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Sensory Prognostics and Management Systems Implemented in an Electronic Power Distribution System

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16. Abstract

Airframe designers are exploring new methods for the continuous monitoring and management of aircraft systems. Sensory Prognostics and Management Systems is a set of activities performed on an integrated system that include smart sensors, in an aircraft to maintain a safe and operable condition. Sensory systems have the ability to sense systems information in real time, identifying and reacting to a perceived damage while recording and communicating the precursors to incidents. This should help to reduce the flight crews' workload in emergency situations, increase aircraft safety, increase maintenance efficiency, and decrease schedule downtime. These systems can provide real time data from composite structure monitoring, electrical systems monitoring, health usage systems monitoring, and maintenance prognostics.

This research investigated the use of a modified EPDS (Electronic Power Distribution System) to act as the hub of an SPMS. Since an EPDS already supplies power to nearly everything that is electrical in an aircraft, wires to the loads are already in place. The EPDS also has the capability to monitor load current and voltage as well as analog and discrete sensor inputs, has a large amount of data processing power, and has multiple data bus input/output to other aircraft systems. The primary goal of this research was to use only the EPDS and the existing power wires to gather all necessary information to evaluate load health and performance. To achieve that goal, the possible EPDS architectures that would facilitate this additional usage were investigated and documented. In general, it was found that the distributed architecture used to minimize wire weight in an aircraft was also the one required for optimal use as an SPMS hub.

A full SPMS also needs to measure nonelectrical parameters, such as temperature, pressure, and position. Various sensor types were identified and analyzed for suitability to be interfaced with the EPDS. An EPDS may have analog sensor input capacity, but using it requires extra wiring for the sensors. As an alternative to adding sensor wiring, the addition of simple sensors that communicate over the power line to the ECBs within the EPDS was investigated. Several techniques for powerline communication (PLC) were investigated, but a technique for communicating directly to the ECB by means of time-spaced current pulses on the power feed to the sensor (and associated load) was determined to be the simplest and easiest method.

In conclusion, this report determined that an EPDS can act as a complete SPMS with a few small modifications and the addition of sensors (PLC or analog) as required for the particular aircraft. Absorption of control functions into the EPDS is also viable; this technique also provides better data on the health of the system loads by eliminating the masking effects of a control LRU on the current signatures of the actual loads. The benefits of using the EPDS as an SPMS includes reduced aircraft weight and cost, better data-acquisition capability, and less wiring complexity.

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LIST OF ACRONYMS

A/D	Analog-to-digital
AC	Alternating current
CB	Circuit breaker
DC	Direct current
ECB	Electronic circuit breaker
ECBU	Electronic circuit breaker unit
EPDS	Electronic Power Distribution System
GHz	Gigahertz
GUI	Graphical user interface
LED	Light-emitting diode
LRU	Line replacable unit
PDU	Power distribution unit
PLC	Powerline communication
PWM	Pulse-width modulation
RF	Radio frequency
RFID	Radio frequency identification
RTD	Resistance temperature detector
SCIU	System control interface unit
SPMS	Sensory Prognostics and Monitoring Systems

EXECUTIVE SUMMARY

Sensory Prognostics and Monitoring Systems (SPMS) enables the monitoring of aircraft sensor data to provide faster reaction times to in-flight fault conditions, improved diagnostic capability, and prognostic ability to identify potential future equipment and system failures. Improved overall system health monitoring allows several key benefits to aircraft operation, including reduction in aircrew workload, improved safety, reduced unscheduled downtime, and faster maintenance and repair times. Many systems of a modern aircraft are electrically powered, such as pumps, lights, heaters, actuators, and valves, as well as the sensors feeding data to the avionics. Therefore, much of the data needed for the assessment of system health that is performed by an SPMS are electrical data, and can be obtained by monitoring and analyzing the current drawn by the electrical loads.

This research investigated the use of a modified EPDS (Electronic Power Distribution System) to act as the hub of an SPMS. Since an EPDS already supplies power to nearly everything that is electrical in an aircraft, wires to the loads are already in place. The EPDS also has the capability to monitor load current and voltage as well as analog and discrete sensor inputs, has a large amount of data processing power, and has multiple data bus input/output to other aircraft systems. The primary goal of this research was to use only the EPDS and the existing power wires to gather all necessary information to evaluate load health and performance. To achieve that goal, the possible EPDS architectures that would facilitate this additional usage were investigated and documented. In general, it was found that the distributed architecture used to minimize wire weight in an aircraft was also the one required for optimal use as an SPMS hub.

Current draw over time is a key parameter in assessing the health and function of an electrical system, so load current data collected by the electronic circuit breakers (ECB) in the EPDS can be recorded, analyzed, and used to provide prognostics data for the aircraft. Various electrical loads were identified and categorized to determine how fast and with what precision the ECB needed to monitor current to gather useful diagnostic and prognostic information. Changes to the ECB and the ECB unit designs to enable faster and more precise data collection were then identified and the EPDS was modified accordingly. A breadboard of an electrically actuated linear actuator was created to demonstrate the collection and analysis of load current as a means of detecting actuator faults.

A full SPMS also needs to measure nonelectrical parameters, such as temperature, pressure, and position. Various sensor types were identified and analyzed for suitability to be interfaced with the EPDS. An EPDS may have analog sensor input capacity, but using it requires extra wiring for the sensors. As an alternative to adding sensor wiring, the addition of simple sensors that communicate over the power line to the ECBs within the EPDS was investigated. Several techniques for powerline communication (PLC) were investigated, but a technique for communicating directly to the ECB by means of time-spaced current pulses on the power feed to the sensor (and associated load) was determined to be the simplest and easiest method. The current pulses are seen by the ECB current measurement circuit and translated by the ECB back into the sensor data. This current pulse technique can reliably send information from a load to an ECB with minimal circuitry and high noise immunity. Information from multiple sensors can be multiplexed over the power line and sent back to the ECB for status monitoring of the load (temperature, pressure, position, force, etc.). Power health data can also be sent by the current

pulse technique, to monitor for such conditions as intermittent load power (sign of series wiring fault or loose connection) or low voltage (sign of bad wiring or high resistance crimp or connection). Sensors using current pulse PLC allow the EPDS to act as a full SPMS system without adding any additional processor boxes, analog-to-digital converters, or sensor wiring. A breadboard of a current pulse-based PLC system was built and used to demonstrate the method in an EDPS system.

Most information gathered by an SPMS is valuable to the ground maintenance personnel, but some information can be valuable to the aircrew as well. This report summarizes the findings on a methodology to determine which information is to be analyzed and prepared in flight and provided to the aircrew, versus which information is stored for on-ground analysis and action by the maintenance personnel. It is recommended that anything that aids the pilot in determining whether the aircraft can continue to fly safely be provided to the aircrew.

Because an EPDS can also act as a power switch or relay, it can also control the loads it powers. A feedback control scheme can be implemented by using the PLC sensors that were developed for this project. An example of this would be the collection of position data from a linear actuator and using that data to precisely position the actuator by using the ECB to turn the actuator motor on and off. A breadboard of this system was built and used to demonstrate the PLC data collection method for linear actuator position. The use of the EPDS to control motors, actuators, pumps, heaters, lights, and valves directly, without the need for a separate control line replaceable unit (LRU), would serve to both simplify the aircraft and gather better information on the electrical loads.

Wireless data transfer was also found to be feasible for the collection and transmission of data from a remote sensor to a central location. Wireless control of the EPDS system was also demonstrated to be feasible, permitting data collected from the EPDS system to be downloaded, on demand, to an off-aircraft terminal. This technology could also be used as a backup method of EPDS control in the event of damage to the primary interface systems.

In conclusion, this report determined that an EPDS can act as a complete SPMS with a few small modifications and the addition of sensors (PLC or analog) as required for the particular aircraft. Absorption of control functions into the EPDS is also viable; this technique also provides better data on the health of the system loads by eliminating the masking effects of a control LRU on the current signatures of the actual loads. The benefits of using the EPDS as an SPMS includes reduced aircraft weight and cost, better data-acquisition capability, and less wiring complexity.

1. INTRODUCTION.

Sensory Prognostics and Management Systems (SPMS) enables monitoring of aircraft sensor data and sensor performance to collect data used to maintain the aircraft in a safe and operable condition. The SPMS are designed to collect useful systems information in real time, recording or communicating the data for later retrieval and analysis. This helps to increase aircraft safety and maintenance efficiency and to decrease unscheduled downtime. These systems can provide real time data from composite structure monitoring, electrical systems monitoring, vibration monitoring, and other aircraft system sources.

To provide these benefits, the SPMS needs to perform the following functions:

- Interface and communicate with other aircraft systems. Use common standards, such as ARINC 429, ARINC 629, RS-422, RS-485, and others, for data transfer.

- Interface and communicate with sensors to acquire data for diagnostic and prognostic functions.

- Gather power usage statistics on the electrically powered systems and loads. The current consumed by a load carries much information about the health and status of the load. The variation of current over time carries information about the wear out and lubrication requirements of motor-operated mechanisms, and the peak instantaneous value of current can signal a failure or an impending failure to a critical system.

- Provide real time, on-aircraft failure notification to the aircrew to support safe operation at all times. Coordinated operations with other aircraft systems (such as the power distribution system) will allow automated emergency procedures, such as load shedding or a backup system, which could substantially reduce aircrew workload.

- Transfer of stored health and status data off-aircraft for detailed diagnostic and prognostic processing.

An Electronic Power Distribution System (EPDS) already does, or can be modified to do, all of these functions. That means that an SPMS can be implemented on an aircraft having an EPDS without the addition of an SPMS line replacement unit (LRU), additional current/voltage sensors, or sensor wiring.

This research project investigated the use of an EPDS to act as an SPMS. Data are collected by the ECBs (electronic circuit breakers) in the EPDS, either directly measured (load current and voltage) or from sensors that communicate to the EPDS, either directly or over the ECB power line to the loads that the sensors are monitoring.

1.1 BACKGROUND: HISTORY OF AIRCRAFT POWER TECHNOLOGY.

Thermal circuit breakers (CBs) have been used for the protection of aircraft wiring almost since their invention in 1924. The thermal breaker provided a way to automatically disconnect a load from the power system if a fault occurred, hopefully before a hazardous condition developed, and the aircrew or mechanics had the ability to reset the breaker when the fault was cleared. Individual loads could also be turned off by means of the CBs if the electrical load needed to be reduced, and multiple switched power buses to groups of breakers provided a crude method of load management.

As electronics and electrical systems became critical to the safe flight of the aircraft, the complexity and size of the supporting aircraft electrical systems grew. The number of breakers in the cockpit grew significantly, with some commercial aircraft having up to 400 breakers arranged in multiple panels. Even smaller, business-type aircraft often approached the 200-breaker level. The wiring to the CBs became correspondingly complex and heavy. A good example is shown in figure 1. A need for emergency, pilot-activated load management (load shedding, smoke clearing) was seen, and so even more bus structure, wiring, bus contactors, and control switches were added.

Figure 1. Panel With 100 Thermal CBs

1.2 BACKGROUND: EXISTING EPDS TECHNOLOGY.

Over the last few years, several aircraft have been certified with an EPDS. An example is shown in figure 2.

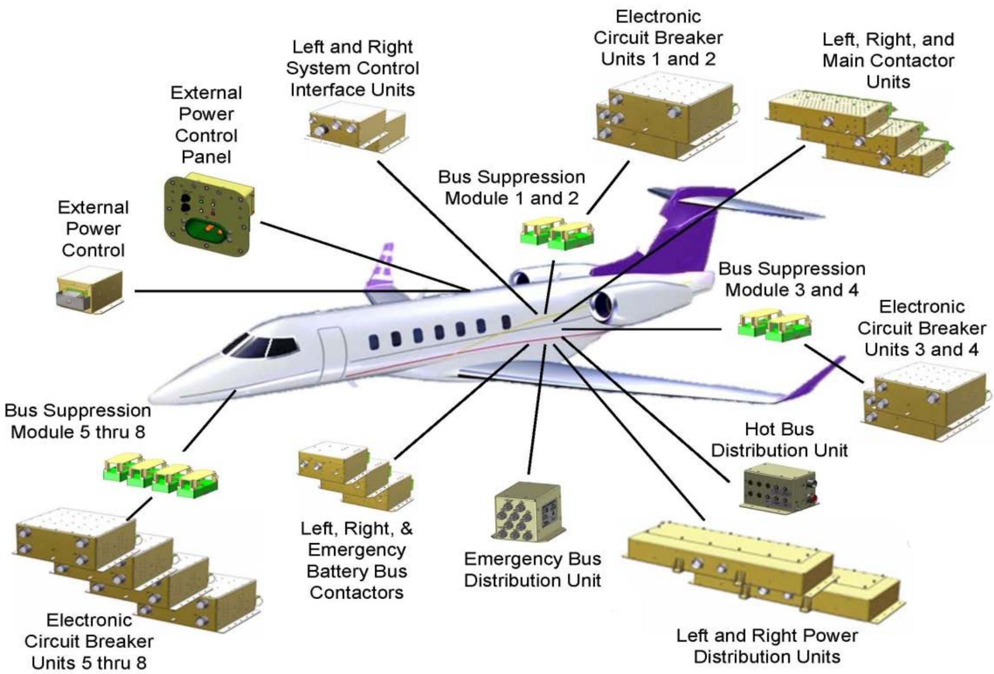

Figure 2. The EPDS Installation on a Business Jet

This system is highly automated and requires little pilot input. Since ECBs act as switches as well as circuit protectors, many simple control systems have been integrated into this system, such as windshield heat control, thrust reverse deploy, and fuel pump management. This system is able to measure load current/voltage and already serves as a data-collection system for electrical system health.

2. SYSTEM ARCHITECTURE DEFINITION.

An EPDS provides a unique opportunity for an SPMS by providing a backbone for sensor integration. Since the EPDS directly interfaces with a large portion of aircraft electronics, a portion of health monitoring is inherent within the normal load monitoring performed by the electronic circuit breaker units (ECBU). A general EPDS architecture is outlined below, then a hypothetical SPMS-enabled EPDS is explored, followed by a discussion of general aircraft loads and potential health-monitoring features that can be realized with a standard EPDS system.

2.1 THE EPDS ARCHITECTURE.

An EPDS system level block diagram is shown in figure 3.

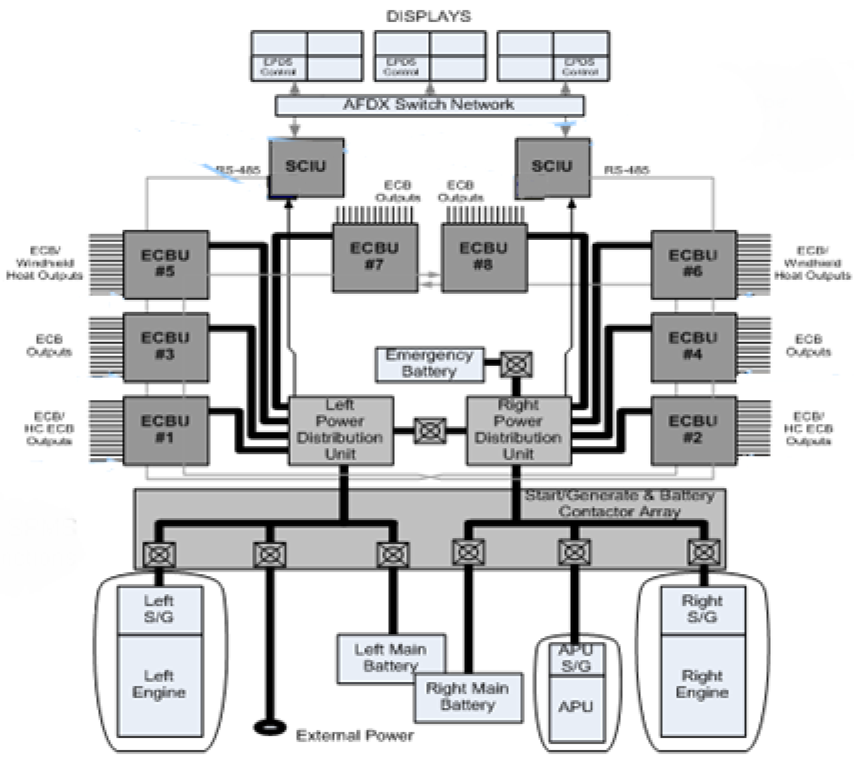

Figure 3. The EPDS System Level Block Diagram

The block diagram highlights the following primary EPDS elements:

- The ECBUs contain individual ECBs that provide the secondary power distribution, protection, and control of aircraft loads. Because the ECBs are already interfacing with the majority of aircraft loads, ECBs can provide some level of SPMS functionality with inherent capabilities. Load current can provide a major piece of health diagnostics, especially when considering electro-mechanical loads.

  With a distributed ECBU architecture (i.e., noncentral location), the ECBUs are in the unique position of being able to spread the sensor interfacing requirements across the entire plane with existing hardware, reducing the total weight/cost of implementing an SPMS system. Specific sensors will be required, contingent on the load being monitored, and the ECBU can be used to gather the required sensing information. If specific loads are physically close to the installed ECBU, inherent analog/digital inputs can be used to gather the required sensing information. When loads are required to be monitored more remotely, the ECBU can again interface with sensors through novel means (such as powerline communication (PLC)), allowing for various methodologies to be used to maximize the functionality of the system while adding minimal weight/cost.

- System control interface units (SCIUs) provide the EPDS system control through digital bus interface to the distributed ECBU elements. The SCIU receives commands from the flight control system and responds accordingly by exercising specific system features (on/off/reset, breaker control, etc.). In an SPMS-enabled system, the SCIU would provide the primary memory/data storage and algorithmic data processing. In-flight processing would likely be minimized to just essential loads while the rest of the data collected would be preprocessed and stored for on-ground processing. This is primarily due to the amount of processing power that is required to run real time prognostic algorithms; if every monitored load had real time prognostic algorithms running on the aircraft, the amount of processor throughput would be astronomical. Preprocessing the data would involve a primary decision as to whether or not the gathered data must be stored.

- Power distribution units (PDUs) provide power switching, bus isolation, and cross-coupling capability. A simple PDU provides minimal features compared to a fully integrated SPMS.

2.1.1 The SPMS-Enabled Elements.

Integrating numerous sensors within an EPDS system requires an architectural approach that alleviates the complexities of sensor networking and avoids certification issues. With sensors distributed throughout an aircraft, a multitude of data will be required to be captured, processed, and stored, all while not interfering with the normal flight-critical operation of the system. A hypothetical system architecture is shown in figure 4. The primary enabling factors are within the ECBU and SCIU, which would provide the required sensor data gathering and the data storage, respectively. A secondary sensor data bus is required between the ECBUs and the SCIUs to avoid interfering with the flight-critical system control, and data storage elements would be required within the SCIU to allow for post-flight analysis.

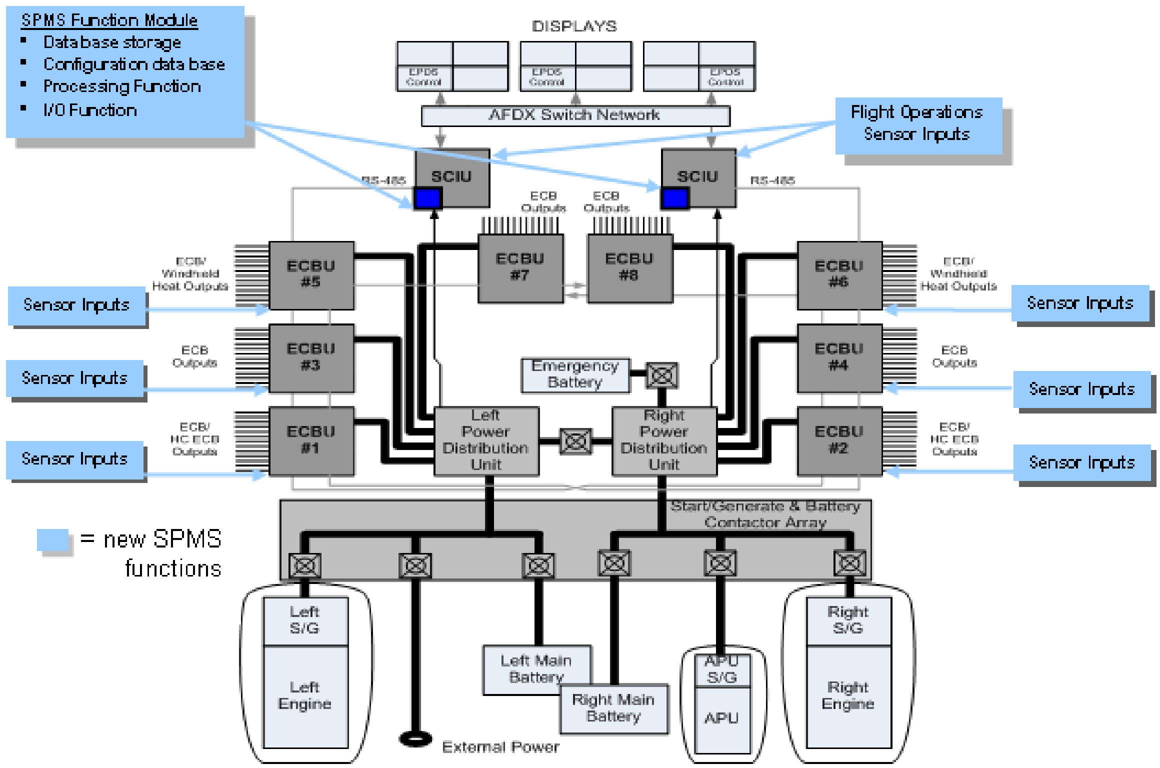

Figure 4. Example of an SPMS-Enabled EPDS System

While simply capturing this data is important, it is paramount to ensure the entire system is synchronized to enable correlation between sensors within different locations, yielding a look at the entire aircraft's health. System time correlation will be handled by the primary SCIU and will periodically broadcast time sync information to the pertinent ECBUs within the system. This will allow for every sampled data point to be correlated to the same timeline.

