

Intelligent Devices

- Sensors and Actuators -

A KSC Perspective



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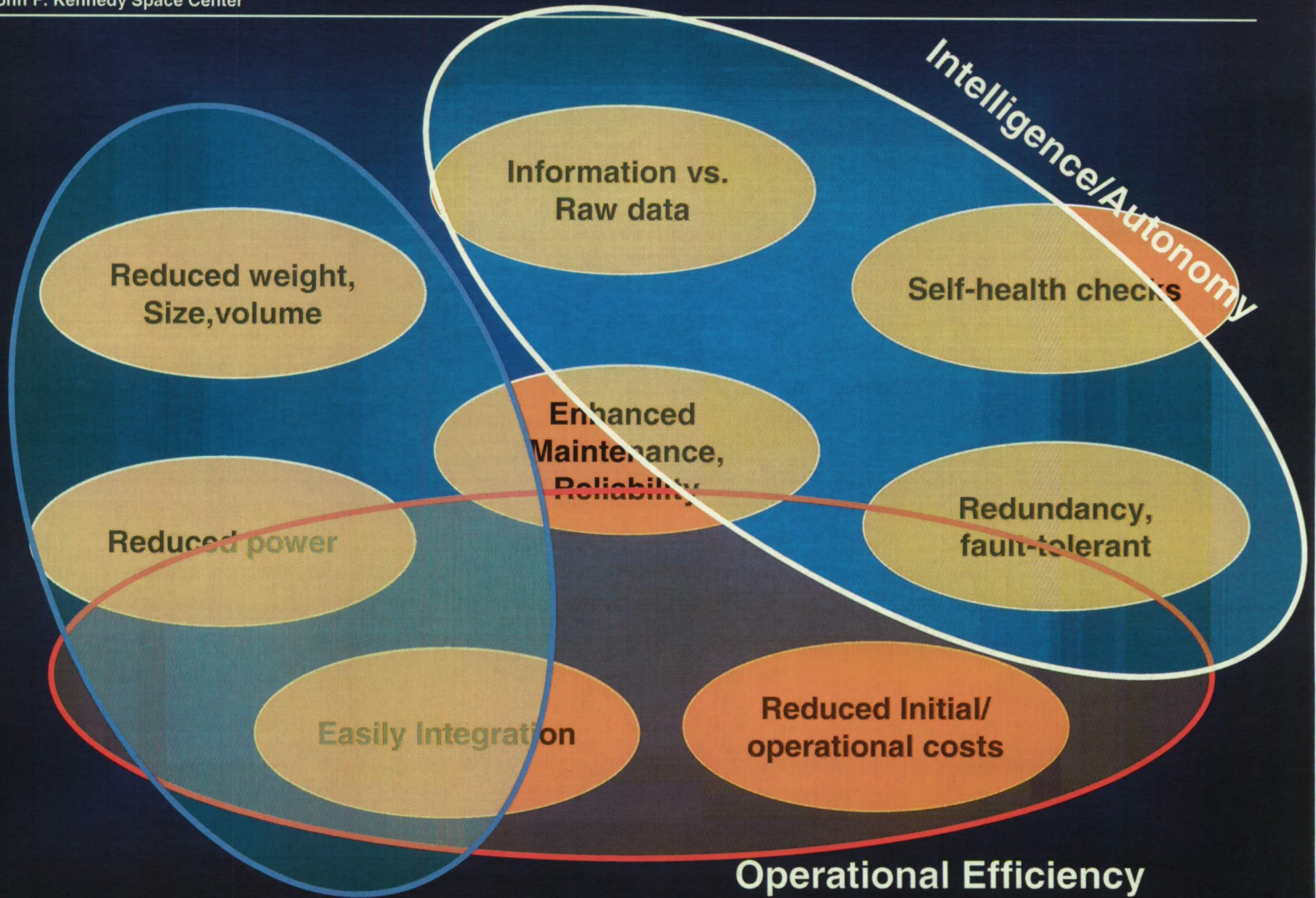
Introduction

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- **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**

* **Data:** Cost of launching commercial payloads into GSO (page 4), " Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000", September 6, 2002, *Futron Corporation* report

Miniaturization / Power Efficiency



Health Management Concept

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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

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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

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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

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- **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

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- **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

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- **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

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- **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)

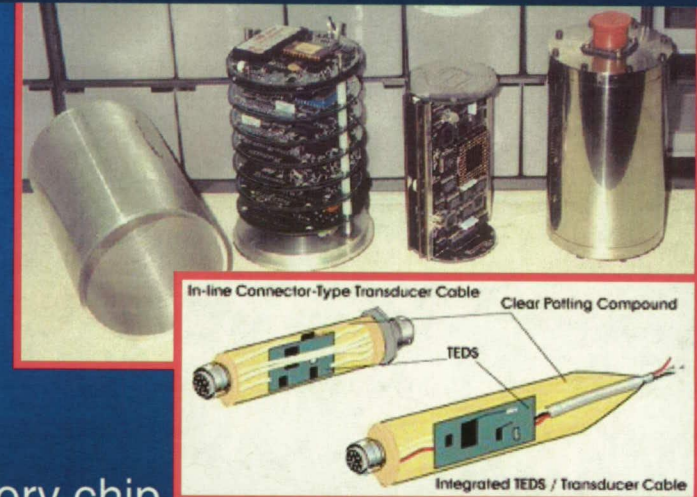
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Year 1995, U.S. Patent # 5,734,596

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, 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 (Current Signature)

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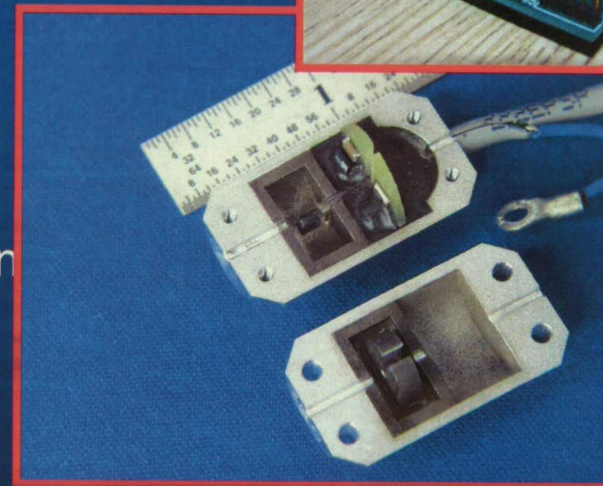
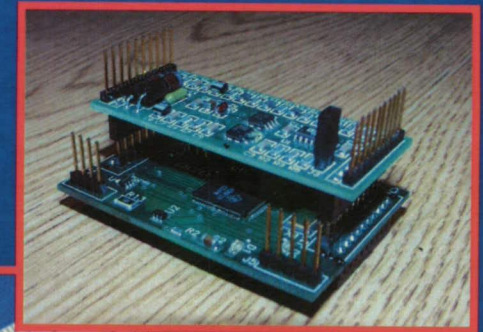
Valve Health Monitor is a non-invasive transducer, with embedded process-knowledge capability to detect valve's electromechanical anomalies, degradation and/or failures. Ultimately, it provides failure trending and prediction

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.



