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Intelligent Sensor Node as an Approach to Integrated Instrumentation & Sensor Systems for Aerospace Systems Control

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This paper proposes operational requirements for integrated instrumentation / sensor systems intended for use in aerospace equipment test and evaluation, diagnostics and health management, and control. Their application is exemplified by a description of the design and development of an integrated sensor node suited to the demanding aerospace equipment environment.

Nomenclature

BIT	=	Built In Test
DHM	=	Diagnostics And Health Management
FADEC	=	Full Authority Digital Engine Control
IISS	=	Integrated Instrumentation / Sensor Systems
ISN	=	Intelligent Sensor Node
KPP	=	Key Performance Parameters
LCC	=	Life Cycle Cost
SBIR	=	Small Business Innovation Research
SOI	=	Silicon On Insulator
T&E	=	Test And Evaluation

I. Overview

THE objective of the work reported herein[3] was to guide development of Integrated Instrumentation / Sensor Systems (IISS) incorporating communications, interconnections and signal acquisition with enhanced suitability and effectiveness for aerospace:

- system verification and validation,
- equipment health management, and
- precision control of system behavior and performance.

IISS operational imperatives identified include factors such as tolerance of the bulk of aerospace equipment operational environments, low intrusiveness, rapid reconfiguration, and affordable life cycle costs. The functional features identified include interrogation of the variety of sensor types and interfaces common in aerospace equipment applications over multiplexed communication media with flexibility to allow rapid system

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reconfiguration to adapt to evolving sensor needs. This implies standardized interfaces at the sensor location (preferably to open standards), reduced wire/connector pin count in harnesses (or their elimination) and embedded sensor identification and calibration data in non-volatile memory.

This paper demonstrates the application of IISS concepts with the help of a “case study” involving the development of an “intelligent sensor node” (ISN) system. The concept of an ISN was born as a part of the development of distributed architecture for full authority digital engine control (FADEC) systems. A description of the issues and potential benefits of distributed FADEC architecture can be found in Ref.1. It is worth noting that this transition towards distributed architecture is consistent with emerging distributed data aggregation trends in industrial and aerospace systems. (See Johnson[2].)

The primary obstacle to the affordable realization of the proposed ISN was the lack of suitable high temperature capable electronic components. While the basic Silicon On Insulator (SOI) technology had been developed earlier[3], the lack of a business case and a limited portfolio of components needed to demonstrate the feasibility of the concepts presented a Catch-22 situation. In addition, the operational imperatives and functional constraints for an IISS resulted in large number of challenging requirements for the functionality, environmental capability, durability and life cycle cost (LCC) of these building blocks. This stalemate was broken with the help of a series of SBIR programs for proof of concept (POC) demonstrations focused on the needs of high temperature capable building blocks for distributed FADEC. This case study will examine the issues and challenges encountered during the development of the ISN and describe the capabilities and features of the architecture from the IISS perspective. In particular, the requirements for reconfigurability to support a wide range of sensors and the need for self contained intelligence and memory to perform on-board DHM and reduce the logistics trail will be examined in some detail.

II. Background and Scope

This paper addresses instrumentation/sensor systems applied to the following three aerospace domains: sub-system or system test and evaluation (T&E), diagnostics and health management (DHM), and control systems. The focus of this work encompasses instrumentation and sensors, the data acquisition function, and the intervening communication media, thus “integrated instrumentation/sensor systems” [IISS]. This basic functionality is common across all three domains.

Some of the most challenging IISS applications involve the complex mechanical systems required for propulsion & power, environmental control, flight control and other essential functions that are weight and volume constrained, tightly integrated with vehicle structure and exposed to the full rigors of the flight envelope and environment.

Aerospace system and sub-system T&E covers a range from sub-system rig test through system test bed to flight test. Current developments in flight test instrumentation (described by Musteric[4], Visnevski[2], Berard, et al[6]) lead the way in advancing IISS for aerospace T&E applications, primarily because the challenges of sensor environment, space and access constraints are less challenging than those of instrumentation embedded in onboard equipment, aloft and on the test bed.

Sensor systems used for system diagnostics and health management (DHM) and those employed in control systems share qualitatively similar requirements. The growing complexity of DHM and control systems (as described by Urban[7], Behbahani et al[8], Litt et al[9], Culley and Behbahani[10] and Paris et al[11]) is driving increased scope of sensor applications and leading to consideration of distributed DHM and control architectures to overcome the cost, weight and dependability challenges of centralized system architectures.

