Intelligent Sensor Systems for Integrated System Health Management in Exploration Applications

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ABSTRACT

Future exploration missions will require significantly improved Integrated System Health Management (ISHM) capabilities throughout the mission. Vehicle systems that require intense human intervention or monitoring take valuable crew time from other critical functions and overall are impediments to realization of NASA's Exploration Vision. Therefore, ISHM and the sensor systems that enable ISHM, are necessary throughout the vehicle to enable the next generation Exploration Vehicles. This paper focuses on recent developments in sensor technology necessary to enable the next generation ISHM systems. These developments include improved ease of sensor integration, improved sensor reliability, redundancy and cross-correlation in vehicle sensing systems, and orthogonality in sensor measurements. This means sensors must be smarter, smaller, multifunctional, more reliable, and easy to apply. Examples of cutting-edge sensor systems which illustrate aspects of these improved capabilities are given: Smart Sensors, "Lick and Stick" technology, spray-on sensors, multi-parameter physical sensors, and a fire detection system using sensor orthogonality to improve reliability. Further, the successful operation of a sensor in a given environment depends strongly on supporting technologies beyond the sensor element itself, e.g., packaging, signal conditioning, and an understanding of what a sensor response means in a given environment. Examples are given of some technologies necessary to make a sensor element into an operational sensor system. It is concluded that improvements in sensor technology are necessary to enable ISHM and achieve the goals of the Exploration program. Most importantly, decisions must be made early-on in the vehicle design supporting the inclusion of an integrated sensor system for ISHM. While this paper focuses Exploration applications, the technical themes presented have relevance throughout aerospace.

INTRODUCTION

Future exploration missions will require significantly improved Integrated System Health Management (ISHM) throughout the mission in the vehicle, crew habitat environments, and in Extravehicular Activities. For example, long duration missions mean that reliable, autonomous, and long-term operation is necessary. Due to accessibility, cost, and communication constraints, spacecraft traveling on extended missions or between planets will have limited ground support for the standard maintenance presently done when the vehicle is on-site. The crew is constrained in time, resources, and capabilities from performing extensive system maintenance, repair, or replacement. Performance of future systems can significantly be improved by knowledge of vehicle state and an ability to respond to mission conditions. Even near-Earth missions will require improved system safety, reliability, and efficiency in order to meet the needs of the future Exploration program. Overall, vehicle systems that require intense human intervention or monitoring are impediments to realization of the Exploration Vision.

This implies that the inclusion of automated vehicle intelligence into the system design and operation is necessary. Potential problems with the vehicle or habitat must be identified before they cause irreparable harm. The vehicle system will have to incorporate technologies that will allow on-board systems to monitor component conditions, analyze the incoming data, provide caution and warning if necessary, and modify operating parameters to optimize system operations to achieve improved performance and reliability. If problems do occur, some autonomous prognosis/diagnosis, fault isolation, and remediation are necessary, i.e., the vehicle will need integrated intelligence and advanced ISHM systems.

However, the implementation of ISHM and vehicle intelligence overall has been limited in flight systems. One example application area, which highlights a number of forefront issues in the application of ISHM, is the propulsion system. Propulsion systems are flight critical systems whose degradation and failure can cause loss of mission and/or crew. A significant history exists in the development and implementation of propulsion health management systems for real-time diagnostics and post-test/flight analysis. A legacy of activities include ISHM applied to propulsion articles [1]. Areas of research include sensor validation/data qualification, real-time anomaly detection, and real-time fault isolation and diagnosis. Even with the limited sensor technology presently integrated into propulsion systems, this pioneering work demonstrated improved system capabilities by the application of ISHM. However, despite these successes, there is only limited application of propulsion ISHM into flight systems. While there are a number of reasons for this, both technical and programmatic, the net result is that existing operational systems do not have the ISHM infrastructure to adequately perform the missions envisioned by the Exploration program.

One component of the ISHM system in particular that will need to be improved to meet Exploration mission challenges are the sensor systems, i.e., sensors and their associated data acquisition systems, packaging, communications, power, etc. High-quality data provided by sensor systems is a foundation of ISHM; present sensor technology does not meet NASA Exploration needs. This is so mainly because NASA's needs in sensors and instrumentation are specialized and revolve around its unique mission. Standard off-the-shelf technology is often comparatively large and tailored for medical/industrial markets where size, power, and all-in-one multifunctionality are not the primary issues. For example, one can conceive of taking off-the-shelf technology and using it on Moon/Mars missions. There are two major flaws with that approach.

The first is that size, weight, and power consumption of these systems would significantly affect the mission parameters, in some cases rendering the mission untenable. A Moon mission could be conceived repeating the Apollo missions using outdated technology. However, that outdated technology is generally significantly larger and more power consumptive than that developed in intervening decades and lacks some capabilities, like built-in self test, most needed to improve system reliability. Such an approach may save in initial development costs, but would significantly increase the payload and mission costs perhaps beyond what is allowed in NASA's plan. Likewise, we could also go to Mars with literally tons of off-the-shelf equipment. However, that would significantly change the mission profile and likely be prohibitive due to excessive additional weight and mass from components not designed for this application.

A second flaw in the off-the-shelf approach is that commercial industry does not standardly design off-the-shelf equipment that meet NASA specifications. Typical systems are not designed to be radiation hardened, and do not have design contingencies that allow the systems to last potentially for years without even the possibility of new spare parts or a service call. In the propulsion system example above, limited on-board sensors and instrumentation exist for harsh environments, leaving significant areas of the propulsion system unmonitored in high temperature conditions beyond those of standard or MIL-SPEC electronics and sensors. An ISHM system responds to the data provided; in the propulsion system little data can be provided since sensor systems operational in those environments are limited. If ISHM is going to be effective, then it should be applied where it is needed, such as in critical, harsh environment areas, not just where it is convenient. Further, sensors designed for other applications may not work in propulsion systems or for NASA applications in general. While NASA might leverage sensor technology being developed elsewhere, NASA unique problems require specialized solutions. Additionally, off-the-shelf technologies may impact overall cost and schedule due to additional testing/analyses required for space qualification.

While this paper focuses Exploration applications, the technical themes presented have relevance throughout aerospace. The general drive to reduce system complexity through limited sensor coverage and often minimization of new technology inclusion is common issue both in aeronautics and space applications.

