ELECTRIC POWER RESEARCH INSTITUTE

Conceptual Design of a Modular Wireless Triaxial Vibration Sensor

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REPORT SUMMARY

This report describes the conceptual design of a wireless triaxial vibration sensor. The current work is divided into two separate components. The first component is aimed at understanding the need for innovation on wireless triaxial vibration sensors within power plants, quantifying the specifications required, and determining the gap between these specifications and existing commercial products. The second component conceptualizes a novel system capable of accommodating the needs of a plant.

Background

Within power plants, vibration monitoring of moving parts provides information regarding the health of the equipment and potentially alarms the operators to the necessity for periodic maintenance. The installation costs of such sensors are significant because of the costs that are accrued when bringing the signal back to the control room, leading to a limited number of these sensors being deployed. Although wireless is capable of reducing these costs, the periodic maintenance cost (for example, changing batteries) and transmission reliability reduce the desirability of these sensors. Innovation is required to realize more efficient and numerous wireless sensor deployments within power plants, thereby providing more information to operators and allowing great operational efficiency.

Objectives

- To understand the need for innovation on wireless triaxial vibration sensors within power plants
- To quantify the specifications required and the gap between existing products
- To conceptualize a novel system capable of accommodating the needs of the plant

Approach

To better understand the need for innovative novel wireless sensors within power plants, a survey of power plant personnel was conducted. The results from the survey were used to identify requisite specifications for a wireless vibration sensor system. These specifications were compared with existing commercial products, and the gap between available hardware and the specifications desired by the plant was identified. Subsequently, information from the datasheets of various commercially available components was gathered. This information has been used to determine the possibility of integrating a sensing system that is capable of achieving the requisite specifications.

Results

In addition to the integration of a wireless triaxial vibration sensor, a modular system was explored. A modular system would allow a plant to choose which sensor is plugged into the remaining monitoring platform or which power module to plug into the processing and sensing modules. Modularly designing the platform for measuring the data output from the vibration sensor further reduces the cost of deploying sensors within the power plant because of the ability to repurpose modules for other deployments within the plant or easy reconfiguration of the wireless framework. Finally, a conceptualization of a modular wireless triaxial vibration sensor is presented, along with a high level component list for each of the modules.

Applications, Value, and Use

This report provides requirements and specifications for the prototype modular wireless sensor development.

Keywords

Industrial wireless sensor
Triaxial vibration sensor
Wireless sensor

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1
INTRODUCTION

Within power plants, vibration monitoring of moving parts provides information regarding the health of the equipment and potentially alarms the operators to the necessity for periodic maintenance. The installation costs of such sensors are significant because of the costs accrued when bringing the signal back to the control room, leading to a limited number of these sensors being deployed. Although wireless is capable of reducing these costs, the periodic maintenance cost (for example, changing batteries) and transmission reliability reduce the desirability of these sensors. Innovation is required to realize more efficient and numerous wireless sensor deployments within power plants, thereby providing more information to operators and allowing great operational efficiency.

The purpose of the work that is the subject of this report is aimed at understanding the need for innovation on wireless triaxial vibration sensors within power plants, quantifying the specifications required and the gap between existing products, and conceptualizing a novel system capable of accommodating needs of the plant. To better understand the need for innovative novel wireless sensors within power plants, a survey of personnel within existing power plants was conducted. The results from the survey were used to identify requisite specifications for a wireless vibration sensor system. These specifications were compared with existing commercial products, and the gap between the available hardware and the specifications desired by the plant was identified. Subsequently, datasheet information from various commercially available components was gathered. This information has been used to determine the possibility of integrating a sensing system that is capable of achieving the requisite specifications.

In addition to the integration of a wireless triaxial vibration sensor, a modular system was explored. A modular system would allow the plant to choose which sensor is plugged into the remaining monitoring platform or which power module to plug into the processing and sensing modules. Modularly designing the platform for measuring the data output from the vibration sensor further reduces the cost of deploying sensors within the power plant because of the ability to repurpose modules for other deployments within the plant or easy reconfiguration of the wireless framework. Finally, a conceptualization of a modular wireless triaxial vibration sensor is presented, along with a high level component list for each of the modules.

2
TECHNICAL FOCUS

Modular Design

The primary function of every sensor product is to directly or indirectly convert physical and/or chemical parameters into data that are informative as well as actionable by the operators. To accomplish this, a transducer converts the physical/chemical property into an analog voltage or current. This current/voltage is then converted into a digital signal and, subsequently, processed and transmitted. Many transducers are capable of measuring a wide range of physical and/or chemical properties. However, after the physical/chemical property is converted to an electrical signal, the hardware for digital conversion, processing, and transmission between different sensors is relatively similar. Proprietary calibrations of the transducer and implementations of these auxiliary functions force the end user to repeatedly purchase the same hardware to use the unique features of a different transducer. A nonproprietary system capable of providing the previously described functionality in a modular fashion would allow power plant personnel to build and modify sensor hardware for use with different transducers, wireless protocols, and processors.

The focus of the work that is the subject of this report is to conceptually build such a system that ultimately will reduce the amount of capital equipment required to deploy wireless sensors. This system includes different modules, each performing one or more of the tasks described previously. Examples include processing, wireless communications, and battery modules. It is envisioned that each of these modules will have plug-and-play capability. Effectively, plant personnel can quickly and efficiently change the to-be-deployed sensor (for example, from WirelessHART[1] to ISA100 or from monitoring vibrations to temperature). In the opinion of this report's author, no such platform exists today, but the benefits include more efficient and increased deployment of sensors. The additional information will allow the plant to operate safer and more efficiently.

In order to accomplish this task, the different functionality for each component of the sensor must be identified, modules that cover the requisite functionalities must be integrated, and all of the resultant modules must be designed so that plug-and-play is possible. At a high level, five separate subsystems must be completed. They are as follows:

- Transducer and analog signal conditioning
- Digital signal processing
- Onboard data storage
- Wireless transmission
- Power management and harvesting

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[1] *WirelessHART* is a registered trademark of the HART Communication Foundation.

Power harvesting is a focus of this project because of the difficulty of powering wireless sensors in the field. Frequent sensor maintenance resulting from short battery life nullifies the primary benefit of wireless sensors, which is their convenience in deployment.

The areas of design that have the most degrees of freedom are the transducer, data storage, wireless transmission, and power harvesting. Best practices are well established for the other areas (that is, processing, signal conditioning, and batteries). A triaxial vibration sensor was chosen as the transducer for the initial design. It was chosen because there are significantly more requirements for analog signal processing of the data from the transducer as opposed to a simpler device. Other possible transducers that are not covered in this report include temperature, pressure, current, voltage, speed, and flow. The resultant system that focuses on this complex transducer will be compatible with simpler signals from other transducers. Furthermore, this type of transducer has immediate uses within industrial power plants.

Uses of Triaxial Vibration Sensing

As equipment within power plants ages, early detection of faults and failure becomes crucial for safe and efficient operation. This is especially true for equipment that contains moving parts (for example, turbines or pumps); unforeseen catastrophic failure can cause significant damage to capital equipment and injury for operators. Such instances can be avoided by preventive maintenance and early detection of fault. Remote monitoring of the vibration modes emanating from such equipment can provide crucial information that will empower maintenance on demand. This will reduce the number of hours required to collect data by plant personnel, thereby providing more time to analyze data.

For example, monitoring the vibrational modes emanating from mechanical pumps can detect early faults. These vibrational modes are unique to the specific pump depending upon the make, model, and build of the pump. Sporadic monitoring of these vibrational modes is typically sufficient for identifying general long-developing faults. However, transient conditions that can lead to catastrophic failure are missed. Deploying a vibration sensor that can continuously monitor the vibrational modes can capture these faults. Furthermore, sporadic monitoring requires a plant technician to dedicate time in performing the measurements, whereas a wireless sensing system reduces the amount of work-hours required to collect data while providing more time to analyze the data and information [1].

The primary barriers for deployment of such a system are cost and reliability. In this situation, the data gathered are purely for informative/monitoring purposes and are not connected to any plantwide response or operation (that is, the plant can continue to operate if the signals are not being received). Although the goal is to eventually demonstrate reliability so that these wireless systems can be used in crucial functions, the purely informative nature of these sensors lowers the reliability criteria for the pilot phases of this sensing system.

There is a significant up-front cost associated with deploying wired sensors. However, after they are installed, the maintenance cost of such a deployment is minimal. In this paradigm, the number of sensors to be deployed is not scalable to a large number of sensors. In a wireless paradigm, the up-front costs of deploying sensors are reduced, but there is a continued maintenance cost associated with replacing batteries and ensuring signal reliability. This is the reason that the potential for power harvesting is part of this work; given clever power management, it is possible to increase the interval between battery replacements and even have fully sustainable sensors, thereby reducing the periodic maintenance cost.

Beyond cost savings, the envisioned system can provide the power plants additional flexibility in deploying sensors. There are two types of sensor deployments within power plants: permanent and temporary. In permanent deployments, the sensor is placed in the field for an indefinite amount of time. Wired deployment conditions are well suited for this type. In temporary deployments, the sensors are deployed between six months and a year. Data are collected, and the sensor is decommissioned. Wireless sensor technology is perfect for this type of deployment. Furthermore, if the device is modular, the sensor can be taken apart and used in other temporary deployments around the plant. Ultimately, the goal is to allow plants to use wireless sensors for permanent installations. This will allow the plant to deploy more permanent sensors without the significant up-front costs.

