Intelligent Devices
- Sensors and Actuators -
A KSC Perspective

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Introduction

• Access to space has become very competitive
  • Europe, Japan and China has driven down the cost-per-pound of payload to almost a third from 1990 to 2000 (10 years span)
  • Cost has leveled in recent years to around $12,000/lb*

• One of NASA’s goals is the reduction of operations and maintenance costs associated with processing and launch through new technologies infusion

• Systems and processes standardization, process automation and autonomous operation are technology areas that will help achieve these goals

• Technology approaches such as the one presented here will provide the characteristics (automation, health determination, standardization) required to reduce NASA operations and maintenance costs

Health management (HM) is an essential concept to support these goals

- HM systems automatically and autonomously acquire information from sensors and actuators and determine their health as well as the health of the processes they are performing

- HM establishes the health of the system and processes based on the combination of the newly acquired information and stored prior knowledge

- HM identifies the source of the problem in the system, thus providing autonomous failure detection and isolation

- Ultimately, HM shall provide failure prediction and remediation before actual failures occurs, preventing its costly consequences

- High-quality data is a key component of HM. Data from sensors, actuators, and their associated data acquisition systems constitute the foundation of the approach
Intelligent Devices - Definition

Intelligent Devices (as scoped in this presentation) are sensors and actuators that have embedded knowledge and are capable to autonomously monitor their health, determine their fitness to support the assigned process, and communicate with associated devices and systems.

The Institute of Electrical and Electronics Engineers (IEEE) defines in its standard IEEE 1451.1 (page 12) the smart transducer. It is defined as follows:

3.134 Smart Transducer: "A transducer that provides functions over and above that necessary for generating a correct representation of a sensed or controlled physical quantity. This functionality typically simplifies the integration of the transducer into applications in a networked environment."

- IEEE standards describe detailed architectures and interfaces for smart transducers. The main goal of IEEE 1451 is to develop an architecture that is network and vendor independent with a common transducer interface. The IEEE standards are the foundation for Intelligent Devices.
Intelligent Devices - Purpose

Why Intelligent Sensors

- Develop a smart sensors and actuators architecture in support of the acquisition of reliable, high quality data to be used by HM

- Ultimately, develop an HM infrastructure that support the autonomous operation of systems and processes with failure detection, isolation and recovery capabilities, with reduced human intervention

What is needed for Intelligent Devices?

- To establish and standardize a thorough definition of Intelligent Devices
  - Architecture
  - Embedded diagnostic agents
  - Communication protocols

- To define and establish Command, Monitoring and Control architectures to support the incorporation of HM concepts and approaches
Intelligent Devices - Roles

- Provide good data (assess and qualify the validity of the data)
- Provide processed data (data conversion and compensation)
- Provide device health status (degradation and failure detection)
- Provide embedded self-healing capabilities (self-calibration and self-reconfiguration)
- Provide networking capability (wired and/or wireless)
- Provide higher reliability and availability, lower operation and maintenance costs and longer calibration cycles
- Provide automation and autonomy, reducing human intervention (reduced maintainability costs)
Intelligent Devices - Characteristics

- **Self-identification (Configuration Control)**
- **Embedded intelligence**
  - Data digitization and conversion
  - Time stamping and data synchronization
  - Complex signal processing (trending, averaging, etc)
  - Data storage
- **Self-health assessment (Data Validity and Availability)**
  - Auto-calibration capability
  - Self-reconfiguration capability
- **Health Management capability**
  - Health Electronic Data Sheets (HEDS) approach

  "health parameters are calculated, monitored and stored in the Intelligent Devices to aid in the determination of the device's health"
Intelligent Devices - Benefits

• Assure Data Validity
  • Measurement “self-health” capability
  • Embedded calibration capability
  • Embedded failure detection and correction capabilities

• Assure Data Availability
  • Networked sensor system
  • Provide alternate path to measurement
  • Embedded data storage capability
  • Embedded self-reconfiguration capability