This paper is intended to give an overview of some of the major issues related to sensor technology and its use in ISHM for NASA applications. While the paper will often use propulsion systems applications to illustrate examples, the discussion is meant to be broad-based in its implications. First, an overview will be presented of approaches in sensor technology development to allow its increased inclusion in ISHM and Intelligent Systems. Features of the future systems that would enable better ISHM operation include: Ease of application, reliability, redundancy/cross correlation, and orthogonality. Second, examples will be given of developing sensor systems and their advantages for ISHM. One trend is the development of complete sensor systems which are smarter, less intrusive, and use less power; providing more complete system information. Third, long-term development of sensor systems needs corresponding development of supporting technologies. These include packaging, communications, and component characterization to maximize sensor system effectiveness and data interpretation. Advancing these technology areas will increase the system information available for the more complete, accurate health assessments required for ISHM. Finally, the near term steps for the inclusion of sensor systems into the Exploration program will be presented, followed by a longer-term view of future direction of sensor technologyas it relates to general aerospace applications is also included.

SENSOR TECHNOLOGY APPROACHES

A significant change in approach to sensor and instrumentation technology would be the design and inclusion of intelligence into the vehicle from the planning stage forward. The ability to monitor a vehicle should be first considered at the same level as other subsystems. That is, if ISHM is to be an integral part of future vehicle operation, then it should be treated that way throughout vehicle development. This includes the application of intelligence-enabling technology to gather and interpret the relevant information regarding a vehicle state. Sensor technology, as well as ISHM, should be integrated into the vehicle system from the beginning, not added as an afterthought.

Overall, three uses of sensor systems and intelligence enabling hardware are envisioned in the development of a vehicle [2]. The first is system development and ground testing and where the sensors or instrumentation provide information on the state of a system that does not fly. This information could be used for the design and advanced modeling of systems that are in flight. Second is application of Integrated System Health Monitoring that involves long-term monitoring of a system in operation to determine the health of the vehicle system (e.g. is the engine increasing fuel burn or increasing emissions). This information could be used to change system parameters to in-flight or assist in ground-based maintenance. This is active control of the vehicle in a feedback mode where information from a sensor system is used to change a system parameter in real-time (e.g. fuel flow to the engine changed due to system measurements).

The sensor needs of flight systems are very different than those of ground systems. Each application area has different requirements for sensor systems. However, a common thread of technology attributes enables the sensor technology to be useful no matter the stage of implementation. These include the following [2].

• EASE OF APPLICATION:

Sensor system development, including the use of micro/nano fabrication, optical techniques, spray-on technology, etc., to enable multipoint inclusion of complete sensor systems throughout the vehicle without significantly increasing size, weight, and power consumption. If adding vehicle intelligence becomes as easy as “licking and sticking” like postage stamps (or even spray painting) smart sensor systems that are self-contained, self-powered and do not require significant vehicle integration, one major barrier to inclusion of sensors for intelligence is significantly lessened.

• RELIABILITY:

Sensor systems have to be reliable and rugged. Users must be able to believe the data reported by these systems and have trust in the ability of the sensor system to respond to changing situations. Presently, removing a sensor may be viewed as a way to improve reliability and decrease weight. In contrast, removing sensors should be viewed as decreasing the available information flow about a vehicle. Broad use of intelligence in a system will also have a much better chance of occuring if the inclusion of intelligence is achieved with highly reliable systems that users want to have on the vehicle. Further, reliable sensor systems enable the vehicle as whole to be more reliable.

• REDUNDANCY AND CROSS-CORRELATION:

If the sensor systems are reliable and easy to install, while mimimally increasing the weight or complexity of a vehicle subsystem, the application of a large number of sensor systems is not problematic. This allows redundant systems, e.g. sensors, spread thoughout the vehicle. Multiparameter sensor systems i.e. those which can measure multiple systems health measurands at the same time, can be combined together give full-field coverage of the system parameters but also allow cross-correlation between the systems to improve reliability of both the sensor data and the vehicle system information.

• ORTHOGONALITY:

The information provided by the various sensory systems should be orthogonal, that is, each provide a different piece of information on the state of the vehicle system. A single measurement is often not enough to give situational awareness. Thus, the mixture of different techniques to "see, feel, smell, hear" can combine to give complete information on the vehicle system and improve the capability to respond to the environment.

While not exhaustive, this list of attributes combined together significantly addresses a range of sensor system shortcomings. A new generation of sensor technology with new capabilities is necessary to incorporate these attributes as a whole. For example, the use of integrated electronics, networking systems, and micro/nano processing technology can produce smaller, multifunctional, smarter systems with improved capabilities. The following are examples of cutting-edge sensor systems using new technology approaches that often incorporate more than one of the above attributes. These examples illustrate different aspects of the technology attributes listed above. In addition they show a current direction of sensor technology that leads to the ability to make measurements in ways not previously possible.

SENSOR SYSTEM DEVELOPMENT EXAMPLES

Smart Sensors

Smart Sensors are one of the essential components of future ISHM systems. The following describes the basic approach to Smart Sensors and their implementation into ISHM. Smart Sensors are defined as basic sensing elements with embedded intelligence, capable of networking among themselves and with higher-level systems (processors, gateways and controllers) to provide not only process data but also data validity qualifiers to assess the sensor/measurement health. This new generation of sensors will possess embedded intelligence to provide the end user with critical data in a more rapid, reliable and efficient manner. Embedded intelligence, such as self-calibration, self-health assessment, self-healing, and pre-processing of raw data at the sensor level, will provide for a more reliable and robust system. New methods of sensor communication architectures are being investigated, such as arranging sensors in networks. New communication protocols (such as IEEE 1451) and modes (wireless, Ethernet, etc.) are being developed.

Smart Sensors [3-5] allow an ISHM architecture that relies on acquiring information from Smart Sensors and actuators, processing this information, comparing/augmenting the information provided by the sensors' embedded knowledge to its own knowledge information system, and establishing the health of the system. (See Figure 1). The Smart Sensor approach includes process and diagnostic agents, as well as communication protocols that will allow it to acquire raw data, convert the data to engineering units, process this engineering data, and extract health information to be transmitted among the other sensors and from sensor to next higher assembly (Data Collection Points or DCP). Each Smart Sensor will have embedded intelligence that will allow it to check its own health and to validate the data provided to the DCP. This ISHM system continuously refines its knowledge by learning from the system being monitored. Health monitoring and evaluation augment traditional data acquisition functions to create overall ISHM benefits.

