Development of an FPGA-based Online Condition Monitoring System for Railway Catenary Application

[1]Young Park, Presenting Author; Yong Hyeon Cho, Kiwon Lee, Hosung Jung, Hyungchul Kim, Samyoung Kwon, Hyunjune Park, Coauthors
Korea Railroad Research Institute, Uiwang-City, Republic of Korea[1]

Abstract

The aim of this paper is to develop a Field Programmable Gate Array (FPGA)-based online condition monitoring system for sensor network applications in railway catenary systems. The system is designed to perform in IP network-based wireless environments and is capable of storing data in a live wire state at 25 kV. A real-time controller, chassis (including a reconfigurable FPGA), and several I/O modules are used in the condition monitoring system. To check the validity of our approach for the intended application, we monitored temperature, vibration, strain, and displacement in the overhead wire of a high-speed catenary system in Korea.

Introduction

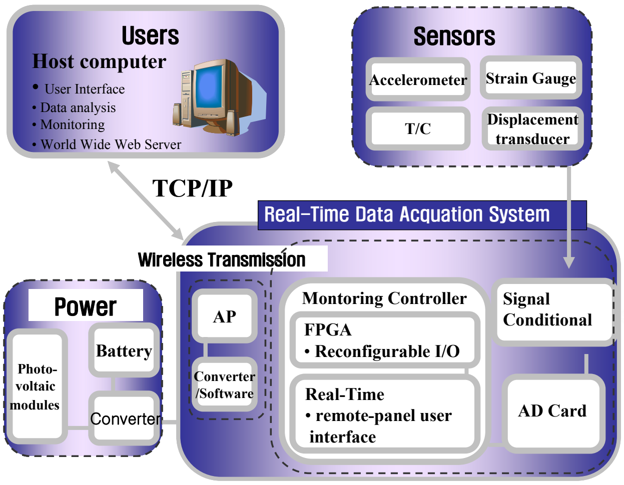
In response to increasing interest in reducing the costs of operation and maintenance in overhead catenary systems, various methods of condition monitoring have been developed. However, the lack of a reliable online real-time (RT) measurement system with the ability to evaluate dynamic behavior at high voltage is a big obstacle to assessing the quality of catenary systems in electric railways. Numerous applications exist for condition monitoring in railway catenary systems, such as optical-based applications, video image processing and telemetry. [1, 2] However, the lack of reliable real-time measurement system with the ability to evaluate dynamic behaviors of the catenary systems at high voltage is a big obstacle to assess continuous condition monitoring.

The need to develop versatile platforms with many applications for condition-based maintenance to assess structural health has recently been established. Since many of these applications involve condition monitoring in railways, a field programmable gate array (FPGA) is one of the most promising candidates for such a versatile platform; it can be optimized and reconfigured for the monitoring architecture design in catenary systems. Furthermore, the recent advances in wireless communications technology make it promising candidate for potential applications for railway automation.

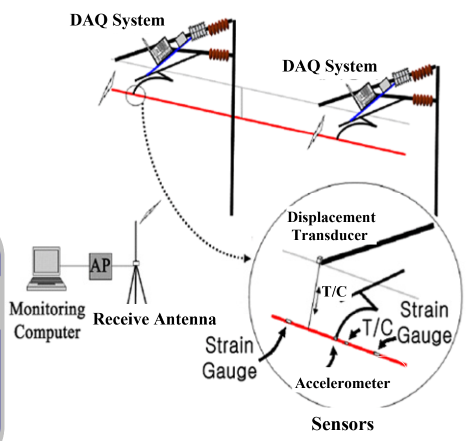
This paper describes the development of a real-time remote monitoring system using an FPGA; it can acquire data from any kind of sensor and transmit it by wireless communication from the overhead line and structure at 25 kV to a computer in the catenary system. This allows for the measurement of dynamic behavior and fault inspection with various sensors without changing the hardware, since the FPGAs are flexible and reprogrammable. To check the validity of our approach for the intended application, experiments were conducted to obtain remote data from a live wire state at high voltage and make it available for sensor installation to measure parameters like uplift at the registration arm, dynamic strain in a contact wire, and temperature on the overhead contact line and catenary wire.

