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Automating Surveillance Activities in a Nuclear Power Plant

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Automating Surveillance Activities in a Nuclear Power Plant

Ahmad Al Rashdan and Shawn St. Germain

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ABSTRACT

The workforce cost of operations and maintenance (O&M) in the United States nuclear power industry is mostly attributed to the manual and human-reliant nature of work activities. More than 80% of work historically performed in a United States nuclear power plant (NPP) is associated with surveillances or preventive-maintenance activities. Surveillances are performed on a periodic or as-needed basis to test the functionality of important equipment in compliance with the plant's technical specifications and are part of the plant's operating license. Operations, as an organization, is responsible for ensuring these surveillances are performed.

To reduce costs associated with surveillance activities, it is necessary to reduce the number of activities by eliminating them or reducing their frequency, when possible, and automating them if they are still required. Automation of surveillance activities benefits the NPP by both reducing labor costs and providing insight and evidence to enable a reduction in frequency or elimination. This effort targeted research and development of solutions to automate vibration monitoring, which represents a significant share of the manual surveillance activities performed in a plant. A technology-gap analysis for online vibration monitoring revealed that solutions are already commercially available for continuous monitoring. However, standby equipment, which represents most surveillance equipment in an NPP, seems to lack a suitable monitoring technology.

A research was conducted into the typical monitoring requirements of standby equipment. Accordingly, a set of necessary features were identified for a standby equipment monitoring system. These features are not available in existing market products that target continuously running equipment. These features are: 1) start when the equipment starts and shutdown when the equipment shuts down (to preserve battery and reduce the acquisition and storage of data to useful data only); 2) generate data in a raw form to provide an additional level of information on equipment condition (none of the continuous monitoring vendors engaged allowed access to raw data); 3) store the data locally (necessary when a network is not available and reduces the concerns with cybersecurity); 4) take measurements on-demand (because surveillance conditions exist at certain points in equipment run time); 5) use a highly secure communication method for data transfer from the sensors to the storage location; and 6) be reconfigurable and adaptable enough to support installation on any equipment that requires immediate attention with minimum effort (i.e., enable a monitor-it-now concept). These features were used to develop a set of technology requirements and a customized multi-sensor measurement unit (MSMU) in collaboration with a specialized technology developer

The scope of work targeted as part of this effort was automating the surveillance of residual heat removal (RHR) pumps at Cooper Nuclear Station. However, the MSMU was evaluated and piloted on a fire protection pump, because it has the same functional nature as the RHR pump and is much more accessible (outside of the reactor building and outside radiologically controlled areas). This enabled the plant to develop confidence in the MSMU before its used on more critical equipment (such as the RHR pumps). The pilot refined the requirements of standby equipment monitoring, demonstrated their potential and

constraints, and revealed methods to reduce needed reviews and approvals to deploy similar pilots at NPPs before investing in a detailed engineering review. Additionally, this effort equipped condensate booster pumps with a commercially available vibration monitoring system in order to: benchmark it with the MSMU in terms of data, quality, use, and applications; gain practical insight on the type of functions and data fidelity provided by the readily available commercial products; evaluate the technology for use on surveillance equipment that are continuously running (i.e., not standby equipment); and as a step towards breaking the change barriers for automating monitoring for various plant equipment. The outcome from both pilots is described in this report.

ACKNOWLEDGEMENTS

The authors would like to thank the Light Water Reactor Sustainability (LWRS) program for funding this effort and Cooper Nuclear Station for collaborating on this effort as part of Cooperative Research and Development Agreement 19-CR-15 in an effort to reduce the workforce cost at Cooper Nuclear Station using online monitoring and streamlined work processes. The author would like to also thank Benchmark Electronics for collaborating on developing the MSMU and Flowserve for providing the continuous online-monitoring solution. The authors would also like to acknowledge the contribution of Randall D. Reese from Idaho National Laboratory.

CONTENTS

FIGURES

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ACRONYMS

ADC	Analog to Digital Converters
DOE	Department of Energy
EMI	electromagnetic interference
gpm	Gallons per minute
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
LWSN	Low-power Wireless Sensor Network
MIN	monitor-it-now
MSMU	multi-sensor monitoring unit
NPP	Nuclear Power Plant
O&M	operations and maintenance
RFI	radiofrequency interference
RHR	residual heat removal

AUTOMATING SURVEILLANCE ACTIVITIES IN A NUCLEAR POWER PLANT

1. INTRODUCTION

The workforce cost of operations and maintenance (O&M) in the United States nuclear power industry is mostly attributed to the manual and human-reliant nature of work activities. More than 80% of work historically performed in a United States nuclear power plant (NPP) is associated with surveillances or preventive-maintenance activities (Nuclear Energy Institute 2017). To reduce costs associated with surveillance activities, it is necessary to reduce the number of activities by eliminating them or reducing their frequency, when possible, and automating them if they are still required. Automation of surveillance activities benefits the NPP by both reducing the labor costs and providing insight and evidence to enable a reduction in frequency or elimination when possible. To support the nuclear power industry in achieving these cost saving opportunities, the Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program has been funding an Idaho National Laboratory (INL) effort to conduct research on automating the nuclear power industry's manual monitoring activities.

This work focuses on reducing the cost of surveillances. Surveillances are performed on a periodic or as-needed basis to test the functionality of important equipment in compliance with the plant's technical specifications (e.g., Nuclear Regulatory Commission 2011), and are different from preventive maintenance, defined as activities performed to prevent the condition of the equipment from degrading at a rate that is faster than the projected safe rate of degradation due to aging. Al Rashdan and St. Germain (2018) discuss preventive monitoring and its modern evolution into predictive and proactive monitoring. Automating activities plays a key role in enabling and expediting this evolution.

Surveillances are a legal requirement performed as part of the plant license. An NPP operations organization is assigned ensuring surveillances are performed per the license requirements. Due to the number of surveillances performed in a plant, this effort targeted automating such activities. This can be achieved by automating data collection, analysis, management, and visualization (Al Rashdan and St. Germain 2019 and Al Rashdan et al. 2018), provided this results in cost saving and is feasible. The focus of this effort is on data collection—specifically, on vibration monitoring of equipment—which is often performed by operations staff in an NPP. Vibration is expected in all mechanical systems and often represents a key direct indication of the health of equipment. Simple vibration-analysis methods are based on, first, establishing a baseline vibration spectrum for the machine under normal operating conditions, then detecting deviations from that baseline. More-complex vibration analysis is performed, tracking the frequency and amplitude of vibrations, to detect faults in the equipment, faults that can include rotational misalignment and unbalance, bearing wear, or resonance conditions. Detecting and classifying anomalies in the expected vibration spectrum is central to most vibration analyses. Examples of vibration analysis can be found in Becker et al. 2002, Goldman 1999, Lee 2012, and Matsushita et al. 2017.

1.1 Problem Statement

The scope of this work targeted automating surveillance of residual heat removal (RHR) pumps. An RHR pump motor is shown in Figure 1. The current process for performing the RHR vibration analysis surveillance on each of the RHR pumps is a labor-intensive manual activity. The pump is started, specific system operating conditions, such as pressure and flow rate, are established, and plant staff use probes connected to portable vibration-monitoring devices to acquire vibration measurements. These measurements are analyzed by system engineers, with special focus on the peak amplitude of the measured signal. RHR pumps are vertical, large, and tall. To reach the top of the pump, operations personnel install a ladder and use it to place probes on fixed locations. The staff remains at the location until pump-vibration measurements are obtained in a process that occurs periodically and is both time consuming and expensive.