The overall data path requires transducer information to be transferred from the monitored load to the SCIU, which has adequate processing available to handle real time monitoring/storage. The SCIU also possesses a direct communication link to the flight computer for error identification/download to a fleetwide database once at a hangar. Potentially, there is an extremely large amount of data that needs to be transferred from the various transducers throughout the aircraft to the area where the information is to be processed/stored (SCIU). This limits how the overall interface can be configured because of theoretical maximum data rates that can be achieved. Figure 5 shows a generalized data flow from sensor to data storage. As these data are digitized within the system and transferred to the ECBU, the module within the ECBU will have an opportunity to compress the data and determine whether or not the information needs to be further processed/stored for later evaluation, reducing the throughput requirements of data bus interface to the SCIU. Once these data have progressed to the SCIU, fault identification/remaining useful life algorithms will potentially be applied to the data, depending on whether the information was flagged as a high priority. If a critical fault is about to occur, the SCIU will have an opportunity to annunciate the condition to the crew before further compression and storage of the data.

In figure 5, two portions of the data flow are highlighted in red. These pertain directly to this report as these data buses have the largest impact on the cost, feasibility, and weight of the entire EPDS/Prognostics system. The interface between the sensing element and ECBU has vastly different requirements than the ECBU-to-SCIU interface. Aircraft loads will next be discussed to better understand the requirements of these interfaces.

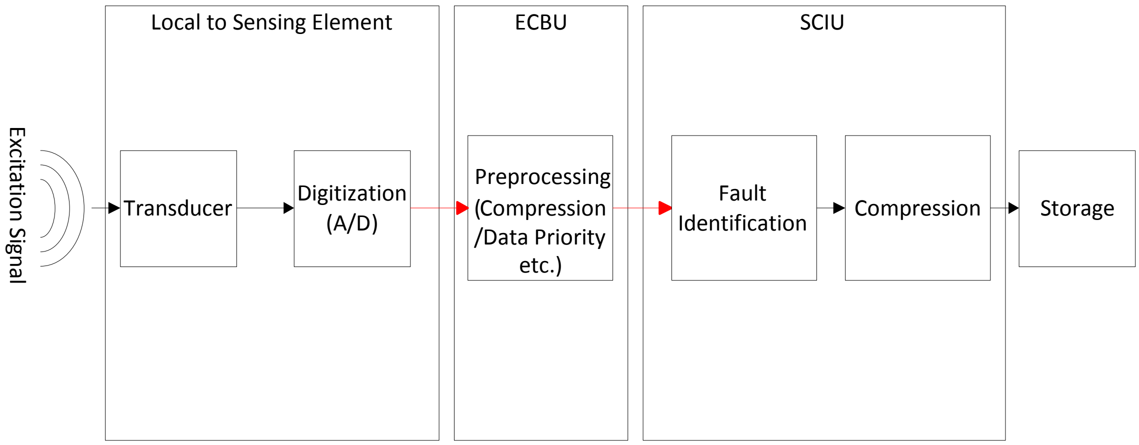

Figure 5. System Data Flow

2.2 AIRCRAFT LOAD DEFINITION.

Electrical loads can be categorized in the broad categories highlighted in table 1. Key current characteristics are unique to certain categories. Some loads that are similar in function (i.e., light-emitting diode (LED) landing lights vs. incandescent landing lights) have been assigned to different categories because of differences in electrical characteristics. Some loads are complex blends of circuits (i.e., LED strobes) that can be placed under multiple categories.

Table 1. Load Categorization

Category	Turn-on Characteristic	Turn-off Characteristic	Steady State Characteristic	Examples
Resistive				Heaters, certain simple LED lighting products
Capacitive	10x steady state		Varies. Batteries and capacitors charge and discharge	Batteries, capacitors
Inductive	Ramp up of current	Voltage spike		Solenoids, solenoid valves
Incandescent	10x steady state for about 10ms			Incandescent lighting, certain PTO heater devices
Motor	Ramp up of current	Voltage spike	Periodic current spikes, Voltage spikes, current ripple	Series wound brushed motors, brushless motors, linear actuators, linear motors
Pulsating	Varies	Varies	Periodic current pulses	Strobes, markers, blinkers, stepper motors
Power Regulation	10x steady state	Varies	Periodic current pulses, current inversely proportional to applied voltage	Radios, gauges, EFIS, LRUs, inverters, constant intensity LEDs, fluorescent lights

2.2.1 The ECB Data Sampling Rates.

Table 2 shows the diagnostic and prognostic information that can be gleaned from various load current sampling rates for each category. The existing ECBU design updates current data (by request via the RS-485 bus) for each ECB at a 1-sec rate. Each ECB samples the current at a

100-msec rate to perform the internal I2t calculation. Faster data acquisition will require hardware and software changes to the ECB. It should be noted that most loose connection faults can be observed at a sample rate of 100 Hz. All parallel arc faults are detected by the existing ECB.

Table 2. Prognostic/Diagnostic Information Available vs. Load Current Sampling Rate

Category	1 sample per second (standard ECBU data transmission interval)	10 samples per second (existing ECB internal calculation sample rate)	100 samples per second (maximum sample rate with existing ECB/ECBU uProcessors)	1000 samples per second
Resistive	• Load connected • Correct wattage	• Intermittently shorted heater coils	• Series arc fault/bad connection	
Capacitive	• Load connected • Correct wattage		• Series arc fault/bad connection	
Inductive	• Load connected • Correct wattage		• Series arc fault/bad connection	
Incandescent	• Load connected • Correct wattage • Pending failure (with time and cycle information)		• Series arc fault/bad connection	
Motor (pumps, fans, jackscrews, gear drives)	• Load connected • Load trending (i.e., clogged filter) • Stalled rotor	• Pending binding of gears/screw • Broken linkage	• Gear or jackscrew lubrication uneven • Loose linkage • Series arc fault/bad connection	• Bearing health • Bearing lubrication • Missing tooth
Pulsating	• Load connected • Correct wattage	• Incorrect pulse rate • Input filter cap failure	• Series arc fault/bad connection	
Power Regulation	• Load connected • Correct wattage	• Input filter cap failure	• Power converter stage failure • Series arc fault/bad connection	

2.2.2 Diagnostic and Prognostic Information Collection.

An analysis of the load categories identified in the previous sections of this paper was performed to identify what information could be collected to either diagnose an existing or pending failure. The estimated sample rate to reliably measure the data needed was also determined. The tables below present this information for each category.

2.2.2.1 Resistive Loads.

This is a common load type with well-behaved loads. Faults are obvious and easily measured, as shown in table 3.

Table 3. Resistive Load Faults

Condition	Metrics	Sample Rate	Comments
Load connected	Current greater than 10% of expected load	1 sample/second	
Correct wattage	Current within specified limits	1 sample/second	
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorting heater elements, film heater shorts
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.2.2.2 Capacitive Loads.

Capacitive loads are uncommon on a direct current (DC) system, as most capacitor banks will feed a switching regulator, which is differently characterized. Batteries that float on the 28VDC bus are placed in this category. Batteries connected through an ECB need to be specially isolated to prevent backfeed, or are used with a special bidirectional ECB designed for this purpose. Capacitive-type load faults are shown in table 4.

Table 4. Capacitive Load Faults

Condition	Metrics	Sample rate	Comments
Load connected	Current greater than “to be determined” of expected load	1 sample/second	Very low current draw after charge is complete. May be immeasurable.
Charging	Current within specified limits	1 sample/second	
Discharging	Negative current within specified limits	1 sample/second	
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorting heater elements, film heater shorts
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.2.2.3 Inductive Loads.

Pure inductive loads are electromagnet coils (relays) and solenoids (valves, locks). Motors, while also inductive, have other characteristics that are very important. Motors have commutation elements (brushes, electronic commutators), while solenoids do not. Inductive-type load faults are shown in table 5.

Table 5. Inductive Load Faults

Condition	Metrics	Sample Rate	Comments
Load connected	Current greater than 10% of expected load	1 sample/second	
Correct operation	Current within specified limits	1 sample/second	May be possible to detect jammed solenoid by looking at current vs. time after application of power
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorted turns
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.2.2.4 Incandescent Loads.

Incandescent filaments, which are becoming less common in aircraft, have similar characteristics to resistors, but have a large inrush due to a resistance characteristic dependent on filament temperature. Potential incandescent load failures are shown in table 6.

Table 6. Incandescent Load Faults

Condition	Metrics	Sample Rate	Comments
Load connected	Current greater than 10% of expected load	1 sample/second	
Correct wattage	Current within specified limits	1 sample/second	
Impending failure	Time of operation approaching average lifetime	1 sample/second	
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorting of filament segments
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.2.2.5 Motor Loads.

Almost all electric actuators are motors coupled with some sort of mechanical drive train. The others are solenoids, which have no commutation elements. The motor current is proportional to work performed, up until the point of stall. A stalled motor draws a current proportional to the resistance of its windings. Table 7 shows common potentially detectable motor load faults.

Table 7. Motor Load Faults

Condition	Metrics	Sample Rate	Comments
Load connected	Current greater than 10% of expected load	1 sample/second	
Normal load range	Current within specified limits	1 sample/second	
Abnormal high load	Current above specified limits	1 sample/second	Lack of lubrication, damage
Abnormal low load	Current below specified limits	1 sample/second	Clogged filters
Stalled	Current above specified limits	1 sample/second	
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorted turns
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.2.2.6 Pulsating Loads.

These loads pulse as part of normal operation. Lack of pulsing, or incorrect pulsing, is a prime diagnostic tool and other potential faults are shown in table 8.

Table 8. Pulsating Load Faults

Condition	Metrics	Sample rate	Comments
Load connected	Current greater than 10% of expected load.	1 sample/second	
Correct load draw	Current within specified limits	1 sample/second	During pulses. May be voltage dependent
Correct pulse frequency	Current pulses within specified limits	10 samples/second	
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorted or defective input capacitors, shorted output of pulsed device
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.2.2.7 Power Regulation Loads.

Switching and linear power supplies fit in the category of power regulation loads, and potential current-based failure detections are shown in table 9.

Table 9. Power Regulation Faults

Condition	Metrics	Sample rate	Comments
Load connected	Current greater than 10% of expected load.	1 sample/second	
Correct Wattage	Current within specified limits	1 sample/second	May be voltage dependent
Efficiency loss or output load fault	Current above specified limits	1 sample/second	
Failure of LRU	Current below specified limits	1 sample/second	
Intermittent shorting	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Shorted or defective input capacitors, shorted output of device
Intermittent opens	Current spikes above/below specified limits for more than a specific percentage of a small time window	10-100 samples/second	Bad connector or loose crimp, series arc fault

2.3 COMPLETE AIRCRAFT MONITORING SYSTEM.

A complete aircraft monitoring system was studied to determine quantities of sensors and theoretical amounts of data that an enabled EPDS would have to process/transfer throughout the system. Some typical sensors that could be found within a typical health monitoring system and the data measured are quantified in table 10. The required storage for each of the monitored sensor parameters is an estimate based on a nominal resolution (2 bytes gives 16 bits of resolution and is a conservative estimate).

Table 10. Sensor Parameters

Sensor	Units	Sample Rate (Hz)	Data Format*	Bytes
Accelerometers	G's	10-1000	Value/Time	2
Current	Amps	1-100	Value/Time	2
Flow	lbs-mass/sec	1-100	Value/Time	2
Force	lbs-force	10-1000	Value/Time	2
Pressure	psi	1-100	Value/Time	2
Rate (angular)	Deg/Sec	10-1000	Value/Time	2
Temperature	Degrees C	1-100	Value/Time	2
Torque	ft-lbs-force	10-1000	Value/Time	2
Vibration	G's	10-1000	Value/Time	2

<u>2.3.1 Aircraft Level Data Requirements</u>.

Sufficient memory must be incorporated into the system to store preprocessed data to allow subsequent diagnostic and prognostic processing. The SCIU will perform some diagnostic/prognostic processing in flight (based on criticality) and will control the storage of data for postflight processing to ensure safety and proper maintenance cycles.

The estimates for data quantities are shown in table 11. All directly controlled EPDS loads were considered, along with major aircraft components. The sensor types and quantity for each component were defined as were estimated data size and sampling rate requirements.

Table 11. Data Quantity Estimate

Components	Qty	ECB Current	External Current	Temp	Flow	Force	Rate	Vibe	Torque
Sensors Per									
Defogger	4	1		1					
Heater	16	1		1					
Valve	21	1							
Motor	5	1						1	
Servo	3	1							
Pump	4	1			1				
Relay	7	1							
Fan	8	1							
Light	92	1							
Electrical Panel	16	1							

Table 11. Data Quantity Estimate (continued)

Components	Qty	ECB Current	External Current	Temp	Flow	Force	Rate	Vibe	Torque
Electrical System	13	1							
Other ECB Device	64	1							
Control Surface	9		4			2	1	1	
Landing Gear	3		4			2	1	1	
Engine	2			4	1			3	1
Fuel Pump	2		1	1	1				
Total Sensors									
Defogger		4	0	4	0	0	0	0	0
Heater		16	0	16	0	0	0	0	0
Valve		21	0	0	0	0	0	0	0
Motor		5	0	0	0	0	0	5	0
Servo		3	0	0	0	0	0	0	0
Pump		4	0	0	4	0	0	0	0
Relay		7	0	0	0	0	0	0	0
Fan		8	0	0	0	0	0	0	0
Light		92	0	0	0	0	0	0	0
Electrical Panel		16	0	0	0	0	0	0	0
Electrical System		13	0	0	0	0	0	0	0
Other ECB Controlled		64	0	0	0	0	0	0	0
Control Surface		0	36	0	0	18	9	9	0
Landing Gear		0	12	0	0	6	3	3	0
Engine		0	0	8	2	0	0	6	2
Fuel Pump		0	2	2	2	0	0	0	0
Data Size (x2)									
Defogger		8	0	8	0	0	0	0	0
Heater		32	0	32	0	0	0	0	0
Valve		42	0	0	0	0	0	0	0
Motor		10	0	0	0	0	0	10	0
Servo		6	0	0	0	0	0	0	0
Pump		8	0	0	8	0	0	0	0
Relay		14	0	0	0	0	0	0	0
Fan		16	0	0	0	0	0	0	0
Light		184	0	0	0	0	0	0	0

Table 11. Data Quantity Estimate (continued)

Components	Qty	ECB Current	External Current	Temp	Flow	Force	Rate	Vibe	Torque
Electrical Panel		32	0	0	0	0	0	0	0
Electrical System		26	0	0	0	0	0	0	0
Other ECB Controlled		128	0	0	0	0	0	0	0
Control Surface		0	72	0	0	36	18	18	0
Landing Gear		0	24	0	0	12	6	6	0
Engine		0	0	16	4	0	0	12	4
Fuel Pump		0	4	4	4	0	0	0	0
SAMPLES/SEC		100	100	10	10	1000	100	1000	10
Defogger		800	0	80	0	0	0	0	0
Heater		3200	0	320	0	0	0	0	0
Valve		4200	0	0	0	0	0	0	0
Motor		1000	0	0	0	0	0	10000	0
Servo		600	0	0	0	0	0	0	0
Pump		800	0	0	80	0	0	0	0
Relay		1400	0	0	0	0	0	0	0
Fan		1600	0	0	0	0	0	0	0
Light		18400	0	0	0	0	0	0	0
Electrical Panel		3200	0	0	0	0	0	0	0
Electrical System		2600	0	0	0	0	0	0	0
Other ECB Controlled		12800	0	0	0	0	0	0	0
Control Surface		0	7200	0	0	36000	1800	18000	0
Landing Gear		0	2400	0	0	12000	600	6000	0
Engine		0	0	160	40	0	0	12000	40
Fuel Pump		0	400	40	40	0	0	0	0
BYTES/SECOND		50600	10000	600	160	48000	2400	46000	40
RAW DATA SUB TOTAL		157800							
IDENTIFICATION/TIME STAMPS		24120							
TOTAL		181920							
BITS PER SECOND		1455360							

The sensor data will require time stamps and identification for correlation with aircraft parameters. Based on the Total Sensors section of table 11, there are 402 sensors (including ECBs) for the entire SPMS. Each block of data for a given sensor will require identification (2 bytes) and a time stamp (4 bytes) of the first reading. The time stamps of subsequent bytes can be derived from the configuration database known sample rate of the particular sensor.

Assuming a data transfer rate of 10Hz, this calculates to an additional 2412 bytes for each transmission frame or 24,120 bytes/sec.

For this business jet example, the size estimates for EPDS-supplied SPMS data are 181,920 bytes/sec or 1,455,360 bits/sec.

It is unlikely that all of the data quantified above would need to be sent to the SCIU. The ECBUs would perform some real time preprocessing functions to reduce the number of bytes to 50% (or less) of the total number collected. In this case, this would reduce the required data transfer rate to 727,680 bits/sec. The greater the reduction in the number of bytes of sensor data needing to be transferred to the SCIU due to preprocessing, the lower the serial data rate requirement.

Once these data are received by the SCIU, they can be processed or stored as is appropriate for the type of sensor and the criticality of the data. It is likely that most data can be evaluated against limits and, if none are exceeded, discarded. Out-of-limits or suspect data can be compressed and saved for further off-aircraft analysis.

Assuming that 5% (a rough estimate) of the received or processed data needs to be stored in the SCIU, the required memory is:

(727,680 bits/sec) x 0.05% (storage factor) = 36,384 bits/sec or 4,548 bytes/sec, which corresponds to 16.4 megabytes per flight hour of data storage for a business jet containing eight ECBUs.

The SCIU must also store data from other sources that relate to the EPDS-acquired data. For example, sensor data associated with control surfaces and landing gear would need to be correlated with aircraft attitude, airspeed, and position. Not all data would need to be continuously monitored and stored. Control surfaces and landing gear data would need to be acquired only during actual operation of those systems.

2.3.2 The ECBU-to-SCIU Sensor Data Bus.

The SCIU and ECBU elements of the EPDS incorporate significant capability for data transfer and processing. The multitude of ECBs that reside in each ECBU allows the system to acquire significant amounts of electrical load data, such as on/off cycles, on time, electrical current profile, and power consumed. These data can be processed to determine load status and performance trends, and to implement diagnostic and prognostic health assessment functions for a large portion of the aircraft's onboard systems.

Architecturally speaking, the EPDS system is generally configured as is shown in figure 6. The SCIU interfaces the multiple ECBUs to the flight system through dual redundant data buses. A control processor interprets commands from the SCIU and sends commands through a parallel bus to the proper ECB channel. Current ECBU design allocates a single processor per ECB to monitor the load for trip conditions. If data collection were then added to this processor's work load, it would cause certification issues within the processor's software, requiring a large level of separation between critical (ECB operation) and noncritical (prognostics data collection) functions. To avoid impinging on the flight-critical operation of the ECBU's load control, a dedicated data collection processor will be implemented. Along with concern for certification issues with regard to the ECB processor, the data path between the ECBU and the SCIU could not overload, as this would effectively prevent either a command from the SCIU from being received or data collected for prognostics from being stored properly. In figure 6, the red components identify the additional interfaces and hardware required to implement a successful prognostics/EPDS.

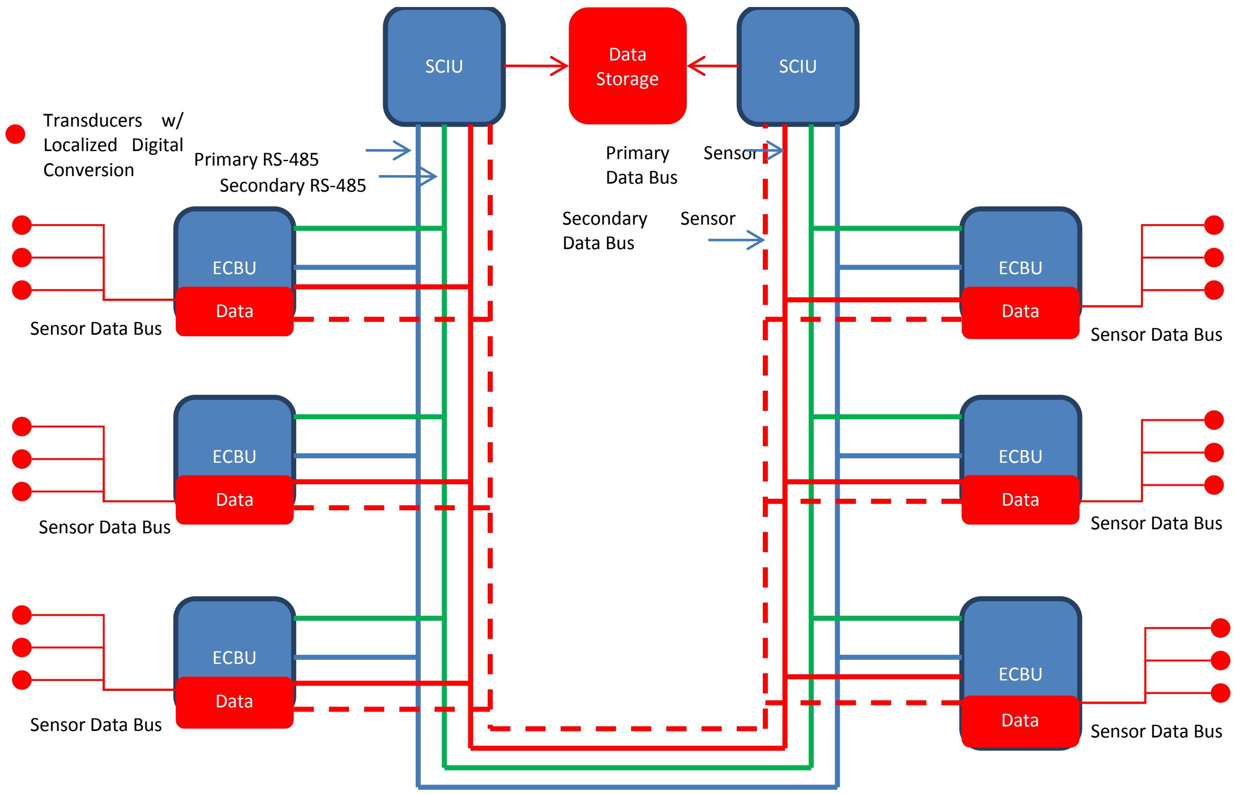

Figure 6. Additional SPMS Interface Buses

Interfacing the various transducers directly to the SCIU is plausible if a wireless data link is adopted. However, this yields transducers that require additional wiring for power or require energy harvesting from some other mechanical source (i.e., vibration, thermal, etc.). Given the possibility of a distributed architecture within an EPDS and PLC being implemented to interface the ECBU with the required transducers, it follows that this provides the ideal backbone for a transducer data network.

