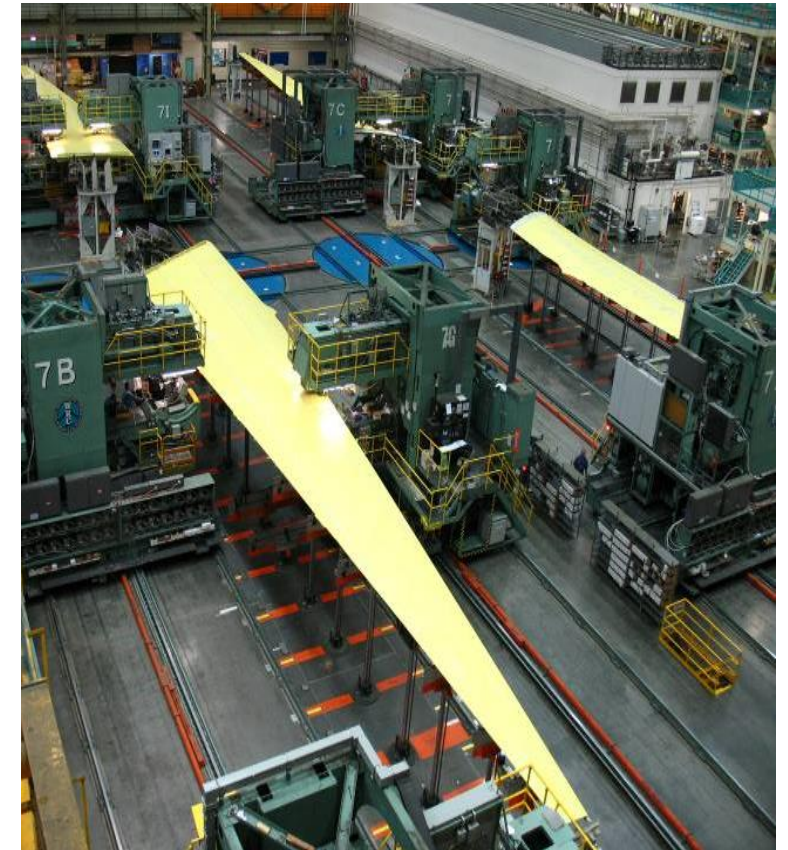
Infrastructure Health Monitoring
Cranes, Power, Compressed Air, Vacuum, HVAC

Air Handling System

Traffic Mgt. – Cranes

Wireless sensors can be used as needed and moved around

Vibration, Power Quality, Temperature, Humidity, Alignment
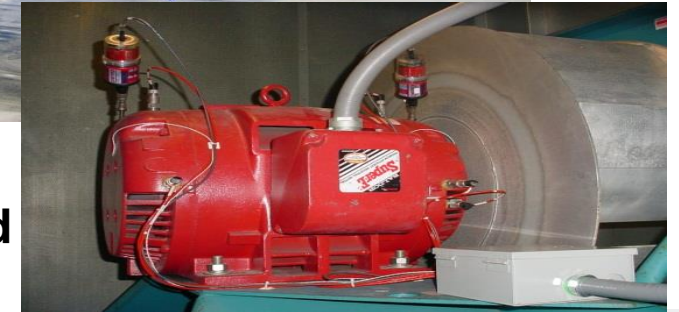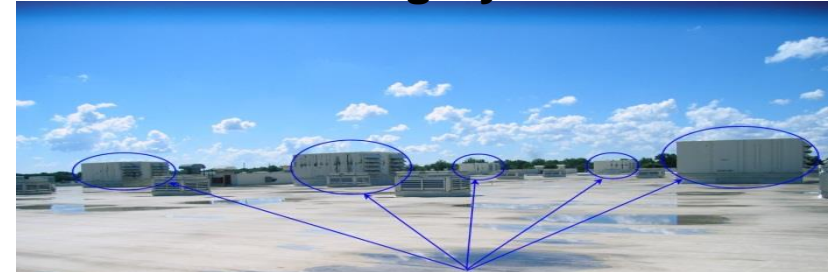
Instrumented Motor