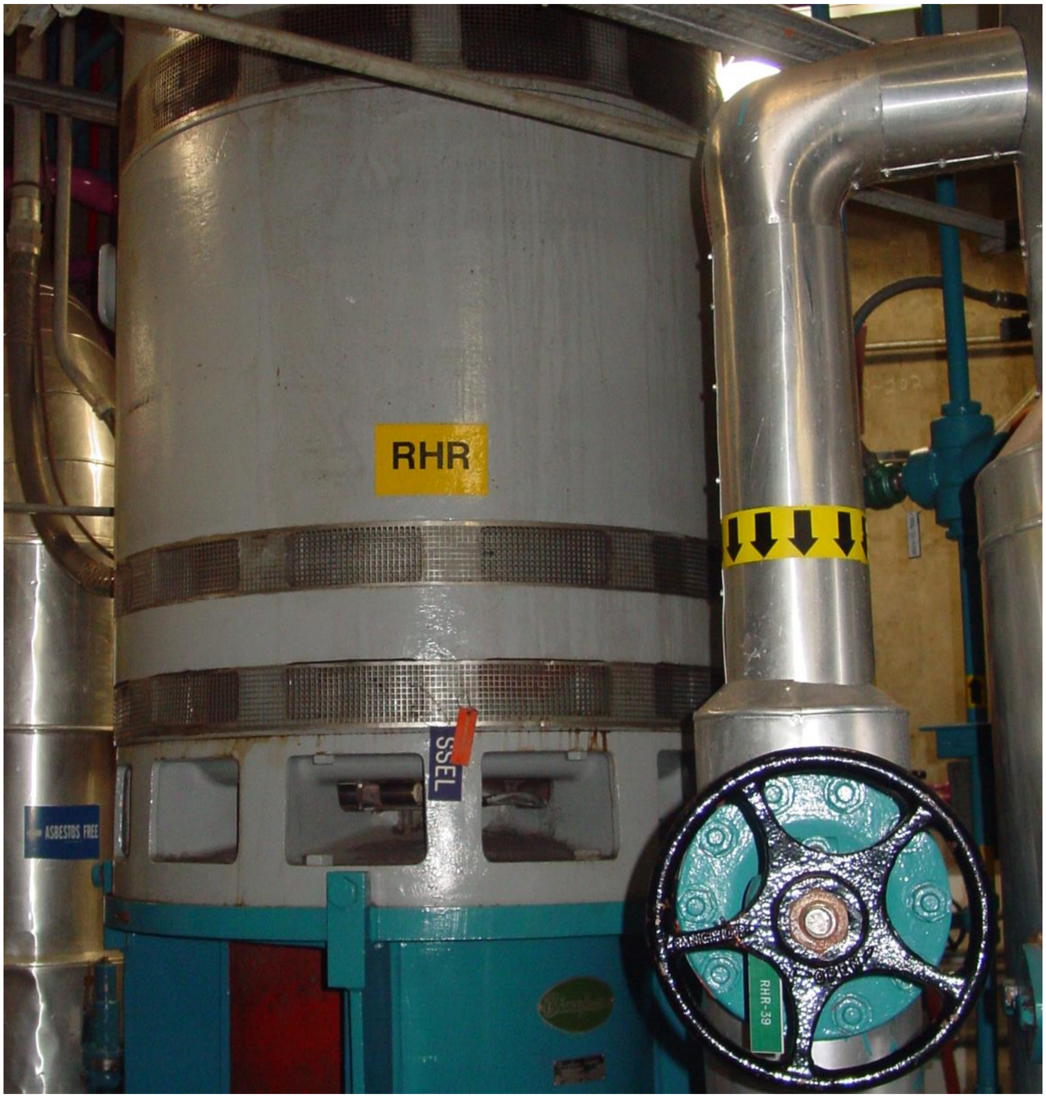


Figure 1. RHR pump picture at Cooper Nuclear Station.

This effort targets elimination of the need for staff to be present, installing the probe and measuring the vibration levels. Additionally, it explores the possibility of reducing the frequency of pump test starts by acquiring high-fidelity data. The effort was performed in collaboration with Cooper Nuclear Station and targeted their RHR pumps. A gap analysis revealed that solutions for continuous vibration monitoring of equipment are already available through several vendors. However, most surveillance equipment (like the RHR pumps themselves) are standby equipment; they do not run under normal conditions and thus lack a suitable technology to monitor them. A set of standby equipment features was deemed necessary, but not available in existing market products. For this reason, a customized multi-sensor monitoring unit (MSMU) was developed, based on research that identified standby-equipment requirements, in collaboration with a technology-development vendor. The resulting solution was piloted at Cooper Nuclear Station.

In this effort, the MSMU was evaluated for monitoring a fire protection pump that has the same functional nature as the RHR pump (see Section 2). The MSMU was developed to enable a monitor-it-now (MIN) concept (i.e. the resulting MSMU can adapt so as to be installed on any equipment that requires immediate attention with minimum configuration). The use of the MSMU to monitor fire protection pumps was deemed necessary to develop confidence in the MSMU performance before it could be piloted on highly critical equipment like the RHR pumps. The fire protection pumps were also more accessible as they are outside of the reactor building and outside radiologically controlled areas.

Additionally, this effort equipped condensate booster pumps with a commercially available vibration monitoring system in order to benchmark it with the MSMU in terms of data, quality, use, and applications, to gain practical insight on the type of functions and data fidelity provided by the readily available commercial products, to evaluate the technology for use on surveillance equipment that are continuously running equipment (i.e., not standby equipment), and as a step towards breaking the change-barriers for automating monitoring for various equipment in the plant.

The MSMU and fire protection pump pilot findings and results are described in Section 2. The condensate booster pumps pilot findings and results are described in Section 3. The conclusions from both pilots are described in Section 4.

2. SURVILLANCE OF RHR AND FIREWATER PUMPS

Surveillance on an RHR pump requires the pump to run for up to an hour. The surveillance is performed at a specific time during the pump run, when specific process conditions are met. The pump also runs for longer durations during tests of other equipment, to cool the suppression pool, and to remove shutdown decay heat. RHR surveillances are performed quarterly, but the pumps are run on a weekly basis for these other activities and can run for days during plant outage. The vibration is measured as part of the surveillance on a single axis at five locations on the pump, one on the top and four on the sides, 90 degrees apart. Temperature is also acquired at eight locations: six in the motor stator and two in the bearings. To pilot the MSMU on one of the four RHR pumps, the collaborating NPP recommended using less-critical equipment, e.g., fire protection pumps, as a transient step for use on RHR pumps. The fire protection pumps are smaller in size (RHR pumps motors extend to 12 ft high while fire protection pumps are between 3 and 6 ft wide) and include both a diesel and an electric pump. Surveillances on the electric pumps are performed quarterly at 150% load (i.e., 4500 gpm). The pump also runs once a month at lower flow rates (100 gpm) to test the sprinklers. RHR pumps are similar to the fire protection pumps in that both require periodic surveillance to satisfy plant requirements, both are standby in nature and start for the surveillance or to support other plant activities, and both are monitored for vibration at specific locations on the pump. The differences are mainly in the size (RHR pumps are tall and the sensors are installed at a significant distance apart while fire protection pumps are smaller). Other differences include the location of measurement points, the need for temperature measurement on the RHR pumps only, the orientation (RHR pumps are vertical while fire protection pumps are horizontal), and the requirement of surveillance (RHR pump surveillance is a technical specification requirement while fire protection pump surveillance is performed per the technical requirements manual). The process to pilot the MSMU on the fire protection pump required the following evaluations:

- A design modification work package was not needed, and the pilot was considered a routine work order (i.e., it did not require planning and was developed by engineering). This is because the MSMU was designed to be non-intrusive, for condition monitoring, and for temporary use.
- A radiofrequency interference/electromagnetic interference (RFI/EMI) is normally required; however, this was waived for the fire protection room because the fire pumps are outside the power block.
- The fire protection pump room had no network connection, so the MSMU had to be on a local system with no connection to the plant network. This significantly reduced the cybersecurity evaluation requirements.
- The MSMU was neither installed in or supporting a critical system function, or has connection to any critical digital asset. This also significantly reduced the cybersecurity evaluation requirements.

- Fire protection review was performed.
- Civil protection review was not needed.
- A security evaluation was not needed.
- No electrical evaluation was needed because the MSMU did not connect to plant electrical systems.
- No mechanical evaluations were needed because the MSMU did not impact the equipment's mechanical performance.
- An operations evaluation was performed, and the pump was considered out-of-service while the pilot system was installed (as a temporary step).

2.1 Technology Requirements

According to the nature of the surveillance process, and to reduce the needed evaluations described in the previous section, the MSMU requirements were defined:

- The MSMU will connect to multiple sensors. Vibration (accelerometer) and temperature sensors were deemed necessary (as they are used by the RHR pump). Each sensor should have unique identifier. Acoustic-sensor connectivity was deemed desirable for future integration into the surveillance process.
- The sensors will communicate with a fixed mobile computer (connected to a power outlet) through a battery-powered interfacing transmitter (Figure 2). The communication between the transmitter and the mobile computer will be based on an encrypted secure radio signal.
- Data will be stored in the mobile computer. The mobile computer will have enough storage for saving several data sets from multiple surveillances (i.e., no network connection will be needed).
- The transmitter will run for at least 2 years before requiring a battery replacement.
- The transmitter will start when the equipment is started and is shutdown when it stops. This ensures optimal use of the transmitter battery and reduces the acquisition and storage of data to useful data only. Vibration was suggested as the mechanism to auto-start the transmitter.
- The setup will be safe, rigid, and water resilient (using industrial rigidity standards). It should be enclosed and ready to use.
- The sensor and MSMU will be capable of adhering to a metallic unit reliably. All sensors will be magnetically attachable, with enough sticking force to sustain contact in the desired locations. This will enable a non-intrusive solution for condition monitoring and a temporary-use solution (i.e., no design modification work package will be needed).
- The sensor and MSMU will have a calibration procedure. Calibration will be performed by replacing expiring units with calibrated units while the out-of-calibration units are being calibrated.
- The data will be generated in raw form—i.e., the sensor data will not be modified—with every data unit time stamped and files labeled with the unit identifier.
- The extraction of data from the mobile computer can be performed on demand through wireless (Wi-Fi) signal or by use of external storage devices, such as a portable drive.
- The data acquisition process will be periodic (when the equipment is running), and an option for an on-demand data acquisition should be possible (for use when the surveillance conditions are met).
- The transmitter parameters, such as acquisition frequency and auto-start vibration threshold, will be remotely configurable. This will enable the MIN concept, defined earlier.
- All system elements should be time-synchronized with each other.