3
TECHNOLOGY OVERVIEW

This section aims to provide some theoretical background on the different technologies and protocols that were used in the conceptual design of this system. Discussion regarding the viability of each technology will also be included in the section about the technology. The technologies covered are the following:

- Triaxial vibration sensors
- Comparison of wireless protocols
  - 802.15.4
    - WirelessHART
    - ISA100
  - 802.11 – WiFi
- Power harvesting
  - Thermal harvesting
  - Vibrational harvesting

Triaxial Vibration Sensors

Triaxial vibration sensors typically consist of three different vibration sensors placed orthogonal to each other. Each sensor measures the vibration in the given direction. There are many different types of vibration sensors ranging from piezoelectric sensors to advanced laser-based systems. Laser-based systems reflect a laser off a vibrating surface. The location of the reflect beam changes with the position of the surface (that is, the vibration). The magnitude and frequency of the vibration are directly correlated with the magnitude of deflection of the reflected beam [2]. This type of system is incredibly sensitive. It is typically not used in industrial monitoring and therefore will not be covered further in this report.

Most vibration sensors are piezoelectric-type sensors. Piezoelectric materials generate an electric field when stresses and/or strains are applied. When a sensor is placed atop a vibrating surface, force is applied onto the sensor, thereby inducing dipoles on the surface of the material, which emit an electric field and a voltage in a given direction. The magnitude of the voltage scales controllably with the magnitude of the strain and size of the sensor. There are three different operational modes for this type of sensor. They are as follows:

- Transverse effect
- Longitudinal effect
- Shear effect

A diagram of the three types is shown in Figure 3-1. The primary difference in the different effects is the application of the force and directionality of the dipoles generated. In transverse piezoelectric effect, the dipoles form along the axis that is stressed. The magnitude of the field depends on the size and shape of the material because the force is distributed over the area in which the charge is collecting. In the longitudinal and shear piezoelectric effects, the magnitude of the dipole formation depends solely on the magnitude of the force and not on the size and shape of the sample. The overall equation of state for the piezoelectric effect is shown in Figure 3-1, where Q is the amount of charge generated, D_{xy} is the piezoelectric tensor, which incorporates the constants for different directionality, n is a geometrical constant, and F is the amount of applied force [3, 4].

$$Q = nD_{XY}F$$

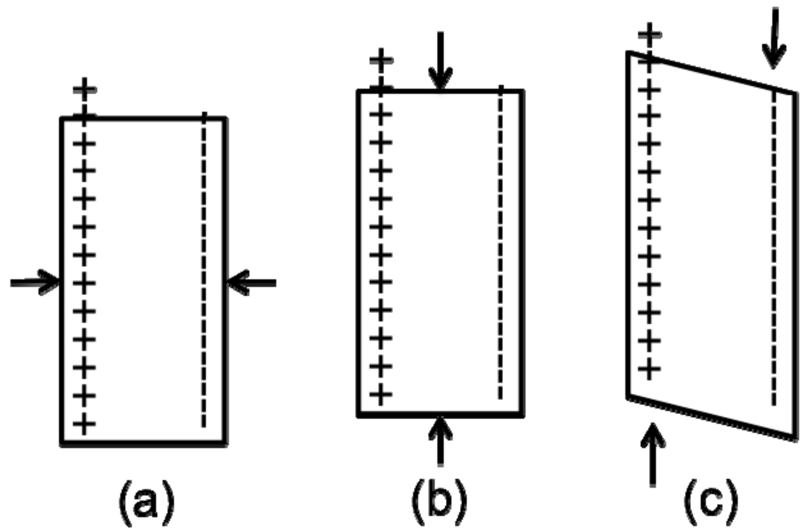


Figure 3-1
Transverse (a), longitudinal (b), and shear (c) modes of the piezoelectric effect; the positive and negative charges are denoted by + and -, respectively [4]

In general, the magnitude of this charge is relatively small, and the signal must be amplified. There are many different amplification circuits that are being used in commercial vibration sensors. A simplified circuit is shown in Figure 3-2. A high-gain inverting amplifier is used. The equation for the output voltage of this amplifier is given by the following equation, where V_O is the output of the circuit, Q is the charge generated by the sensor (determined from the preceding equation), C_r is the range capacitor, C_t is the sensor capacitance, C_c is the cable capacitance, and A is the open-loop gain [4].

$$V_O = \frac{-Q}{C_r} \frac{1}{1 + \frac{1}{AC_r}(C_t + C_r + C_c)}$$

In addition to the static output voltage of the circuit, dynamic responses must be considered (for example, phase lag of the sensor and/or the amplification circuit). Care must be taken when selecting the components to ensure that the circuitry is capable of measuring the vibration of interest. The specifics of these design criteria are specific to each use case and will not be covered further in detail.

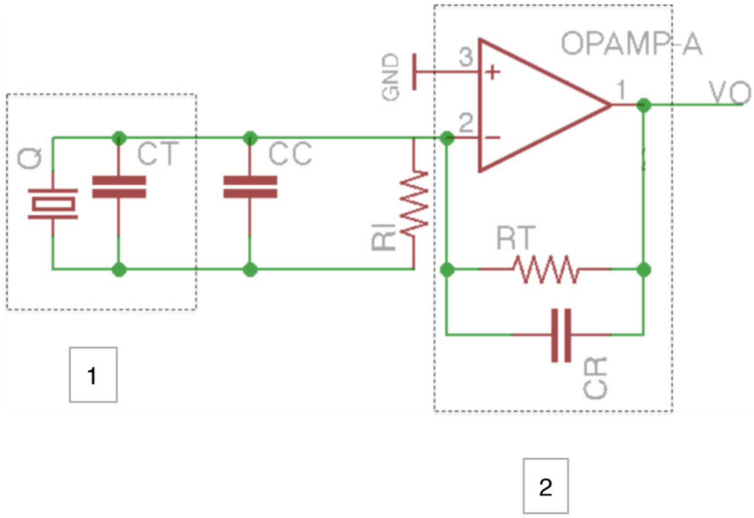


Figure 3-2
A simple circuit for measuring a vibration sensor (The sensor is indicated by the *1* and the charge amplifier, by the *2*; C_c and R_i are the cable capacitance and the insulation resistance of the input circuit. Typically, a high-impedance field-effect transistor is included at the input of the amplifier to increase R_i.) [4]

This output voltage can then be further filtered and/or amplified. The resultant analog signal is measured using an analog-to digital-converter (ADC). Care must be taken to ensure that all components are capable of responding at frequencies greater than the desired vibration. Typically, a frequency response specification of two to three times the frequency of the desired vibration is necessary to remove phase lag and interlacing. When they are digital, the raw values of the magnitude of force are collected over a period of time, and the series of data can be processed (for example, calculating root mean squared [RMS] average and/or Fourier transform to find the vibrational spectra), provided that an adequate number of points were sampled for the specific analysis.

Wireless Protocols

After the data have been processed to a usable form (for example, RMS average or vibrational spectra), they must be transmitted. If possible, it is always more advantageous to use existing wireless infrastructure over installing new infrastructure to support a different protocol. The primary concerns for wireless are radio-frequency (RF) penetration through obstacles and power consumption required to implement a specific protocol. Different RF waves have different penetration through various materials; in some cases, protocols are favored because of the superior attenuation properties of the specific part of the spectra they employ. Almost all industrial wireless protocols use 2.4 and 5.2 GHz, eliminating the transmission frequency as part of the design consideration. Power consumption, allowable bandwidth of the wireless protocol, and the range of wireless transmission are significant design considerations. In all wireless protocols, there exists a startup time for the electronics to initialize and a time for the electronics to perform its shutdown procedure. The overall power consumption per transmit is the power consumption for this fixed time period plus the time it takes to transmit the data. The intuitive argument that high bandwidths allow for shorter communication times must take this into account.

Generally, three different protocols make up the basis for the majority of the wireless in industrial settings: 802.11 (WiFi/WLAN) [5], WirelessHART [6, 7], and ISA100.11a [8]. The differences among these three different wireless protocols are covered in this section. Both WirelessHART and ISA100.11a use IEEE 802.15.4 radio technology [7, 8]. Most proprietary wireless solutions also use the 802.15.4 radio technology.

All network architectures can be described in layers; each layer is independent of the others, but the same functionality can be injected at multiple points (for example, encryption can occur on the application layer as well as the presentation layer). Within the Open Systems Interconnection model developed by the International Standards Organization, the following seven different layers describe networks: [9]

- Physical layer: providing the actual transmission through a medium (for example, radio)
- Data link layer: synchronization and error control
- Network layer: packet routing and addressing
- Transport layer: establishment and maintenance of connections (for example, new sensors being added; old sensors leaving the network)
- Session layer: management of sessions between nodes (for example, if interference is present, this layer will stop communication until interference goes away)
- Presentation layer: packet syntax and data translation
- Application layer: establishment of communication between network and different applications on device [9]

The details for a given protocol within each are very complex and will not be covered in this report. If more information is needed, each protocol is described in detail within its specification sheets [5, 6, 8, 9]. A brief overview of the differences within each layer for WirelessHART and ISA100.11a is included in this report.