• Increase Reliability
  • Reduced calibration cycles
  • Self-reconfiguration capability

• Information versus data
  • Data trending, bandwidth reduction, etc
KSC Precursors to Intelligent Devices
- Past Developments -
KSC Precursors

John F. Kennedy Space Center

- Kennedy Space Center has been developing sensors, actuators, instrumentation and special tools with embedded capabilities for over 10 years
  - Most projects have been driven and funded by unique operational and processing requirements of the Space Shuttle Program

- The products from these projects have been developed meeting NASA and specific program requirements (such as Space Shuttle) related to performance, environmental and compatibility/standardization requirements

- Although efforts to leverage and standardize developed technologies for further use in other projects and programs have been a main goal at KSC, no formalized standards (except for the ones dictated by the programs) has been followed during these years

- In recent years, our group has started to develop and formalize an approach for Intelligent Devices and products have been developed using such approach
Universal Signal Conditioner Amplifier (USCA)

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USCA is a self-calibrating, programmable device which performs real-time signal processing. The device configures itself up for operation based on information stored in an electronic data sheet (TEDS). The USCA significantly reduces the time required to set up a new measurement, from several hours to a few minutes.

Approach

- When transducers are calibrated, a small memory chip is attached to them. The memory chip contains information required by the USCA to configure itself (TEDS). This includes transducer type, excitation level, output voltage range, linearization coefficients, measurement identification number, digital filtering, sampling rate sampling rate, and other information.
- When the USCA is connected to a transducer, it reads the information stored in the TEDS, and configures itself for proper operation. The analog input gain, excitation level (voltage or current), digital filter, and output range are set within six seconds after connecting the transducer to the USCA.
- The USCA has an internal reference to perform continuous self-calibration. The continuous calibration is used to verify and adjust the gain and offset of the amplifier. This allows to compensate for rapid (such as temperature changes) and slower variations (such as component aging)
Valve Health Monitor is a non-invasive transducer, with embedded process-knowledge capability to detect valve's electromechanical anomalies, degradation and/or failures. Ultimately, it provides failure trending and prediction.

**Approach**

Present implementation combines Hall Effect technology with KSC developed diagnostics algorithms to perform valve health determination. Embedded electronics provides autonomous self-calibration and health checks.

**Technology Status**

- Technology is applicable to electromechanical valves and devices with defined current signatures
- Hardware and KSC-developed algorithms were developed and tested
- Valve failures simulation was performed to validate software algorithms
- Ruggedized prototype was developed and tested
- Patent was granted to technology. Commercialization license was issued to SCHAFFER LLC.
Multi-Sensor Array (MSA) Transducer

MSA is a fault-tolerant transducer architecture designed to increase measurement reliability and extend traditional calibration cycle times.

Approach
Array of MEMS sensors and KSC developed software algorithms. Embedded electronics provides autonomous self-calibration and health checks.

Technology Status
- Technology implemented for pressure measurement. Technology is also applicable to other measurement disciplines
- Reliability studies were completed on 8-element pressure sensor array
- KSC-developed algorithms were developed and tested
- Sensor failure simulation was performed to validate software algorithms
- Ruggedized prototype was developed and tested
- Patent was granted to technology. Commercialization license was issued to TABER industries

Year 2001, U.S. Patent # 6,757,641
The ADAS technology autonomously performs health checks and self-repair operations upon failure detection (self-reconfiguration capabilities), increasing system's reliability with reduced number of components. It provides embedded fault detection, isolation and repair (FDIR) capabilities.

**Approach**
Developed architecture autonomously re-route signals when a failed component failed is detected. Component redundancy is achieve by sharing of components among channels.