Fault detection and time to failure
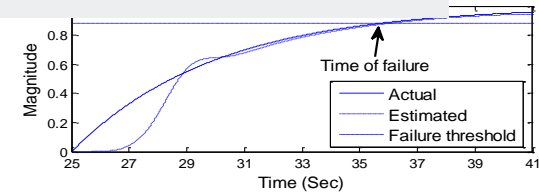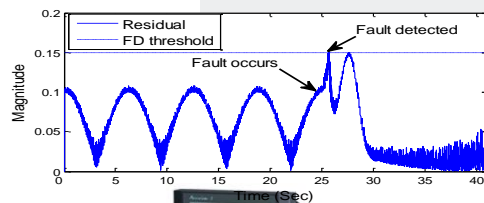
User interface

On-line Power Monitoring
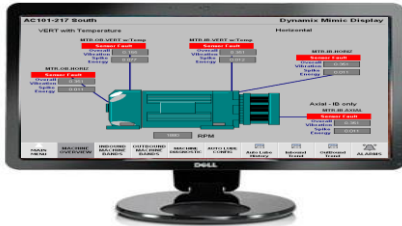
PLC and data acquisition system

Wireless Capability Eliminates Cabling costs and can be installed in remote locations

Sensor Based Process Monitoring and Safety Systems

Environmental Monitoring: Freezer Health

Receiving & storage

Walk-in Freezer Material Location & Age Tracking

Temperature Recorder, Min/Max Data, Data History
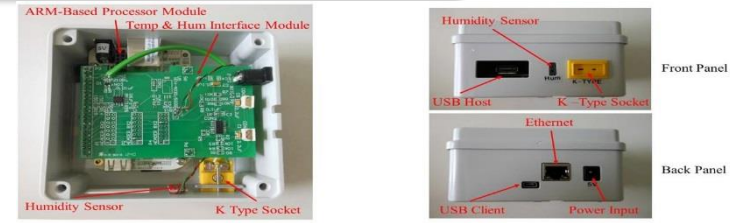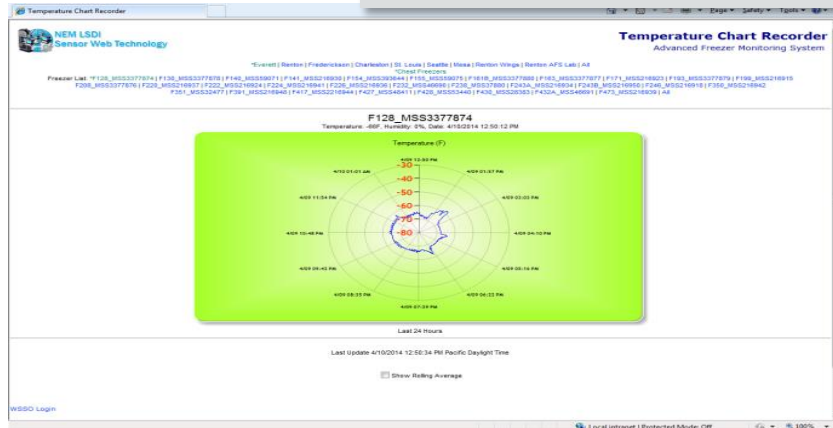
777X Continuous Clean Room Monitoring System – Deployed in Multiple Sites

Pressure Sensors Outside the Clean Room

Temperature, Humidity, Particle Count, and Pressure – Units inside the Clean Room
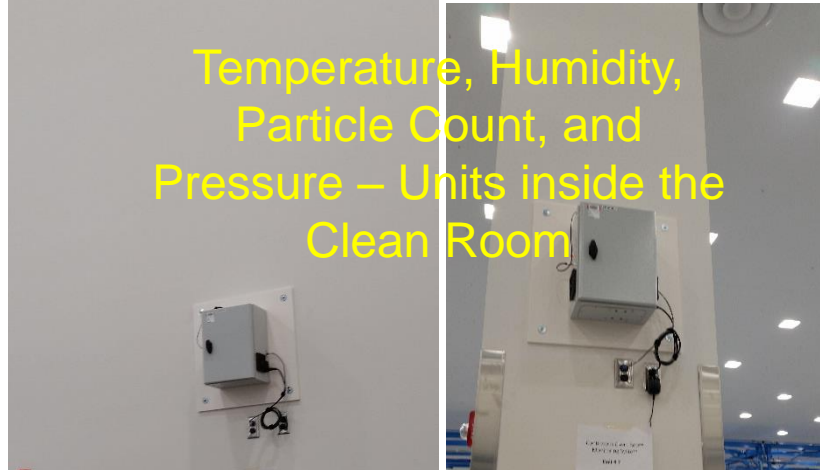
System keeps the clean room in compliance and sends out alerts if any degradations occurs
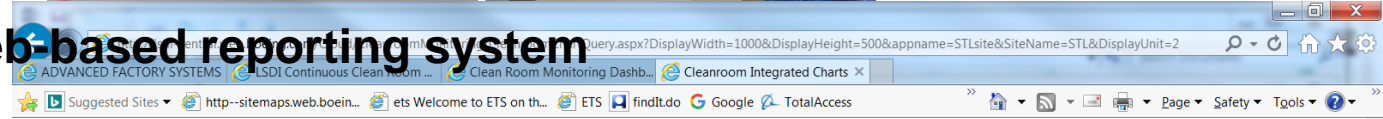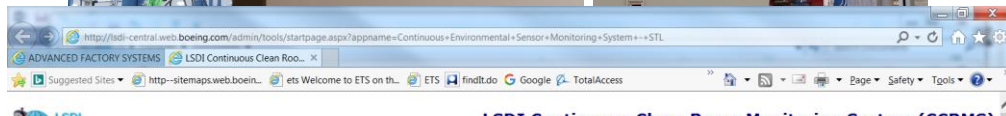
Integrated web-based reporting system

