The Possibility of Wireless Sensor Networks for Industrial Pipe Rack Safety Monitoring

Jieun Jung
IoT Convergence Research Center
Korea Electronics Technology Institute
jejung@keti.re.kr

Byunghun Song
IoT Convergence Research Center
Korea Electronics Technology Institute
bhsong@keti.re.kr

Abstract

Previously Wireless Sensor Networks (WSN) was not the preferred choice for offshore monitoring in the oil and gas sector for many reasons such as reliability and security concern. Today, much has changed. Advances in reliability, security, and affordability within the constraints of frequency allocation now enable organizations to take full advantage of WSN for challenging industrial environments. In this paper, we propose an industrial pipe rack safety monitoring system based on WSN, which uses the ISA100.11a standard for industrial field instruments. We designed and implemented the system, which consists of field nodes, field network gateways, and a control server, and evaluated its operation at large-scale petrochemical plants. The data obtained from WSN-based safety sensors show that the proposed system can continuously monitor and evaluate the structural stability of the pipe rack, and provide risk management guidelines based on real-world measurements.

1. Introduction

Over the years, many pipe racks have been built to support pipelines which contain dangerous materials such as gasoline and natural gas, with the passage of time, and they have been wearing out. Because these pipe racks are embedded in the hearts of industrial complexes, when accidents happen, high social and economic losses are more likely to ensure [1]. In most cases, to transfer material efficiently, pipe racks are exposed to the outside so that safety measures have to be taken 24 hours a day.

To guarantee the safety of a pipe rack structure, the installed pipe rack should be inspected for safety, followed by reasonable repair or strengthening measures if necessary. Regular inspections and nondestructive safety check-ups are conducted for the sake of effective maintenance, but these procedures alone cannot prevent unexpected accidents. To guarantee the usability and structural stability of pipe racks, a continuous monitoring technique based on nondestructive means should be employed so that an evaluation of the performance and soundness of the pipe system is possible [2].

The evaluation techniques of the structural stability of pipe racks have evolved greatly with the development of essential technologies such as sensors [3], measurements [4], and information technologies [5]. In particular, smart sensors such as optical fiber [6] and piezoelectric sensors [7] have paved the way for evaluating the stability of the pipe-rack structures. Efforts to reduce the installation cost of the sensors and the maintenance expense of the pipe-racks are leading to the development of new sensors with the ability to simultaneously analyze the data obtained from the sensors. In addition, new research is being conducted to develop a WSN technique that detects the abnormalities of pipe racks using real-time analysis and control of the measured data.

Recently, industrial plants have applied WSN technology, which has been used for the control and monitoring of logistics management, water quality, indoor temperature and humidity, and so on, in their facilities. However, the application of current WSN technology in large, complex industrial plants still lacks reliability and security. In addition, because of a limitation of standardized technology for interoperability between existing equipment and related communication devices, the currently-used WSN suffers from its practical application [8].

For many issues, WSN have not been the preferred choice for offshore monitoring in the industrial area. Despite their reluctance, engineers and researchers have persevered in their interest in applying reliable, standardized wireless communication technology, and in their attempts to replace the wired systems, have faced difficulties with maintenance and management. As a result of industry demand for wireless technology, new communication standards for Wireless HART [9]...
and ISA 100 [10], in addition to Wireless Fieldbus and Modbus have emerged. With the recent development of highly reliable wireless communication standards, industrial plants have attempted to construct a WSN-based monitoring system while reducing overall administrative and operating costs. Industrial WSN technology using IEEE 802.15.4 standards has been the focus of attention as the next generation of WSN technology applicable to the field of industrial plants requiring high reliability and security. Moreover, using the WSN-based monitoring system, we can constantly monitor and evaluate the conditions of facilities and provide more efficient risk management with ample reliable and accurate field data [11].

Thus, the present study suggests a WSN-based safety monitoring system using highly flexible and reliable industry-standard communication standards for the pipe-rack structures largely distributed in industrial plants. The WSN safety monitoring system proposed in this paper will contribute to the improvement of detection technology, the automation of management, and the increase in the efficiency of the automated system.

The paper is structured as follows. In Section 2, we present the motivation to evaluate the structural stability of exposed pipe racks. In Section 3, we propose a WSN-based safety monitoring system for industrial pipe racks in detail. Section 4 presents the test-bed constructed to evaluate the system, and analyses the monitoring data. Section 5 concludes the paper.

2. Motivation

Numerous plants currently in operation are experiencing serious deterioration of pipe racks as shown in Figure 1(a), and excessive extension, as shown in Figure 1(b), threaten their structural stability. What they require is a method of determining the optimal time to repair and upgrade the structures [12]. In addition, the industrial complex is continuously expanding the number of pipe racks directly responsible for the safety of the pipelines. Thus, without an accurate evaluation of the current condition of operating structures, damage to pipe racks (i.e., the aging, deterioration and extension of pipe racks) will lead to serious accidents.