However the assessment of the factors to be considered (key performance parameters, design criteria, etc.) is subject to differences in their relative weightings. Thus the hope that these three applications will provide a market for broadly similar sensor systems, but also the caution that their differences need to be considered in the conceptual and detail definition of tailored technical requirements, architectures and design approaches.

A further distinction between sensor systems, or elements of sensor systems, relates to the signal acquisition bandwidth and inherent data processing requirements. The majority of the physical parameters sensed in the domains considered require discrete samples at relatively low rates, on the order of 100 to 1 per second. Periodic quasi-static samples of parameters such as pressure, temperature, rotational speed, strain, position, and flow are adequate for most physical system state assessments; the challenge is more often (e.g. DHM) the appropriate averaging of the data to suppress high frequency disturbances or noise.

On the other hand, dynamic sensor measurements (acoustic, pressure fluctuations, vibratory motion and strain…) require high bandwidth, high frequency records. The purpose is also qualitatively different; it usually is focused on the behavior and state of individual components. Although the latter sensor types may play a significant role in the application domains considered here, their integration into the IISS may inappropriately influence decisions on the system architecture selection, and needs to be attempted selectively. This study focuses on sensor system applications interrogating a multiplicity of diverse sensed parameters at relatively low bandwidth, presuming the high bandwidth signal acquisition may best be left to systems dedicated to individual sensors or sensor types.

III. Objectives & Method

It is hypothesized that, within the above bounds, a top down systems engineering approach will be more fruitful than a bottom up pursuit of advanced sensor technology in meeting user needs for more suitable and economic instrumentation and sensor solutions. The objective of the following analysis is to provide a common framework of integrated instrumentation/sensor system [IISS] operational objectives, to define relevant functional architectures, and identify functional features that may transform the performance, suitability and cost/benefit trades limiting the exploitation of advanced sensor capabilities.

Based on many years of discussion of sensor requirements within the aerospace community, basic IISS requirements and their suitability/life cycle cost imperatives are reviewed with consideration of the differences between the three application domains. Various features that enable and complement the requirements in responding to operational needs are also suggested,

This paper concludes with the description of a prototype “Intelligent Sensor Node” defined in response to one of the proposed IISS functional architectures and the requirements and desirable features identified in the following analysis. This exemplifies the “smart sensor” approach of distributing the basic signal acquisition and the analog to digital conversion for data bus communication with or in proximity to the sensor.

IV. Basic Sensor System Requirements

What are the instrumentation/sensor features inherent to the basic IISS functionality - physical data acquisition – and how do the requirements and their importance vary across the three domains of application considered?

A. Precision and Range

All three applications require accurate measurements, usually covering the full range of conditions experienced by the system in normal and abnormal operation. However, quantitatively, T&E users will tend to value accuracy more than DHM and control system sensors generally need. T&E often needs precise measurement over a wide range and time span, while the range of interest may be narrower for DHM and control. These differences are not universal however; certain critical control sensors may demand precision over a wide range (e.g., propulsion system compressor delivery pressure).

B. Repeatability and Stability

Again, these basic sensor Key Performance Parameters [KPP] vary in their salience; T&E applications may be more accepting of periodic recalibration between test episodes, but the operational implications of diagnostic or control sensor servicing or recalibration on intervals less than months and even years of service are usually unacceptable. In all applications signal acquisition servicing may not be as onerous, but it is still an undesirable cost and unavailability driver.

C. Endurance and Reliability

Similarly, T&E may not demand the dependability required for diagnostic applications, or the extreme reliability needed in critical control sensors. Nevertheless, loss of sensor data due to failures on test can require retest or increase the uncertainty in interpreting test results. T&E typically needs numbers of sensors an order of magnitude greater than DHM, which may in turn exceed the numbers of control sensors, so the overall mission vulnerability to sensor system failures may be comparable in all domains. Note that interconnections are usually the largest contributors to loss of data and unscheduled sensor system servicing in the all domains. Furthermore, in the DHM and Controls domain interconnections are an important source of failures and false alarms that reduce mission capability and availability, and contribute to the high maintenance cost of aerospace systems.

