Development of Mobile Radiation Monitoring System Utilizing Smartphone and Its Field Tests in Fukushima

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***Abstract*—We developed a series of inexpensive but accurate and mobile radiation detectors, which we named Pocket Geiger (POKEGA), to address the desire of ordinary people to own a radiation detector following the March 2011 Daiichi Nuclear Power Plant accidents in Fukushima, Japan. To reduce costs while maintaining accuracy and flexibility, we used a combination of a p-i-n photodiode detector connected to a smartphone via a microphone cable. The detector circuit design is optimized for simplicity and low cost, whereas the smartphone software application is tasked with handling the complex processing required. Furthermore, the device also used the GPS and networking capabilities of the smartphone for logging and data sharing. The ^{137}Cs measurement range for a POKEGA-equipped smartphone is approximately from 0.05 to 10 mSv/h, which covers most radiation levels measured in Japan. Approximately 12 000 POKEGA units were shipped in the six months following its release, and 2 000 users have joined a Facebook community where they report measurement results and discuss hardware and software improvements. In parallel, we have addressed practical problems for POKEGA, such as vibration noise, energy consumption, and operating temperature, by conducting field tests in the Fukushima evacuation zone. The POKEGA series has been improved by solving such issues. This article reports on a new style of pragmatic sensor networking methodology, from the aspects of emergency response engineering, open-sourced development, and consumer-generated measurements.**

***Index Terms*—Radiation detector circuits, radiation monitoring, wireless sensor networks, project management.**

Fig. 1. Pocket Geiger (Type 4) and its PCB.

I. Introduction

THE Daiichi Nuclear Power Plant accidents in Fukushima have stimulated desire of ordinary people to own radiation sensors. A portal site named Radmonitor311 [1] has been reporting summarized radiation data observed by public agencies or institutions since March 16, 2011, while at almost the same time, the SAFECAST [2] team started data collection of air dose-rates using mobile sensors. However, even though people were able to learn the geographical trends of radiation levels from those sites, they still needed their own sensors to measure radiation levels in their homes, schools, or playgrounds. Unfortunately, conventional radiation sensing instruments, such as scintillation counters or GM Tube survey meters, are too expensive for members of the general public, as well as being difficult to obtain and use. Furthermore, all such instruments were in short supply due to the demand surge that followed the accident.

To address these needs, we founded Radiation-watch.org in May 2011. This is an open-source and non-profit project involving a number of volunteer engineers and scientists. As part of this project, we initially released a unique radiation detector named POKEGA (Figure 1) in August 2011, designed to be connected to a smartphone.

In order to reduce costs while maintaining accuracy and flexibility, we used a combination of a PIN photodiode detector and a smartphone connected via a microphone cable. It has previously been known that a PIN photodiode can detect various nuclear radiations at its depletion layer [3]–[8] and functional, sample implementation has been shown using general PIN photodiode and charge amplifier [9].

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Yacong *et al.* presented a special CMOS circuit for efficient and low-power, radiation detection [10]. However, our project marks the first time a photodiode of this type has been combined with general smartphone in a practical manner. Similar products, such as S.T. Air Counter® or SHARP 107SH, have been released following POKEGA, but they are commercial goods and neither open-sourced nor social product.

In Section II, we will discuss hardware design incorporated into the device, such as its smartphone linkage, cost minimization, and rapid development, and provide a history of POKEGA modifications made in response to requests from the general public and field tests. In Section III, we show the software design for POKEGA, including its geographic information system (GIS) features for sharing radiation readings. In Section IV, we show the results of POKEGA performance testing and discuss related considerations. In Section V, we show results of field tests in the Fukushima area. Because collaboration between scientists, engineers and users was (and is) crucial to the rapid development of POKEGA, in Section VI, we discuss how such social inclusion was made possible via the Internet. Finally, in Section VII, we summarize the development model of the action research in terms of the startup, development, and operation phases.

II. Hardware Design

As shown in Table I, the POKEGA series was designed to supply low-cost radiation detectors capable of connecting to smartphones. Types 1, 2 and 3 use eight general-purpose PIN photo diodes, while Type 4 and 5 mount single FirstSensor X 100-7 high-sensitivity, large-are PIN diode. Figure 2 shows block diagrams for Types 1 through 5, while Figure 3 shows a circuit diagram for the Type 1 device.