Year 2000, U.S. Patent # 6,917,203

Multi-Sensor Array (MSA) Transducer

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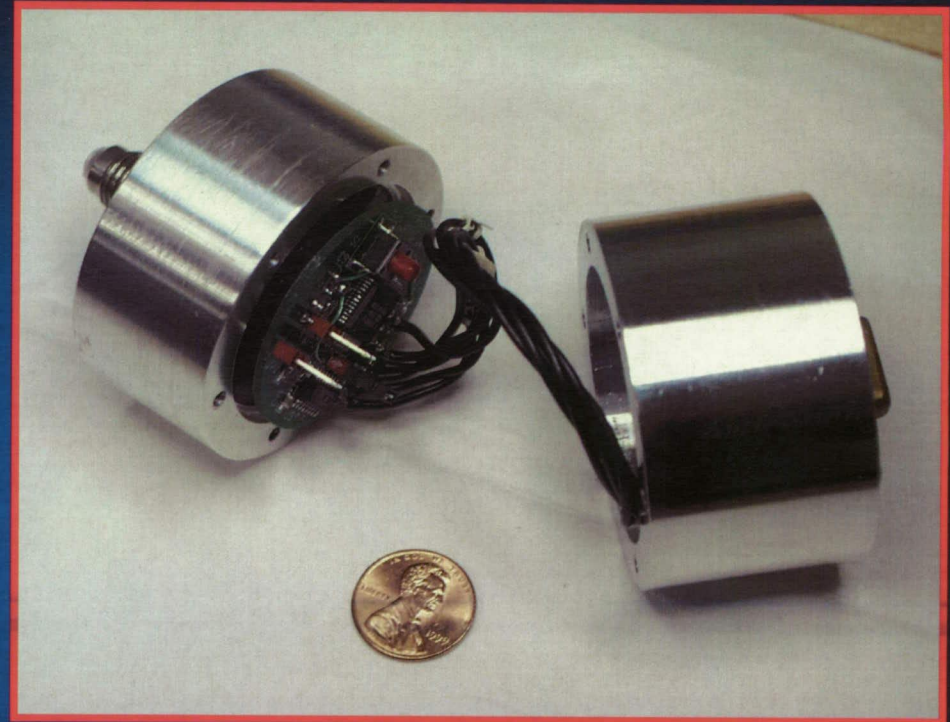
MSA is a fault-tolerant transducer architecture designed to increase measurement reliability and extend traditional calibration cycle times

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

Advanced Data Acquisition System (ADAS)

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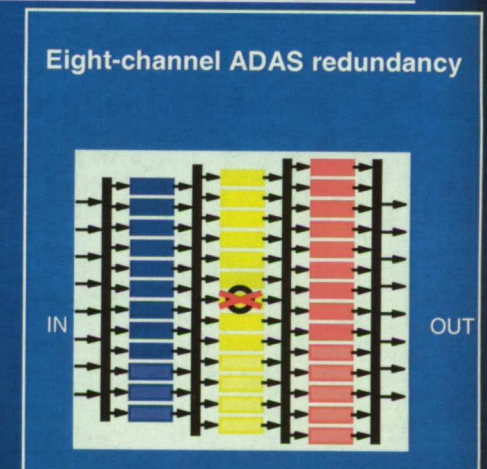
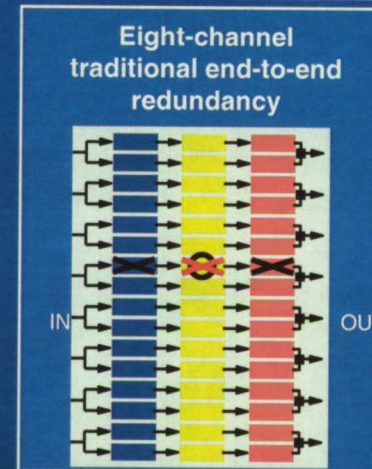
The ADAS technology autonomously performs health checks and self-repair operations upon failure detection (self-reconfiguration capabilities), increasing system's reliability with reduced number of components. It provides embedded fault detection, isolation and repair (FDIR) capabilities

Approach

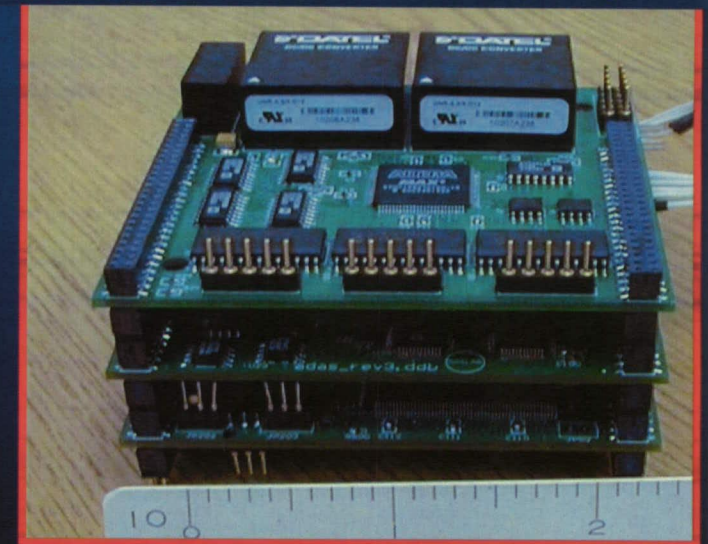
Developed architecture autonomously re-route signals when a failed component failed is detected. Component redundancy is achieved by sharing of components among channels.

