

Smart Sensor Demonstration Payload

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Sensors are a critical element to any monitoring, control, and evaluation processes such as those needed to support ground based testing for rocket engine test. Sensor applications involve tens to thousands of sensors; their reliable performance is critical to achieving overall system goals. Many figures of merit are used to describe and evaluate sensor characteristics; for example, sensitivity and linearity. In addition, sensor selection must satisfy many trade-offs among system engineering (SE) requirements to best integrate sensors into complex systems [1]. These SE trades include the familiar constraints of power, signal conditioning, cabling, reliability, and mass, and now include considerations such as spectrum allocation and interference for wireless sensors.

Our group at NASA's John C. Stennis Space Center (SSC) works in the broad area of integrated systems health management (ISHM). Core ISHM technologies include smart and intelligent sensors, anomaly detection, root cause analysis, prognosis, and interfaces to operators and other system elements [2]. Sensor technologies are the base fabric that feed data and health information to higher layers. Cost-effective operation of the complement of test stands benefits from technologies and methodologies that contribute to reductions in labor costs, improvements in efficiency, reductions in turn-around times, improved reliability, and other measures. ISHM is an active area of development at SSC because it offers the potential to achieve many of those operational goals [3-5].

MLAS: Max Launch Abort System

NASA's Constellation Program sought to develop a new generation of rockets as part of plans to replace the Shuttle Transportation System (STS). The Ares-I is designed to insert crews into orbit in the Orion capsule similar to the architecture of the Apollo program. Ares-V is a heavy lift vehicle to loft large payloads such as exploration vehicles or large scientific instruments. Ares-I included a requirement for a launch escape system (LES) that would

provide the means for crew escape from on-pad to near orbit. The nominal Ares-I LES was to be a tower-based separation system similar to the Apollo escape system designed by Maxime (Max) Faget and Andre Meyer [6]. The LES was deemed so important that two alternative designs were also investigated: the alternate launch abort system (ALAS) and the Max launch abort system (MLAS) [7-8]. The MLAS approach is based on a fairing over the capsule with integral rocket motors instead of the tower mounted motors used in the Apollo LES. Fig. 1 shows the MLAS flight test vehicle stacked on the launch stool at Wallops Flight Facility.



Fig. 1. MLAS flight vehicle stack.

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In addition to the primary flight objectives to prove the aerodynamic stability of the LES concept, the MLAS project also included opportunities for technology demonstration payloads. Our group proposed a smart and intelligent payload (SiSP) project to advance the technology readiness level (TRL) of several sensor technologies [9]; due to MLAS project timeline constraints, SiSP was approved for ground operations associated with the MLAS launch with the possibility of a future flight opportunity.

SiSP Project Objectives and Embodiment

The SiSP project sought to demonstrate a suite of sensor and sensor system advances including:

- (1) Smart sensors. Demonstrate sensor technologies that adhere to defined standards.
- (2) Advanced commercial off the shelf (COTS) data acquisition system. Demonstrate the use of flexible COTS data acquisition architectures to make redundant (and other) ground based sensor (GBS) measurements.
- (3) RFID. Integrate radio frequency identification (RFID) technology for tracking system elements and to link to transducer electronic data sheets (TEDS).
- (4) PoE. Use power over Ethernet (PoE) to provide subsystem power.
- (5) Wireless sensors. Employ wireless sensor technologies.
- (6) Intelligent sensors. Incorporate intelligent sensors with embedded health assessment.
- (7) Other sensor-related opportunities as time and budget permitted.

Smart Sensors

Objective: Incorporate smart sensors adhering to defined standards to reduce SE and maintenance costs.

Rationale: Methods are needed that offer “plug-and-play” to support automatic configuration of a data acquisition system to recognize the collection of sensors present as well as to allow simple reconfiguration when sensors are replaced. IEEE 1451.x standards define various “Smart Transducers and Actuators” and associated logical function and physical interface definitions that can contribute to achieving the goal of “plug-and-play” sensor technologies [10-11].