The Smart Sensor provides several functional layers: signal detection (provided by the raw sensing elements), signal processing (signal conditioners, data acquisition and translation), signal validation (by embedded intelligence), and signal transmission (communication interface). Raw sensors will interface with signal conditioning stages that will provide excitation and signal conditioning. The data acquisition stage will convert the signal from analog to digital, and also acquire other parameters of interest to provide compensation if needed (i.e., thermal drift, long-term drift, etc.). Embedded intelligence will also continuously monitor the raw sensors, validate the engineering data provided by the sensors, and periodically verify sensor calibration and health. This will be accomplished by algorithms such as data trending, boundary checking, and cross validation with data from associated sensors. Other statistical, empirical, and logical rules will be used to verify that the data transmitted to the next higher assembly is valid and accurate. A network architecture is proposed utilizing Smart Sensors and the Data Collection Points (DCPs). The network can have one or more DCPs depending on the specific application. The DCP function is to establish communication with the Smart Sensors, to transmit and/or receive data and health information, and to collect, store, process and distribute this data to the users requiring the information. This network architecture approach allows communication of information not only up/down (Smart Sensor-to-DCP), but also among the associated peers (Smart Sensor-to-Smart Sensor). The method of communication in the network is selected based on the needs of the application. Wireless and Ethernet are examples of methods envisioned.

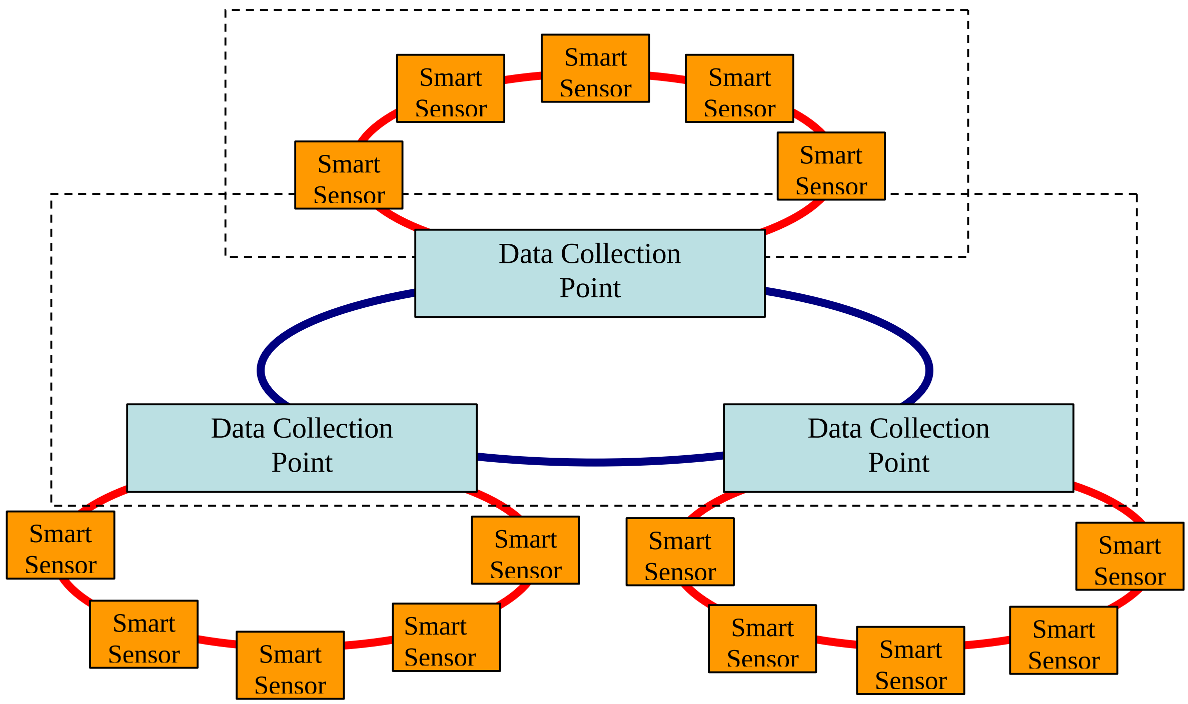


Figure 1. ISHM architecture using Smart Sensors. Individual Smart sensors internally evaluate information, correlate with each other, and feed results to Data Collection Points. The ISHM architecture is based on intelligence residing within each Smart Sensor contributing to the intelligence of the complete sys-

The Smart Sensor architecture is modular. One or more of the functional layers previously discussed are physically housed in different modules. This modularity allows for an easy reconfiguration for different applications. The number and type of physical modules utilized depend on the specific application for which the system is configured. The Smart Sensor communication layer defines its interface to other Smart Sensors and to the DCPs. This interface addresses not only the physical (electrical signals) interface requirements (i.e., Ethernet, RS485, wireless, optical) but also the communication protocols required by the system (i.e. proprietary protocols, IEEE 1451, etc.). The modular nature of this architecture is flexible to accommodate many different communication requirements. At the present time, efforts are being conducted to develop Ethernet-based communication modules. Other communication implementations, such as wireless communication, have already been accomplished and demonstrated using this architecture.

The sensor interface module encompasses the analog functional layers defined above (sensors, signal conditioning, and data acquisition functional layers). This module will change with the application. It could be a single sensing device module or a multi-sensing device (sensing array) module. This module will perform the following functions: interface to the raw sensing device(s), provide signal conditioning and filtering to the sensing devices, provide required excitation to those sensing devices, convert the signal from analog to digital, and provide any other additional parameters of interest to process the signal (i.e., ambient temperature, electronics temperature, etc.).