Given the nature of the EPDS system, a PLC bus between the sensors and the ECBUs would give the most functionality with the least amount of cost/weight impact. Between the ECBU and the SCIU, an RS-485 bus ideally will be adequate and, as mentioned in the section 2.3.2, is straightforward to implement. However, if data rate/number of drops becomes an issue, it is likely that another bus will need to be chosen. General aircraft would likely have between 15 to 20, or more, ECBUs within the EPDS system, which is well within the acceptable range of number of drops allowable; however, the protection that will be required on these lines adds additional capacitance and will reduce the theoretical maximum data rate given the number of ECBUs and a nominal length of wire. For smaller aircraft configurations (four to six ECBUs), the RS-485 bus would be sufficient. Knowing the data rates and the number of ECBUs that are needed would likely increase theoretical maximum data rates for larger aircraft configurations. For example, the AFDX bus has a maximum data rate of 10 megabits/sec, which is more than adequate to handle the full data rate requirement (i.e., no data reduction algorithms) of around 40 ECBUs, based upon the assumptions laid out in section 2.3.1. Using this bus as a high-speed data bus for sensor information has the added benefit of a well-defined protocol stack, further enhancing robustness.

The system architecture proposed in figure 6 yields the most functionality with the least impact to the criticality of the system and other systems within the aircraft. Wired data buses were chosen to circumvent issues that can arise from wireless data transfer use. The ECBM must have separate processing elements to allow separation between the critical function of load monitoring and the noncritical function of sensing element data collection. Similarly, additional data buses between the SCIU and ECBU are included to remove the possibility of overencumbering the existing flight-critical data bus.

3. SENSOR REQUIREMENTS.

Primarily, the enabling factor of any health monitoring system is its capability to gather sensor information from a broad number of sources and locations. Section 3.1 discusses what types of sensors would be required to interface with an enabled EPDS. Potential interfacing scenarios are then explored, some of which are ideally suited for an EPDS.

3.1 SENSOR TYPES.

Each of the sensor types required for aircraft specific loads have different technologies that can be used to measure the required physical parameter. A sensor, by definition, takes a specific physical parameter and transfers that to an electrical signal through a naturally occurring physical phenomenon.

3.1.1 Force Measurement.

A tension/compression load cell would be required to measure forces applied on, for example, a flight control actuator, while a strain gauge (taking advantage of similar physical parameters) could be used to measure static forces on the aircraft structure. Regardless, in many cases, force sensors will be required throughout the aircraft for an SPMS. Electrically, force sensors can be manufactured by capitalizing on one of the following electro-mechanical phenomena.

3.1.1.1 Piezoelectric.

Piezoelectric devices (generally a crystalline structure, such as quartz) produce a charge based on a force applied. Piezoelectric load cells work in botch tension and compression and have excellent accuracy and linearity, but do not work well with static force measurements due to the limitations of the piezoelectric crystals' energy output. Quasistatic measurements can be made and would be along the lines of the force loads applied within the test setup. In addition, all piezoelectric sensing elements exhibit pyroelectric properties, giving them sensitivity to changes in ambient temperature.

3.1.1.2 Piezoresistive.

Piezoresistive devices (generally silicone-based) vary in resistance, based on a force applied that is similar to the piezoelectric effect. However, since no charge is produced by the piezoresistive element, static forces can be measured easily. Although other technology can be used within strain gauges, the piezoresistive effect is commonly used. One major drawback of the piezoresistive load cells is the nonlinearity of their output.

3.1.1.3 Capacitive.

Capacitive devices vary in capacitance, based on a change in geometry of the sensing element. Two plates and a dielectric material are used to create a capacitance; as pressure is applied, the plates move closer to each other, slightly increasing the capacitance of the device. The reverse applies for tension-type loads.

3.1.1.4 Optical.

Optical devices measure the physical change within an optical fiber to detect the applied force. Taking advantage of Bragg's Law, fiber Bragg grating is generally used to detect an applied force relative to a shift in wavelength.

3.1.2 Accelerometer.

Acceleration measurements will be used to monitor the vibratory loads induced within the structure of the aircraft, a control surface, or specific electro-mechanical loads. Vibration measurement requirements drive a large portion of the data throughput of an SPMS due to the high sampling rate required. Accelerometers throughout the aircraft will likely be kept to a minimum because of the high data rates associated with these types of sensors.

3.1.2.1 Capacitive.

Capacitive devices generally measure acceleration by creating two distinct capacitances with a single movable plate and two fixed plates. When acceleration occurs, the movable plate adjusts, based on the acceleration force applied, and capacitance between one of the fixed plates increases while the other decreases.

3.1.2.2 Piezoelectric.

Piezoelectric elements, as stated before, produce an electrical charge when force is applied. To transfer the mechanical acceleration to a force acting upon the element, a seismic mass is generally used.

3.1.2.3 Piezoresistive.

Piezoresistive accelerometers have a similar function to piezoelectric accelerometers. Force is exerted on a piezoresistive strain gauge element by a seismic mass and the resistance change corresponds to the acceleration measured.

3.1.2.4 Hall Effect.

Hall Effect accelerometers use a spring and a seismic mass to correlate acceleration to a linear movement of the sensing element—a Hall element. As the element moves within a nonuniform magnetic field, voltage is produced on the Hall element that corresponds to the experienced acceleration.

3.1.2.5 Magnetoresistive.

Magnetoresistive accelerometers are very similar in operation to the Hall effect types, except that, instead of measuring a voltage produced by a Hall element, the resistance of the magnetoresistive element is measured.

3.1.3 Position Sensing.

Linear position sensing can be used to monitor linear actuators, extend/retract rates, and position command accuracy, for example. Generally, flight control actuators have position sensing inherent within the actuator and are used within the feedback loop of the flight system. Position monitoring, along with current drawn, can be used to determine whether or not an actuator is jammed or degrading because of the actuation time. Position sensing can be accomplished by numerous methods; three of the most common are linear potentiometers, linear variable differential transformers (LVDTs), and encoders.

3.1.3.1 Linear Potentiometers.

Linear Potentiometers consist of a resistive element and a sliding contact (wiper). As the wiper moves, a resistance is formed that can be measured to determine the position of the wiper arm. These devices are extremely accurate, but are generally not used where longterm reliability is required because of longterm drift characteristics and mechanical wear.

3.1.3.2 The LVDT.

The LVDT is a device that measures linear displacement based on applying an alternating current (AC) to a primary coil and measuring the voltage induced across secondary coils within the device. An armature is moved within the device changing mutual inductance between the primary and secondary coils, causing a variance in the AC output voltage correlating to a specific linear displacement. DC input/output versions are available, but are generally more expensive due to the integrated electronics required to produce and measure the AC signals.

3.1.3.3 Encoders.

Encoders, through an optical medium, produce digital patterns that correlate to linear distances. Optical methods are highly accurate and resolute over a wide temperature range; however, the optical method requires additional hardware that might not be feasible for all applications (e.g., encoded rail).

3.1.4 Temperature.

Temperature can be used in an SPMS to monitor various loads throughout the aircraft. Motor windings or any interface that requires lubrication (e.g., jackscrew nut) are examples of areas where temperature measurements would benefit health monitoring as, because of the thermal mass associated with them, a large temperature shift from normal operation could be used as an indicator. The following types of temperature sensors can be used: resistance temperature detectors, thermosistors, temperature bridges, solid-state temperature sensors, and thermocouples.

3.1.4.1 Resistance Temperature Detector.

A resistance temperature detector (RTD) is a temperature-sensitive resistor that has an accurate and repeatable temperature coefficient of resistance. Several different alloys can be used to form the resistor, the most common being platinum. Resistance at room temperature (25°C) is commonly 100 Ohm or 1000 Ohm, with the change per degree Celsius being approximately 0.4%. The resistance change is not linear with temperature, but it is repeatable. Other values of initial resistance are also used. Common measurement techniques are to: a) push a constant current through the device and measure the voltage across the RTD and b) place a constant voltage across the device and measure the current. Both techniques suffer from errors due to wiring resistance, but the errors can be either calibrated out or nulled out by using a three- or four-wire connection. Care must be taken to avoid self-heating during measurement, either by using a low current or by limiting the duration of the measurement.

3.1.4.2 Thermistors.

A thermistor is similar to an RTD in that it changes resistance with temperature. It is usually made with a conductive ceramic; various temperature coefficients and resistances are available. The measurement techniques are identical to those used by an RTD.

3.1.4.3 Temperature Bridge.

A bridge circuit can be made with thermistors or RTDs to measure temperature more accurately than a single device, especially where physical stress is present and thin film devices are used (e.g., windshields, skin surfaces). Physical stress causes changes in RTD or thermistor resistances that are not related to temperature. The bridge circuit balances temperature-dependent and nontemperature-dependent devices to null out the resistance changes due to stress.

3.1.4.4 Solid-State Temperature Sensor.

These devices, from various vendors, have a linear temperature-dependent output. The output may be voltage or current.

3.1.4.5 Thermocouples.

Thermocouples are bimetallic devices that output a millivolt-level signal in response to temperature. These devices are generally used only to measure temperatures above what can be measured by RTDs (greater than 600°C) and are found mostly in engine temperature monitoring systems.

3.2 SENSOR INTERFACING.

Primarily from a top-level hardware-oriented perspective, there are two distinct ways that information can be transferred from one location to another on an aircraft: wired and wireless. Wired forms of communication include: single-wire, optical fiber, PLC, and dual-wire (balanced) buses. Each of these types of wired interfaces has its own strengths and weaknesses. Wireless forms of communication all take advantage of some form of the electro-magnetic spectrum to achieve data transfer. From the line-of-sight-dependent infrared transmissions to the more robust form of radio frequency transmissions, wireless transmissions seem a likely candidate to allow a data-intensive system to be implemented within an aircraft without a significant impact on weight and installation complexities. Within each of the different types of physical interfaces, numerous standards exist that also identify the protocol along with the physical implementation. Protocol options will be discussed later; the focus of this section is mainly on the physical implementation and its impact on the overall aircraft system.

3.2.1 Wired Interface Options.

Each of the wired options outlined below could potentially be used for either the sensor-to-ECBU interface or the ECBU-to-SCIU, except the direct analog wiring interface, which is specific to the sensor-to-ECBU interface. Whether or not the overall wired interface implementation would be advantageous or disadvantageous for the system health monitoring-enhanced EPDS system is discussed.

3.2.1.1 Analog Sensor Direct Wiring.

The most straightforward option for collecting data from distributed sensors is directly wiring the analog sensors to an A/D (analog-to-digital) converter within the distributed ECBUs, (see figure 7). The analog information would generally be transferred through use of shielded, controlled impedance cables to minimize the losses and noise that could potentially corrupt the underlying data. New aircraft designs would benefit from the best implementation option within the use of direct analog wiring in that a fully distributed ECBU architecture could be realized, minimizing the overall wiring required to conduct the analog sensor signals. Retrofit applications, where ECBUs cannot be placed in ideal locations, will likely not be able to manage the additional weight that would be required from a wiring perspective. This is mainly due to the requirements that power and analog sensor wiring would be needed for most sensors within the aircraft (some forms of force/vibration sensors are powered and convey sensed information on the same wiring). Direct wired sensors are relatively noise-immune and are simple in theory to apply, but require additional hardware in the EPDS, additional software, and the running of multiple wires to each of the sensors.

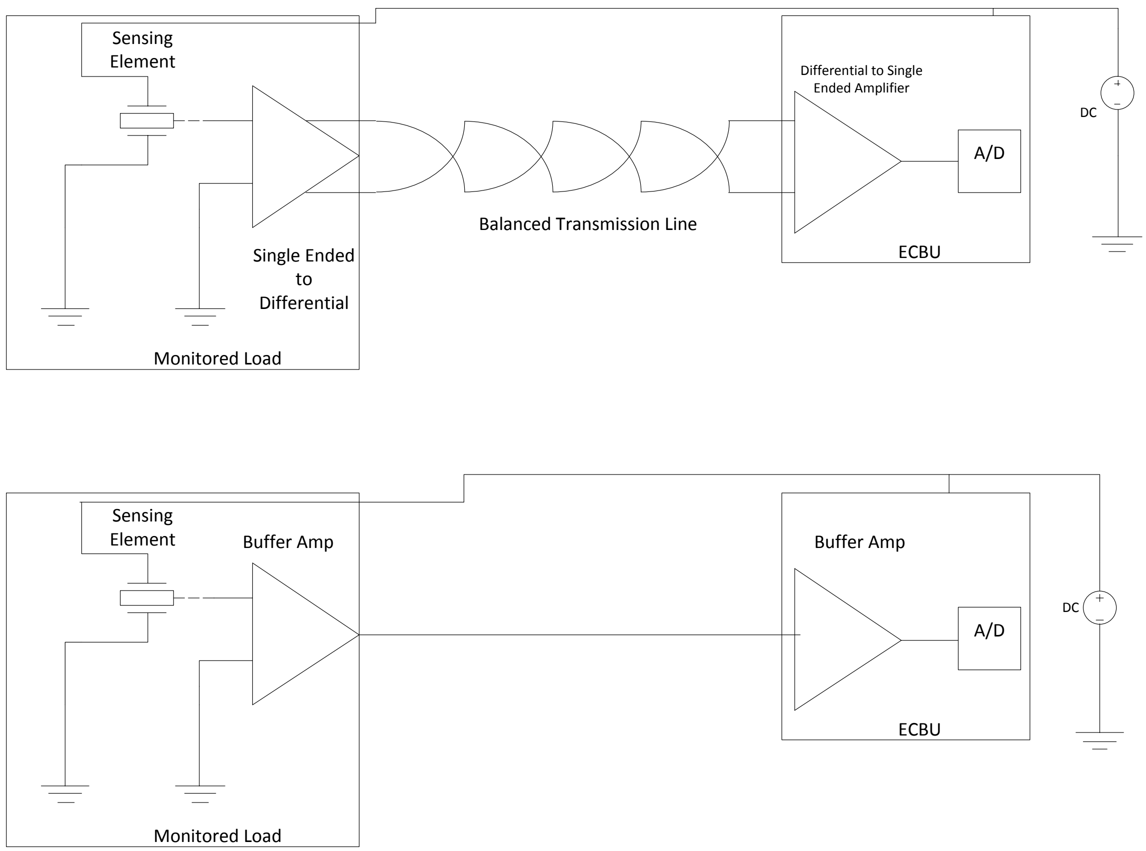

Figure 7. Examples of Direct Wiring of Analog Sensors

3.2.1.2 Single- and Two-Wire Electrical Digital Data Bus.

Digital data buses exist from the simplistic one-wire (e.g., Maxim 1-wire®) and differential pair implementations (RS-485, RS-422, etc.) to the more complex networked, differential pair (e.g., CANBUS). A simplified representation of a digital bus interface is shown in figure 8. The main difference between the simplistic differential pair and networked differential pair is the associated software overhead implemented in each of these. For example, where the RS-485 bus has little overhead for operation, the CANBUS has well-defined layers within the software protocol. This results in a much more robust communication link, capable of handling bus collisions and intermittent dropouts within a packet that is being transferred with little or no overall data loss. The focus of this section is a preferred physical interface; there is further discussion regarding protocol capabilities in section 6. Generally, single-wire buses suffer from low noise immunity and data throughputs, effectively making them unlikely candidates for aircraft implementation.

Regarding the sensor-to-ECBU interface, a digital data bus is extremely advantageous if there is an abundance of sensors available that directly communicate over the chosen bus (both physical and protocol layers). If an off-the-shelf sensor does not communicate over a given physical bus interface, it is an extremely unlikely candidate, as it would not alleviate the need for large amounts of extra hardware/wiring. There are some commercial grade protocols that allow for a common digital data bus integrated within various sensor types, such as IEEE 1451. Labeled smart sensors, they generally have some form of a microcontroller and memory integrated within the sensing element to allow communication and information to be stored about the sensor locally. This gives an added benefit of allowing multiple sensor types to be coupled to a bus with little or no configuration software needed. However, the smart sensor standard has not been fully accepted within the industry and, thus, a limited selection of sensors is available; even fewer meet aircraft grade operational conditions.

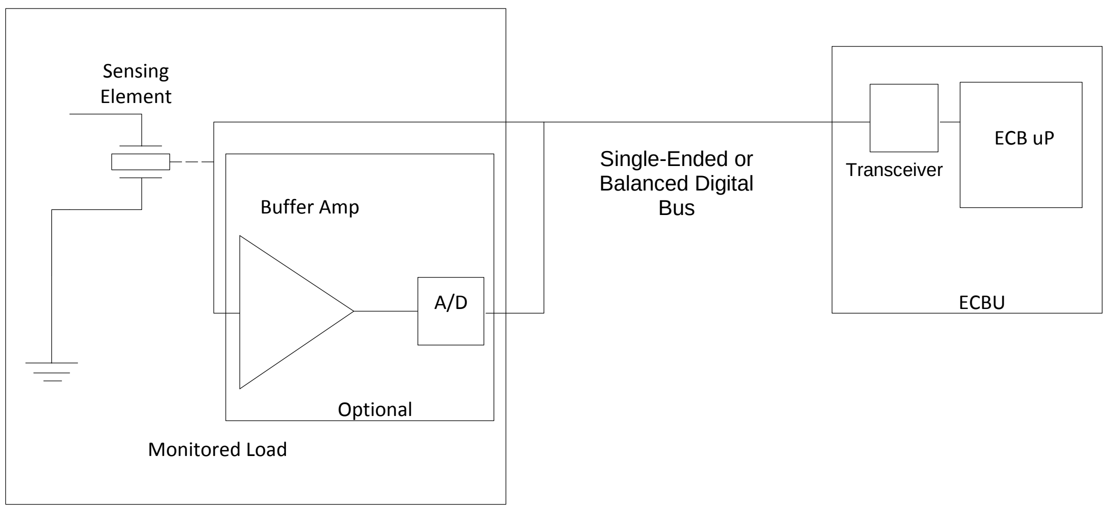

Figure 8. Digital Data Bus Interface

<u>3.2.1.3 Optical Digital Data Bus</u>.

Optical data transfer has some beneficial properties when compared to the use of copper as a transmission media. The theoretical limitations of throughput are almost nonexistent (limits become the driving circuitry and the number of colored beams used) and the data is transferred along an optical fiber that is generally much lighter than copper. However, the frailty of the optical fiber (usually some form of glass) is a major concern, along with the amount of circuitry generally required to implement a high-speed optical data bus, precluding this option from being used within an aircraft environment. If a more robust optical fiber can be produced, this option will become more viable, as advances in the miniaturization of driving circuitry are continually being motivated by the commercial computer market.

<u>3.2.1.4 Power Line Digital Data Bus (PLC)</u>.

When a sensor is associated with a load, such as measuring the temperature of a heater, PLC of the sensor data makes the most sense. No extra wiring is needed for this, and the analog sensor is coupled with a power line interface module to get the sensor power and enable the communication of data over the power line feeding that particular load/sensor combination. Numerous commercial off-the-shelf implementations of PLC exist: Orthogonal Frequency Division Multiplexing, frequency shift keying, and Direct-Sequence Spread Spectrum, to name a few. All commercially available PLC implementations, however, use voltage to convey the digital signal and, in high noise environments (noise from motors, transmitters, and switching power supplies), either data packets are lost or data rates suffer to ensure their reliable delivery. In an aircraft environment, especially a 28 VDC aircraft, there is generally a large amount of capacitance on the power lines, making voltage-encoded data even more difficult to use successfully.

A scheme is proposed where, rather than using voltage modulation, the sensor data will be modulated onto the load current. Modulating the data onto the load current, either as a digital pulse stream or as a pulse-width modulation (PWM)-encoded analog signal, is completely noise immune, and requires the least additional hardware and software. Data from the sensor can be acquired in the ECB by the circuitry that is already present to monitor the current/voltage of the load, so no extra hardware is needed and any bus failure affects only that particular load, giving a level of isolation between all the sensing elements. Figure 9 shows a simplified block diagram of the proposed current mode PLC. This method will be ideal for slow-moving phenomena (temperature, force, pressure, etc.). However, it is unlikely that vibration signatures can be captured without some other method, separation of the ECB functionality from the PLC functionality, or a combination of both.

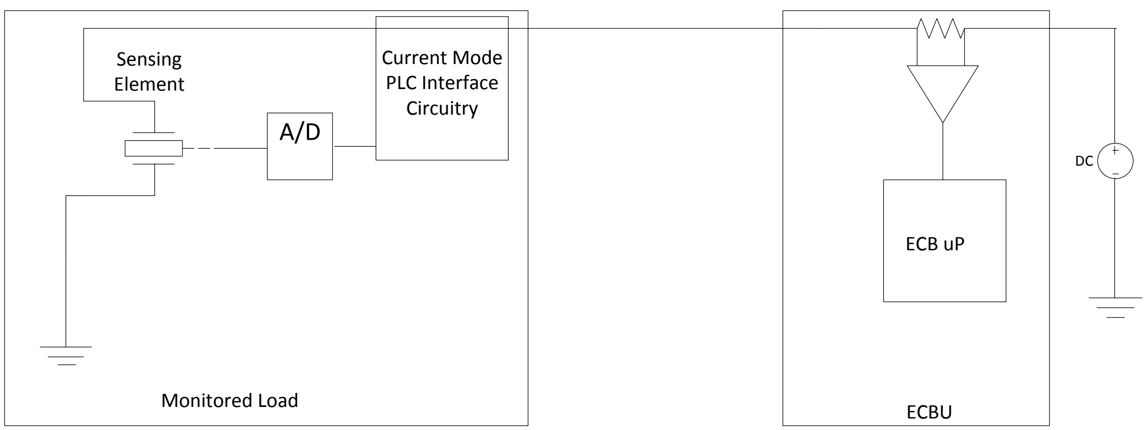

Figure 9. Current Mode PLC

3.2.1.5 Preferred Wired Interfacing Option.

Since the EPDS system has a direct interface to all the power lines within a given aircraft, PLC makes the most sense for the sensor-to-ECBU interface. The PLC would be extremely efficient and retrofit-capable, especially if the information can be encoded within the load current without the need for an additional microprocessor at each of the sensing elements. Qualification of the ECBU hardware as flight-critical will likely force a new PLC processor on the ECBU side to ensure an adequate level of separation.