One of the most immediately useful elements defined in the standards is the Transducer Electronic Data Sheet (TEDS). IEEE 1451.4 defines TEDS data structures for storing and sharing basic sensor information including manufacturer, model, calibration status, calibration coefficients, etc. Systems with TEDS-enabled sensors can be rapidly configured and easily updated as sensors are exchanged for maintenance actions. The use of TEDS helps minimize configuration errors made during repetitive sensor database updates. IEEE 1451.4 provides detailed

TEDS templates for commonly encountered sensors including the bridge (pressure), accelerometer, and thermocouples used by SiSP, as well as the thermistors used as part of the MLAS GBS measurements.

IEEE 1451.0 and 1451.1 address network centric sensor capabilities. The network capable application processor (NCAP) supports many plug-and-play functions including sensor discovery and data exchange with a publish-subscribe approach. One advantage of a shared data acquisition system typical of legacy systems is shared timing and voltage references. Disadvantages include the reliability risks of a single system and the increased cabling costs due to all sensors having to be routed to a single point. Advantages of a distributed smart sensor are reduced risk of failure due to distributed functionality and minimization of cabling if a bus topology is used. Disadvantages include timing uncertainty and the need for redundant elements such as voltage references for each sensor.

Embodiment: A tri-axial accelerometer (PCB Piezotronics, TLD 356A16) containing integral IEEE 1451.4 TEDS was incorporated. Fig. 2 shows the 3-axis accelerometer. Signal conditioning/acquisition functions and TEDS reader capability were provided by the NI 9234 IEPE module (see below). IEEE 1451.1 NCAP functionality was implemented using an ARM-based microcontroller to communicate with internal and external elements.



Fig. 2. 3-axis accelerometer with TEDS.

COTS Data Acquisition System

Objective: Employ a small reconfigurable commercial off the shelf (COTS) data acquisition system to make redundant GBS and other measurements.

Rationale: The CompactRIO (C-RIO) chassis is a field programmable gate array (FPGA) based system that offers a low power (< 25W fully populated) chassis that supports up to eight signal conditioning modules [12]. Software is developed using the LabVIEW graphical programming environment; resulting code is downloaded to the FPGAs. The result is a rapid development environment. Our group’s experience with the C-RIO hardware and software suggested it as the way to acquire redundant IOP measurements and to make additional thermal, acoustic and accelerometer measurements.

Embodiment: An 8-slot C-RIO system was used; Table 1 summarizes the mapping between conventional sensor and signal conditioning module.

Table 1. SiSP CompactRIO data acquisition functions.

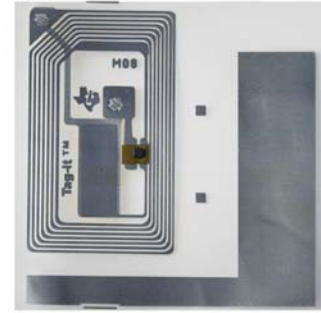
Module	Chan. Count	Samples/s (sps), Size	Measurement Function
Bridge NI 9237	4	1.6k – 51.2k	Ignition Over Pressure
Digital IO NI 9203	32	0 – 100k	T-600, T0 Triggers IRIG-B DC
IEPE Analog Input NI 9234	4	1.6k – 51.2k	Accelerometer Microphone
TC, Type K NI 9211	4	0 – 14	Internal Temperature
Universal Analog Input NI 9219	4	2 – 100	Radiometers, Battery Voltage
SD Memory Card NI 9802	2	2 GB per slot	Data storage

RFID Tags

Objective: Integrate radio frequency identification (RFID) technology for tracking system elements and to link to transducer electronic data sheets (TEDS).