For some specific sensor requirements in the domains considered here, e.g., assessing system behavior and component state in gas turbine hot sections, sensor durability may limit the possibilities but research and development continues to expand the environmental capabilities of available sensors.

The above metrics are central to sensor selection, and the overall sensor system architecture and functionality must accommodate these requirements. However, we must also consider other requirements driven more by suitability and life cycle cost (LCC) considerations, requirements related to the process more than the product. Is the sensor system suitable for meeting usage and affordability objectives?

V. Suitability and Life Cycle Cost Objectives

Considering the application and usage of the IISS as a system serving the needs of the three domains of application and how do the affect IISS design objectives?

D. Serviceability and Affordability

Test instrumentation acquisition, installation and maintenance can be the main cost driver in component and subsystem rig test, diagnostic sensor cost/benefit ratios often make them an undesirable option, and most control system sensors are seen as a necessary evil to attain system operational capabilities. These cost trades within constrained acquisition budgets militate against the data acquisition and design verification needed to mitigate risk and manage life cycle cost. Justifying total DHM system LCC, including maintenance and data analysis, vs. the known and accepted burden of direct periodic inspection, or removal and test, of aerospace system components is a major hurdle for DHM IISS applications.

A prime factor driving cost in instrumentation and sensor systems in aerospace applications is the usual architecture of a single sensor communicating over a dedicated channel to a unique signal acquisition interface. This is less common today in industrial applications, where networked "smart" sensors (e.g. Madrini[12]) that locally process sensor readings and communicate the results in a standard format over a digital data bus to a central data recorder, etc., are common. The possibility of distributed sensor & signal acquisition architectures has been the subject of much analysis and research (For examples, see Behbahani et al[8], Litt et al[9], and Culley and Behbahani[10].) but has been limited in application to date. This is because in the demanding aerospace operating environment, the limited thermal and vibration capabilities of available analog and digital circuit components constrain the use of such "smart" sensors.

A related issue, particularly relevant to T&E applications, is quality assurance for instrumentation systems, in situ. Once all sensors have been installed and hooked up, verifying that the sensors are correctly wired and functional, and correcting the faults, may take as long as the installation. In aerospace equipment control and health management, sensors are usually expected to be field replaceable with no change in signal acquisition calibration or compensation. This drives sensor cost and limits capability.

E. Compatibility vs. Intrusiveness

Sensor size, the need for access and interconnections, sensor system effects on the parameters measured and fidelity of system behavior, not least due to test only component designs to allow ingress and egress; all these constrain the application and utility of sensor systems in T&E. While the accessibility of sensors and interconnects has significant impact on the cost of servicing and repair, the reduced numbers of sensors necessary for DHM and control may mitigate this issue, but the growing need to measure more parameters, more reliably, increases equipment design complexity and cost.

System weight is also an issue, particularly in DHM and Controls IISS. As aerospace programs proceed through design and development, with tightening cost and weight margins, the weight & cost of IISS combine to drive reduction or (indefinite) deferral of capabilities.

F. Adaptability and Flexibility

A central issue in all instrumentation/sensor systems is uncertainty, the risk that what needs to be measured to meet the system performance and reliability/ availability objectives has not been anticipated or considered. Although on different timescales, in all three domains considered here it is desirable, if not essential, to be able to rapidly reconfigure the sensor system to acquire data not foreseen when the system was specified and acquired. (Xu et al [13] emphasizes these imperatives.)

In T&E the "decision loop" is essentially overnight if the additional data is to be acquired without affecting test schedules. DHM systems should be reconfigurable in days or weeks to enable informed root cause determination and preempt significant degradation of operability and mission availability by proactively fielding DHM system upgrades. The ability to increase control system capability through new or modified sensor functionality in less time than it takes to redesign and qualify the usual alternative – a major physical system configuration change affecting sensors, harnesses and signal acquisition circuitry & enclosures – would speed response to new and emerging operational imperatives.

Rapid sensor system reconfiguration may also enable non-materiel, procedural, change that mitigates life cycle cost impacts, such as faster changeovers between tests, more efficient and effective maintenance, and redeployment of legacy equipment to serve new missions.

VI. Qualitative Summary

Qualitative requirements and objectives for features of IISS deployed across the three sensor application domains are summarized in Table 1 below. The features map to the requirements and objectives described in the preceding sections, and it is evident that these differences may drive architectural, functional and design differences in sensor systems defined to suit a specific domain. However, on balance the architectures and functionality discussed in the following sections will provide benefits to all three domains, although their value to users in different domains will vary.

