Wireless Sensors in Space – Three Families of Wireless Capability

A. Aaron Trott[1], B. Kevin Champaigne[2]
1: Invocon, Inc., 19221 IH-45S, Ste 530, Conroe, TX 77385, USA, 281-292-9903, atrott@invocon.com
2: champaigne@invocon.com

Abstract: The capability of wireless sensing technology is increasing rapidly. Three families of wireless sensors are presented with their advantages and trade-offs as well as the unique challenges that are considered for their associated applications. Key design parameters include power consumption, unit size, sensor interfaces, processing power, telemetry capability, and synchronization.

Keywords: Wireless Sensors, Space, Telemetry, Synchronization, Smart Sensors

1. Introduction

Demand for wireless sensing technology is increasing rapidly as engineers and scientists continue to discover the myriad of advantages these systems provide for the testing and monitoring of structures. As demand for these devices increases, their capabilities are also growing, further expanding their application to real-world problems. Aerospace applications in particular can benefit from the advantages that wireless sensors offer.

Three families of wireless sensors are presented herein along with their advantages and trade-offs as well as the unique challenges that are considered for their associated applications. The Wireless Instrumentation System (WIS) family of devices is highly capable instrumentation able to gather large amounts of high-resolution data indefinitely under changing RF conditions. Multiple WIS units are currently distributed throughout the International Space Station for acquiring structural dynamics measurements and will soon monitor the micro-gravity environment of the experiment racks. The Wing Leading Edge (WLE) System is a member of the Micro-Wireless Instrumentation family of instrumentation systems that comprises small, low-power data acquisition units capable of processing raw data in order to reduce transmit bandwidth requirements. Forty-four units are being installed in the wings of each Space Shuttle for monitoring the critical wing surfaces for impact events similar to the one that caused the Columbia disaster. The Distributed Impact Detection System (DIDS) is a next generation system composed of small and ultra low power devices designed for long-term health monitoring of aerospace vehicles. This system is currently under development as part of NASA's new Exploration Program.

2. Application Descriptions

Each of the three families of wireless data acquisition systems discussed herein is designed for a different category of requirements. A brief description of these requirements is presented in order to clarify the results of the trade studies described later.

2.1 Wireless Instrumentation System

There are currently four applications for the Wireless Instrumentation System: Shuttle WIS (SWIS), Internal WIS (IWIS), Microgravity Measurement Apparatus (MMA), and External WIS (EWIS). Requirements that are common among these applications include high-resolution data, low to moderate sample rate, moderate data transmission rate and distance, automated network configuration, tight synchronization, and extended power-on time. These applications include permanent installations of the equipment inside and outside the International Space Station (ISS). They also include systems that are more easily repositioned to enable multiple temporary installations of the equipment on both the ISS and the Space Shuttle. Figure 1 shows an IWIS node installed in the US Lab Module of the ISS.

These systems incorporate a modular design, where various sensor interfaces can be provided for a given installation. Sensor interfaces for space applications have included accelerometers, strain gauges, and RTD temperature sensors. Additionally, temperature is always gathered as a secondary parameter for temperature compensation of the accelerometers and strain gauges

.

Figure 1 : WIS Installation in ISS Module (NASA Photo)

2.2 Wideband MicroTAU

The Wideband Micro-miniature Tri-axial Accelerometer Unit (WB MicroTAU) family of sensors currently comprises five separate systems: Shuttle Flowliner Instrumentation, Environment Control and Life Support System (ECLSS) Instrumentation, Wing Leading Edge (WLE) Impact Detection, Ultrasonic Leak Detection (UltraWIS), and Shuttle Arm Wireless Strain Gauge Instrumentation System (WSGIS). Requirements that are common among these systems are small size, long life using battery power, on-board data processing, and synchronization. These applications include monitoring various components of the Space Shuttle in order to verify models for life extension on parts, monitoring Shuttle systems to determine cause of excessive aging, detecting impacts on the leading edge of the Shuttle's wing, and the ultrasonic triangulation of leaks in the hull of the ISS. Figure 2 shows a crack discovered in the Space Shuttle Main Engine (SSME) flowliners, which supply liquid hydrogen and oxygen to the engines. Wideband MicroTAU is being used to monitor the vibration environment during launch in order to prove the hypothesis that the cracking is caused by high cycle fatigue [2].