Rationale: The benefits of TEDS functionality are out of reach of systems composed of conventional sensors unless some means of retrofitting TEDS is available. The standard makes provision for a virtual TEDS (VTEDS) by allowing a keyed lookup into a database where the TEDS information is stored. Radio frequency identification (RFID) tags offer one means of retrofitting TEDS to legacy sensors. Simple passive RFID tags contain a 128-bit memory with a unique code value. A reader excites the RFID tag with RF energy sufficient to power the device in order to transmit its code to the reader. The unique RFID tag is then used as the key for a database search to find the associated VTEDS. IEEE 1451.7 is a recently approved standard that incorporates RFID into the smart sensor framework. Another application for RFID in a system is for subsystem identification. This offers a means to validate system builds to confirm that all the elements have been qualified for flight.

Embodiment: Medium frequency, 13.56 MHz, RFID tags (Texas Instruments, RI-I03-112A-03) were used for VTEDS and inventory control. These tags have an additional 2048-bit user memory to allow future upgrades to local TEDS storage in the RFID tag. Fig. 3 shows a typical passive RFID tag.

**Fig. 3.** Passive RFID tag.**Shared Signal and Power Cabling**

Objective: Provide power using network cabling.

Rationale: Cabling and interconnections for wired applications represents high costs as measured by mass, volume, electromagnetic interference (EMI) susceptibility, etc. Ways to reduce cabling and connector mass could prove beneficial in many aerospace applications. IEEE 802.3af defines Power over Ethernet (PoE). Up to 12.95 W of dc power at approximately 48 Vdc is available to a powered device. Power sourcing equipment can source up to 15.4 W. Table 2 summarizes the power levels available at a device.

Table 2. IEEE 802.3af power levels.

Class	Maximum Power at Device, Watts
0	0.44 – 12.95
1	0.44 – 3.84
2	3.84 – 6.49
3	6.49 – 12.95
4	(Reserved)

A recently approved extension, IEEE 802.3at-2009 extends the available power up to 25W for a powered device.

Embodiment: PoE was used to power the C-RIO data acquisition system and two external sensors: (1) an intelligent sensor located at the base of the launch stool, and (2) a wireless sensor node. PoE injectors were contained within the SiSP package.

Wireless Sensors

Objective: Employ wireless sensors.

Rationale: Wireless communication offers the means to reduce cable mass. There are many wireless communication standards in widespread use such as IEEE 802.11 (WiFi), IEEE 802.15.1 (Bluetooth®), and IEEE 802.15.4 (ZigBee®). Some of the considerations affecting the possible use and choice of wireless sensors include distance, interference with other Rf devices, signaling rate, and power consumption. The importance of each of these factors is highly dependent on application; for example,

applications such as a quick turn monitoring problem may not be concerned about power consumption.

Embodiment. The original plan was to monitor one channel of ignition over pressure using a Zigbee® wireless smart sensor MOBEE (Mobotrium Corp.). Because the 1 sps sampling rate was too low for dynamic pressure measurements, the wireless sensor was applied to the much lower bandwidth requirements of tracking ambient temperature. A frequency utilization request was submitted—and permission obtained—for this low-power RF application. Redundant launch stool temperature measurements were made in the days prior to launch. Fig. 4 shows the 4-channel wireless sensor.

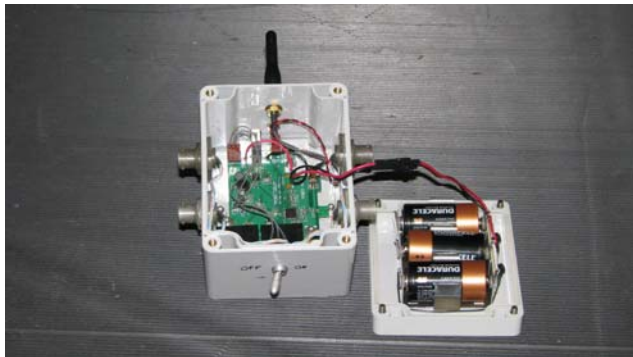


Fig. 4. Wireless sensor.