WirelessHART is based upon the highway addressable remote transducer (HART) communication protocol and application layer [7]. ISA100.11a was issued by the International Society of Automation (ISA) and was aimed at fulfilling industrial plant needs [8]. There are major differences between the two protocols on all layers except the physical layer. Both use the IEEE 802.15.4 standard with direct sequence spectrum spreading and 2.4-GHz radios [10]. Table 3-1 outlines the major differences in each layer. More information can be found in Wang’s article [10].

Table 3-1
Major differences between ISA100.11a and WirelessHART [10]

Layer	ISA100.11a	WirelessHART
Architecture level	• Device roles • Security manager • Subnet definition	• Network access points • Peer-to-peer communication with potential security risks
Digital link	• Three-channel hopping scheme • Active and passive neighbor discovery • Subnet routing	• One-channel hopping scheme • Passive neighbor discovery
Network	• Fragmentation and assembly • IPv6 addressing • Compatible with 6LoWPAN	• End-to-end session security • HART addressing
Transport	• User diagram protocol • End-to-end session security • Compatible with 6LoWPAN	• Transmission control protocol-like communication service
Application	• Object-orientation • Three communication/ interaction models • Legacy protocol tunneling	• Command-orientation • Predefined data types • HART protocol
Join process	• Symmetric and asymmetric methods	• Only symmetric method

There are many different varieties of 802.11. It operates between 2.4-GHz and 5-GHz band and has bandwidth ranging from 11 Mbps to greater than 1 Gbps [5, 11]. It requires a significantly larger amount of power for the greater bandwidth. The amount of bandwidth available is excessive, but significant investment in 802.11 infrastructures has been made within the power plants. If such existing infrastructures were installed within the plant, 802.11 would be the preferred protocol. The power consumption for this protocol is significantly higher than that of 802.15.4. IEEE 802.11ah is a low-power version of conventional WiFi that uses sub-1-GHz bands [12, 13]. The standard is expected in 2016, and it shows promise for eventual utilization of WiFi for such sensing systems. The hybrid 802.11/802.15.4 solutions have shown promise in the interim.

Power Harvesting

Battery life is a parameter of great concern. Harvesting the power from the surrounding environment will help greatly in prolonging the battery life of the sensor. The most common types of power harvesting are photovoltaic cells; however, in most power plants, there is not enough photonic energy to generate any significant amount of power. The chosen power source must be available within the environment that the sensor is deployed into. Two kinds of power harvesting technologies were considered: thermal and vibration.

Thermal Power Harvesting

These power harvesters take advantage of the thermoelectric effect (Seebeck effect) to produce energy. Upon the introduction of a thermal gradient, electric and magnetic fields are induced. Typical thermoelectric generators are 5%-8% efficient, less than that of heat engines. An image of a thermoelectric generator is shown in Figure 3-3. Upon the introduction of heat to one side of the material, the electrons on the heated side now have higher energy than that of the cold side. These electrons move to seek the lowest possible energy, thereby traveling to the cold side of the thermoelectric generator. This causes a current and a voltage across the generator, which can be used to power electronics. The magnitude of the generated current density (J) is determined by the Seebeck coefficient (S), temperature gradient (∇T), and the conductivity of electrons within the material(s) [14, 15].

$$J = \sigma(-\nabla V + E_{EMF})$$
$$E_{EMF} = -S\nabla T$$

∇V = local voltage gradient
S = conductivity
E_{emf} = electromotive force
S = Seebeck coefficient or thermopower
∇T = temperature gradient

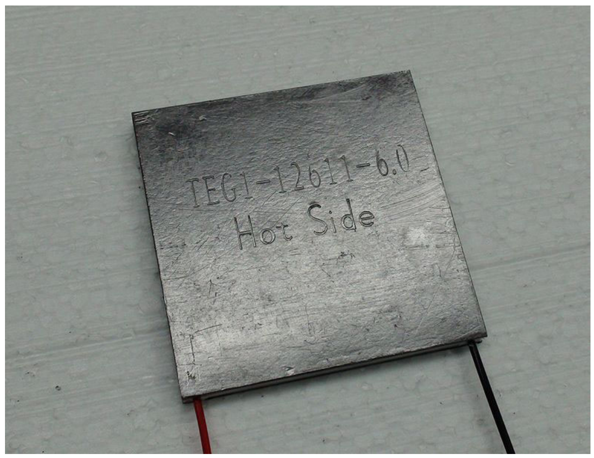


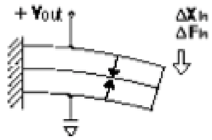
Figure 3-3
Thermoelectric generator [16]

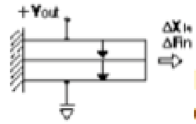
Practically, there is a major problem with thermoelectric generators in this application. The power is generated through a thermal gradient. The transfer of electrons across the material represents not only a current but also a thermal conduction path. It is difficult to cool the cold side of the thermoelectric generator. The thermoelectric power generated decreases drastically with increasing cold-side temperature. The most efficient commercial thermoelectric generator produces 14.1 W at 4.2 V with a thermal gradient of 100°C. This requires a significant amount of heating on the hot side and cooling on the cold side. Careful thermal design or water cooling is required for practical operation. In many use cases of wireless triaxial vibration sensors, a temperature gradient of such magnitude is not available. This makes thermoelectric generators unviable for many of the use cases. Therefore, these generators were not considered; however, they should be considered if the thermal gradient can be reached.

Vibration Power Harvesting

Vibration power generators work very similarly to vibration sensors. Both take advantage of the piezoelectric effect. In the generation case, the material is designed to produce the maximum field, thereby powering electronics. The energy conversion is highly dependent upon the frequency of the harvested vibration and the amount of force generated. Two separate types of vibration generators are commercially available: bend generators and extend generators [17]. A schematic and the power generation specifications of each are shown in Figure 3-4.

Bending Generators





Extending Generators

Spec – Single Generator	Value
Max Power	8.8 mW
Deflection	+/-1.22 mm
Frequency	100 Hz
Stiffness	9E2 N/m
Force for Max	1.098 N
Power in 0.21 Days	44.4 mW-hr

Spec – Single Generator	Value
Max Power	2000 mW
Deflection	+/-25 microns
Frequency	1000 Hz
Stiffness	15E6 N/m
Force for Max	375 N
Power in 0.21 days	10080 mW-hr

Figure 3-4
Specifications for bending- and extending-type generators [17]

Extending generators are capable of generating significantly more power (over 100 times) than that of bending generators, but they require significantly more energetic vibrations. Practically, the type of vibration in extending generators is rare in the case of pump monitoring, making this less practical. The vibrations required for bending generators are significantly more reasonable, which is practical for deployment. The maximum continuous power generated of 8.8 mW is low but, given the noncontinuous measurement and output, can be used to greatly augment battery life and/or enable a sustainable system. Furthermore, if additional power is needed, multiple generators can be placed in parallel to allow for greater power generation.

4
REQUIREMENTS AND SPECIFICATIONS

The aim of this section is to identify the requisite specifications of the sensor. To accomplish this goal, multiple power plants were surveyed regarding the parameters of greatest importance for a wireless triaxial vibration sensor.

Requisite Specifications from Survey

Survey Design

This section focuses on the structure and intent of the different questions within the distributed survey. The entire survey is included in Appendix A of this report. The survey consisted of 18 questions; these 18 questions can be further divided into three separate sections. The associated questions and the purpose behind each section are indicated in Table 4-1.

Table 4-1
Details regarding each section of the survey

Section Number	Questions	Purpose
1	1, 2, 3, 17, 18	Background and miscellaneous information
2	5, 6	Interest in modular design
3	4, 6, 7, 8–13, 14, 15, 16	Quantify the perceived utility of a wireless triaxial vibration sensor (Questions 8–13 were a partial factorial preference survey.)

Background and Miscellaneous Information

The background and miscellaneous information sections are meant to understand the demographic of the survey participants and, if necessary, allow them the chance to provide additional feedback. This examined the extent to which the industry was polled, as well as background information regarding existing experience with triaxial vibration sensors.

Modular Design

The second section of the survey aims to understand the interest in readily reconfigurable hardware for easy sensor deployment into a wide range of plant activities. This allows significantly greater flexibility in sensor deployment. Such a system would consist of a series of plug-and-play modules that can be exchanged with other modules of the same type that are better suited for a different set of deployment conditions (for example, the vibration sensor can be unplugged and replaced with a temperature sensor while maintaining all previous wireless capability). Furthermore, this section of the survey is aimed at prioritizing the most important modules in such a system. The explored modules are as follows:

- Transducer (sensor, for example, vibration, temperature)
- Processor/signal processing
- Wireless (standard protocols—WiFi, WirelessHART, ISA100)

- Power harvesting
- Power supply

Specification Priority

The final section of the survey aims at quantifying the perceived utility of different specifications of the device. Eight different specification categories were identified as the primary drivers for utility. They are as follows:

- Cost
- Accuracy
- Precision
- Measurement range
- Standard or proprietary wireless protocol
- Battery life
- Data transmit frequency
- Wireless range

First, the respondents were asked to rank these specifications in order of greatest priority (Question 4). The respondent was then asked to complete a partial factorial preference study where respondents choose between two sensors, each with a specific set of specifications. To prevent an inappropriately large number of questions, only three levels of three specifications were chosen as part of the study. The selected levels and specifications are shown in Table 4-2. Cost, battery life, and transmit frequency were chosen because they were the most interrelated (for example, the amount of time between transmissions will affect the battery life, and the amount of batteries will affect cost) and will require the most trade-off in the design process. Direct questions (14) were posed to understand the parameters where very little trade-off was allowed (that is, the sensor must meet minimum requirements, or deployment into the plant will not be possible—for example, sensor accuracy and precision and transmit frequency).