Figure 2: Crack in SSME Flowliner Prompting the use of WideBand MicroTAU (NASA Photo)

The primary parameters of interest with this family are acceleration, strain, and ultrasonic energy. Secondary parameters include temperature (for temperature compensation of primary parameters) and ultrasonic surface acoustic emissions for impact-triggered wake-up and determining impact proximity.

2.3 Distributed Impact Detection System (DIDS)

In many ways, the DIDS application is similar to the Wing Leading Edge application. However, the power efficiency of the system has been increased considerably. In addition to power efficiency, requirements include synchronization, high sample rate, small size, and on-board data processing. The primary parameters of interest for DIDS are acceleration and acoustic emissions.

3. Trade Studies

Each application has unique requirements that are not always directly related to the primary parameters to be measured. This is particularly true for structural monitoring applications when power is limited and wiring is impractical or impossible. Requirements that must be evaluated include power consumption, size, sensor interfaces, processing capability, telemetry characteristics, and synchronization. For many applications, these requirements are tightly coupled to each other. Each of these requirements is discussed below.

3.1 Power Consumption

As with most electronic devices, capability is directly proportional to power consumption. For ultra low-power devices, this is a critical trade-off that must take into account operational lifetime, unit size, functionality, and cost. Each family of wireless sensor considered here is designed to consume substantially less power than its predecessor. This is possible for several reasons including a more widely distributed topology of sensor nodes, lower power data transmission, simpler networking protocols, and significantly improved methodologies.

WIS: The WIS family has the highest power consumption of the three families. However, size and weight are not as critical for this family as for the others, therefore larger battery packs can be used. Additionally, two of the four WIS systems use prime power on the ISS, so issues related to battery servicing are eliminated.

The features that drive higher power consumption for WIS are greater wireless transmission distances, higher wireless transmission rates, more sophisticated networking protocols, duration of data acquisition events, and higher accuracy and resolution measurements.

IWIS is used to monitor gather modal data from the Space Station. Due to the size and configuration of the ISS, the wireless nodes must communicate among themselves in a dynamic environment. The network protocol enables the system to continually calculate and update the best communication paths for commands and information. However, this sophistication also leads to greater bandwidth requirements due to higher overhead.

The MMA system is installed in the Japanese Experiment Module (JEM) in order to measure the microgravity environment of the experiments being conducted. This will help researchers validate their results and explain any anomalies that occur due to variations in the microgravity environment of the JEM due to bumping the experiment racks, repositioning the ISS, or other phenomena. Since the experiments must be monitored continually in order to be properly validated, the MMA system must be able to gather and transmit its data continually from multiple nodes to an on-board computer where it can be stored permanently and analyzed. This requires that the telemetry bandwidth be capable of high-speed transmissions which, in turn, increase the power requirements.

The WIS family uses very high precision and high reliability accelerometers to insure micro-g resolution and stable operation over long periods of time. These transducers require ±13 Volts to operate correctly. For low-power instrumentation systems, this is a significant portion of the power budget.

<u>Wideband MicroTAU</u>: The Wideband MicroTAU systems have substantially reduced the per-node power requirement when compared with WIS. This is due to more thoroughly distributing the nodes across the application platform, and the ability to reduce or eliminate some of the most power-hungry capabilities. It must be noted that some of the requirements for these systems are much more stringent than for WIS. For example, WIS is sampled at 1.2 kHz, but the sample rate for the Wing Leading Edge system is 20kHz and for UltraWIS it is 100kHz since they are gathering impact data and acoustic data respectively [1].