Industrial plants are subject to various administrative regulations, and they have no established integrated management system that can monitor or promote information sharing regarding the status of equipment safety between related companies and organizations. To reduce overall administrative and operating costs, these entities require the development and application of technology for the safety monitoring and evaluation of industrial plant facilities.

Figure 1. (a) A case of aging and corrosion of pipe racks, (b) excessive extension of pipe racks

However, the only wired solution does not meet all of the industry requirements because there is area network access is still not possible due to the geographical location. Although a high-speed internet network has been rapidly expanded throughout the country, some facilities located in difficult-to-reach sites or requiring cable that is difficult to construct needs a wireless solution.

In consideration of the limitations, we propose a WSN-based safety monitoring system of pipe-rack structures at a current large-scale petrochemical plant located at the Yeosu National Industrial Complex in Korea. We performed operating tests on the system for almost 15 months from March 2012 to June 2013. The advantage of the system developed in this study is its capabilities of detecting and diagnosing abnormalities in pipe racks before they pose a risk. Detailed technology and installation of the integrated safety monitoring system for the pipe racks will be explained in the following sections.

3. WSN-based Industrial Pipe Rack Safety Monitoring

3.1. Field Devices

One of our research goals is to construct a marketable WSN prototype of a pipe-rack safety monitoring system. We develop the WSN system, which supports an industrial WSN standard, called ISA100.11a [10], for reliable and secure data transmission. The architecture of the ISA100.11a system can combine a variety of functional entities such as a field node, field network gateway, backbone router, and system manager, and thus provide flexibility from various network topologies according to the requirements of the application.

In contrast to automation and monitoring applications originating from enterprise and home environments, those of industrial plants have specific requirements such as strict delay requirements,
To fulfill these requirements, we developed an ISA100.11a standard-based network system composed of a field node and a field network gateway, as shown in Figure 2.

The field node platform, specially designed to meet the requirement of the ISA100.11a standard, is equipped with an RF amplifier and antenna diversity functions to eliminate radio fading, and high-precision RTC for the Time Division Multiple Access (TDMA) operation. The field node also consists of a small IC chip in which detection, signal processing algorithm, and data transmission modules coexist as built-in units. The field node, which calls signals and performs data acquisition and processes itself, is loaded with a low-power measuring device, a microprocessor, and an RF transmitter. The microprocessor controls all functions, including signal measurements, and executes the analysis algorithm. The measured signals and the analyzed results are transmitted to a field network gateway or remote server through RF transmission module IEEE 802.15.4 PHY.

ARM Coretex-M3 [13] is used as the main processor, and the RF transceiver consists of a four-wire SPI interface. Monitoring of the data and movement of each platform is performed through RS-232 communication. The interface is made for JTAG and SPI, which are used for programming the board of the field node. The MFC interface includes a two-pin connector designed to act as an A/D transformation port and execute GPIO through the ATmega128 setting so that the MFC interface can be used as an all-purpose interface. The Silicon Serial Number IC used for the ID of each board reads data only through a 1-wire interface.

The field network gateway is responsible for application layer connectivity between the field nodes and the plant network. It also allows interaction between nodes utilizing ISA100.11a protocols and system non-ISA100.11a such as legacy or foreign protocols. The gateway operates on a Linux-based platform, and it connects WSN mesh networks to the Internet via Wi-Fi/Ethernet interface.

3.2. Transmission Protocol

For the wireless transmission, we adapted the ISA100.11a network protocol. At the physical layer, the field network gateway and all the field nodes use an IEEE 802.15.4-compatible radio transceiver that uses the 2.4 GHz ISM band at a data transmission rate of 250 Kbits/s. The field network gateway has both a wired and a wireless connection. The wireless connection is used to communicate with the field nodes while the wired connection of the gateway is used to communicate with the wired legacy devices and servers.

The Medium Access Control (MAC) layer is based on the TDMA operation and channel hopping for reliable data transmission. The sensing data are transmitted in a series of timeslots, and each slot has a fixed number of packets to transfer, called the “window size.” For example, if we have 100 packets and a window size of 5, the 100 packets are divided into 20 timeslots. Only one acknowledgment is transmitted back to the sender, and lost packets in each round are retransmitted by looking at the lost packet information in the acknowledgment. Once the receiver has acquired every packet in the current timeslot, the sender and receiver can move on to the next timeslot. This prevents any packet collisions in the networks.

Moreover, the network protocol utilizes a channel hopping technique to minimize interference on the network in Figure 3. In this system, we define six channels for hopping and set a specific hopping sequence as a system parameter, so that the devices are able to change their frequency by a timeslot unit when interference occurs. The transmission protocol mentioned above is designed to meet both reliable data communication and power efficiency requirements.
4. Evaluation

To evaluate the performance of the proposed system, we chose a specific pipe rack structure called an over-bridge rack as a test model. As is widely known, the over-bridge rack piled up with multi-layered racks is cost-effective, but vulnerable to structural instability. In this section, we apply our system to resolve the practical concerns of implementation. We also analyze its current condition and suggest a management guideline based on real-world measurement.