The ECBU-to-SCIU interface will require something with a much higher data-rate capability and multiple bus drops (the envisioned sensor-to-ECBU interface allows one per line to eliminate the need for a microprocessor on the sensor side of the bus). Some form of a balanced differential pair bus would be the best fit for this option as it provides the best data-rate/noise immunity for the application.

3.2.2 Wireless Interface Options.

A wireless sensor network within an aircraft health monitoring environment has some unique advantages when compared to wired scenarios. If the proposed wireless sensor network takes advantage of energy-harvesting techniques, the sensor nodes can be installed without additional wiring being required. This saves weight and eases the installation within a retrofit environment. Different wireless sensor network protocols exist within the commercial environment and may be applicable to aircraft applications. However, a major hurdle exists in getting these protocols approved for use within an aircraft environment. Currently, only one company has received approval from the Federal Aviation Administration/Federal Communications Commission for using a wireless network in-flight: Gogo Wi-Fi. Along with the approval concerns, there could be substantial interferences, security issues, and reduction in data throughput with a wireless sensor network if both were to operate within the same bandwidth. Of these concerns, the security of transferred data and of the overall network is of primary concern. A wireless sensor network and the allowance of everyday passengers to use wireless devices increases the potential for the network to be compromised. While the current Wi-Fi internet offered does not have a direct data link to the aircraft's flight computer, the wireless sensor bus within the EPDS system would have this direct link. Ideally, if implemented, the wireless data bus would need to operate within a separate frequency band on which general off-the-shelf consumer electronics could not communicate. Wi-Fi within the aircraft uses 802.11 b/g (2.4 gigahertz (GHz)) technology, and a large majority of personal electronics can communicate within the 802.11 n optional range (5 GHz). A sensor network would need to avoid these frequency bands to provide the maximum amount of security within this link. Figure 10 shows the ideal wireless sensor network, in which each of the sensors acts as a repeater in some sense to extend the maximum range of the network and ideally through metallic structures (without the need for wireless repeaters).

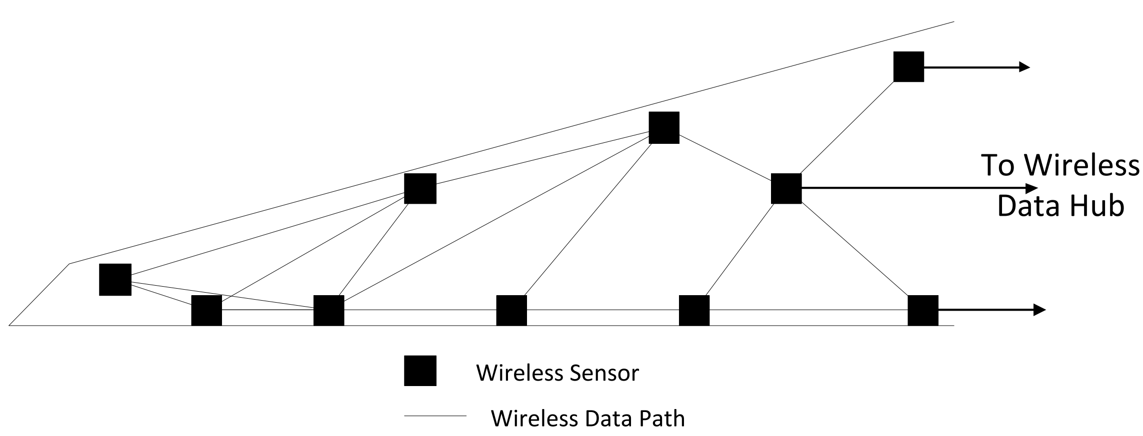

Figure 10. Wireless Sensor Network

Aside from security concerns, when using a wireless implementation, power for sensor and wireless antenna operation will be required. Wiring power to the sensors makes the most sense, but defeats the purpose of having a wireless data interface. An interesting option for powering these sensing elements is energy harvesting. Energy harvesting uses some form of a physical phenomenon to gather enough energy to operate the required circuitry (thermal, vibration, etc.). Implementing energy harvesting is fairly straightforward, and specialized devices are available to allow rapid development [1]. However, this would likely cause the sensor network to be "dead" during periods where the expected physical input is not present, because a majority of sensors are designed to excite only under specific input ranges (i.e., on the ground when the plane is powered, but is not experiencing the particular vibratory impulses needed to power the devices). Multiple forms of energy harvesting techniques could potentially be used to alleviate this issue.

Another possibility of having an autonomous wireless sensor network would involve using radio frequency identification (RFID) technology to implement the sensing network. Currently, there has been some work within the field to create a suite of sensor modules that are powered completely by a standard RFID reader (operating within the 860 to 960 MHz band). Rather than being powered by some form of naturally occurring harvesting technique, these devices power the required circuitry from the radio frequency (RF) energy being broadcasted by the RFID reader. However, as a result, the maximum range of these devices is fairly limited (approximately 10 ft) [2] and they can only feasibly be used on extremely low power sensors (1-10 uA). With the limited range of these types of devices, multiple readers would need to be placed periodically throughout an aircraft and would require power and data feeds to them. For example, to allow wireless RFID sensing along the entire length of the wing of a Boeing 737, at least three readers would have to be placed within the wing section, with power and data lines running to each of them (figure 11).

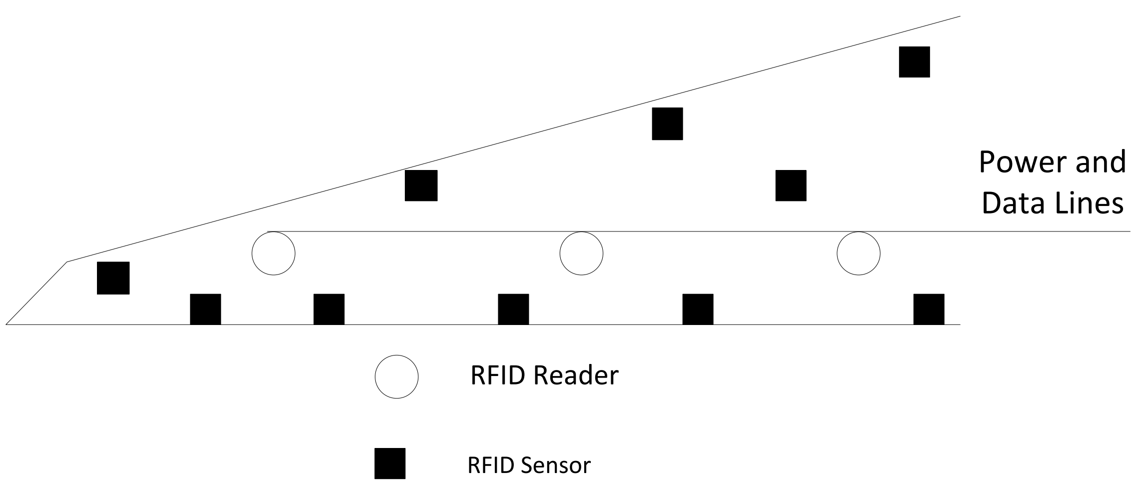

Figure 11. Example of Wing Layout of RFID Sensors and Readers

<u>3.2.2.1 Preferred Wireless Interface</u>.

Wireless data transfer within an aircraft structure has a few inherent problems aside from security concerns. When determining the effective broadcast range, metallic structures (such as bulk heads) would reflect the RF energy, potentially causing a major issue with whole aircraft coverage through a minimal number of broadcasters/readers. If a more centralized wireless hub is adopted, repeaters will need to be placed throughout the aircraft to allow complete coverage.

RFID would be the preferred wireless interface from the sensors to the ECBs. This preference is based mainly on the operational frequency range. If the number of readers that would be required across the aircraft could be greatly reduced (range increase), and if the RFID sensing elements could be powered (rather than relying on the limited energy contained within UHF signal without a large impact on the weight/cost of implementation) RFID would be an ideal sensor network. It is possible to outfit an RFID sensor with an energy harvesting technique to avoid running power within standard wiring; however, this may not alleviate the problems associated with having limited energy available for running higher-powered sensors. If the sensors were to be powered from an aircraft bus, they could also broadcast the data. This would replace the current method of transmitting the data, in which the impedance of the receiving antenna is changed, thereby reflecting some of the broadcasted signal back to the reader (indicating a digital bit). By potentially broadcasting (rather than reflecting transmitted power), the number of readers on a plane could be significantly reduced to one or two since each of the sensors could act as a repeater for sensors farther away from the reader.

Regarding the ECBU-to-SCIU interface, a standard wireless network (IEEE 802.11 b/g/n) would be ideal because of its inherent robustness of data transfer and much higher data rates than can be achieved through standard RFID implementations (54 Mbit/s for 802.11g, and 150 Mbit/s for 802.11 n). Items within the 802.11 protocol allow for multiple users (ECBUs) through multiplexing/sharing, and g/n extension would allow access throughout most of the plane (with a maximum theoretical range of 460 ft).

3.2.3 Advantages of the EPDS Communicating Directly With Sensors.

The EPDS can be used as a sensor data acquisition device to replace special purpose data acquisition systems. However, the most interesting reason for acquiring sensor data in the EPDS is to enable the EPDS to implement closed-loop control systems without the need for special LRUs unique to each system. For example, with a windshield temperature control system, the EPDS supplies the power to heat the windshield, so it can also modulate that power in response to windshield temperature, thus eliminating the windshield temperature control system LRU entirely. The EPDS has to acquire the windshield temperature to perform this function. Many other system LRUs can be eliminated, with a corresponding decrease in aircraft weight and an increase in reliability (fewer parts that can fail), by using the EPDS to implement a closed-loop control system. To be used as a closed-loop control system or as a monitoring device, the EPDS must gather information from sensors. These sensors can be of any type that measures a physical parameter, such as a position, temperature, pressure, or level. Sensors can have either an analog or digital output. There are several ways that sensor data can be acquired by the EPDS.

4. FAULT PROGNOSTICS.

Much of the data gathered by the ECB is useful for the detection and diagnostics of failures in real time operations, but there have been various efforts to use this data to predict the remaining lifetime or the impending failure of the load. Numerous companies and government agencies have developed prognostics algorithms for electrical and electro-mechanical components and assemblies. The NASA FLEA (Flyable Electro-Mechanical Actuator) test stand has been used to develop and test prognostic algorithms, and is of particular interest because of the public availability of the information. The jackscrew actuator that was used in the Astronics test stand is similar to that used by Balaban et al. [3].

This project will not attempt to develop and use prognostics algorithms, but will explore the acquisition of electrical data required for load and health monitoring, augmented by sensors that can be interfaced to the ECB via PLC techniques. This data is also the basis for the prognostics algorithms that are being developed by other investigators. For a device like a jackscrew linear actuator, the primary identified failures and measurement techniques are similar to that of the ball screw actuator used by Balaban.

The required minimums of resolution, accuracy, and sample rate listed in table 12 are determined by the physical characteristics of the sensor used in this testing. Better resolution, accuracy, and sample rate do not necessarily improve the quality of the data for this linear actuator, but an actuator with a faster or slower speed, higher or lower thermal mass, or higher or lower weight may require different measurements. In certain cases, increased resolution and a faster sample rate may detect a developing fault at an earlier stage; however, in a real world aircraft situation, electromagnetic interference, electrical generation noise, normal ambient temperature variations, and airframe vibration will limit the usefulness of faster, more precise data acquisition devices. Balaban [4] shows that one of the primary techniques for predicting remaining actuator lifetime during a mechanical fault (high mechanical resistance) is the gradual increase of the temperature rise over ambient of the coil. The coil temperature cannot change rapidly because of the thermal mass, and time variation in temperature in subsecond increments is not useful data for the prediction, so the measurement of temperature at intervals of less than 1 second is unnecessary.

Table 12. Fault Modes and Potential Determination Indicators

Condition	Symptoms	Estimated Resolution, Accuracy, and Sample Rate Required
Electrical		
Intermittent opens	Current spikes below specified limits for random frequency, length, and magnitude.	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 10 Hz minimum
Winding damage	Current spikes above normal maximum levels for random frequency, length, and magnitude.	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 100 Hz minimum
	Abnormal temperature rise on actuator windings	Temperature Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
Mechanical		
Underload (broken linkage to load)	Current below specified limits	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
Overload (linkage to load damaged or rated load exceeded by external factors)	Current above specified limits	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
	Abnormal temperature rise on actuator windings	Temperature Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
Jammed linkage or load	Current above specified limits	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
	Abnormal temperature rise on actuator windings	Temperature Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
Bent shaft	Current fluctuations related to the shaft rotational speed	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 100 Hz minimum
	Vibration above expected operational limits	TBD

Table 12. Fault Modes and Potential Determination Indicators (continued)

Condition	Symptoms	Estimated Resolution, Accuracy, and Sample Rate Required
Thread damage (spalls, nicks, foreign matter)	Current fluctuations related to the shaft linear position (not due to normal load positional variance)	Current measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 100 Hz minimum
	Vibration above expected operational limits Abnormal temperature rise on actuator nut	TBD Temperature Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
Lack of lubrication	Current above specified limits	Current Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
	Abnormal temperature rise on actuator windings	Temperature Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum
	Abnormal temperature rise on actuator nut	Temperature Measurement Resolution 0.5% of full scale Accuracy ± 1% of reading Sample rate 1 Hz minimum

4.1 CURRENT CAPABILITIES.

As a baseline, the existing system samples and reports current/voltage back to the SCIU at a rate of 1 Hz. Although this sample rate is adequate for basic load monitoring, prognostic/diagnostic capabilities are severely limited. Information that can be gathered from a 1 Hz current update rate includes:

- On/off cycle measurement: Actual operation time can be kept track of and potentially used for rudimentary time replacement programs.

- Basic current overload detection: A current overload condition can be caused by any number of potential failures within or external to the actuator. High resistive fault to ground, motor winding failure, and jamming conditions, whether external or internal, will all exhibit a higher than normal current consumption.

- Load connected: When a load is commanded "on," whether the load is connected properly can be determined by looking for nominal current flow. If no current flow exists, it may be determined that the load is disconnected (because of a loose pin, broken wire, etc.).

Along with the current monitoring capabilities, the ECBUs have a number of spare analog inputs that could be used to monitor directly wired sensors within an aircraft environment. When an EPDS system is distributed, this would greatly reduce the amount of equipment and wire that would be required to embed analog sensors throughout the enabled aircraft.

4.2 REAL TIME VS. POST-FLIGHT HEALTH ANALYSIS.

An EPDS detects and interrupts the circuit in response to overload faults, as well as arc faults and load faults. The EPDS also collects voltage, current, and time data for each load as part of its normal operation. These data can be analyzed for anomalies so that problems with the connected load or wiring can be diagnosed, or to predict that certain maintenance actions will need to be performed at a future time. A cursory look into the requirements of the EPDS system with regard to information needing to be annunciated to the crew or logged for postflight analysis was completed. Emphasis was placed on the ECB as a sensor. Evaluation of the test system will allow secondary sensors to play a role in fault determination within the EPDS system.

4.2.1 Requirements for Performing In-Flight Processing.

These data will be processed and annunciated if the crew needs to take action in regard to a detected fault. Actions may include resetting a CB, shifting to a secondary system, or shutting down a malfunctioning load.

These data will be processed and annunciated if the detected fault requires an immediate landing, as the continuation of the flight is, or can quickly become, hazardous.

These data will be processed and annunciated if the crew needs to avoid certain situations or actions for a continued safe flight.

The faults listed below generally require in-flight detection and annunciation (table 13), but certain noncritical loads may not need to be annunciated to the flight crew, as no action is required. These must be decided on a circuit-by-circuit basis.

Table 13. Table of In-Flight Detection/Annunciation Faults

Fault Detected	Action Required In-Flight	Action Required On-Ground
Parallel arc fault	System dependent. Must be annunciated to crew.	Repair wiring
Series arc fault	System dependent. Must be annunciated to crew.	Repair wiring
Overload fault	System dependent. Must be annunciated to crew.	Repair wiring or load
Inoperative load	System dependent. Must be annunciated to crew.	Repair or replace load or wiring
Unacceptable current draw, but under the overload trip limit	System dependent. Must be annunciated to crew.	Repair or replace load or wiring
Bus voltage below acceptable limit	Switch to alternate bus.	Power source maintenance
Load voltage below acceptable limits	Disconnect load. Annunciate to crew.	EPDS maintenance
Bus voltage above acceptable limit	Switch to alternate bus.	Power source maintenance
Load voltage above acceptable limits	Disconnect load. Annunciate to crew.	EPDS maintenance

4.2.2 Requirements for Performing On-Ground Processing.

For all other situations, where the flight crew does not need to perform any actions or modify any operations, these data collected will not be processed in the flight hardware, but will be downloaded from the EPDS and analyzed on ground-based equipment. The types of anomalies listed in table 14 are impending faults. In these cases, no action need be taken immediately, but investigation by maintenance personnel is required.

Table 14. Table of Detected Faults With No In-Flight Action Required

Fault Detected	Action Required In-Flight	Action Required On-Ground
Load current above normal, but within CB rating	None	Repair or replace load
Load current below normal	None	Repair or replace load
Operating time of load approaching maintenance requirement	None	Perform maintenance action or replace load before failure
Load current trending upwards	None	Perform maintenance action or replace load before failure
Load current trending downwards	None	Perform maintenance action or replace load before failure
Load current has peaks or valleys outside of the normal range	None	Perform maintenance action or replace load before failure
Bus voltage above normal	None	Perform maintenance action on power source
Bus voltage below normal	None	Perform maintenance action on power source

5. DEMONSTRATION SYSTEM HARDWARE.

A demonstration/test system was developed to highlight the functionality that is achievable through an enabled EPDS system. To exercise the system and provide a series of test cases, a DC linear actuator was selected as the primary load for demonstrating the various data-collection methodologies that are applicable to health-monitoring applications. A simplified block diagram of the demonstration hardware is shown in figure 12.

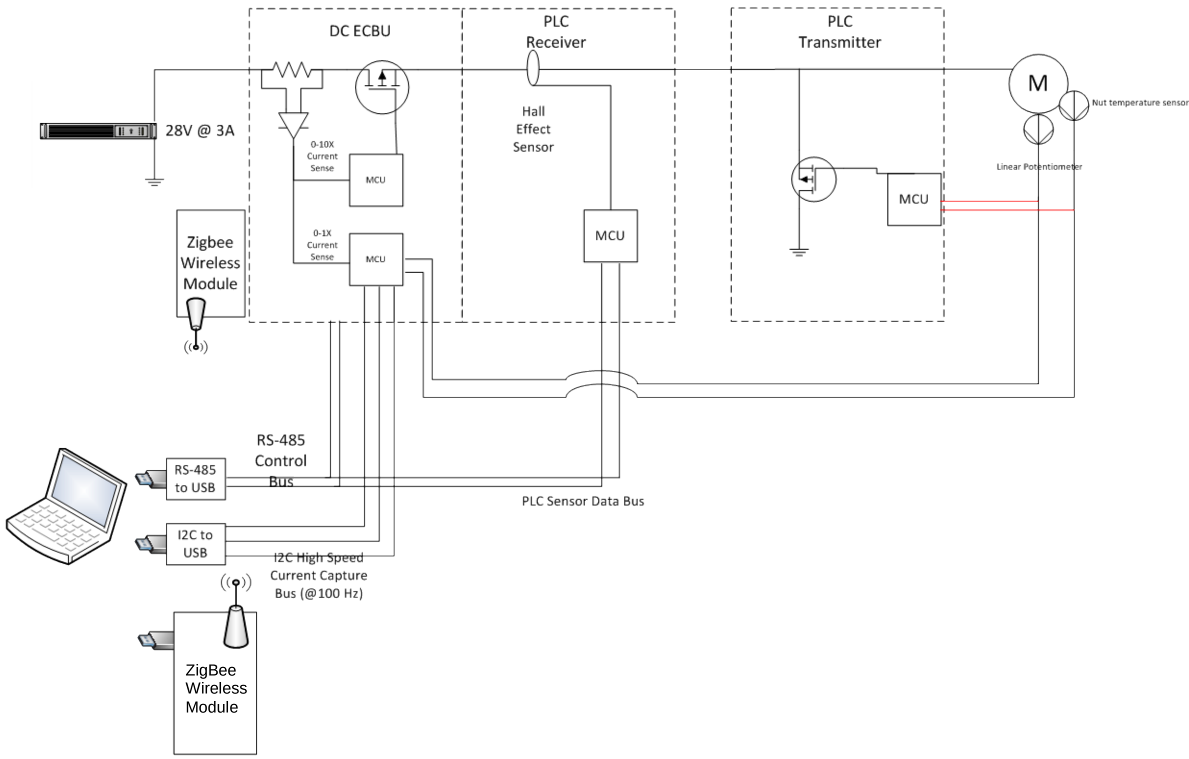

Figure 12. Demonstration Hardware Block Diagram

The primary elements within the demonstration system include:

- Laptop Computer—A laptop computer was used to simulate the SPMS functionality of the SCIU. Load commands were sent from the laptop and sensor/load information gathered through various interfaces. The different interfaces highlighted the capabilities that can be achieved through an enabled EPDS system. The RS-485 was used both as the primary control/load current information bus and to interface with a custom PLC receiver highlighting the PWM PLC functionality. A second digital interface (I2C) to the ECBU was used to show that, with minor modifications, a much more resolute (both in amplitude and time) current could be gathered through the ECBU. A ZigBee® wireless interface was used to show the capability of using wireless as a secondary control/sensor gathering bus.