Because one of the goals for the WLE system is to minimize the load on each individual sensor unit, there are 22 data acquisition nodes placed in each wing. This decreases the number of transducers that are connected to each sensor unit and decreases the amount of signal conditioning and processing required per unit. This, in turn, minimized the power requirements per unit (See Figure 3).

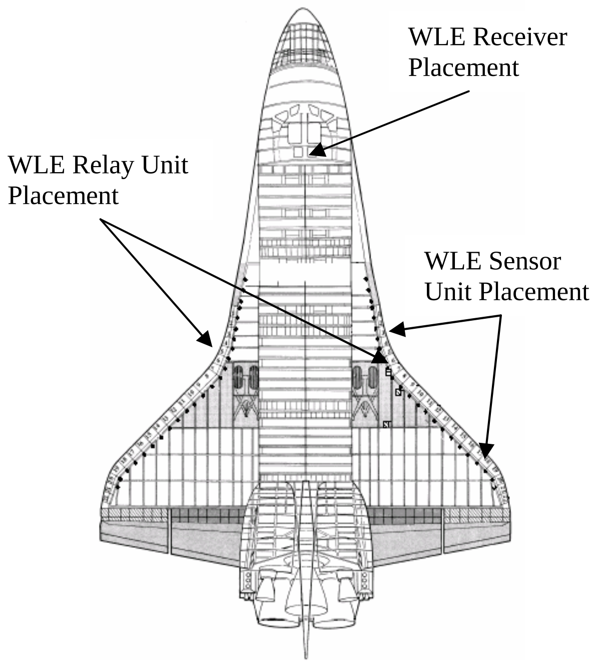


Figure 3 : Distribution of WLE Sensors in Shuttle

The transmission distance for this family is shorter due to the tighter quarters in which they are used. This saves power by decreasing the transmit power as well as minimizing overhead by simplifying communication protocols.

Since these systems are typically used only during specific windows in a mission profile, the total capacity of their batteries can be smaller than those used in the WIS system. As will be discussed later, this is controlled through aggressive power control and sophisticated triggering methods.

The final requirement enabling these devices to be used at lower power is the resolution of the data. Micro-g resolution is a requirement for the WIS systems, but milli-g resolution is appropriate for WLE and its siblings. This enabled the designers to use transducers with much lower power consumption.

<u>DIDS</u>: The design goal for the Distributed Impact Detection System is to produce a system much like the Wing Leading Edge system that is able to maintain a triggering state using almost zero power. This will dramatically increase its operational lifetime using an even smaller power source.

The power savings for DIDS comes from operating the system in a fundamentally different mode than the previously discussed systems. The Wideband MicroTAU system operates by sampling at its full system speed during pre-event trigger mode as well as post trigger data acquisition mode. This enables the system to report pre-trigger information as well as any events of interest. Although this enables the collection of very good data sequences, it consumes power that serves no long-term purpose beyond high reliability triggering.

DIDS solves this problem by using the energy generated in the transducer during significant events to wake up the system. Through the use of ultra fast circuitry, the system is able to remain in a sleep state until it is triggered. It then wakes up and captures all of the significant data produced by the event within 2 microseconds of the threshold crossing. Only pre-trigger ambient data is not captured. Since only the event is desired, this loss is truly insignificant.

3.2 Unit Size

Size is another critical property of these systems. As with power consumption, size decreases with each subsequent family discussed here for many of the same reasons. The early WIS system includes nodes with a volume of approximately 2200 cubic centimeters and 2.3 kg each. This is decreased to 220 cubic centimeters and 0.23 kg for the WLE system. The migration to the DIDS will focus on decreasing power requirements and the integration of multiple functions on a single integrated circuit, potentially allowing for another order of magnitude size improvement. Figure 4 shows the relative size between a WIS Remote Sensor Units (RSU) and a Wideband MicroTAU sensor unit. The Wideband MicroTAU unit is an order of magnitude smaller than the RSU.