System architecture

Developing condition-based maintenance systems for the assessment of structural health is a very competitive field, and condition monitoring systems are constantly being improved to increase equipment functionality and cut unit costs. Our basic proposal is to achieve continuous online condition monitoring through remote data access, and to easily acquire data from all sensors in order to reduce costs and increase information for condition-based maintenance in catenary systems at high voltage. Figure 1 (a) shows the overall block diagram of a continuous online condition monitoring system. The system is composed of sensors, a data acquisition system, wireless transmission with a 10/100BaseT Ethernet port and receiver elements for users, and a control and monitoring system. The data acquisition system is available with different numbers of modules and different FPGAs. The I/O modules communicate with sensors and directly with the FPGA. Sensor data is transferred between the FPGA and the real-time controller over the system PCI bus. National Instruments hardware is used for all systems and modules. The system uses three separate processors: a controller developed with LabView Real-Time OS, an FPGA and monitoring PC developed with LabVIEW FPGA, and system software developed with LabVIEW. The system is extended via an attractive wireless solution such as GSM, GPS, WLAN or ZigBee for network-based condition monitoring. Using an FPGA in this application provides the reliability of a hardware solution, which does not require the same level of code review as processor-based systems. Another benefit is the ability to add functionality in the future and to easily expand or customize the system when needed. A variety of sensors for acquiring catenary data are used to measure parameters like uplift at the registration arm, dynamic strain in a contact wire, and temperature on the overhead contact line and catenary wire. Figure 1 (b) shows the overall block diagram of the continuous online condition monitoring system.



(a)



(b)

Figure 1: The overall block diagram of the continuous online condition monitoring system: (a) Functional blocks of the monitoring system, and (b) Schematic diagram of the monitoring test.

Experimental setup

The experiments were performed on the KTX and Chungbuk lines (speeds up to 300 km/h) in Korea, with a high voltage of 25 kV applied to the catenary system. These experiments monitored temperature with a J-type thermocouple in both the overhead contact wire and the catenary wire, measured vibration with a one-axis accelerometer in the overhead contact wire, measured dropper force with a strain gauge in the overhead wire and dropper, and measured up-lift with a displacement transducer in the overhead wire. The system can be installed on the catenary line and structure with a variety of sensors in a live wire state at 25 kV, as shown in Figure 2. Extreme conditions at the site, including below-freezing temperatures and electrical arc, are accounted for by mounting the system on waterproof steel housing. The system is controlled by a Windows-based user-friendly interface. All of the sensor signals are synchronized by means of an FPGA. The NI real-time software is used for FPGA data acquisition, embedded data logging and wireless Ethernet communication with the ground remote users [3]. The host computer software was also developed in NI LabVIEW for Windows and runs on a notebook using Windows XP OS. The host computer allows the user to interface with the Real-Time Engine, which implements the real-time requirements of the application. The host computer has been set to control parameters such as on/off control and battery levels, and to recode parameters such as sensor data. The system software and application architecture are shown in Figure 3.