Table 1: Qualitative IISS Requirements & Objectives Summary

Feature	T&E	DHM	Controls
Types and Quantity of Sensors	Large numbers, diverse	Some specialized, many generic	Mostly well defined, fewer types
Design Types	Adaptable	Mixed, some experimental	Optimized, Point Designs
Signal Processing Bandwidth	High (100 Hz – 20,000 Hz.)	High (~3000 Hz)	Medium (100Hz)
Performance	High Accuracy & Range	Mixed (some threshold only)	High Accuracy
Durability/ Dependability	Medium/High	High	Higher than current offerings
Accessibility, Deployability	High	Medium	Low – Medium
Adaptability	High	High	Medium
Affordability/LCC	Medium	High	Medium

VII. Functional Architecture and Implications

A. Sensor System Architecture Alternatives

The first and more common alternative is the standardization and multiplexed transmission of the digital outputs. This functional architecture is almost essential for state of the art T&E, DHM & control, where data bus based architectures for digital data transmission are the norm. However, for many aerospace applications the sensor environment and space constraints typically require placing the analog output signal acquisition, digital conversion and further processing in an avionics bay or other protected environment, grossly curtailing the benefits of digital signal multiplexing.

"Smart sensors" in a distributed architecture, where the analog to digital conversion and signal multiplexing function is allocated with the "smart sensors", is thus seen as highly desirable in all three domains, and is becoming common in T&E in applications where available "smart sensors" can survive the test environment - which remains a severe limitation with conventional silicon based digital electronic components. The environmentally hardened Intelligent Sensor Node (ISN) described in the next section is intended to enable this architectural approach for more demanding applications.

A second architectural alternative exploits standardized analog output signals to attain the benefits of multiplexed signal transmission at this interface, as exemplified by applications of optical fiber Bragg gratings (FBG), where multiple fiber optic sensors are interrogated by over a single optical fiber. (See Abad et al[14].) This alternative architecture requires sensors designed to conform to standardized analog outputs (electrical, optical or radio frequency) communicated over a common transmission medium using time or wavelength division multiplexing for acquisition by a shared signal acquisition device. This is attractive in both reducing the size and complexity of harnesses and limiting the number and variety of signal acquisition interfaces and devices.

The second architecture puts severe constraints on the analog output, and demands innovation in sensor design to suit this common interface. The design disclosed in Millar[15], for example, requires that all sensors are designed such that diverse sensed physical parameters strain the fiber or otherwise modify the optical characteristics of a FBG in compliance with a defined common standard, so all results can be read out with a single optoelectronic signal acquisition subsystem.

However, the latter approach is an attractive option for environments and applications where the cost and immaturity of robust smart sensors would otherwise put the benefits noted below out of reach. (Designing sensor suites to standard analog outputs alone would enable some of the features proposed below, but the ability to multiplex the sensor is necessary to radically address suitability and life cycle cost objectives .

B. Features Satisfying Suitability & Life Cycle Cost Objectives

In general, the implication of the suitability and life cycle cost driven objectives for integrated instrumentation/sensor system design is to make the sensors "smart" by moving the sensor specific interface as close as possible to the sensed parameter, without compromising the first three objectives. Distributed systems with standardized multiplexed interfaces at the sensor location should reduce the weight, complexity and cost of interconnections and facilitate IISS modification in response to sensor requirements changes or capability improvements.

If the standard interface is "open", to a public specification, system capability will increase and life cycle costs will reduce as suppliers compete to provide improved sensors meeting the standard interface, for both existing measurements and novel sensor requirements.

A capacity to support multiplexed communication will yield gains in cost and compatibility, particularly if it allows a single signal acquisition unit to interrogate multiple sensors over less complex interconnections. A variety of communication network architectures become viable, allowing optimization for enhanced system reliability and reconfiguration on the fly.

Another desirable feature would be functionality for automated sensor identification (type and item) and characterization, avoiding the onerous signal tracing of conventional instrumentation and alleviating the high costs of manufacturing sensors with essentially identical calibrations. Embedded identification and calibration (or classification) data interrogated over the signal acquisition network would be ideal, allowing plug & play sensor addition, configuration management and interchange on the network. The non-volatile memory function implied by this requirement might also be used to store usage, fault and system configuration data to guide maintenance.