Figure 4 : Size Comparison between WIS and WideBand MicroTAU

WIS: The size constraints for the WIS systems are much more relaxed than for the other families discussed. In the case of EWIS, the size has actually grown in order to accommodate EVA connectors. However, earlier versions of WIS were shrunk to the smallest possible size for their functionality. One of the biggest factors determining size is the battery pack which is 298 cm^3; this is larger than an entire WLE node.

Wideband MicroTAU: The Wideband MicroTAU family is an order of magnitude smaller and lighter than the WIS family. Many of the reasons for size reduction are the result of decisions that also decreased power. By distributing the units spatially throughout a structure, each unit samples fewer channels. Signal conditioning real estate is reduced, smaller processors are used, and smaller batteries are required. Since the mass of the circuitry is reduced, lighter materials can be used for the enclosure which further reduces its weight. In some cases, the units are light enough to bond into place, thus further reducing size and weight by eliminating mounting flanges. Figure 5 shows a WideBand MicroTAU unit bonded into place in the Space Shuttle; notice the adhesive extending below the unit.

Figure 5 : WideBand MicroTAU Bonded to Shuttle

3.3 Sensor Interfaces

The sensor interface for these systems has migrated from higher power and extremely accurate to lower power with higher sample rates. The WIS family currently samples at rates up to 1.2 kHz. Since it has been used for modal analysis of large structures (e.g., International Space Station) these sample rates are appropriate. The WLE system samples at 20 kHz in order to capture impacts on the leading edge of the Space Shuttle's wings, and UltraWIS samples at 100 kHz in order to capture ultrasonic data. DIDS will sample at up to 1.2 MHz in order to accurately evaluate acoustic emissions data or to utilize active sensing techniques for damage detection and location on spacecraft.

WIS: As discussed in the power section, WIS uses extremely accurate accelerometers that require ±13 Volts. Since size and weight are not restricted as tightly with WIS as with the other families, enough power can be supplied to these transducers to make the system operate properly. The micro-g resolution is non-negotiable since the smallest movements must be detected for both the structural analysis and experiment verification applications.

One feature of the WIS family that makes it very flexible for many different installations and applications is that its sampling parameters are software selectable. A graphical user interface (GUI) running on a laptop PC enables astronauts to select the sample rate and other parameters or load configuration files that are preprogrammed on the ground. This functionality comes with a price of both size and power consumption. However, as previously mentioned, the specifics of this application demand extra functions over miniaturization and power savings.

WideBand MicroTAU: Sample rates vary between 100 Hz and 100 kHz among the various WideBand MicroTAU systems. In order to minimize both size and power consumption, the sample rate is preset during manufacture. Although these systems are less flexible than WIS, they operate in locations for which WIS is unsuitable.

The transducers for this family are more varied than for WIS. They measure acceleration, strain, temperature, ultrasonic, and acoustic emissions. Each unit type typically measures a single parameter plus temperature for thermal compensation. This follows the philosophy of distributing units very broadly throughout the structure. There is typically no need for multiple parameters in a single unit since another unit type can be easily added to the configuration.

DIDS: The sensor interface for DIDS units will sample at much higher rates in order to capture the high speed events for which it is designed. One of the trade-offs of this design is that it is limited to charge output type transducers in order to keep the power consumption to an absolute minimum. Since it is primarily designed for long-term monitoring of impacts, this constraint is not a significant limitation of the system.