User Interface Report Selections

Readings by each Unit

Trends & thresholds by date range

System Composition: Continuous Clean Room Monitoring Systems and Continuous Pressure Monitoring Systems

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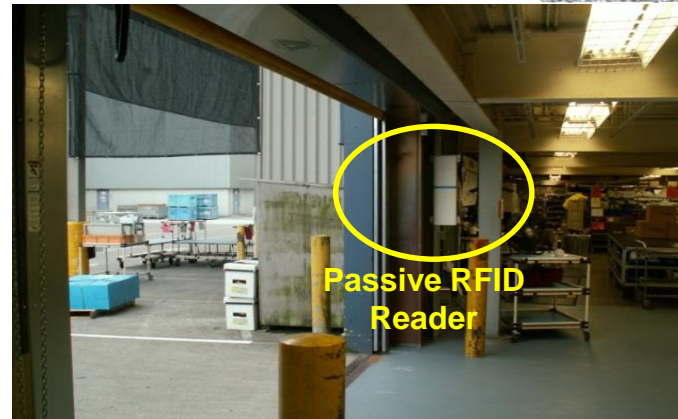
Situational Awareness

- **Asset Location**
- **Dwell Time & Utilization**
- **Point of use Deliveries**
- **Automated Transactions**
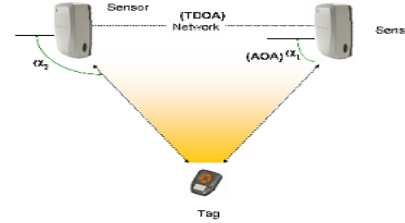
Indoor RFID Infrastructure
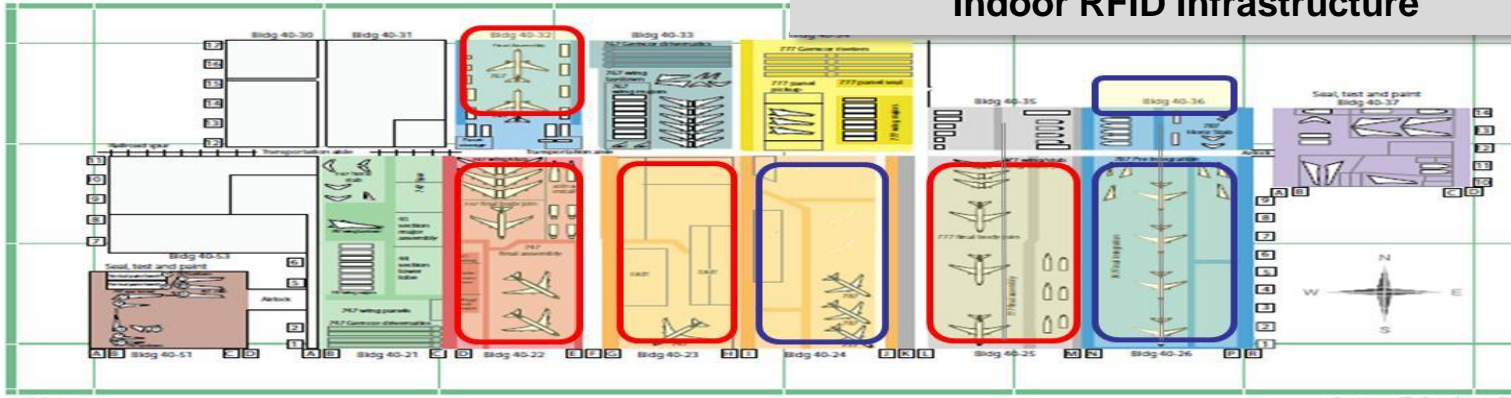
Outdoor Flight Line Asset Tracking

