Implementation of an FPGA-based System for Temperature, Flow, and Hydraulic Pressure Measurement of Fluids

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***Abstract*—In this study, an FPGA-based monitoring system that can analyze the characteristics of an automobile cooling system and various fluid systems was implemented. The system can simultaneously measure changes in the temperature, flow rate, and pressure of a fluid flowing inside a pipe. Furthermore, the measured data can be displayed on a computer screen in real time so that changes in the fluid's condition can be observed and recorded. The cooling efficiency of the system was measured using contact and noncontact temperature sensors. A 24-bit analog-to-digital converter was used for accurate temperature measurements. The system was also constructed using a digital semiconductor pressure gauge and a turbine flow meter. The FPGA-based system consists of a temperature IP, a flow IP, a pressure IP, an LCD IP, and a communication IP.**

***Index Terms*—FPGA, metering, temperature, flow, pressure , cooling system.**

I. Introduction

A car engine cooling system is used to improve fuel efficiency and power by keeping the engine at an appropriate temperature.

Most modern cars use water-cooled systems, which consist of cooling pumps, a radiator, and various connecting pipes. Integrated modularization and weight-reduction research is being done for water-cooled systems in line with the recent trend of lighter cars.

In particular, research is being conducted on the weight reduction of systems that use plastics as the material for water pumps and cooling pipes, but not the radiators [1].

Temperature can be measured easily using various sensors, such as resistance temperature detectors (RTDs), thermocouples, and infrared detectors sensors. Studies have been conducted on various control systems [2] and using RTD temperature sensors [3] to improve the error for this thermocouple method. A system has been developed to monitor the measured temperature [4]. Temperature measurements are also used in various monitoring systems [5]. There are two types of temperature measurement methods: contact and non-contact, aside from infrared.

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In this study, we implemented an FPGA-based system that can measure temperature, pressure and flow rate of fluid at the same time and transmit measured data to a personal computer in real time. By using FPGA, real-time data measurement and transmission are possible unlike the system driven by software. Each IP designed in this system can be reused in all systems using FPGA.

Temperature IP, pressure IP, flow IP, LCD IP, serial communication IP are implemented. Fig. 1 shows the monitoring system configuration.

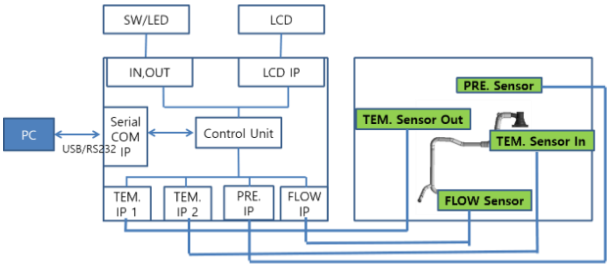

Figure 1. Temperature, flow, and pressure monitoring system configuration.

II. System Configuration

A. System Overview

The temperature sensors are capable of measuring –40 - 120℃, which is the temperature range of an automotive engine. A K-type thermocouple sensor with fast temperature response was selected. The pressure gauge can accurately measure low pressure (0 - 1.6 kgf/㎠). An electronic pressure gauge was used, as well as flowmeter with a compact design that enables high-precision flow detection (10 - 160 LPM). The turbine flowmeter[6] can withstand changes low temperature to high temperature.

The temperature of the input part and output part of the cooling system is obtained by a contact method, and the temperature is displayed on an LCD monitor in the FPGA-based system in units of 1℃. Serial data is transmitted to the main controller to continuously monitor temperature changes at the input and output sites. The transferred temperature data can be displayed in a separate window on the monitor.

A separate 24-bit analog-to-digital converter(ADC) was used to enable each temperature sensor to operate independently, enabling precise measurement in real time.

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A sensor interface capable of flow measurement and pressure measurement was added to the developed thermometer system. The system was designed to transmit all data to the main control unit so that changes in the temperature, flow rate, and hydraulic pressure of the cooling system could be continuously monitored, and it was also designed to display the transmitted data in a separate window on the monitor.

B. *Temerature Sensor*

Fig. 2 shows the A/D converter circuit. To convert the temperature signal into a digital signal, an LTC2402 with 24-bit delta-sigma conversion [7] was used.

