



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

VIBRATION ANALYSIS VIA WIRELESS NETWORK

by

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September 2007

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2007	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE Vibration Analysis via Wireless Network			5. FUNDING NUMBERS
6. AUTHOR(S) Wallis, David, C			8. PERFORMING ORGANIZATION REPORT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE
13. ABSTRACT (maximum 200 words) <p>This thesis addresses the problem of early detection of fault conditions in an air compression system. Initially, pressure transducers, and MaxStream ZigBee devices, were utilized to provide data to a remote GUI interface through wireless data transmission. The research also included a study of vibration analysis utilizing a Kullback-Lieber algorithm for spectral distance. This algorithm was programmed in LabView 8.0 using the FFT at the point of measurement to process the raw data obtained from a set of accelerometers. The results of the FFT were wirelessly transmitted to an end node where a LabView program processed the Kullback-Lieber algorithm to obtain a spectral distance value. This value was then compared to a reference value to ascertain whether the bearings on a particular piece of equipment required maintenance.</p> <p>The expected contribution from this research is to highlight the capability for greater wireless capability aboard U.S. Naval vessels. Wireless networks offer an inexpensive, reliable, survivable method for leveraging the power of information throughout the ship. Additionally, there are significant advantages to be realized through the reduction of manpower assigned to the repetitive and highly error-prone process of monitoring the thousands of sensors aboard any naval vessel.</p>			
14. SUBJECT TERMS Vibration, ZigBee, Mesh			15. NUMBER OF PAGES 87
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU

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VIBRATION ANALYSIS VIA WIRELESS NETWORK

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This thesis addresses the problem of early detection of fault conditions in an air compression system. Initially, pressure transducers, and MaxStream ZigBee devices, were utilized to provide data to a remote GUI interface through wireless data transmission. The research also included a study of vibration analysis utilizing a Kullback-Liebert algorithm for spectral distance. This algorithm was programmed in LabView 8.0 using the FFT at the point of measurement to process the raw data obtained from a set of accelerometers. The results of the FFT were wirelessly transmitted to an end node where a LabView program processed the Kullback-Liebert algorithm to obtain a spectral distance value. This value was then compared to a reference value to ascertain whether the bearings on a particular piece of equipment required maintenance.

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LIST OF ABBREVIATIONS

BIST	Built in Self-Test
CBM	Condition Based Maintenance
ICAS	Integrated Condition Assessment System
MEMS	Micro-Electro-Mechanical Systems
FFT	Fast Fourier Transform
GUI	Graphical User Interface
AC	Alternating Current
DC	Direct Current

EXECUTIVE SUMMARY

The construction and maintenance of naval vessels is both time consuming and manpower intensive. In order to validate the trust of the American tax payer the Navy must demonstrate a commitment to continually improve the efficiency and cost effectiveness of both construction and maintenance. Technology is not the solution to every problem faced in this recursive endeavor but, it does provide the ability to focus available assets and make decisions based on high quality filtered data.

One of the main areas in which manpower can be reduced while simultaneously improving the decision making capability of the human interface is in shipboard maintenance. Naval vessels require an endless cycle of recording measurements from the thousands of sensors emplaced in the ship. It is through this repetitious ritual that the ship's operating environment is maintained. This cycle is the target for the research conducted in this thesis.

The hypothesis for the research was that a wireless sensor network has the potential to greatly reduce ship construction and maintenance costs. Additionally, a wireless sensor network, if validated, has potential for manpower reassignment and focused engineering decision making. The main goal of the research was to validate the potential to create several sensors and transmit the results of those sensors via a wireless medium.

The critical assumptions of this research are that an interface can be constructed that will serve as a gateway for the wirelessly transmitted sensor data and a shipboard internet. Additionally, by offering decision makers the ability to obtain sensor data from any piece of machinery, at near real-time rates, from any workstation on a ship will improve the maintenance and operational performance of the vessel.

The backbone of this research is a wireless mesh network. The mesh network has an inherent robustness. The network has the capability to route traffic to any other node in the network. Additionally, every node in the network has a receiver and a transmitter. Therefore, a received message is analyzed and then retransmitted to the appropriate node

in the network. The mesh network can be implemented in several different protocols but, the ZigBee protocol shows the greatest promise because this protocol was designed for low power transmission and the incorporation of mesh network interfaces.

A pressure sensor, synonymous with a temperature sensor, was designed to operate as a remote node. The sensor was created with commercially available components. The parts are not the most efficient and the design itself can be improved but, the node served to validate the ability to fuse a robust sensor with a ZigBee Radio Frequency (RF) modem to enable the wireless transmission of sensor data from the sensor's position on specific equipment to a remote location. The pressure sensor was battery operated and transmitted a measure of the battery power in order to facilitate an acknowledgement of when to change batteries. Continuous use will drain the batteries in 25.2 hours, for this particular sensor, but with a sleep mode capability added to the network it is expected that batteries will not need to be replaced for up to eight months or more.

The vibration sensor has direct application to Condition Based Maintenance (CBM). This theory advocates that certain measures of equipment operating conditions can be used to determine whether a machine will soon have problems and what that problem may be. This analysis utilized a formula originally designed to identify different biological life forms from sonar readings. The formula was adapted to use on measuring the vibration of motors and was proved to be effective in determining when the equipment is operating outside of normal operating conditions. This result was also validated for wireless transmission.

Continued research in the use of wireless networks, the incorporation of sensor calibration, and refinement of the vibration sensor's use for CBM are recommended in order to refine these concepts into operational realities.

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ACKNOWLEDGMENTS

Thank God through whom all things are possible. I would also like to thank my beautiful wife, Hope. Her patience, common sense, and understanding have served as a constant inspiration in everything that I do.

I would also like to acknowledge the generous financial grant from SPAWAR San Diego. The fellowship was served as a critical source of funding for the purchase of equipment and travel used in the support of this thesis.

James Calusdian was a critical component of all practical experiments conducted as part of this thesis. His quiet suggestions, intuitive grasp of the theoretical fundamentals, and infinite patience were invaluable.

Finally, I would like to thank Professor Xiaoping Yun for all his guidance during this thesis.

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I. INTRODUCTION

A. BACKGROUND

In a modern guided missile destroyer (DDG), there are approximately 2,670 hull, mechanical, and electrical (HM&E) sensors that require periodic calibration, the vast majority of which are pressure and temperature sensors, switches, or gages. Of these, 1,189 are independent visual type sensors and 1,480 are integral parts of shipboard Machinery Control Systems (MCS) which can only be read at system consoles, located far from the original sensor location. To monitor this equipment, and the associated wiring, requires a significant investment in manpower. For example, the typical engine room watch on board a U.S. Naval vessel may spend up to 25% of their watch manually recording, or observing, readings from the various sensors in a specific workspace. Additionally, calibration of the equipment can take 30 minutes to one hour for a simple pressure sensor. The amount of man-hours required for calibration is directly proportional to the complexity of the sensor to be calibrated. [1]

To investigate the feasibility of minimizing the manpower intensive routine of checking the various sensor systems on naval vessels will require the creation of a sensor node, research into vibration analysis, and construction of an integrated wireless sensor network.

1. Vibration Analysis

Vibratory motion is a characteristic of all types of machinery, especially rotating machinery. Measuring vibrations is one part of a Condition Based Maintenance (CBM) system in which repair and maintenance decisions are based, not on machine hours or time, but on the condition or state of the machinery. The so called “vibration signature” of the device will tell the operator whether the device is operating properly and can offer an early warning if the machinery is beginning to fail. [2]

Accelerometers provide one method of measuring the vibration signature of a particular piece of machinery. Accelerometers provide either a digital, or an analog, output signal that can be captured by a computer. Once the data, from the accelerometer, is in the computer, a series of signal processing tools can be used to refine the data, apply appropriate algorithms, and utilize the data to identify trends, or outliers, for a specific piece of equipment. The state of a specific piece of equipment can be determined by comparing the measured data with a reference signal obtained for that equipment during normal operating conditions.

In order to utilize the lower bandwidth ZigBee protocol to transmit vibration data, it is beneficial to execute some signal processing at the sensor site. An Efeotor Octavis [3] device was used to conduct a Fast Fourier Transform (FFT) at the sensor site. Additionally, the data obtained was passed through an Analog to Digital Converter (ADC) to prepare the data for transmission via a wireless medium.

2. Wireless Networks

A shipboard wireless sensor network transmits all required sensor readings into a database via the ship's intranet. This database could then be accessed, via graphical user interface (GUI) applications. The applications will facilitate the abilities of engineers, and other supervisors throughout the ship, to rapidly analyze the data, determine trends, and rectify problems. The data would be available to any terminal connected to the ship's intranet, and could be transmitted to reach back assets for diagnostic assistance. The wireless network will be a mesh. A mesh ensures that the network would not be compromised by a single shipboard incident. This wireless network would eliminate the hours spent tabulating sensor results by hand, and would greatly facilitate a decision maker's ability to highlight problems and establish a functioning condition based maintenance program.

The ZigBee standard offers a solution for a wireless network focused on obtaining various sensor readings. This standard provides a low power, low bandwidth solution

that can also be configured to handle different types of sensor data. Maintaining power for the various ZigBee nodes can be managed through the selective use of sampling rates and a power down “sleep” mode.

B. OBJECTIVE

The primary focus of this thesis will be to determine the feasibility of using a ZigBee wireless network to pass two different types of sensor readings: a measure of pressure and a measure of plant vibration. The thesis will be conducted in three stages. The first stage will be to build a ruggedized pressure sensor. This will require the construction of a robust sensor package that will be integrated with a LabView interface to provide visual results of the sensor’s readings. The second stage will be the utilization of the Efactor Octavis to obtain vibration data. This data will be analyzed utilizing a LabView program to determine the spectral distance, of a specific set of data, from a given reference signal. The last stage will be to send both sensor readings across a ZigBee enabled wireless network.

C. RELATED WORK

The thesis builds upon the research foundation established by several students at the Naval Postgraduate School. Chimi Zacot [4] initiated research into the feasibility of using a ZigBee protocol to measure pressure in a shipboard environment. This work was combined with the research conducted by Jonathan Young [5] into vibration analysis. The intent was to couple the use of wireless transmission initiated by Zacot with the theoretical hypothesis postulated by Young to produce the wireless transmission of all major sensors in shipboard engineering spaces. The most difficult sensor to transmit was the vibration analysis so the work was initiated sequentially starting with the creation of a robust pressure sensor and culminating in the wireless transmission of a vibration analysis signal. Research conducted by Joseph Davis [6] was essential to a conceptual visualization of what sensor parameters are fundamental to the successful operation of MESH networks. Additionally, Davis’ work was helpful in estimating the level of attenuation expected from the various nodes, and how to potentially maximize the

performance of the network. Finally, a thesis conducted by Adnen Chaabane [7] was important to the understanding of the limitations of a wireless network within a shipboard environment. The concerns of interference in the electro magnetic (EM) spectrum in a shipboard environment, and the limitations in range on a vessel that is heavily compartmentalized with metal doors, were highlighted in this research.

D. PROPOSED CONCEPT OF NEW TECHNOLOGY

The thesis will demonstrate that laptop computers and Personal Digital Assistants (PDA) can be used to display data anywhere within the range of the ZigBee network. It will require some additional programming to feed the output of the network directly into an IP gateway for a shipboard intranet. The results may be stored on a server linked to the shipboard intranet. Thus, any shipboard terminal can be used to access real time sensor data. Condition based maintenance will be facilitated through a series of alarm points for specific equipment. These alarm points will alert decision makers when the data from the sensor has exceeded some defined value. The alarm will indicate that maintenance is required. With all ships in the fleet operating wireless sensor networks the Navy can then identify trends across entire classes of ships. These trends will improve maintenance efficiency, extend the life of the ships, and reduce maintenance downtime.

E. BENEFIT OF CONCEPT TO THE NAVY

The potential for reduction in crew size aboard naval vessels provides significant incentive for dedicated research in condition based maintenance and shipboard wireless networks. Additionally, a ZigBee enabled sensor network provides filtered information to the decision makers. This information can also be transmitted to “reach back” units that can provide maintenance advice or, facilitate supply chain management of maintenance equipment. A data enabled supply chain can ensure that minimal time is lost in obtaining required maintenance parts and making necessary fixes prior to catastrophic breakdowns.

ZigBee enabled sensor networks are robust, when established as a mesh, and provide a high degree of survivability for the Navy in combat operations. When one sensor is dropped from the system a mesh network will reconfigure to continue to pass data via other existing nodes.

Finally, the data obtained from wireless networks, across the fleet, will assist in acquisition decisions, improve contract regulation, and raise the accountability of Department of Defense (DoD) contractors.

F. DESCRIPTION OF CHAPTERS IN THESIS

The first chapter is the introduction. The second chapter discusses the development of both hardware, and software, to take pressure measurements of compressed air at 100 psi. The third chapter outlines the theory behind the use of a spectral distance formula to measure the vibration signature of a specific piece of equipment. The fourth chapter focuses on the use of the ZigBee protocol to transmit sensor readings from the sensors outlined in chapters two and three. The fifth chapter lists the conclusions obtained from the research and, any areas that will require further investigation.

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II. CONSTRUCTING A PRESSURE SENSOR

A. INTRODUCTION

This chapter examines the critical equipment and software required to obtain an analog pressure measurement. The key sensor used was a 242PC100GS pressure transducer manufactured by Honeywell. The need to examine a pressure sensor was identified in the work done by C. Zacot [4]. However, the pressure sensor constructed during that research was not robust enough to survive testing in a shipboard environment. To fully test the capabilities of a wireless network to handle both analog and digital sensor readings required a robust pressure sensor package. The design of the pressure sensor is cataloged and a synopsis of the experimental testing is presented. Finally, the lessons learned in constructing the pressure sensor module are outlined.

B. PRESSURE SENSOR

1. Hardware

a. Why a New Pressure Sensor?

The original pressure sensor used to obtain the results achieved in reference four is shown below.

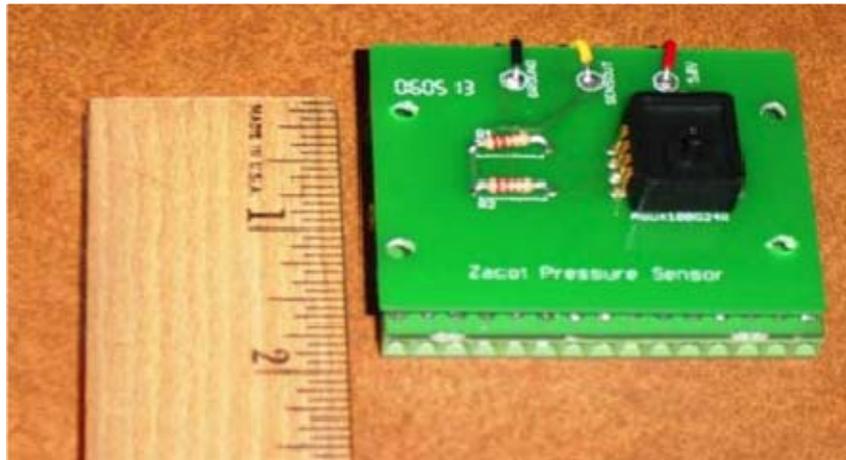


Figure 1. Pressure Sensor Used for Wireless Transmission [From 4].

The pressure sensor was connected to the device to be measured by a small plastic hose. Unfortunately, the pressure sensor could not handle pressures above 20 psi: the hose connecting the pressure sensor to the source would become disconnected. The Honeywell pressure transducer shown in Appendix A was selected to provide a robust sensor that could be connected to a wide variety of shipboard pressure valves. The 242OC100GS had a threaded 1/8 inch National Pipe Thread (NPT) connection with which to attach the sensor to the pressure source to be measured.

b. Sensor Package Design

The pressure sensor required a voltage source between 7 and 16 volts. It was envisioned that the sensor would be utilized as a stand-alone module. Therefore, the sensor node would have to be battery powered. Given the requirements of the pressure sensor the power source selected was a nine volt battery. The other components required for the sensor module were an analog to digital (ADC) converter and a processor to packetize the digital data and transmit the data via the wireless network. The MaxStream XBee, and XBee-Pro, shown in Appendix E contained four ADC devices. However, the XBee module required a constant 3.3V in order to power the device. To meet this requirement a voltage regulator was incorporated into the design to ensure a constant 3.3V supply to the XBee module. The XBee supply voltage was also the reference voltage for the input to the ADC. The output voltage of the pressure transducer varied in range depending on the supplied voltage. After studying the output characteristics of the Honeywell pressure sensor it was decided to step down the supplied voltage to eight volts. This decision was made to allow for a one volt drop in supplied power prior to requiring that the batteries in the pressure sensor node be changed.

