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Research Article

Industrial Pipe-Rack Health Monitoring System Based on Reliable-Secure Wireless Sensor Network

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Energy and power industrial plants need to improve the health monitoring systems of their facilities, particularly high-risk facilities. This need has created a demand for wireless sensor networks (WSNs). However, for the application of WSN technology in large-scale industrial plants, issues of reliability and security should be fully addressed, and an industrial sensor network standard that mitigatesthe problem of compatibility with legacy equipment and systems should be established. To fulfill these requirements, this study proposes a health monitoring system of the pipe-rack structure using ISA100.11a standard. We constructed the system, which consists of field nodes, a network gateway, and a control server, and tested its operation at a large-scale petrochemical plant. The data obtained from WSN-based sensors show that the proposed system can constantly monitor and evaluate the condition of the pipe-rack structure and provide more efficient risk management.

1. Introduction

Energy and power plants, although a critical element of a national infrastructure, are also high-risk facilities. Accidents that occur in industrial plants cause significant loss of life and property, which threatens national economies. From the gas explosion accident at the Union Carbide pesticide plant in Bhopal, India to the recent massive explosion during the operation of a coal-fired plant in Connecticut, we know that accidents at industrial plants often have catastrophic results in the form of property damage and fatalities. Thus, to secure the safety of the industrial plant facilities, we should construct a health monitoring system of pipe-rack structures, which typically support cables and pipes conveying resource material between equipment, with reliable and secure detection and communication technologies. In addition, the pipe-rack structures require a continuous monitoring technique that can evaluate the performance and the soundness of the structure [1].

Structural health monitoring system has gradually become a technique for ensuring the health and the safety of civil infrastructures. Furthermore, some recent advances in wireless sensor technologies have greatly explored wireless sensors for structural monitoring of civil engineering structures, such as long-span bridges and high-rise buildings [2, 3]. Network monitoring systems composed of low-cost wireless sensors were successfully installed to monitor the dynamic response of the bridge structures [4, 5]. In particular, high-rise buildings have used the global positioning system (GPS), capable of wirelessly autonomous operation and straight-line independence between target points, for the structural health monitoring of build structures [6–8]. In addition, a modular wireless micro electromechanical inclination sensor system was developed to provide structural health monitoring of large-scale hook structures [9]. Such installations allow researchers to quantify the accuracy and robustness of wireless monitoring systems within the complex environment encountered in the field.

The evaluation techniques of the structural stability of pipe racks have also evolved greatly with the development of essential technologies such as sensors [10], measurements [11], and information technologies [12]. In particular, smart sensors such as optical fiber [13] and piezoelectric sensors [14] have paved the way for evaluating the stability of the

Figure 1: A case of the aging and corrosion of pipe racks.

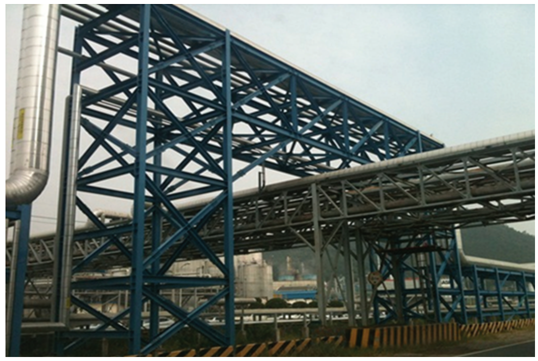


Figure 2: A case of the excessive extension of pipe racks.

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 the real-time analysis and control of the measured data.

Recently, industrial plants have applied wireless sensor network (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 lacks reliability and security. In addition, because of the limitation of standardized technology for interoperability between existing equipment and related communication devices, the currently used WSN suffers from its practical application [15]. However, high-risk facilities such as energy and power plants emphasize a reliable health monitoring system based on wireless sensor technology.

In the past, industrial plants were reluctant to apply wireless technology because of safety and security issues. Despite their reluctance, engineers and researchers have persevered in their interest in applying reliable standardized wireless communication technology, and they have attempted to replace the wired systems they have faced difficulties with their maintenance and management. As a result of the industry demand for wireless technology, new communication standards for Wireless HART [16] and ISA 100 [17] in addition to Wireless Fieldbus and Modbus have emerged. Since ISA 100 places far greater emphasis on connectivity between devices than Wireless HART, it ensures compatibility among field devices, field routers, gateways, and system managers based on the 6 LowPAN frame structure [18]. With the recent development of highly reliable wireless communication standards, industrial plants have attempted to construct a WSN-based health monitoring system while reducing overall administrative and operating costs. 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 health monitoring system, we can constantly monitor and evaluate the condition of facilities and provide more efficient risk management with ample reliable and accurate field data [19].