One approach to Smart Sensors is to have an embedded “Smart Sensor Agent” (SSA) on each sensor. The SSA Module is the heart of the Smart Sensor architecture. It contains the Smart Sensor’s main processor. The SSA module not only executes/supervises the operation of the Smart Sensor basic functions (i.e., signal conditioning, sensor excitation, data acquisition, communication, etc.), but it is also contains the embedded intelligence that enables the Smart Sensor to perform sensor and system health management functions. One of the Smart Sensor agent (SSA) responsibilities is to validate the data provided by the raw sensing device. To perform this task, the SSA works together with the calibration and health assessment module and performs sensor and electronic calibrations, data trending, comparisons to predefined upper and lower limits, and verification of the actual sensor’s output to a calculated output obtained from knowing the process rules and the outputs of associated sensors in the process. Other statistical, empirical and logical rules are also used to verify that the data transmitted to the system is valid and accurate. Other features or tasks of the SSA are related to configuration control issues (Sensor ID, calibration date, calibration parameters, next calibration due date, etc.). Presently, efforts are aimed at ensuring this architecture complies with the IEEE 1451 guidelines. In summary, some of the SSA responsibilities are to: provide accurate and reliable data to the user, conduct sensor and system health checks, communicate with other sensor suites to validate the data and health of the sensor(s), contain sensor identification and characterization parameters, contain parameters to perform sensor validation and measurement interpretation, and to provide sensor data synchronization. The calibration and self-assessment layer supports the SSA as it performs the required operations to verify the health of the Smart Sensor, and to aid in the validation of the data to be provided to the system. Several hardware and software algorithms are used in the performance of this task.

Thus, a new generation of sensors are envisioned throughincorporating embedded intelligence. Smart algorithms such as self-calibration, self-health assessment, self-healing, and pre-processing of raw data at the sensor level, will provide for a more reliable and robust system. New communication methods and architectures will also be required. This new generation of Smart Sensors will form ISHM systems capable of predicting the near- and long-term health issues of the system being monitored.

“Lick and Stick” Leak Sensor Technology

One specific area of sensor development is an integrated smart leak detection system for a range of propulsion systems [6]. This leak detection system is an example of a smart microsensor system that is also a multifunctional system. The objective is to produce a microsensor array, including hydrogen, oxygen, and hydrocarbon sensors, fabricated by microfabrication (MEMS) based technology. Thus, a range of potential launch vehicle fuels (hydrogen or hydrocarbons) and oxygen can be measured simultaneously [7]. The array is being incorporated with signal conditioning electronics, power, data storage, and telemetry. The final system will be self-contained with the surface area comparable to a postage stamp. Thus, this postage stamp sized “Lick and Stick” type gas sensor technology can enable a matrix of leak detection sensors placed throughout a region with minimal size and weight as well as with no power consumption from the vehicle. The sensors can detect a fuel leak from next generation vehicles, and combine that measurement with a determination of the oxygen concentration to ascertain if an explosive condition exists. The electronics hold calibration tables and sensor history with built-in test. They can be programmed to provide the user with certain information required on a regular basis, but much further diagnostic information when needed. Sensor outputs can be fed to a data processing station, enabling real-time visual images of leaks, and enhancing vehicle safety.

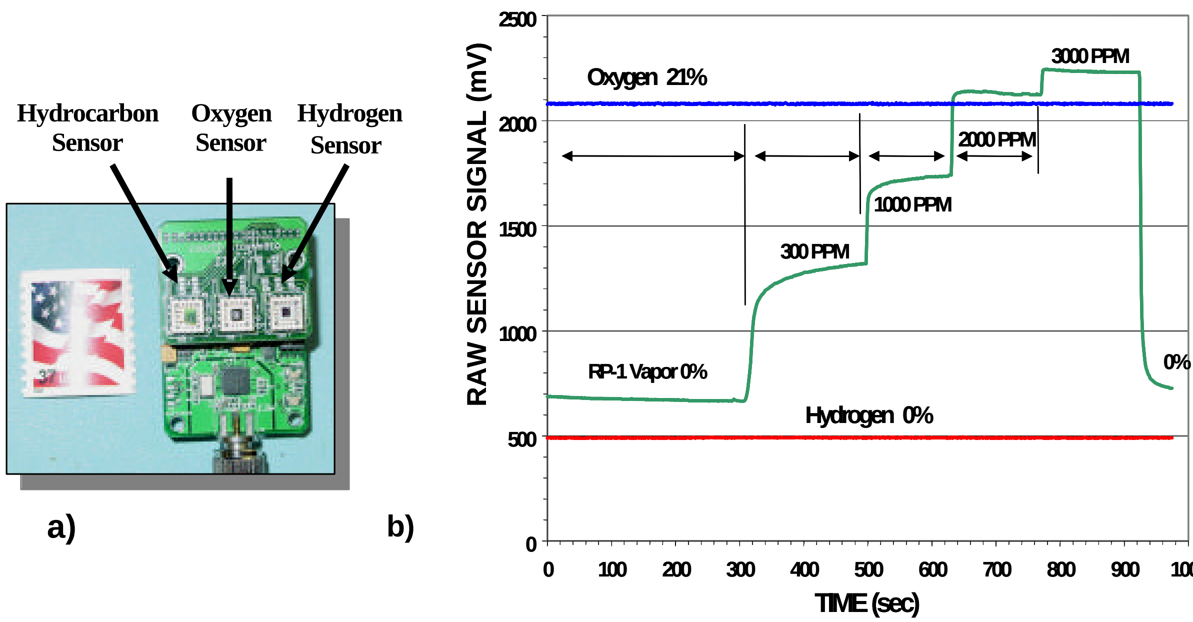


Figure 2a) A prototype version of a “Lick and Stick” leak sensor system with hydrogen, hydrocarbon, and oxygen detection capabilities combined with supporting electronics. b) Response of the three sensors of this system to a constant oxygen environment and varying hydrocarbon (RP-1) concentrations. The sensor signal shown is the output from the signal conditioning electronics which processes the measured sensor current at a constant voltage.

A prototype model of the “Lick and Stick” sensor system has been fabricated and is shown in Figure 2a. The complete system has signal conditioning electronics, power, data storage, and telemetry with hydrogen, hydrocarbon, and oxygen sensors. Figure 2b shows the operation of the electronics with the three sensor system simultaneously. The data highlights the response of the SiC-based gas sensor at various hydrocarbon fuel (RP-1) concentrations. The oxygen concentration is held constant at 21% and the hydrogen sensor signal shows no response, suggesting a lack of cross-sensitivity between the hydrogen and hydrocarbon sensors to the detection of this hydrocarbon. The hydrocarbon sensor is able to detect fuel concentrations from 300 ppm to 3000 ppm although lower concentrations are possible.

This example demonstrates the combination of multiple sensor types into a complete system giving more full-field information than would be available individually. The modular “Lick and Stick” approach allows sensors to be placed where they are needed without the addition of lead wires for power and communication. While further system development is still necessary, this is an example of a complete “Lick and Stick” smart, multi-parameter sensor microsystem that is usable wherever and whenever needed thus opening a range of monitoring applications.