Intelligent Sensors

Objective: Use intelligent sensors with embedded health assessment.

Rationale: Further system benefits can be achieved if smart sensors can perform additional assessment tasks. In addition to converting raw data into final engineering units, such “intelligent sensors” can also perform data validity checks and other functions that reduce processing overhead at a central monitoring station. The availability of smart sensors with sufficient computing capability to implement NCAP functions makes it possible to embed those additional algorithms to make the smart sensor intelligent.

Embodiment: We had previously collaborated with a group at Kennedy Space Center (KSC) who had developed a smart networked element (SNE) [13]. In addition to supporting the IEEE 1451.1 protocol, the SNE implemented a number of health detection routines. A KSC SNE was modified to support ignition over pressure measurements and was installed at the base of the launch stool. Fig. 5 shows an unpackaged SNE.



Fig. 5. Intelligent Sensor (SNE).

Other Opportunities

Objective: Identify and incorporate other related sensor technology elements as time and budget permit.

Rationale: Ways are needed to address the new challenges posed by distributed sensors including timing and data acquisition accuracy. The timing problem arises from asynchronous sampling; techniques are needed to ensure that all samples can be accurately time aligned. IEEE 1588 defines methods for achieving time synchronization across a network that supports multicast messaging. Using the IEEE 1588 protocol, timing jitter between network nodes can be kept below one microsecond. This technique provides orders of magnitude improvement over legacy IRIG-B timing.

Embodiment: We investigated the use of IEEE 1588 in the lab, but decided to postpone 1588 integration due to resource constraints. IRIG-B was available at the launch pad and was used since all other launch systems also were based on IRIG-B.

SiSP Implementation

The SiSP development approach adopted the MLAS Resident Engineer model; two early-career SSC engineers were tapped as the electrical (A. Bracey) and mechanical leads (S. Rawls). They were supported by senior NASA personnel and a contractor team. The project started in 2Q 2008 and was to be completed by 3Q 2008 in keeping with the original MLAS flight schedule. Rapid prototyping approaches were used where possible including use of 3-d ABS printing for custom housing fabrication (Fig. 6.); panels and chassis elements were fabricated using an abrasive water jet (AWJ).

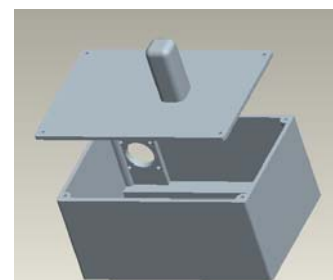


Fig. 6. 3-d solids model of sensor housing for fabrication using ABS printer.

Software development costs were manageable due to the availability and reuse of significant portions of code for data acquisition and smart/intelligent sensor support from prior projects.

Fig. 7 depicts the block diagram of the SiSP. Ethernet (802.3af) provides the communication core of the system. Onboard power is available from a primary cell; however, an external power supply was used to power the system due to launch pad safety considerations that required remote control of all power sources during motor arming procedures.