The ADC operates from a 2.7 to 5.5-V supply, has two channels of 24-bit ADC, is noise-resistant, and has a built-in oscillator. The converter uses delta-sigma technology and a new digital filter structure with a single period. The serial output data stream for conversion is 32 bits. Fig. 3 shows the data timing. The first four bits indicate the indication, selection channel, output range, and conversion status information. The next 24 bits are data bits. It displays from the MSB to the LSB.

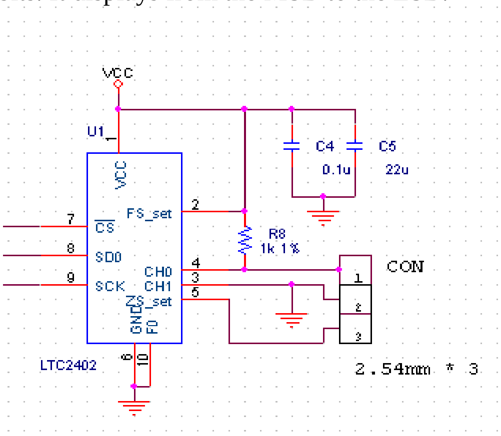

Figure 2. A/D converter circuit.

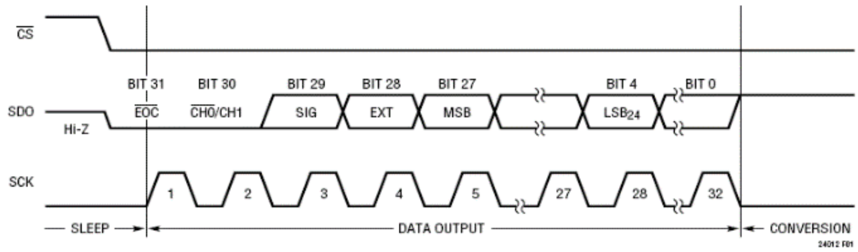

Figure 3. Temperature sensor data timing.

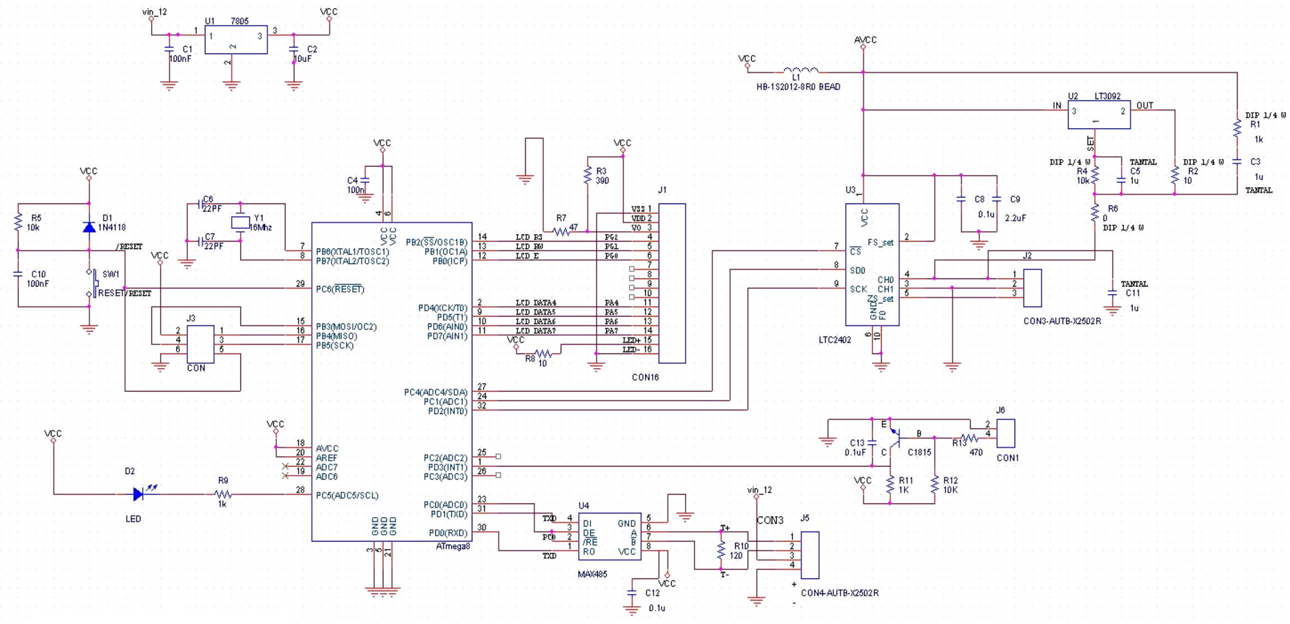

Figure. 4. Flow Input.