Spray-On Sensors: Temperature Sensitive Paints

Advanced optical techniques enable interrogation of the status of an engine often in a non-intrusive manner. If optical access to the engine environment is available, a wide variety of information can be obtained: ranging from planar measurements giving full field information without disturbing the flow field to sensor measurements where components can be interrogated without the lead wires [8]. An example of optical technology enabling a user to “see” system conditions is the use of temperature sensitive paints [2]. A luminescent material is coated on an engine component and illuminated by a pulsed excitation light. The material will then emit light whose intensity drops at a known decay rate in response to the pulsed source. Depending on the material, the decay rate may vary with pressure, temperature, or both. Decay rates are acquired using gated imaging and delaying the gate times and widths accordingly to measure the decay time. The combined effect of these phosphors is to provide a temperature mapping distribution of a surface. In effect, each phosphor is its own miniature temperature sensor with an optical wireless transmission capability.

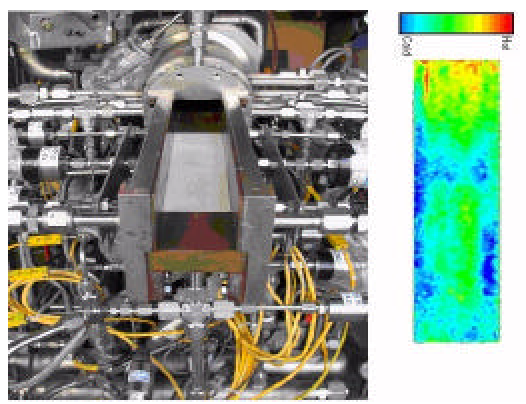


Figure 3. Rocket plume test rig and surface temperature distribution taken through rocket plume.

The world's first demonstration of a sprayable phosphor paint to measure full-surface temperature distributions through a rocket plume [9] shows the potential of “seeing” component conditions in engine environments (Figure 3). The floor of a square duct nozzle was painted with Temperature Sensitive Paint (TSP) and full-field lifetime decay measurements acquired for multiple firings of the rocket. Temperatures near the nozzle exit appear to have reached as high as 1100°C during some test conditions, based on paint degradation in that region. Good agreement with predicted results was obtained, matching temperature gradients along the length of the nozzle and clearly showing shock structures.

This technology demonstrates the ability to simply spray, in effect, a multitude of sensors on a surface and “see” the properties of the system in real-time. This ease of application makes it possible to include this type of sensor technology in a system where wiring would prohibit the inclusion of large of number of sensors. Further, implementation of this system on existing surfaces is significantly easier than implementation of a standard sensor transducer, such as wire thermocouples.

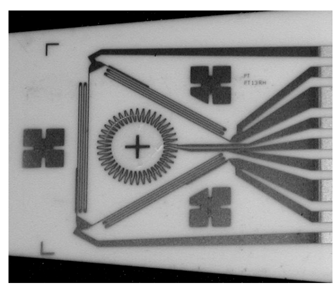
Thin Film Multifunctional Sensors

While physical measurements can be made in harsh environments by shielding the sensor or moving it to a more benign location, these approaches decrease the direct accuracy and increase the time response of the measurement. The objective for ISHM is to provide the most information possible on system conditions, even in the harshest environments, preferably with the sensor directly exposed to the environment being characterized or in intimate contact with the component to be monitored.

Progress has been made in developing physical sensors to operate in-situ in harsh environments. Thin film sensors that can provide accurate surface temperature, strain, and heat flux measurements have been developed to characterize advanced propulsion materials and components in hostile high-temperature environments. The advantages of the thin film sensors include intimate contact with the component, minimal addition of mass by the inclusion of the sensor, and minimal perturbation of the flow surrounding the component. Thin film thermocouples and strain gauges for the measurement of surface temperature and strain have been demonstrated on a number of materials. Thin film sensors have been tested in environments including air-breathing and space propulsion engines, as well as in burner rigs at surface temperatures up to 1100°C with high gas flow and pressure conditions [10].

Multiple thin film sensor technologies have been integrated into a single multifunctional gauge for the simultaneous real-time measurement of surface temperature, strain, heat flux, and potentially flow rate [11]. Figure 4 shows the design of this multifunctional sensor. Each element of the multifunctional sensor is fabricated in thin film form and has a thickness of less than a few microns. Different materials are used depending on the parameter to be measured e.g., platinum (Pt) and platinum-13% rhodium for temperature measurements and palladium chrome (PdCr) or Pt for strain measurements.

Figure 4. Multifunctional Sensor prototype which combines temperature, strain, heat, and possibly flow rate measurements in one sensor.



Various prototypes of the gauge have already been bench-tested for all of the parameters except flow rate. The gauge was tested for strain response in a Dynamic Load Test Rig. Measurements of both the static and dynamic response of the sensors were made and the strain magnitude was measured to an accuracy of within +10% of the nominal value. The strain angle was measured to an accuracy of within 1^{o} of the nominal value. The sensor reacted to heat flux as predicted when exposed to a heat flowing perpendicular to the sensor surface. Longitudinal flows over the sensor produced twice the response of transverse flows, demonstrating the feasibility of measuring flow. Thus, operation of the major components of this multifunctional system has been shown demonstrating the basic concept of an "all-in-one" physical parameter microsensor.

The basic idea of an "all-in-one" physical sensor is a technology that provides improved reliability, redundancy and cross-correlation, and orthogonality. The sensor's thin film nature allows integration into vehicle component surfaces without disruption of system operation while the sensor's small size allows redundant sensors to be placed around region. The multi-parameter measurements of temperature, strain, heat flux, and flow each tell something different about the environment, whereas cross-correlation of these measurements can improve confidence in each individual measurement increasing reliability. In principle, “all-in-one” sensor systems could be a core building block for a range of measurements: providing the ability to replace larger single parameter sensors with one providing much more information in a smaller size.

Orthogonal Fire Detection Sensor Systems:

The detection of fires on-board commercial aircraft as well as in environments such as the International Space Station (ISS) is extremely important for safety applications. Fire detection systems, e.g., existing cargo hold fire detection equipment, have been shown to be susceptible to false alarms [12]. A second, independent method of fire detection to complement the conventional smoke detection techniques, such as the measurement of chemical species indicative of a fire, will help reduce false alarms. Although many chemical species are fire indicators, two species of particular interest are carbon monoxide (CO) and carbon dioxide (CO_2). Further, miniaturization of the fire detection equipment, both chemical species and particulate detectors, will allow distribution of sensors at a wider variety of locations and improve early detection and location of a fire.