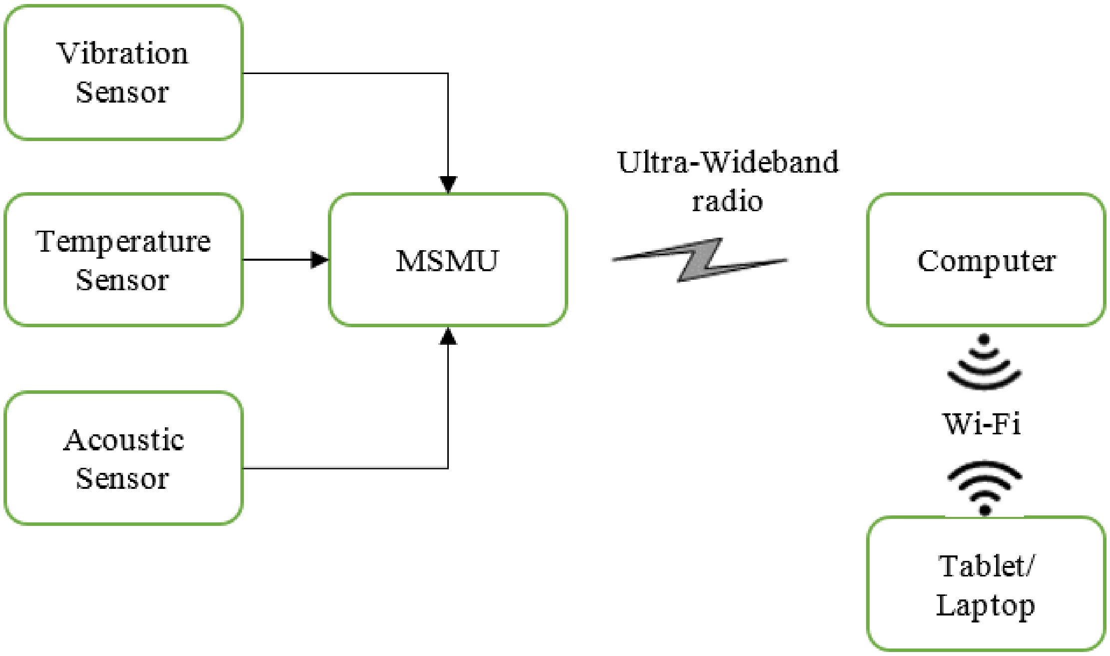


Figure 2. Conceptual layout of the MSMU setup.

2.2 Multi-sensor Monitoring Unit

The requirements of Section 2.1 were used to develop a custom system (shown in Figure 2). The development process required a hardware and software scope of development. The resulting setup is shown in Figure 3.

2.2.1 Hardware

The mobile computer (also referred to as micro-computer) is a miniature Microsoft Windows computer. It can be a computer with no screen or input/output peripherals, or a wall-mounted tablet (i.e. combine the computer and tablet/laptop functions of Figure 2 in one wall-mounted tablet). An ultra-wideband radio device is used to communicate between the computer and the MSMU to capture and store data.

The sensors used were commercially available sensors. The selected vibration sensor was a magnetically mounted accelerometer with a range of 1 to 10 KHz to cover the expected spectrum of significant vibration frequencies and match the surveillance requirements for the plant's RHR pumps. Wilcoxon 793 accelerometers (Wilcoxon 2019) were used because of their similarity to already approved sensors (Wilcoxon 736 and 736T) for online monitoring in the RHR surveillance procedure. The sensor's cable was selected to meet the length requirement (the RHR sensors are placed at approximately 10 ft apart) and be routed in a safe and secure manner. The temperature sensors were K-type thermocouples that are equipped with magnetic heads to enable non-intrusive installation on the RHR pump. For acoustics monitoring, a PCB 378C01 microphone (PCB 2019) was selected as its acoustic measurement range matched that of the vibration sensors.

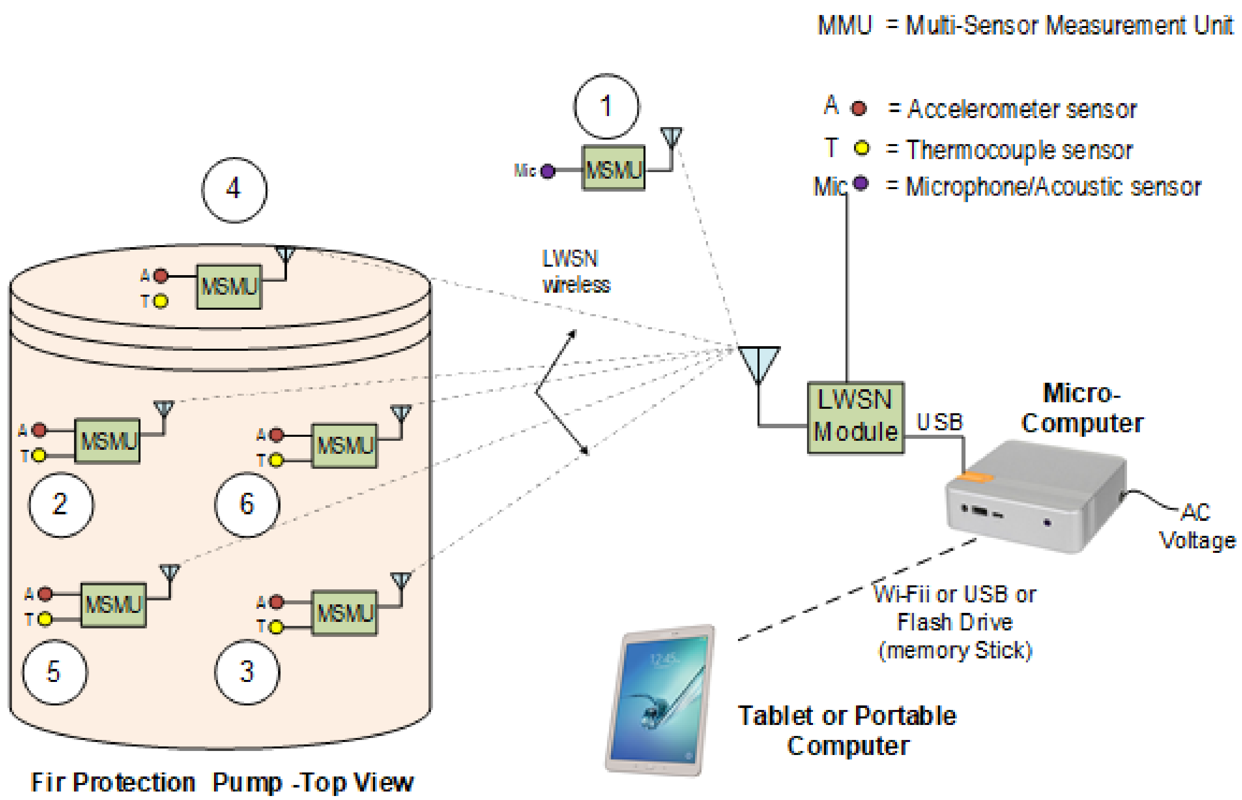


Figure 3. Implemented layout of the MSMU setup.

The MSMU layout of the transmitter components is shown in Figure 4. The roles of the components are:

- Microprocessor: communication, coordination, code execution, and memory storage
- Signal pre-processing: conditioning the sensor signals through filters
- Analog to digital converters (ADC): conversion of the analog signal to digital values
- Vibration detector: detection of pump vibration to trigger auto-start of the MSMU
- Voltage regulator: to amplify and condition the vibration-detector signal to a level that can be used by the microprocessor
- Memory Card: temporary storage of data from sensors.
- Battery: power the unit (rechargeable)
- Low-power Wireless Sensor Network (LWSN): proprietary radio technology to enable low-power and secure communication.

The end product was integrated into a customized enclosure that is equipped with magnets to enable installation on metallic surfaces or structures with minimal intrusion to the equipment (Figure 5). A picture of the resulting MSMU is shown in Figure 6.

