

The thermal effect compensation technology for highly integrated sensor modules

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In recent years, “IoT (Internet of Things)”, in which all “things” are connected by a network, has attracted attention. In IoT, advanced sensing devices that can process and transmit sensing data are being expected in order to create new services by sensing various states and analyzing acquired data.

They are required to be able to output accurate information without being affected by disturbances regardless of the installation environment. However, the realization was not easy due to thermal effect from highly integrated embedded devices, and external equipment at the installation locations.

We have developed the world smallest IoT sensor that is not affected by the thermal effect from either internal or external heat source by correcting unwanted disturbances utilizing thermal effect compensation technology from the heat flux detected by two built-in temperature sensors.

1. Introduction

In recent years, expectations have been running high for IoT (Internet of Things) technology to play key roles in society^{1,2,3}. Internet-connectable devices will amount to 50 billion units in 2020, and sensors required for these devices are expected to be produced in order of one trillion pieces per year.

Sensors in an IoT society^{4,5} are required to be versatile to support seamless connection with various devices for easy access to data. This means that not only do sensors have to have high connectivity with host devices and provide accurate output data but they also must remain usable regardless of the surrounding installation environment or site. An easy-to-use sensor with such diverse applicability would have to be small, install well anywhere, and remain unaffected by the external environment.

Because of such demand for device size reduction, expectations are mounting for advancements in micro electromechanical systems (MEMS) technology and for MEMS sensors based thereon as indispensables for IoT devices. MEMS is a generic name for minute electromechanical systems manufactured through the application of semiconductor process; these small devices provide both high-sensitivity sensing and mass-production capabilities at the same time and have been making their way into diverse applications as core parts for IoT-compatible sensor modules in various scenes in society. Their prospective areas of application have remarkably expanded to

cover a wide range from social infrastructure to individuals' lives⁶. Thus, developments in MEMS technology contribute significantly to the size reduction of devices into which sensors are embedded.

On the other hand, the self-generated heat in sensors and other parts poses a problem for the size reduction of sensor modules. Usually, a sensor module contains many heat-generating parts, such as heater-equipped sensors and power supplying parts. This means that the sensor module becomes more susceptible to heat from within proportionally to the decrease in size. Therefore, anti-heat measures are an absolute necessity for package size reduction.

Additionally, depending on the physical quantity of interest or the sensor's detection method, the temperature environment of the installation site affects the detection results. A sensor would have a very narrow range of applications if it were connectable only to a particular device under constant environment conditions and could produce correct outputs only at an environmentally stable installation site.

Then, as a solution to these problems, we developed a small sensor module intended specifically for IoT applications. This has been achieved by implementing an algorithm designed for compensation of the thermal effect of internal parts or external environments into microcontroller units (MCUs) embedded as a compensation technology for small devices. This paper outlines the sensor module thus developed and explains the temperature compensation algorithm for thermal effect compensation.

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2. Integrated IoT sensor

2.1 Configuration

The sensor module developed this time can perform more than one type of measurement simultaneously and produce a corresponding number of types of sensor data. This sensor module consists of an industry's smallest package (29.1 mm wide × 14.9 mm long × 7 mm thick) and a circuit board contained therein. The circuit board is densely populated with seven sensor elements for measuring the following physical quantities: temperature, humidity, atmospheric pressure, illuminance, sound pressure level, triaxial acceleration, and volatile organic compound (VOC) concentration. Fig. 1 shows the appearance of our IoT sensor. For data communication with a host device, such as a personal computer or gateway, this IoT sensor supports USB communication, which is widely used as the standard form of communication for serial bus interfaces, as well as Bluetooth[®] low energy (hereinafter "BLE") used as the standard form of near field communication. Thus, this is an integrated IoT sensor capable of environmental data collection for diverse applications or at various sites.

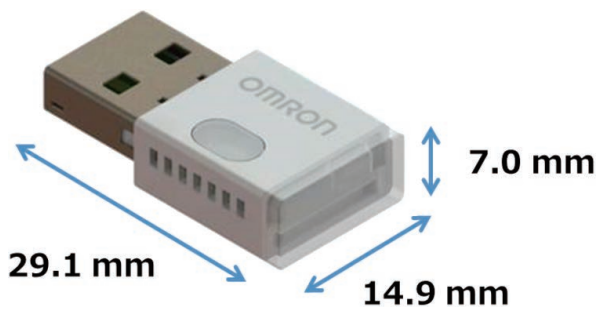


Fig. 1 Appearance and configuration of the IoT sensor

Fig. 2 shows the block diagram of our sensor module. A system-on-a-chip (SoC) equipped with BLE to write programs in the internal memory area has been adopted to provide a configuration with no host MCU used in it. Moreover, the integration of the radio frequency (RF) function and the MCU into one-chip form has led to parts reduction and thereby size reduction.