Development of miniaturized chemical sensor arrays and miniaturized particulate detectors has been on-going to provide a fire detection system that has a significantly lower false alarm rate. The chemical sensor array includes CO and CO_2 sensors as well as the ability to measure other species of interest such as hydrocarbons. The particulate detector has also been miniaturized and has the potential for particulate size classification. The objective is to microfabricate chemical sensor arrays and particulate detectors, integrate them with pattern recognition software and electronics, and demonstrate these systems in relevant fire environments.

A microsystem based fire detection system has been fabricated. The system, a Multifunctional, MultiParameter Fire Detection System (MMFDS), combines micro and nano based systems with signal processing hardware and software to interpret the data. The sensors include CO, CO_2 and particulate as well as relative humidity and hydrogen/hydrocarbons. Simplified fire detection algorithms were used with the MMFDS detection for this testing to show the basic system operation and the results with two algorithms are shown in Figure 5; more complete algorithms are available and can be tuned given knowledge of the application environment. This system has been tested for possible ISS applications and in a relevant aerospace environment in the cargo bay of aircraft at the Federal Aviation Administration (FAA).

The results of this comparative FAA testing are dramatic [12]. Over a series of exposures to both dust and humidity, the MMFDS had a zero false alarm rate. The commercial system had a 100% false alarm rate. Over the entire test series with real fires, the MMFDS sensed the onset of actual fire nearly equally as well as the conventional smoke detectors if not better, depending on how the MMFDS software was set. Figure 5 shows the response of all the sensors with two algorithms (simply listed as fast or slow) as well as the response of the commercial sensor. The standard FAA requirement for aircraft fire detectors in cargo bays is the detection within 1 minute. In all cases, the MMFDS system met the FAA standard of 1 minute. These tests demonstrate that the combination of these very different types of sensing technologies is significantly more effective in understanding a fire event than an individual technology alone.

These results show the significant advantages of using orthogonality to improve system reliability. The chemical sensors involved are designed to measure orthogonally with respect to each other (although there may be some cross-sensitivities) while the particulate detector is strongly orthogonal to the chemical sensors. The combination of the technologies has allowed drastic improvements in the reliable detection of fires without false alarms. It is suggested that this same approach of orthogonal, multi-parameter detection can be used to gain better understanding of the environment in a range of applications.

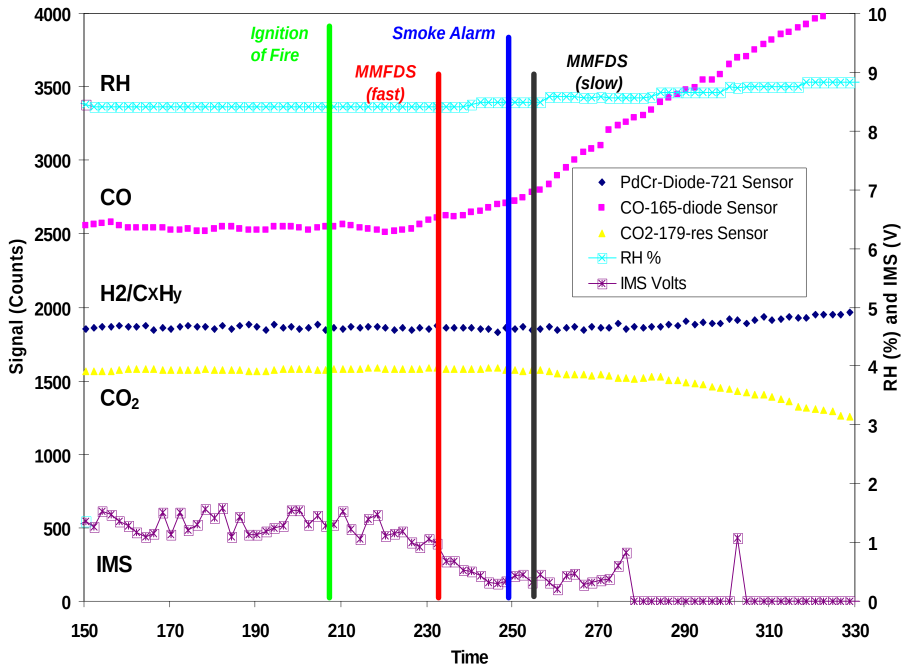


Figure 5. Response for Several Different Sensors Including both Chemical and Particulate Detection to the Ignition of a Resin Block. The time of ignition of the fire, detection of a fire by the commercial system, and detection of the fire by the MMFDS using two different algorithms are indicated. The MMFDS responds comparably to the commercial sensor and within the 1 minute limit set by the FAA.

SUPPORTING TECHNOLOGIES: HIGH TEMPERATURE ELECTRONICS EXAMPLE

The ability of a sensor system to operate in a given environment often depends as much on the technologies supporting the sensor element as the element itself. If the supporting technology cannot handle the application, then no matter how good the sensor is itself, the sensor system will fail. An example is high temperature environments where supporting technologies are often not capable of operation in engine conditions. Further, for every sensor going into an engine environment, i.e., for every new piece of hardware that improves the in-situ intelligence of the components, communication wires almost always must follow. The communication wires may be within or between parts, or from the engine to the controller. As more hardware is added, more wires, weight, complexity, and potential for unreliability is also introduced. Thus, in-situ processing of data and wireless communication would significantly improve the ability to include sensors into high temperature systems. In other words, smart sensors need high temperature electronics to make them viable in harsh environments. Presently, the choices in harsh environment electronics are limited and not mature.

Silicon carbide (SiC) presently appears to be the strongest candidate semiconductor for implementing high temperature electronics. Alternate electronic technologies are either physically incapable of functioning at this high temperature range (silicon and silicon-on-insulator), or are significantly less-developed (GaN, diamond, etc.). SiC is a mechanically strong material, inert, and a wide band-gap semiconductor capable of operation at temperature in excess of 600°C. However, the performance and operational lifetime of SiC-based transistors at 600 °C is not limited by the semiconductor itself, but instead is largely governed by the SiC crystal surface and the stability of various interfaces with SiC [13]. Further, problems with the quality of the oxide growth on SiC have led to difficulty in the application of the standard Metal-Oxide-Semiconductor Field Effect Transistors (MOSFET) technology on which the vast majority of semiconductor integrated circuit chips in use today in silicon rely.