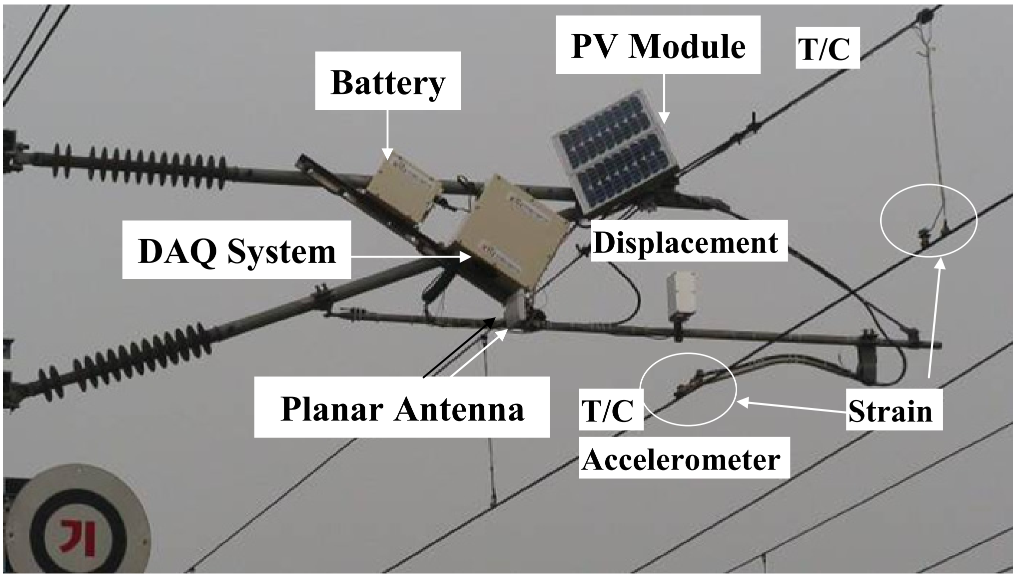


Figure 2: Picture of the online condition monitoring system in the Chunbuk line.