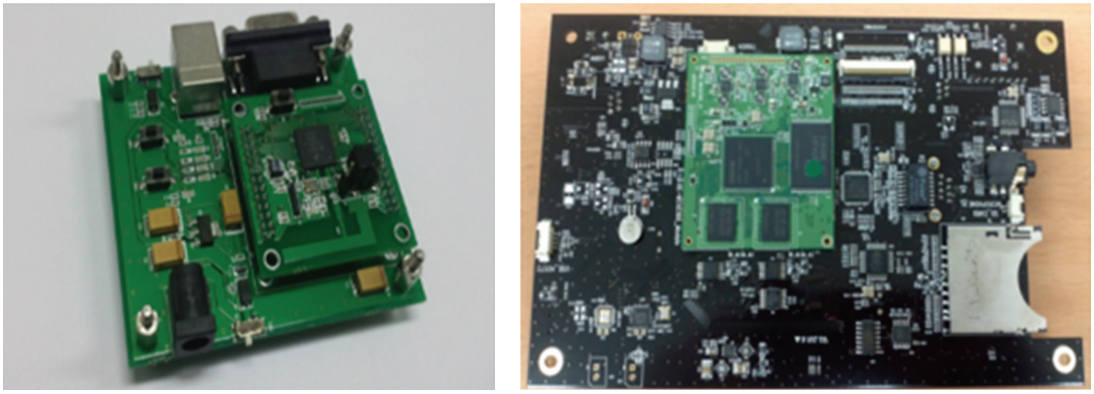
Thus, the present study presents a WSN-based safety monitoring system using highly flexible and reliable industry-standard communication standards for the safety of pipe-rack structures largely distributed in industrial plants. The WSN health monitoring system proposed in this study could contribute to the improvement of detection technology, the automation of management, and the increase in the efficiency of the automated system. The proposed integrated monitoring system could also have a great "ripple effect" on social security framework technology.

2. Motivation

Numerous plants currently operating at home and abroad experience serious deterioration of pipe racks (Figure 1), which requires a method of determining the optimal time to repair and upgrade these structures [20]. In addition, the industrial complex is expanding its number of pipe racks (Figure 2), which support pipelines directly responsible for its safety. Thus, without an accurate evaluation for the current condition of operating structures, damage to pipe racks (i.e., the aging and deterioration of pipe racks) will lead to serious accidents that lead to loss of life and property.

Furthermore, although industrial plants are subject to various administrative regulations, 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 WSN technology to the health monitoring and evaluation of industrial plant facilities. With the introduction of WSN technology to the health monitoring system of pipe racks, we could reduce the risk of serious accidents.

Using a reliable and secure WSN, we constructed a monitoring system of pipe-rack structures, a current large-scale petrochemical plant located at the Yeosu National Industrial Complex in Korea. We performed operating tests on the system for three months from March 2012 to June 2012. The



(a) ISA100.11a field device (b) ISA100.11a field network gateway

Figure 3: ISA100.11a standard-based network system developed in this study.

advantage of the monitoring 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 health monitoring system for the pipe racks will be explained in the following Section.

3. WSN-Based Health Monitoring System of Pipe Racks

One of our research goals is to construct a marketable WSN prototype of pipe-rack health monitoring network system. We develop the WSN system, which supports an ISA100.11a (ISA100.11a is an open wireless networking technology standard developed by the ISA. The official description is "Wireless System for Industrial Automation: Process Control and Related Applications.") standard for reliable and secure data transmission. The architecture of the ISA100.11a system can combine a variety of functional entities such as field device, field gateway, backbone router, and system manager and thus provide flexibility to various network topologies according to the requirements of the application.

3.1. Field Device and Field Network Gateway. 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, deterministic performance guarantees, and network security. To fulfill these requirements, we developed an ISA100.11a standard-based network system composed of a field device and a field network gateway, shown in Figure 3.

The field device platform, especially designed to meet the requirement of 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 device also consists of a small IC chip in which detection, signal processing algorithm, and data transmission modules coexist as built-in units. The field device, which calls signals and performs data acquisition and processes itself, is loaded with a low-power measuring device, a microprocessor, and an RF transmitter.

Table 1: Major characteristics of the field device.