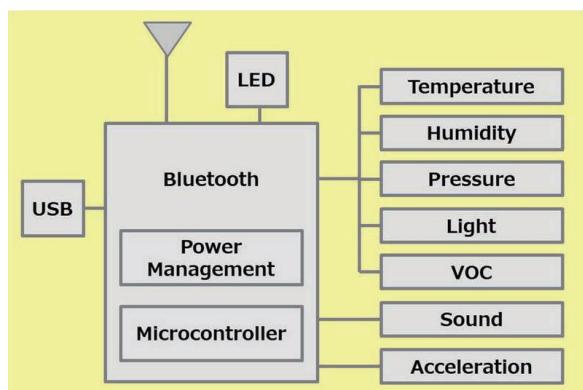


Fig. 2 Block diagram of the IoT sensor

2.2 Advantages

The distinction of our sensor module is that it has been implemented in a super-small package while equipped with multiple sensors and communication functions, as well as a high-performance algorithm. Its package size has been reduced by an approximate ratio of 1:100 on a volumetric basis as compared with that of a power supply-dependent conventional IoT sensor (210 mm wide × 148 mm long × 12 mm thick) equipped with a built-in VOC sensor. In addition, this sensor module is equipped with our proprietary high-performance algorithm that combines and converts more than one type of sensor data into information valuable to the user. Typical examples of such information are heatstroke alert levels or discomfort index values. These are indices computed using temperature data and humidity data and are expected to be utilized mainly to watch over infants, elderlies, and pets. Thus, combinations of more than one type of simultaneously collected sensor data allow creation of new value-added data.

2.3 Challenges to the conventional technology

As explained in the above section, heatstroke alert levels and discomfort index values are computed from temperature data and humidity data. Hence, accurate temperature and humidity in the surrounding environment must be obtained. A densely populated integrated IoT sensor contained in a small package is, however, vulnerable to the heat generated in a USB-connected external device or to the self-generated heat in parts mounted inside and, hence, has a problem with getting accurate ambient temperature. The basic idea of the accuracy assurance method of a conventional temperature sensor is either isolation from the heat source or reference to another temperature sensor. This makes size reduction difficult and has limited mountable sensors to those with low heat generation. As a solution to these problems, however, a temperature compensation technology has been established based on the principle of a heat flux sensor⁷⁾, which allows our sensor module to achieve accurate ambient temperature detection.

3. Thermal effect compensation technology

3.1 Causes of heat generation

Temperature is a basic physical quantity detectable by sensor devices. As such, temperature outputs must be of high accuracy. There are, however, two factors that cause larger output errors. One is the self-generated heat in electronic parts mounted in the sensor device itself, while the other is the heat generation in the external device USB-connected to the sensor device. The thermal effect from a USB-connectable device may vary depending on the temperature rise in the connected device such

as a personal computer or an AC adapter and hence may cause an error of approximately 4°C to 8°C to the temperature sensor output.

Moreover, some sensors such as VOC sensors have a built-in heater inside and may, by nature, become a heat generation source, thereby resulting in the loss of thermal equilibrium. Therefore, to miniaturize and integrate such sensors without compromising their output accuracy, it is necessary to establish a temperature compensation algorithm for eliminating thermal effects.

3.2 Principle of compensation

Our device consists of two temperature sensors arranged in series and two heat generation sources each disposed beyond that⁷⁾ and estimates the ambient temperature from the heat flow based on the difference in output between these two temperature sensors. The distinction of our device lies in its configuration in which the two heat generation sources, namely the self-generated heat in the internal parts with a high heat generation rate and the externally generated heat in the connected device, are arranged so that they can be regarded as a single heat source as viewed from the temperature sensors. Our temperature compensation algorithm performs temperature compensation based on the difference in output between the two temperature sensors arranged in series relative to the heat sources. Accordingly, this algorithm can handle multiple heat generation sources as an equivalent single heat generation source and, hence, can temperature-compensate both the self-generated heat and the externally generated heat based on a single relational expression. Fig. 3 shows the sensor layout diagram and thermal equivalent circuit of our device:

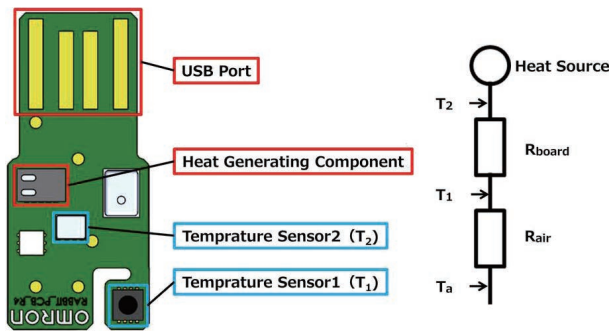


Fig. 3 Layout of on-board sensors and thermal equivalent circuit

The thermal equivalent circuit is an electrical representation of heat in which temperature, heat flow, and thermal resistance are, respectively, expressed as voltage, current, and electrical resistance, among which the following relation holds:

$$T_a = -\frac{R_{air}}{R_{board}}(T_2 - T_1) + T_1 \quad (1)$$

where R_{air} is the air thermal resistance and R_{board} is the thermal resistance of the circuit board. With these values derived beforehand by experiment, the ambient temperature T_a can be calculated from the output values T_1 and T_2 of the two temperature sensors.

In addition, the two temperature sensors used here limit the heat transfer paths on the circuit board by means of the slits formed therein. Moreover, the enclosure structure serves as a barrier and hence provides a spatially isolated structure to reduce the influence of disturbances such as natural convection on this principle of compensation, thereby enhancing the independence of the relational expression.

3.3 Experiment results

To demonstrate the effectiveness of our temperature compensation algorithm, we conducted an experiment to verify that a change in the USB-connected device or in the ambient temperature does not invalidate the compensated temperature and that the output value remains unaffected under any inclined conditions sensitive to natural convection.

(1) Thermal effects of the connected devices

Fig. 4 shows the results from the temperature output measurement performed with our sensor module connected to multiple AC adapters (ports 1 to 7), each of whose output was set differently from that of others in a 5 to 12 W range with the surrounding ambient temperature and humidity environment kept constant (at 25°C and 50%, respectively). It was confirmed that while the temperature-uncompensated outputs showed errors ranging from approximately 4°C to 8°C, the temperature-compensated outputs fell within a $\pm 1^\circ\text{C}$ error range from the reference thermometer (VAISALA MI70) regardless of the connected device.

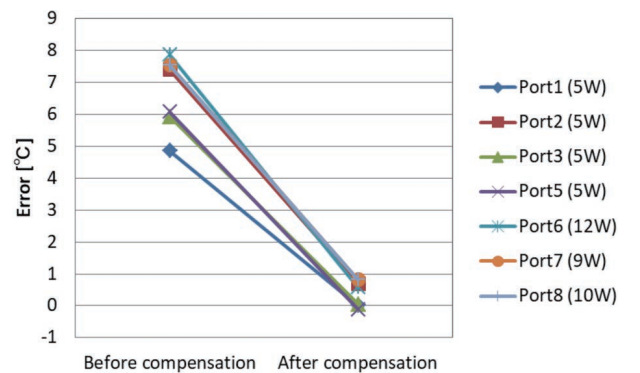


Fig. 4 Thermal effects of connected devices

(2) Fluctuation effects of the ambient temperature

Our temperature compensation algorithm is required to compensate for thermal effects properly, whether under an ordinary-temperature environment or under shifty surrounding

ambient temperature conditions. Therefore, with the connected AC adapter being the same, the ambient temperature was changed using a thermostatic bath to obtain the temperature output values from the sensors ($n = 3$; samples 1 to 3). Figs. 5 and 6 show the temperature-uncompensated and temperature-compensated errors relative to the reference thermometer. It was confirmed that by use of the temperature compensation algorithm, errors relative to the reference thermometer can be reduced to within $\pm 2^\circ\text{C}$ in the operating temperature range from -10°C to 70°C for typical modular devices.