With a supplied voltage of eight volts for the pressure transducer a second voltage regulator was added to the circuit. The voltage regulator used was a Dimension Engineering adjustable voltage regulator. Unfortunately, the voltage regulator exhibited a very low tolerance when maintaining eight volts from a nine volt power source. This required an increase in the required voltage source for the pressure sensor node. It was decided to connect two nine volt batteries in series thereby increasing the supplied

voltage to 18 volts. With this power source a circuit was created in the lab as shown in Figure 2. It should be noted that a rail to rail Op-Amp was utilized to buffer the input to the XBee chip. The characteristics of the National Semiconductor Op-Amp LMC6464 are shown in Appendix B.

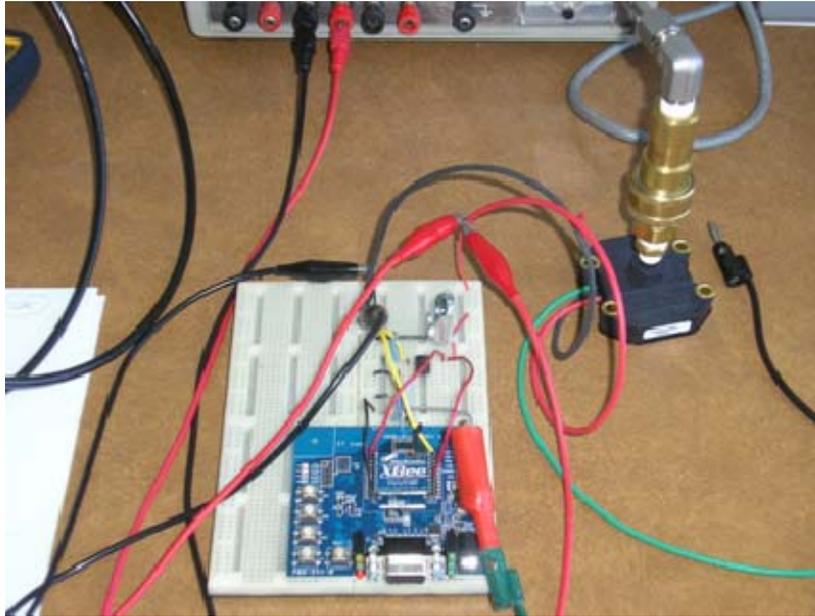


Figure 2. Test Circuit for Pressure Sensor Node.

Once a test circuit was constructed the circuit was tested to obtain the characteristic curve for the pressure transducer. Values of pressure from 0 psi to 100 psi were obtained and the resultant voltages from the pressure transducer and input to the XBee were recorded.

Pressure (psi)	Output from Pressure Transducer (V)	Input to Xbee (V)
0.02	0.97	0.54
10	1.465	0.82
20	1.96	1.1
30	2.46	1.38
40	2.96	1.65
50	3.46	1.93
60	3.96	2.21
70	4.46	2.49
80	4.96	2.77
90	5.45	3.05
100	5.95	3.33

Table 1. Characteristic Curve of Honeywell Pressure Sensor.

The following two graphs show the linear characteristics for the Pressure Sensor node.

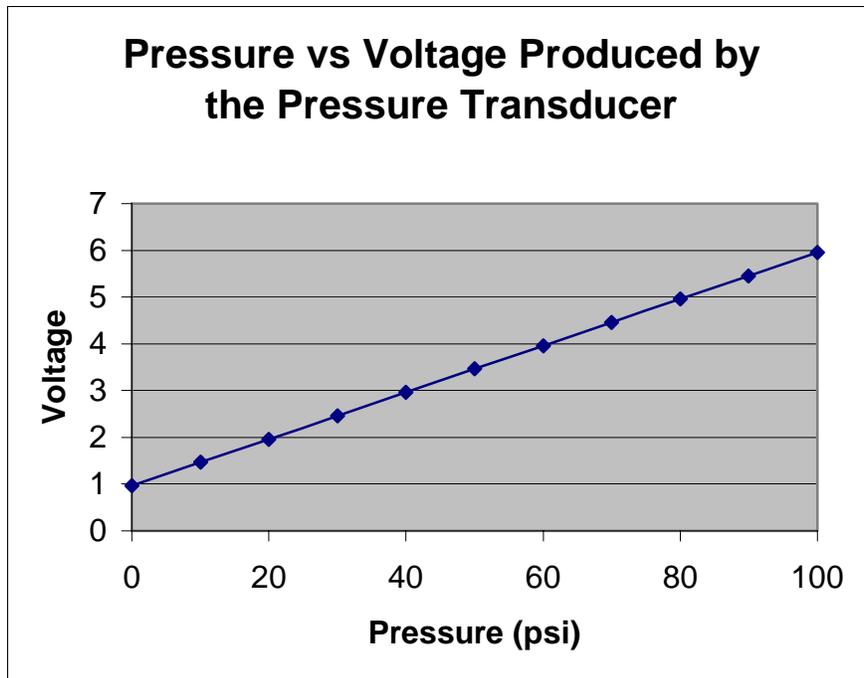


Figure 3. Graph 1 of Test Results for Pressure Sensor Node.

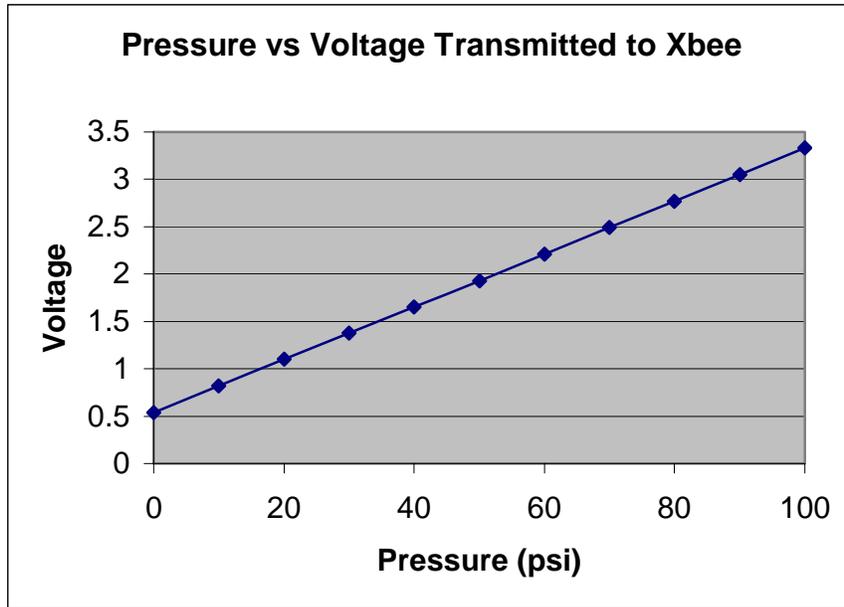


Figure 4. Graph 2 of Test Results for the Pressure Sensor Node.

The results of these two graphs will be used to establish the necessary variables in LabView to receive the results from the XBee ADC in hexadecimal and convert the result to a decimal value. For example: the maximum voltage output from the pressure transducer is 5.95 volts. This voltage represents 100 psi. Given this result the following formula provides the linear multiple to convert the voltage, output by the pressure transducer, into a pressure value in psi.

$$pressure_{out} = \frac{(V_x - 0.97)}{(5.95 - 0.97)} * 100$$

c. Construction of the Sensor Node

A program called Easily Applicable Graphical Layout Editor (EAGLE) was used to create a Computer Aided Design (CAD) file to build the Pressure Sensor. The test circuit shown in Figure 2 was transferred to a board through the use of the EAGLE software.

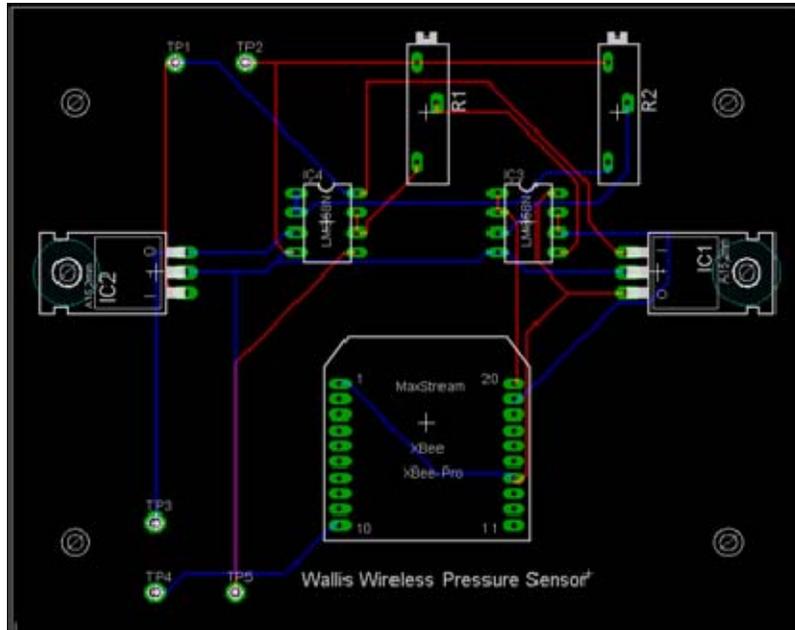


Figure 5. Circuit Board Design for Pressure Sensor.

The circuit board was designed to allow for a small electric circuit that was easy to construct, capable of being run with commercial off-the-shelf (COTS) batteries, and easily integrated with the MaxStream XBee, or XBee Pro, processors. The board selected was four inches by three inches and provided enough room to make adjustments to both the adjustable resistors and the adjustable voltage regulator. As noted earlier the design requires an 18 Volt power source and the assumption was that two nine volt batteries would be connected in series and strapped to the underside of the circuit board. The top of the board was open so that any antennas attached to the XBee chip would not be obstructed. Finally, the board was small enough that the entire package could be mounted in a container with a magnetic base for shipboard deployment.

The completed circuit board is shown in Figure 6.



Figure 6. Pressure Sensor Node.

The completed Pressure Sensor Node shown in Figure 6 is 3.5 inches by 4.5 inches. A plexi-glass board was used to mount the pressure transducer and the two nine volt batteries. The entire node was then measured at (5.5 x 4 x 3) inches in volume. There is ample space on the board for other electrical components. Additionally, there is potential for further minimization, of the sensor, if so desired.

2. LabView Interface

A LabView interface was designed to take the raw data received from the XBee device and convert it into a user friendly pressure reading. The LabView received data from the pressure sensor through either the RS232 ports or the USB port. This data had to accept a raw voltage from an XBee chip in the range 0.54 volts to 3.33 volts and convert it to the voltage accepted from the pressure transducer. The pressure transducer was utilizing eight volts to power the sensor and this place the output in the range 0.97 volts to 5.95 volts. The relationship was linear, in this range, and therefore the slope of the line between the voltage delivered by the XBee, and the voltage measured by the pressure transducer, was calculated to be:

$$\text{Slope}(m) = \frac{5.95 - 0.97}{3.33 - 0.54} = 1.7978$$

$$\text{Intercept}(C) \Rightarrow 0.97 = 0.54m + C$$

$$C \approx -0.00083$$

These values were programmed into LabView in order to calculate the required pressure in psi. Figure 7 shows how the equations were programmed to calculate the desired output. The input was an expected string of 32 bytes. The first 11 bytes were header information and there was a byte of information that followed the data string. There were 20 bytes in the data string. The pressure transducer was sampled five times every 100 milliseconds. The reference voltage was also sampled five times every 100 milliseconds. These ten measurements were delivered as a 20 byte data string. Each measurement was two bytes in length.

At the input, the data was buffered to ensure that enough data had been received to manipulate one full data string. Once the data string was obtained the node number was determined and the remaining 11 bytes of header information stripped off the string. Then, using a “For-Loop” each pressure reading and reference voltage reading was removed from the string, converted to appropriate units, and displayed as shown in Figure 7. The display shows the data string values, in hexadecimal, and the values of the transducer voltage as it is converted to a pressure reading. The user display is shown in Figure 8. The easiest interface to observe is the pressure gauge but, the exact pressure readings, and reference voltage, are also shown as a decimal value. These values are constantly changing due to the rapid sampling rate selected.

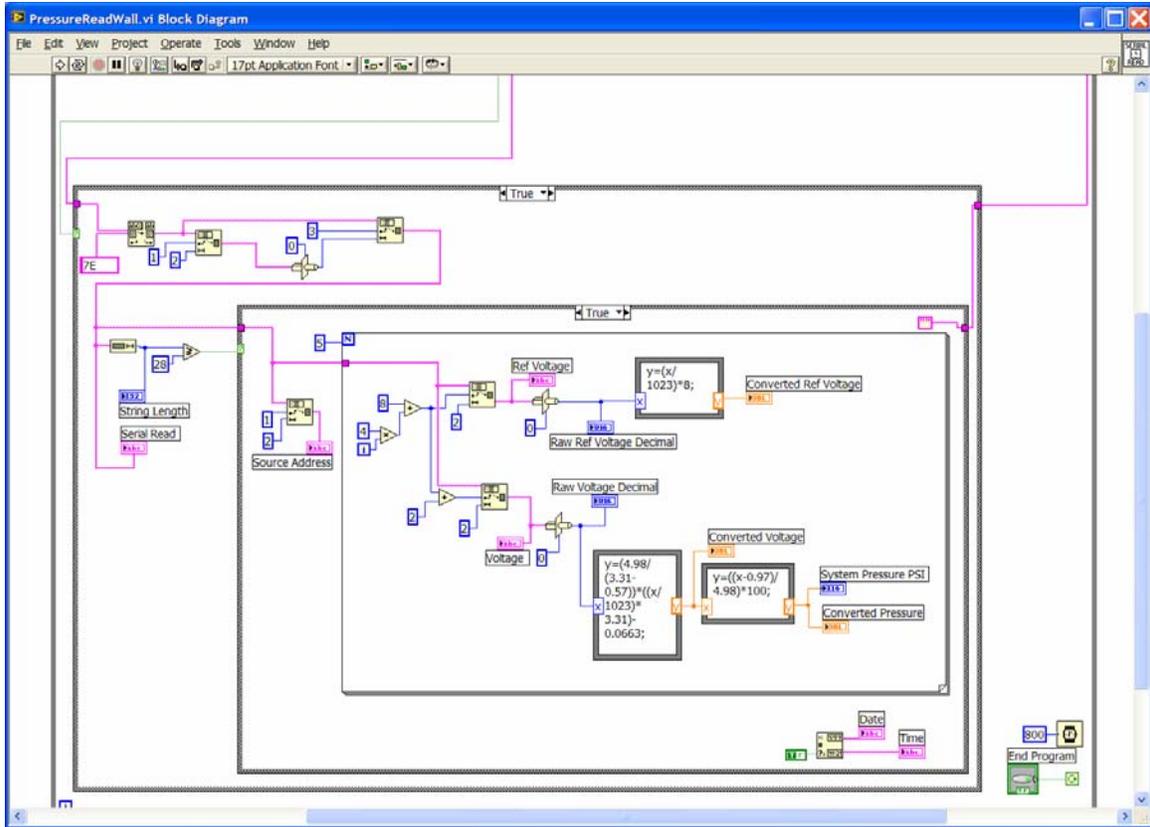


Figure 7. LabView Program to display output of the Pressure Sensor.

C. RESULTS

To test the pressure sensor a hand held pressure pump was attached to the remote sensing device. The pressure pump had a range of zero psi to 120 psi. An underlying assumption of the test was that the pressure pump, and the pump's attached gauge, was calibrated. The sensor was tested by applying a known pressure to the system through the pressure pump and observing the resultant pressure reading on the LabView program display (see Figure 7 & Figure 8). The test was conducted from zero psi to 100 psi. The results are shown in Table 2. The readings obtained from the pressure sensor showed an error of plus or minus 0.5 psi. This error is acceptable given that a ten bit ADC can only read up to 0.1 psi. It must also be noted that there was some fluctuations in the pressure readings from the pressure sensor within every 0.1 second interval.