A further desirable characteristic is a technology base shared by current and future applications in other fields, preferably ones with commercial markets that can contribute to financing technological maturation and add production volume for common components. These alternative markets would then share in recovering the sensor system investments.

Is an integrated instrumentation/sensor system [IISS] exploiting the alternative functional architectures proposed, and enabling these features, a viable goal? A case study of the design and demonstration of the "smart sensor" approach, in the next section, describes a Navy sponsored SBIR (small business innovation research) program for a generic Intelligent Sensor Node (ISN) specified and designed to conform to the objectives, requirements, and functional features proposed by exploiting digital multiplexing in severe aerospace equipment environments.

A variety of design approaches implementing the second alternative functional architecture – standardized multiplexed analog sensor outputs - have been defined and are in the early stages of feasibility demonstration and development. Five years ago Mrad and Xiao[16] pointed out a key technology hurdle for optical fiber sensor systems: the need for robust optoelectronic signal acquisition. Luna Innovations Inc.[17] is under Ph. II contract with the Navy to meet this requirement for airborne fiber optic sensor systems.

Recent Navy SBIR topics exploring the potential of multiplexed analog signals are also bearing fruit. Birnbaum, et al[18] presents a SBIR project exploiting a wireless transducer concept applicable to a variety of sensor types which will allow numerous sensors in a gas turbine hot section to be interrogated by a single signal acquisition unit. English, et al[19] earlier demonstrated an analogous approach using multiple pressure transducers responding to microwave interrogation. Syntonics LLC[20] is developing a novel surface acoustic wave (SAW) transducer with similar capabilities for use up to 750 deg. C.

VIII. Intelligent Sensor Node – A Case Study

The concept of a "smart" sensor node was born from distributed control architecture concept studies, in which robust Intelligent Sensor Nodes (ISN) are distributed around the aerospace (propulsion) systems and communicate with a remote computer to enable a distributed Full Authority Digital Engine Control (FADEC) system. A description of the issues and potential benefits of such a distributed FADEC architecture can be found in Behbahani et al[8].

This ISN follows the first functional architecture, with the signal conditioning and analog to digital conversion function collocated with the sensors (the physical to analog sensing device) with multiplexed digital output to remote recording, processing and display functions. Noting that control systems employ dozens of sensors, but that most were of a few types (temperature, pressure, frequency, position, etc.…) and that most control system components hosted a mix of such sensors, a functional requirement of the ISN was to support analog input to digital output conversion for the most common sensor types.

Although defined for propulsion system control, the benefits of this "smart sensor" distributed architecture are expected to accrue across all of the three domains, other types of aerospace equipment, and possibly industrial applications involving extreme environments. In all cases, the primary obstacles to the affordable realization of this architecture are basic ISN design requirements, namely:

- electronics capable of reliably operating in the harsh, high temperature environment found around the engine and
- a generic design that is capable of interfacing with the wide variety of propulsion system DHM and control sensors.

The high temperature requirement is the outcome of the desire to distribute "smart" nodes in proximity to the sensors in order to enhance the DHM and control capability of the FADEC system while minimizing the weight and cost of the associated wiring harnesses. While a variety of technical approaches were considered, the most feasible in the near term was agreed to be the use of electronic components suited to use in thermal environments from -60 to +200 deg. C. This was a pragmatic compromise based on availability of electronic components meeting this requirement and the observation that most active components (hydraulic, electrical, and mechanical devices) and fluids (lubricating and hydraulic oil, fuel) in aerospace applications can only reliably and safely operate within this range, with the expectation that ISN suited to this thermal environment would meet the bulk of sensor requirements.

Silicon On Insulator (SOI) components (early noted by Wick[21]) are being developed to meet the needs of the down-hole oil exploration industry for electronics operating in similar thermal environments, giving impetus to the formulation of a Proof-of-Concept demonstration SBIR program by the Navy[22] which has led to the development of the Intelligent Sensor Node (ISN).

While other semiconductor technologies were considered, they were as yet not mature enough (e.g. Silicon On Sapphire) or did not provide components with sufficient level of functionality (e.g. silicon carbide) to realize a "smart" node. The demonstrated reliability of SOI components over the specified operating temperature range made SOI a first choice for the ISN design.