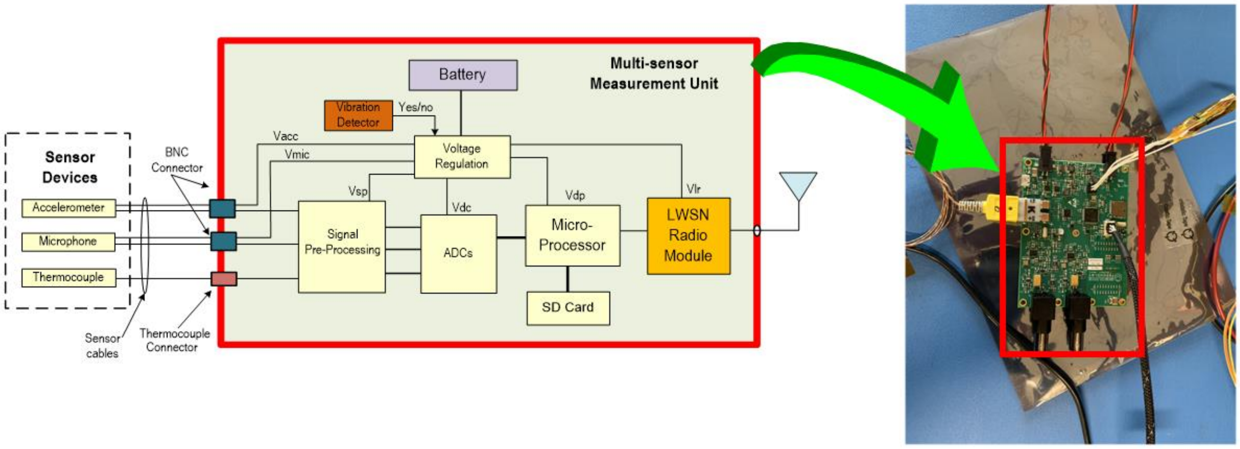
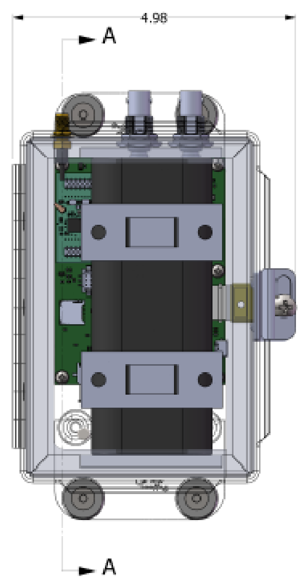


Figure 4. MSMU main components.

(a) Holder external design showing the magnets



(b) Holder internal design showing the internal parts.

Figure 5. Design of the MSMU enclosure.

Figure 6. MSMU electronics board and battery (in black, mounted to the case).

2.2.2 Software

The software developed for the MSMU was split into key parts representing required tasks:

- Power management, including on/off triggers and the auto-start trigger
- Execute tasks, respond to commands, transfer data, acquire data
- Prioritize tasks (i.e., commands, wireless transfer, data acquisition).

Power management is driven by a simple check on the onboard vibration sensor. Once vibration is detected for a certain period of time, the device starts (left part of Figure 7). The MSMU then enters into a loop state in which it periodically checks for commands coming in from the mobile computer. If no commands are received, it goes back to sleep for a set period of time (right part of Figure 7). This enables an optimized use of the battery to achieve a minimum of 2-years battery life. If a command is received, it is processed. If the command requests an update of data, they are sent wirelessly through the process described in Figure 8. The wireless data-transfer process is started by preparing the data for transfer, enabling the radio to transmit the data, then transferring the data to the radio channel. For capturing the measurements from the sensors, the data-acquisition process is performed (Figure 9). The data-acquisition process is started by preparing the storage media and powering up the sensors' power. This is followed by a series of three processes, one for each type of sensor (temperature, vibration, and acoustic). For each of these sensors, the developed software will acquire the time from the mobile computer to timestamp data, start the sensor ports communication, and measure and store the value. Once all data are acquired, the unit will disable all communication ports and turn off their power supply to save power.

The communication between the MSMU and the mobile computer is based on two modes (Figure 10). The first mode starts when the pump runs. In this scenario, data are acquired once every 10 minutes for 2 hours before switching to one measurement every hour. This is to accommodate scenarios in which the pump runs for long periods to support other activities, and data are not needed for the surveillance. The second communication mode is a command mode. This mode is triggered by a user (the operator in this case) requesting data acquisition. This is ideal for surveillance applications because surveillance measurements are taken at specific times when certain process conditions are met.

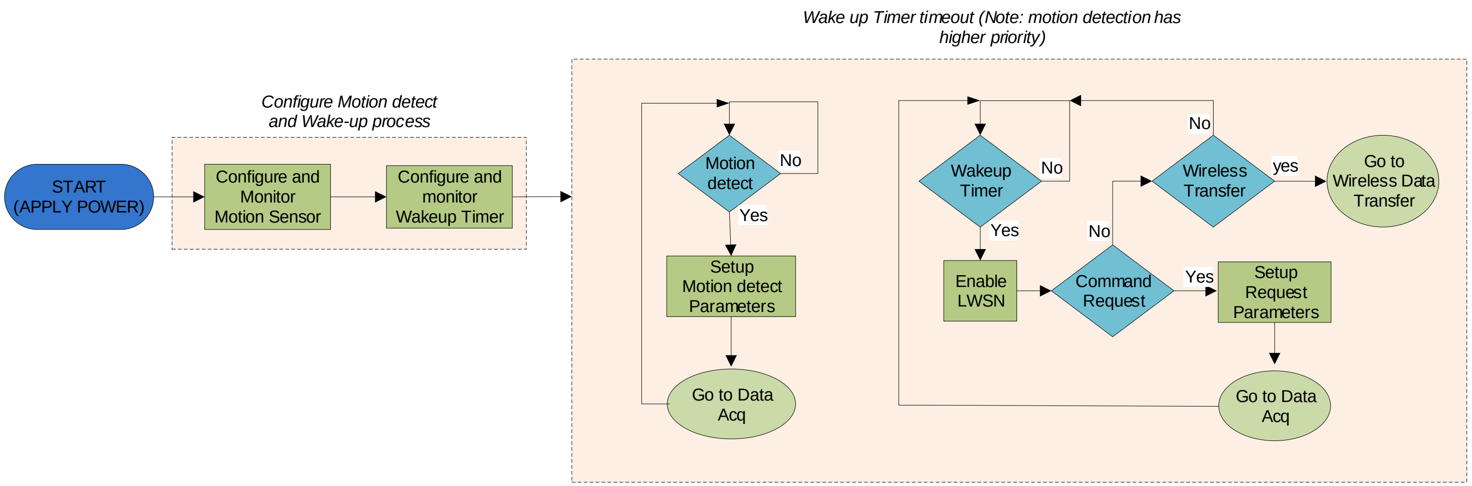


Figure 7. Monitoring motion and sleep-timer setup flow chart.

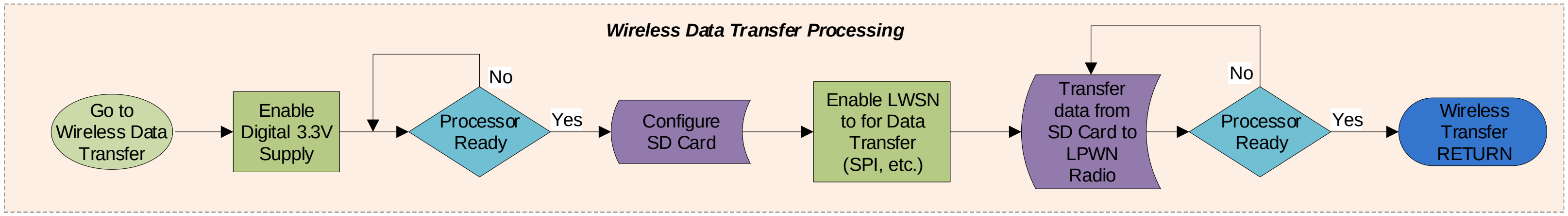


Figure 8. Wireless data-transfer flow chart.