Pressure Shown on Pump	Voltage from Pressure Transducer	Hexadecimal Received by Computer	Calculated Voltage from Pressure Sensor	Calculated Pressure (psi)
0	0.966	00A2	0.922	-1.9
12.71	1.6	0111	1.587	12.394
20.35	1.98	0154	2.0	20.22
30.1	2.48	01A8	2.47	29.79
40.1	2.97	01FB	2.96	40.07
49.6	3.44	024D	3.431	49.002
59.3	3.92	02A2	3.937	59.117
69.153	4.43	02FA	4.432	69.163
100.2	5.93	03F9	5.91	99.8

Table 2. Results of Pressure Sensor Test.

The reference voltage holds steady at eight volts. This is also shown in Figure 8. The reason that the reference voltage was displayed was to provide a method through which the supplied battery voltage could be monitored in order to ensure the integrity of the measured pressure.

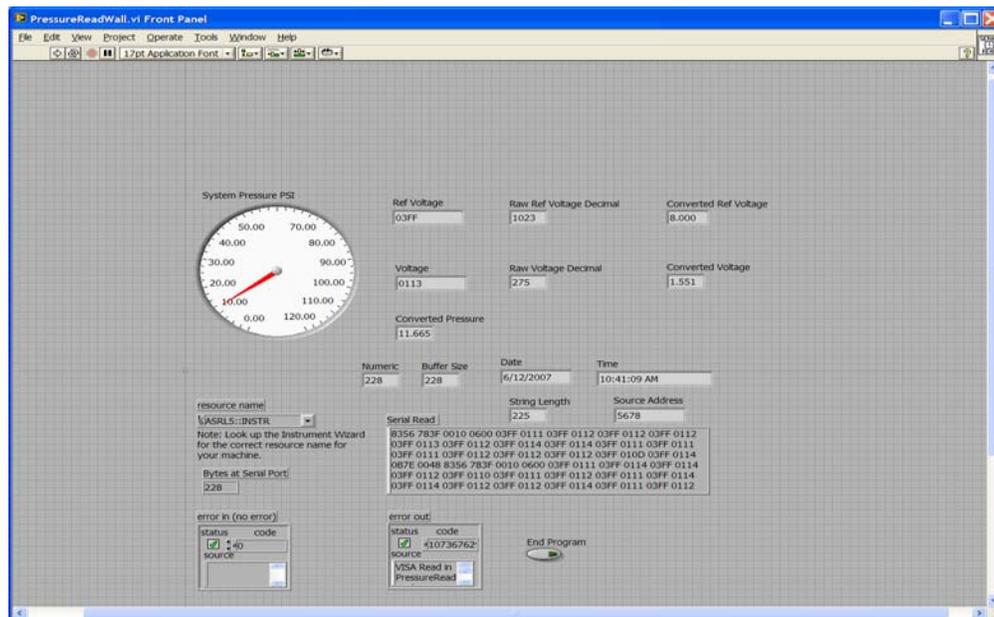


Figure 8. User Display for Pressure Sensor LabView.

D. LESSONS LEARNED

The Pressure Transducer did not function as anticipated when viewing specifications on the World Wide Web. The linear nature of the output voltage was not expected to be dependent on the voltage that powered the transducer. Although, rather expensive, the sensor was not as accurate as desired and rather unwieldy. The nature of the sensor was dictated by the requirement for a threaded connection that could withstand pressure in excess of 120 psi. The need to supply at least eight volts to the pressure sensor and 3.3 volts to the XBee chip resulted in two voltage dividers. If this sensor was to be mass produced it would be advisable to ask for a sensor that met very detailed design specifications. Economies of scale should result in an accurate, affordable pressure sensor that requires less power.

A draining battery has an effect on the calculated linear scale of the pressure transducer. To mitigate this effect it was decided to maintain the voltage supplied to the pressure transducer at eight volts. This voltage was also transmitted with the pressure readings to allow the user to identify when the battery, at the sensor, required changing and to maintain the validity of the outputted results. This increased the number of ADCs used on the XBee chip to two. This solution allowed a remote user to identify when the batteries at the sensor site required changing and thereby maintain the known linear relationship between the pressure transducer's outputted voltage and the pressure displayed on the pressure sensor.

Testing a circuit on a breadboard is critical. Although intuitive, it is mentioned here to highlight the invaluable lessons learned in the lab prior to the design of a CAD file. Firstly, it was determined that buffers would be required to isolate critical elements of the circuit. For example, buffers separated the output of the voltage divider circuits from the inputs to the XBee chip. When buffers were not used different loads were seen at the terminals of the voltage divider circuit. These differing loads did not provide a maximum output of 3.3 volts and thereby impacted the calculations to convert the digital signal into a valid pressure measurement. Secondly, the linearity of the pressure transducer limited the number of available supply voltages. The linear relationship

between the output voltage, from the pressure transducer, and the measured pressure was directly proportional to the supplied voltage. Therefore, it was important to identify a voltage supply that facilitated the conversion of the pressure transducer's output voltage into a pressure measurement. Finally, the initial supplied voltage of eight volts could not be maintained by the adjustable voltage regulator. The regulator could only maintain eight volts if the supplied voltage stayed within 0.1 volts of the supplied value of nine volts. This tolerance was too slim for the sensor and it was determined that 18 volts would need to be supplied in order to maintain a steady supply voltage of eight volts to the pressure transducer.

The ability to access user-friendly CAD software is invaluable. This software can rapidly reduce complex circuits into CAD files for computer manufactured circuit boards. However, small errors in the schematic can lead to a circuit board that will not function as expected. There were some connections to ground that appeared complete on the schematic but, upon closer inspection were determined to be a broken circuit. The computer will complete the board "exactly" as designed.

Calibration of the sensor node may be conducted using the LabView interface program. However, this will require a "true" measurement source with which to compare the reading from the pressure sensor. Since the pressure sensor is based off a linear relationship in the conversion of the voltage to pressure: the slope of this linear relationship and its intercept on the y-axis can be adjusted in order to ensure correct measurements are obtained. Manipulation of the data in LabView, or user defined inputs to manipulate the calibration constants, are both possible avenues for maintaining the calibration of the pressure sensor. Given that temperature sensors can be configured in an identical manner to pressure sensors these results should be valid for either pressure or temperature sensors. These are the two sensors that dominate the shipboard engineering spaces.

III. VIBRATION ANALYSIS WITH THE SPECTRAL DISTANCE FORMULA

A. INTRODUCTION

This chapter examines the critical equipment and software required to obtain a vibration measurement. The key sensor used was an Efector Octavis [Appendix C] which was a commercial off the shelf (COTS) sensor purchased to test the feasibility of wireless networks. The critical elements of the LabView program, used to execute the experiments, are outlined. The theory behind the mathematical formula that was used to access the vibration signature for a specific piece of equipment is also discussed. Additionally, the results of two experiments demonstrating the use of the spectral distance formula are presented. Finally, the lessons learned in researching the vibration sensor are outlined.

B. BACKGROUND ANALYSIS

1. MEMS Devices

The vibration signature of a specific piece of equipment can be measured using MEMS accelerometers. A MEMS accelerometer senses vibration through the use of micro-fingers in close proximity to anchored electrodes. When the assembly is subjected to vibrations the fingers are deflected and the electromagnetic field between the micro-fingers and the anchored electrodes changes. This will produce an analog signal which continuously indicates the acceleration of the sensor. If there is no acceleration, that is the sensor is at a constant velocity, the signal will be constant. If, however, the sensor is subjected to continuous but, possible varying accelerations; as it would be when mounted on a vibrating object, the signal will be directly proportional to the actual vibration. Figure 9 is a picture of a MEMS accelerometer showing the fixed electrodes and the deflecting fingers.

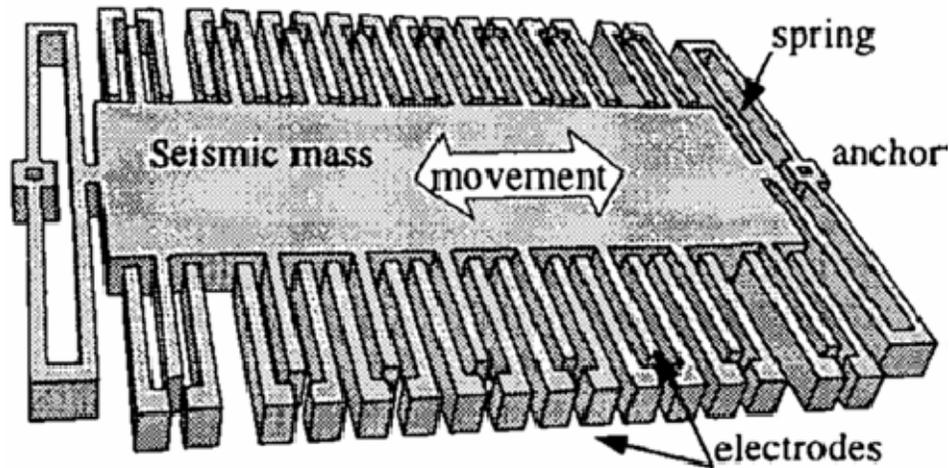


Figure 9. MEMS Vibration Sensor [After 5].

One MEMS device can be used to measure the vibration in one dimension. A typical sensor package will contain three MEMS devices in order to measure vibrations in three dimensions.

MEMS devices come in two major categories: Complementary Metal Oxide Semiconductor (CMOS) compatible bulk micro-machined and surface micro-machined. There are efforts underway to generate MEMS using light sources to measure the deflection on a membrane that is a suspended surface within the MEMS sensor.

The theory of electrostatic fields, generated due to capacitance, provides the foundation of how a MEMS works. When a force due to acceleration acts on a MEMS device, the force is applied to a thin membrane within the MEMS device. The deflection of this membrane produces an analog voltage signal that is proportional to the change in the capacitance caused by the membrane deflection. In order to appropriately analyze the data produced by a MEMS device the analog signal produced by the device must be converted to a digital signal through the use of an Analog to Digital Converter (ADC). [8], [9]

2. Efactor Octavis

The Efactor Octavis [data sheet shown in Appendix C] is a Vibration monitor designed to detect rolling element bearing failures and shaft unbalance. The sensor

contains MEMS accelerometers. The sensor was originally designed for use in automotive airbag applications. Additionally, the Octavis contains a built-in 16-bit ADC and a Digital Signal Processor (DSP). The DSP takes the output from the ADC and converts the sensor signal from the time domain to the frequency domain. This is executed through a Fast Fourier Transform (FFT). The final output from the Octavis is a vibration signature displayed in the frequency domain. The Octavis has a sensitivity of 1.25 Hz, a sampling rate of 20 KHz, and operates in the frequency range: 0 Hz to 7550 Hz. It should be noted that, within the sensor’s frequency range, the Octavis is set to operate in eight different frequency windows. This had to be taken into consideration when developing the LabView program to interface with the Octavis device. The sensor used an RS232 cable to connect to the serial port of a computer.

Transmission Rate	57600 baud
Parity	None
Data Bits	8
Start Bit	1
Stop Bit	1

Table 3. Efector Octavis Interface Parameters.

The Octavis comes pre-packaged with software that enables a user to set up the sensor to measure up to five diagnostic objects and 20 sub-objects. To execute a detailed analysis of multiple objects requires a series of parameters from the user: bearing manufacturer, gear ratio, specific bearing to monitor and several other values. The Octavis functions by checking critical frequencies, determined by user specified parameters, in order to determine if preventative maintenance is required.

3. Spectral Distance Formula

The method for examining the vibration signature for a specific piece of equipment stemmed from efforts to classify various marine biological signals. In previous

studies, auto regressive parameters were obtained for various biological species and compared to a specific signal in order to determine which species produced the signal [10]. To compare the spectral data in each data segment required normalized spectra of the biological signals. The formula developed to obtain a measure of divergence was:

$$D_{xy} = \sum_0^{N-1} \left(\frac{\ln \left(P_x \left(\frac{2\pi k}{N} \right) \right)}{P_y \left(\frac{2\pi k}{N} \right)} \right) P_x \left(\frac{2\pi k}{N} \right) - \sum_0^{N-1} \left(\frac{\ln \left(P_x \left(\frac{2\pi k}{N} \right) \right)}{P_y \left(\frac{2\pi k}{N} \right)} \right) P_y \left(\frac{2\pi k}{N} \right) \quad k = 0..(N-1)$$

[10]

D_{xy} is the divergence between the spectral density functions of signals $y(n)$ and $x(n)$.

P_x and P_y are the normalized probability density functions of the signals $y(n)$ and $x(n)$ respectively.

N is the number of samples used to computer the spectral expressions.

\ln is the natural logarithm.

Further research into this formula revealed that the formula was derived from the Kullback-Lieber formula:

$$D_{xy} = \sum_0^{N-1} \left(\ln \left(\frac{P_x \left(\frac{2\pi k}{N} \right)}{P_y \left(\frac{2\pi k}{N} \right)} \right) \right) P_x \left(\frac{2\pi k}{N} \right) - \sum_0^{N-1} \left(\ln \left(\frac{P_x \left(\frac{2\pi k}{N} \right)}{P_y \left(\frac{2\pi k}{N} \right)} \right) \right) P_y \left(\frac{2\pi k}{N} \right) \quad k = 0..(N-1)$$

[11], [12]

Note the change in the values applied to the natural logarithm.

The previous formula had been programmed to LabView. It was determined that the FFT amplitudes outputted from the Octavis could be used as the probability density functions P_x and P_y . The value for P_x is the current frequency domain signal to be

evaluated and P_y is the reference signal. The output of the Kullback-Lieber formula was an absolute measure of how closely related the two signals were. A very low result of the Kullback-Lieber formula would indicate that the signals were very similar. In theory the vibration signature of a piece of equipment could then be stored as a reference signal. Regular measures of the equipment's performance would be compared to the reference signal, using the Kullback-Lieber formula, and the obtained value should be very small. If the equipment began to operate outside of its normal parameters the Kullback-Lieber formula would begin to show an increasing divergence from the original reference signal by becoming a larger absolute value.

4. LabView Program

The LabView program, written to research the feasibility of using the Kullback-Lieber formula to measure the vibration signature of naval equipment, is shown in Appendix D.

The user was required to specify whether a reference array, for the Kullback-Lieber formula, was to be created. If the user did not want the program to create a reference signal, arbitrarily selected to be an average of five signals, then the user had to specify a data file from which a reference signal could be obtained. At the end of the program the user was asked whether the current reference signal should be saved. Programming LabView to allow stored reference signal to be utilized to measure the spectral distance facilitated the use of standardized signals that could be maintained in a database. This signal formed a recognized baseline against which any variations in normal operating conditions could be compared.

The LabView program was written so that the entire frequency range of the Octavis could be exploited. Previous efforts at using the Octavis had been limited to machinery that had a vibration signature of less than 500 Hz. A series of steps were taken to facilitate the full utilization of the Efactor Octavis' potential. Firstly, the program opened the appropriate serial device to accept data. The program then instructed the Octavis to begin sending the FFT data. When the data was received the program striped a specific byte off the received packets and evaluated this byte to determine what

frequency range the Octavis was currently operating in. This parameter was essential to correct functioning of the program because it delineated the size of the data string that was being sent. Additionally, this parameter ensured that the probability density like functions, P_x and P_y , were appropriately normalized. The variable in the Octavis supplied packet that determined the frequency range was “ShF”. This variable also determined the length of the data string required to fully process the FFT data.

Value of ShF	Frequency Range (Hz)	String Length (Bytes)
0	0 – 550	896
1000	500 -1550	1696
2000	1500 – 2550	1696
3000	2500 – 3550	1696
4000	3500 – 4550	1696
5000	4500 – 5500	1696
6000	5000 – 6550	1696
7000	6500 - 7550	1696

Table 4. Data Parameters for the Efactor Octavis.

The value of ShF was used later in the LabView to calculate the frequency array. If $ShF = 0$ the frequency is calculated using the following formula:
 $Frequency(Hz) = ShF + 1.25i$
(i is the index for the specific byte in the supplied data string)

If ShF equals any other value, then the frequency is calculated using:
 $Frequency(Hz) = ShF - 500 + 1.25i$
(i is the index for the specific byte in the supplied data string)

The LabView program also calculated the amplitude of each supplied frequency. Once these initial calculations were completed, the program applied the Kullback-Lieber formula to the data. The results were then output to a graphical display (see Figures 13 & 14).