Table 4-2
Tabulated values for each of the parameters and levels explored using the partial factorial preference regression

	Low Level	Mid-Level	High Level
Cost	$50	$100	$500
Battery life	6 months	12 months	36 months
Transmit frequency	1/minute	2/day	1/day

Survey Results

Background and Miscellaneous Information

The survey yielded 14 responders—multiple U.S. and foreign organizations. Thirteen of the 14 responders worked within power plants, and one was from a corporate office. Job titles of the respondents include section manager, research engineer, work controls manager, senior system engineer, maintenance director, I&C manager, predictive maintenance engineer, and asset management and reliability manager.

Although not significantly high in the number of respondents, the respondents represent a significant number of organizations that operate power plants and roles within these organizations. Therefore, it is believed/assumed that the opinions generated from this survey serve as a sufficient proxy for the opinions of the industry.

Of the 14 responders, only one has wireless vibration sensors installed within the responder's plant; it was used to monitor the vibration within a turbine. Given the interest in wireless sensors, this lack in deployment indicates a potential gap in the capabilities of existing products and the specifications desired by the plants.

Modular Design

Of the 14 respondents, a significant number (12) indicated interest in a sensor whose different components are modular and reconfigurable. The average ranking of each of the proposed modules is given in Table 4-3. The average ranking was calculated by

$$\bar{x} = \frac{\sum_{x=1}^{5} N_i x_i}{n}$$

$$\begin{aligned} \text{where } \bar{x} &= \text{average rating} \\ N_i &= \text{number of responses at i} \\ \mathrm{x}_i &= \text{specific rating} \\ n &= \text{sample size} \end{aligned}$$

Table 4-3
Average priority of each proposed module—lower average priority indicates greater importance

	Transducer	Processor	Wireless	Power Harvesting	Power Source
Average priority	2.00	3.64	2.14	4.07	3.14
Ranking of importance	1	4	2	5	3
Number of Most Important rankings	7	1	5	1	0

From these results, the specifications of the transducer (for example, accuracy and precision) are most important, maintaining a standard wireless protocol is second, and the power source is third. There are minimum transducer requirements for deployment. Unless the resultant sensing system is capable of performing above these minimum requirements, no deployments are possible, thereby making it the most important specification of any given sensor. The wireless module and power source being the second and third most important, respectively, reaffirms the significant interest in nonproprietary wireless communication protocol-based sensors and battery life.

Specification Priority

The first method for identifying the priority of different specifications of a sensor product was ranking. Eight different specifications were ranked; the average ranking and priority based on the average ranking are shown in Table 4-4. Accuracy and precision were Priorities 1 and 3 according to the ranking. It must be noted that the purpose of this report is not to develop fundamentally new transducer elements but to integrate existing components into an overall system that is usable by the power plants. Similar to the previous module rankings, utilization of a standard wireless protocol and battery life were prioritized fourth and sixth, respectively. Cost of the sensor was prioritized second.

Table 4-4
Average ranking of importance for each specification category

Specification Category	Average Ranking	Priority Based on Average Ranking
Cost	3.36	2
Accuracy	2.71	1
Precision	3.86	3
Measurement range	4.79	5
Standard wireless protocol	4.57	4
Battery life	5.07	6
Data transmission frequency	5.57	7
Wireless range	6.07	8

The survey directly asked respondents to provide the requisite sensor accuracy and precision. The results are shown in Table 4-5. Based on these responses, average accuracy and precision were 2.24% and 2%. Note that these averages exclude one of the responses in Table 4-5; it is highlighted. These values were not used in work to design new transducer components but were used as design criteria for selecting an existing transducer. These values were used as requirements for the conceptual design in the subsequent section.

Table 4-5
The requisite accuracy and precision for sensors deployed into the power plant – the data points in red were excluded as an outlier

	Accuracy	Precision	Notes
	5%	1%	
	5%	5%	
	1%	2%	Preferred, but documented procedurally
	0.1%	0.1%	
	10%	10%	
	0.1%	-	
Mean	2.24%	2%	
Standard deviation	2.55%	2.13%	

With specifications defined for sensor accuracy, precision, and wireless protocol, a partial factorial preference study was used to understand the effect of cost, battery, and transmit frequency on preference. Unlike the previous specifications, which all have minimum requirements, these three specifications are intimately interrelated, and each can be augmented at the cost of the others.

For each question in Questions 8–13, the percentage of respondents who chose one specification set was interpreted as the interest to buy that specific sensor. The difference between the percentage of respondents choosing one specification set and the percentage of respondents choosing the other was interpreted as the difference in interest-to-buy given a change in the specification set. Predictors for the effect of each parameter on the change in interest-to-buy can be regressed from this data set using a logit model. The general form of the logit model is given by

$$U = \ln\left(\frac{\Delta\, \text{int}\, erest}{1-\Delta\, \text{int}\, erest}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$$

where x_1, x_2, and x_3 are cost, battery life, and interval between transmissions, respectively, β_1, β_2, and β_3 are the coefficients, and β_0 is the intercept. The results of the regression are tabulated in Table 4-6.

Table 4-6
Results from logistic regression of the partial factorial preference questions – the r^2 value of the regression is 0.88

	Value	Standard Error	T-Stat	P-Value
β_0	-1.1803	0.39821	-2.9641	0.2074
β_1	-0.0073058	0.0032176	-2.705	0.26411
β_2	0.088761	0.052356	1.6954	0.33927
β_3	-2.4979e-5	1.2963e-5	-1.9269	0.30476

By comparing the values of the coefficients, the trade-offs between each of the different parameters can be calculated. An additional month of battery life adds equivalent utility to nearly an hour increase in the transmit frequency. The parameter that affects the marginal utility the most is a single month of battery life. It must be noted that the p-values are significantly high and nonlinear convolution effects might be present but could not be explored because of the small sample set. Furthermore, the survey was designed for brevity to minimize the burden placed upon the responders.

Although not being able to systematically explore the nonlinear effects, the effect of battery life on preference can be locally explored by closely examining the response of select questions. The two specification sets on Questions 10 and 11 have no change in the transmit frequency, but they contain changes in battery life and cost. In these two questions, a nearly identical increase in price led to increases in battery life by 30 (Question 10) or 24 months (Question 11). In Question 10, 57.1% of respondents preferred the longer lasting battery, whereas in Question 11, 71.4% of respondents preferred the shorter lasting battery. This indicates that there exists an initial sharp rise in interest to buy beyond the first year, but significant increases in battery life beyond a year lead to diminishing returns. In order to conservatively set specifications for battery life, a minimum lifetime of two years was selected.

The final component of the survey focused on data reporting. Two reporting regimes were considered: fixed interval reporting and alert-based reporting. Different types of reported data were also considered, specifically RMS average and vibration spectrum reporting. The survey directly asked the respondents the requisite transmit frequency for reporting both. The results are tabulated in Table 4-7.

Table 4-7
The requisite reporting frequency for RMS and frequency spectra on a fixed interval

	RMS Average	Frequency Spectra	Notes
Responses (seconds)	1	60	Waveform on demand
	21,600	86,400	
	86,400	86,400	
	1	1	
	3,600	43,200	
	1		
Mean	18,600 (0.215 days)	54,000 (0.625 days)	
Standard deviation	32,055	43,184	

Within the alert-based reporting regime, the sensing system will output data only when the measured values exceed user-defined bounds or is demanded by an operator at a remote console. This paradigm is favorable for power savings because the interval between data transmissions can be longer than the requisite transmission interval given fixed-time interval reporting. Of the respondents, 50% were interested in this type of reporting scheme. Within this paradigm, the sensor would transmit heartbeat data to indicate that the sensor was still operational. On average, the respondents indicated the longest acceptable heartbeat reporting frequency to be once every 0.323 days.

Sensor Functional Requirements

From past Electric Power Research Institute (EPRI) surveys [18] to the industry regarding this topic, the requisite transducer specifications are 0–10 g on each axis, capable of responding to up to 1–10 kHz. The EPRI survey associated with the present work provided functional requirements for sensor accuracy, precision, reporting interval, battery life, wireless standards, and design modularity. The combined functional requirements for the resultant sensor are given in Table 4-8. These functional requirements will be used to guide conceptual design of the sensor in the next sections.