The second system level requirement, namely that of a generic design, was very critical because in its absence each "smart" node would have to be customized to the application, thereby dashing any hope of standardizing on a hardware module across the FADEC system - a necessity to reduce development and unit cost, i.e. LCC of the smart node. To be truly generic, the design would have to be capable of interfacing with the wide range of sensor specifications for each sensor type found in FADEC systems, without any hardware change. In other words, the design would have to be reconfigurable by means of software, so that the same hardware could be used to interface with, for example, a 2-wire, 3-wire or 4-wire strain gauge sensor.

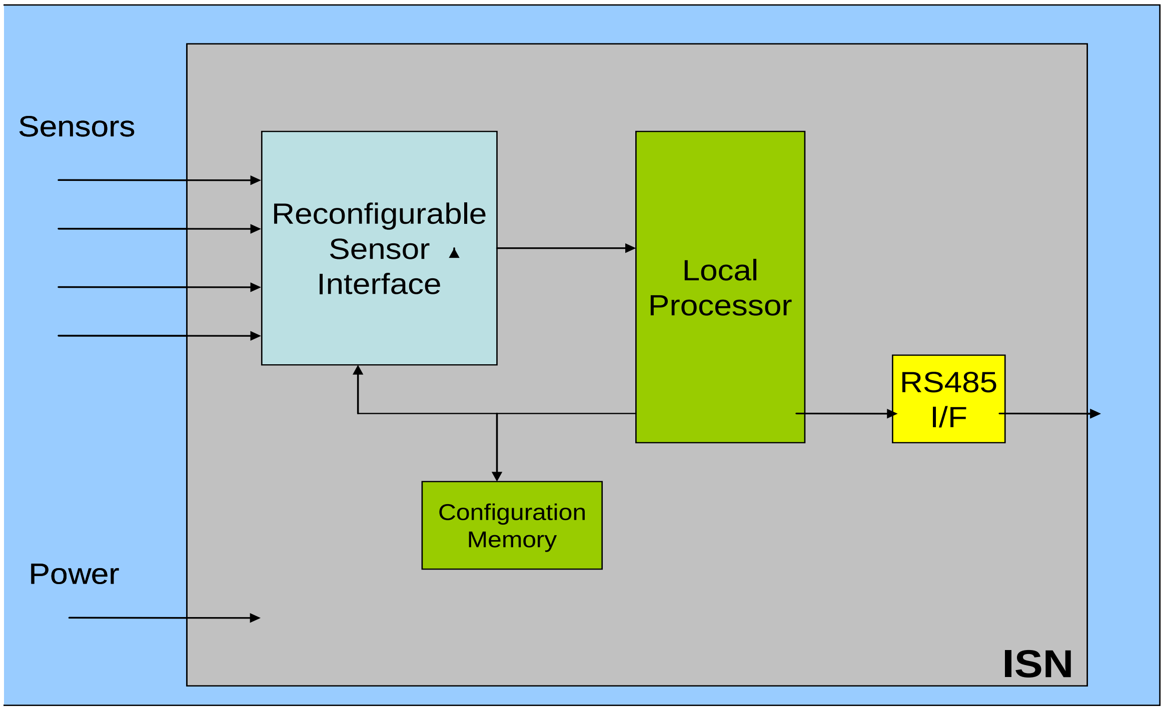

Figure 1: Intelligent Sensor Node Block Diagram

The re-configurability requirement was a major challenge particularly in view of the limited variety of available SOI components and their range of features. However, we were able to design an interface that could be reconfigured for interfacing with most types of FADEC control sensors by a combination of hardware, firmware and software means. A functional block diagram of the reconfigurable ISN is shown in Fig. 1. The types of analog outputs from sensors that can be accommodated include thermocouple, RTD (Resistive Temperature Detector), strain gauge, electromagnetic position sensors such as LVDT (Linear Variable Differential Transformer), DC voltage and current, and frequency/ pulse analog outputs.

As Fig. 1 indicates, the ISN consists of a reconfigurable sensor interface block which interfaces with a local processor for acquiring the sensor data and re-configuring the ISN. The processor communicates with a Host (e. g. FADEC) via an Open Standard, 2 wire, data bus, such as, RS485. The data bus can be "daisy chained" in to interconnect multiple sensor nodes thereby further reducing wire harness weight and cost. Since the data bus is "intelligent" the diagnosis and isolation of failures is a very straightforward process which contributes to reducing the cost of maintenance and DHM. The cost is even further reduced because the ISN performs its own Built In Testing (BIT) thereby performing the health checking of itself and its associated sensors.