C. *Flow Meter and Hydraulic Pressue Meter*

In the flow meter, constant pulses are generated according to the flow rate inside the pipe, which can be transmitted to calculate the cumulative flow rate and the net flow rate.

Fig. 4 shows the flow input circuit. The sinusoidal signal input through the connection part is half-wave rectified and amplified using a transistor and transferred to the flow IP. The digital hydraulic system uses a separate external 24-bitADC. Up to 1.6kgf/ cm^2 could be displayed.

III. IP Simulation

A. Introduction

TABLE I. IP Logic Synthesize Result

Device Utilization Summary			
Logic Utilization	**Used**	**Available**	**Utilization**
Total Number Slice Registers	516	3,840	13%
Number Used as Filp Flops	514		
Number Used as Latches	2		
Number of 4 input LUTs	1,284		
Number of 4 occupied Silces	751	1,920	39%
Number of Silces containing only related logic	751	751	100%
Number of Silces containing only unrelated logic	0	751	0%
Total Number of 4input LUTs	1,431	3,840	37%
Number used as logic	1,284		
Number used as a route-thru	147		
Number of bounded IOBS	61		
Number of BUFGMUXs	7		
Average Fanout of NON-Clock Nets	3,81		

An XC3S200 from the Spartan 3 device family was used in an HBE-Combo II-SE [8] used. Table I shows the synthesis results of the IPs designed for the monitoring system.

The total number of slice registers used inside the FPGA was 516, which is 8% of 3840, and the total number used as the logic of 4 input LUTs is 1431, which is about 37%.

B. Temperature IP

The temperature IP consists of three states. First, it always starts with ad_idle state and if the state of the input signal is LOW over 25us, the state is converted into data_ad. In data_ad, the CLK signal is transmitted to the AD converter so that the AD converter transmits the digital output. When all 32 bits of data are transmitted, it changes to ad_stop state.

At this time, temperature data is input and ready to transmit it to the serial communication IP. In ad_stop state, it waits for 10 clocks. The internal state of the temperature IP circulates in the order of ad_idle → data_ad → ad_stop → ad_idle. The simulation state was shown in Fig. 5.

C. Flow IP

The flow IP also consists of three states, such as the temperature IP, which waits for 10 clocks in the first flow_idle state and then converts the state into data_flow.

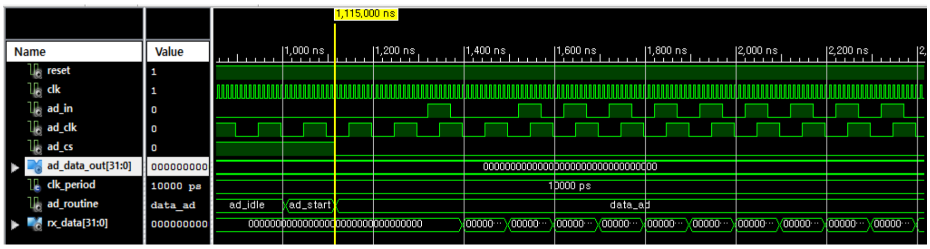

Figure 5. Temperature IP simulation.

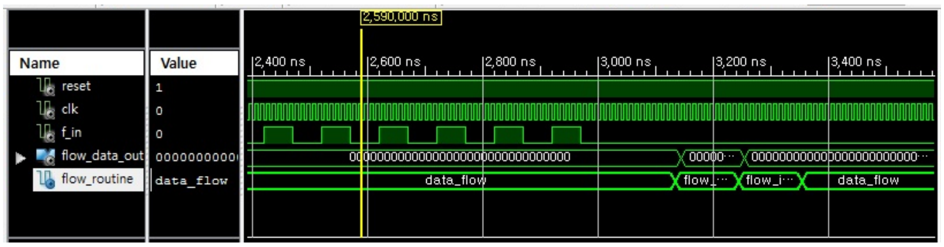

Figure 6. Flow IP simulation.