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



Year 2001, U.S. Patent # 6,462,684

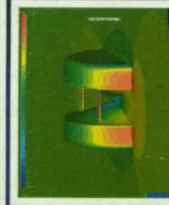
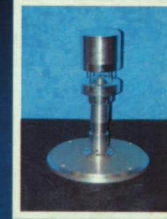


Other KSC Precursors - Sensors

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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)

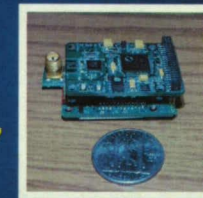
Year 2000, U.S. Patent # 6,452,510



**Intelligent
Sensors**

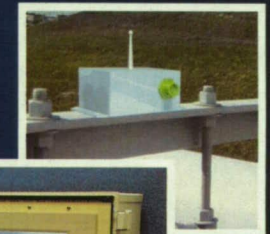
Wireless Sensor Network
(multi-sensor, smart algorithms)

Year 2003, U.S. Patent # 7,274,907



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

Year 2003



Vacuum Jacketed Lines (VJ) Wireless Sensor Network
(multi-sensor, smart algorithms, automation)

Year 2001



Other KSC Precursors – Special Tools

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Orbiter Tire and Strut Pressure Monitor (TPM)
(multi-disciple 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



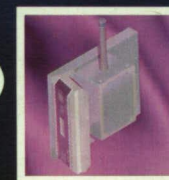
VJ Wireless Sensor In-Situ Calibration Station
(smart algorithms, wireless system, hazardous environment)

Year 2003



Orbiter Hang Angle Wireless Inclinator
(smart algorithms, wireless system, hazardous environment)

Year 2003



Other KSC Precursors – Algorithms

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Real-Time Calibration Method For Signal-Conditioning Amplifiers

ADAS, Year 2002, U.S. Patent # 6,801,868

**Extreme Velocity Wind Sensor (EVWS) Wind Speed and Wind
Direction Determination Algorithm.**

3-D Venturi Wind Sensor, Year 2001

**Piece-wise Linearization of Analog-to-Digital (A/D)
converters for Highest Accuracies**

ADAS, Year 2002

**Intelligent
Algorithms**

**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

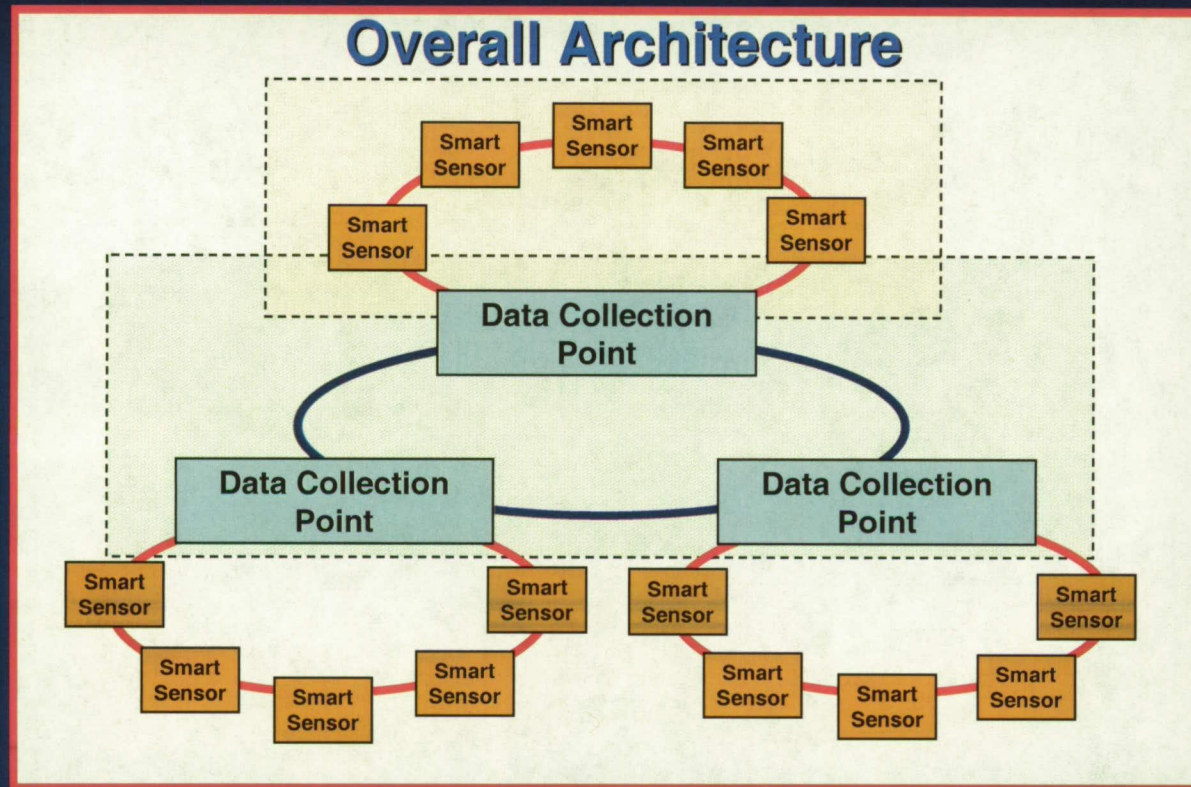
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OUTLINE

- **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 - Architecture

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- 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

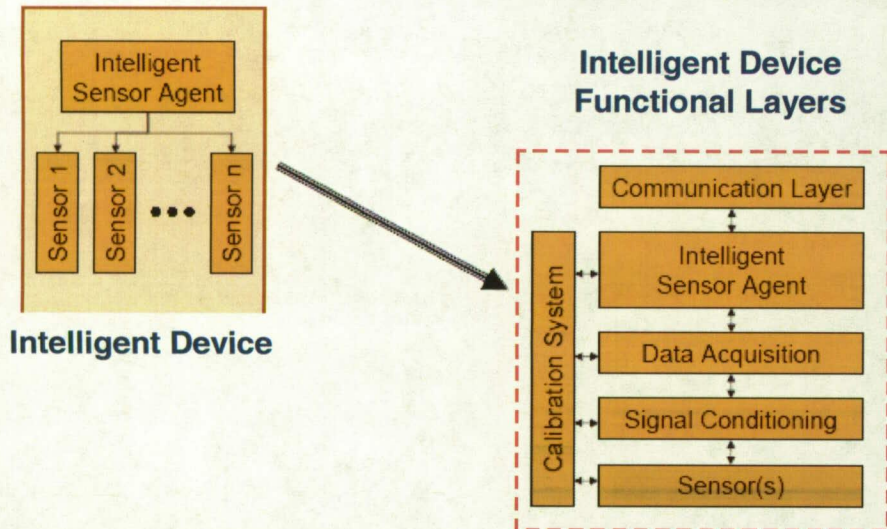
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- **Intelligent Devices, arranged in network configuration, fully provides the enhanced benefits described in the presentation**
- **Communication is now expanded beyond sensor-to-system. These devices can not only send/receive data to the system but 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

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Intelligent Device Architecture

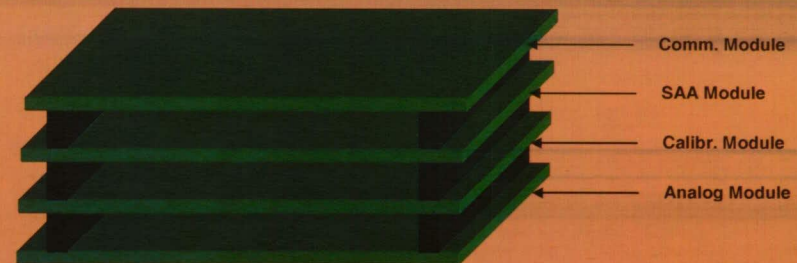


- The proposed architecture allows full implementation flexibility.
- The defined physical layers of the architecture allows for adapting to different applications' requirements
- This modular approach allows for reuse of prior engineering development, thus providing cost savings