Table 4-8
Requisite specifications for a wireless triaxial vibration sensor as derived from current and past EPRI surveys [18]

Parameter	Required Level
Accuracy	2%
Precision	2%
Data reporting	
RMS average	0.21 days
Wave form	0.625 days
Battery life	>24 months (maximize)
Standard wireless protocol	
Modular sensor accuracy/precision, wireless design, power source, and harvesting	
Past surveys 1–10 kHz response, 3-axis 0–10g [18]	

Current Technological Gap

An overview of currently commercially available wireless triaxial vibration sensors was developed to determine whether existing products complied with the requisite specifications determined previously. Seven different products were considered. The manufacturers and product names are omitted, but the wireless protocol, battery life, and bandwidth frequency are tabulated in Table 4-9. These three specifications were chosen because of the high variability from product to product. In all products examined, the user can configure the data reporting frequency. However, the battery life is greatly affected by the operational configuration (for example, sampling and transmission rates). Because of this dependence, the battery lifetime is difficult to quantify and many manufacturers omitted this specification in their product literature.

Table 4-9
Tabulated specifications for wireless triaxial vibration sensors

	Wireless Protocol	Battery Life	Bandwidth Frequency
Product 1	802.15.4	-	0–800 Hz
Product 2	WSDA	8 hours in streaming	1–512 Hz
Product 3	Proprietary	-	4–2300 Hz
Product 4	WDAU-20XX	-	-
Product 5	Bluetooth	-	-
Product 6	Proprietary	8 hours in streaming	-
Product 7	Proprietary	8 years @ 1/hour	0–1600 Hz

Note: Products 1–7 refer to different manufacturer or model numbers of different wireless triaxial vibration sensors

The battery life specification was reported only under certain operational details. In the case of Products 2 and 6, the lifetime under intermittent (that is, a transmission every 0.21 days) cannot be determined from the specification of 8 hours of streaming data. The amount of time per transmission is unknown and can vary depending on the amount of data transmitted. Furthermore, the power inefficiency by intermittently transmitting data instead of streaming, as well as the available low-power modes when not transmitting, is uncertain. No significant detail was given about the operational conditions of Product 7, except that it lasts eight years while outputting data once an hour.

The majority of the available products use a proprietary wireless protocol, which defeats the idea of modular design. Modular design in conjunction with the adoption of standard wireless protocols for a wireless sensor platform provides flexibility of choosing various modules from various vendors and uncomplicated scalability for future installations. The measurement bandwidth of all products ranges from 0 to 2300 Hz, which is well below the 1- to 10-kHz response. Product 7 is the only product to comply with the battery life specification, but it uses a proprietary wireless protocol and is unable to sample at a high enough frequency. Additional development is required to comply with all of the requisite specifications provided by the survey of the power plants.

5
CONCEPTUAL DESIGN

Given the need for a modular wireless triaxial vibration sensor, the product was conceptualized, and an initial balance of materials was generated. The different subsystems and functionality were first overviewed. Different components to fulfill these functions are then tabulated, followed by integration of these components into modules. The resultant design with adequate battery life was presented, along with a high level balance of materials.

Overview of Requisite Modules

Based on the specifications determined in the previous section, designs of a sensor platform and an associated triaxial vibration sensor were conceptualized. These designs divided the functionality of the sensor into separate modules that would eventually be interchangeable with other modules of a similar type. The entire system must enable communication of two types of information: data and control. The platform must accurately and reliably collect data from the sensor and, in the meantime, receive commands that control the operation of the sensor from a remote panel.

Figure 5-1 shows a breakdown of the different requisite functionality and the pathways for information to travel. The overall sensor was broken down into five separate subsystems. They are as follows:

- Analog signal processing
- Digital signal processing
- Onboard data storage
- Wireless
- Power management

A system controller manages the operation of the entire sensor. The system controller must interpret the commands from a remote panel, manage operating parameters, and direct the background operation of the device.

The raw analog data signal is collected by the transducer, which translates the vibration that it experiences into a voltage or current. This raw analog signal must then be processed (for example, filtering) and normalized (for example, amplification) so that it is measurable to a sufficient resolution by an ADC. This digital signal is communicated to a signal processor. Upon instructions from the system controller, the signal processor will perform requisite calculations on the raw signal (for example, RMS average and/or Fourier transform calculations) and output the resultant information to the system controller. The requisite calculations will be specified upon preparation of the sensor and can be changed when repurposing the sensor, or wirelessly. This provides significant flexibility in the calculations that are of interest. However, it must be noted that calculations that are purely informative and do not alert to faults should occur not on the processing modules of the sensor, but on the associated computer to minimize power consumption and more efficiently use the abundant computing power within the computer.

The system controller will interpret and transmit the information using the wireless modules. Firstly, the information must be converted to the correct wireless packet(s). The information relayed and the size of the packet vary depending upon wireless protocol. In many protocols, if the wireless packet is larger than the maximum allowed, the information will be distributed over multiple packets. Typical information added to the sensing data includes sender address, destination address, time stamp, and checksums. The packet generator then sends the information to the wireless antenna and drives the transmission of the packet. This is typically accomplished through the use of a balun that converts a balanced signal to an unbalanced signal.

Complementary to all of these subsystems is a power management subsystem, which ensures that adequate power is supplied to all parts of this system. Multiple power management subsystems for individual subsystems are a possibility and must be explored. The power management subsystem includes power supply (for example, batteries), power harvesting, and power conditioning (for example, battery charging and dc-to-dc voltage conversion).

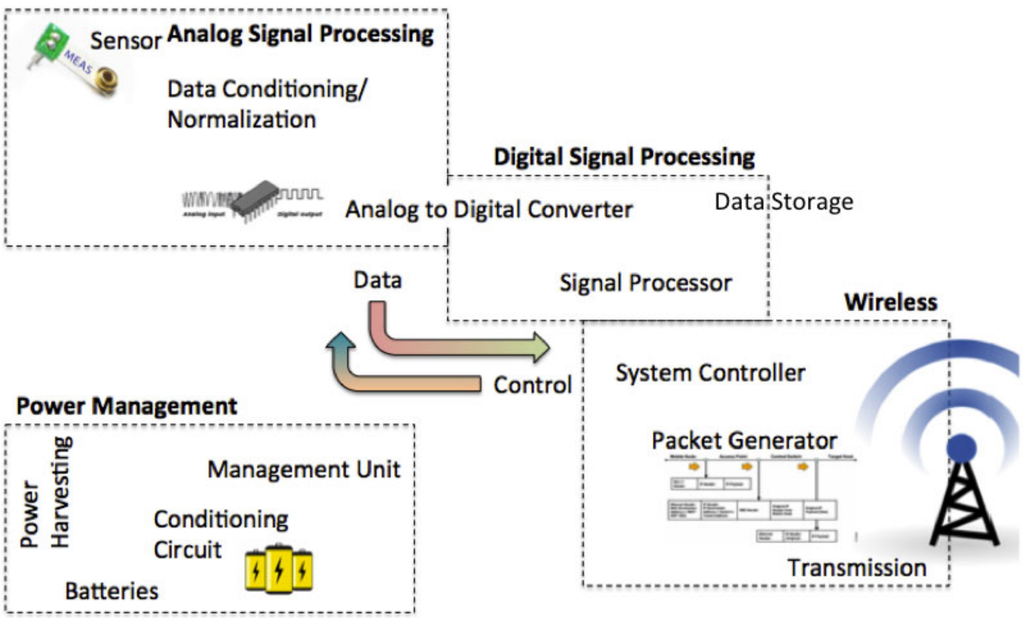


Figure 5-1
A breakdown of the different subsystems (bolded in figure) that must be included within the conceptual design of the sensor (Individual modules are included within the dotted boxes of each subsystem.)

For power management concerns, multiple tasks can be integrated into a single piece of hardware (for example, signal processor, system controller, and packet generator can be integrated into a single powerful processor). However, the power management and functionality consequences of such decisions must be explored. The focus of the conceptual design is to identify possible components for each of these subsystems and explore the benefits and trade-offs of integrating multiple modules into a single piece of hardware.

Aside from fulfilling the requisite tasks, maximizing battery life is of great importance within this design process. The battery life is broken down into two separate components: battery capacity and power usage rate (power/day). The trade-offs of maximizing battery capacity and minimizing power usage rate will be considered. The governing equations for the power management design are shown in the following equations. These equations were used to evaluate different integrated sensor systems. The end goal of this design process is to identify designs that have the potential to fulfill all requirements from the preceding section.

$$battery\ life = \frac{battery\ \ capacity\ [W - hr]}{power\ usage\ [W - hr]/time\ [day]}$$

where

$$\frac{power\ usage\ [W - hr]}{time\ [day]} = \#_{RMS} P_{RMS} + \#_{raw} P_{Raw} + 1440 P_{sleep}$$

$$P_{\frac{RMS}{raw}} = P_{measurement} + P_{Processing} + P_{Wireless} + P_{Conditioning}$$

$$P_{Measurement} = (p_{transducer} + p_{ADC}) t_{RMS/raw}^{measurement}$$

$$P_{processing} = p_{processing} t_{RMS/raw}^{measurement}$$

$$P_{wireless} = p_{transmit} d_{transmit} t_{RMS/raw}^{transmit}$$

$$P_{conditioning} = \eta_{conditioning} P_{total}$$

$$P_{sleep} = p_{sleep}(1 + \eta_{conditioning}) - 1440 p_{harvest}$$

$$P = total\ power$$

$$p = power\ per\ minute$$

Components for Each Module

Different components for each module were examined; the most promising of the examined components were tabulated and used in subsequent conceptual design. It is important to note that no laboratory evaluation of these components was conducted; information given in this section is directly from or calculated using information from specification sheets of these products.