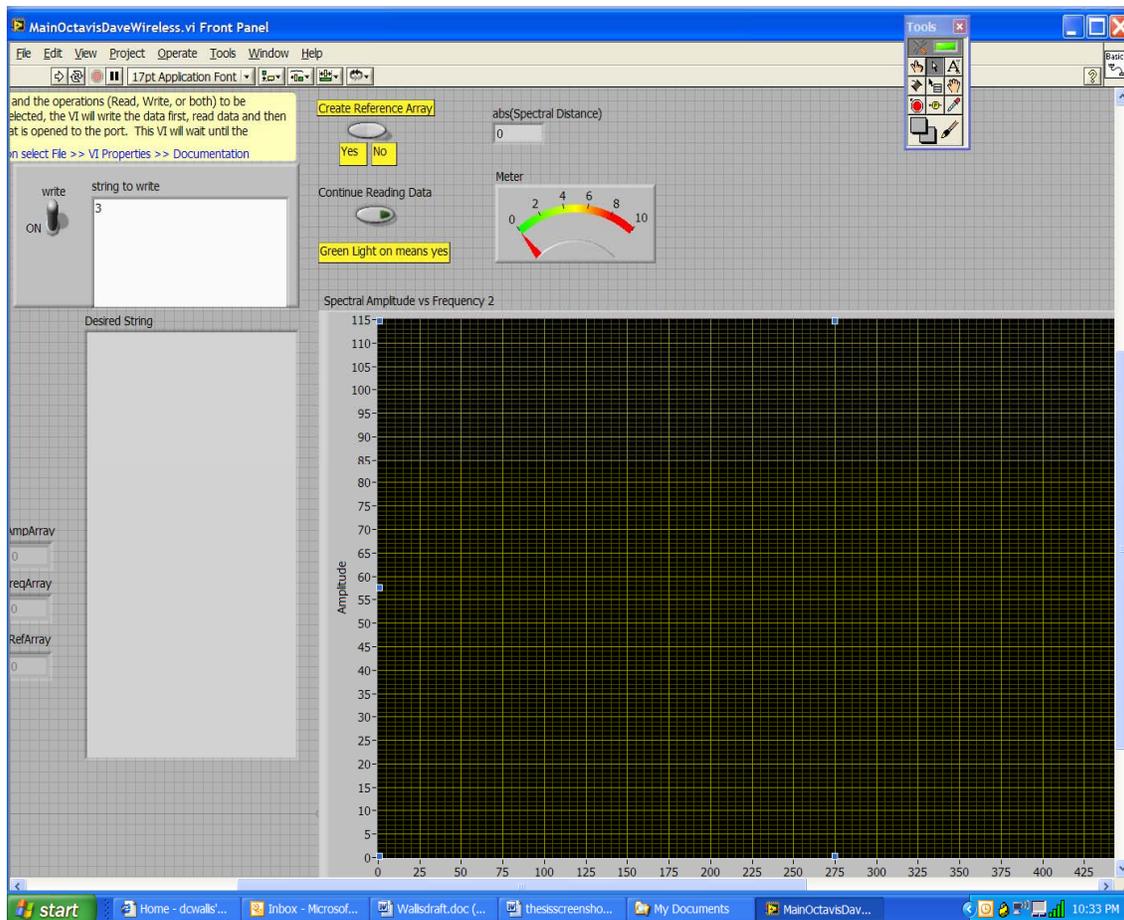


Figure 10. GUI interface on LabView program to calculate the Spectral Distance.

The front panel in Figure 10 is shown with a “3” in the “String to write” box. This is required to initiate the Octavis. The spectral distance is show as a number and is also indicated on the gauge.

C. RESULTS

1. Experiment on 115 V Single Phase Motor

A 115V DC pump motor was selected to test the feasibility of using a spectral distance formula to evaluate a vibration signature. (see Figures 11 & 12) The Octavis was mounted to the motor using a magnetic base that was supplied with the sensor. The 115V pump motor had a small air valve on top of the motor that could be blocked in

order to simulate a stress on the motor. To execute the test the Octavis was connected to a laptop via a RS232 cable. The laptop would run the spectral distance LabView program shown in Appendix D. The Octavis had an independent power source providing ten volts DC.



Figure 11. Placement of Efector Octavis on 115V pump motor.

Tests were taken of the motor's vibration signature with the motor off, and with the motor running. The motor was run long enough to generate a reference signal, approximately 20 seconds, and then a load applied to the air valve in order to generate a vibration signature that was not within the normal operating parameters. It should be pointed out that the motor used in this experiment was not bolted to the table but, all efforts were made to ensure that there was very limited translational motion when a load was being applied to the motor.



Figure 12. Close up of Efeor Octavis on 115V pump motor.

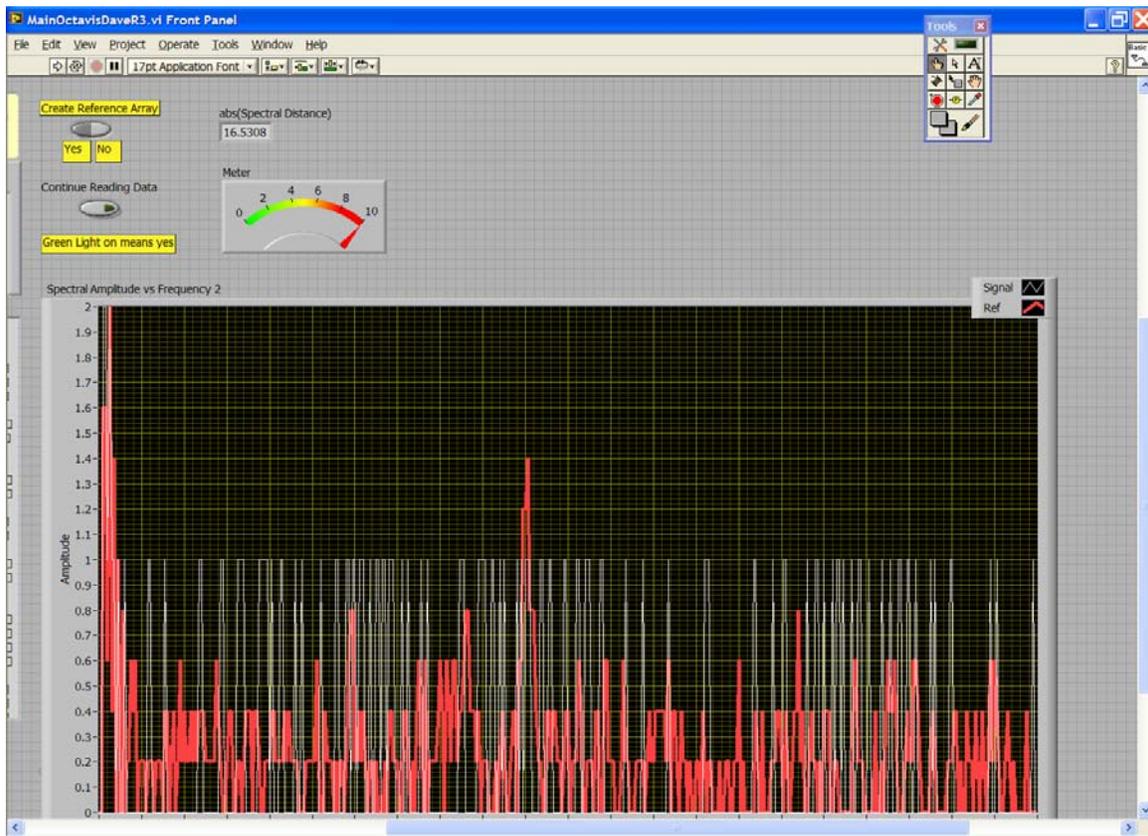


Figure 13. Spectral Distance Result for a Non-Operating 115V DC Motor.

The result achieved when the motor was not running is show in Figure 13. Under analytical examination these results mirror the expected outcome. Since the motor is not operating the Octavis is merely measuring “noise”. Since noise is completely random the spectral distance is very large, no two signals are the same. The spectral distance that is measured in this signal has smaller amplitude than that results observed in Figure 14. The negligible vibrations picked up by the Octavis when the machine is off results in a random Frequency Domain signal that has impulses of very small amplitudes. It is important to remember that the two power density signals that are being compared are normalized to the maximum value for either signal. The output is measured in one thousandth gravity constants (mg) at each frequency.

When the motor was turned on the following results were obtained.

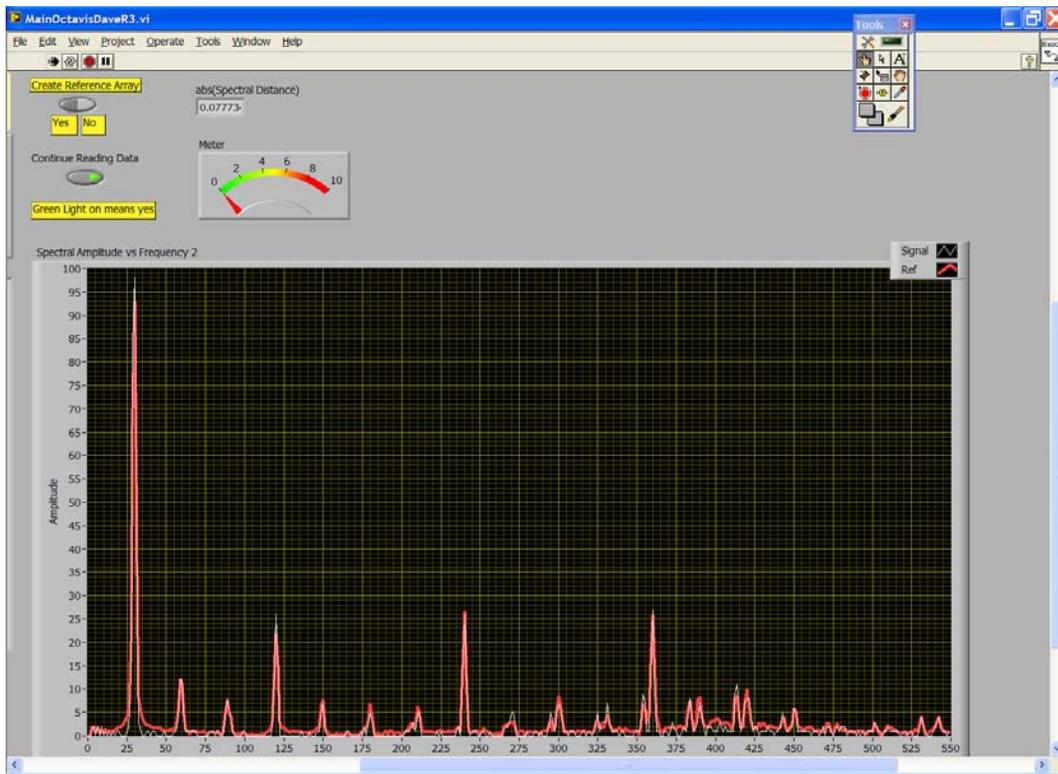


Figure 14. Spectral Distance Result for 115V DC Motor under Normal Operating Conditions.

The results were excellent. The red line shows the reference signal. The white line, often barely visible, shows the current operating status of the motor at the time that the screenshot was taken. The value of the absolute spectral distance was 0.078.

The valve, extending from the 115V DC motor, was blocked to provide a load to the motor. The results achieved once the load was applied are shown in Figure 15. The program had a delay of approximately five seconds before it began to register the changes in the spectral distance due to the applied load.

The measurements reflect a reading of a MEMS device in only one coordinate axis, one degree of freedom. To fully understand the vibration of the machinery would require an analysis of the signal in three dimensions and the manipulation of the absolute spectral distance formula to compensate for the cross correlation of the signals between the coordinate axis.

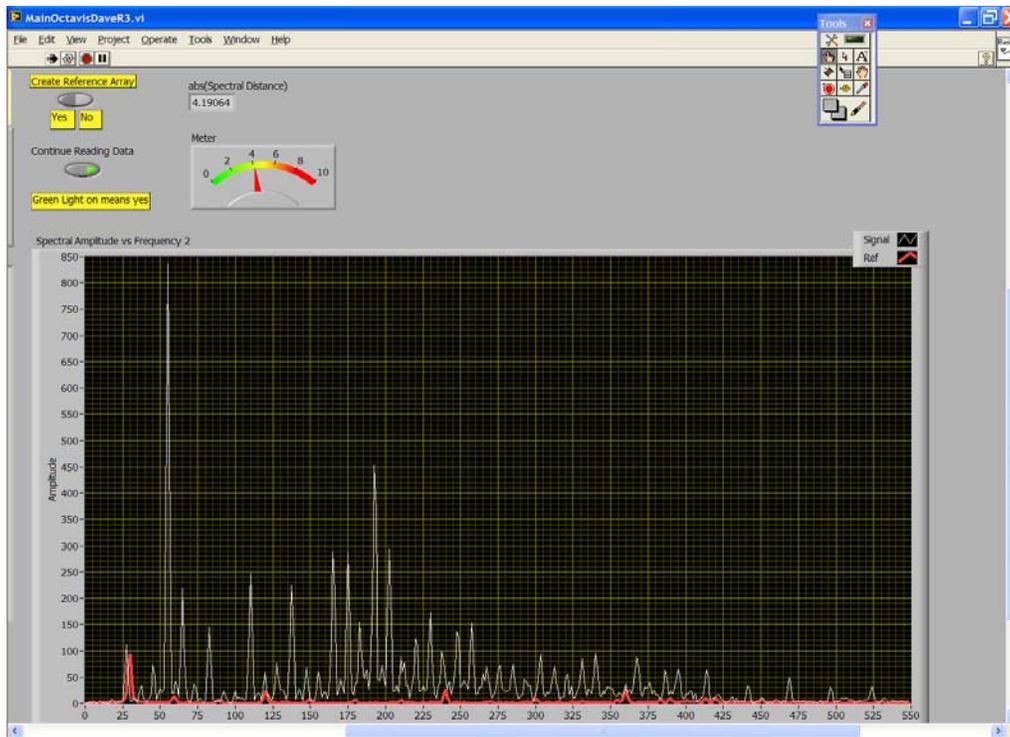


Figure 15. Spectral Distance Results for 115V DC Motor with Load Applied.

Measured Condition on 115V DC Motor	Spectral Distance
Noise Only (Motor Off)	16.53
Normal Operating Conditions	0.078
Load applied to the Motor	4.19

Table 5. Summary of Spectral Distances for 115V DC Motor under Different Operating Conditions.

2. Experiment in Power Lab

To further validate the spectral distance results and, to determine how robust the measurement interface was; tests were conducted on two induction motors in the Naval Postgraduate School's (NPS) Power Lab. Both an AC and a DC generator were evaluated. A picture of one of the two induction motors is shown in Figure 16. The reasons that the induction motors were selected for the experiment were that the induction motors were fixed, had variable frequencies, and various loads could be applied to the motors.

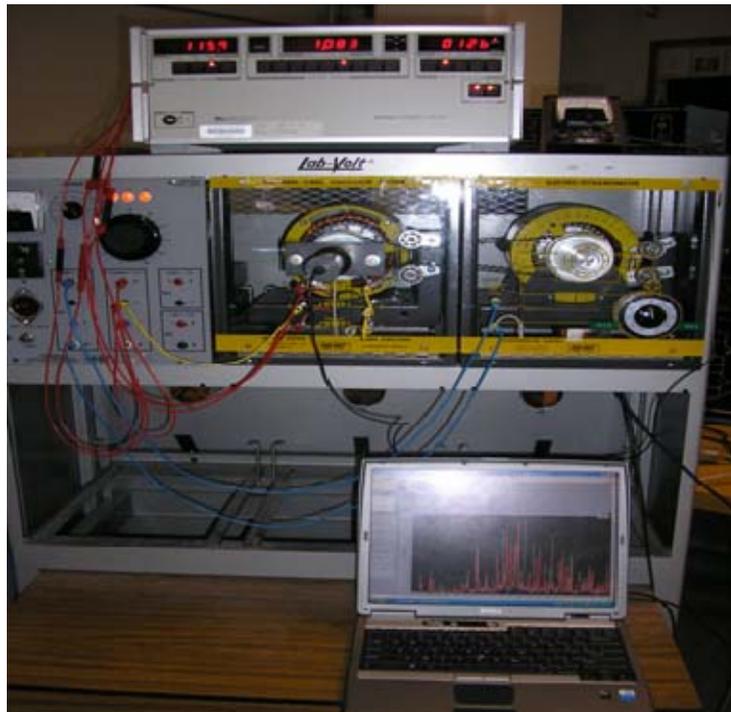


Figure 16. Experiment set up in Power Lab.