**Technology Status**
- Architecture was defined and baselined
- Prototypes were designed and fabricated
- System was tested at laboratory environment
- Embedded software was developed and tested
- 4-channel generic system was demonstrated
- Patent was granted to KSC for this technology
- Commercialization licensing rights were issued to Circuit Avenue Netrepreneurs, LLC
Other KSC Precursors - Sensors

3-D Venturi Hurricane Wind Sensor
(Multi-sensor, multi-disciple array, smart algorithms)
Year 2001

Self Validating Thermocouple Sensor
(smart algorithms)
Year 2003, Patent applied for

Cabin Pressure Monitoring System
(multi-sensor, smart algorithms)
Year 2000, U.S. Patent # 6,452,510

Intelligent Sensors

Wireless Sensor Network
(multi-sensor, smart algorithms)
Year 2003, U.S. Patent # 7,274,907

NIST Traceable Pressure Transfer Standard
(multi-sensor, smart algorithms)
Year 2003

(multi-sensor, smart algorithms, automation)
Year 2001
Other KSC Precursors – Special Tools

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Orbiter Tire and Strut Pressure Monitor (TPM)
(multi-discipline sensors, smart algorithms)
Year 2002

Intelligent Cable Tester
(smart algorithms for failure detection)
Year 1996, U.S. Patent # 5,894,223, 5,977,773

Intelligent Tools

External Tank Centering and Alignment
(smart algorithms, wireless system, hazardous environment)
Year 2002

VJ Wireless Sensor In-Situ Calibration Station
(smart algorithms, wireless system, hazardous environment)
Year 2003

Orbiter Hang Angle Wireless Inclinometer
(smart algorithms, wireless system, hazardous environment)
Year 2003
Other KSC Precursors – Algorithms

Real-Time Calibration Method For Signal-Conditioning Amplifiers
ADAS, Year 2002, U.S. Patent # 6,801,868

3-D Venturi Wind Sensor, Year 2001

Intelligent Algorithms

Piece-wise Linearization of Analog-to-Digital (A/D) converters for Highest Accuracies
ADAS, Year 2002

Smart Power Management Scheme for High-Reliability Electronic Circuitry
ADAS, Year 2002

Wireless Vacuum Jacketed (VJ) Fault-Tolerant Instrumentation Software

Wireless VJ System, Year 2001

Embedded Process-Knowledge In Sensors
Year 2002
KSC Intelligent Devices

- Present Effort -
Intelligent Devices

OUTLINE

• KSC Architecture
  • Overall architecture
  • Intelligent Device Architecture
• Standards
  • IEEE 1451.1, 1451.2, 1451.3, 1451.4
  • IEEE 1588
  • IEEE 802.3af
• Embedded Diagnostic Agents (software algorithms)
• Communication protocols
• Present Implementations
• Future Research
Intelligent Devices are connected in a network fashion (Ethernet, Wireless)

Information is shared among the associated devices and the next higher device (PLC, Launch Control System, etc)

The Intelligent Devices architecture can support one or multiple raw sensors of same sensing discipline, or multi-discipline raw sensors.
Intelligent Devices - Architecture

- Intelligent Devices, arranged in network configuration, fully provides the enhanced benefits described in the presentation

- Communication is now expanded beyond sensor-to-system. These devices can not only send/receive data to the system but also to associated Intelligent Devices in the network

- Sensor’s data, configuration, health, and process status information can be easily exchanged between devices and between devices and system

- System becomes more tolerant to communication failures. Network configuration supports alternate communication paths when primary path fails

- Intelligent Devices can be implemented as wired network configurations (Ethernet, RS485, optical) or wireless network configurations or a combination of them
Intelligent Devices - Architecture

- The proposed architecture allows full implementation flexibility.
- The defined physical layers of the architecture allows for adapting to different applications’ requirements.
- This modular approach allows for reuse of prior engineering development, thus providing cost savings.