- DC ECBU—A modified ECBU was used to control/gather current and sensor information pertaining to the health of the actuator load. Along with the inherent current measurement capabilities, the circuitry was slightly modified to gather current at a 100 Hz rate, with the sensing range 1-1.5 times the ECB's rated load. The ECBUs have the inherent capability of gathering sensor information through the use of analog inputs. This was demonstrated by monitoring the nut temperature and actuator shaft position.

- PLC Receiver—The PLC receiver is a piece of custom hardware, shown in figure 12, that could be easily integrated within each of the ECBs. As discussed in section 3.2.1.4, the receiver interprets current pulses sent by the PLC transmitter and converts this information to a sensed parameter value. In the demonstration, system temperature of the actuator jackscrew nut and position of the actuator shaft was received through the PWM PLC approach.

- PLC Transmitter—The PLC transmitter uses the load power to operate local circuitry used for digitization and transmission of analog sensor information. Transmission to the PLC receiver is achieved through modulating current pulses on top of the load current; pulse width timing corresponds to sensor information. Different sensors are transmitted through the same bus by a preamble within the PWM transmission.

5.1 DEMONSTRATION SYSTEM SOFTWARE.

A graphical user interface (GUI) was developed and implemented on a laptop computer for primary control and data collection/storage of the SPMS demonstration system. The GUI/laptop combination emulates the SCIU functionality that would be present within a full system implementation.

The GUI is designed to provide individual control of all interfaces for system development, as well as a coordinated start of all interfaces for running tests and collecting/storing the data within a database. Figure 13 shows the primary interface panel for the GUI.

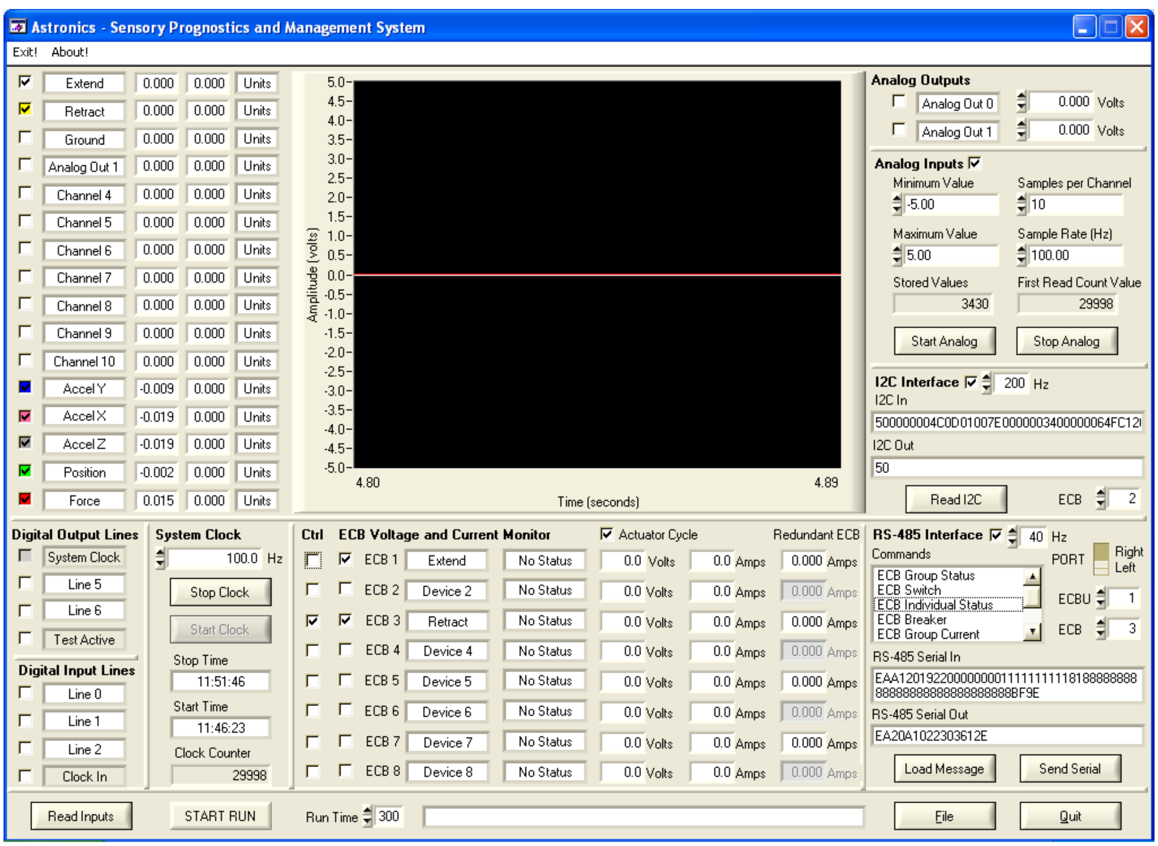

Figure 13. The GUI Interface Panel

5.1.1 The GUI Functional Blocks.

The following are the GUI Functional Blocks:

- Analog Inputs—The user is able to select and name up to 16 analog input channels. Controls are provided to set the sample rate and the minimum and maximum values to be displayed on the real time graph.

- Analog Outputs—Two general purpose analog outputs are provided. These are not required for SPMS, but are used to verify operation of the data acquisition system.

- I2C Interface—Controls the I2C interface to the redundant ECBs. Displays the input and output messages and sets the data transfer rate.

- RS-485 Interface—Controls the RS-485 interface with the ECBU. Displays the input and output messages, sets the data transfer rate, and selects the COM port of the laptop computer.

- System Clock—Adjusts the overall system clock provided by National Instrument's NI-DAQ™. Displays the start and stop times of a test run.

- Digital Input—Monitors the system clock for timing control. Provides three general purpose digital inputs not used by the SPMS.

- Digital Output—Outputs the system clock, and provides two general purpose outputs and start and stop transitions on one line for triggering of external equipment.

- ECB Voltage and Current Monitor—Displays the voltage, current, and state of the individual ECBs. Two checkboxes are provided per ECB. One checkbox is used to turn the ECB on and off, and the other is to activate recording of data from that ECB. This will allow the capture of data when an ECB is turned on or off. The Actuator Cycle checkbox controls a test mode that alternates the activation of ECBs 1 and 3. These may be connected to the extend and retract lines of an aircraft actuator for prolonged cycle testing.

6. SYSTEM DEMONSTRATION.

A system demonstration highlighting findings and potential system capabilities was completed on July 12, 2012, with additional testing completed on September 12, 2012. Additional demonstration was required because of some unexpected hardware failures that caused the PWM PLC circuitry to have an uncharacteristic error. The primary technology demonstrations were of the previously discussed PLC technique and the capability of the ECB itself to be used as a sensing element.

6.1 DEMONSTRATION SETUP.

Figure 14 shows the demonstration setup, highlighting the potential for the ECB to be used as both a diagnostic tool (in sensing the load current of an electro-mechanical actuator) and the receiving element of a PLC signal. The PLC receiving element is currently external to the ECBU, but future development will include the required circuitry at very little cost/weight impact to the overall system. The PLC transmitter circuitry could be easily integrated within the monitored load itself.

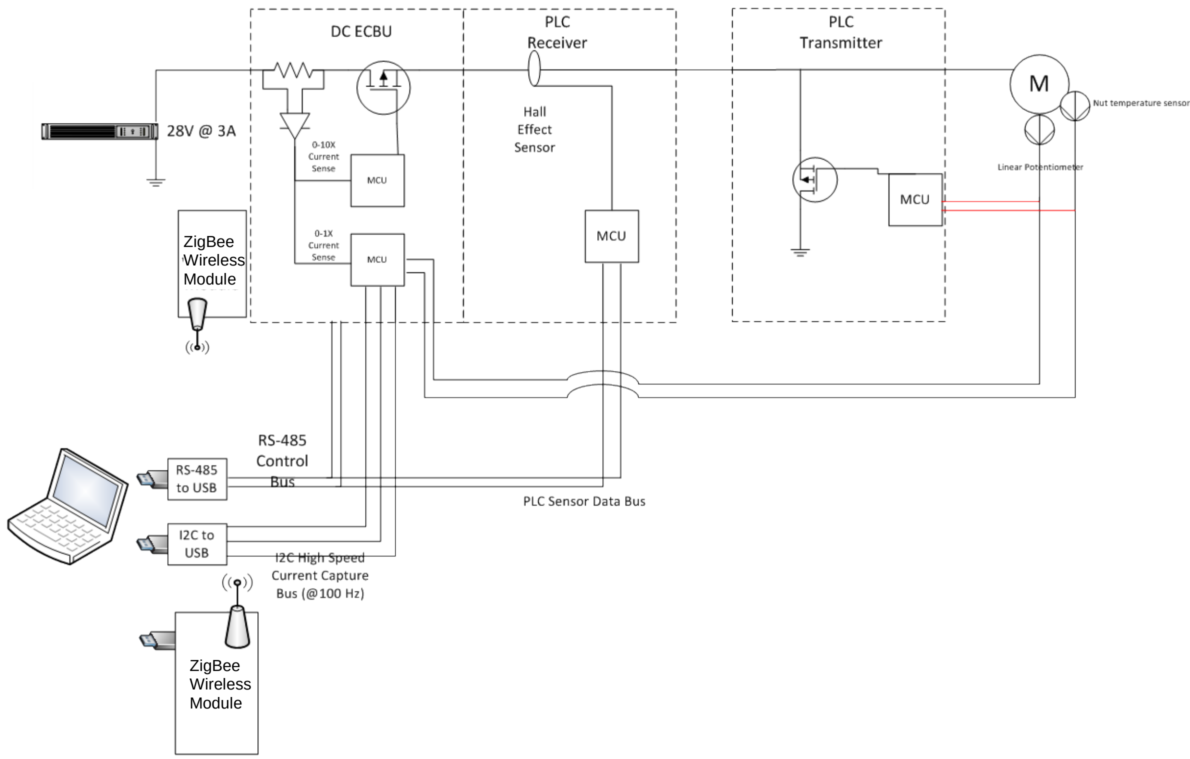

Figure 14. System Demonstration Block Diagram

Figure 15 shows a simplified actuator test fixture that allows the linear actuator to work against various loading conditions. Various weights and spring loading can be used to determine what type of data can be accumulated from monitoring the load current.

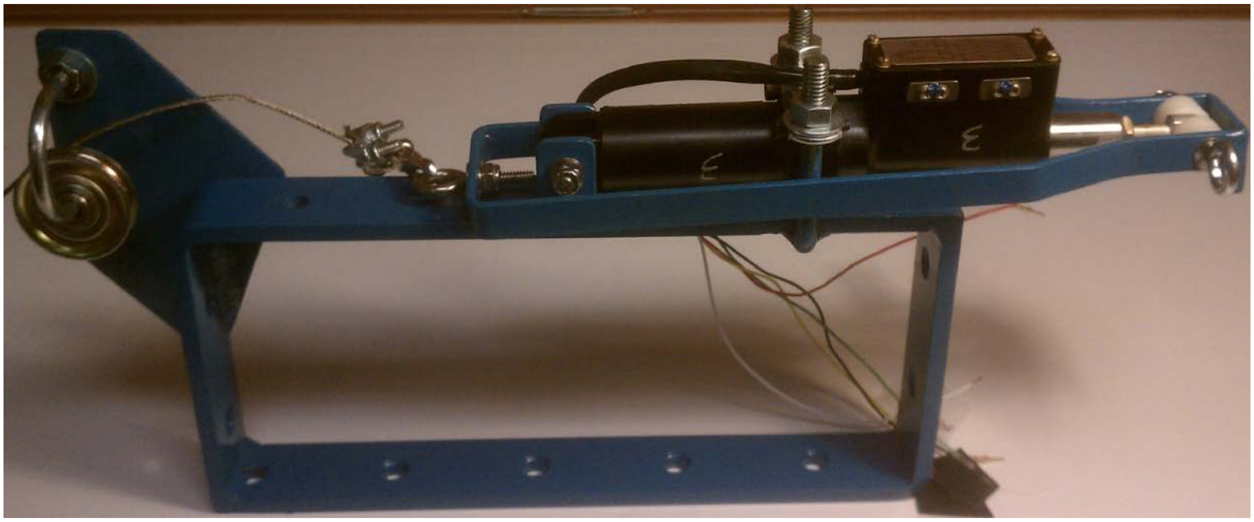

Figure 15. Actuator Loading Test Fixture

6.2 THE ECB AS A SENSING ELEMENT.

The primary tests performed highlighted the ECB's capabilities as a sensing element. Tables 15 and 16 show the test conditions that the electro-mechanical actuator was initially exposed to and, thus, what the ECB can detect when monitoring this type of load. Two different actuators were used in this demonstration: one was an unmodified actuator in new condition and the other was in simulated worn condition (and had silicon grit packed within the threads).

Table 15. Unmodified Actuator Test Conditions

New Condition Actuator	
Push Load Conditions	Side Load Conditions
100 lb push load	No off-axis load
	25 lb off-axis down load
50 lb push load	No off-axis load
	25 lb off-axis down load
Zero push load	No off-axis load
	25 lb off-axis down load

Table 16. Worn Actuator Test Conditions

Worn Condition Actuator	
Push Load Conditions	Side Load Conditions
50 lb push load	No off-axis load
Zero push load	No off-axis load

6.2.1 The ECBU Sensing Capabilities.

Since the ECBU currently samples at a 1 Hz rate, its diagnostic/prognostic capabilities are fairly limited. In the tests performed, mainly load changes within the actuator current were detected. The graph shown in figure 16 compares the reported ECB current at a 1 Hz rate between a 50 lb and 100 lb load on the actuator. The vertical axis represents amps and the horizontal represents seconds.

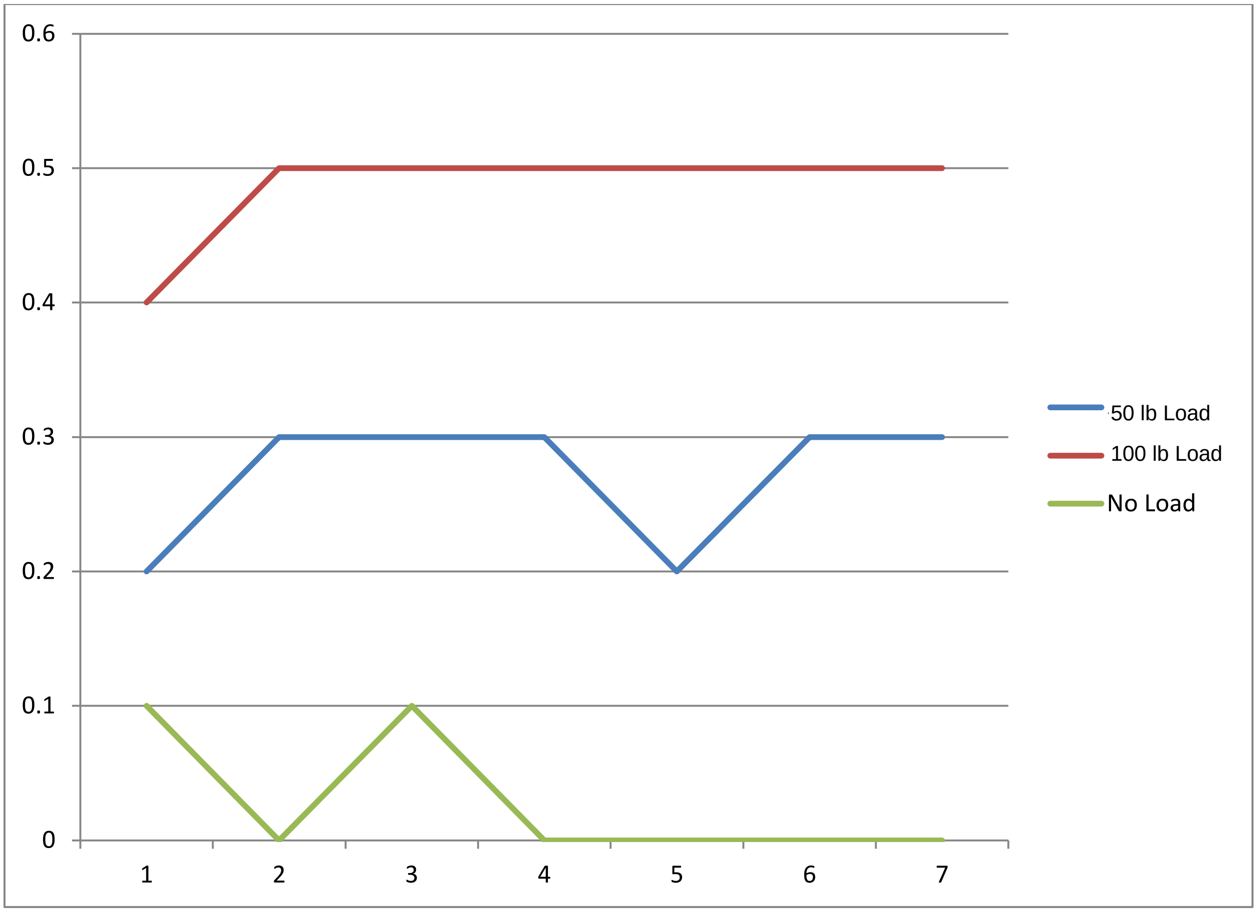

Figure 16. Current Drawn vs. Loading Conditions

One of the primary issues with the way the ECBU is currently configured is the current resolution it is capable of measuring. As discussed earlier, the ECBU currently has a resolution of 100 milliamperes per bit, which is the primary reason that the "No Load" run shows up as zero current draw.

Throughout the program, the ECBU's current sensing capabilities were drastically improved, both in resolution and sampling speed. This was to allow further diagnostic information to be gleaned from the load current. Figure 17 shows the increased sampling capability and the additional information that is revealed. It was confirmed that basic loading characteristics of the actuator were easily detected through load current monitoring.

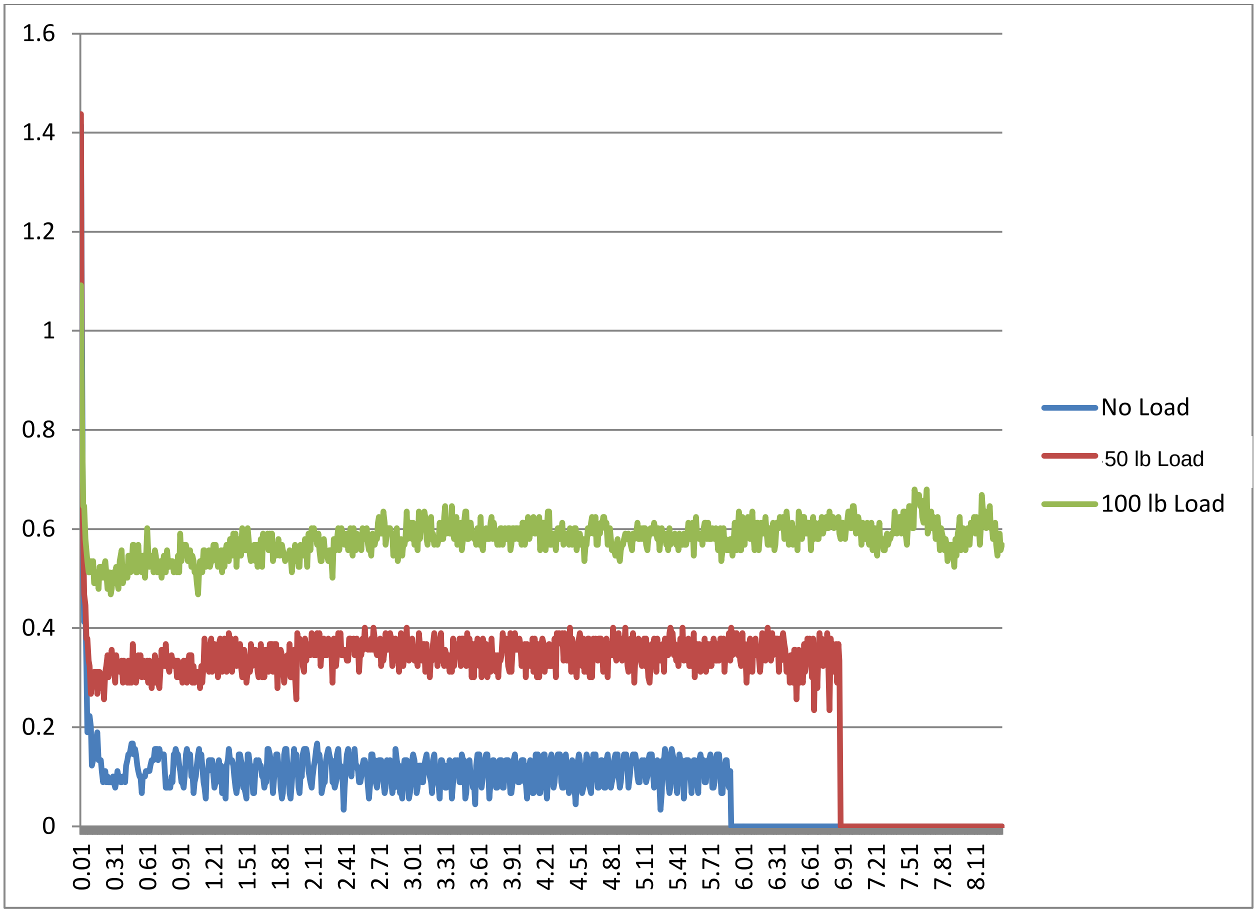

Figure 17. Modified Current Sense Loading vs. Various Loading Conditions

When comparing the information from the new actuator to that of the simulated worn actuator, it may be observed that the actuator is not functioning within the normal operational window. Figure 18 shows a comparison of the unloaded actuator with and without contaminants within the actuator threads. Figure 19 shows a magnified view of the comparison between extend cycles with and without contaminants packed within the threads.