Characteristic	Unit	Min.	Type	Max.
Operating frequency	GHz	2.4		2.483
Operating voltage	V		3	
Operating temperature	°C	−40		+85
Power supply current sleep	uA		<10	
Transmit mode (10 dBm)	mA		85	
Receive mode	mA	45		
Sensitivity for 1% PER	dBm	−107		
Maximum output power	dBm	18		
Over the air data rate	Bps	250 K		2 M

The microprocessor controls all functions, including signal measurements, and executes the analysis algorithm. The measured signals and the analyzed results are transmitted to a remote server through RF transmission module IEEE 802.15.4 PHY. The block diagram of the filed device platform is shown in Figure 4, and the major characteristics are given in Table 1.

ARM Coretex-M3 [21, 22] 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 device. 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 devices and the plant network. It also allows interaction between devices utilizing ISA100.11a protocols and system non-ISA100.11a (legacy or foreign) protocols. Our gateway system shown in Figure 3(b) operates on the Linux-based platform, and it connects WSN mesh networks to the Internet via Wi-Fi/Ethernet interface.

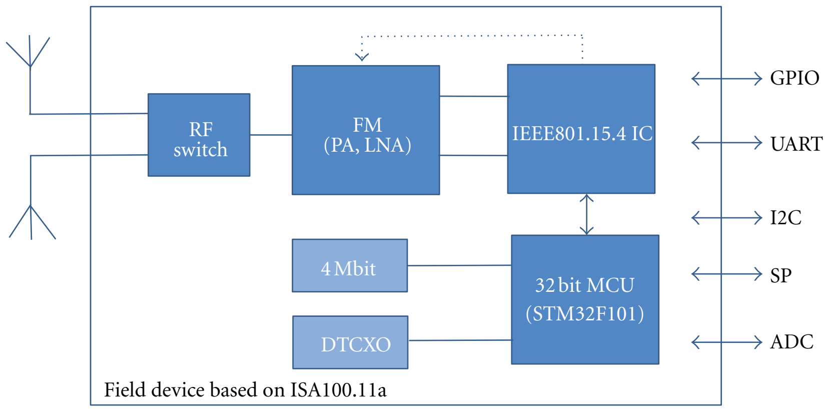


Figure 4: Block diagram of the field device.

Figure 5: Configuration of the WSN health monitoring system for pipe racks.

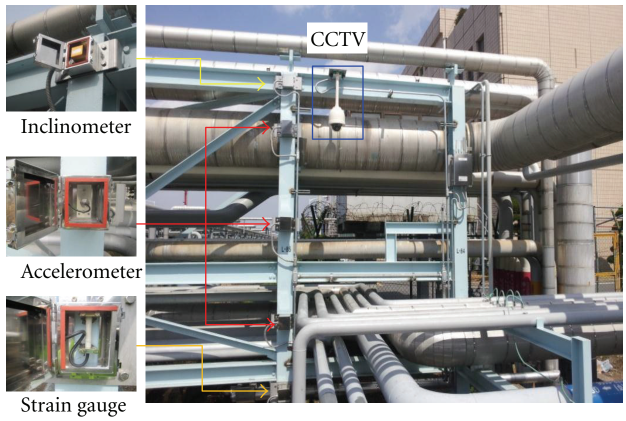


Figure 6: Locations of the sensors for the health monitoring of pipe rack.

3.2. Transmission Protocol. For wireless transmission, we adapted the ISA100.11a protocol, which consists of wireless field devices, field network gateways, and system manager. At the physical layer, the field network gateway and all the devices 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 devices while the wired connection of the gateway is used to communicate with the servers.

The medium access control (MAC) layer is based on the TDMA and channel hopping for reliable data transmission. The accelerometer, inclinometer, and strain gauge data are transmitted in a series of rounds, and each round 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 rounds. 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 round, the sender and receiver can move on to the next round. This prevents any packet collisions in the networks. Moreover, we used a specific parameter, an RF group ID, to avoid radio frequency interference from surrounding wireless devices or systems. When the data packet is transmitted, the gateway will check whether it contains the same group ID or not. The transmission protocol is designed to meet both reliable communication and power efficiency requirements.

4. Implementation of the WSN Monitoring System

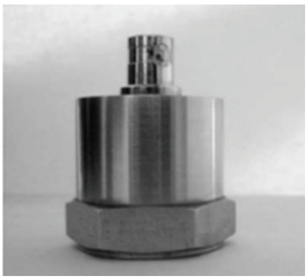
Using WSN-based sensors and network modules, we constructed a pipe-rack health monitoring system at an industrial complex. The sensors include accelerometers, an inclinometer, a strain gauge, and a closed-circuit television (CCTV). For the reliable acquisition and transmission of the data obtained from the sensors, the proposed pipe-rack health monitoring system entails FD nodes and FNG gateways.