Modular architecture
- Analog and signal conditioning
- Digital
- Power and communication
Modular architecture
- Analog and signal conditioning
- Digital
- Power and communication

- Communication
  - Smart Sensor Agent
  - Data Acquisition
  - Signal Conditioning
  - Sensor(s)

  - Standardized communication protocol (i.e., TCP over Ethernet)
  - Health checking
    - Validates data and sensor health
    - Sensor identification
    - Measurement interpretation
  - Analog-to-Digital Conversion
    - Time stamping (RTC on board)
    - Sampling rate determination
  - Sensor Excitation
    - Signal Amplification (gain, offset)
    - Signal Filtering
- Autonomous calibration
  - Sensor/Electronic health
  - Degradation detection
  - Self-healing capability
- Single Sensor
  - Multi Sensor Array (MSA)
  - Multidiscipline Sensor Array
Intelligent Devices - Architecture

Analog Module
- Redundant multiplexers, signal conditioning stages, and analog-to-digital converters (ADCs)
- Digital-to-analog converter (DAC) for feedback
- Ability to connect up to eight individual sensors
  - Redundant (Array)
  - Multidiscipline

Implementation of an Eight element Pressure Sensor Array analog module

Digital Module
- TI 200MHz Floating-point Digital Signal Processor (DSP)
- 512 KB external RAM
Intelligent Devices - Architecture

Power and Communication Module
- Power over Ethernet
  - Data and power on one cable
  - No external power source or battery required
- Real Time Clock with battery backup
- Standard RJ-45 connection

All these put together is ...

The KSC Smart Networked Element (SNE), first implementation of Intelligent Device)
Intelligent Devices - Standards

- One of the Intelligent Devices' main goals is the standardization of functions, information exchange and communication protocols.

- NASA is incorporation established industry standards (when applicable) as part of the development of products, processes, and technologies for new programs such as the Constellation program.

- The National Institute of Standards and Technology (NIST) has been developing standards for sensors and actuators' communication protocols, networking and information exchange (IEEE 1451).

- The Intelligent Device approach incorporates many of the IEEE 1451 recommended practices.

- Tailoring of the IEEE 1451 standards have been necessary to accommodate specific NASA requirements, optimize the use of on-board memory and incorporate the health management capabilities being pursued.
Intelligent Devices - Standards

- The IEEE 1451 standards being incorporated (to different degree) in the Intelligent Devices are the following:
  - IEEE 1451.1 Network Capable Application Processor (NCAP) Information Model
    - Network-level, object-oriented model for 1451 devices
  - IEEE 1451.2 Transducer to Microprocessor Communication Protocols and TEDS Formats
    - Specification for TEDS
    - Digital interface for accessing TEDS, reading sensors and setting actuators
  - IEEE 1451.3 Digital Communication and TEDS Formats for Distributed Multidrop Systems
    - Specification for NCAPs with multiple sensors and actuators
  - IEEE 1451.4 Mixed-Mode Communication Protocols and TEDS Formats
    - Support for legacy sensors
    - Combining analog and digital communication buses
Intelligent Devices - Standards

• Additionally, the Intelligent Device development team is looking at the following standards:
  
  o IEEE 1588 “Precision Time Protocol (PTP)”
    ➢ On-board time synchronization with sub-μs accuracy
  
  o IEEE 802.3af “Data Terminal Equipment (DTE) Power Via Media Dependent Interface (MDI)”
    ➢ Power of Intelligent Devices over Ethernet
Software algorithms have been implemented to:

- Provide a "light" version of IEEE 1451.1 "implementation of the network-level object model"
  - Customize measurement sampling rate, message contents, and health parameters via a graphical user interface
  - Established User-defined TEDS – the Health Electronic Data Sheet (HEDS)

- Algorithms for monitoring the health of the sensor
  - Voltage reference/current excitation monitoring
  - Trending
  - Threshold detection
  - Sensor connection status
Intelligent Devices – Embedded Diagnostic Agents

Network Capable Application Processor Block Monitoring Tool GUI
Intelligent Devices – Embedded Diagnostic Agents

IEEE 1451 Protocol Analyzer

Publication Messages: 630
- 10:56:51.8900000
- 10:56:52.8900000
  - Length: 43
  - Header Length: 22
  - Publication Key: Physical Parametric Data
  - Publication Domain: ff ff ff ff ff ff ff
  - Publication Topic: SNE Meas
  - Argument Array