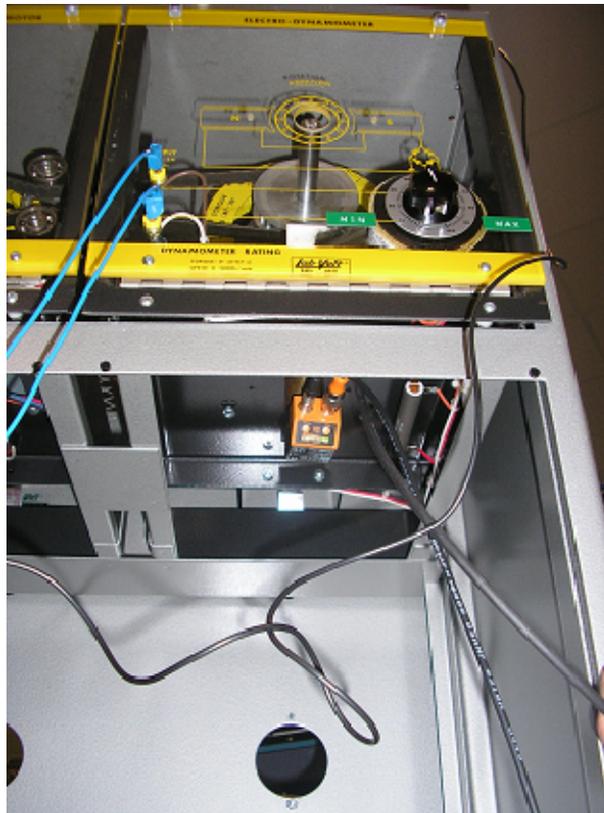


Figure 17. Placement of Efeor Octavis on 3 Phase Induction Motor.

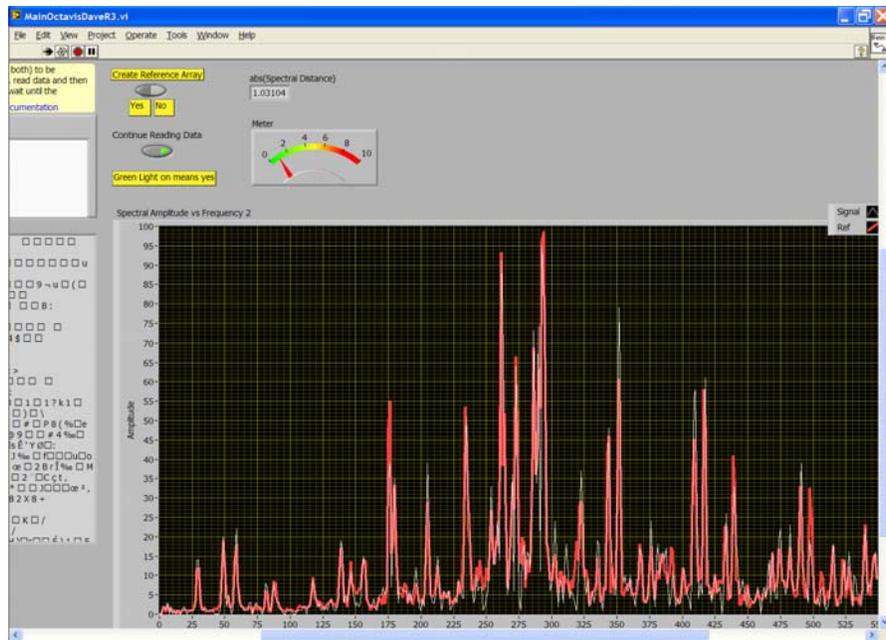


Figure 18. Induction Motor under Normal Operating Conditions, 3 Phase AC, Operating at 1500 Hz.

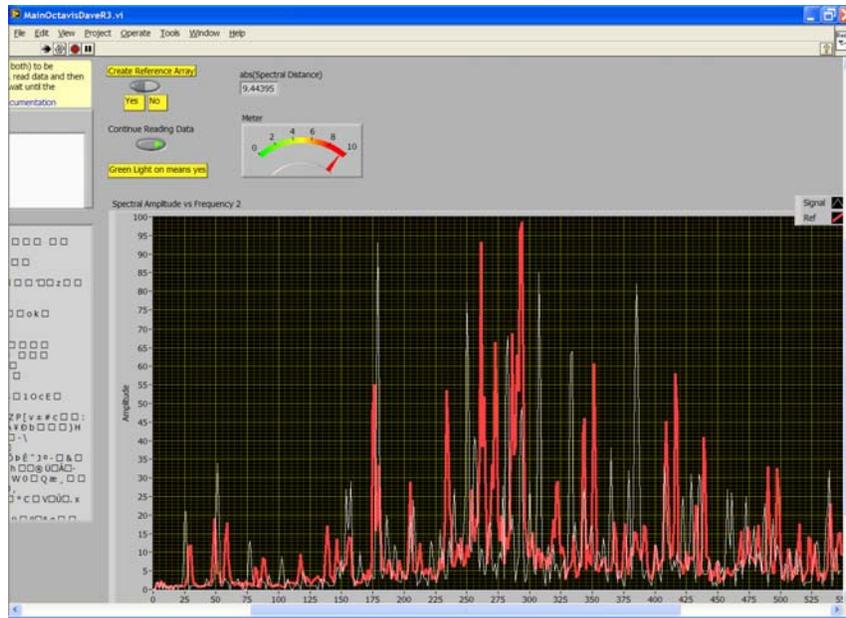


Figure 19. Induction Motor with a Load Placed on the Motor, 3 Phase AC. Operating at 1500 Hz.

The tests on the induction motors demonstrated the same effects as seen on the 115V DC pump motor. Under normal operating conditions the spectral distance, for the 3-phase AC motor was 1.03. When a load was applied to the induction motor the spectral distance increased to 9.44.

The increased frequency applied to the induction motor did not translate to a dramatically increased frequency range for the vibration signature.

D. LESSONS LEARNED

The spectral distance formula is capable of measuring the vibration signature of a specific piece of equipment. Further tests must be developed to access the sensitivity of the spectral distance formula to various problems expected on naval equipment. For example, if a specific bearing is being tested for wear the impact of a bad bearing of this type must be carefully categorized so that the changes in the spectral distance can be matched to a specific condition of the bearing.

The spectral distance formula can be quickly executed with a simple GUI interface like LabView. However, the complexity of the sensor increases the complexity

of the LabView program. Several recursive layers of the LabView can be simplified if a specific sensor is formed for equipment operating in identified frequency regions. The data stream to the LabView is continuous due to the large string size emanating from the sensor. The minimum number of bytes required to evaluate one set of data points was 896. The LabView results can be quickly exported into a shipboard intranet for wider dissemination.

The fact that one of the induction motors showed a higher spectral distance than the 115V DC pump motor can be attributed to the fact that a 3-phase AC motor was being tested. The alternating phases of the motor each operated at a slightly different signature frequency and this caused small aberrations in the vibration signature.

It is very difficult to obtain a vibration frequency that exceeds 500 Hz. Four different pieces of equipment were tested and none of the equipment exceeded the 500 Hz range: 115V DC pump motor, AC induction motor, DC induction motor, and an air conditioning unit for one of the NPS classrooms. Equipment that is operating at very high rotations per minute (rpm) must be used to validate whether the LabView program will produce correct results for signature frequencies above 500 Hz. However, this equipment will have to be similar to a propeller shaft on a ship. A more robust sensor will be required to access the vibration signature of items such as propeller shafts or Close In Weapon System (CWIS) drive motors.

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IV. WIRELESS TRANSMISSION

A. INTRODUCTION

This chapter examines the capability to transmit measured samples from the two sensors previously constructed, a pressure transducer and a vibration analyzer, in order to receive the results at a remote location. The primary tool for investigating this capability was a series of microprocessors produced by the MaxStream Corporation. The specific radio-frequency (RF) modems used will be described. The methods in which these RF modems were utilized will also be examined. Finally, results of experiments conducted to verify the capability to transmit the results of the sensors across a simple network will be outlined.

B. MAXSTREAM NETWORKS

1. ZIGBEE PROTOCOL

The MaxStream Corporation produces a series of radio modems, the XBee series, which are designed to use the ZigBee protocol in order to establish wireless networks. The ZigBee protocol was designed by the ZigBee Alliance to address the problems associated with sensor and control devices. These devices require lower bandwidth, very low energy consumption, and a simple set of interfaces for enhanced interoperability. [13] The results of these requirements were the ZigBee protocol which is built on the IEEE 802.15.4 standard.

The 802.15.4 standard is a wireless communication standard developed by the IEEE (Institute for Electrical and Electronics Engineers). The IEEE is a technical professional association that has put out numerous standards to promote growth and interoperability of existing and emerging technologies. This protocol was developed with lower data rate, simple connectivity and battery application in mind. The 802.15.4 standard specifies that communication should occur in 5 MHz channels ranging from 2.405 to 2.480 GHz. [13] What ZigBee is designed to do is add mesh networking to the

underlying 802.15.4 radio. Mesh networking is used in applications where the range between two points may be beyond the range of the two radios located at those points, but intermediate radios are in place that could forward any messages to, and from, the desired radios. A ZigBee network consists of three specific types of devices: end nodes, coordinators, and routers. A router can also be used as an end node. A coordinator sets up the network, transmits beacons, manages network nodes, stores network information, and routes messages between paired nodes. An end node is designed to facilitate high energy savings (battery powered), to continuously search for available networks, to transfer data from an attached application, to determine when data is to be received, to sleep when necessary, and to request data from the network coordinator.

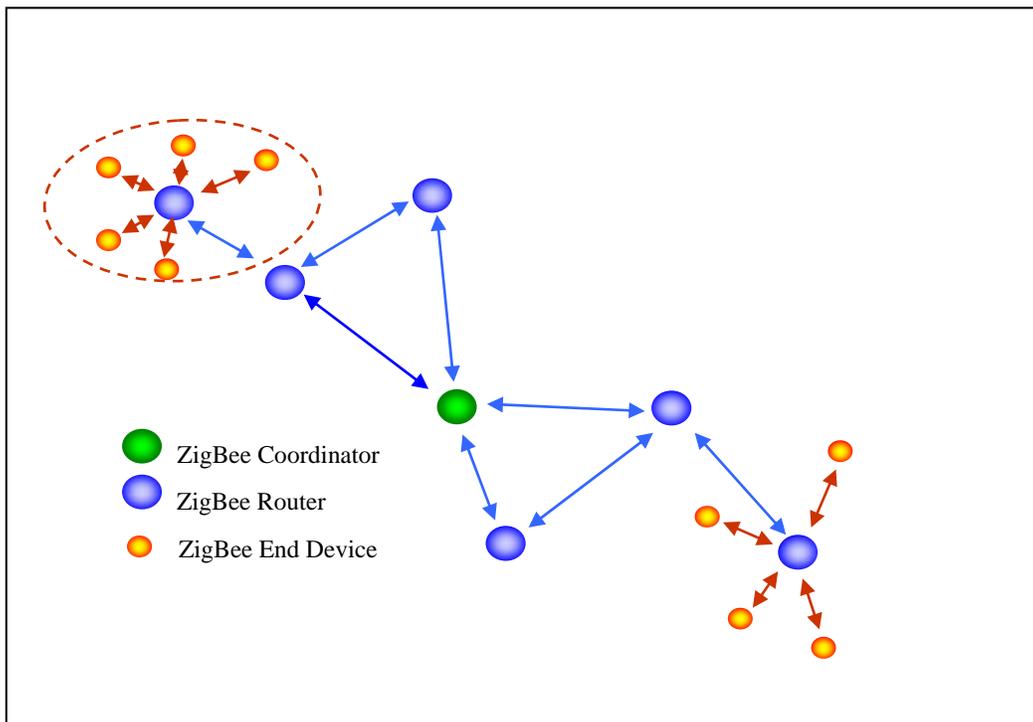


Figure 20. ZigBee Network Model [After 14].

The three types of device may be configured as shown in Figure 20. The intent of using a mesh network is to allow multiple paths for the data in order to increase the probability of data receipt at the desired end point. Since each end device/node may also be configured as a router; the ZigBee protocol can be configured to ensure that multiple

paths are available for data moving from one point in the network to another. A ZigBee network allows an end node to pass information to another node that is beyond the range of an individual RF modem. This process is executed through the routing capability inherent to each ZigBee node. Thus, the intermediate nodes can route the data through to the designated destination. The underlying assumption of this thesis is that the sensors that obtain the initial sensor measurements are end nodes within a ZigBee network.

2. XBEE AND XBEE-PRO

The XBee and the XBee-Pro are RF chips designed by MaxStream. The two modules are very low power and utilize the 2.4 GHz bandwidth defined for 802.15.4 and ZigBee protocols. The modules are interchangeable and both modules can operate on the same network. The XBee and XBee-Pro specifications are shown in Appendix E. The major difference between the two modules is that the XBee-Pro has three times the range of the XBee but utilizes more power.

The XBee modules must be programmed to designate whether the ZigBee or the 802.15.4 protocols are to be used. The program interface is retained as proprietary software by MaxStream. The X-CTU application must be used to program the modules in order to set up a network. For the research conducted in this thesis a developer's kit was used to program the modules. The X-CTU interfaces to the developer's board through either a RS-232 serial cable or a USB cable.

Each module has 20 pins and requires a 3.3 volt power source. The modules have the capability to support up to six ADC inputs. There are two different antennas that can be attached to each module. In the experiments conducted for this thesis both types of antennas were utilized: a chip antenna and a monopole whip antenna. External antennas can also be attached to the chip. The MaxStream RF modules use a Universal Asynchronous Receiver Transmitter (UART) to convert the serial telecommunications data into an asynchronous start/stop bit stream. Incoming data, the serial stream, is buffered prior to being converted through the UART into a signal that can be transmitted. The buffer can hold up to 100 characters. Each ZigBee modem can be set to be either a coordinator or a router. Additionally, each XBee can support four different types of

network operations. The two types of network operations for a Personal Area Network (PAN) are non-beacon and non-beacon with coordinator. The default is a non-beacon network; this was the network used to transmit the sensor measurements in this thesis. [14]

The modems must be programmed with a unique identifier so that data can be appended with a source and destination identifier. This assists in the routing of the data through the network. The amount of bytes in a packet of data, up to a maximum of 100 bytes, can be adjusted for specific applications. Both short, 16 bit, and long, 64 bit addresses can be handled by the XBee. The RF modules operate by default in “unicast” mode, which requires acknowledgement of received data. This mode can be adjusted by assigning the module to operate in “broadcast” mode. This mode does not require an acknowledgement and therefore does not automatically resend packets. The XBee does have a checksum procedure, if the Application Programming Interface (API) is used, that can ensure the integrity of the data received by the destination node.

The format of a data packet, for the default setting on the RF modules, is shown in Figure 21.

C. RESULTS

1. Wireless Analog Sensors (Pressure Sensor)

The pressure sensor required the use of two Analog to Digital Converters (ADC). Therefore, the 802.15.4 protocol on the XBee, and XBee-Pro, was required. A 20 pin connector as used to connect the XBee RF module into the sensor circuit. The circuit designed to accommodate this modem is shown in Figure 6. For the pressure sensor: pin one and pins 14 were connected to 3.3 volts. [Appendix E] Pin one is the high power for the module and pin 14 is the reference voltage. Pin 10 was connected to ground. Two ADC were used and these were fed to pins 19 and 20.

The X-CTU application was used to program two RF modems. One modem was used at the sensor site and the other modem was used to pass the received data into a LabView program for display. The base RF modem, connected to the LabView interface,

was given an address of “1234”. The destination address was specified using the X-CTU command: DL=5678. The input/output (I/O) of the RF modem must be enabled with the command: IU=1. Finally, the I/O Input address was set to the destination address to which all outbound packets are designated. In this case all packets were going to the sensor node therefore the command “IA=5678” was used.

The following commands were used to set up the remote RF modem. The remote modem would be receiving the measurements from the sensor, converting the measured values to a digital string with an ADC, and sending the results to the base RF modem. The destination address for the base RF modem was designated as the address for the remote modem: MY = 5678. The destination address for the remote modem was designated as the address of the base modem: DL = 1234. The two ADC needed for the pressure sensor readings were initiated with: D0 = 2 & D1 = 2. Finally the sampling rate was set as “IR = 14” which translates from 14 Hex to 20 decimal and is thus equivalent to a sample every 20 milliseconds. Finally, the remote module must designate how many samples will be buffered before the data is packetized and transmitted. The command: IT = 5, sets the remote module to take five samples before transmitting the data.