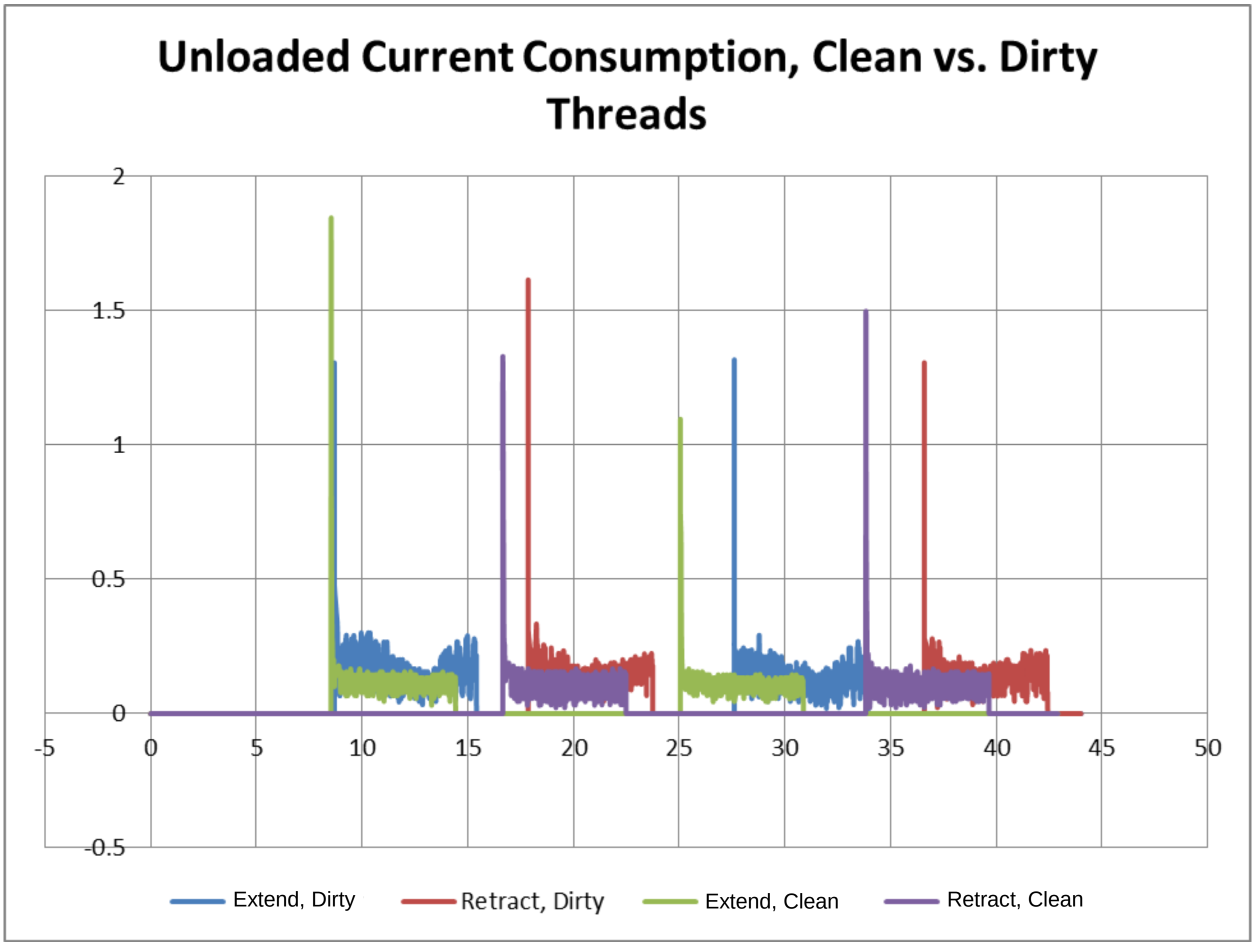

Figure 18. Debris vs. Nondebris Unloaded Actuator Current Draw

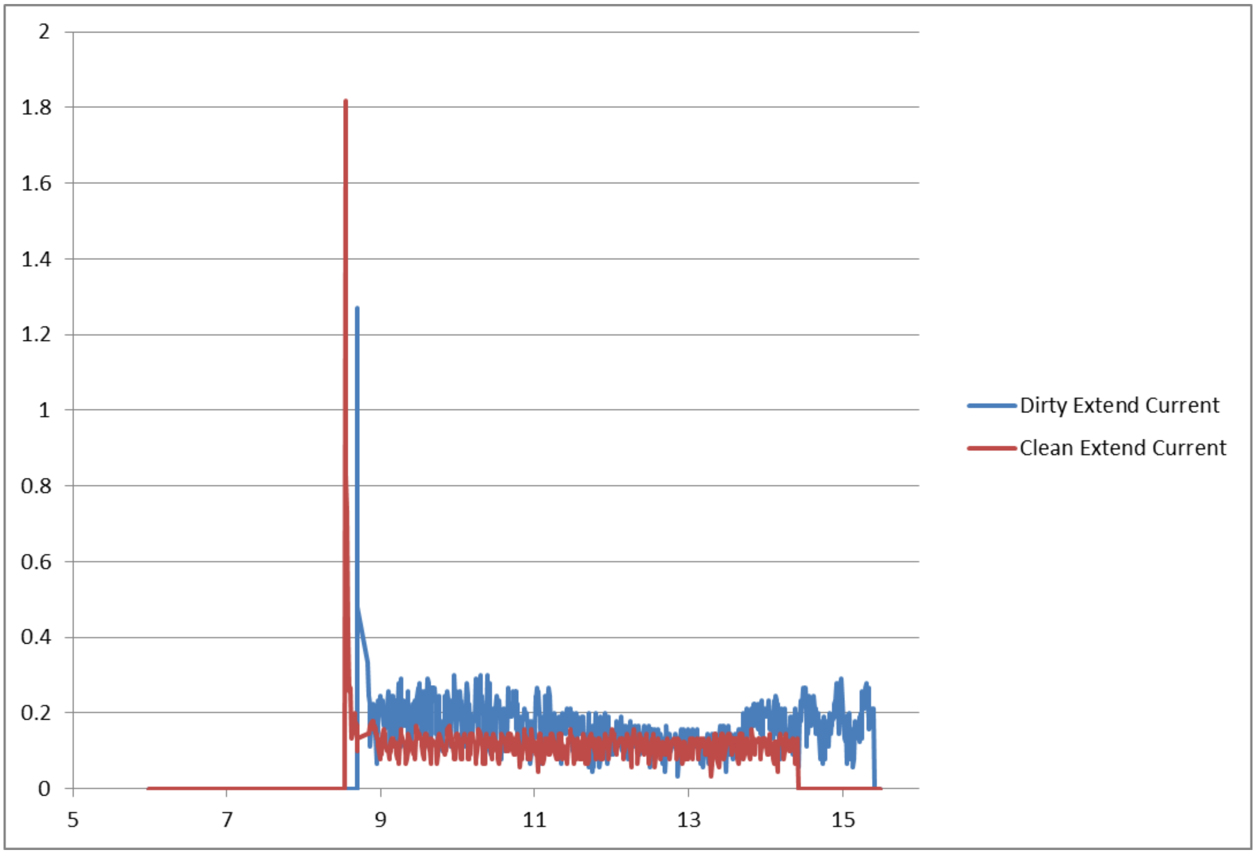

Figure 19. Magnified Comparison of Debris vs. Nondebris

Although the ECB, as it is currently designed, has some inherent diagnostic capabilities, the testing proved that much more information could be obtained in relation to load health with the current detection improvements made within the program.

6.3 THE ECBU DATA COLLECTION.

Using the system depicted in figure 20, the DC ECBU was used to gather sensor information pertaining to the actuator. Primarily, two sensing elements were monitored by the ECBU, and the graph below shows the plotted sensor information during the test, in which the ECBU was controlled through a GUI that commanded the actuator through multiple extend/retract cycles. The gathered analog sensor information is shown in figure 21.

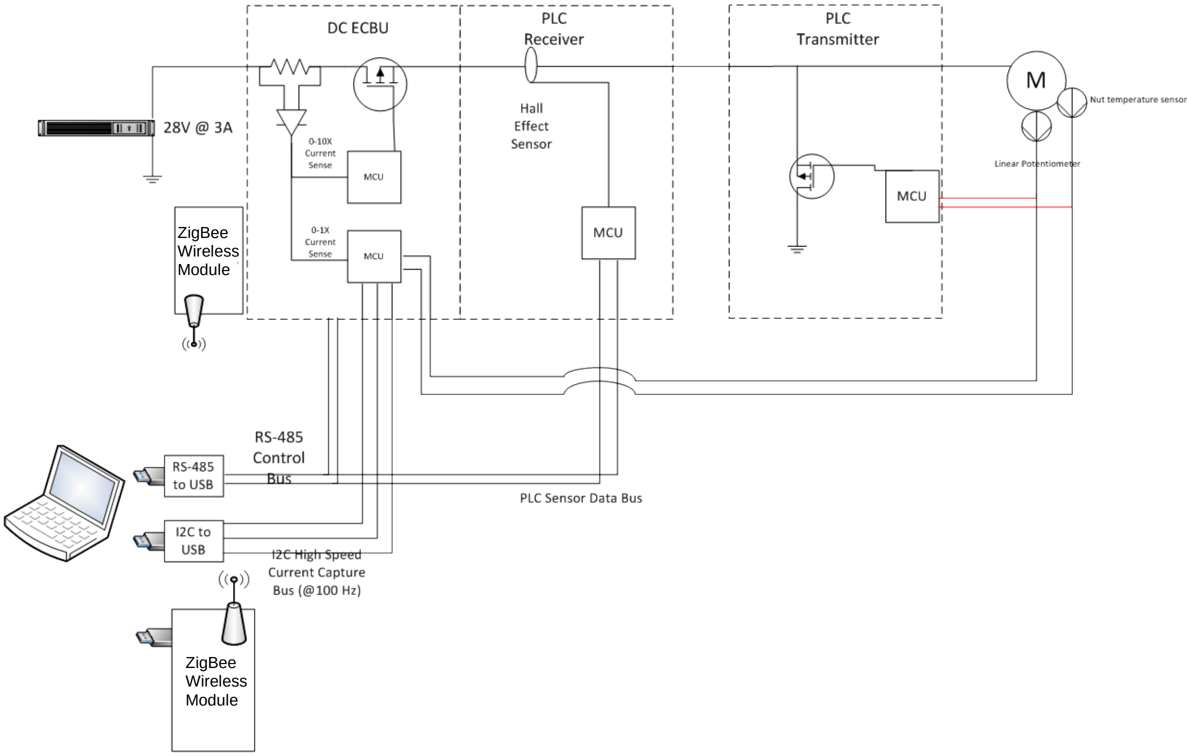

Figure 20. Block Diagram of the Demonstration System With Sensors Wired Directly to the ECBU

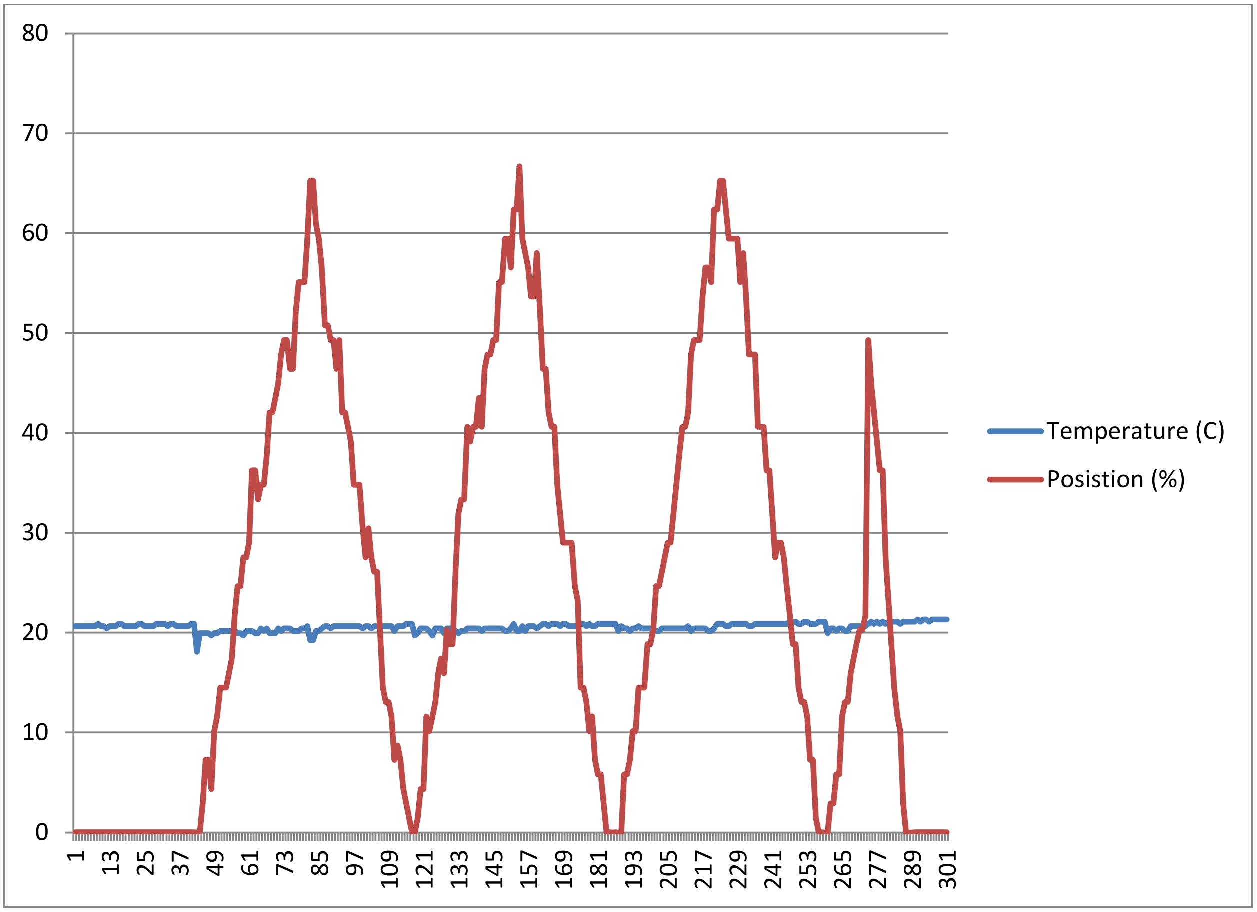

Figure 21. Position and Temperature Data Gathered Through the ECBU

There is some inherent noise within the actuator position voltage, as shown in figure 22. The scope trace is the raw analog voltage that is being sampled by the ECBU. There is a significant amount of noise on the raw signal that is being sampled and this accounts for the small variations within the actuator position.

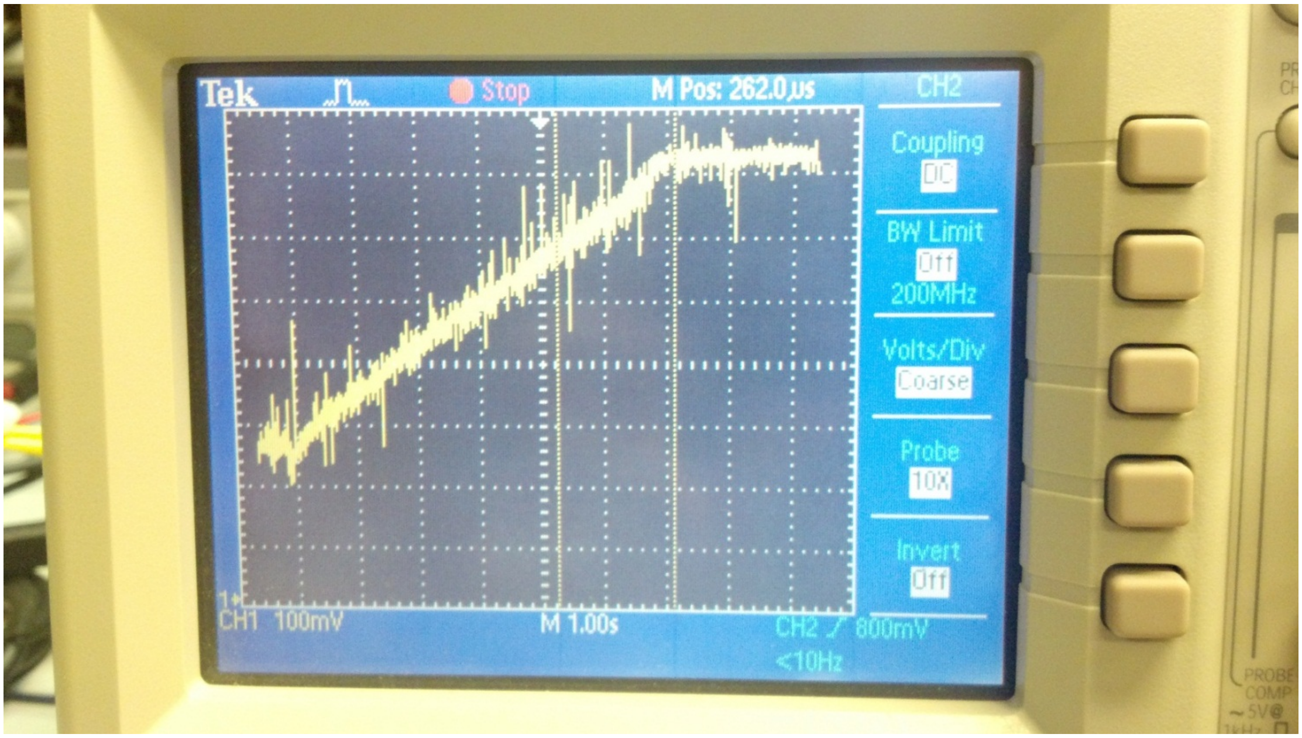

Figure 22. Single Extend Cycle Scope Capture (Linear Potentiometer)

The ECBU's inherent general purpose analog voltage inputs were used to sample the sensor information. Analog information was sampled through the use of a status command sent to the ECBU from the GUI through an RS-485 interface. The ECBU was polled at a 10 Hz rate, and the sensing elements were sampled with a 10 bit A/D converter. The current design has four general purpose analog inputs that are all reported within the same command; however, during the demonstration, only two analog inputs were used, giving a total data throughput of 10 bit * 10 s/s * 4 = 400 bit/s. This is not a large amount of data to push through the RS-485 bus, primarily because of the other polling functions that exist within a full distributed power system and the bus sharing that exists between all ECBUs. Within a full EPDS, the maximum polling rate of each ECBU drops to around 1 Hz, although current RS-485 signaling rates could be increased slightly to allow more data throughput for current/sensor/status information.

6.4 THE ZigBee INTERFACE.

For demonstration purposes, a secondary interface bus was established through a ZigBee wireless module. The secondary interface was used as a redundant bus to implement data collection and system control. While the GUI was controlling the ECBU (actuator) through the oscillatory motion shown in the sampled sensor data (figure 21), the primary RS-485 bus was cut through use of a momentary dual-pole switch. With the switch enabled, the GUI automatically switched over to the secondary ZigBee bus to continue data monitoring and ECBU control. A block diagram, shown in figure 23, highlights the setup.

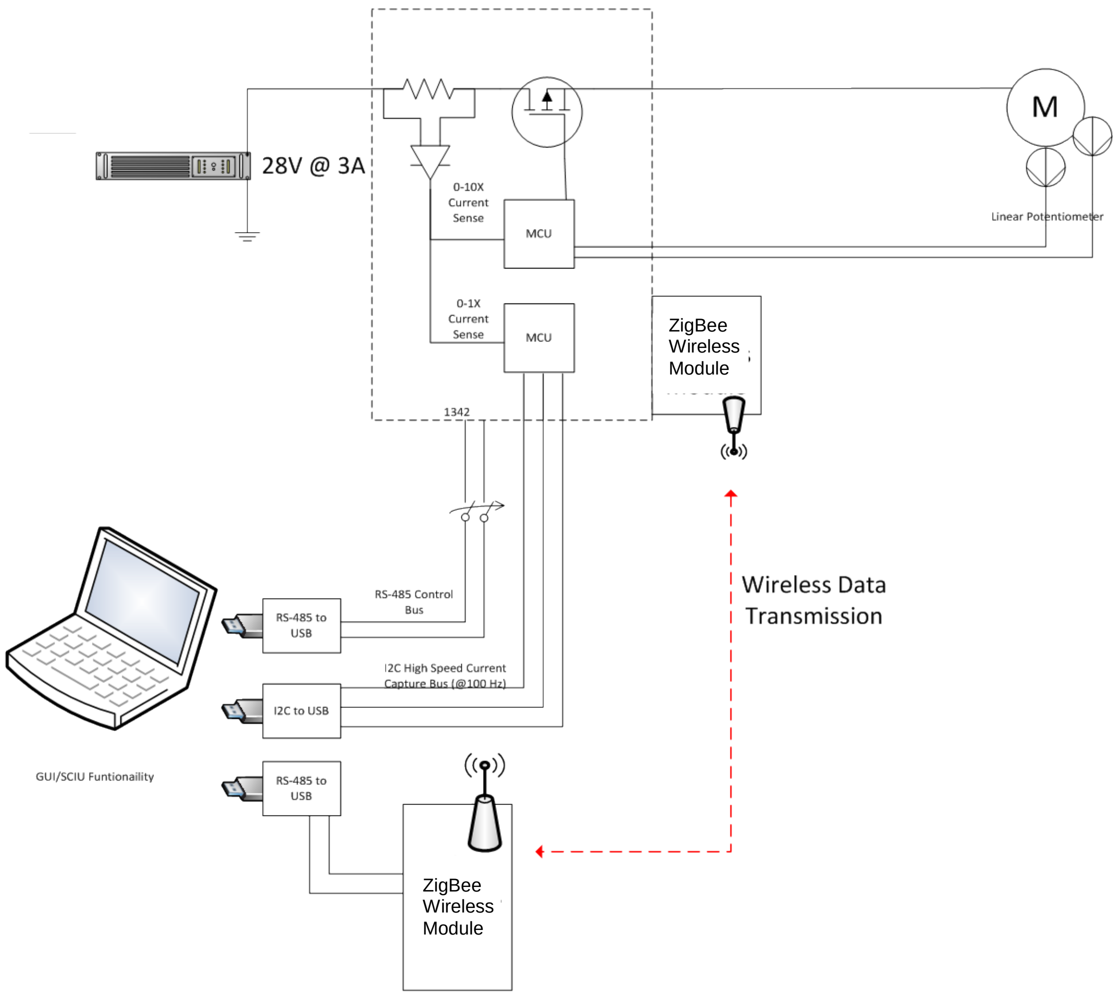

Figure 23. Wireless Module Setup

During the testing, the bus was cut multiple times and no loss in data/control was perceived. With the ZigBee wireless, the overall data throughput was analogous to the RS-485 limitations. The primary RS-485 bus operated at 115.2 Kbaud/s and the wireless bus was configured to operate at the same rate, to ease the interface to the primary microcontroller within the ECBU. The ZigBee wireless modules have a maximum signaling data rate specified as 1M bit/s, which is bit less than the maximum theoretical data rate capabilities of RS-485. However, the RS-485 maximum data rate is directly related to the cable and interface circuitry-associated capacitance. Because of lightning-protection requirements, the maximum achievable data rates for an aircraft-implemented RS-485 bus do not align with the specified data rates for a given length of wire. Knowing this, wireless ZigBee-type data buses could provide a higher bandwidth interface for prognostic sensor/current information.