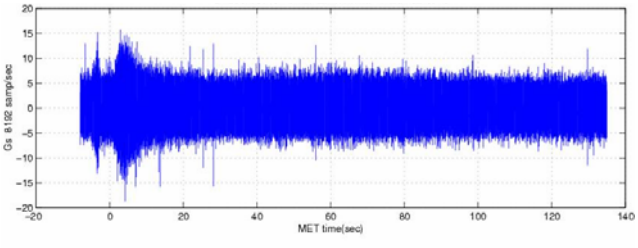
3.4 Processing Power

The processing capability of nodes in distributed data acquisition systems is an important consideration. This consideration is amplified when the system uses wireless communications. The low-power nature of these devices demands that power efficiency is maximized at the sensing devices. After data is converted into the digital realm, it must be handled with switching circuitry. One of the biggest tradeoffs to consider is where the data will be processed. The raw data can be transmitted in its entirety and processed at the receiver; it can be processed at the sensor unit and a final answer transmitted; or some compromise of these two techniques can be employed. Each of these methods has its advantages and is more suited to specific types of applications. All three systems discussed here are capable of both providing raw data and performing local processing. Each system has been optimized for its application taking into consideration human aspects of the customer as well as the technical challenges of the application.

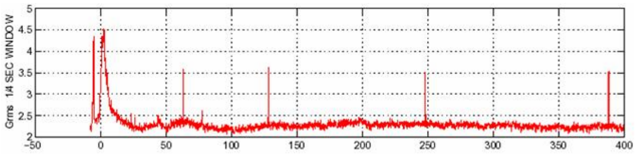
WIS: The WIS family is used primarily for gathering and transmitting raw data. This is driven primarily by two reasons. First, verifying structural models of this magnitude requires more processing capability than can be efficiently implemented in low power instrumentation. Although faster and lower power hardware will provide better platforms for these algorithms on remote hardware, the algorithms are also increasing in complexity. Therefore, the tension between processes and processors will remain in many applications for the foreseeable future. The second reason for transmitting raw data is that many engineers and scientists are not comfortable with automated analysis. They work very hard to develop, refine, and process their calculations on the raw data, and do not yet trust machines to interpret the results accurately. As these systems are used more, their capabilities continue to receive greater acceptance. This will lead to the implementation of more automated algorithms on embedded hardware. This progression has already started with various NASA applications.

WideBand MicroTAU: The Wideband MicroTAU family has taken the next step in implementing automated algorithms on the sensor units. Each successive system has increased its repertoire of available algorithms in order to provide more kinds of information to the end users. There are three reasons why this has been possible with these systems. The first is increasing confidence in the instrumentation's ability to provide accurate results. This has already been discussed and will not be belabored here.

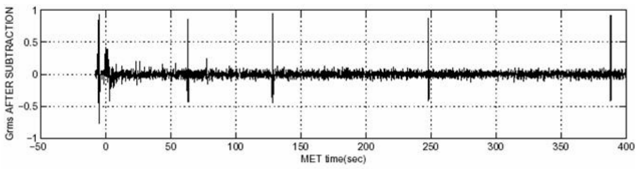
The second reason is that the applications for these systems lend themselves to local data processing. Many of the requirements for an impact detection system involve gathering ambient data and comparing anomalies to this data. Depending upon selected thresholds, decisions can be made regarding what to do with the information. Actions can include saving small pieces of raw data or calculating energy and frequency of the signal. An alarm is also a possible algorithm output for some applications where human intervention or is required or safety is compromised. Figure 6 shows the raw vibration data at the wing leading edge along with the processed data [3].



(a) Raw Flight Data Set



(b) RMS Peaks Algorithm Results with Impact Signatures



(c) Relative RMS Peaks Algorithm Results with Impact Signatures

Figure 6 : Results of Embedded Processing Algorithm

The third reason for on-board processing is communication bandwidth is limited due to power requirements. Distributed processing is ultimately more efficient than transmitting large quantities of data from dozens of units prior to processing. The total number of clock cycles required to provide answers is reduced.

3.5 Telemetry Capability

The telemetry portion of these systems is one of its greatest consumers of power. Therefore, it is important to closely match its characteristics to the application. For example, both the range and data rate for the WIS applications are greater than for the other systems, so it uses higher power radios. However, some versions of the WIS system have access to prime power, so they no longer require battery operation. This reduces subsequent maintenance of the system required for battery replacement. The WLE system does not require the high bandwidth and transmission distance of WIS, but it must operate reliably for extended periods of time on battery power without the luxury of changing the battery. The telemetry requirements of DIDS are very similar to WLE. However, it must operate using lower power than WLE system.