When the data is packetized it is structured as shown in Figure 21.

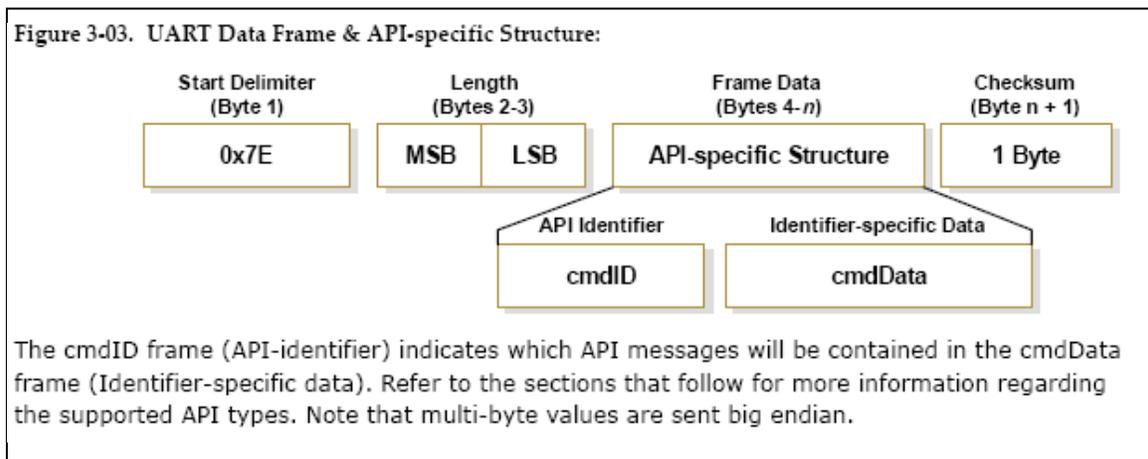


Figure 21. Breakdown of a packet for XBee & XBee-Pro [From15].

The use of the 802.15.4 protocol to transfer data from the pressure sensor constructed in Chapter II is demonstrated in Figure 22. The figure shown is from a screen-shot of the X-CTU during transmission of the voltages from the pressure sensor.

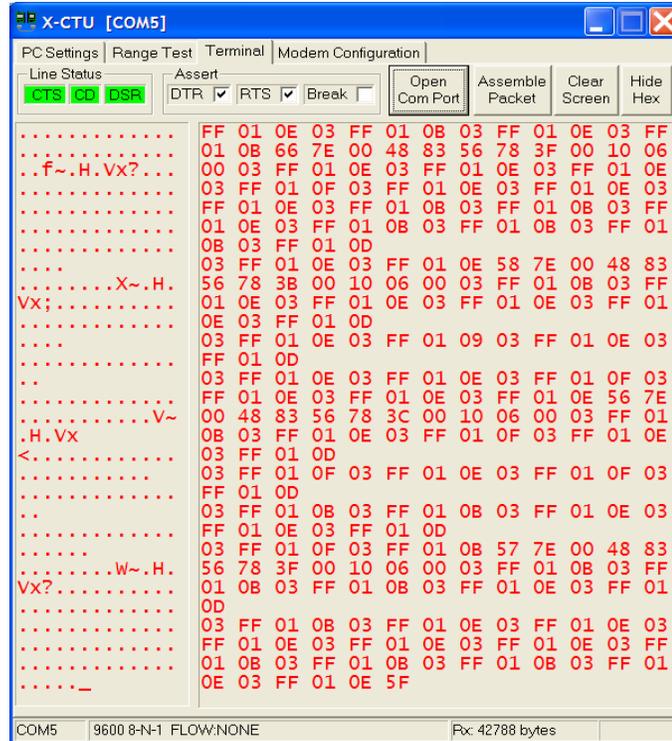


Figure 22. X-CTU screenshot for an 11 psi measurement.

An experiment was devised as shown in Figure 23. The pressure was set using a hand pump with an attached gauge as seen in the foreground of Figure 23. Using the packet structure laid out in Figure 21 the following information can be obtained from Figure 22. Hex “7E” is the starting delimiter. The next two bytes “0048” give the length of the packet as 72 bytes. The “83” is the API identifier byte for 16 bit A/D data. “5678” is the source address. There is a total of 11 bytes of data in the heading followed by 20 bytes for the 10 samples and one byte for the checksum. In the two cases shown the reference voltage reading is steady at “03FF”. This value is 1023 in decimal and is equivalent to 3.3 volts. The first voltage obtained from the pressure transducer output in Figure 22 is “010E” or 270. Using the formulas outlined in Chapter II this value gives a voltage reading of 0.8736 volts relative to the reference voltage of 3.33 volts. This value is applied to the linear characteristics shown in Figures 3 and 4 and results in a voltage of

1.5697 volts. This is the voltage that was read from the pressure transducer's output. Converting the transducer voltage to a "psi" measurement results in a reading of 11.9 psi. The error rate in the measurement is acceptable considering that the original reading of 11 psi was taken from a gauge that had not been calibrated. Additionally, the transducer has a tolerance of 0.05 volts for every one psi.



Figure 23. Experiment for Wireless Transmission of Pressure Sensor.

The data screen shown in Figure 22 was obtained on a laptop that was 150 meters from the sensor node. The transmission between the sensor node and the receiving node, connected to the laptop via the USB port, was via the 802.15.4 protocol. Over 20 tests were conducted to validate the data could be transmitted wirelessly. All tests were conducted indoors. The wireless readings were obtained using a sensor node that was powered by two nine volt batteries. Since no sleep mode was utilized, the transmissions were continuous and it was observed that the batteries maintained power for 25.2 hours.

2. Wireless Serial Streams (Vibration Sensor)

The vibration sensor did not require the use of an ADC but, the 802.15.4 protocol was still utilized to establish a wireless connection between the sensor and the receiving station. In order to establish a simple two point network the X-CTU was used to program the RF modems as shown in Figure 24.

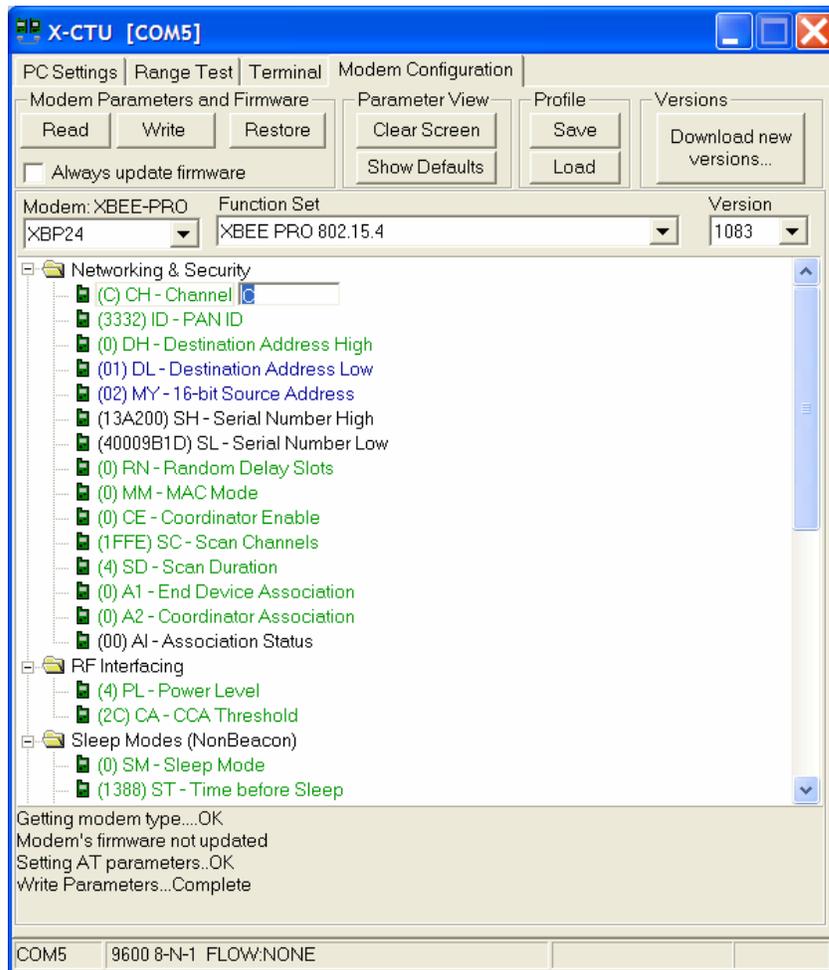


Figure 24. X-CTU Interface for Programming RF Modules.

Since the RF modems would be passing a serial data transmission, the key element in setting up the base, and remote, nodes was to ensure that the baud rate of both

modems was identical. The baud rate for this experiment was 57600. The experiment is shown in Figure 25. The two developer's boards shown on the desk are the base and remote RF modems. The remote modem is transmitting data from the Efector Octavis to the base modem. The laptop is showing the results of the data once it has been manipulated in a LabView program.

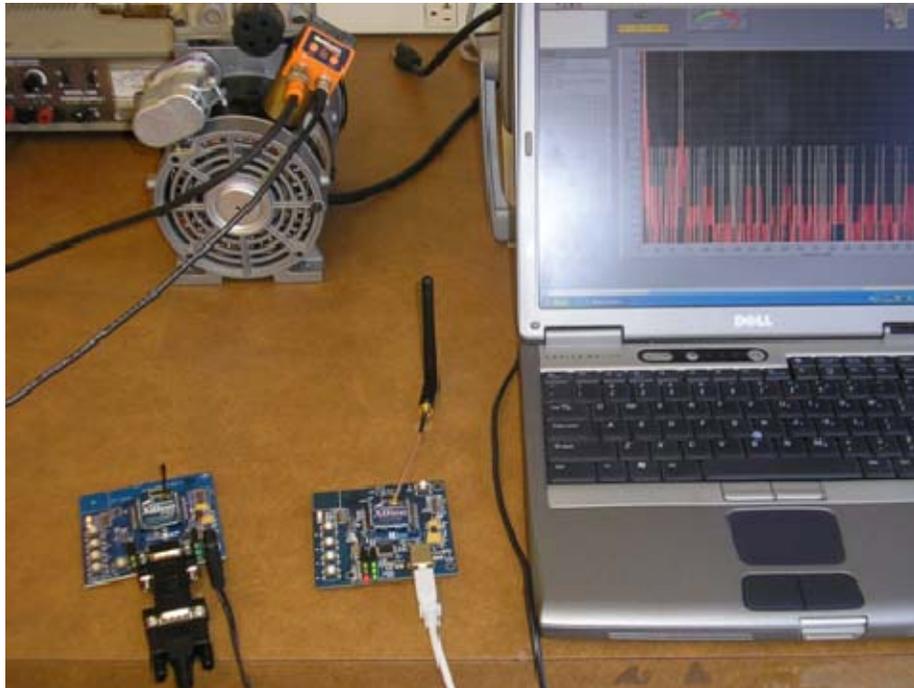


Figure 25. Wireless Transmission of data from Vibration Sensor.

The wireless experiments uncovered a point of interest. Initial tests on the wireless transmission of the Efector Octavis data showed that a certain amount of data was lost. The Octavis requires a string of either 942 or 1742 bytes in order to obtain a valid spectral distance measurement. The LabView program was designed to receive a full string approximately every two seconds. Initial tests showed that 20% of the strings received were not of the correct length. This was corrected through programming in LabView. However, it increased the amount of time take to obtain a full string and indicated a certain amount of degradation in the signal being transmitted. Bit error rate was calculated at 0.0011, for a string of 942 bytes. It should be noted that the

experiments were conducted in broadcast mode which does not require an acknowledgement; this is in comparison to unicast mode which does require an acknowledgement.

D. LESSONS LEARNED

The MaxStream RF modems used for this thesis proved to be easy to integrate into existing LabView programs. Additionally, the hardware specifications for the modems facilitated the rapid design of all required hardware components for the sensor nodes. Although the wireless transmission of the sensor results was only conducted on a very simple network the concept was validated. The results of the both the sensor transducer and the vibration sensor were successfully received via the 802.15.4 wireless protocol.

Attempts to utilize the ZigBee protocol were successful for the vibration sensor but could not be tested for the pressure sensor. MaxStream currently does not support ADC on the XBee and XBee-Pro for the ZigBee protocol. This is under development and is expected on the market within six months. When MaxStream releases the changes to the ZigBee beta software, utilized by the X-CTU, the changes will be programmed into the modules in the same manner that the modules were programmed for the pressure transducer measurements in the 802.15.4 protocol.

Use of sleep modes was not tested in this thesis. However, sleep mode is a desired capability. Sleep mode will extend the battery life required to maintain the sensor nodes. The sleep mode will require a significant change to the LabView code used in this thesis. The current LabView code is not designed to shut down in order to allow the nodes to transition into the sleep mode. To allow the nodes to sleep the LabView must be designed to send the appropriate commands to sleep, or wake up, to all pertinent end nodes.

Finally, it would be very beneficial to have an end unit that could serve as both a coordinator and an IP gateway. This would enable a direct method for receipt of the sensor network into a shipboard intranet. This issue was discussed with the MaxStream

engineers. Testing is currently being conducted for an XBee module that may serve as a gateway to allow the data transmitted across the network to seamlessly integrate into a Local Area Network (LAN) access point.

The MaxStream Corporation maintains Engineers at the help desks and proved to be very helpful for any issues pertaining to the utilization of the RF modules.

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V. CONCLUSION

A. SUMMARY

The cost associated with the design and wiring of ships, to maintain the myriad sensors for normal naval operations, is prohibitive. Additionally, the maintenance associated with the thousands of miles of wiring that are embedded within the skin of a naval vessel can be both time intensive and frustrating. Finally, the manpower consumed in monitoring various sensor stations that are spread throughout the compartments and frames on any vessel are a critical asset that the U.S. Navy can ill afford to waste. These persuasive arguments formed the genesis of the concept that envisioned a wireless mesh network that would feed sensor data into a ship's intranet and thereby make it accessible to any workstation.

This thesis focused on evaluating two different sensor types, creating a robust sensor node, and testing the feasibility of wirelessly transmitting the data from either sensor. A pressure sensor was created that was robust enough to handle 100 psi of shipboard pressure. The sensor was constructed around a Honeywell pressure transducer with threaded couplings for connection to the pressure source. The sensor was incorporated with MaxStream RF modems to create a stand alone wireless sensor source that could transmit the values for the pressure transducer's measured voltages to a remote destination. It must be noted that the central component of this wireless transmission was that the MaxStream modems contain six ADC that were essential to preparing the output of the pressure transducer for transmission via the MaxStream RF Modems.

The protocol selected for this research was the 802.15.4 protocol. This protocol is a backbone for the ZigBee protocol. MaxStream is developing a ZigBee compatible version of its proprietary X-CTU software. The new version of the X-CTU software will allow the RF modems to execute analog to digital conversions while operating within the ZigBee standard. The ZigBee standard is desirable because of the low power requirements and the inherent networking capability designed into the protocol.

The second sensor was a vibration analysis sensor that is a fundamental component of Condition Based Maintenance (CBM). The vibration sensor utilizes Digital Signal Processing (DSP) to conduct a Fast Fourier Transform (FFT) from a set of data samples taken over a very short period of time. A spectral distance measurement was obtained from the FFT in order to assess the potential for utilizing vibration analysis to determine the condition of a piece of operating equipment. The spectral distance formula was obtained through a manipulation of the Kullback-Liebr formula. This manipulation was used to program a LabView routine that manipulated the FFT results to obtain an absolute value that defined how far apart the current operating condition of a piece of equipment was from the “normal” operating condition of the equipment. The normal operating condition was defined as an average of a certain number of samples obtained under normal operating conditions.

To accomplish the vibration analysis a commercial sensor, Efector Octavis, was used to conduct the research. The output of this sensor was transmitted via a wireless network to a destination at which the data was manipulated via the LabView application to obtain the spectral distance measurement.

B. CONCLUSION

Wireless sensors can be used for shipboard applications. A wireless mesh network has an inherent flexibility that facilitates the incorporation of such a network to shipboard use. Wireless networks are flexible, provide redundant paths, and have a quantifiably adjustable reliability rate. The feasibility of incorporating sensors, pressure, temperature, and vibration, into a shipboard network has been validated.