In data_flow, the pulse input from f_in is counted for 60 seconds. After 60 seconds, the state is changed to flow_stop, and in this state, the flow data is input and ready for transmission to the serial communication IP. Wait 10 clocks in flow_stop state. The internal state of the flow IP cycles in the order of flow_idle → data_flow → flow_stop → flow_idle. Fig. 6 shows the flow IP simulation state.

D. Pressure IP

The pressure IP is very similar to the temperature IP because it uses an AD converter of the same kind as the temperature sensor. In the first adp_idle state, if the state of the input signal is LOW over 25us, the state is converted into data_adp. In data_adp, the CLK signal is transmitted to the AD converter so that the AD converter transmits the digital output. When all 32-bit data is transmitted, it changes to adp_stop state. At this time, it receives pressure data and prepares to transmit it to the serial communication IP.

Wait 10 clocks in adp_stop. The internal state of the pressure IP cycles in the order adp_idle → data_adp → adp_stop → adp_idle. Fig. 7 shows the simulation state.

E. Communication IP

The communication IP used in the system used Analog Device's ADM3202 and FTDI's FT232R IC to convert the signal to RS-232C.

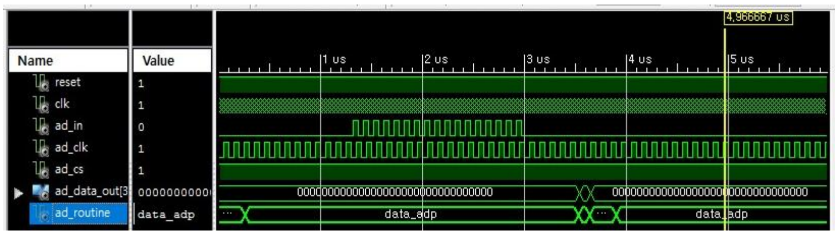

Figure 7. Hydraulic pressure IP simulation.

Table II shows the communication IP protocol. 22 bytes are used to transfer the fluid data once per second, bytes 3 to 5 are thermometer # 1, bytes 7 to 9 are thermometer # 2, and 11 to 13 are pressure gauge, Bytes 15-18 assigned flowmeter data.

TABLE II. SERIAL COMMUNICATION IP PROTOCOL

Byte	contents	
0	'\r'	0D
1	'\n'	0A
2	blank	
3 ~5	Temperature 1	std_logic_vector
6	blank	
7~9	Temperature 2	std_logic_vector
10	blank	
11~13	Pressure	std_logic_vector
14	blank	
15~18	Flow	std_logic_vector
19	blank	
20	'\r'	0D
21	'\n'	0A

IV. EXPERIMENTS AND RESULTS

A. Temperature Sensor

When the resistance value of the sensor changes due to a change in temperature, the resistance value is converted into a voltage again, and the temperature data is transmitted to the temperature IP using an ADC. To receive the voltage value of the sensor through SPI communication, the Temperature IP performs SPI enable and sends SCK to the LTC2402 ADC. The SPI is disabled when SCK is completed. From the received 32-bit data, we convert up to 4095.99 using the 20 data bits except the initial 4 bits and the last byte.

$$V_R = V_{ref} * R/(R + R_{ref}) \qquad (1)$$

Where V_R is the sensor voltage, V_{ref} is the reference voltage, R is the sensor resistance, and R_{ref}(998Ω) is the reference resistance.

The resistance of the measuring line (0.33Ω) is removed from the measured resistance of the sensor. The length of the temperature sensor is 1 m, and the 3-wire method is used. As a result of the temperature measurement, resistance values of 96.9 Ω at -7℃ and 130.6 Ω at + 80℃ are shown. Fig. 8 shows the input signal of the LTC2402 ADC for the temperature sensor. When the chip enable pin is low, a 64-bit SCK corresponding to 2CH is transmitted, and the voltage values of the 32-bit temperature sensors are input.

However, in the method using the PT100Ω RTD sensor, the response speed of the sensor is slow, so the signal shakes when the measurement time is short. Initially, 10 inputs were averaged to minimize the signal shaking. There was also a temperature change of about 0.75℃ due to the line resistance of the temperature sensor. Fig. 9 shows the temperature measurement display screen.

Figure 8. Temperature sensor data.