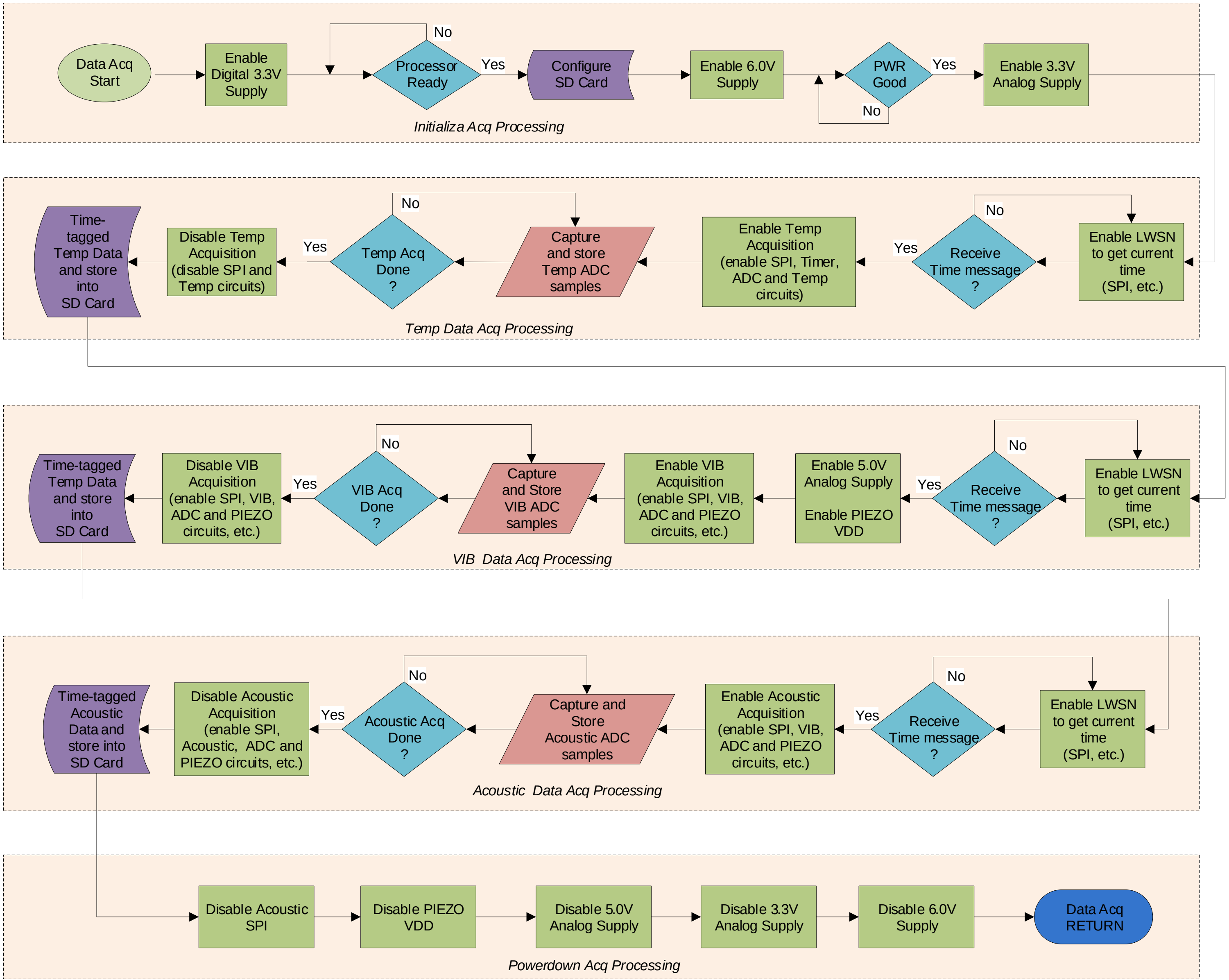


Figure 9. Data-acquisition process flow chart.

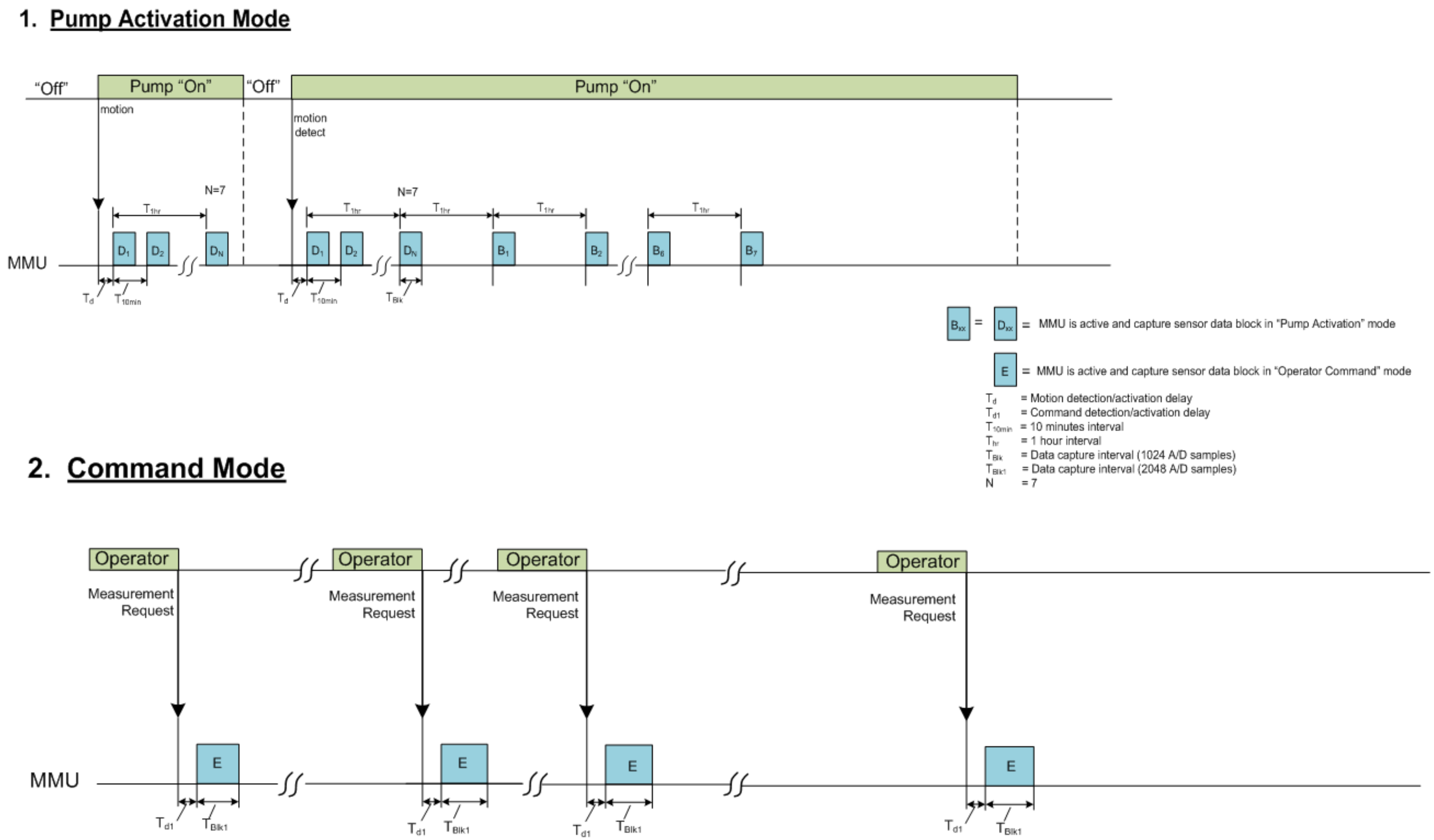


Figure 10. Communication modes with the MSMU.

2.3 Pilot and Results

The MSMU setup was evaluated at the technology development center of the collaborating vendor prior to the pilot deployment at the NPP. Figure 11 demonstrates the magnetic mounting capability of the MSMU and the sensors on metallic surfaces of an equipment that is vibrating. A detailed system critical-frequency identification was not performed to determine the amount of force exerted on the magnets and whether it would be sufficient to move or detach the MSMU. This is because the sensor location is the critical element of the measurements, not the MSMU. The sensors are light in weight in comparison to the magnetic force—i.e., the sensors inertia will not be sufficient to move the sensor.

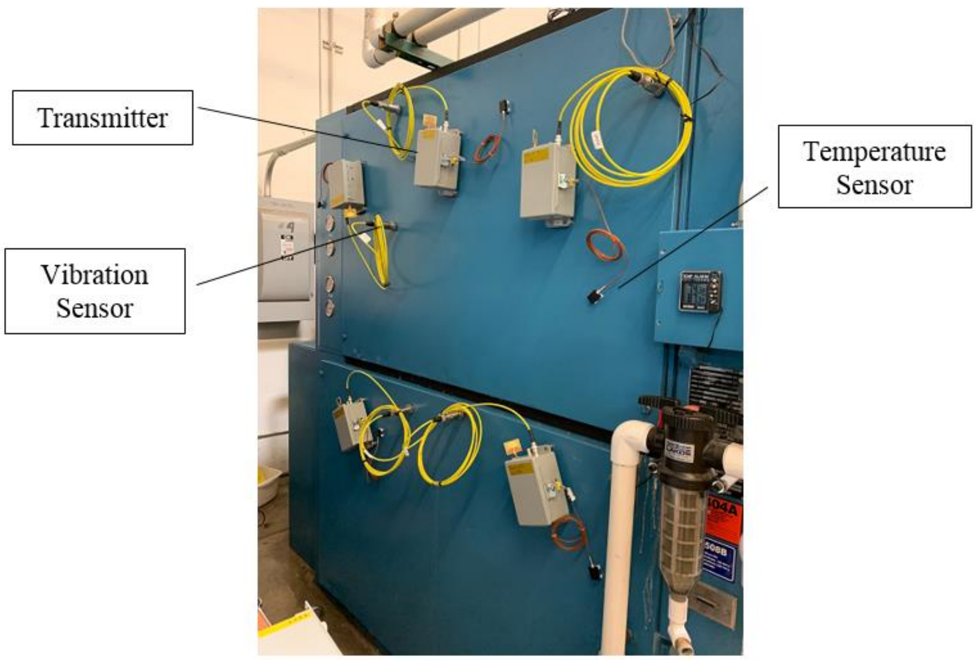


Figure 11. In-factory testing of the MSMU.

The MSMU was piloted at the collaborating NPP in August 2019. It was installed on a fire protection pump prior to a scheduled surveillance (Figure 12). The presence of a jockey pump near the fire protection pump was immediately found to cause false auto-start trigger, which emphasized the need for a configurable auto-start trigger threshold. As with RHR pumps, fire protection pumps require five points of vibration measurement. However, temperature measurements were not required for the fire protection surveillance (unlike the RHR pumps). The location of these sensors on the pump is shown in Figure 3 (using a circle with the sensor index). The same index is used to present the time-basis results for vibration data in Figure 13. The frequency domain results are shown in Figure 14 using Fourier transfer analysis. These values demonstrate that each sensor location generated a profile with unique peaks. The highest frequency for each can easily be extracted from these values. Figure 14 shows that Sensors 2 and 5 of Figure 3 resulted in higher vibration magnitudes than the rest. The developed profiles introduce much more insight as each frequency peak results from specific parts of the equipment. The values captured were in Volt. Sensor sensitivity can be used to convert these values to acceleration, which is a measure of vibration.