Simple sensor nodes for pressure and temperature can be produced that are low power, small in scale, and extremely rugged. These sensors can be designed so that they will automatically configure to a mesh network that is already in place. Maintenance for these nodes can be monitored from a distant location through the transmission of certain key variables that indicate the status of the device. For example, the pressure sensor used in this thesis transmitted the reference voltage from the pressure sensor node. The reference voltage is an indicator of the supply power for the circuit.

Applications such as LabView provide an excellent platform for data manipulation prior to the data being displayed to the user, or storage in an intranet database. LabView facilitates the receipt of the data in the standard formats used for transmission, and executes the related calculations required to convert the transmitted data into a meaningful format. There is potential to utilize other applications that can provide the same capability. However, in this thesis LabView provided the environment in which the research was conducted.

The utilization of the Kullback-Liebr formula to determine a relative measure of the difference between two vibration signatures was also validated. This formula was originally used to distinguish the difference in different biological signals obtained through sonar. The formula has theoretical application to use as a tool for measuring the vibration of operating equipment. The use of the formula to indicate abnormal operating conditions has enormous potential for Condition Based Maintenance (CBM).

C. RECOMMENDATIONS FOR FUTURE WORK

There are several areas in which additional research could be conducted in order to further refine the results of this thesis. It is highly recommended that any further work in this area be conducted in conjunction with the Computer Science and C4I departments. ZigBee mesh networks are being extensively researched for use in multiple roles within the Armed Forces. This corporate knowledge should be leveraged to push forward the results of this thesis to provide a working mesh network that can fully demonstrate the reliability, efficiency, and robustness of the concept in a shipboard environment. The Computer Science Department can assist in creating a TCP/IP interface for the data received from the various networks and create the Java based user interfaces within the intranet environment.

1. Future Pressure Sensor Work

The pressure sensor requires the addition of a microprocessor. This microprocessor will contain a certain amount of flash memory. The variables associated with the characteristics of the specific pressure/temperature sensor being utilized will be

stored on the microprocessor. The microprocessor can then be utilized to calibrate the sensor via a remote location. It should be noted that the underlying assumption of this capability is that a “true” measurement is obtained with which to compare the current measurement. If these conditions are met then the addition of a microprocessor to the pressure sensor will enable calibration of the sensor from remote locations. Additionally, smaller, more rugged components that have greater accuracy can be emplaced on the sensor node to reduce its size and power requirements.

2. Future Vibration Sensor Work

The vibration sensor offers a wealth of potential in the arena of CBM. To validate the capability of the Kullback-Lieber formula to accurately predict maintenance requirements requires refinement of the formula and the creation of a database of reference signals for specific maintenance issues. The spectral distance formula can be applied in three dimensions and linked to specific bearings on any given piece of equipment. It would be extremely useful to investigate whether specific maintenance issues are indicated by a change in specific frequencies. For example, vertical bearings on a shaft motor tend to show wear problems by spikes in certain frequencies above the normal operating conditions. Other questions that can be asked about the use of the formula for CBM is to what extent must the spectral distance change to indicate that there is a problem? What is the safe operating range, in terms of spectral distance, for any given piece of equipment? This research has specific interest for the mechanical engineers as well as the electrical engineers.

Finally, the creating of a vibration sensor node is also an item that requires additional work. This research requires the incorporation of accelerometers, a microprocessor that will conduct the FFT, and ADC devices into a single package. The intent of this research is to determine the cost of creating such a device. The Efector Octavis used in the research for this thesis had additional capabilities that were not utilized and it is hypothesized that the Navy could create a vibration sensor that operates remotely for a much cheaper price.

3. Future ZigBee Work

The use of the MaxStream ZigBee software to create a mesh network should be investigated. This software was not available with ADC capabilities at the time that this thesis was conducted. However, the changes to the X-CTU application are pending. The capabilities and limitations of a mesh network operating on the ZigBee protocol are critical elements to fully understanding the potential for this technology. Some of the questions that require answers are:

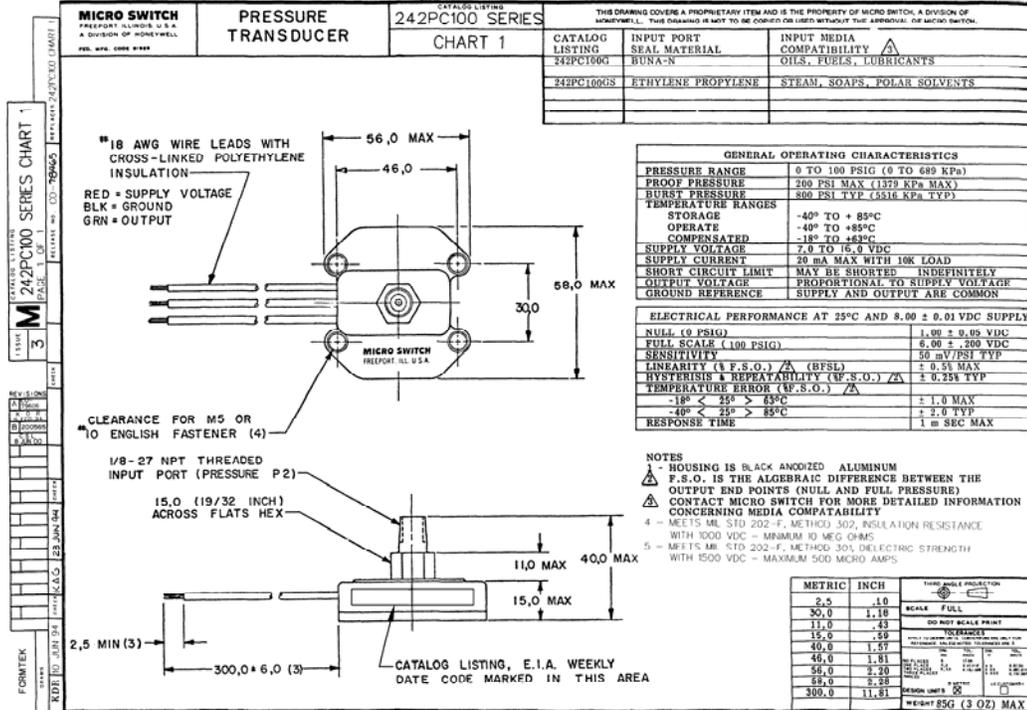
- The ability to put the nodes to sleep from a remote location.
- The capability to route network traffic through different nodes to increase the network range, to maintain a robust network, and to ensure receipt of the information at the desired endpoint.
- The capability to monitor the network and pinpoint critical problem areas.
- The maximum amount of data that can be transferred on a ZigBee network.
- Finally, obtaining the measures of network reliability: rate of packet loss, attenuation, and bit error rates.

Research into these additional areas is required to make shipboard sensor networks an operational reality.

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APPENDIX A: 242PC100GS HONEYWELL PRESSURE SENSOR

[16]



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APPENDIX B: NATIONAL SEMICONDUCTOR OP-AMP LMC6462

[17]



February 2004

LMC6462 Dual/LMC6464 Quad Micropower, Rail-to-Rail Input and Output CMOS Operational Amplifier

General Description

The LMC6462/4 is a micropower version of the popular LMC6482/4, combining Rail-to-Rail Input and Output Range with very low power consumption.

The LMC6462/4 provides an input common-mode voltage range that exceeds both rails. The rail-to-rail output swing of the amplifier, guaranteed for loads down to 25 k Ω , assures maximum dynamic signal range. This rail-to-rail performance of the amplifier, combined with its high voltage gain makes it unique among rail-to-rail amplifiers. The LMC6462/4 is an excellent upgrade for circuits using limited common-mode range amplifiers.

The LMC6462/4, with guaranteed specifications at 3V and 5V, is especially well-suited for low voltage applications. A quiescent power consumption of 60 μ W per amplifier (at $V_S = 3V$) can extend the useful life of battery operated systems. The amplifier's 150 fA input current, low offset voltage of 0.25 mV, and 85 dB CMRR maintain accuracy in battery-powered systems.

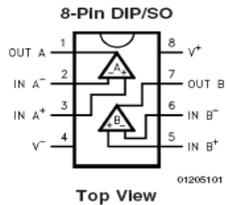
Features

(Typical unless otherwise noted)

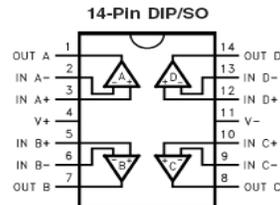
- Ultra Low Supply Current 20 μ A/Amplifier
- Guaranteed Characteristics at 3V and 5V
- Rail-to-Rail Input Common-Mode Voltage Range
- Rail-to-Rail Output Swing (within 10 mV of rail, $V_S = 5V$ and $R_L = 25 k\Omega$)
- Low Input Current 150 fA
- Low Input Offset Voltage 0.25 mV

Applications

- Battery Operated Circuits
- Transducer Interface Circuits
- Portable Communication Devices
- Medical Applications
- Battery Monitoring

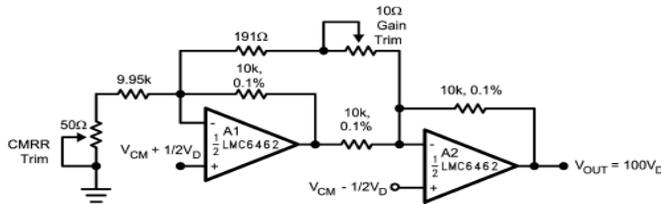


Top View



Top View

Low-Power Two-Op-Amp Instrumentation Amplifier



LMC6462 Dual/LMC6464 Quad Micropower, Rail-to-Rail Input and Output CMOS Operational Amplifier

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APPENDIX C: EFECTOR OCTAVIS

[3]

efector800

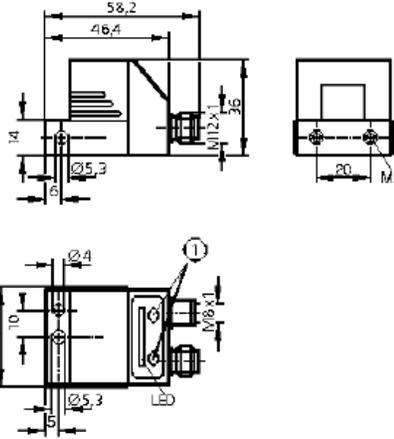


Diagnostic systems

VE1001

Vibration diagnostic unit
Connection via M12 x 1 and M8 x 1 connectors

Spectral analysis / FFT
Envelope-curve FFT
Trend analysis



1: Programming buttons

Application	Up to 20 frequencies in the spectrum, freely selectable, diagnostic level adjustable
Electrical design	DC PNP
Operating voltage [V]	10...32 DC
Current consumption [mA]	100 (24V DC) *
Measuring range [g]	± 25 (**)
Sensing principle	micromechanical accelerometer / capacitive measuring principle / one measurement axis
Overload protection [g]	100
Minimum measuring time [s]	0.8
Frequency range [Hz]	3...6000
Spectral resolution [Hz]	1.25
Monitoring range [rpm]	120...12000 (the actual rotational speed range depends on the type of the rolling element bearing and can therefore differ)

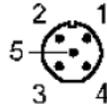
ifm efector, inc. 782 Springdale Drive, Exton, PA 19341

We reserve the right to make technical alterations without prior notice. — US - VE1001 - 1/2 — 21.06.2006

VE1001

Operating temperature [°C]	-30...60
Protection	IP 67, III
EMC	IEC 1000-4-2/3/4/6
Housing material	housing: diecast zinc nickel-plated; keypad: polyester

Wiring

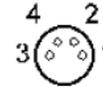


M12
connector
(electrical
connection)
Pin 1: supply +
Pin 2: red function; switching output 2 / 100 mA / NO/NC programmable
Pin 3: supply -
Pin 4: yellow function; switching output 1 / 100 mA / NO/NC programmable
Pin 5: rotational speed, 0...20 mA or pulse input

Wiring

M8 connector (RS-232
communication)

Pin 1: -
Pin 2: TxD
Pin 3: GND
Pin 4: RxD

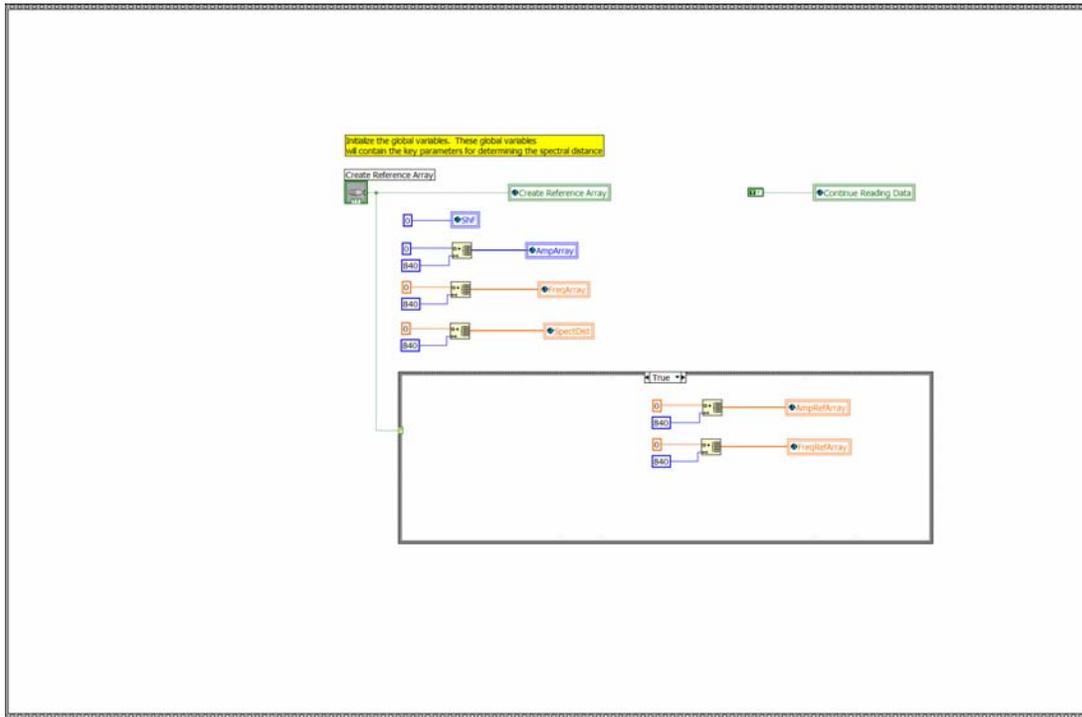


Remarks

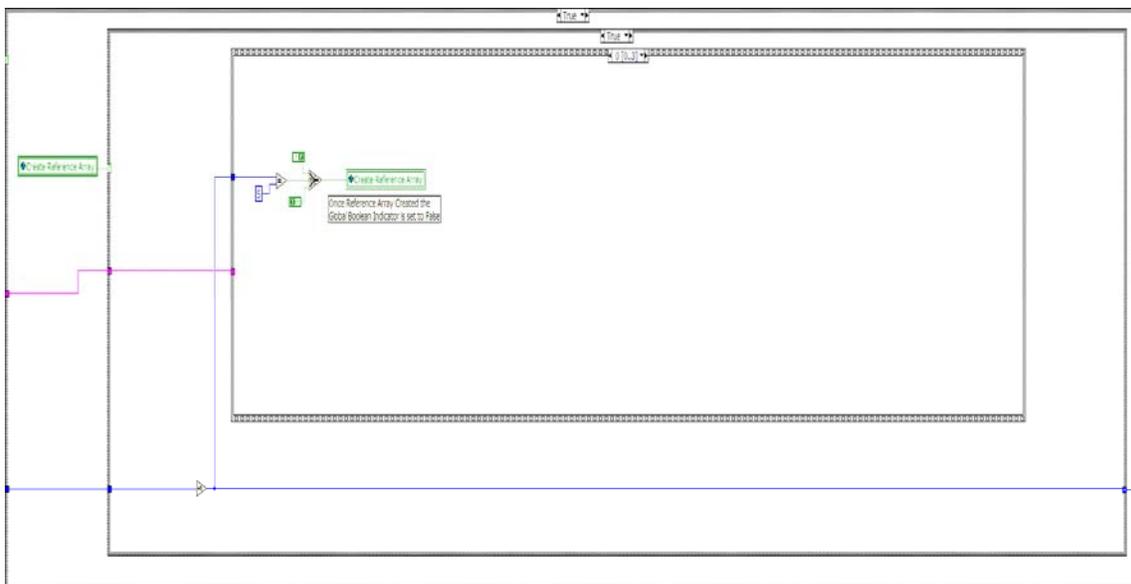
history memory: 2580 data sets as ring buffer
*) plus optional external pulse pick-up
**) nominal ± 20
Pin 2 (switching output 2) and pin 4 (switching output 1) can only be programmed in pairs