Modular architecture

- Analog and signal conditioning
- Digital
- Power and communication

Intelligent Device Physical Layers



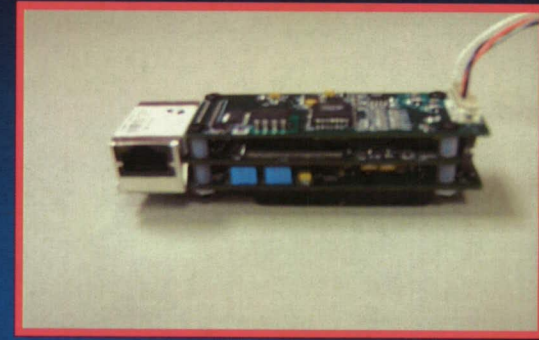
Prototype stacking concept

Intelligent Devices - Architecture

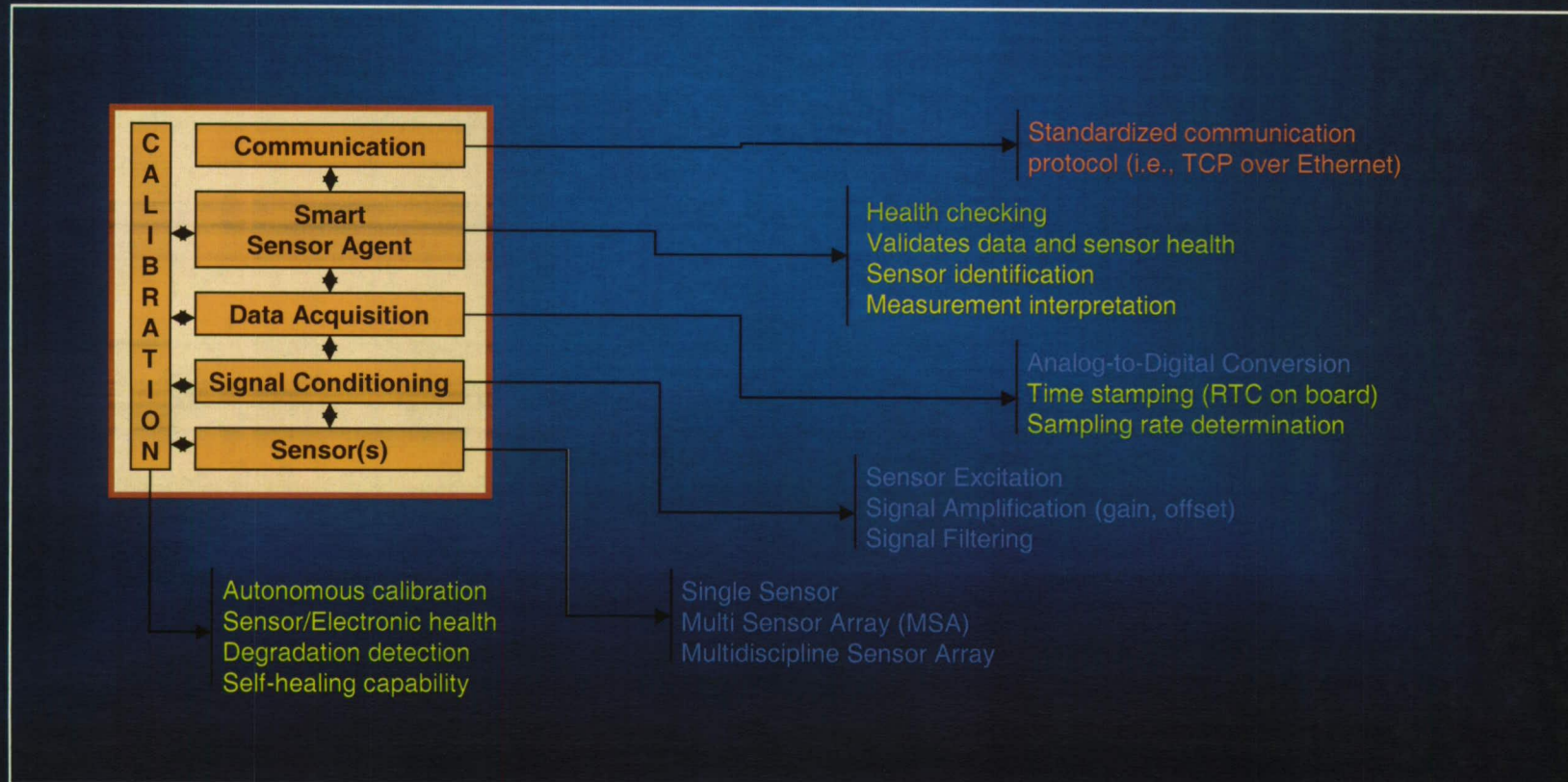
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Modular architecture