Server Messages: 2
- 10:56:40.9060000
- 11:07:20.9060000
  - Length: 16
  - Client Server Return Code: 4278190080
  - Server Object's Block Cookie: 3
  - Execute Mode: 1
  - Server Object ID: 3
  - Operation ID: 4103

Client Messages: 0

C:\Documents and Settings\Beck the W\reck\Desktop\test4.bin
192.168.0.3:11000  2/15/2006 10:56:47 AM
Intelligent Devices – Present Implementations

The following implementations of Intelligent Devices have been conducted at KSC. Some of these implementations required further design, development and testing. They are the following:

- **Advanced Miniaturized Instrumentation and Control Node (AMICON)**
  - Project incorporates both monitoring and control capabilities in the implementation. The implementation adds a control module for closed-loop feedback control

- **ControlNet-Based Intelligent Device**
  - Project incorporates the capability to connect and communicate through ControlNet communication protocols. ControlNet is the preferred communication protocol for Allen Bradley’s Programmable Logic Controller (PLC)

- **Ethernet-Based 8-Element Multi-Sensor Pressure Transducer**

- **Ethernet-Based 8-Element Cryogenic Temperature Sensor**
  - Project incorporates silicon diode temperature probes
Intelligent Devices – Future Research

- Continue the development of a control module for closed-loop feedback control
- Continue the development of firmware to fully utilize the multi-sensor array capabilities
- Develop capability to real-time downloading of algorithms to the Intelligent Device
- Continue the IEEE 1451 Standards implementation’s tailoring to maximize Intelligent Devices capabilities and efficiency
- Continue the IEEE 1588 standards implementation in present architecture
- Continue the development of embedded health management algorithms
  - Develop architecture and concept of operations to incorporate a library of embedded health monitoring algorithms for the Intelligent Devices
- Draft a NASA standard for Intelligent Devices, based on IEEE 1451, IEEE 1588, and IEEE 802af standards, further defining NASA requirements for the development, testing, and validation and verification of Intelligent Devices
SUMMARY & CONCLUSION

The HM approach provides for vast enhancements in reliability and reduction of maintenance and operational costs in vehicle and surface support equipment. NASA recognizes the potential of HM technologies and supports development of specific subsystems and components.

Intelligent Devices’ approach merges seamlessly in the HM approach, providing additional capabilities and benefits for failure detection, isolation and recovery capabilities.

The Exploration program has set the goals of autonomy, modularity, reconfigurability, and data-rich virtual presence for technologies, processes and products to be used by the program.

Intelligent Devices are developed following the above criteria, supporting the determination of nominal/off-nominal conditions in systems and processes, to increase system reliability and reduce operations and maintenance costs.

The combination of Intelligent Devices and HM technologies presents the optimal approach for success.
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Kennedy Space Center Intelligent Device team
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Outside KSC contributors:
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- Dr. John Schmazel, Rowan University, New Jersey
BACK-UP SLIDES
**Objective**
Design intelligent sensor network with embedded process-knowledge at the sensor level. Decentralize process decision making.

**Design**
- Complex processes broken down into simpler, smaller processes. Relationship rules are created to link all processes to overall process.
- Share process knowledge/information among sensors and controlling equipment via wireless communication.
- Process health monitoring done through individual sensor performance and process knowledge rules.

**Status**
- Process composed of 2 sub-processes and 6 measurements have been modeled and implemented.
Mini Smart Leak Detector Sensor

- Joint effort between GRC, KSC, MSFC, and MAKEL Engineering

- MEMS type hydrogen/oxygen/pressure/temperature sensor with embedded electronics and processing algorithms

- KSC provides technical expertise to transition design into final product. KSC is also performing functional testing, environmental testing and materials compatibility analysis.

- KSC is developing a Wireless hydrogen/oxygen sensor Network (wireless sensor prototype under test)
Development of embedded wireless data link capability in Smart Sensors Architecture creates a robust sensor network design (capable of autonomous or "user-demand" reconfiguration)
Development provides networked sensors with embedded process-specific intelligence.