6.5 THE PWM PLC.

Demonstrating the potential use of PWM PLC and the ECB receiving circuitry involved two different setups: one for AC bus voltage and one for DC bus voltage. For both test cases, a test pattern was transmitted to validate the overall accuracy achievable. This test pattern is shown in figure 24.

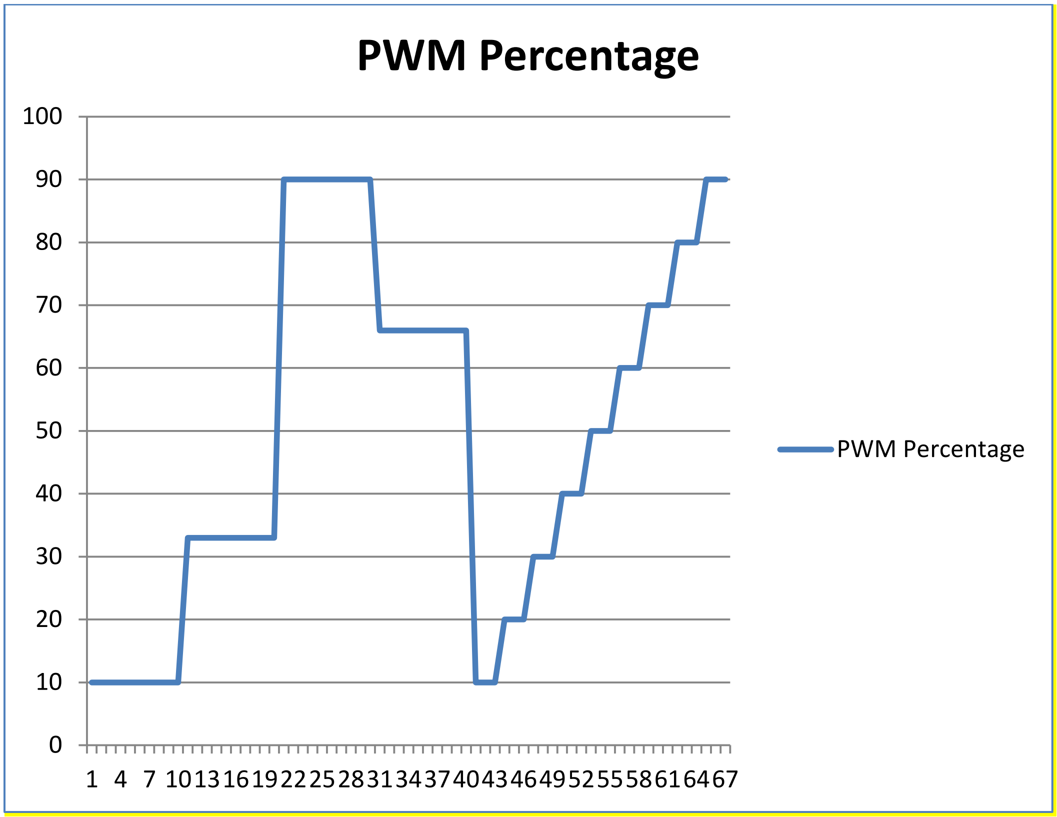

Figure 24. The PWM Test Pattern

<u>6.6 THE DC PWM PLC</u>.

The demonstration setup shown in figure 25 was used for DC PWM PLC testing. Initially, to demonstrate the accuracy of the PWM PLC technique, the test pattern mentioned in section 6.5 was transferred and the receiving circuitry interpreted the data and saved it to a .csv file. The test pattern was transferred while the actuator was lifting a 25-lb. load. Figure 26 shows the graph of the received test pattern.

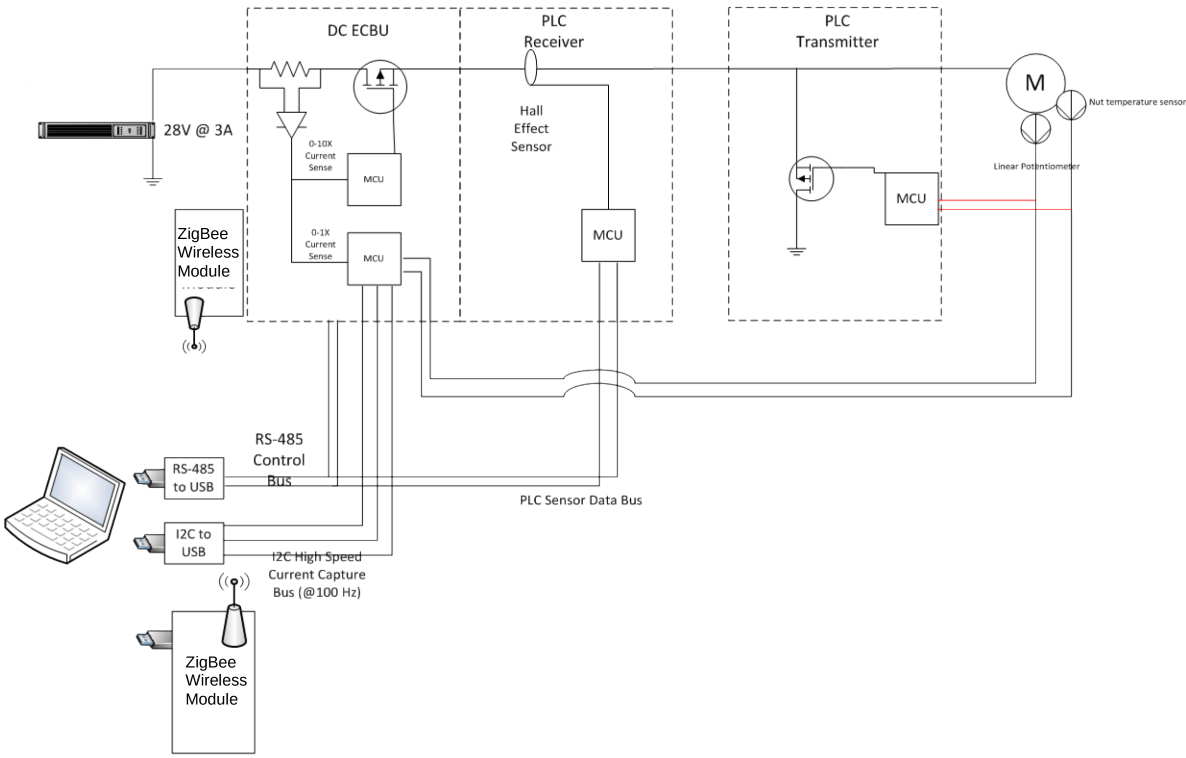

Figure 25. The DC Demonstration Setup

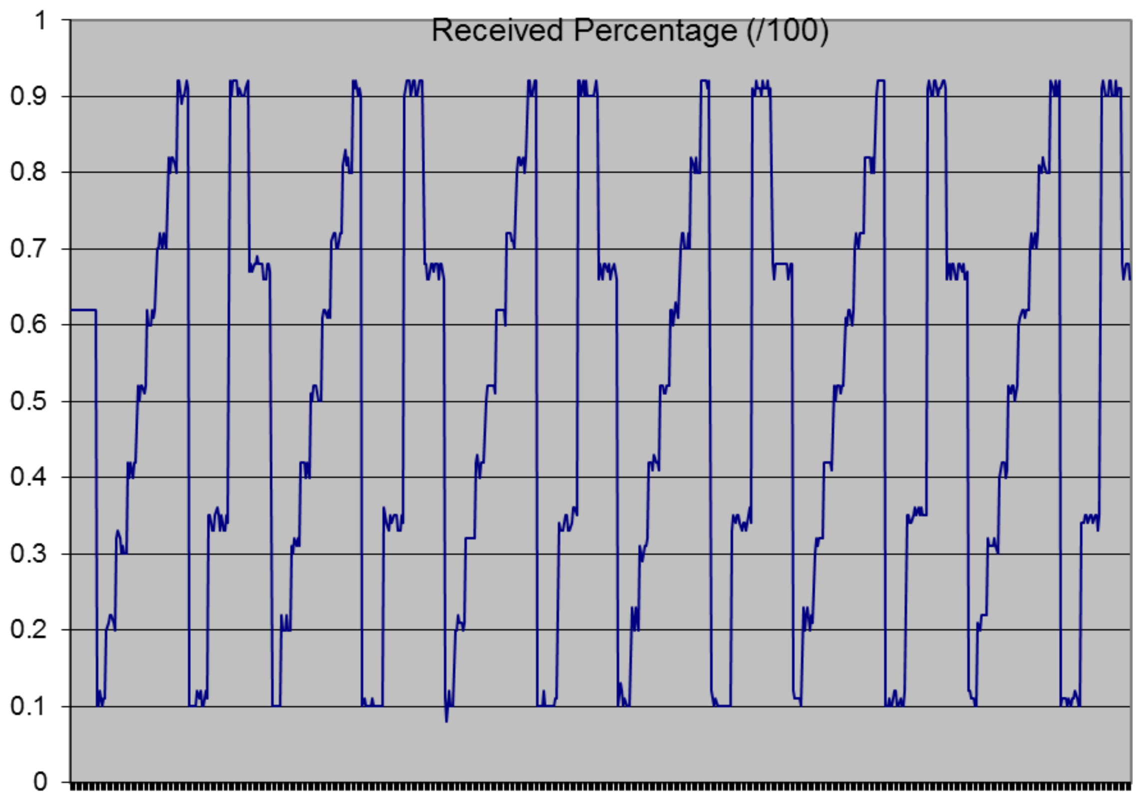

Figure 26. Received DC PWM PLC Pattern

One full test pattern was graphed with reference to the actual test pattern sent and the acceptance bands desired and is shown in figure 27.

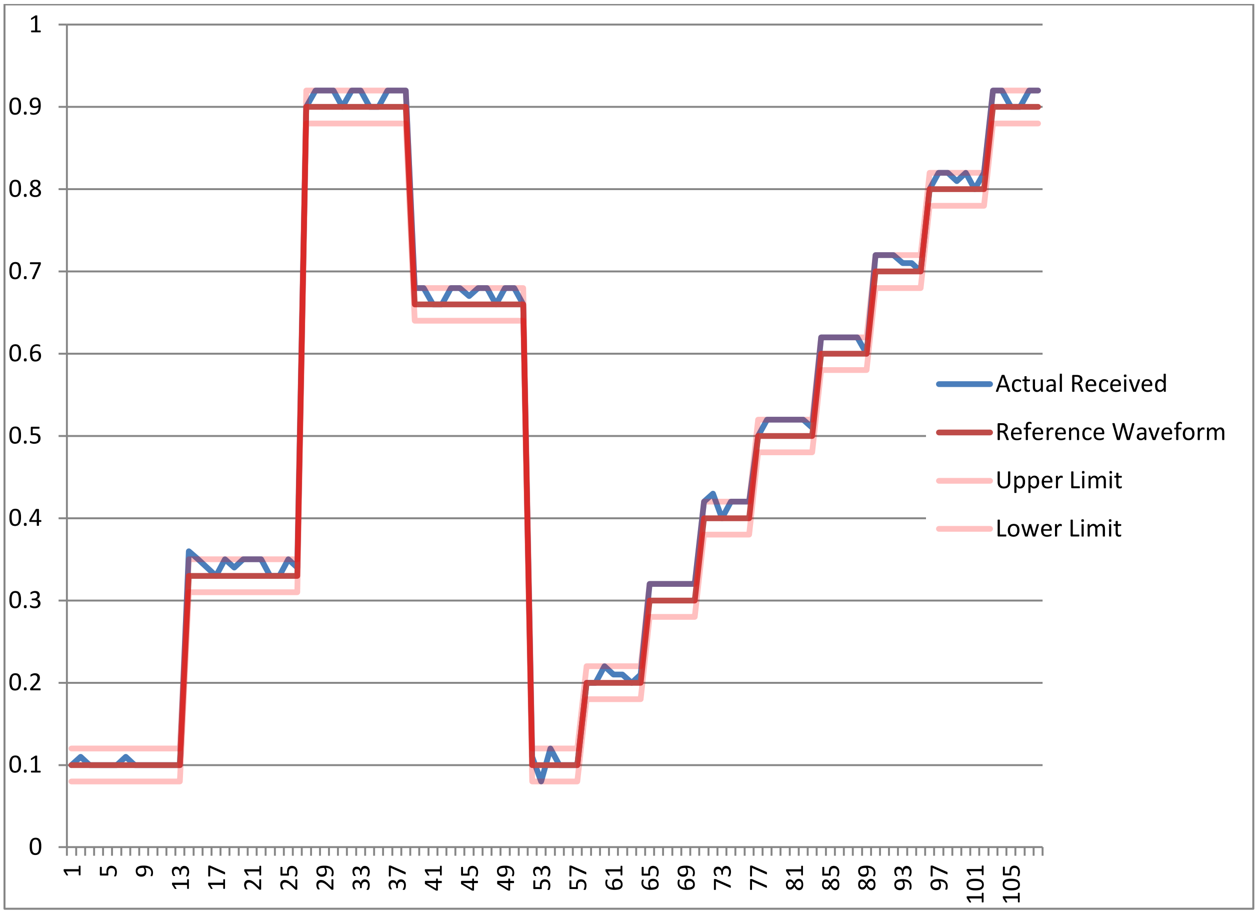

Figure 27. Received Information Compared to Tolerance Bands

Once the DC PWM test pattern was successfully sent and received, the actuator was put through multiple cycles while the PWM PLC transmitted pertinent position and temperature information. It should be noted that the PWM PLC operates only while the bus being used for transmission is operational; thus, the actuator extend cycle is all that is shown in figure 28.

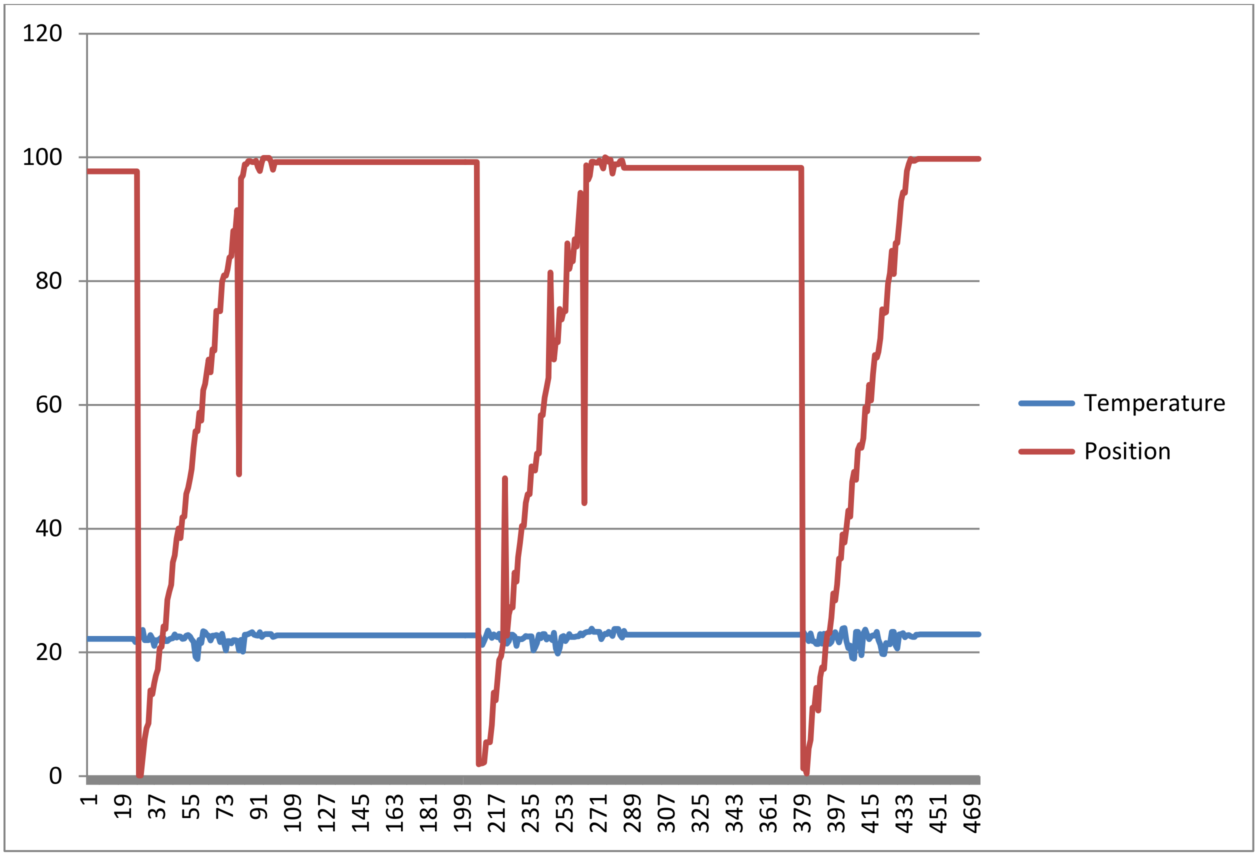

Figure 28. Temperature and Position Transmitted Over PWM PLC

During the demonstration portion of the testing, as may be observed in figure 28, large step changes within the translated position occurred because of noise from the actuator motor causing erroneous triggering of the receiver circuit. In a final implementation, this can be easily filtered out based on the sensing element. For example, it is impossible for the position of the actuator (or temperature) to have large step changes instantaneously and this type of erroneous information, when received, can be determined to be invalid and ignored.