Passive RFID Reader

Automated Receipt Transactions

Vehicle Management Safety System

Boeing Research & Technology is focusing on path monitoring with alerts that enable safe autonomous AGV operation in manufacturing areas. This effort will avoid possible injuries and property damage, eliminating the current practice of spotters/mechanics following the AGV as a precaution. This system is currently targeted for Composite small parts movements from lay-up fabrication area to autoclave and will be replicated toward similar use cases.

LiDARS & Cameras to Monitor Vehicle Path & Traffic Pattern

Parts Flow

Cycle Count for Tool Clean-up

RFID Enabled Autoclave Staging Areas/Unbag/Tool Clean-up

Small Parts Autoclave

Small Parts Autoclave

NDE

Confined Space Communication & Air Quality Detection

Current Process

1. Radio checkout & registration
2. Location, Scan a flag
3. Chemicals in work area
4. Radio place in stand-by mode
5. In workplace radio placed in active mode
6. Communication with command center
7. Radio check-in upon completion

Communication System for Confined Space Areas
(CSCHA) Command Center

Registration
BEMS ID, Supervisor Name

Enter Chemicals, Location

Push to Talk

Check our Two-Way Radio

EHS Air Monitoring
Equipment

Optional
MX-4 Gas Sensors
Used by Mechanics

New Process

Base station   UHF

Interface
controller

UHF   BLE

Beacon

3-in-1 Personal Safety Device

Beacon

ACSMS Backend server

Command Centre
Monitoring Console

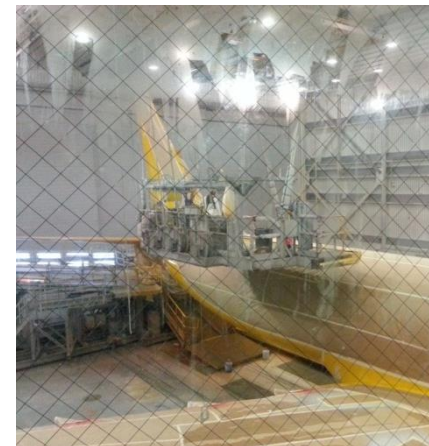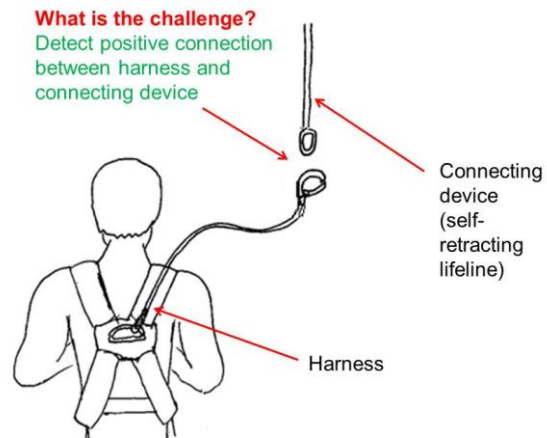Location Detection: Device Location = Nearest Beacon

Configuration:
Beacons vs. Map

Beacon
Location = Radio
Location

Beacon Placement

Fall Protection Safety System

- **System detects if a person working on stackers is attached to a self retracting lifeline cable.**

- **Alerts to the operator if an unsafe condition is suspected**

- **Intrusive toward the painters but the system cannot be easily turned off**

- **Meets all Fire and Safety Standards**

737-700   737-800   737-900   BBJ   P-8

What is the challenge?
Detect positive connection between harness and connecting device

Connecting device (self-retracting lifeline)

Harness

Implementation Roadmap for Physical Systems

Design Plan

Construction & Networking Contractors + IT Systems

Equipment Supplier

Network Infrastructure

Equipment Installation

Data Integration

Requirements for 110V power connection and Ethernet drop connection

O Work Stations and Capital Equipment
O Temp/Humid/Positive Pressure Sensors
O Particle Count Sensors
O Zigbee Routers
△ Network Camera
✕ UHF (Ultra High Frequency) RFID
★ UV Sensors

Digital Thread

Network Drops; Capacity; Interoperability