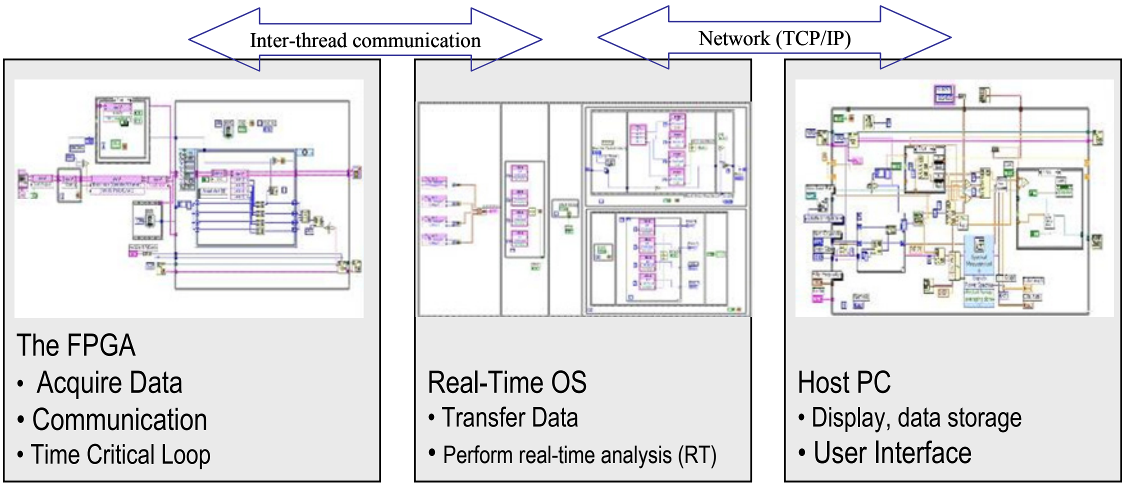


Figure 3: The system software and application architecture

Measurement Results

One of the major accomplishments of this system is the successful installation of both DAQ systems, including the battery and antenna, and a variety of sensors on the catenary system. The experiments were in Korea on the KTX line at speeds of 150 to 300 km/h and on the Chungbuk line at speeds of about 100 km/h. A number of tests were carried out to check the safety of the online condition monitoring system as the high-speed train moved past the measuring point. Figure 4 shows a picture of an FPGA-based condition monitoring system installed in the KTX overhead line with various sensors at 25 kV. All data were transmitted from the condition monitoring system to a host computer 50 m away, with wireless communication capabilities. This online condition monitoring system can also extend its capabilities to work together with other systems, such as Multi-Agent technology. This implies that data can be collected by the online condition monitoring system using Ethernet and TCP/IP. Figure 5 shows the proposed framework of an IP network-based condition monitoring system for railway catenary automation. Further work is required to incorporate the IP network-based informatics grid included in power systems for railway e-automations. Figure 6 shows the main panel of the host computer software. The main panel receives data from the condition monitoring system, stores the data, and reports on it. Figure 7 shows the results of measurements of the overhead wire and catenary wire temperature (a) and vibration (b), measured using a one-axis accelerometer in the overhead contact wire. It is clear that the results obtained from T/C and accelerometer data can be clearly identified without filtering. The results from a field test in the KTX line show that the proposed technique and system can be practically applied to measure the assessment quantity or quantities of temperature, displacement, vibration, and strain on the catenary system for online condition monitoring.

(a) Honam KTX line from Sonjeong-ri to Mokpo station over 150 km/h

(b) Gyenogbu KTX line from Cheonan to Daejeon station over 300 km/h

Figure 4: Picture of an FPGA-based condition monitoring system installed in the KTX overhead line with various sensors at 25 kV.

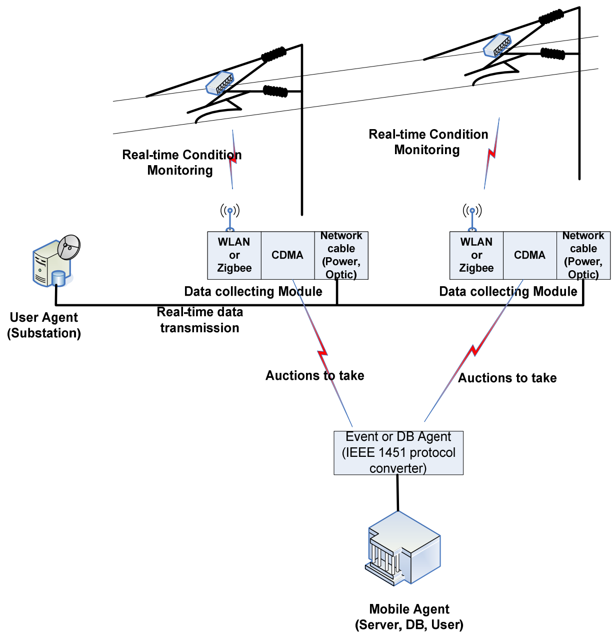


Figure 5: Framework of an IP network-based condition monitoring system for railway catenary automation.