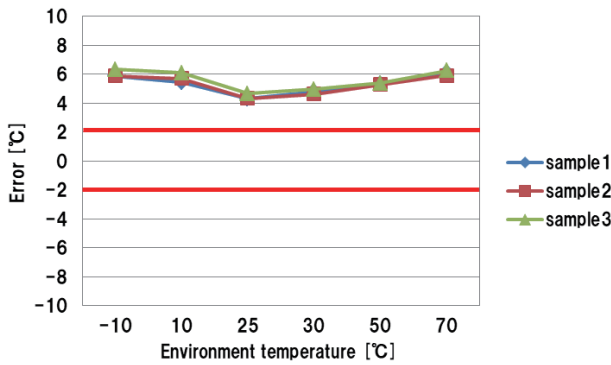


Fig. 5 Temperature-uncompensated errors relative to the reference thermometer

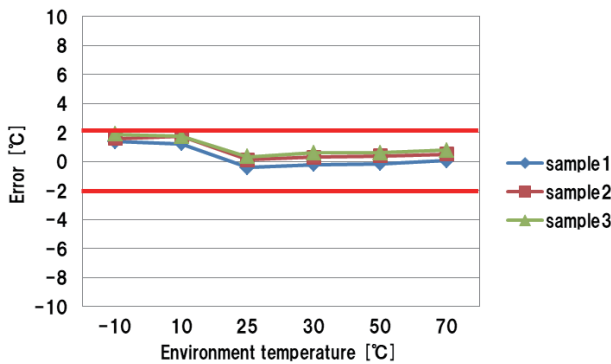


Fig. 6 Temperature-compensated errors relative to the reference thermometer

(3) Installation angle effect

The installation orientation of our device depends on that of the USB port of the external device to be connected. This means that our device must not show any temperature effect from the inclination regardless of its connected orientation. Therefore, Fig. 8 shows the evaluation results of the temperature outputs of the sensors ($n = 3$; samples 1 to 3) inclined in $\pm X$ -, Y -, Z -directions (Fig. 7) with the connected AC adapter being the same. For each inclination, the error relative to the reference thermometer was kept to within $\pm 2^\circ\text{C}$, thereby indicating that our device provided effective temperature compensation regardless of its installation angle.

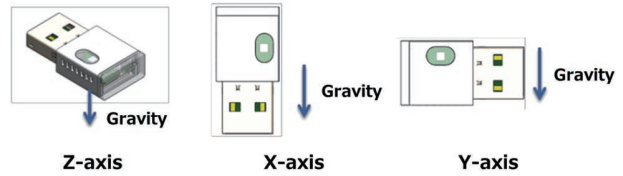


Fig. 7 Installation angles

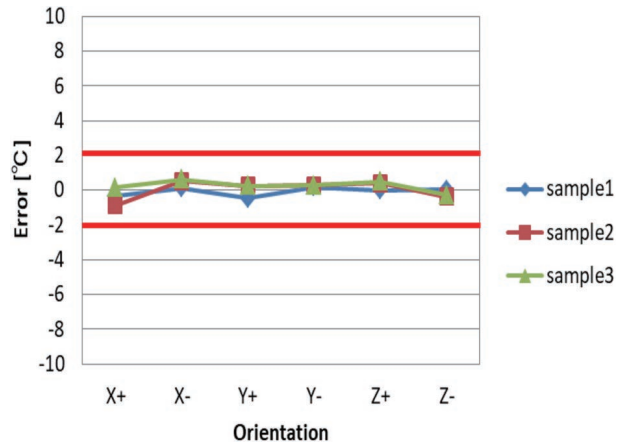


Fig. 8 Installation angle effects

The above results demonstrate that our temperature compensation algorithm serves its purpose effectively when implemented in a densely populated, small sensor device.

3.4 Discussion

The experiment results shown in the section immediately above have demonstrated that the thermal effect compensation algorithm based on the heat flow detection by the two temperature sensors can keep the sensor temperature output accuracy unaffected by the self-generated heat in the VOC sensor and by the heat generation in external devices with various heat generation rates, and hence can serve its purpose effectively.

In the relevant sensor device, two temperature sensors are arranged in series to allow estimation of the ambient temperature around the heat sources provided on the straight line extended from the sensors. We assume that it will become possible to compensate for thermal effects from more than one direction based on the ambient temperature estimates provided by an arrangement of multiple temperature sensors equipped with this thermal effect compensation technology.

When this has become a reality, our sensor device will find application in environments where the locations of heat sources are indeterminate because circuit boards are embedded singly as sensor modules in various systems. We expect that as a result, this sensor device will also support diverse use environments or applications not dependent on the power supply configuration of sensor modules, including battery-powered types.

4. Conclusion

This paper has presented a heat flow detection-based thermal effect compensation technology applicable to sensor modules. By implementing this technology into a sensor module, we developed a USB-power supply compatible, small sensor module unaffected by the thermal effect of self-generated heat or external connected devices.

This sensor module is an integration of an MEMS technology-based small sensor device, a sensor control system, and a wireless communication function. As a result of the application of our algorithm, this sensor module can keep temperature outputs at high accuracy of $\pm 2^\circ\text{C}$ under any use environment. Moreover, it has achieved the world's highest level of integration through miniaturization among integrated sensor modules provided with heater-equipped sensors such as VOC sensors.

Size reduction frees sensor modules from installation site constraints and leads to a significant improvement in the degree of freedom in the design of equipment or structures into which the sensor modules are embedded. This will make it possible for an IoT society swarming with an infinite number of data collection sensors and sensors installed in various places to come into close contact with our communities and lives to obtain information so far unobtainable. This, as a result, will accelerate the creation of new applications and services, which in turn will contribute to solving social problems. We will continue with the development of easy-to-use sensor modules that enable various forms of sensing required in the IoT society to come.

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