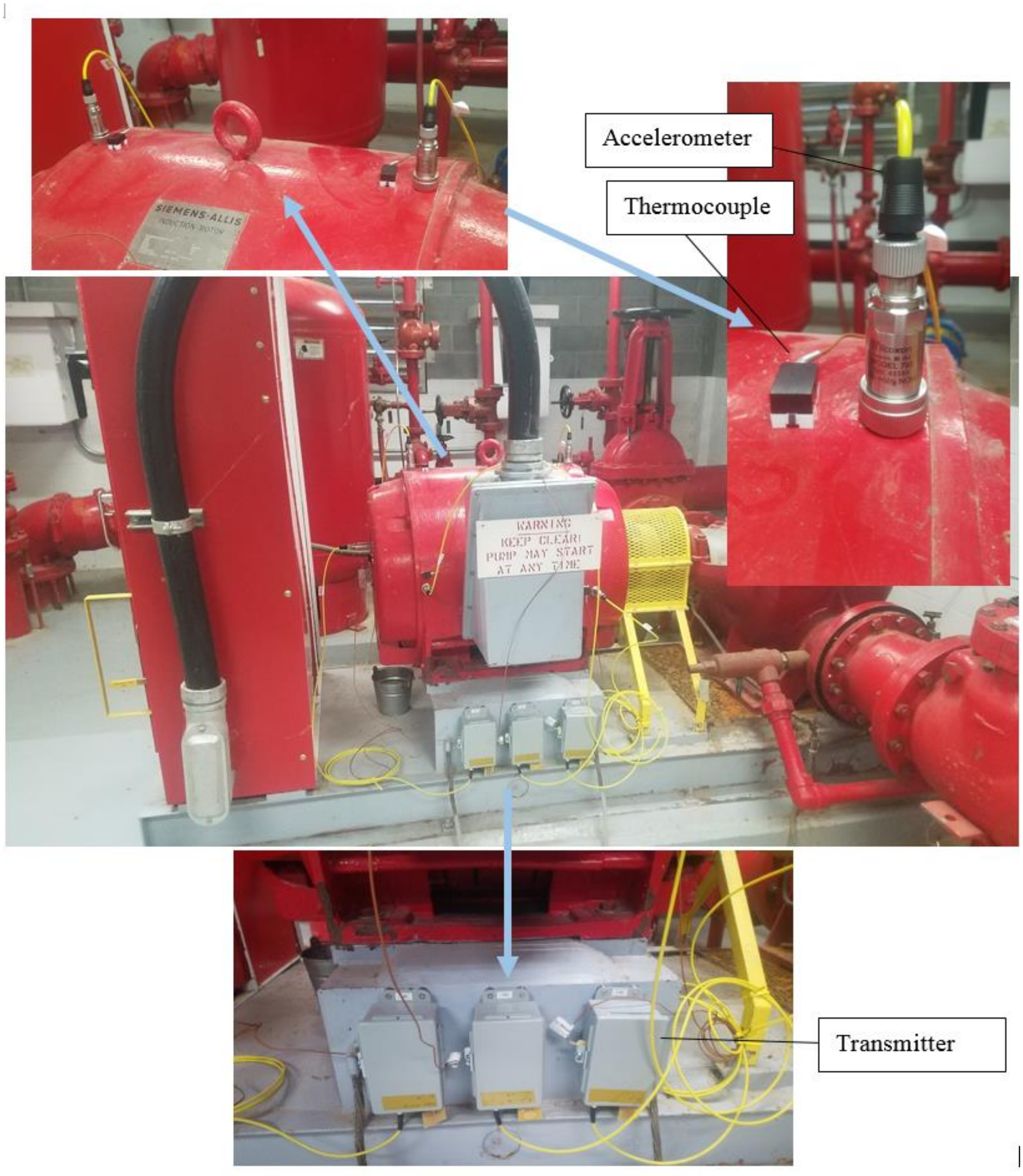


Figure 12. Vibration and temperature sensors and MSMU installation on the fire protection pump.

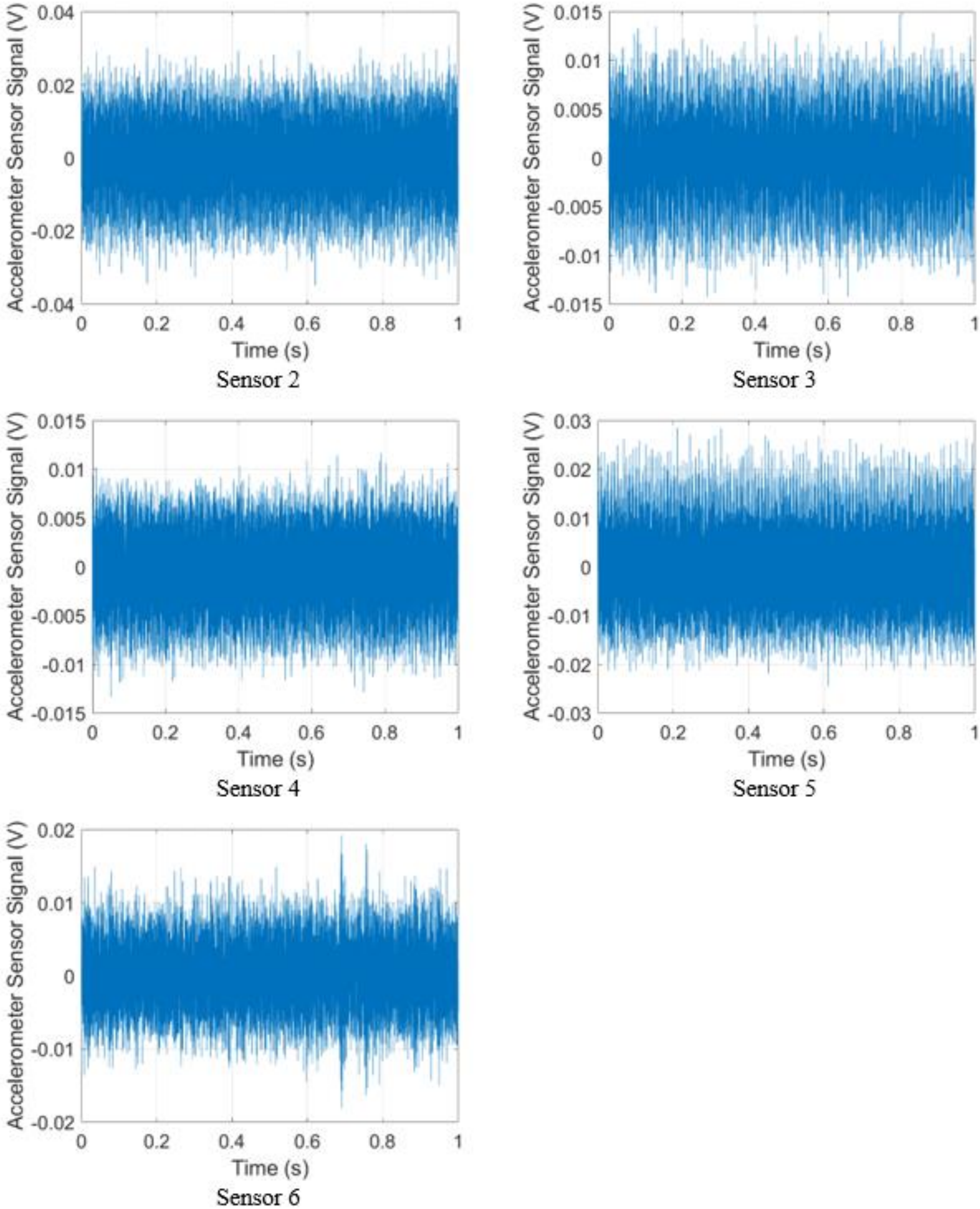


Figure 13. Vibration measured profiles in time domain (Sensors 2–6).