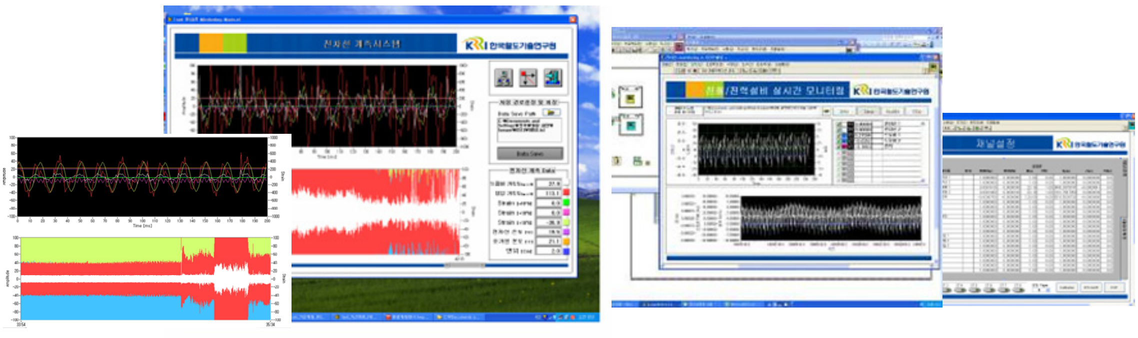
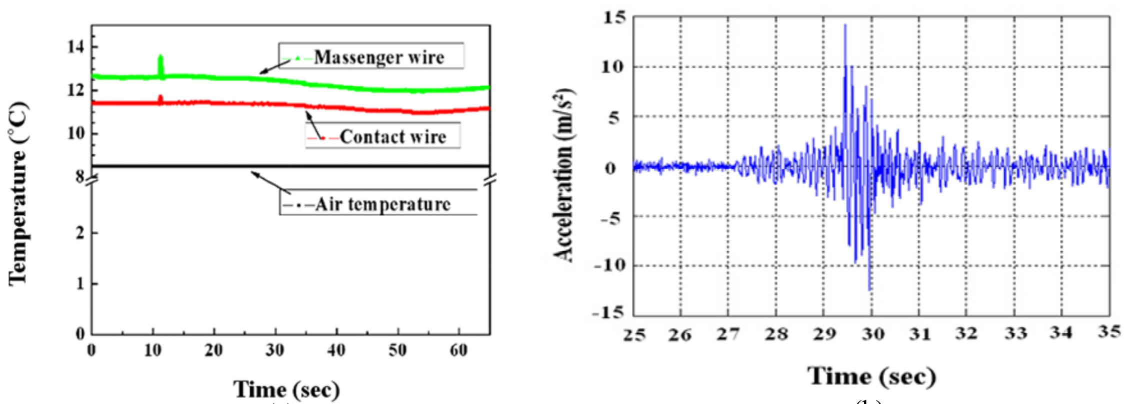


Figure 6: The main and control panels of the host computer software designed in LabVIEW



(a) (b)

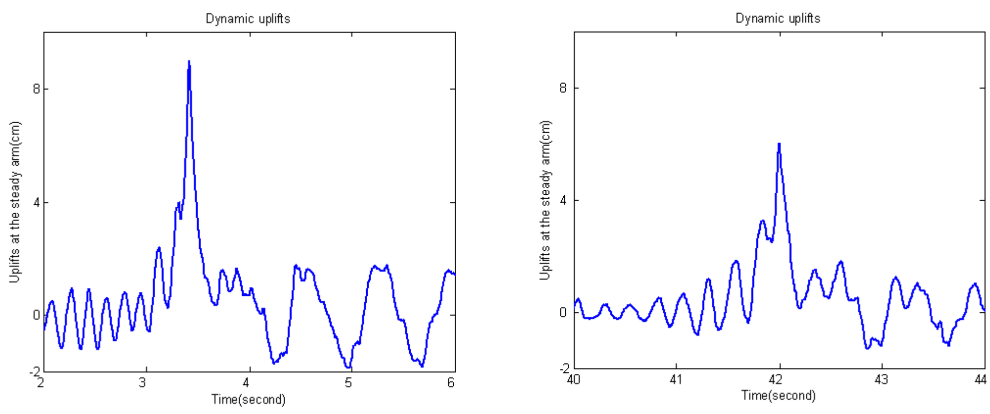
Figure 7: Results of the overhead wire and catenary wire temperature (a) and measured vibration in the overhead contact wire (b).

Figure 8 shows that the dynamic uplifts at the registration arm are around 9 cm and 6.5 cm when the high-speed train moves at 245 km/h and 300 km/h, respectively. In order to avoid the high-frequency terms caused by external noise, the measured data was low-pass filtered with a cut-off frequency of 60 Hz, using the equi-ripple FIR filter available in Ref [4]. Two peculiarities can be noted in the uplifts. One is that the maximum uplift is consistently obtained with measurements taken in similar conditions. The maximum depends on the train speed, the uplift forces caused by the pantograph, the wind speed, etc. However, the difference in uplifts for trains of different speeds is quite noticeable, as shown in Figure 9 Thus; the maximum uplift can be used to monitor the operating condition in the field. The other peculiarity is that there are oscillations preceding the maximum of the uplift. Basically, these disturbances happen because of a stiffness variation along the span of the contact wire when the pantograph passes. Due to the Doppler effect, the frequency of the disturbances depends on the train speed, the wave propagation speed and the span length. When the train moves at speed *V,* the frequency of the disturbances f_d is given by