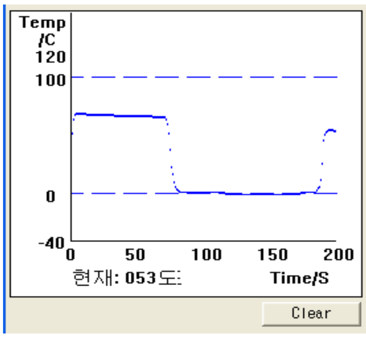

Figure 9. Temperature measurement display screen.

B. Hydraulic Pressure Meter and Flow Meter

Hydraulic pressure enters the analog voltage signal (0.5 to 3.3 V) input from the pressure sensor through the 24-bit AD converter.

Unlike temperature measurements, the two-wire pressure system does not calibrate the line resistance, and the measurable range is 0.0 to 1.6kgf/cm^2.

Fig. 10 shows the half-wave rectified signal (maximum voltage: about 700 mV) of the pulse signal input from the flow sensor, as well as the signal inverted and amplified by a digital waveform to enable the flow IP. Fig. 11 shows a monitoring screen that displays the measured flow rate.

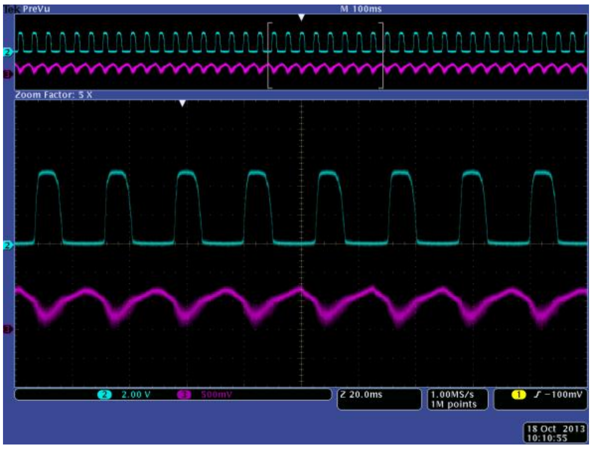

Figure 10. Flow sensor input waveform.

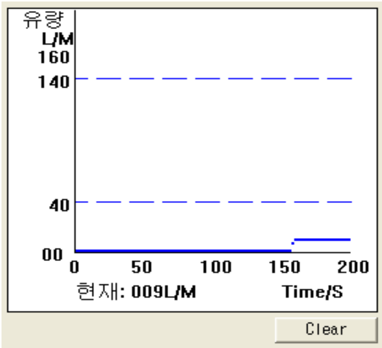

Figure 11. Flow measurement display screen.

C. *Fluid Temperature, Flow Rate, and Pressure Measurement*

The temperature, flow rate, and hydraulic pressure data from the fluid measurement module are transmitted to the computer through an FPGA-based system. In serial communication transmission, thermometer #1 was assigned as No. 1, thermometer #2 was No. 2, the hydraulic system was No. 3, and the flow meter was No. 4. The communication baud rate was set to 9600 BPS with 8 bits of data bit, a stop bit, and no parity.

In the thermometer, the error of the temperature sensor is up to 2℃, and error of less than 0.4Ω occurred due to the resistance error of the circuit. Therefore, the temperature sensor module was adjusted by a program to generate an error of less than 1℃ through each calibration.

In addition, the RTD thermometer has a slow response time, so it is possible to increase the response speed by using a K-type thermocouple.

The results of the mechanical pressure gauge were compared with those of the digital pressure gauge of the fluid measurement module. The error was less than 0.1kgf/ cm^2 at less than 1.6kgf/ cm^2. Fig. 12 shows a pressure measurement display screen.

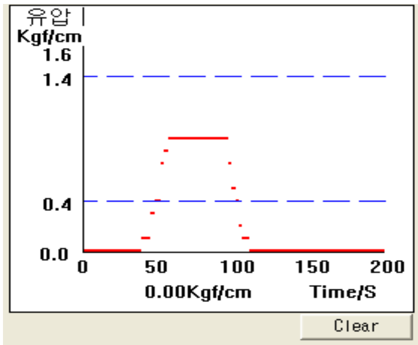

Figure 12. Pressure measurement display screen.

The flow rate sensor is a turbine type sensor, so measurement below a flow rate corresponding to about 5% of the maximum flow rate may not be possible. In this experiment, a 1-inch aperture measuring up to 160 L/min was used, so measurement was not possible at flow rates below 7.5L/min. Fig. 13 shows an FPGA-Based monitoring screen.