Since the ISN stores on-board all the necessary characterization parameters for calibration of the associated sensors, different equivalent sensors can be interchanged making this an attractive solution for T&E as well as the DHM and control domains. The ISN also stores on-board the failure history and configuration changes making the post event removal in the diagnostics and depot maintenance cycle very efficient, further reducing LCC. Since the ISN can be reconfigured without any hardware changes to interface with these sensors; it goes a long way in the need to reduce the development and unit cost, i.e. LCC of the smart node. The prototype ISN module can support one each of the types of sensors described above. Finally, the ISN design consists of building blocks that can be combined in multiple ways to create more capable, alternate configuration Nodes making the resulting distributed architecture scalable for interfacing with different numbers and types of sensors for multiple applications.

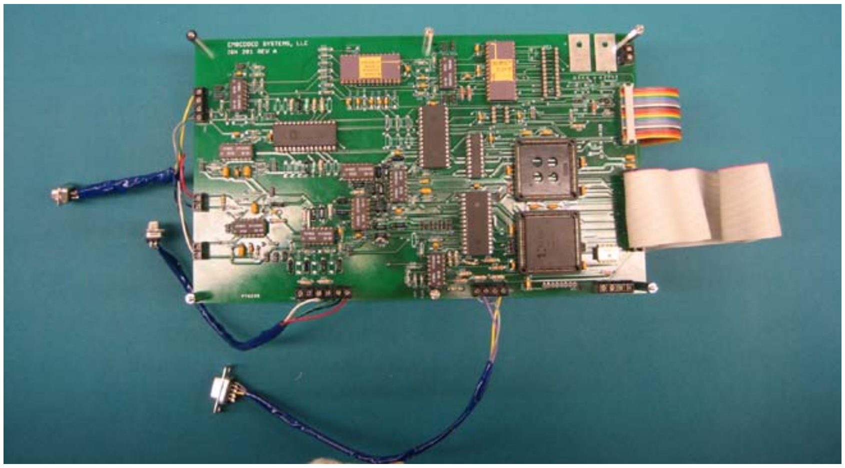

Figure 2: Intelligent Sensor Node Prototype

The concept of a generic, reconfigurable ISN was demonstrated with the prototype hardware module shown in Fig. 2. The prototype ISN was connected to different types of sensors and reconfigured by means of software/ firmware to collect the appropriate data and communicate with a host PC.

To evaluate the high temperature performance of the ISN design, several thermal tests were conducted to learn about the behavior of these components and improve the design. The lessons learned from these thermal tests have proved to be valuable in modifying the design to be capable of meeting the stringent performance requirements for FADEC sensors and interfaces over the high temperature range. This limited thermal testing process has also given us insight into the "real requirements" and exposed several deficiencies associated with the SOI components which are being incorporated into more robust and affordable ISN designs.

IX. Conclusion and Future Work

The foregoing demonstrates the potential for a systems engineering approach to guide concept development for aerospace integrated instrumentation/sensor systems [IISS] tailored to the unique design objectives and requirements of aerospace equipment in terms of performance, suitability and affordable life cycle cost. (See Blyler[23] for a related focus on interface management.) IISS design objectives are also defined to capture the spectrum of system operational imperatives and guide definition for both performance and suitability.

A simplified sensor functional architecture is defined and used to guide definition of alternative functional architectures exploiting multiplexed sensor signal communication and identify design features responsive to the system operational imperatives.

A feasible technical approach satisfying the identified requirements and objectives while conforming to one of the alternative functional allocations proposed has been designed, developed and demonstrated, providing an integrated sensor node [ISN] intended as a component of distributed aerospace gas turbine control and diagnostic & health management systems. Work to improve the ISN design by incorporating more capable components and circuitry continues.

Proprietary implementations of the other alternative sensor system functional arrangement, multiplexing the analog output from the sensor, are also the subject of recent SBIR contracts and will be described in future publications as their feasibility is demonstrated.