- Analog and signal conditioning
- Digital
- Power and communication



Ethernet Based Implementation

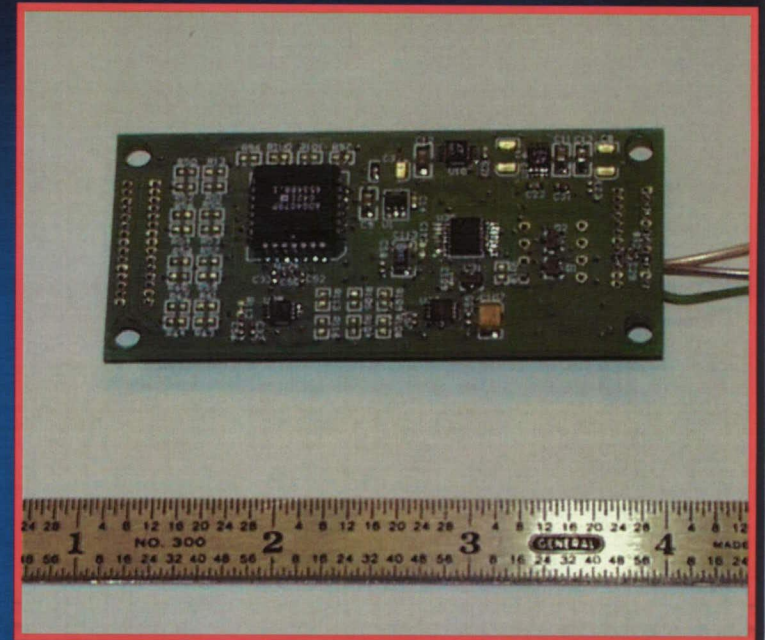


Intelligent Devices - Architecture

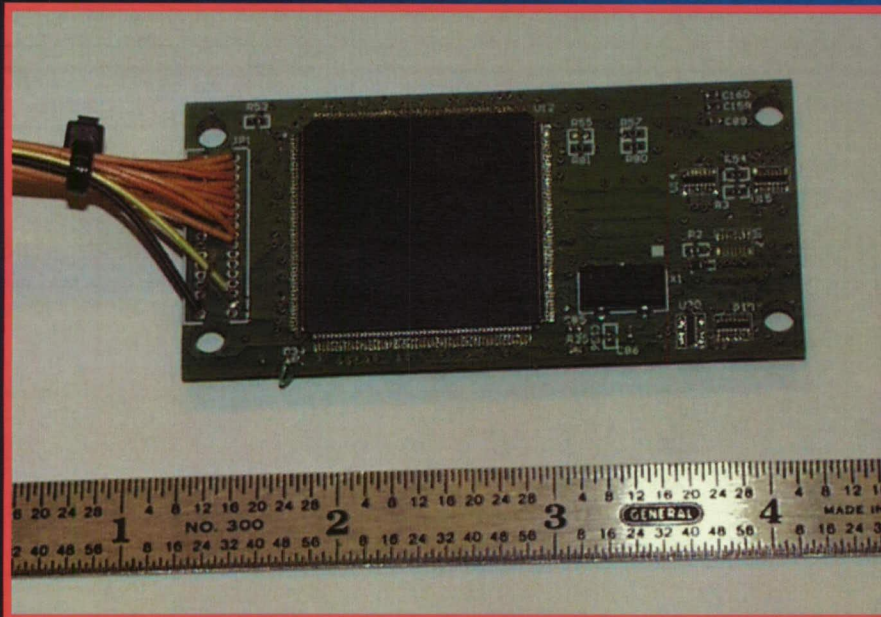
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Analog Module

- 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



SSA/Embedded Intelligence module

Digital Module

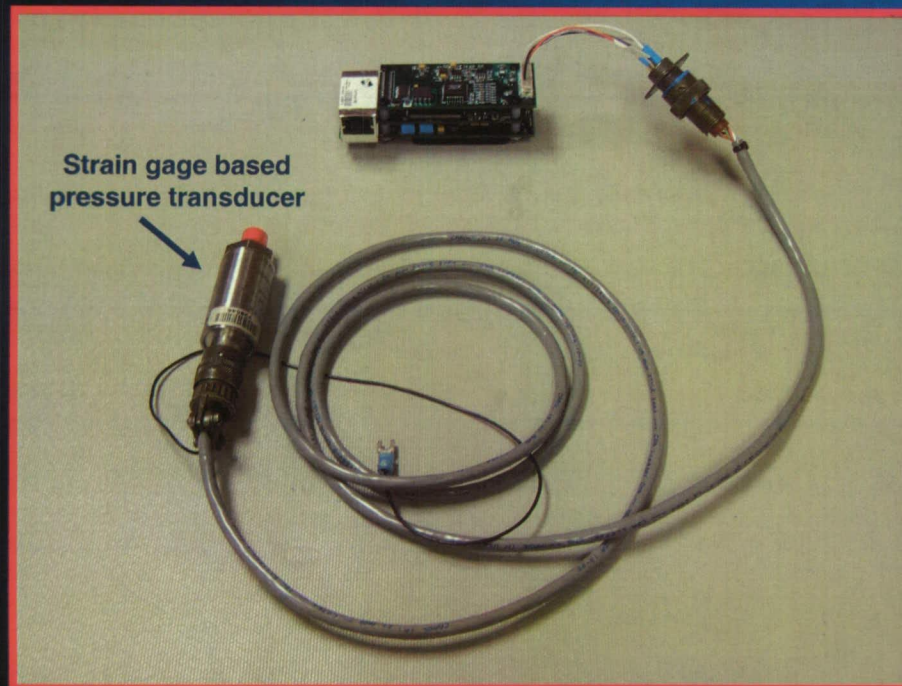
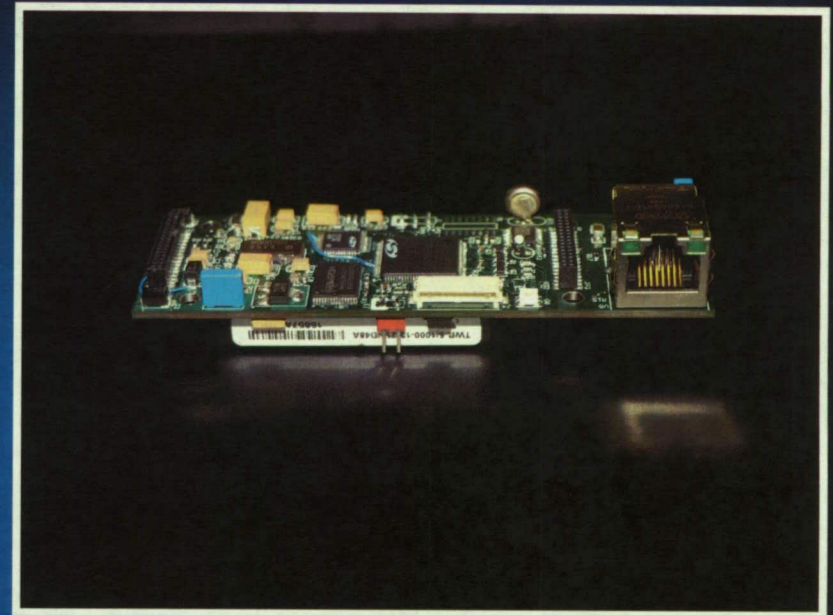
- TI 200MHz Floating-point Digital Signal Processor (DSP)
- 512 KB external RAM

Intelligent Devices - Architecture

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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

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- 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

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- 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