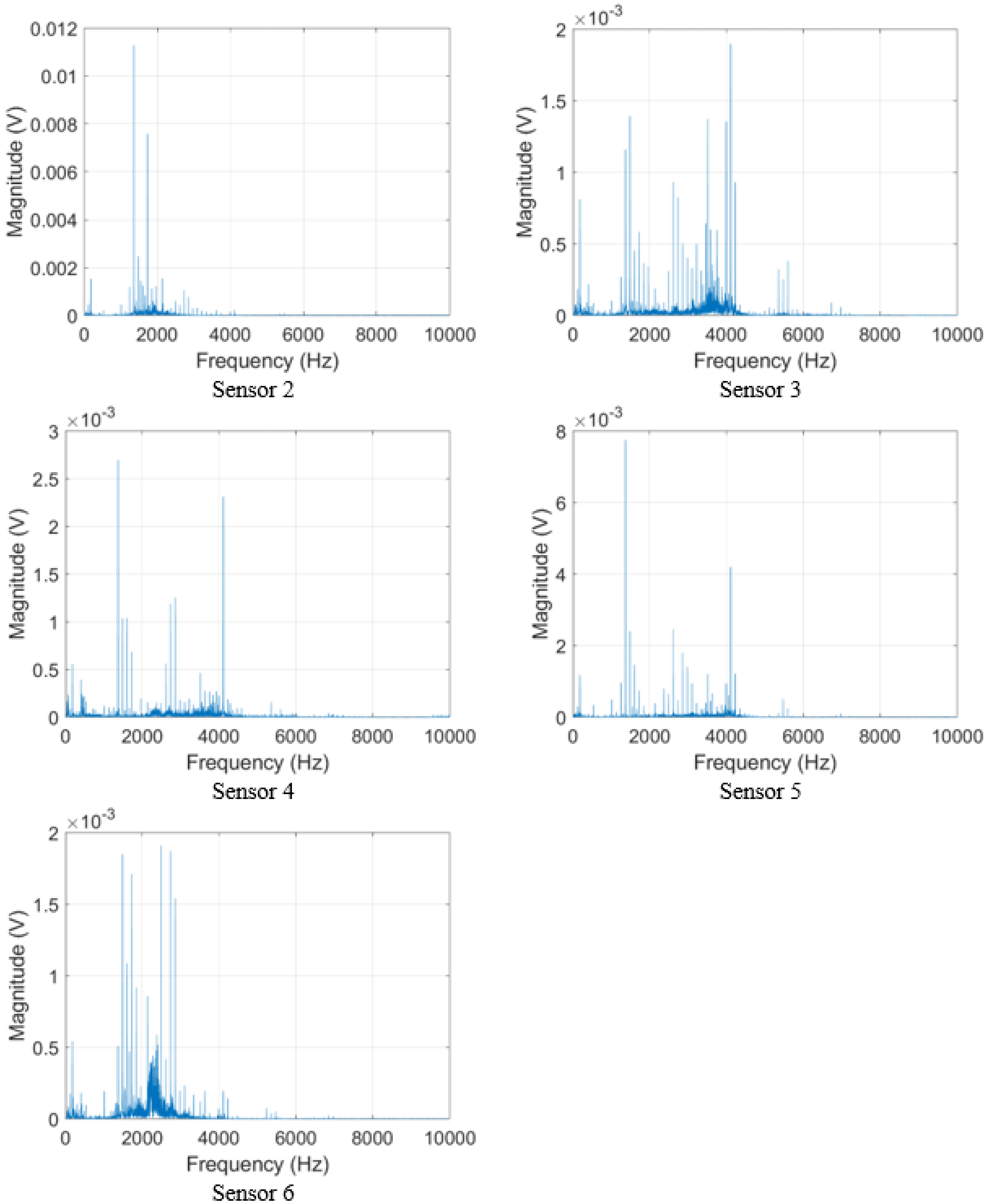


Figure 14. Vibration measured profiles in frequency domain (Sensors 2–6).

A microphone was placed at the room corner facing the pump (Figure 15). This sensor produced the time and frequency-domain profiles shown in Figure 16. These were captured to introduce acoustic-environment monitoring into the condition monitoring of the plant as a means to replace or augment operator rounds, and also to benchmark acoustics with vibration measurements, with the aim to evaluate the potential to replace the vibration sensors with contactless sensors and the feasibility of using a grid of acoustic sensors to monitor several equipment in a closed environment. The acoustic-sensor frequency domain profile in Figure 16 does not match the profile shapes of the vibration sensors. However, a common peak was observed at frequencies less than 1.5 KHz. The outcomes of this phase were mainly to 1) automate the data collection process and benchmark the high-fidelity data with peak measurements taken by handheld devices to fully replace manual processes, and 2) to enable extensive data analysis including fusion of the acoustics and vibration profiles in the next stage for better equipment diagnosis (as discussed in Loutas et al. 2011). Though the first outcome was achieved, more analysis is needed for the benchmarking of data. The second outcome is planned for the next phase of work.

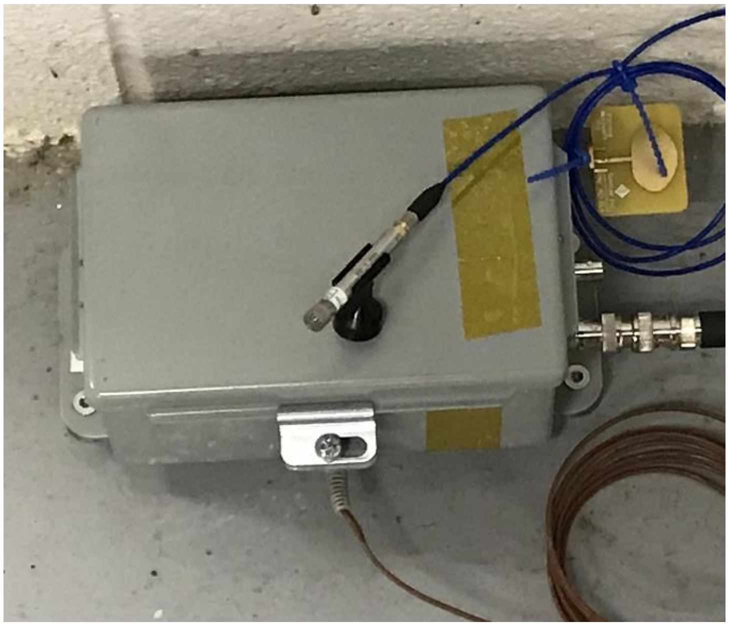
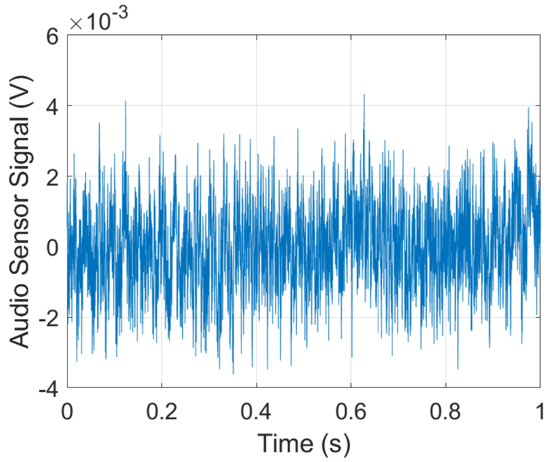
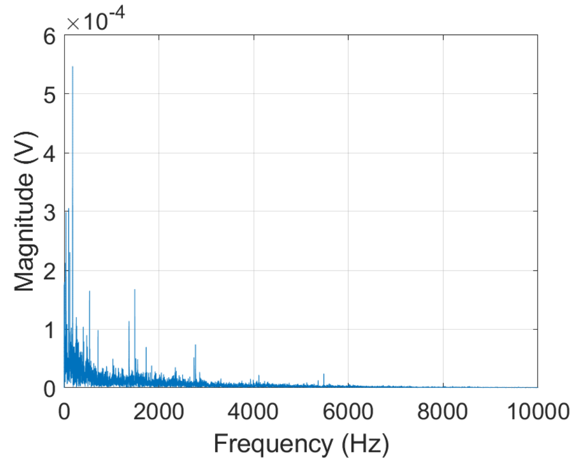


Figure 15. Acoustics MSMU installation in the fire protection room.



(a) Time domain



(b) Frequency Domain

Figure 16. Acoustic measured profile in time and frequency domains.

3. MONITORING OF CONDENSATE BOOSTER PUMPS

Online monitoring has been attracting increasing attention in various industries, due to its ability to reduce cost in preventive maintenance and provide in-depth knowledge about equipment conditions. This has resulted in several commercially available products to monitor plant equipment. As part of this work, several vendors active in the field of online monitoring were contacted. None of the contacted vendors had a solution that matches the requirements of Section 2.1; therefore, none was deemed suitable for standby equipment surveillances. Despite this finding, the researchers decided to install a commercially available product for continuous monitoring of equipment to:

- Gain practical insight on the type of functions and data fidelity provided by the existing commercial products
- Evaluate the technology for use on surveillance equipment that are continuously running equipment (i.e., not standby equipment)
- Benchmark the technology with the MSMU in terms of data, quality, use, applications
- Use the solution as a step towards breaking the change-barriers for automating monitoring for various equipment in the plant.

The condensate booster pumps of the Cooper Nuclear Station, shown in Figure 17, were selected for installing a system provided by one of the online monitoring vendors that is active in this field. The process to pilot monitoring equipment on the condensate booster pump required the following evaluations:

- A design modification work package was not needed, and the pilot was considered as just a routine work order (i.e., did not require planning and was developed by engineering). This is because the system is magnetically mounted (i.e., not intrusive) for condition monitoring and is for temporary use.
- An RFI/EMI evaluation was performed.
- The data were stored locally and not passed into the network. This significantly reduced the cybersecurity evaluation requirements.
- Fire protection review was not needed.
- Civil protection review was not needed.
- A security evaluation was not needed.
- No electrical evaluation was needed because the sensor does not connect to plant electrical systems.
- No mechanical evaluations were needed because the sensor does not impact the equipment mechanical performance.