For example, Figure 6 is an optical image of a SiC wafer showing two adjacent 200 μm mesas on which SiC epitaxial layers are grown. Mesa B on the right is affected by surface defects that commonly affect SiC materials with defect features dominating the surface morphology. Mesa A on the left is fabricated by new procedures that can produce atomically flat, step-free SiC surface and is featureless. The formation of SiC mesa surfaces as large as 0.2 x 0.2 mm completely free of a single atomic step has been reported [14]. Results have shown improved gas sensor performance using atomically flat SiC over standard commercial materials [15]. However, the sensor needs other technologies, like signal processing, for it to be a smart sensor.

The ability to form basic circuits that have unique properties from even flawed material has been demonstrated. The present state of the art is the fabrication and demonstration of the world's first metal-semiconductor field effect transistor (MESFET) that exhibited continuous, prolonged, stable electrical operation in a 500°C air environment [16]. This MESFET demonstrates a new ability to amplify an electrical signal at 500°C using a semiconductor transistor and is a key foundation for realizing useful circuits with sensing, intelligence, and wireless communications for high temperature environments. This MESFET relies on advances in processing technologies [16], contacts to the semiconductor [17], and packaging [18]. Efforts are under way to extend the operational temperature range of these devices, produce more complex circuits even with flawed material, and improve material quality.

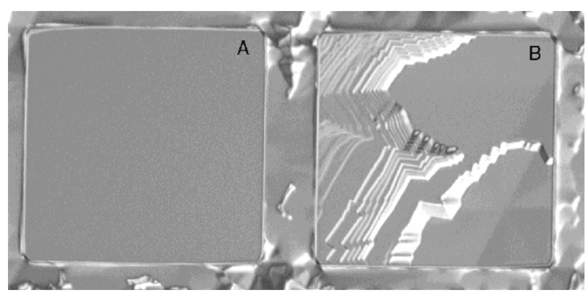


Figure 6. Optical Nomarski images of two adjacent 200 μm square mesas on a 4H-SiC wafer. Mesa A is step-free and mesa B contains a screw dislocation which provided a continuous source of steps during growth.

Thus, intelligent sensor systems for harsh environments require technology beyond the sensing elements. Material processing, fabrications techniques, device contacts, and packaging systems are just few examples of supporting technologies necessary for a complete system. Even without technical maturity in these areas, progress toward smart sensors and intelligent systems can be made (e.g. processing circuits with flawed materials). Nonetheless, the realization of intelligent systems requires parallel development in a wide range of technologies that are not directly related to the sensing elements and software.

TEST INSTRUMENTATION AND NDE

Consideration of ISHM measurements needs should be part of the life development of the system - including ground testing. Knowledge of the flight system should be obtained in development testing, i.e., long before flight. Development testing should include full field characterization and life testing of the system with data provided by test instrumentation and non-destructive evaluation (NDE). This information can be later used by the ISHM system to interpret the data provided by the sensor systems during system operation. Examples of these technologies that can contribute to Intelligent Sensors System and ISHM are NDE technologies such as Thermoelastic Stress Analysis (TSA), or Impedance-Based Structural Health Monitoring.

TSA is an NDE technique based on the fact that materials experience small temperature changes when compressed or expanded. When a structure is cyclically loaded (i.e., cyclically compressed and expanded), a surface temperature profile results, which correlates to the stress state of the structure's surface. The surface temperature variations resulting from a cyclic load are measured with an infrared camera. Traditionally, the temperature amplitude of a TSA signal was theoretically defined to be linearly dependent on the cyclic stress amplitude (i.e., the changing stress). As a result, the temperature amplitude resulting from an applied cyclic stress was assumed to be independent of the cyclic mean stress. [19]

Impedance-based ISHM uses piezoelectric (PZT: lead, zirconate, titarate) patches that are bonded onto or embedded in a structure. Each individual patch behaves as both an actuator of the surrounding structural area as well as a sensor of the structural response. The size of the excited area varies with the geometry and material composition of the structure. When a PZT material is subjected to an electric field it produces a mechanical strain, and when stressed it produces an electrical charge. For a PZT patch intimately bonded to a structure, driving the patch with a sinusoidal voltage sweep, for example, deforms and vibrates the structure. [20]

These NDE methods are examples of technology that allow better characterization of the vehicle system on the ground. Sensor data is harder to interpret without a history in test conditions of what that data implies. Thus, while some NDE systems may not fly with the vehicle, they form a strong basis for allowing the realization of an Intelligent Sensor System.

TRANSITION OF SENSOR SYSTEMS TO FLIGHT

Several areas of consideration are required to be addressed in order to transition developing sensor system from a low maturity level design to a certifiable product. Experience in such projects as the Integrated Vehicle Health Management (IVHM) Hardware Technology Demonstration 1 (HTD-1) and HTD-2 (flown in STS-95 and STS- 96 shuttle flights respectively) suggest the following.

The development of a full life-cycle plan for the product is fundamental. At a minimum, it is recommended that sufficient understanding of the different parts of this life-cycle is obtained by the team and issues identified at the early stage of the project. The first step in the process of sensor inclusion into a vehicle is the establishment of a team composed of the product developer (scientist, designer and/or engineer), the end-user (vehicle engineer, systems engineer, etc), and the flight vehicle or ground support equipment (GSE) responsible organization. This team will also include experts from safety, reliability, logistics, system integration and project management. The certification process starts with the development of a detailed set of requirements. These requirements should be jointly developed and approved by the team. It is critical to establish a detailed set of requirements very early in the process to avoid unnecessary delays and/or costly redesigns. Some elements of this requirement process are:

- Performance Considerations

Performance considerations are usually levied by the end-user. Specific parameters are identified and their tolerances defined up front that will drive the design of the product. Examples of performance parameters identified for a transducer being designed are linearity, repeatability, hysteresis, accuracy, measurement range, output range (full scale), output type (voltage, current, frequency, and digital) and power requirements. Other parameters are defined based on the environment the product will have to operate in. Performance drift over the environment temperature range is a good example of parameters to be considered during the development of the product.