Triaxial Vibration Sensors

The primary requirements for triaxial vibration sensors were the ability to measure between 1 and 10 g of force and response at frequencies exceeding 1–10 kHz. The three products of greatest promise are tabulated in Table 5-1. Each converts measured vibration to an electrical signal. In some cases (for example, Transducer A), signal conditioning is needed to adjust the output to a standard analog signal. Relevant specifications for each sensor are tabulated in Table 5-1. These specifications were taken from the product information sheets of each respective component. Components that do not completely fulfill the requirements were purposely chosen to understand the power consumption benefits given a slightly relaxed specification set.

The requisite specifications for this component of the system are the ability to measure ±10 g of vibration at frequencies between 1 and10 kHz. Of the components examined, only Transducer A completely fits the requisite specifications. However, it is also the component that requires the most power. Transducer B is the second closest component, and it requires half the power.

However, it does not fulfill the requisite specifications. Transducer C requires approximately the same power consumption, as Transducer A but is incapable of measuring vibrations above 1 kHz, which is significantly below the requisite specification. Transducer A is the best choice, but, if a low-power option is necessary, Transducer B can be considered.

Table 5-1
The frequency, range, and power specifications for the three most promising triaxial vibration sensors

Name	Frequency	Range	Power
Transducer A	Up to 15 kHz	80 g	72 mW
Transducer B	4 kHz	± 7 g	36 mW
Transducer C	10 Hz–1 kHz	50 g	60 mW

Note: *Transducer A*, *Transducer B*, and *Transducer C* refer to different manufacture or model numbers of transducers

Analog-to-Digital Converters

Multiple ADCs were examined; a range of promising ADCs along with relevant specifications from the product information sheet are tabulated in Table 5-2. In order to avoid aliasing when measuring vibrations at frequencies up to 10 kHz, ADC response frequencies of greater than 30 kHz are required. A 24-bit resolution would be ideal, if possible.

Every component is capable of fulfilling the frequency requirement. However, the resolution requirement and power consumption requirement differ greatly. ADC B requires the smallest amount of power and greatly exceeds the frequency requirement but offers only 12-bit resolution, which correlates with 4096 divisions of measurement. ADC A requires a similar amount of power and measures at up to 100 kHz, which complies with the requisite specification but provides 16-bit resolution. This increases 4096 divisions of measurement to 65,536, which represents significantly greater resolution. ADC C represents a significant upgrade from ADC A and B, but it requires nearly three orders of magnitude of power. Because of the greatly increased resolution, ADC A is the preferred component, but, should a low-power alternative be needed, ADC B is a viable choice provided that the transducer output and amplification electronics is altered so that the reduced resolution is still capable of measuring the vibration to ±2%.

Table 5-2
The resolution, frequency, and power consumption for the three most promising ADCs

Name	Resolution	Frequency	Power
ADC A	16 bit	100 kHz	1.8 mW
ADC B	12 bit	1 MHz	0.367 mW
ADC C	24 bit	2.5 MHz	661 mW*

* Low-power mode

Note: *ADC A*, *ADA B*, and *ADA C* refer to different manufacture or model numbers of ADCs.

Microcontroller/Processor

A microcontroller/processor is used within the signal processing, power management controller, system controller, and packet generator modules. All of these modules can be integrated in to a single piece of hardware. However, this is not necessarily beneficial. There is a drastic trade-off between power consumption and processing speed. If all of these modules are integrated, a more powerful controller is needed, and it will be on for longer periods of time. In some cases, a less powerful controller can be used to trigger the operation of a more power intensive unit. The processing power and power consumption of these controllers are tabulated in Table 5-3.

Table 5-3
The processing power and power consumption specifications for multiple microcontroller/signal processor products

Name	Manufacturer	Processing Power	Power
μC A	Manufacturer 1	166 MHz	66 mW
μC B	Manufacturer 1	8 MHz	25 mW
μC C	Manufacturer 2	8 MHz	1.8 mW^{+}
μC D	Manufacturer 2	16 MHz	15 mW
Integrated RF and Controller			
RFμC A	Manufacturer 1	8 MHz	60 mW
RFμC B*	Manufacturer 2	20 MHz	75 mW

$^{+}$@ 1 MHz

* 900-MHz RF

Note: *Microcontroller A (μC A)*, *Microcontroller B (μC B)*, and *Microcontroller C (μC C)* refer to different model numbers of microcontrollers, and Manufacturers 1 and 2 refer to different manufacturers.

There are multiple RF integrated controllers; these units do not contain onboard antennas, and the tabulated power consumption does not include the power required to transmit the signal (for example, inefficiency of the antenna). The tabulated power consumption includes the power required to generate the wireless packet and to drive an antenna that is powered off an external balun.

The primary difference between the microcontrollers is the power consumption. There is always a trade-off between clock speed (processor power) and power consumption. The lowest power consumption controller is μC C, operated at 1 MHz clock speed. When significant computational power is required, the minimum amount of power consumption/computer power should be used. Of the microcontrollers listed, other than μC C, the microcontroller with the optimal power consumption efficiency is μC A, which is 2.515 MHz/mW. However, mC A requires significant power to operate. A better alternative is μC D, which uses approximately 15 mW to operate but allows 16 MHz, which equates to a power efficiency of 1.066 MHz/mW. In extreme low-power use cases, μC C should be used; in situations where greater computational power, μC D is suggested, but the decision should be decided by the amount of processing power required and the drive to optimize power efficiency.

Field programmable gate arrays (FPGAs) were also considered for power reduction. When programming microcontrollers, only the firmware aboard the controller can be changed (that is, the designer can change only the routine that the controller performs), whereas with FPGAs, the designer can change the hardware and the software. The gate array allows rapid changes to the hardware configuration on chip. This introduces significant amounts of complexity in the design of the device (for example, if a microcontroller is desired, a microcontroller must first be designed on the FPGA, additional firmware must be written). The primary use case for this type of device is when circuits need to be rapidly reconfigurable to allow for additional redundancy and robustness or when a single device is needed to accomplish a wide range of functions.

In this case, an FPGA may be attractive because the processing power of the device can be changed in the field, thereby allowing for power savings. When operated at lower processing power and with a power conscious design, power consumption as low as 25 μW [19] can be reached. However, the controllers listed in Table 5-3 have sleep modes that draw as low as nanowatts of power. Furthermore, controller operational power draws range as low as 1.8 mW, which, although significantly higher than the lower range of the FPGA, is not the bottleneck for power consumption within the system. For simplicity's sake, at a first pass, a microcontroller-based solution is viable; however, it should be noted as a possible place for improvement in power consumption.

Onboard Data Storage Systems

Onboard data storage systems are important for operation because they allow a backup of the collected data that is independent of the wireless system. The storage device must contain enough memory to hold all of the data that are collected over the course of the two years of operation. The amount of data storage required is highly dependent upon the type of data stored. If only RMS averages are stored, there would be significantly less data than if raw data or frequency spectra needed to be stored. This is further influenced by the data collection rate (for example, sampling frequency) and the resolution of the data. Data collection schemes can reduce the amount of memory required (for example, backup data are stored for six months before deletion or backup data are transferred once every six months before deletion).

If only RMS average data are stored, 1–2 GB of storage is sufficient; if raw data are required, significantly more storage is required. If 24-bit data are collected at 30,000 Hz continuously, this translates to 432,000,000 bits per minute. Converting to kilobytes (8 bits per byte) yields 5400 kB per minute. If data are taken for 10 seconds per hour with 17,520 operational hours over two years, this translates to 15.768 gigabytes over two years.

Data storage is divided between two types: solid-state memory and magnetic media. Magnetic media storage is fragile, is very sensitive to electromagnetic interference, and requires significant amounts of power. Solid-state media is preferred. Solid-state memory ranges from miniature cards to full hard drives. In this application, the choice falls to compact flash or micro-Secure Digital (SD) cards [20, 21] because of the significant amount of power required for full solid-state hard drives, which can be as high as 2 W during active operation, and the unnecessary storage capacity of most available products. Compact flash and SD memory are sufficiently similar both in operation and in form that the choice between the two is purely stylistic. Compact flash typically offers larger capacities than SD, which is capable of accommodating the data storage required. Both can be operated at 3.3 V and require approximately 50 mA for read and write, yielding a power consumption of 165 mW for write operations [20, 21].

Wireless Transmission

Using nonintegrated wireless transceivers will allow easy integration of any wireless hardware and protocol. This aligns well with the overall modular design concept. Although most wireless protocols now use the 2.4-GHz standard, the power consumption specified by each standard varies drastically. The hardware tabulated in Table 5-4 is fully functional packages; power consumption values include power conditioning and antenna inefficiency. The power consumption for 802.11 is an order of magnitude higher than that of 802.15.4. IEEE is currently working on a new subset of the 802.11 protocol termed *802.11.AH*. This new protocol is aimed at low-power wireless transport and shows promise for being applicable in this effort. It is projected to be released in 2016. As noted previously, 802.15.4 is the preferred wireless protocol unless the plant has an existing wireless network already in place. In this case, it is always better to adapt to existing network infrastructure than to install a new backbone for another protocol.