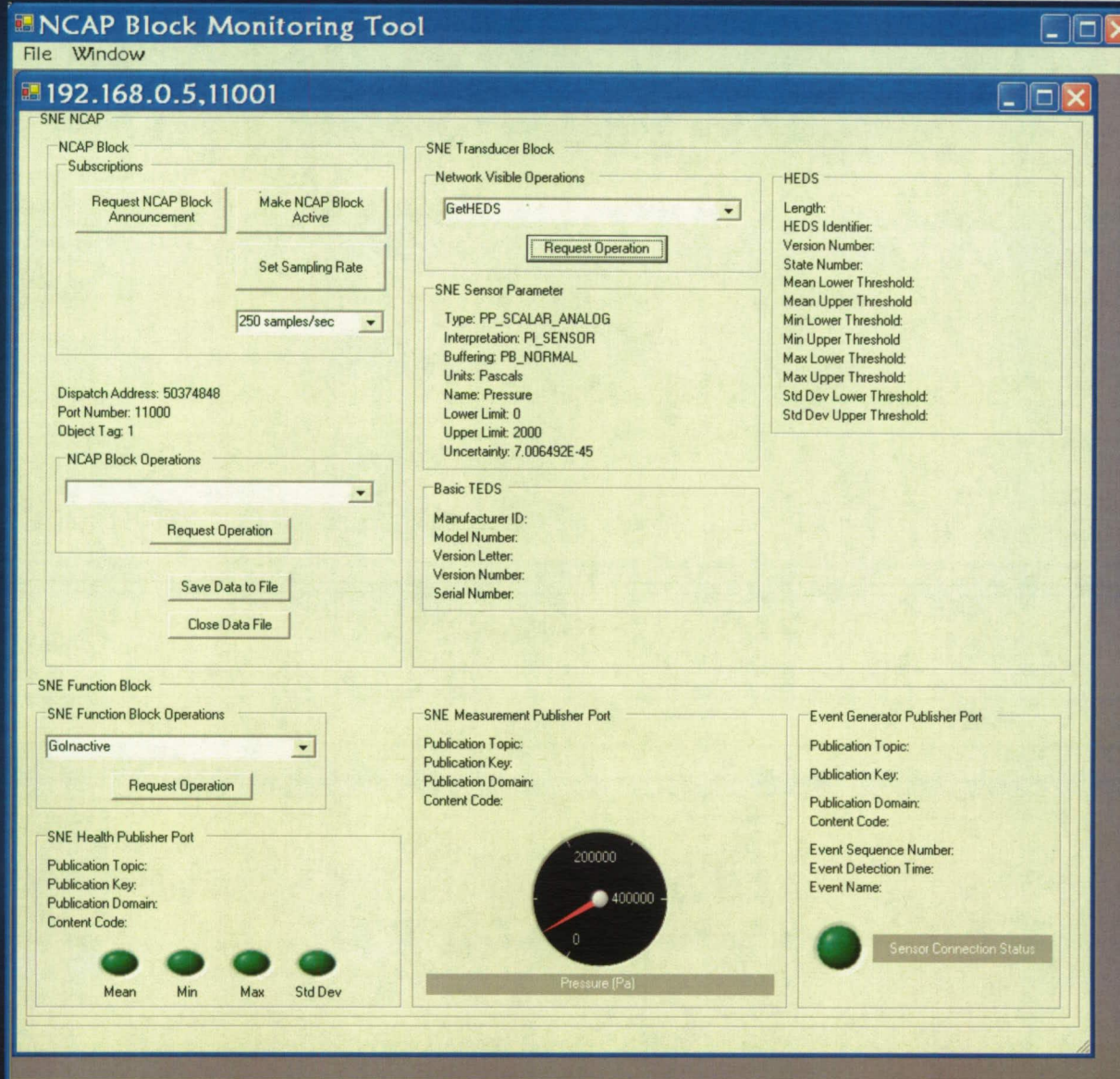
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- Additionally, the Intelligent Device development team is looking at the following standards:
 - IEEE 1588 “Precision Time Protocol (PTP)”
 - On-board time synchronization with sub- μ s accuracy
 - IEEE 802.3af “Data Terminal Equipment (DTE) Power Via Media Dependent Interface (MDI)”
 - Power of Intelligent Devices over Ethernet

Intelligent Devices – Embedded Diagnostic Agents

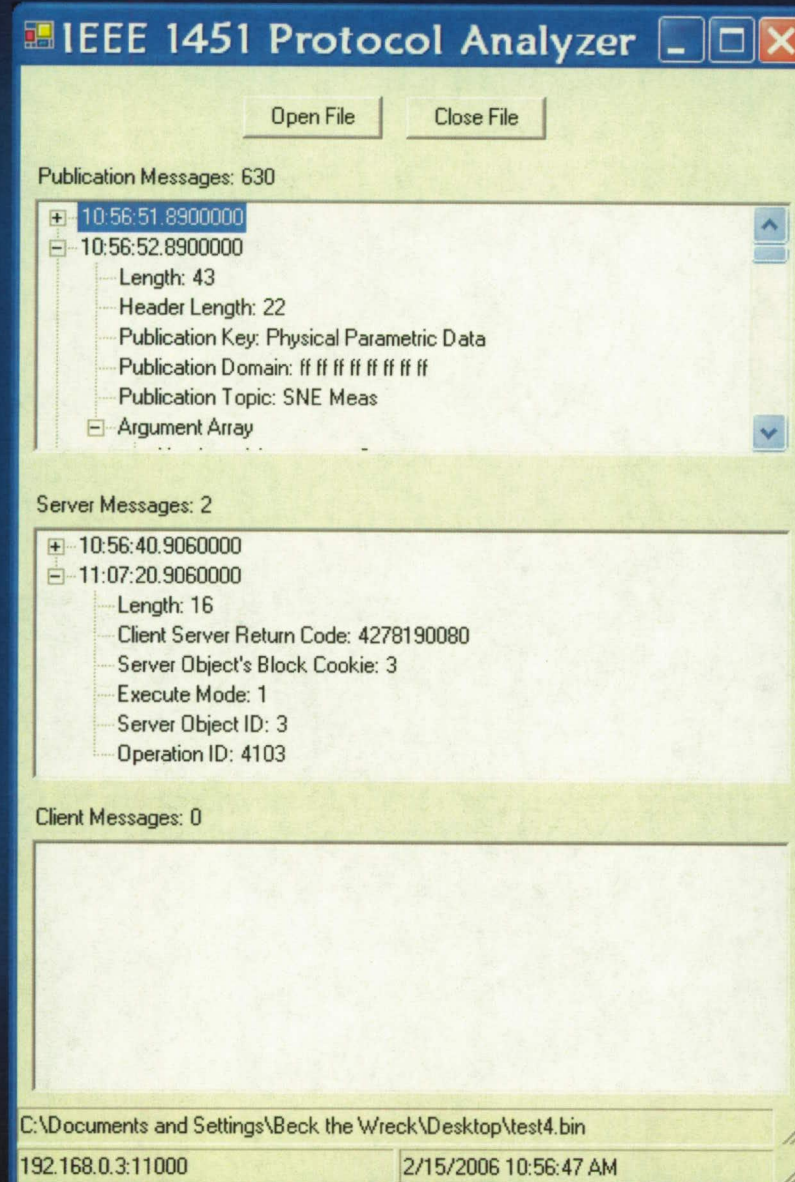
- Software algorithms have been implemented to:
 - o provide a “light” version of IEEE 1451.1 “implementation of the network-level object model”
 - Customize measurement sampling rate, message contents, and health parameters via a graphical user interface
 - Established User-defined TEDS – the Health Electronic Data Sheet (HEDS)
 - o 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 1451.1 Protocol Analyzer

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**
 - **Projects 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

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- 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, re-configurability, 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

ACKNOWLEDGMENTS

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Kennedy Space Center Intelligent Device team