- Generic 433MHz and 918 MHz RF Transceiver and Power Management Module, Sensor Interface Modules (pressure, temperature, strain and Hydrogen detection) and Memory Module have been designed, fabricated and tested.
- Smart software algorithms to overcome RF path problems (communication drop out) have been designed and tested. Smart power management algorithms to optimize battery life have been designed and tested.
- Patent granted. Licensed to commercial companies.
When Space Shuttle connectors are demated, they require a complete system re-test. System re-test could be minimized if troubleshooting could be performed while reducing the number of connectors being demated. Developed product non-intrusively test the continuity of a measurement's signal path. Developed product also allows for the accurate determination and location of a cable electrical open or short so it may be repaired with minimal system disturbance.

Present Design Features
• Location of the discontinuity accurate to a few inches on cable lengths up to 100 ft.
• Distance to the discontinuity is immediately shown in an LCD display.
• Design is battery operated.
• Data is downloaded to user when required.

Future Design Features
• Determination of soft failures (insulation degradation, broken strands) as well as hard failures (open and short circuits).
Orbiter Tire Pressure Monitor (TPM)

**Objective**

- Develop a ground support equipment (GSE) device to monitor and certify the Orbiter tire and strut pressure for flight. System shall be capable to accurately measure 0.1 psi changes on a 400 psi static pressure.

**Status**

- System was designed using highly accurate pressure and temperature sensors and smart compensation software algorithm.
- Field rated prototypes of the device have been designed, fabricated, tested and calibrated.
- Software algorithms have been developed and tested.
- Automated calibration station was designed and tested.
Objective

Provide KSC with a rugged, low profile, high reliable, self-contained wind speed and direction sensor to measure wind speeds up to 300 mph. Project involves multi-discipline sensor technology combined with smart software algorithms.

Status

A 3-D Venturi Wind Sensor has been designed, developed, fabricated and preliminary tested.

- Wind Sensor has been modeled and computer simulation has been performed using CFD software.
- Self-contained electronics has been designed and preliminary testing performed.
- Testing of sensor at Embry Riddle Aeronautical University (ERAU) was performed for winds up to 150 mph.
**Objective**

Develop an accurate alignment/centering tool to align the External Tank (ET) with respect to Solid Rocket Boosters (SRB) during ET/SRB mating. Provide automated distance measurement accurate to 0.01" between ET and SRB.

**Status**

- Designed and fabricated New ET CAS.
- COTS laser sensors with capable accuracy.
- Two wireless sensing systems and a User Interface Console.
- Measurements are temperature compensated for temperature range (20 °F to 120 °F).
- Power management algorithm developed to enhance tool usage.
- System has greater accuracy with no calibration.
"Kennedy Space Center has been designing and developing sensors and instrumentation with embedded intelligence for approximately 10 years. At the beginning, this development was isolated to specific needs and requirements of NASA programs to be used in Ground Support Equipment (GSE) during processing and launch of vehicles such as the Space Shuttle. Examples of these developments are the Multi-Sensor Array pressure transducer, the Valve Health Monitoring system, the Universal Signal Conditioner Amplifier (USCA) among many others. In recent years, and in conjunction with the development of Integrated Systems Health Management for ground and vehicles, the Intelligent Devices (sensors and actuators) approach has been further formalized at KSC with the development of a new smart sensor/actuator architecture. Recent smart transducer standards and protocols, such as IEEE 1451, IEEE 1588 and IEEE 802.1af, have contributed to this development, which has been prototyped, demonstrated, and implemented in several applications. The latest implementation of a smart networked device is the PoE Ethernet-based intelligent sensor. Nevertheless, some of these smart transducer standards require large amounts of memory, making implementations very hard for small embedded systems. Further efforts are being sought to formalize a NASA standard on Intelligent Sensors and Actuators, to overcome some ambiguities in the industry standards, in support of health management, fault detection, isolation and recovery (FDIR) approaches to support NASA programs such as the Exploration Program."