Table 5-4
The protocol and power consumption for fully packaged hardware using 802.11 and 802.15.4 wireless protocols

Name	Frequency	Range	Power
RF A	2.4 GHz	802.11	792 mW
RF B	2.4 GHz	802.15.4	76 mW

Power Management

Power management consists of three major components: power storage (batteries), power harvesting, and power conditioning. Power conditioning consists of dc-to-dc conversion, battery charging, and system power management, which determines the subsystems that need to be on at any given moment. The battery charging circuitry is highly dependent on the type of battery that is used. At the current requirements of most sensors, dc-to-dc conversion and battery charging circuitry will have efficiencies above 85%–90%. There are many different types of batteries that can be used, the most promising of which are tabulated in Table 5-5. Lithium manganate and lithium iron phosphate batteries are considered the safest lithium ion batteries, but they have lower power densities; whereas lithium thionyl chloride has safety concerns given certain discharge conditions but contains the highest power density [22]. Lithium manganate is the battery of choice because of the existing intrinsic safety certifications. Lithium thionyl chloride, while having the highest power density, has significant safety issues and should not be used.

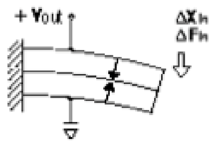
Table 5-5
Different types of batteries that can be used as a power source for the sensor [22]

Name	Power Density
Lithium manganate	280 Wh/kg
Lithium thionyl chloride*	500–700 Wh/kg
Lithium iron phosphate	90–110 Wh/kg

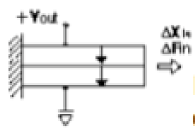
* Safety concerns

Power harvesting was considered as a way to augment the battery life of the sensor. The power source to be harvested differs drastically from environment to environment; in this case, vibration harvesting was a natural choice. There are two separate types of vibration harvesting: bending generators and extending generators. The vibrational modes and force required to operate each type differ. Specifications for generators of each type are given in Figure 5-2. Therefore, the optimal generator will depend on the specific type of vibration to be monitored. The extending generators are capable of generating significantly more power, but they require significantly faster and stronger vibrations. Multiple generators can be placed in parallel to increase the amount of total power generated [17].

Bending Generators



Spec – Single Generator	Value
Max Power	8.8 mW
Deflection	+/-1.22 mm
Frequency	100 Hz
Stiffness	9E2 N/m
Force for Max	1.098 N
Power in 0.21 Days	44.4 mW-hr



Extending Generators

Spec – Single Generator	Value
Max Power	2000 mW
Deflection	+/-25 microns
Frequency	1000 Hz
Stiffness	15E6 N/m
Force for Max	375 N
Power in 0.21 days	10080 mW-hr

Figure 5-2
Specifications for bending- and extending-type generators [17]

Conceptual Integration

The overall integration of the system is detailed in this section. The preferred components and the respective specifications were inputted into the power consumption equations detailed at the beginning of this section. For the purpose of this effort, the components designated as low-power alternatives were not considered because, in most cases, the power consumption reduction is gained by relaxing the requisite specifications. The wireless transmission should be decided by the infrastructure available in the plant. It is for that reason that possible minimal power configuration, as well as a possible configuration using 802.11, is detailed in the following sections.

Overall System

The different potential components for each module were tabulated in the previous section. These components must be integrated to understand performance as an overall sensing system. It must be noted that integration on this level does not encompass final design of the sensor and, therefore, only serves as an approximation of the final specifications. This level of design is useful in identifying the optimal designs to further prototype.

The overall layout of all requisite functionality was shown in Figure 5-1. Integration consists of determining the functionality that a piece of hardware will perform. In this case, the major trade-off for assigning more functionality to a single of piece of hardware is additional operational time, which, in many cases, uses more power than necessary. The conceptual designs were evaluated using the power consumption equations given previously. The optimal integration is tabulated in Table 5-6.

Table 5-6
Optimal integration of sensor modules and functionality

Module	Component	Power Consumption
Sensor	Transducer A	72 mW
ADC	ADC A	1.8 mW
Signal processor	μC D	15 mW
Wireless packet generator/transmission	RF B	76 mW
Power management unit/system controller	μC C	1.8 mW
Batteries	Lithium manganate	280 Wh/kg

A low-power microcontroller is used as a power management system and system controller. The main purpose of this unit is to serve as communications node. This unit determines the type of action required and the modules that need power to perform such action, provides the necessary information, and receives the subsequent output. This low-power microcontroller is connected to the ADC and receives the raw signal. If an RMS average measurement is required, the RMS average is calculated onboard. If a vibrational spectrum is required, the unit will turn on the signal processor, send the raw data, and wait for the frequency spectra from the signal processor. This minimizes the use of the signal processor, which has an order of magnitude more power requirement.

When necessary, the wireless module is turned on and data are transmitted. Data transmission is guaranteed to occur every 0.21 days. The RMS average of displacement, velocity, and acceleration will be measured at a far more frequent interval, but transmission will occur only if the measured value is beyond user-defined bounds. Beyond this action, the receiver will turn on for a heartbeat check at a more frequent interval. Over the course of operation, the remote terminal will send heartbeat requests. When received during a heartbeat check on the sensor side, the sensor will send out a heartbeat message to ensure proper operation. Otherwise, the heartbeat check will not include any transmission, thereby saving power. During the heartbeat exchange, new operational instructions can be exchanged. This minimizes transmission time and thereby power consumption. With this operational routine, most components outside the power manager/system controller are off for the majority of the time.

Using the previously described operational routine, the power consumption can be calculated using the equations detailed previously. By assuming a conservative 10% uptime on all components during a normal transmission event, all time components in the preceding equations are equal to the same value (0.1*5.04 hours), thereby allowing the equations to be further simplified. This is an unrealistically conservative uptime. However, this will yield a high-end estimate for the power consumption, compensating for unaccounted-for inefficiency elsewhere, and providing a large margin of error. In addition to the operation of the sensor to take data, the power management unit is assumed on all of the time. Additional sleep modes can be used to reduce the power consumption. Furthermore, an 85% power conditioning efficiency and another 20% gross inefficiency from spurious elements were introduced.

$$\frac{power\ usage\ [W-hr]}{time\ [day]} = 1.2\left(\frac{5.04\ hours\left(0.1\sum P_{components} + P_{Power\ Management}\right)/0.85}{0.21\ days}\right)$$

$$\sum P_{components} = P_{transducer} + P_{ADC} + P_{wireless} + P_{power\ management} + P_{Processing} = 72 + 15 + 76 + 1.8 + 1.8$$
$$= 166.6\ mW$$

This yields a power consumption of 521.22 mW-hr per day without and 625.45 mW-hr per day with the gross inefficiency from spurious elements. To operate independently for two years, the sensor would require 457 W-hr of batteries, which is a significant amount of batteries. A single AA lithium manganate battery contains ~1.5 W-hr. This translates to approximately 305 AA batteries, which translates to approximately 475 in.^{3} (0.007783 m^3); for comparison, a U1-type car battery has a volume of approximately 281 in.^{3} (0.004604 m^3). A battery pack consisting of nearly two car batteries is not acceptable. Therefore, power harvesting was explored to minimize the size of the requisite battery.

Each bending vibrational generator can generate approximately 212.4 mW-hr per day. The inclusion of a single bending generator into the system will decrease the amount of battery power required to 297.1 W-hr. A second and third generator will reduce the amount of battery power required to 142.1 W-hr and -12.97 W-hr, respectively. The negative value indicates that the sensor is generating more power than it is using. According to these power consumption equations and using this specific operational routine, the sensor can be self-sufficient given the addition of three bending vibrational energy harvesters. This result is calculated using tabulated specifications and must be confirmed within the laboratory in a future effort.

802.11 – WiFi

There has been significant investment into 802.11 WiFi infrastructure within the power plants. If such infrastructure exists, all efforts should be exerted to use the existing infrastructure. In such a case, the optimal components are tabulated in Table 5-7. Using the same operational routine as described previously, the sensor now requires 3065 mW-hr per day to operate, and, in turn, would require 2237.4 W-hr battery to operate for two years. This represents a significant number of batteries and would force the sensor to have an unreasonably large form factor. The amount of power generated by the bending generator would be insignificant. Fifteen bending generators would be required to allow for sustainable operation. If the extending generator can be used at only 30% efficiency, the sensor itself would be sustainable. However, as noted previously, this would greatly depend on the type and force of vibration that is being monitored. These values presented are theoretical values taken from the specification sheets of the different components; the result must be confirmed within the laboratory in a future effort.