3.6 Synchronization

Another topic considered during the design of these systems is synchronization. It is impossible to correlate spatially distributed data without some level of synchronization. Although it is a challenge to provide synchronization with wireless systems, it is possible to offer very tight synchronization among multiple nodes in this type of system.

WLE: Because the primary purpose of the synchronized WIS systems is modal analysis, the nodes are synchronized to within ±300ns. If nodes are out of communication range of the Network Control Unit (NCU), they are synchronized by relaying through other nodes. This decreases the synchronization level for that node, but even with two relays between modes, the synchronization is still less than 1 µs which is better than required for the application. Finally, the propagation of the radio signals decreases the synchronization by approximately 1 ns/foot. The synchronization will still remain within acceptable levels for the transmission requirements of these applications.

WideBand MicroTAU: The WLE system is synchronized to within 4 µs. As has been noted, many of the characteristics of these systems are interrelated. This is no exception. The lower power systems are not as tightly synchronized. However, it can be noted, that the synchronization in the WLE system is an order of magnitude tighter than the time resolution of its sampling. It is also important to note that for this application, synchronization is not used to determine the modes of the Shuttle's wing leading edge. Instead, the primary purpose of synchronization here it so correlate data from several sensors. This enables engineers to determine if the structure experienced a single large impact, or multiple smaller impacts. The extent of possible damage can be more clearly determined through this correlation.

4. Conclusion

Three families of wireless data acquisition systems have been discussed with respect to the tradeoffs required to successfully implement this technology in different types of applications. The applications requiring sophisticated, high-bandwidth wireless network capabilities combined with high resolution data will be larger and heavier and will require larger battery packs or prime power. For low power applications that require high speed data acquisition and distributed processing, smaller units that sample fewer channels are more appropriate. Finally, for ultra low power requirements intended for extended monitoring, many of the power saving features implemented in these systems must be combined with novel power saving methods. Although space is a demanding environment for all kinds of instrumentation, it provides opportunities to develop technology that can be implemented more broadly back on earth.

5. Acknowledgement

The authors acknowledge the engineering contributions of their colleagues to the systems described in this work. Without their creativity, insights, and hard work, the trade studies discussed herein would have remained an academic exercise instead of becoming proven implementations in applications that are out of this world.

6. References

[1] Kevin Champaigne, Jonathan Sumners: "Wireless Impact and Leak Detection and Location Systems for the ISS and Shuttle Wing Leading Edge", IEEE Aerospace Conference 2005, Big Sky, Montana, USA, 2005.

[2] Kevin Champaigne: "Wireless Sensor Systems for Near-term Space Shuttle Missions", International Modal Analysis Conference – IMAC 2005, Orlando, Florida, USA, 2005.

[3] Kevin Champaigne, Michael Walcer: "Wireless Impact Monitoring System for the Return to Flight Mission", Space Technology and Applications International Forum -- STAIF 2005, Albuquerque, NM, USA, 2005.

7. Glossary

DIDS: Distributed Impact Detection System

ECLSS: Environment Control and Life Support System

EVA: Extra-Vehicular Activity

EWIS: External Wireless Instrumentation System

GUI: Graphical User Interface

ISS: International Space Station

IWIS: Internal Wireless Instrumentation System

JEM: Japanese Experiment Module

MMA: Microgravity Measurement Apparatus

NCU: Network Control Unit

RF: Radio Frequency

RSU: Remote Sensing Unit

SWIS: Shuttle Wireless Instrumentation System

TAU: Tri-axial Accelerometer Unit

WIS: Wireless Instrumentation System

WLE: Wing Leading Edge

WSGIS: Wireless Strain Gauge Instrumentation System