Type 1, the first model of the POKEGA series, was marketed in an unfinished, easy-to-assemble kit-style package in order to facilitate rapid development and cost reductions. Users were asked to purchase a package of FRISK® candy as the detector case. They were then instructed to prepare a ten Yen coin for use as a beta-ray shield. The development period for the Type 1 device was just three months, and the retail price was approximately $23 US (when shipped within Japan domestically). It was the first consumer-oriented dosimeter released after the accident in Japan and was the least expensive smartphone-based radiation detector in the world.

Generally speaking, the output pulse from a photodiode is quite low and narrow, while the input gain and sampling rate of a smartphone are extremely low and slow, respectively. Accordingly, in the Type 1 version, the time constant of the charge amplifier was optimized so that narrow radiation pulses could be detected using the low sampling rate of the smartphone audio circuit. Furthermore, since the input gain and frequency characteristics of the analog-to-digital (A/D) circuits vary somewhat depending on the model or generation of the smartphone, the application software discriminates radiation pulses from background noise by means of thresholds, as shown in Table II. In the table, α is a conversion factor between the dose rate r [μSv/h] and the count rate n [cpm] as defined by following formula:

$$n = \alpha r \tag{1}$$

TABLE I

POKEGA Development History

Type / Release date	Platform(s)	Sensor(s)	Feature(s)
Type1 Aug, 2011	iOS®	VBPW34 8 pieces	KIT-style
Type2 Feb, 2012	iOS®	VBPW34 8 pieces	Voltage generation by earphone signal
Type3 July,2012	iOS® Android®	VBPW34 8 pieces	Built-in comparator IC and Vibration detection
Type4 Aug, 2012	iOS®	X100-7 1 piece	High sensitive radiation sensor
Type5 June, 2012	Arduino® AVR®, PIC®	X100-7 1 piece	For embedded micro controllers

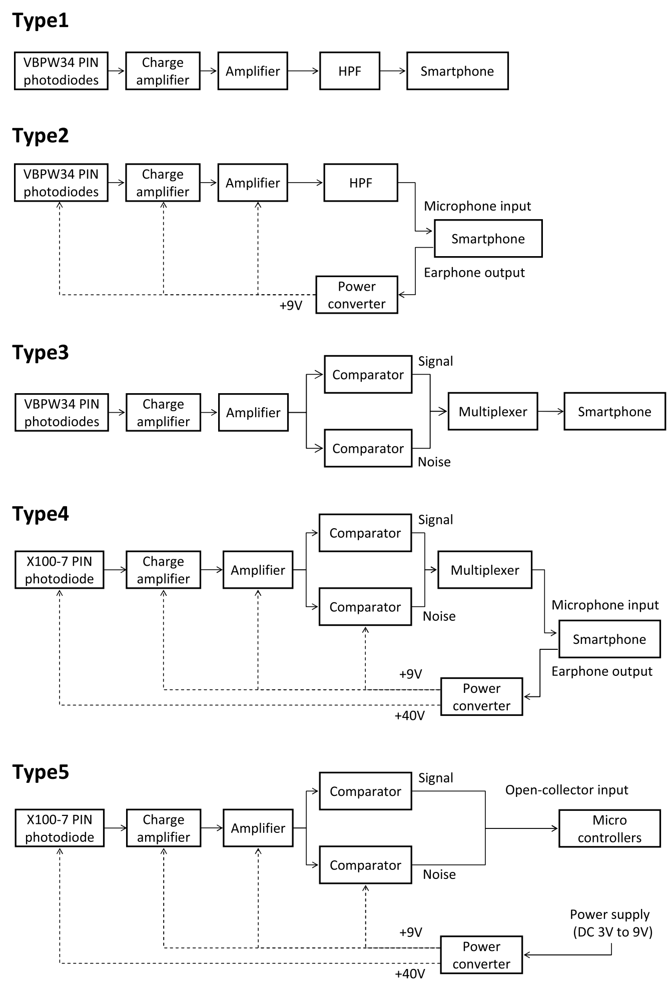

Fig. 2. Block diagrams for Types 1 through 5.

The Type 2 model was designed to power from the smartphone because, in the aftermath of the disaster, dry-cell batteries were difficult to obtain due to the need to power radios and/or flashlights, especially in and around the affected areas, as well as in areas subject to electric power blackouts. Therefore, in the type 2 device, we have implemented an internal voltage-generation circuit that uses an earphone stereo tone generated by the application software.