- Mr. Angel Lucena, software developer, Instrumentation Group, NASA
- Mr. Bradley Burns, software developer, ASRC Aerospace
- Mrs. Rebecca Oostdyk, software developer, ASRC Aerospace

Outside KSC contributors:

- Dr. Fernando Figueroa, NASA Scientist, Stennis Space Center, Mississippi
- Dr. Gary Hunter, NASA Scientist, Glenn Research Center, Cleveland, Ohio
- Dr. John Schmazel, Rowan University, New Jersey

BACK-UP SLIDES

EMBEDDED PROCESS-KNOWLEDGE IN WIRELESS SENSORNET

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Objective

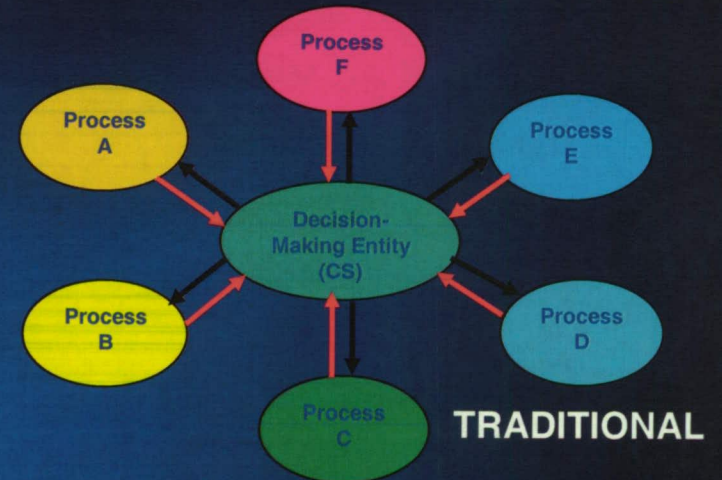
Design intelligent sensor network with embedded process-knowledge at the sensor level. De-centralize process decision making.

Design

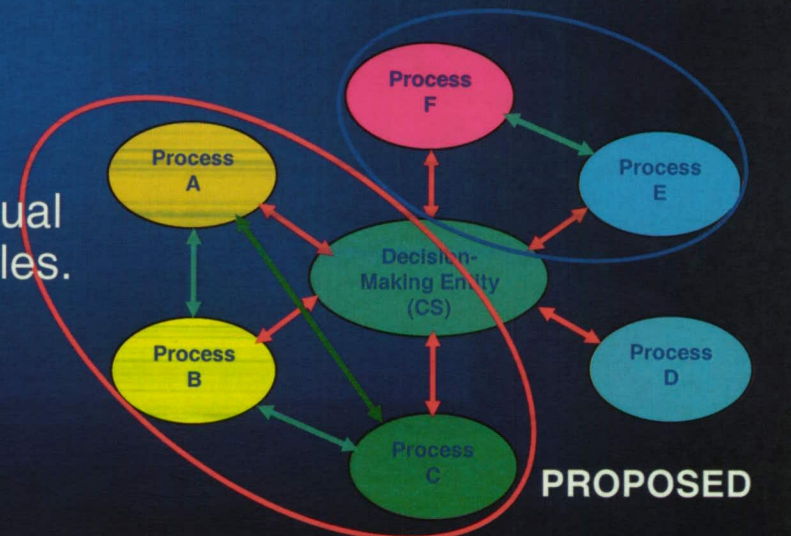
- Complex processes broken down into simpler, smaller processes. Relationship rules are created to link all processes to overall process.
- Share process knowledge/information among sensors and controlling equipment via wireless communication.
- Process health monitoring done through individual sensor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

Status

- Process composed of 2 sub-processes and 6 measurements have been modeled and implemented.



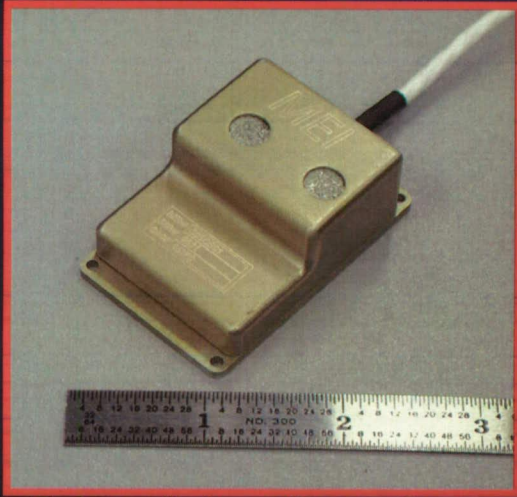
→ Process raw data to Central Station
← Command / decision from CS to Process



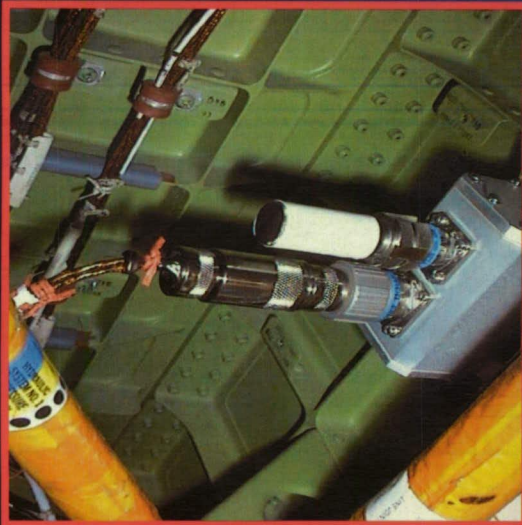
↔ Process information between RS and Central Station
↔ Shared information between processes

Mini Smart Leak Detector Sensor

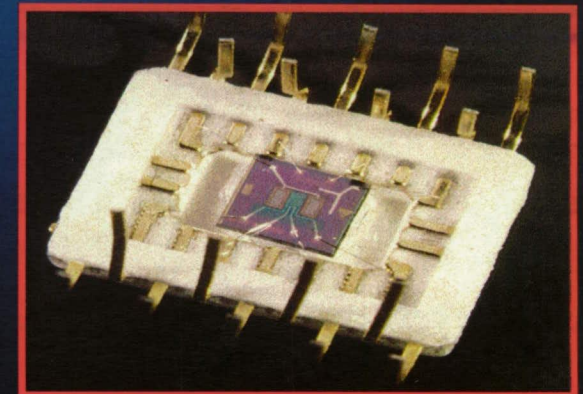
- Joint effort between GRC, KSC, MSFC, and MAKEL Engineering
- MEMS type hydrogen/oxygen/pressure/temperature sensor with embedded electronics and processing algorithms
- KSC provides technical expertise to transition design into final product. KSC is also performing functional testing, environmental testing and materials compatibility analysis.
- KSC is developing a Wireless hydrogen/oxygen sensor Network (wireless sensor prototype under test)