4.1. Test-bed Setups

To monitor and detect the physical vibration and deformation of pipe-rack structures, this study installed a WSN-based accelerometer, inclinometer, strain gauge, and temperature sensor with field nodes, as shown in Figure 4. Table 1 summarizes the information pertaining to the installation and the measurement of sensors. The field node that receives signals from the sensors transmits the data to a main system through the gateway instrument.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>#</th>
<th>Frequency</th>
<th>Comm.</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>6</td>
<td>512/1sec</td>
<td>Wibro</td>
<td>Top, Bottom</td>
</tr>
<tr>
<td>Strain gauge</td>
<td>1</td>
<td>1/1min</td>
<td>ISA</td>
<td>Bottom</td>
</tr>
<tr>
<td>Inclinometer</td>
<td>1</td>
<td>1/1min</td>
<td>ISA</td>
<td>Bottom</td>
</tr>
<tr>
<td>Temperature</td>
<td>1</td>
<td>1/1min</td>
<td>ISA</td>
<td>Bottom</td>
</tr>
</tbody>
</table>

Figure 4. Location of the sensors installed in the pipe racks

To be specific, we installed six accelerometers at the top and bottom of the pipe rack to monitor operational and abnormal vibration in the structure. The accelerometers measure a range of -0.5g to 0.5g and represent an electrical signal of 10mV per 1g acceleration. It is especially transmitted through Wibro due to high sampling frequency. At the bottom, we monitored variation in the strain, which represents the stress condition of the structure using a strain gauge, which exhibited the highest level of stresses in the structural analysis. In addition, to measure changes in the angle of the structure, we installed an inclinometer at the bottom. The inclinometer sensor can measure tilt angles in two directions at the same time. Then we installed a temperature sensor at the bottom to check heat strain.

4.2. Result Data Analysis

From the WSN-based sensors, we monitored ambient variations in the pipe-rack structure during the operation of the industrial equipment. Changes in the strain gauge, slope, temperature, and vibration of the structure were measured using the strain gauge, inclinometer, temperature sensor, and accelerometer installed at the top and bottom of the structure, respectively, at intervals of 60 seconds. Figures 5 (a), (b), (c), and (d) present the example of variations in the strain, tilt, temperature, and average vibration measurements for the selected three days. As shown in Figure 5 (a), (b), and (c), the values of both strain and tilt angles increased as the plant began operation and the daily temperature rose. In particular, the highest values occurred around 3 P.M., when the daily temperature was the highest. Figure 5 (d) exhibits slightly larger values between around 8 A.M. and 8 P.M. when the plant is operating, and overall vibration affecting the structure is quite low. The trends of daily changes in the values were similar on other days.

Figure 5. Examples of variations in (a) strain values, (b) tilt angles, (c) temperature, (d) vibration
As a result of the experiment over the long term, we also found a threshold value used for the structure maintenance. When a certain structure is built up, a designed value (DV) applying all of the loads is pre-calculated. According to equation (1), a management span (MS) is firstly determined, and then the administrator can define a threshold (TS) in stages. For example, in this experiment, we assigned three system parameters (%) in equation (2) with a value of 60%, 80%, and 90% respectively to provide a 3-stage guideline. Figure 6 exhibits the 3-stage thresholds.

\[ \text{MS} = \frac{\text{DV} - |\max(\text{data}) - \min(\text{data})|}{\text{MS} \times \text{System parameter}} \]  
\[ \text{TS}_i = \text{DV} - (\text{MS} \times \text{System parameter}_i) \]  

According to the threshold, more practical management guidelines such as a stability index and alarm messages shown in Table 2 can be provided. This will also help operators in the plants to simply understand the condition of facilities and make an informed decision.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Stability Index</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS₁ &lt; Range of data &lt; TS₂</td>
<td>8 ~ 10</td>
<td>Normal</td>
</tr>
<tr>
<td>TS₂ &lt; Range of data &lt; TS₃</td>
<td>4 ~ 7</td>
<td>Warning</td>
</tr>
<tr>
<td>TS₃ &lt; Range of data</td>
<td>1 ~ 3</td>
<td>Emergency</td>
</tr>
</tbody>
</table>

Figure 6. Example of setting threshold values

5. Conclusion

In this paper, we introduced a WSN-based safety monitoring system applicable to industrial plants that require high reliability and security. The main goal of the system is to maximize maintenance efficiency and minimize the possibility of accidents. For reliable and secure requirements in data acquisition and transmission, this study developed an ISA100.11a standard-based network system composed of a field node and field network gateway. The proposed system was implemented at a large industrial complex to detect abnormal conditions of the structure before they pose a risk. The obtained data from the system showed ambient conditions and variations in the pipe-rack structure triggered by environmental and working conditions. The statistical results and detailed analyses provided in the system will help the operators in the plant to manage its operating condition and make an informed decision.

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6. Reference

Monitoring, International Conference on Information Processing in Sensor Networks RealWIN Workshop, March 2011