To measure the frequency of the erroneous data, multiple data captures were completed to give a more reliable representation of how frequently the errors actually occur. Erroneous triggering is fairly infrequent, as can be seen in figures 29 and 30. The time that it takes for the actuator to extend is approximately 6 seconds. Currently, the position and temperature is updated at 10 times-per-second. For the data captured, there are nine gross errors (large step changes visible within the graph) out of a total of 600 sample points within yielding a percentage error rate of:

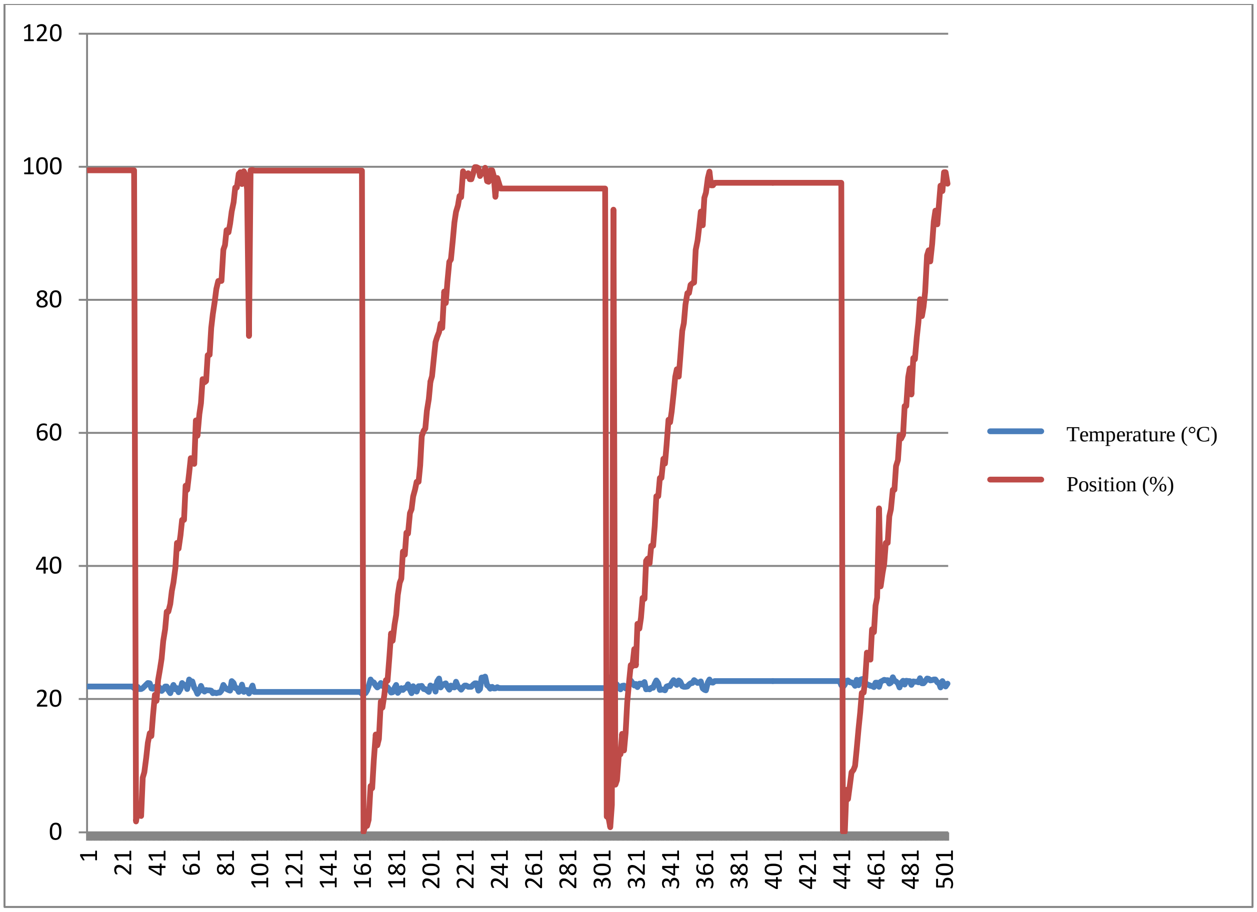

Figure 29. Data Capture 2 of DC PWM Sensor Data

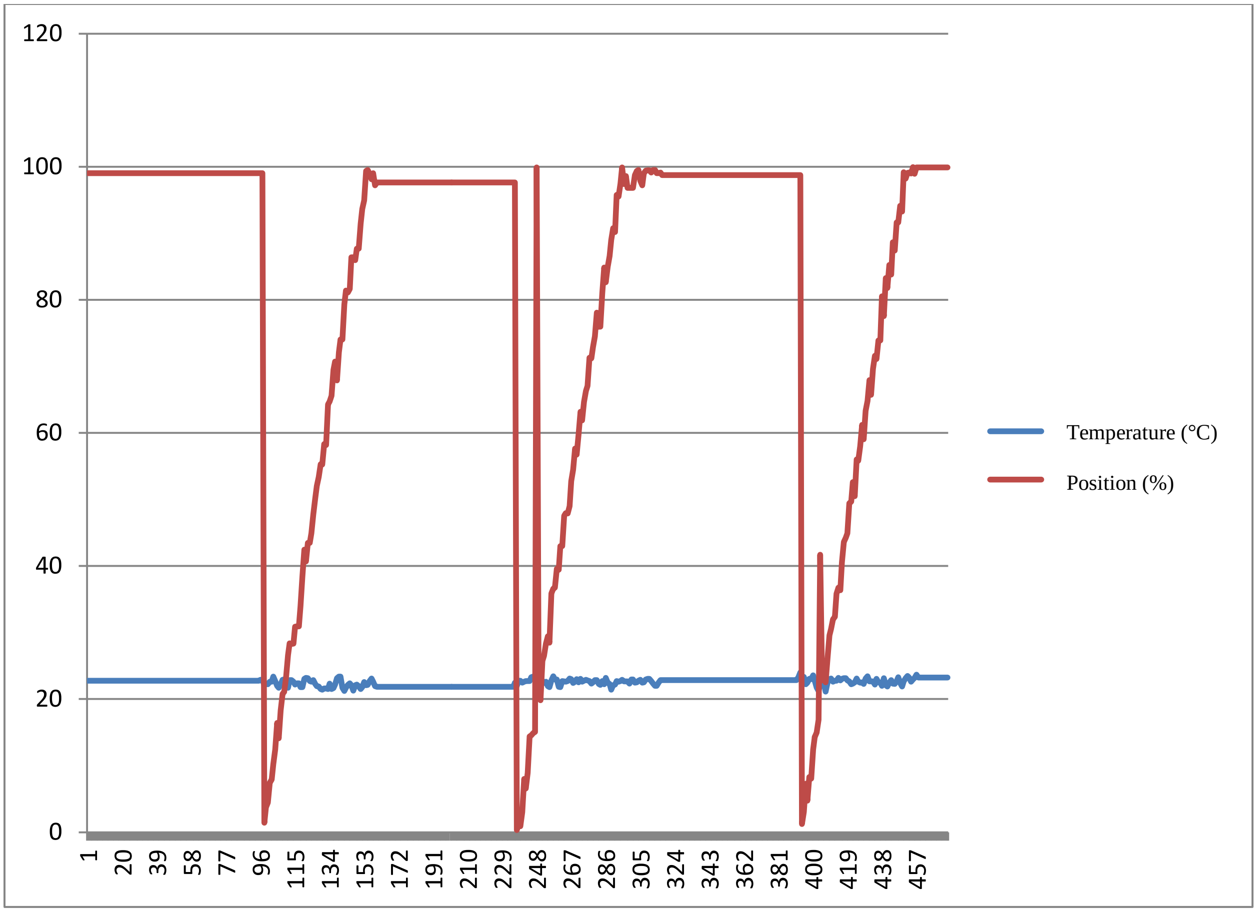

Figure 30. Data Capture 3 of DC PWM Sensor Data

6.7 THE AC PWM.

The AC PWM PLC demonstration setup is shown in figure 31. As with the DC PWM PLC demonstration, the AC bus demonstration first transmitted a test pattern to determine the accuracy of the approach. The AC bus receiver was much more accurate than the DC actuator because of the relatively benign load noise of the blower. The received test pattern is shown in figure 32.

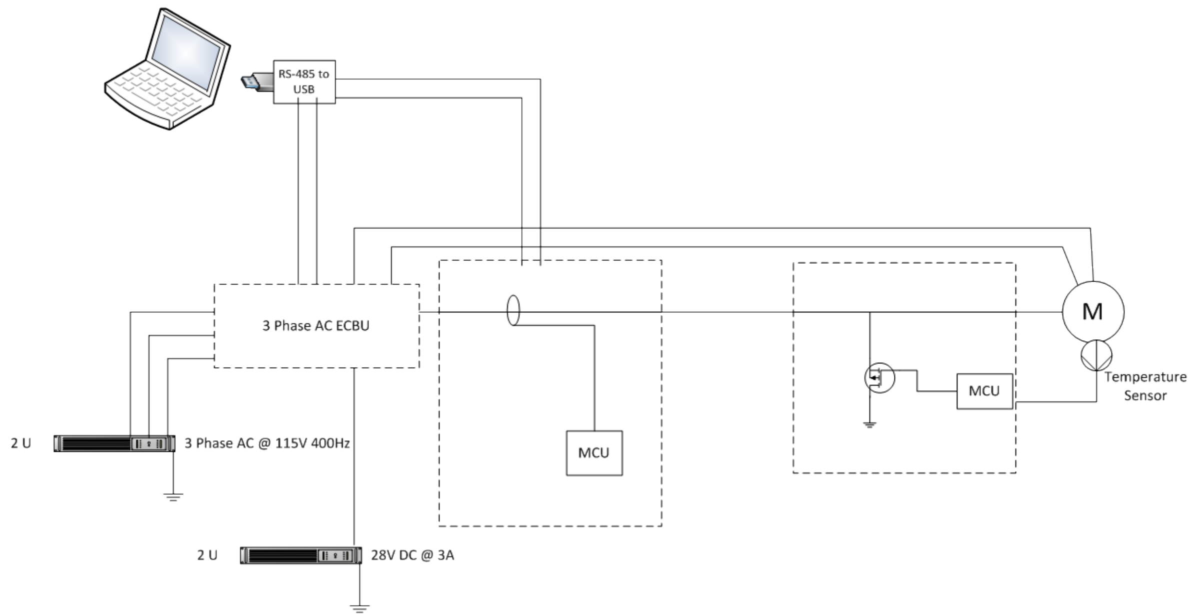

Figure 31. The AC Demonstration Setup

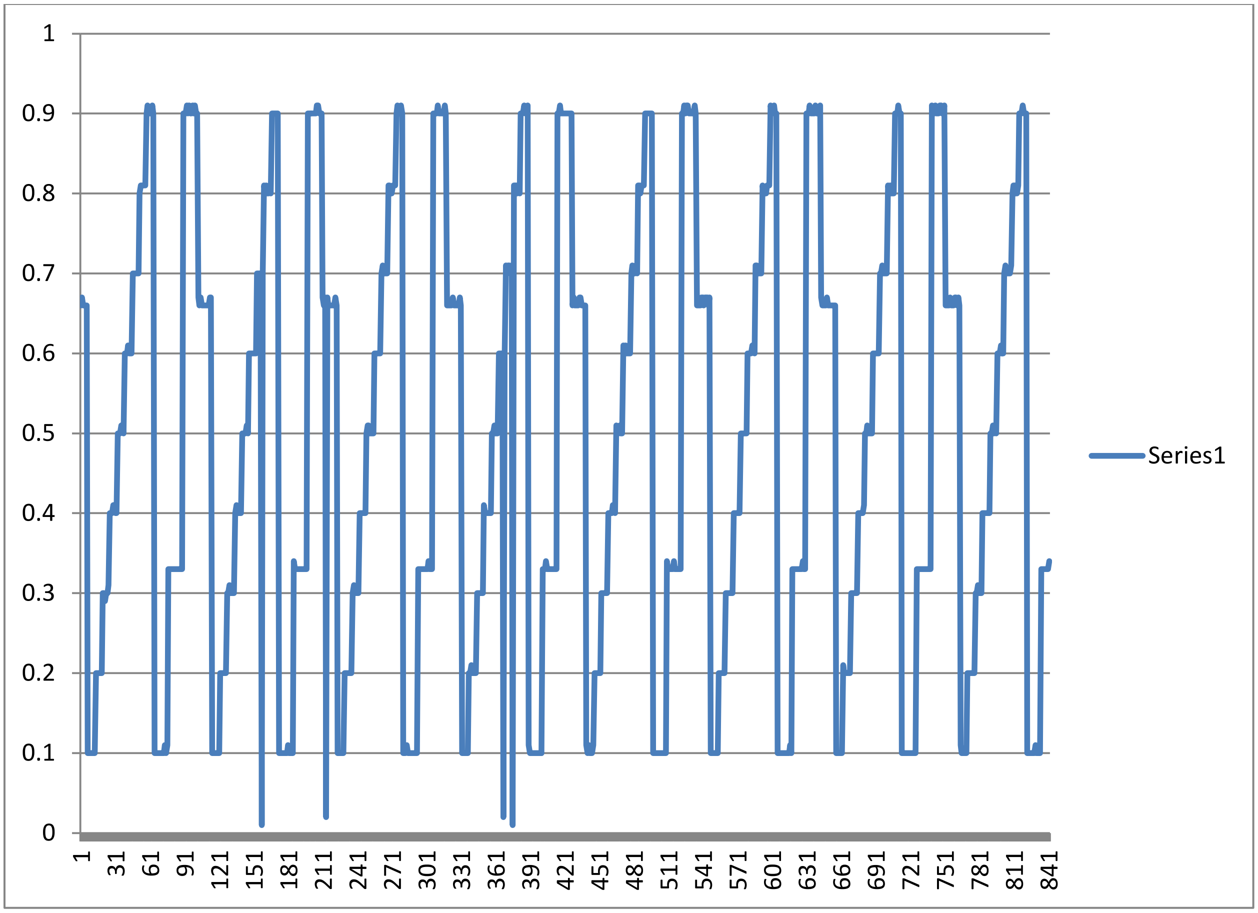

Figure 32. The AC PWM PLC Test Pattern

As in the DC PWM test case, a single PWM test pattern was graphed against the actual percentage sent with acceptance bands. Figure 33 highlights the accuracy achieved through sending the PWM-encoded signal across an AC bus with a three-phase motor load attached.

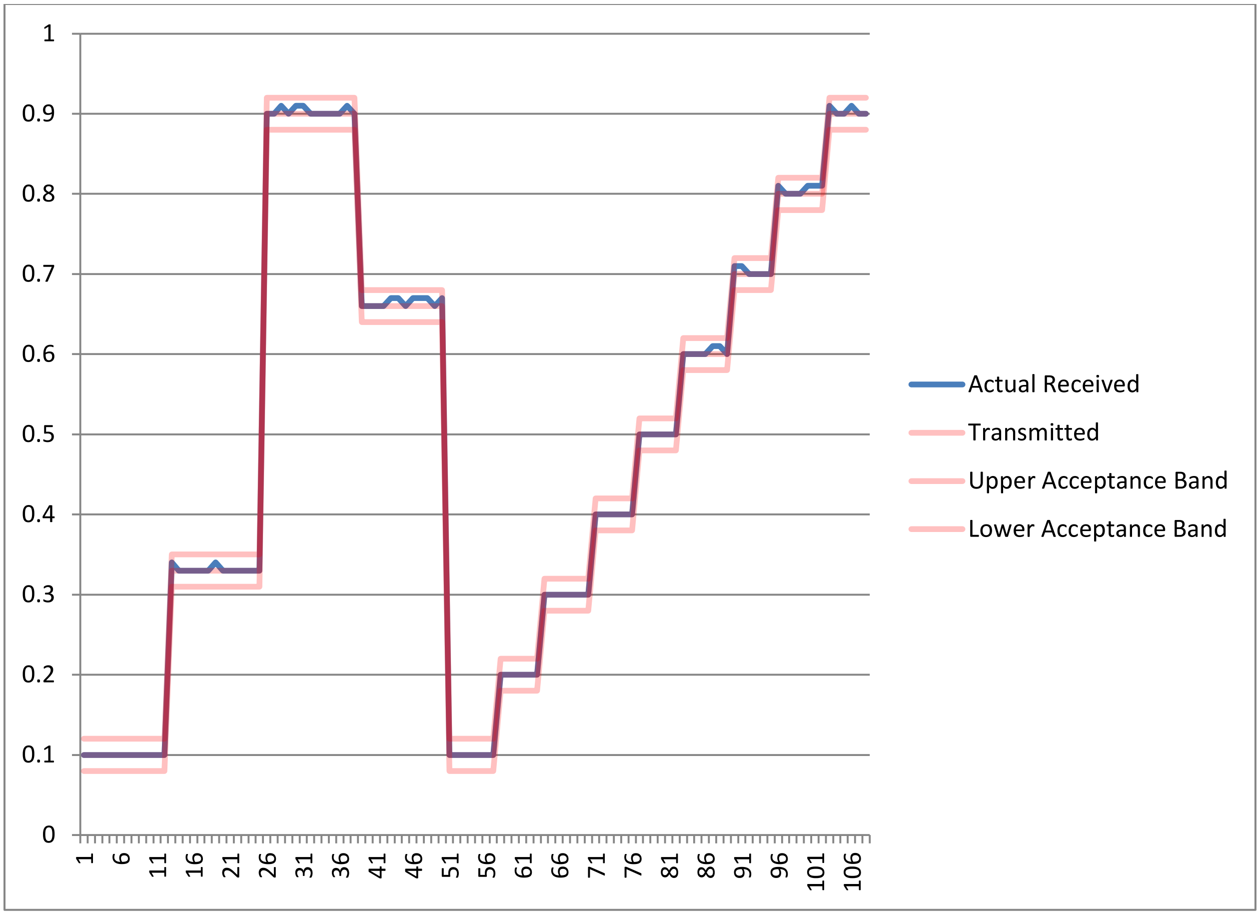

Figure 33. The AC PWM PLC Test Pattern Accuracy

Once the test pattern had been successfully transmitted, a temperature sensor was sampled by the PWM PLC transmitter board and used as the primary data transferred across the bus. While the temperature information was being received, a forced air heat gun was used to change the transmitted information from ambient. With a reference thermocouple attached to the silicon temperature sensor, the temperature was varied between 30 to 40°C. Figure 34 shows the received temperature information.

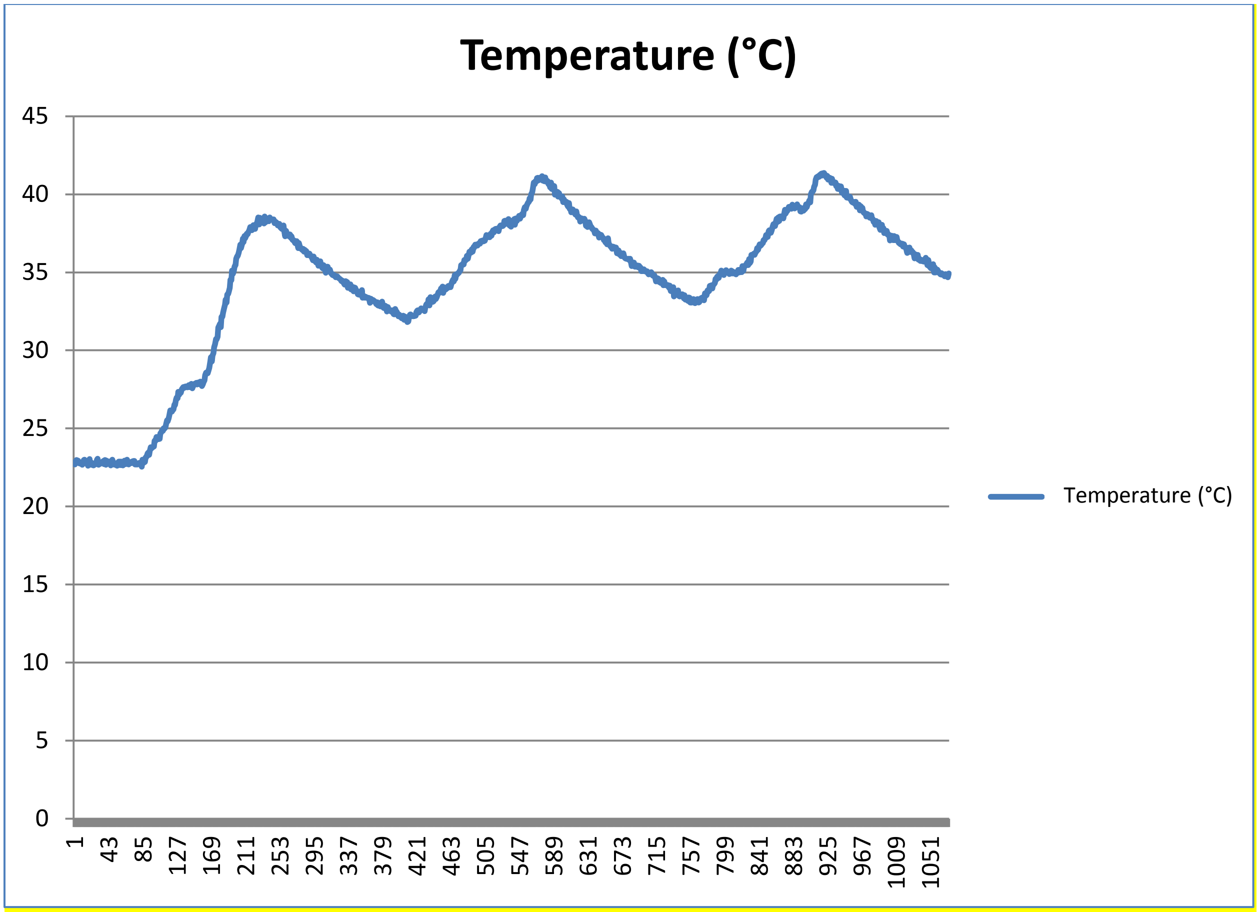

Figure 34. The AC Temperature Transferred

7. CONCLUSIONS.

By interfacing with a large majority of aircraft loads, the base EPDS provides inherent health-monitoring capabilities. The limited load current monitoring provides basic information about the health of the load, and the available analog inputs can be used to collect useful sensor information that further enables the EPDS for health monitoring capabilities. The current consumed by a load carries much information about the health and status of the load, such as:

- The variation of current over time provides information about the wear-out and lubrication requirements of motor-operated mechanisms.

- The peak instantaneous value of current can signal impending failure.

Although the base EPDS system samples at a fairly slow rate, improvements to the sampling capabilities and overall system storage allow a great deal more information to be gathered from the load current. A faster sampling rate allows the ECB to detect such things as variations within motor-wear conditions and intermittent shorting/opening. The faster sampling rate needs to be coupled with a more refined sampling window. Resolution and range of current measurement must be wide enough to accurately measure peak fault currents at 1000% of the ECB rating, as well as small variations in current at 0.5% of the ECB rating. Within the demonstration system, this was accomplished by using two separately scaled current measurement circuits, and this technique seems viable as a permanent solution.

Other improvements to the EPDS to adapt it to perform SPMS functions involve various methods of interfacing with sensing elements or providing the required data bus for transferring the additional sensor information. The demonstration showed that PLC by means of current pulses can reliably send information from a load to an ECB with minimal circuitry and high noise immunity. For example:

- Information from load-mounted sensor(s) can be sent back to the ECB for status monitoring of the load (temperature, pressure, position, force, etc.)

- Data from multiple sensors can be multiplexed on the power line.

- Power health data can also be sent to monitor for:

    - Intermittent power (sign of series wiring fault or loose connection)
    - Low voltage (sign of bad wiring or high-resistance crimp/connection)

Wireless interfaces, such as ZigBee®, can easily be used as the required secondary sensor bus or as a redundant control bus. Although a wireless interface could also be used to interface with sensing elements, the power requirements for continuous monitoring would require an external power connection. With the successful demonstration of a unique current pulse PLC technology that can be integrated within the power distribution system, the power lines required for the sensing elements would be used for data transfer as well.

An EPDS interfaces with a large majority of aircraft loads, allowing for some level of health management without adding hardware. Load current has been proven to be a useful health monitoring variable; by upgrading the current monitoring and recording capability, intermittent faults and electromechanical load faults can be detected. Coupling the current monitoring capability with inherent sensor gathering further enables the EPDS for health monitoring functionality. Sensors can be directly coupled to EPDS either through analog inputs or PLC. Given the nature of the EPDS, PLC provides a straightforward interface potential without requiring rewiring, making EPDS an ideal backbone for sensing and health monitoring.

8. REFERENCES.

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