Table 5-7
Optimal integration of sensor modules and functionality if WiFi infrastructure already exists within the plant

Module	Component	Power Consumption
Sensor	Transducer A	72 mW
ADC	ADC A	1.8 mW
Signal processor	μC D	15 mW
Wireless packet generator/transmission	RF A	796 mW
Power management unit/system controller	μC C	1.8 mW
Batteries	Lithium manganate	280 Wh/kg

A hybrid 802.11/802.15.4 solution can resolve the power consumption issue. A localized 802.15.4 framework can be set up around a central node that contains 802.11 hardware and is powered from an existing power source (for example, 120 Vac). This central node allows 802.15.4 communication within a specific range around its location. Sensors within this proximity are equipped with 802.15.4 hardware and can transmit data to this central gateway node. The central gateway node then processes this data and sends the information through 802.11 using the existing 802.11 frameworks within the plant. In this situation, each sensor node can be the overall design detailed previously; the power consumption of the gateway node that contains 802.11 and 802.15.4 is irrelevant because ac power is available. A schematic representation of this solution is shown in Figure 5-3. Such a solution would require an additional central module but allows the utilization of existing wireless infrastructure while still allowing for the extended battery life of 802.15.4.

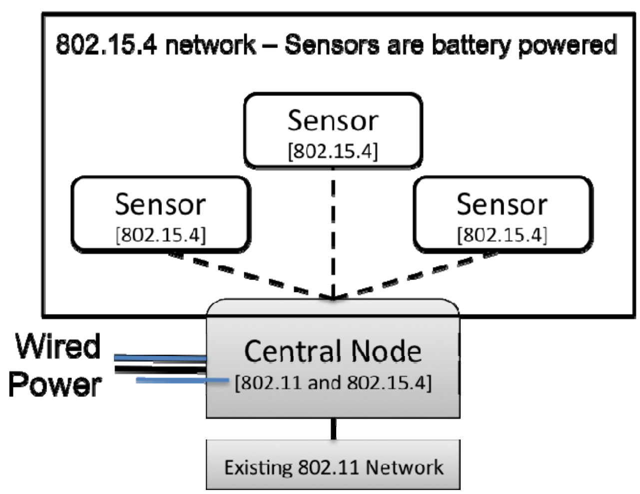


Figure 5-3
A hybrid 802.11/802.15.4 solution

Modular Design

After detailing the individual components required in building a system that can fulfill the requisite specifications, the components and functionality were divided into modules for easy reconfiguration. Although each module is crucial to sensor functionality, certain modules require more careful design because of their central nature to the entire system. The power management unit/system controller and wireless transmission are most important because they are most crucial in diagnosing problems and reducing maintenance of the sensor. The analog signal processing and the signal processor are second and third in importance, respectively.

The overall system was divided into three separate, required modules and one optional module. The three required modules are as follows:

- Transducer and signal processing
- System controller and power management unit
- Wireless transmission

Figure 5-3 shows a schematic of the different modules and the encompassed functionality. The optional module is power harvesting. Each module will be equipped with its own battery power system to allow for troubleshooting even if another module has failed. The transducer and signal-processing module will contain an onboard data storage system, allowing data to be saved given failures in other modules. This division of modules allows for easily changing sensors and wireless protocols.

Analog data taken by the transducer will be stored within onboard storage and transferred to the central processing module. The central processing module will make decisions on transmission and necessary processing of the data. The wireless module will be responsible for heartbeat transmissions and communications. The central processing module will have the ability to stop and/or trigger operations of the other modules. Finally, the power-harvesting module can be plugged into the central processing module; the central processing module will pass the generated power to the other two modules to allow for charging.

The user interface of this modular system must be sufficiently simple so that plant personnel can quickly and conveniently configure and reconfigure sensors. In this case, firmware within the sensor and software within a central computer are required. The firmware should have bare minimum functionality, and, when possible, operations should be performed on the computer side. The functions that must be accommodated are reprogramming of the sensor and calculations on the data upon arrival. The requisite calculations change based upon the sensor that is being deployed (for example, temperature data can be plainly plotted, whereas vibration data may require additional computations). However, care must be taken so that, if necessary, advanced configuration of the computations is possible but not necessary. A two-leveled software system is proposed. The first level contains simple calculations that are ubiquitous for many sensors (for example, plotting, data extraction, and simple calculations). This is preloaded with the software, allowing immediate use of the sensors. The second level contains configurable code allowing complex calculations. The user will define calculations and create a custom computational module. After it is complete, the resultant module can be loaded into the first level, thereby leveraging all of the previous convenience. Additional work is needed to prototype this software system, as well as to further understand the needs of the plant and the preferences with regard to the specific interface.

6
CONCLUSIONS

An in-depth exploration into the needs of the power industry for wireless triaxial vibration sensor was conducted. Significant interest in such a device was found as long as the device contains the specifications tabulated in Table 4-8. A broad overview of available components was conducted, and a set of components was chosen. Integration of the chosen components and determination of the operational scheme of the sensor yielded a design that would effectively meet all of the requisite specifications. A high-level bill of materials for the device was given in Tables 5-6 and 5-7. Without any vibrational power harvesting and assuming significant inefficiencies because of hardware interaction (20%), this device would require a significant number of batteries for operation. However, the inclusion of three vibrational power harvesters would allow such a device to be self-sustaining. The functionality of the overall system was divided into four independent modules. This allows for easy of reconfiguration when planning deployment. The next phase of this project is to prototype the conceptualized modular design.

7
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A
SURVEY

The following is the survey that multiple power plants were asked to complete regarding the parameters of greatest importance for a wireless triaxial vibration sensor.

1. Please provide the following information:

Name:

Company:

Job Title:

Name of the plant:

2. Do you currently have wireless vibration sensors installed in your plant?

Yes

No

3. If Yes, where? [Please provide system, equipment, and component monitored]

4. Please rate the most important requirements for a wireless triaxial vibration sensor. (1 being most important)
[Instruction: Only one of each rating is allowed. Once a duplicate is selected, the other ratings will adjust accordingly.]

Cost

Accuracy

Precision

Measurement Range

Standard Wireless Protocol

Battery Life

Data Transmit Frequency

Wireless Range

5. Do you see any value in modular design?
(For definition of modular design, refer to letter that accompanied invitation to survey.)

- Yes
- No

6. If yes, can you rate the modules that would be most important to you? (1 being most important)
[Instruction: Only one of each rating is allowed. Once a duplicate is selected, the other ratings will adjust accordingly.]

- Power Source (Battery or 120 VAC)
- Power Harvesting
- Wireless (Standard Protocols - Wi-Fi, WirelessHART, etc.)
- Processor/Computation
- Transducer (Vibration, Temperature,etc.)

7. How frequently would you like each type of data from a vibration sensor? (Put 0 (zero) if you don't want the data, put N if you are in-different.)

RMS Average

Waveform

8. Which of the two products do you prefer?
[DISCLAIMER: The quantitative values associated with each parameter are only for reference, and are purely hypothetical]

- Product A: Low cost ($50), Low Battery Life (6 months), Medium Transmit Frequency (2/day)
- Product B: High Cost ($500), Low Battery Life (6 months), High Transmit Frequency (1/minute)

9. Which of the two products do you prefer?
[DISCLAIMER: The quantitative values associated with each parameter are only for reference, and are purely hypothetical]

- Product A: Medium Cost ($100), Medium Battery Life (12 months), Medium Transmit Frequency (2/day)
- Product B: Low Cost ($50), Low Battery Life (6 months), Low Transmit Frequency (1/day)

10. Which of the two products do you prefer?
[DISCLAIMER: The quantitative values associated with each parameter are only for reference, and are purely hypothetical]

- Product A: High Cost($500), High Battery Life (3 years), Low Transmit Frequency (1/day)
- Product B: Low Cost ($50), Low Battery Life (6 months), Low Transmit Frequency (1/day)

11. Which of the two products do you prefer?
[DISCLAIMER: The quantitative values associated with each parameter are only for reference, and are purely hypothetical]

- ☐ Product A: High Cost ($500), High Battery Life (3 years), High Transmit Frequency (1/minute)
- ☐ Product B: Medium Cost ($100), Medium Battery Life (12 months), High Transmit Frequency (1/minute)

12. Which of the two products do you prefer?
[DISCLAIMER: The quantitative values associated with each parameter are only for reference, and are purely hypothetical]

- ☐ Product A: Low Cost ($50), Low Battery Life (6 months), Low Transmit Frequency (1/day)
- ☐ Product B: Medium Cost ($100), Low Battery Life (6 months), Medium Transmit Frequency (2/day)

13. Which of the two products do you prefer?
[DISCLAIMER: The quantitative values associated with each parameter are only for reference, and are purely hypothetical]

- ☐ Product A: Medium Cost ($100), Low Battery Life (6 months), Medium Transmit Frequency (1/day)
- ☐ Product B: High Cost ($500), Medium Battery Life (12 months), High Transmit Frequency (1/minute)

14. What is the minimum accuracy and precision requirements for a sensor deployed into your plant?

Accuracy	
Precision	
Don't know (Put yes if you don't know)	

15. Would you be interested in a sensor that is capable of detecting and reporting data only if it is outside of user-defined pre-set bounds?
[e.g. user-defined temperature bound is 100°C, sensor will transmit data only after measured value is greater than 100°C]

- ☐ Yes
- ☐ No

16. If a sensor has this type of decision making ability (as mentioned in Question 15), what would be the longest acceptable data transmit frequency?

- ☐ 1/minute
- ☐ 1/hour
- ☐ 1/day
- ☐ 1/week

17. Can we contact you for further clarification and/or information? If yes, please provide your phone number and e-mail address below.

Phone	

Email

18. Any additional comments?

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