4.1. Construction of the Proposed System. We have established a WSN-based health monitoring system of the pipe-rack structures in the eighth segment district of the Yeosu National Industrial Complex. Figure 5 illustrates the configuration of the WSN health monitoring system applied to pipe rack. To monitor and detect the physical vibration and deformation of pipe-rack structures, this study installed WSN-based accelerometers, inclinometers, and strain gauge sensors, shown in Figure 6. Table 2 summarizes information pertaining to the installation and the measurement of sensors. The average communication distance of sensor nodes is

(a) Data-logger

(b) Gateway

Figure 7: Data-logger and gateway of the pipe-rack health monitoring system.



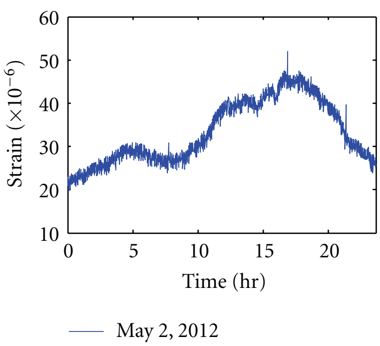
(a) Accelerometer

(b) Strain Gauge

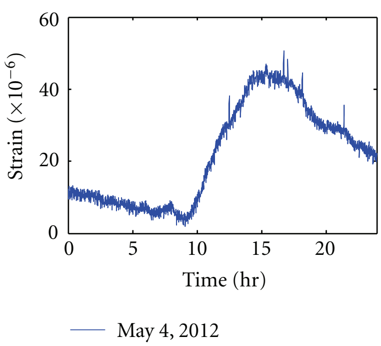
(c) Inclinometer

(d) CCTV

Figure 8: Sensors used in the pipe-rack health monitoring system.



(a)



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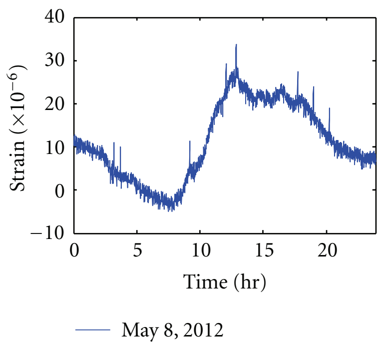
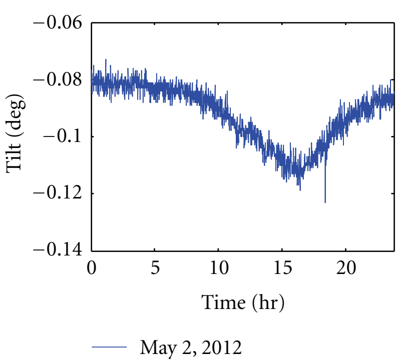


(c)

Figure 9: An example of variations in strain values at the bottom of the pipe-rack structure.



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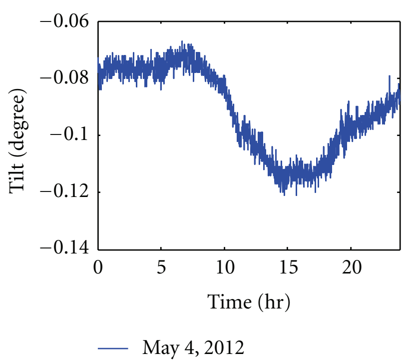

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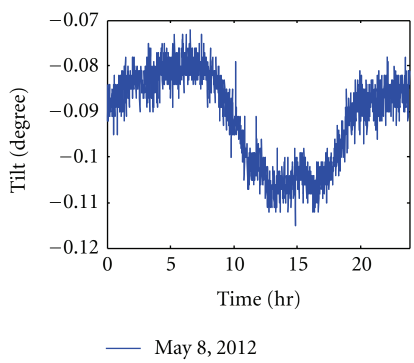

(c)

Figure 10: An example of variations in title angles at the top of the pipe-rack structure.

Table 2: Summary of the sensors installed at the pipe racks.