Figure 17. Condensate booster pump at Cooper Nuclear Station.

3.1 Technology Requirements

The requirements for this system were simpler than those for the stand-by equipment:

- The transmitter will connect to multiple sensors: vibration (accelerometer) and temperature were deemed necessary.
- The transmitter will communicate with a computer (connected to a power outlet) through a battery-powered interfacing transmitter. The data could be stored locally, or the computer could be connected to a network, and the data stored on another system on the network.
- The transmitter will run for at least 2 years before requiring a battery replacement.
- The transmitter will run continuously and sample data at a defined frequency.
- The data will be generated in raw form; sensor data are not modified, with every data unit time stamped and files labeled with the unit identifier.
- The sensor and transmitter will be safe, rigid, and water resilient (using industrial rigidity standards). It should be enclosed and ready to use.
- The sensor and transmitter will be capable of adhering to metallic unit reliably. All sensors will be magnetically attachable with enough sticking force to sustain contact in the desired locations. This enables a non-intrusive sensor for condition monitoring and a solution that allows temporary use (i.e., no design modification work package would be needed).
- The sensor and transmitter will have a calibration procedure. Calibration is performed by replacing expiring units with calibrated units while the out-of-calibration units are being calibrated.
- All system elements must time-synchronized with each other.

3.2 Commercially Available Solution

Despite the presence of multiple vendors, none was found to meet all requirements. Specifically, the survey effort did not find a solution that could provide data in raw form. Another requirement that eliminated several vendors was the need to store data locally. Most of the solutions provided required access to a cloud (i.e. a remote database) to send data to tools that could analyze them. This was not permitted by the collaborating utility through this pilot. Due to time constraints and the nature of the pilot, an analysis into the data security restrictions of sending data to a cloud was not conducted. One question that was of concern was how to ensure the vendor staff accessing data are not forbidden by law from accessing the data due to export-control requirements. This might not necessarily apply to condensate booster pumps, but similar concerns could manifest if the system use were expanded to other essential plant equipment. The researchers decided to select a vendor that allowed local storage of data. However, the data-fidelity aspect was not met (i.e. raw time-domain data) to the level shown in Figure 13. Instead the solution provides the top eight peaks of the vibration measurement in the frequency domain.

The solution provided is shown in Figure 18. The sensors were IPS Wireless 103 vibration and 1000Ω platinum resistance temperature detectors with an overall output from 0–1 inch velocity root mean square and a temperature range from 0 to 185°F. The sensors selected were magnetically mounted to the equipment. The sensors could provide signal through a wire to a transmitter, shown in Figure 19 (a), or could be integrated with the transmitter in one unit (Figure 19[b]). The transmitter could communicate directly with the AC powered receiver (Figure 19[d]) or through an AC-powered repeater (Figure 19[c]). The receiver is connected to a laptop on which data are stored.

3.3 Pilot and Results

The supplied setup sensors were installed on five locations on each of three condensate booster pumps (Figure 20 to Figure 22). The communication was established, and the system ran as expected. The vendor did have a local software solution, but required an annual license fee or the presence of a compatible software to capture the data. Additionally, the vendor solution provided the ability to connect the system through TCP/IP Modbus, a common method of communication. A third-party Modbus tool was needed to capture and store data; this was not immediately available and is procured separately.

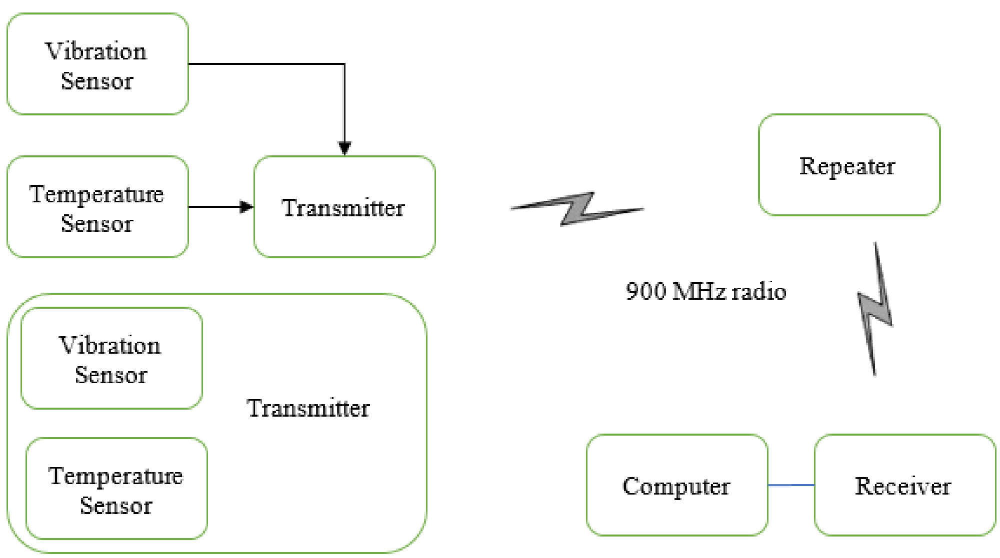


Figure 18. Continuous monitoring multi-sensor system layout.

(a) Multiport (five-port) transmitter with attached sensors

(b) Single-point transmitter (integrated sensor-transmitter unit)

(c) Repeater box

(d) Receiver box

Figure 19 The continuous monitoring solution hardware.

Figure 20. Installation of continuous monitoring vibration sensors on condensate booster pumps.

Figure 21. Installation of continuous-monitoring transmitter on condensate booster pumps.

Figure 22. Installation of continuous monitoring integrated sensor-transmitter units on a condensate booster pump.

4. CONCLUSIONS

This project researched means to automate vibration monitoring activities to meet surveillance requirements. The research highlighted a technology gap that resulted in the development of a customized MSMU. A comparison between the requirements of the monitoring system for the standby and continuously running equipment is summarized in Table 1, with the differences highlighted in grey. In summary, the surveillance monitoring for standby equipment require specific features to:

1. Start when the equipment starts and shutdown when the equipment shuts down (to preserve battery and reduce the acquisition and storage of data to useful data only) with a configurable vibration-threshold setting. The importance of this was emphasized when another pump in the fire protection room started in a periodic manner and caused enough vibration to start the MSMU. The ability to configure the vibration threshold to start the MSMU was thus a necessity.
2. Generate data in raw form. None of the continuous monitoring vendors engaged allowed access to raw data.
3. Store the data locally, which is necessary when a network is not available and reduces concerns for cybersecurity. This requirement was met with the piloted continuous monitoring solution but was not a feature in most of the considered vendor solutions.
4. Take measurements on-demand because surveillance conditions exist at certain points in equipment run time.
5. Easily configure and adapt to different types of equipment.

Additionally, the work performed for this effort provided insights on the needed reviews and approvals to deploy pilot demonstrations at NPPs before performing a detailed engineering review (Table 2).

Future work will benchmark the high-fidelity data with peak measurements taken by handheld devices to fully replace the manual process. Also, future work will benchmark acoustic monitoring with vibration measurements, aiming to evaluate the potential to replace vibration sensors with contactless sensors and to evaluate the feasibility of using a grid of acoustic sensors to monitor several pieces of equipment in a closed environment (as opposed to a sensor for each). Future work will also evaluate methods of data fusion of vibration, temperature, and acoustics sensors for improved condition decision making.

Table 1. Standby equipment vs continuously running equipment requirements.

Equipment Feature	Standby Equipment	Continuously Running Equipment
Auto-start sensing	Yes	No
Battery Replacement	2 years minimum	2 years minimum
Calibration procedure	Yes	Yes
Capable of adhering to metallic unit reliably.	Magnetically mounted or fixed	Magnetically mounted or fixed
Customizable	Yes	No
Connect to multiple sensors	Yes	Yes
Continuously capturing data	No (to optimize battery and data use)	Yes
Communicate securely with a computer/device for storage	Yes	Yes
Data storage locally	Yes	Yes
Industry rigidity standards	Yes	Yes
On-demand data acquisition	Yes	No
Raw data form	Yes	Yes (usually not provided by vendors)
Time synchronized	Yes	Yes

Table 2. Fire protection pump and condensate booster pump review needs for the pilot.

Review	Fire Protection Pump	Condensate Booster Pump
RFI	Not needed	Yes
EMI	Not needed	Yes
Cybersecurity	Required but mostly not applicable (system is isolated and neither installed in or supporting a critical system function, or has connection to any critical digital asset)	Required but mostly not applicable (system is isolated and neither installed in or supporting a critical system function, or has connection to any critical digital asset)
Design modification work package	Not needed (not intrusive, for condition monitoring, and for temporary use)	Not needed (not intrusive, for condition monitoring, and for temporary use)
Fire protection	Yes	Not needed
Civil	Not needed	Not needed
Security	Not needed	Not needed
Electrical Evaluation	Not needed	Not needed
Mechanical	Not needed	Not needed

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