Prototype Hydrogen/Oxygen Sensor System with Electronics



Hydrogen Sensors on Space Shuttle



Micro-fabricated Hydrogen Sensor

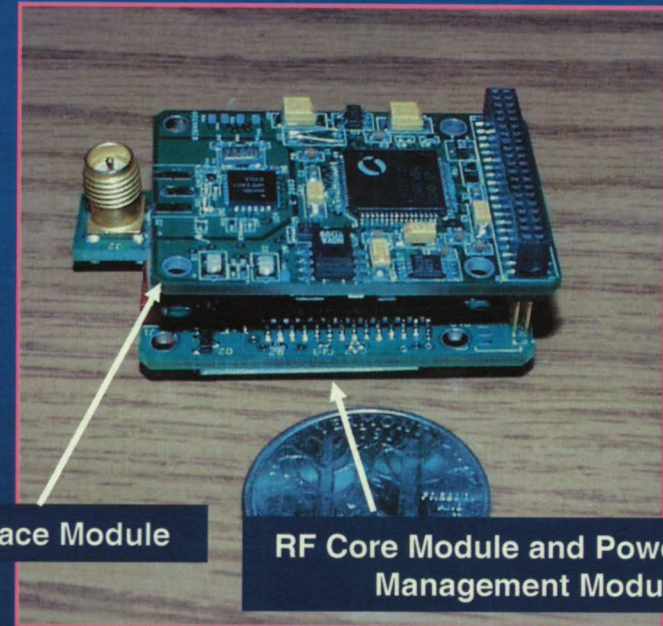
Photos provided by Dr. Gary Hunter (GRC)

Wireless Sensors Network (*SensorsNet*)

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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.



Sensor Interface Module

RF Core Module and Power Management Module

- 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.

CABLE TESTER

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- 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)

John F. Kennedy Space Center

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.



Hurricane Wind Sensors Development

John F. Kennedy Space Center

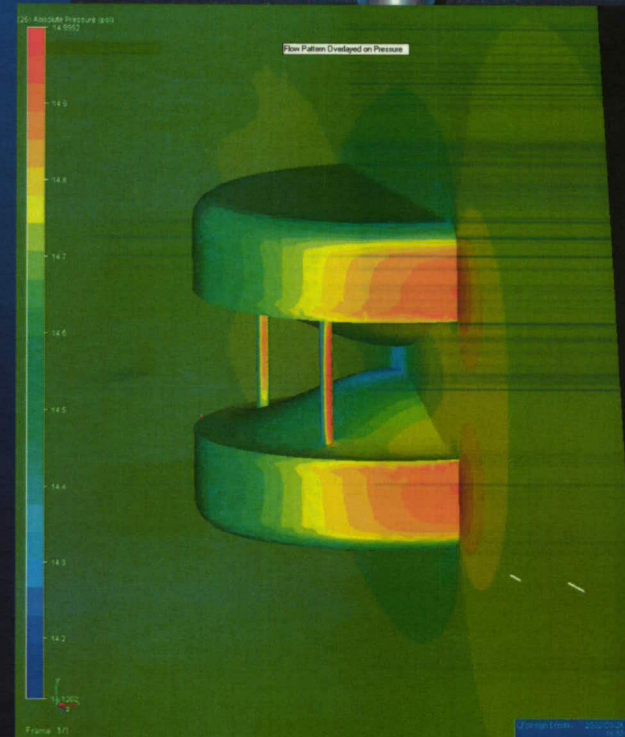
Objective

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.



ET Centering and Alignment (ET CAS) System

John F. Kennedy Space Center

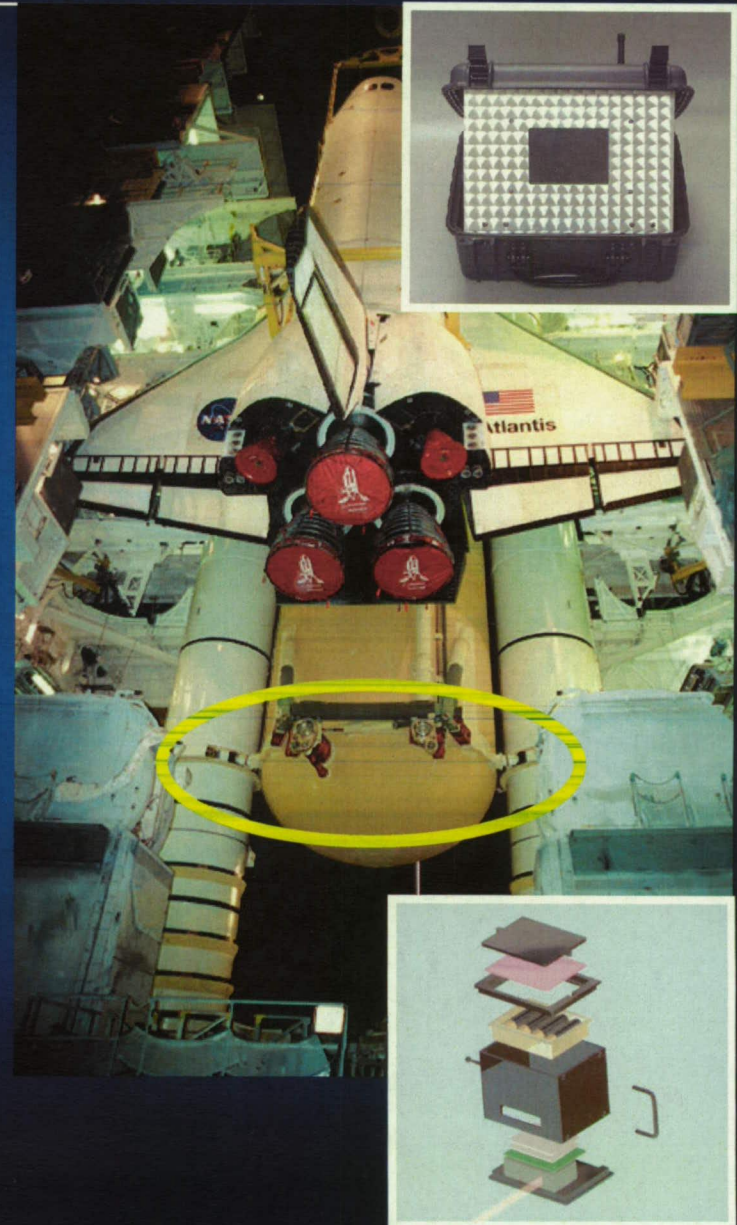
Objective

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.



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14. ABSTRACT

"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.(a)(f), 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."

15. SUBJECT TERMS

Sensors, Actuators, Instrumentation, Health Management, Health Monitoring, Intelligent Sensors, Intelligent Devices, IEEE 1451, Fault Detection, Isolation and Recovery (FDIR)

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