$$f_d = \frac{C}{C-V}\frac{V}{S}, \qquad (1)$$

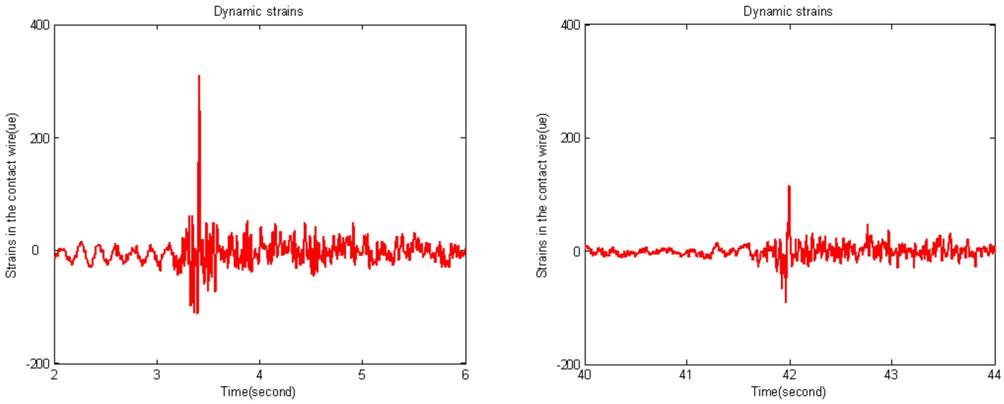
where *C* is the wave propagation speed in the contact wire, *V* is the train speed, and S is the span length. The span length of spans neighboring the measuring point was either 40.5 m or 45 m. For span lengths of 40.5 m, the frequency of the disturbances is 6.4 Hz when the train moves at 300 km/h. If the train speed is reduced to 235 km/h, the frequency of the disturbances decreases to 3.8 Hz. Figure 8 shows that the frequency of the oscillations in the measured data corresponds to Equation (1). Thus, the train speed can be inferred from the frequency of the oscillations.

As the train moves faster, the dynamic strains increases, even though the same uplift forces are applied to the pantograph. Figure 9 shows the dynamic strains in the contact wire at the registration arm to be nearly 300 ue and 100 ue when the train moves at 300 km/h and 245 km/h, respectively. Data processing for the dynamic strains is the same as for the uplifts. Similar to the uplifts, there are oscillations preceding the maximum of the strain when the train moves at 300 km/h. However, it is peculiar that compressive dynamic strains occur as the pantograph approaches the measuring point. This is due to wave reflection at the registration arm. The bigger the compressive strains become, the more strongly wave reflection occurs. In actuality, the arcs occur at the registration arm. The peak of the tensile strains in the contact wire appears when the pantograph passes the measuring point. Because the tensile strains can cause fatigue failure in the contact wire, dynamic strains are also an appropriate measuring item for monitoring the health of the overhead contact line.



(a) (b)

Figure 8: Dynamic uplifts at the registration arm: (a) 300 km/h, (b) 245 km/h



(a) (b)

Figure 9: Dynamic strains at the registration arm: (a) 300 km/h, (b) 245 km/h.

Conclusions

In summary, we propose an FPGA-based real-time measurement system to monitor dynamic characteristics of catenary systems in electric railways. The system performance for sensing the signal and for monitoring the temperature, vibration, strain, and displacement in the overhead wire of a high-speed catenary system in Korea was illustrated. Flexible and reprogrammable FPGAs allow for the measurement of dynamic behavior and fault inspection with various sensors without changing hardware. Our results indicated that a new generation of real-time instruments satisfying various demanding in railway automations can be easily integrated into the FPGA-based system depends on the nature of the application.

References

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