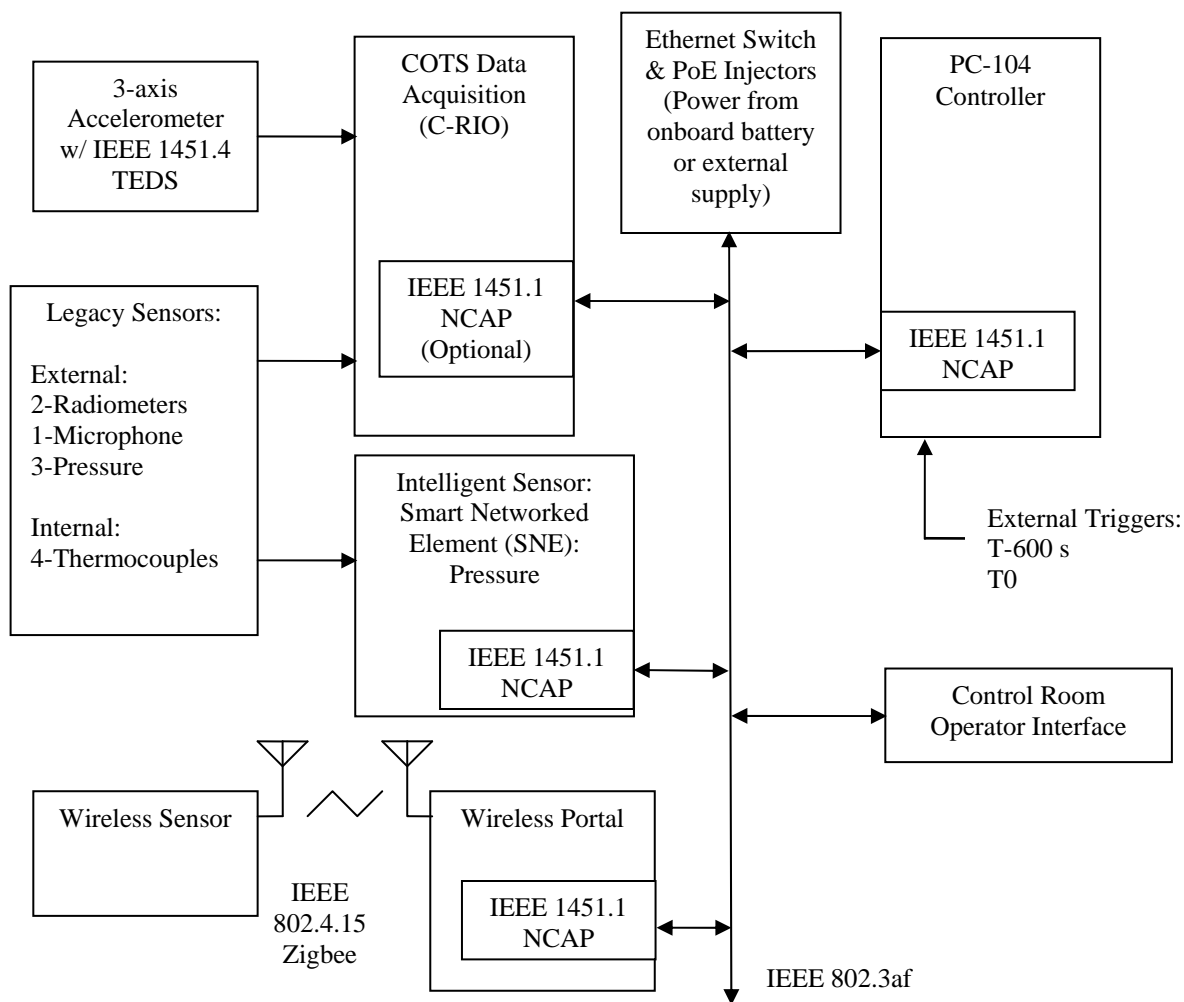


Fig. 7. SiSP block diagram showing major elements.

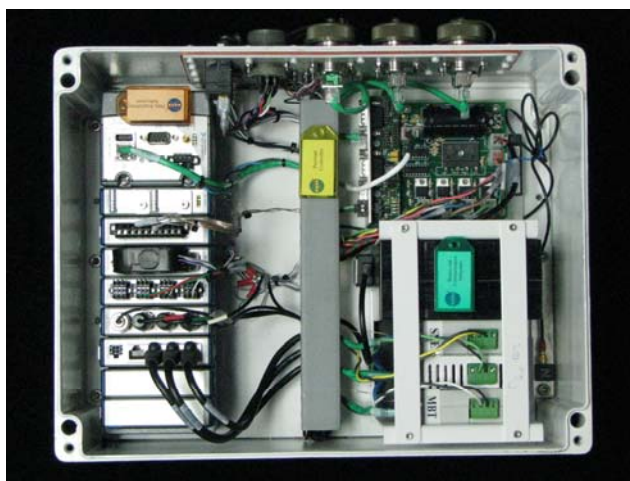


Fig. 8. The completed SiSP.