- Physical Considerations

Physical considerations are usually levied by the flight vehicle responsible organization or program. Size, weight and volume have direct impact on the feasibility of the product to be integrated into the vehicle. Mechanical and electrical interface requirements are also a major issue to be considered up front. Most of these interfaces need to be designed to not only withstand the harsh environments in which they operate, but also provide an easy way to maintain and operate the product. For micro/nano-technologies, size, weight and volume are probably not the major concern. On the other hand, electrical and mechanical interfaces are of great importance. Connector selection and packaging design are a high priority in these cases.

- Environmental Considerations

Environmental considerations are usually set by the mission. These considerations change vastly depending on whether the product operates on the ground, low Earth orbit, deep space or planetary surfaces. Parameters to be considered are: vibration levels and duration, shock levels, Electromagnetic Interferences (EMI), humidity, corrosion, radiation, heat dissipation, etc. When products are to be deployed on the ground, main parameters to be considered relate to earth environment, such as vibration, shock, humidity, rust and corrosion. Factors such as radiation will be less important in this case. In products to be used in space, humidity and corrosion are not factors to be considered. Radiation becomes a major driver in the design. These considerations do change from low earth orbit (where total dose of radiation is not a major issue but Single Event Upset, or SEU, is) to deep space (where both total dose and SEU are considered). Thermal management is another factor that changes depending on the mission (from convection on Earth to conduction and heat radiation in space). These considerations will play a major role in the design cost and complexity and they need to be well understood up front.

- Safety and Reliability Considerations

Safety and reliability considerations are usually established by the end-user and the vehicle or ground support responsible organization. Environments where hazardous fluids are present require a different approach. Materials compatibility needs to be assessed early in the design to assure no adverse conditions are found. Intrinsically safe/explosion proof designs will be required where explosive environments are present. Integrated Hazards Analyses and Failure Modes and Effects analysis shall be performed to ensure safe, reliable and quality products for spaceflight certification.

The team should also establish the qualification process to be followed to certify the product. The above-identified requirements need to be matched to a verification process. Verification mechanisms include analysis, testing and demonstration. A documentation process also needs to be defined up front for the qualification process. Documentation is one of the most expensive and time consuming part of this type of process. Not only design, fabrication and testing documentation are generated during this process, but also integration, operation and maintenance documentation need to be provided. Depending on the program requirements, both a configuration control process and a logistic tracking process are also required. Finally, a quality control process should be established to monitor the design, fabrication, testing and integration of the product into the vehicle or ground system. Depending on the criticality assigned to the product and the system involved, the quality control process will be more or less complex.

FUTURE DIRECTIONS

The discussion above describes an approach to allow the design and fabrication of Intelligent Sensor Systems (ease of application, reliability, redundancy, cross-correlation, and orthogonality), examples which illustrate the use of these principles, the need for supporting technology, and steps leading to flight. This discussion was generally aimed toward Exploration applications but is relevant to all of aerospace systems where ISHM and sensor systems are applied. Overall, a change in the way sensor systems are developed and included into the vehicle is necessary. More complete vehicle system information as well as improved sensor reliability are necessary to enable future aerospace systems. The development of self-contained “smart” sensors or “Lick and Stick” technology is an important step toward allowing sensor systems to be fully integrated in the vehicle. Improved reliability can be obtained by tailoring sensor systems for the specific environment and by increasing the intelligence of the sensor system so the sensors themselves can be self monitoring and correcting. Further, measurements in harsh environments are necessary to fully assess the health and performance of the vehicle, therefore robust sensor technologies applicable to extreme environments must be investigated. Advancing these technology areas will expand the system information available for more complete, accurate health assessments required for ISHM.

However, technology developments may not be enough to ensure the inclusion of Intelligent Sensor Systems for ISHM. Historically, ISHM and sensor systems have been consistently ignored during the planning stage. Rather, it has been implemented later, incurring higher costs and less reliability by adding technology into a system which has not been originally designed with ISHM in mind. The approach an overall program takes to ISHM will have large role in assuring an ISHM system with Intelligent Sensor Systems meeting aerospace application needs. There are a series of system level steps which can ensure an appropriate ISHM system. These include:

- ISHM, including sensors systems, should be included in the vehicle in the design phase.
- Study the vehicle system to determine the operational function and criticality of various sensor systems and how to optimize cross functionalities.
- Instrument the vehicle system to allow measurements that enable damage/degradation prediction at a level to allow autonomous operation.
- Demonstrate sensor reliability and durability before inclusion of sensor systems in vehicle.
- Perform sensor measurements to optimize measurement of multiple parameters simultaneously to improve full-field system information and measurement reliability.
- Develop sensor systems which include integrated intelligence while minimizing size, weight, and power consumption.
- At minimum, Crit 1 systems, i.e. those whose function can affect loss of crew and/or vehicle, should be monitored irrespective of how extreme the inherent conditions are.

A long-term vision for an intelligent system is a system that is self-monitoring, self-correcting and repairing, and self-modifying. One approach is to build the system bottom-up from smart components. These smart components are independently self-monitoring, self-correcting, and self-modifying. Smart components can monitor and adapt their individual status to the mission objectives and local conditions. Information is communicated two-way to local nodes and the collection of these smart nodes encompasses the overall vehicle level operation. Each smart component has the capabilities to be, in a sense, self-aware. In biological terms, the smart component will know its environment (see, feel, hear and smell), think (process information), communicate, and adapt to the environment (move and self-reconfigure). Overall, the approach is self-aware components yielding a "self-aware" vehicle system. While like a biological system which will, in effect, "see, feel, hear, smell and think", the requirements for the components of an intelligent system are far beyond those of biological systems. The realization of such a vision depends not only on developing the technology to enable the vision but also on the sucessful application of the technology.

The realization of such a vision depends on developing a new family of sensing devices that emphasize reliability, autonomy, automation, reusability and reduced weight, power consumption, and physical size. Such a system will require significant advances in test instrumentation, sensors, electronics, nondestructive evaluation, and controls as well as communications, materials, structures. The use of microsystems is becoming mandatory, as is the integration over time of developing nanotechnology. The development of such Intelligent Sensor Systems, near and far term, is not just neat technology. Rather, given increasing budget restrictions and the ambition of the missions such as Exploration, we must implement technology smarter and smaller than we ever have before in order to be successful.

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