References

[1]Tulpule, B., Behbahani, A. and Millar, R., "Vision for Next Generation Modular Adaptive Generic Integrated Controls (MAGIC) for Military/Commercial Turbine Engines," American Institute of Aeronautics and Astronautics, JPC 2007.

[2]Johnson, K., "Mobile Platform Instrumentation, Data Aggregation and Telematic Integration", 56th International Instrumentation Symposium, May 2010.

[3]DARPA HiTeC program final report dated August 24, 1999, Air Force Agreement number F33615-96-2.2618).

[3]DARPA HiTeC program final report dated August 24, 1999, Air Force Agreement number F33615-96-2.2618).

[4]Musteric, S. A., "The Advanced Subminiature Telemetry System (ASMT)" U.S. Airforce T&E Days. Albuquerque, NM, AIAA 2009-1740, pp. 1-18, February, 2009

[5]Visnevski, N. A. "Embedded Instrumentation Systems Architecture" ITEA Journal, pp. 99-110, 2009

[6]Berard, A. P., Golackson, M., Klein, L. D. and Wyzgowski, Tom--., "Airborne Instrumentation Advancements and Challenge – Perspective 2007", U.S. Airforce T&E Days, Destin FL, AIAA 2007-1673, pp. 1-7, February 2007.

[7]Urban, L.A., "Gas Path Analysis Applied to Turbine Engine Conditioning Monitoring," AIAA Paper 72-1082, Dec. 1972

[8]Behbahani, A., Millar, R.C., Tulpule, B., "Vision for Next Generation Modular Adaptive, Generic Integrated Controls (MAGIC) for commercial/ military Turbine Engines", AIAA Joint Propulsion Conference Paper #007-5710, 2007.

[9]Litt, J.S., et al, "A Survey of Intelligent Control and Health Management Technologies for Aircraft Propulsion Systems", Journal of Aerospace Computing, Information, and Communication 2004 1542-9423 vol.1 no.12 (543-563)

[10]Culley, D. E. and Behbahani, A. R., "Communication Needs Assessment for Distributed Turbine Engine Control", NASA/TM-2008-215419, 2008

[11]Paris, D.E., Trevino, L.C., and Watson, M.D., A framework for integration of IVHM technologies for intelligent integration for vehicle management", IEEE Aerospace Conference, 2005

[12]Madrini, A.M., "Smart configurable wireless smart sensors and actuators for industrial monitoring and control", IEEE ISCCSP 2008, March 2008

[13]Xu, X., Liu, Q., and Wu, G., "Restudying on the concept, mechanism and composition of instrumentation flexible developing system", IEEE ICEMI '09, 2009

[14]Abad, S., et al, "Fiber Bragg grating sensor applications for thermal monitoring in satellites" (Poster), International Conference of Space Optics, Toulouse, France, October 2008

[15]Millar, R. C., Patent No. 7,091,472 B1. USA. 2006.

[16]Mrad, N. and Xiao, G. Z., "Multiplexed Fiber Bragg Gratings for Potential Aerospace Applications", icmens, pp. 359-363, 2005 International Conference on MEMS, NANO, and Smart Systems, 2005

[17]Luna Innovations Inc., SBIR N06-121 "Open Architecture Fiber Optic Engine Monitoring System", http://www.navysbir.com/06_2/14.htm [cited August 2010]

[18]Birnbaum, T., Conkle, J., Gregory, O., "Wireless Temperature Sensor for Gas Turbine Engine Applications", ISA 56th International Instrumentation Symposium, 10-14 May 2010, Rochester, NY

[19]English, J.M., and Allen, M.G. and Fonseca, M.A., "Wireless Micromachined Ceramic Pressure Sensor for High Temperature Applications", Journal of Micromechanical Systems, Vol. II, No. 4, August 2002

[20]Syntonics LLC, SBIR N08-037, "High Temperature Sensing Parameters", URL: http://www.navysbir.com/08_1/103.htm [cited August 2010]

[21]Wick, D. G., "Realizing Distributed Engine Control Subsystems Through Application of High-Temperature Intelligent Engine Sensors and Control Electronics", SAE paper 2000-01-1363, SAE 2000 World Congress, March 2000

[22]U.S. Navy, "Intelligent Sensor for Distributed Engine Control for Advanced Propulsion System Application", SBIR Topic N07-175

[23]Blyler, J., "Interface management", Instrumentation & Measurement Magazine, IEEE, March 2008