Controller

SiSP required an onboard controller to perform a number of functions including power sequencing, data storage, and communication with a remote control room computer. Fig. 9 depicts the state diagram for the controller. Every state provides a path to the advance to shutdown (ATSD) state to inert the system, which requires manual reset to override. The power up sequence was initiated by a T-600 s trigger received from the launch pad ground support equipment (GSE). The system could be placed into a hold state to accommodate anticipated launch delays. The GSE T0 trigger initiating MLAS motor ignition was used to start the data acquisition process, which continued for 10 s before entering the ATSD state.

Prior to shipment to WFF, a flight readiness review (FRR) was held at SSC. The only issues outstanding were final integration into the WFF GSE; the project was given the green light to proceed to launch test.

switching, GSE triggers, network access, and IRIG-B timing. A strict network access policy was enforced to ensure security; the control room computer was provided to our project team, which meant that some last-minute software modifications were needed to work around network and operating system features that were different from the baseline development platform.

The SiSP package was placed between the Connex and the launch pad behind a blast barrier. Wiring extended through conduit to the center of the launch stool and then was distributed to the collection of sensors. Four pressure transducers were mounted on the launch stool to make IOP measurements, two radiometers were attached to the blast wall, and a microphone was collocated with one of Marshall Space Flight Center's acoustic measurement positions.

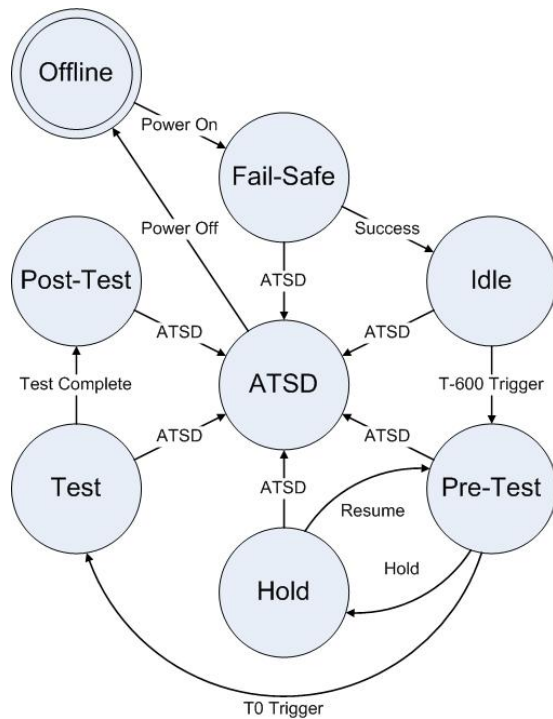


Fig. 9. Controller state diagram.

Launch System Integration

Fig. 10 shows how the SiSP was integrated into the Wallops Island GSE. A Connex shipping container located near the launch pad provided remotely controlled power