APPENDIX D: LABVIEW PROGRAM FOR VIBRATION ANALYSIS

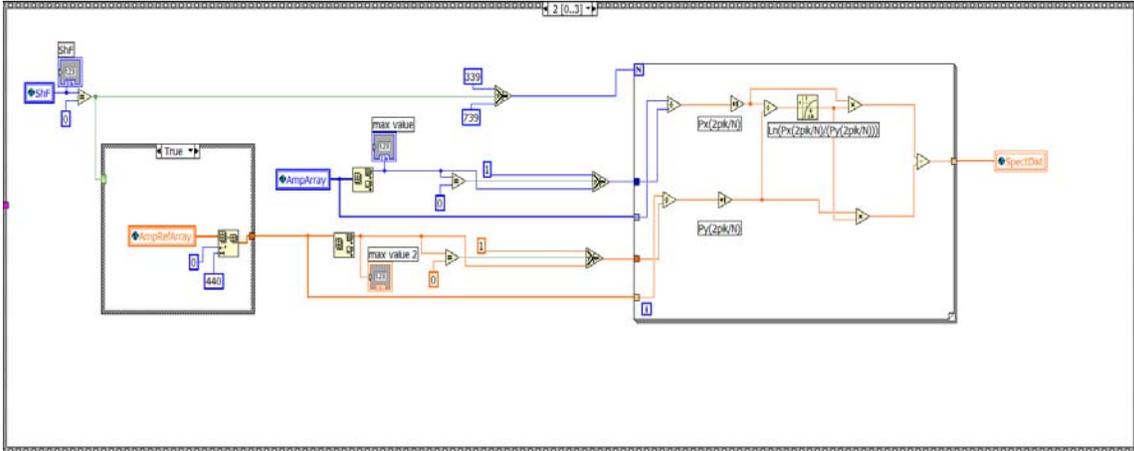
[Source Code may be obtained from Professor Xiaoping Yun at xyun@nps.edu]



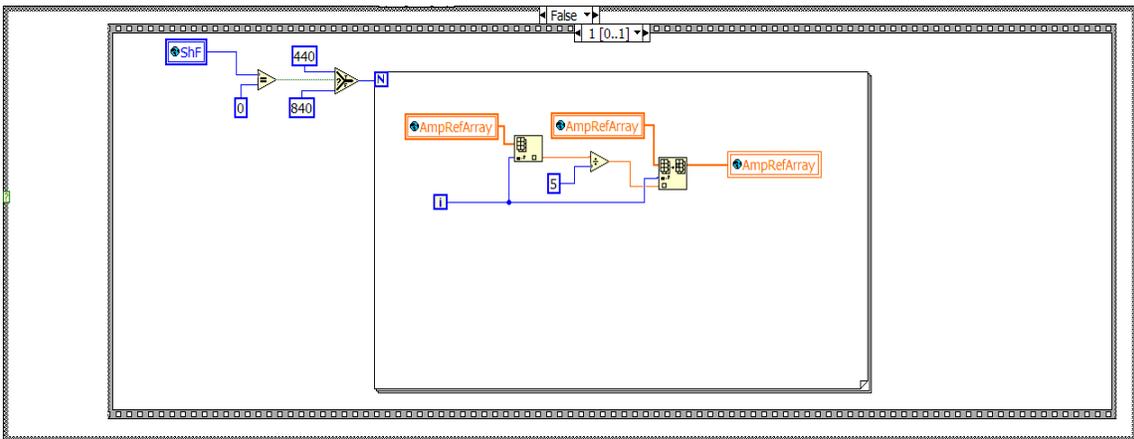
LabView code to initialize all the global variables used in the program.



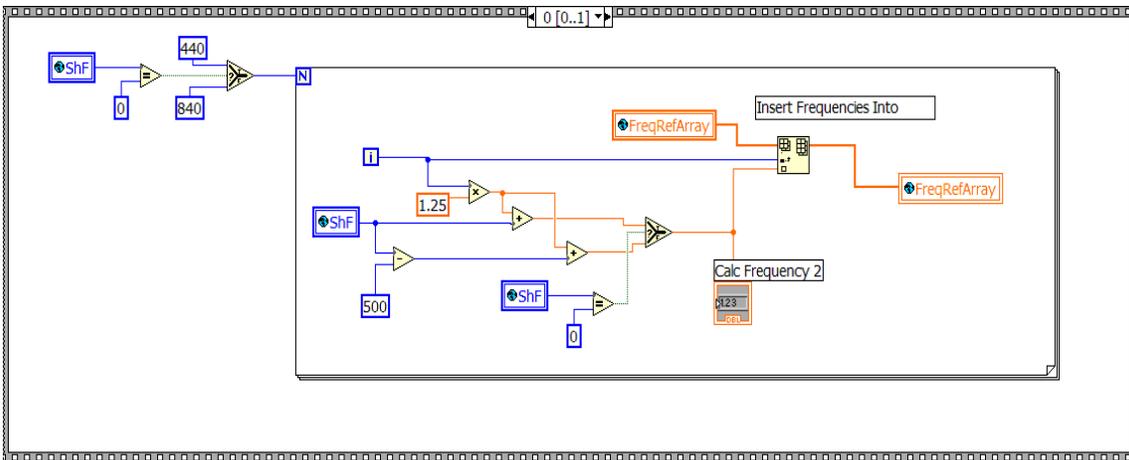
LabView code requesting input from the user to create a reference array. If the user responds “No” then the program will look for a stored reference array from file.



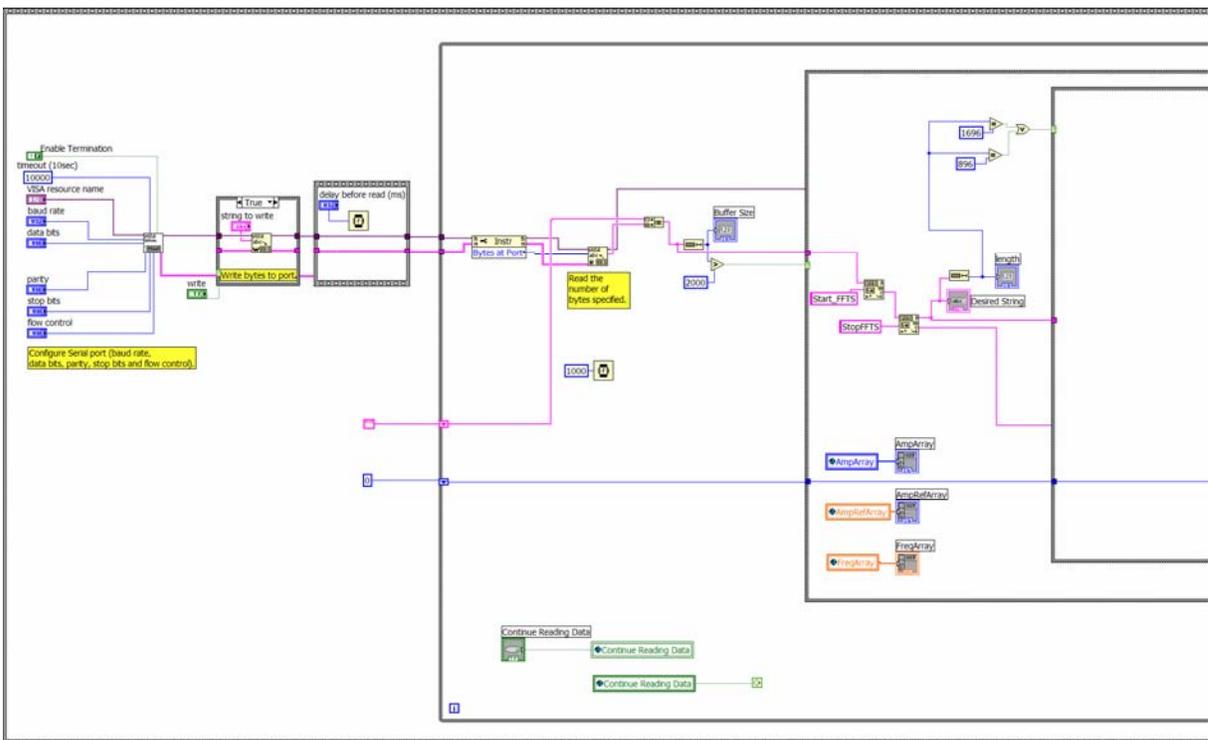
LabView code that calculates the value of the spectral distance.



LabView code that saves the reference array. Note that five signals have been averaged here to create the reference signal.



Section of the LabView saves the frequencies into a variable “FreqRefArray”. The frequencies that are saved change depending on the value of “ShF”.



LabView code demonstrating how the file was buffered to allow the continuous flow of data from the sensor. The buffer ensured that appropriate sized packets were built prior to evaluation of data using the Kullback-Lieber formula.

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APPENDIX E: ZIGBEE XBEE MODULE

[18]

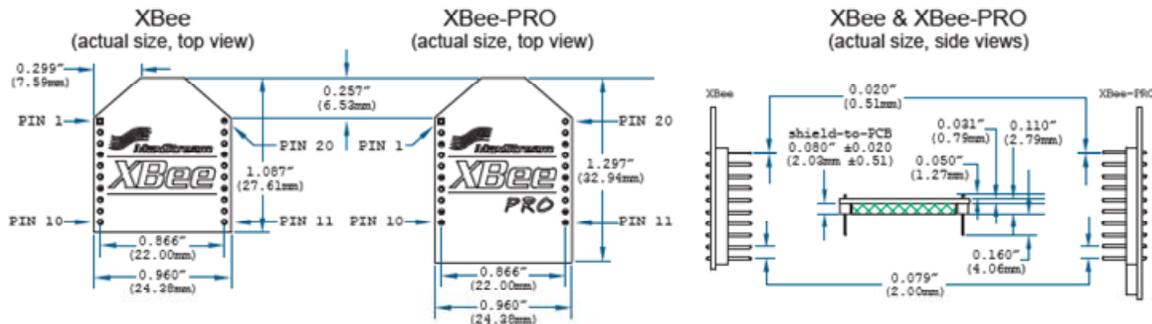
XBee™ & XBee-PRO™ 2.4 GHz DEM RF Modules

Specifications		XBee 	XBee-PRO 
Performance	Indoor/Urban Range	up to 100 ft. (30 m)	up to 300 ft. (100 m)
	Outdoor RF line-of-sight Range	up to 300 ft. (100 m)	up to 1 mile (1.6 km)
	Transmit Power Output	1 mW (0 dBm)	60 mW (18 dBm)*, 100 mW EIRP*
	RF Data Rate	250,000 bps	250,000 bps
	Receiver Sensitivity	-92 dBm (1% PER)	-100 dBm (1% PER)
Power Requirements	Supply Voltage	2.8 – 3.4 V	2.8 – 3.4 V
	Transmit Current (typical)	45 mA (@ 3.3 V)	215 mA (@ 3.3 V, 18 dBm)
	Idle / Receive Current (typical)	50 mA (@ 3.3 V)	55 mA (@ 3.3 V)
	Power-down Current	< 10 µA	< 10 µA
	Frequency	ISM 2.4 GHz	ISM 2.4 GHz
General	Dimensions	0.960" x 1.087" (2.438cm x 2.761cm)	0.960" x 1.297" (2.438cm x 3.294cm)
	Operating Temperature	-40 to 85° C (industrial)	-40 to 85° C (industrial)
	Antenna Options	U.FL Connector, Chip Antenna or Integrated Whip Antenna	U.F.L Connector, Chip Antenna or Integrated Whip Antenna
	Supported Network Topologies	Point-to-Point, Point-to-Multipoint, Peer-to-Peer and Mesh	Point-to-Point, Point-to-Multipoint, Peer-to-Peer and Mesh
Networking and Security	Number of Channels	16 Direct Sequence Channels (software selectable)	12 Direct Sequence Channels (software selectable)
	Filtration Options	PAN ID, Channel & Source/Destination Addresses	PAN ID, Channel & Source/Destination Addresses
	Agency Approvals	FCC Part 15.247 Industry Canada (IC) Europe (CE)	OUR-XBEE 4214A-XBEE ETSI

Specifications are subject to change without notice.

* When operating in Europe: XBee-PRO Modules must be configured to operate at a maximum TX power output level of 10 dBm (power output level is set using the PL command). Additionally, European regulations stipulate an EIRP power maximum of 12.86 dBm (19 mW).

Mechanical Drawings



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LIST OF REFERENCES

- [1] R. Rupnow, J. Walden, X. Yun, D. Greaves, and H. Glick, "New Calibration Standings for Next Generation Ship's Monitoring Systems," *Proceedings of the Thirteenth International Ship's Control Systems Symposium (SCSS)*, April 2003.
- [2] J. Jardine, and D. Banjevic, "Optimizing Condition-Based Maintenance Decisions for Equipment Subject to Vibration Monitoring," *Journal of Quality in Maintenance Engineering*, vol. 5, pp. 192-202, 1999.
- [3] ifm efector Product Support, "ve1001 Datasheet," <http://www.ifmefector.com/ifmus/web/dsfs!VE1001.html>, last accessed January 2007.
- [4] C. Zacot, "Shipboard wireless sensor network utilizing shipboard technology," M.S. Thesis, Naval Postgraduate School, Monterey, CA, 2006.
- [5] J. Young, "Vibration analysis using a MEMS accelerometer." M. S. Thesis, Naval Postgraduate School, Monterey, CA, 2006.
- [6] J. Davis, "An analysis of network and sensor performance within IEEE 802.x wireless MESH networks in the Tactical Network Topology (TNT)." M. S. Thesis, Naval Postgraduate School, Monterey, CA, 2005.
- [7] A. Chabane, "Propagation modeling of wireless systems in shipboard compartments." M. S. Thesis, Naval Postgraduate School, Monterey, CA 2005
- [8] X. Xiong, Y. Wu, and W. Jone, "A Dual-Mode Built-In Self-Test Technique for Capacitive MEMS Devices," *IEEE Transactions on Instrumentation and Measurement*, vol. 54, pp. 1739-1749, 2005.
- [9] B. Charlot, S. Mir, F. Parrain, and B. Cortois, "Generation of electrically induced stimuli for MEMS self-test," TIMA Laboratory, Grenoble, France, 2001.
- [10] M. Fargues, R. Cristi, and M. Vanderkamp, "Modeling and classification of biological signals using Least-Squares PRONY-SVD AR Modeling," *Proceedings of the 36th Midwest Symposium on Circuits and Systems*, Aug 1993, pp. 445-448.
- [11] R. G. Gallager, *Information Theory and Reliable Communication*, New York: John Wiley & Sons, Inc., 1968.

- [12] C. W. Therrien, *Decision Estimation and Classification: An introduction to Pattern Recognition and Related Topics*, New York: John Wiley & Sons, Inc., 1989.
- [13] MaxStream Technical Support Staff, “Demystifying ZigBee and 802.15.4,” <http://www.maxstream.net/wireless/demystifying-zigbee.php>, last accessed July 2007.
- [14] S. Krishnamurthy, “Sensor Networking with ZigBee,” presented at Communications Design Conference, San Jose, CA, October 2003.
- [15] MaxStream Technical Support Staff, *Product Manual v1.xAx – 802.15. 4 Protocol*. MaxStream, Inc., Lindon, UT, 2006.
- [16] Honeywell Technical Support, “242PC100GS Pressure Sensor Datasheet,” http://sensing.honeywell.com/index.cfm/ci_id/140301/la_id/1/pr_id/80858.htm, last accessed July 2007.
- [17] National Semiconductor Customer Support, “LMC6462 Datasheet,” <http://www.national.com/mpf/LM/LMC6462.html>, last accessed January 2007.
- [18] MaxStream Technical Support Staff, “XBee RF Modules Data Sheet,” <http://www.maxstream.net/products/xbee/xbee-oem-rf-module-zigbee.php>, last accessed July 2007.

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