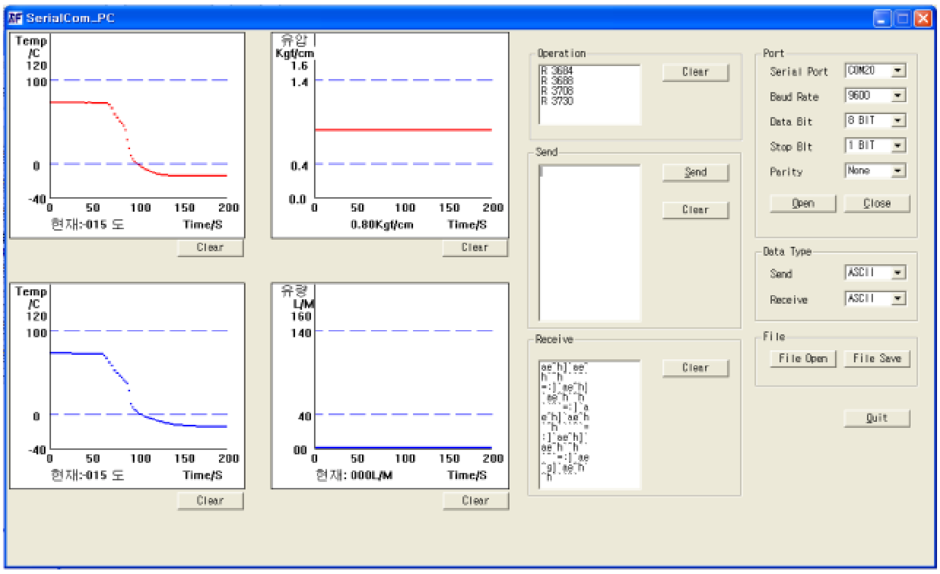

Figure 13. An FPGA-Based monitoring screen.

V. Conclusion

We designed and manufactured an FPGA-based measurement system shown in Fig. 14. This system consists of an FPGA-based system and a fluid data measurement unit that consists of a motor, a pump, an analog pressure gauge, a digital pressure gauge, a flow meter, a valve, and a thermometer. This system can measure fluid temperature, flow rate, and hydraulic pressure to test fluid machines. The FPGA-based system transmits data using a serial communication protocol to display data on a computer screen in real time. The screen shows the overall state of fluid change. In experiments, the oldest data is shifted, and new data is input last. This system measures temperatures of -40 to 120℃, which is suitable for the experiments with passenger car coolers.

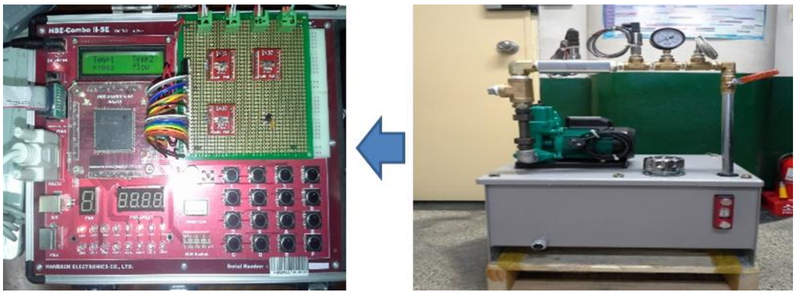

Figure 14. An FPGA-Based monitoring system.

It directly measures the temperature of the fluid a temperature sensor in the fluid pipe. The flow rate is counted using a signal in the form of a pulse from a turbine flowmeter, and it is possible to measure from 10 to 160 L/min. The hydraulic pressure is designed to measure up to 1.6kgf/ cm^2.

The RTD temperature sensor was changed to a K type thermocouple because the temperature response time was slow. The output current of the pressure gauge was very low, so it was necessary to select an IC with a low input current in the interface process.

The FPGA-based monitoring system has no problem in real-time data transmission because each IP interfaces its sensor. Currently, although the general-purpose FPGA board is used, it is possible to reduce the size of the system through a dedicated PCB design and to build a more stable system. When the system is expanded, all IPs and programs can be reused as they are.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

Cheol Hong Moon composed the whole paper.

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