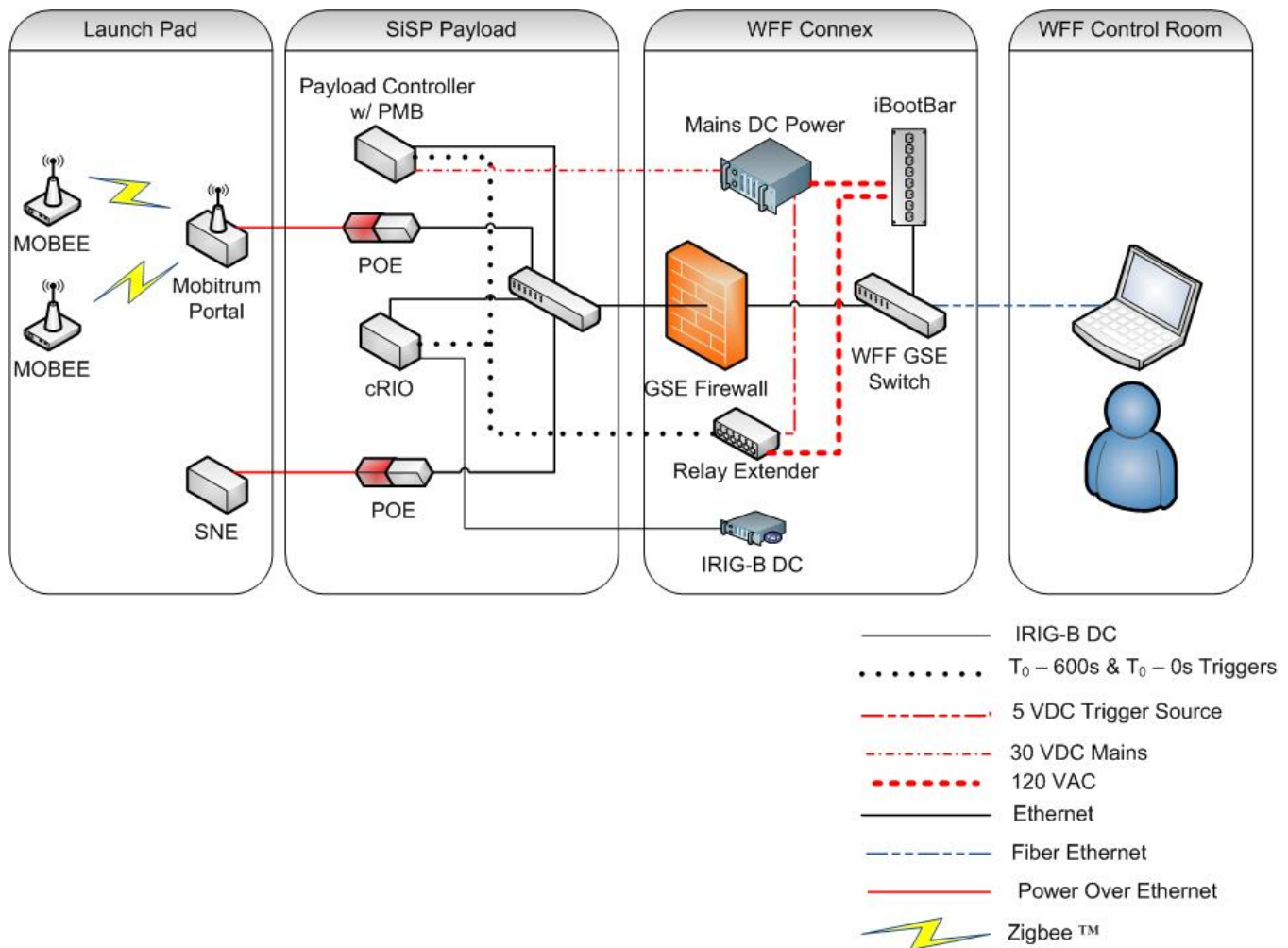


Fig. 10. Integration of SiSP with Wallops Island ground support equipment.

Results

Launch

MLAS was launched on July 8, 2009 early in the morning. See [14] for a video of the launch. Power flight lasted approximately seven seconds followed by a series of spectacular parachute deployments. For SiSP, the first seconds were all that were recorded.

Post-Launch Review

SiSP performed nominally. Fig. 11 shows one example of the data taken from the launch event, which is a plot of thermal data obtained from the blast walls. The signal is lost at the 1.5 s mark due to blast impingement on the sensors and interconnect wiring. Loss of wiring was significant as shown in Fig. 12.