Sensors	Numbers	Measurement frequency	Communications	Locations
Accelerometer	3	256/1 sec.	Wibro	Top, Middle, Bottom
Strain gauge	1	1/1 min.	ISA	Bottom
Inclinometer	1	1/1 min.	ISA	Top
CCTV	1	Real time	Wibro	Top

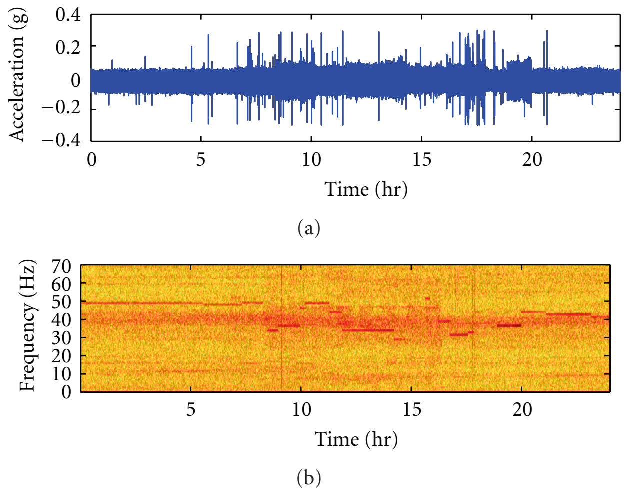

Figure 11: Acceleration and spectrogram data at the bottom of the pipe rack during a day on May 4, 2012.

approximately 300 meters, and power consumption is 60 mA and 25 mA for transmit and receive currents, respectively. The running time, which depends on transmission period, is estimated to be about 3 years with a battery of 34000 mAh in this study. A data-logger that receives signals from the sensors transmits the data to a main system through the gateway instrument, shown in Figure 7. In addition, a CCTV, installed at the top of the pipe rack, records the visual conditions and situations of the health monitoring system and the pipe-rack structures. The images recorded on the CCTV are also transmitted through the gateway and then stored along with the sensor signals in the main system.

4.2. Specifications of the Sensors. To monitor operational and abnormal vibration in the structure, we installed three Lance accelerometers at the top, the middle, and the bottom of the pip-rack structure. The accelerometers measure a range of −0.5 g to 0.5 g and represent an electrical signal of 10 mV per 1 g acceleration. At the bottom of the pipe-rack structure, we monitored variation in the strain, which represents the stress condition of the structure using a strain gauge (manufactured by Tokyo Sokki Kenhyuio Company Ltd.), 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 top of the pipe rack. The inclinometer sensor, manufactured by Digital Advanced Sensors, can measure tilt angles in two directions at the same time. Then we installed a WonWoo Eng EWSJ-330 model CCTV with an optical 33-time zoom at the top of the pipe rack to facilitate an operator's visual inspection and improve the efficiency of the monitoring system. Figure 8 shows the sensors, accelerometer, strain gauge, inclinometer, and CCTV used in this study.

4.3. Monitoring Data. From the WSN-based accelerometer, inclinometer, and strain gauge sensors, we monitored ambient variations in the pipe-rack structure during the operation of the industrial equipment. Changes in the strain and the slope of the structure were measured using a strain gauge and an inclinometer, installed at the bottom and the top of the structure, respectively, at intervals of 60 seconds. Figures 9 and 10 present the strain and the tilt measurements obtained from the strain gauge and the inclinometer for the selected three days. As shown in the figure, 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 PM when the daily temperature was the highest. The trends of daily changes in the values were similar on other days.

Figure 11 shows a variation in ambient acceleration measured at 256 Hz intervals and the spectrogram obtained from a WSN-based accelerometer installed at the bottom of the pipe rack. The amplitude of the acceleration exhibits larger values between around 8 AM and 8 PM when the plant is operating. The frequency of the structure during the working hours was in the range of 35 Hz to 50 Hz, depending on working conditions. During the night when the plant is not fully operating, the frequency was almost constant at around 49 Hz.

5. Conclusions

In this paper, we proposed a WSN-based health monitoring system applicable to industrial plants that require high reliability and security. For reliable and secure requirements in data acquisition and transmission, this study developed an ISA100.11a standard-based network system composed of a field device and a field network gateway. The proposed monitoring system, which was based on WSN-based sensors and network systems, was established and tested at a large industrial complex, where the system monitored the operational condition of the pipe-rack structure to detect abnormal conditions of the structure before they pose a risk. The system generated data that showed ambient conditions and variations in the pipe-rack structure triggered by environmental and working conditions. The findings from this research show that the WSN health monitoring system is capable of monitoring and evaluating the health and/or abnormal conditions of facilities. In the future, with abundant reliable and accurate field data, we should be able to provide more efficient risk management during the operation of industrial plants and contribute to the improvement in detection technology and the automation of management.

Acknowledgments

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