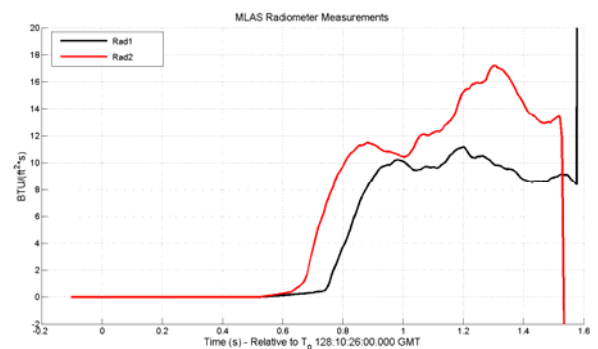


Fig. 11. Radiometer measurements from blast wall.



Fig. 12. Wiring damage, post launch.

Review of the data that resulted from the SiSP experiment shows that it achieved the majority of the important objectives.

1. Sensor standards (e.g., IEEE STD 1451.1/4) provide the ability to simplify sensor installation and maintenance moving toward plug-and-play capability. In particular, TEDS provides key benefits that reduce labor and risks associated with configuration. SiSP showed that RFID technology is a cost-effective method of retrofitting virtual TEDS capability into existing systems with conventional sensors. RFID also offers a simple means for configuration management.
2. The advantage of a flexible COTS data acquisition system has been demonstrated by the ease with which core SiSP data acquisition functions were implemented including the ability to directly connect IEEE STD 1451.4 sensors. The utility of this approach has been demonstrated in other follow-on applications that used instances of the technologies demonstrated by SiSP.
3. Power over Ethernet (PoE) can be used to simplify interconnects. The range of power supported by IEEE STD 802.3af/at covers useful subsystem functions. Development efforts should also be directed at supporting even more flexibility such as adding lower power classes of operation (< 0.44 W) to accommodate evolution in low power smart and intelligent sensor technology.
4. Wireless sensor elements show promise as a means for reducing interconnect. However, wireless sensor node power budgets must support the application requirements as measured by total lifetime of batteries traded against the sampling rates achievable by the sensor. The spectrum used for wireless is used by many other applications so will continue to become more crowded with attendant interference and security issues.

5. Intelligent sensors show promise. A smart sensor combined with health detection algorithms offers future systems data and health measures to help identify failing sensors. Distributed sensors can also contribute to decentralizing monitoring and control functions.

Future Work

The lessons learned from SiSP suggest a number of follow-on actions. Several of the most important are:

1. Flight opportunity. MLAS was unique in that there were few mass constraints—the capsule simulator was approximately 25,000 kg, so the SiSP at 20 kg was inconsequential. However, that is not the norm: a high premium is placed on low mass, small volume, and low power. Advancing the complement of SiSP sensor technologies to TRL8 and beyond requires significant redesign to achieve a flight-ready payload. Flight opportunities should be sought to continue this advancement.
2. Sensor standards. IEEE 1451.4 is well-defined and simple enough to have found commercial adoption; however, that is not the case for IEEE 1451.1 as one example. Efforts to update 1451.1 are underway [15]; this should allow simpler implementations of networked sensors that better meet the goal of plug-and-play sensor architectures.
3. Sensor networks. Optimization of sensor networks will require changes in power management—e.g., network standards that support low-power nodes, and ways to handle distributed timing.

Finally, this project showed that a focused team could be assembled to accomplish a significant project in a relatively short time. The vertical experience model was also shown to be an important way to not only accomplish the project goals but serve as an effective means to convey experience and values to the engineers who will be the vanguard of the next exploration frontiers.

Acknowledgements

A year ago (as of this writing), the SiSP field team was swatting mosquitoes on Wallops Island during the final week of installation and checkout. The project could never have gotten to that point without the leadership of the NESC, the support of the NASA-SSC Innovative Partnerships Program, the NASA-HQ Technical Excellence Initiative Program, and the many contributing NASA centers. L. Langford and W. Mitchell provided continuing systems engineering and technical support. P. Mease (Rowan University) fabricated our AWJ parts. All are gratefully acknowledged.

For Further Reading

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