The signal is a high-volume, reverse-phase sinusoidal wave configured so that any noise elements cancel each other.

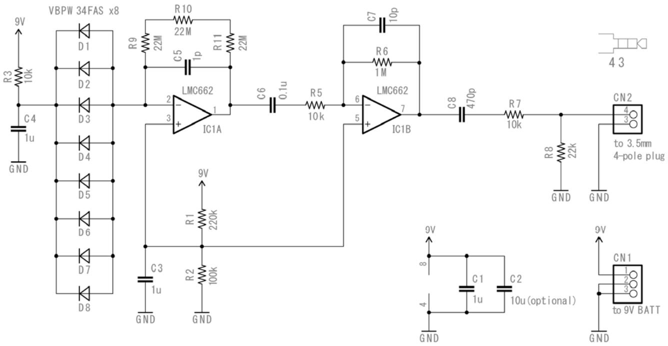

Fig. 3. Circuit diagram for the Type 1 device.

TABLE II
THRESHOLDS OF RADIATION PULSE ON iOS® Devices

Model	Generation	Threshold	[cpm/(uSv/h)]
iPhone® 3G	-	20.0	11.84
iPhone® 3GS	-	14.0	10.46
iPhone® 4	-	14.0	10.22
iPhone® 4S	-	16.9	10.37
iPod® touch	2nd	13.0	12.21
iPod® touch	3rd	13.0	12.21
iPod® touch	4th	13.0	13.33
iPad®	1st	16.0	9.855
iPad®	2nd	17.0	10.64

In order to prevent hearing damage in situations where users accidentally connect headphones to the smartphone while the POKEGA application is running, the signal frequency was set at 20 kHz, which is just above audio frequency for human. However, the Type 2 device does not support iOS® devices sold in Europe, because EU regulations limit headphone output of personal music players to a maximum of 95 dB to prevent hearing loss [11]. This limited audio output is insufficient to power the Type 2 device.

Accordingly, we then developed the Type 3 device to support such European iOS® devices as well as Android® devices. The Type 3 device has a comparator circuit and digital output for radiation pulses along with a pull-up resistor that allows it to be connected to various smartphones. Furthermore, it is also equipped with a noise-detection circuit because, generally speaking, PIN diodes are susceptible to noise vibrations. There are two thresholds in the circuit; one is used to detect radiation pulses, while the other is used to detect the noise vibrations, as shown in Figure 4. The Type 3 device outputs a negative pulse at the microphone when vibration noise has been detected, after which the application cancels any recently detected radiation pulse(s).

The Type 4 device was developed to reduce measurement time. Under Japan's normal radiation levels, it takes about two minutes to get dose-rate readings using the Type 4 device, while it takes about twenty minutes using Types 1, 2, or 3. The Type 4 device uses a large-area X 100-7 PIN photodiode, which requires high voltage bias, so it also incorporates a four-stage Cockcroft-Walton voltage generator. The Type 4 device

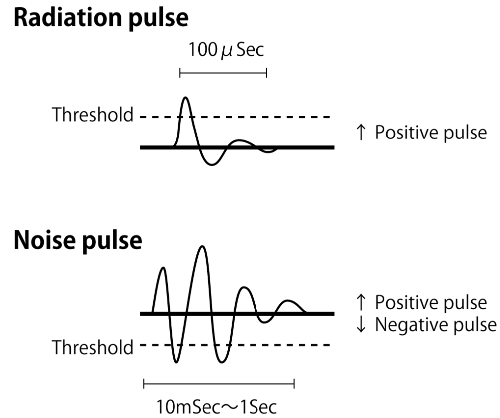

Fig. 4. Detection mechanism for noise and radiation pulses.

also has a comparator and noise-detection circuit similar to the Type 3 device.

The Type 5 device is a latest model, so far. It was designed for remote sensing using embedded microcontrollers, such as Arduino®, AVR®, or PIC®, in widespread open areas such as agricultural land or forests. Furthermore, the device uses one X100-7 and has open-collector radiation pulse and noise pulse outputs similar to the Type 4 device.

III. SOFTWARE DESIGN

Core calculations, such as A/D conversion, filtering and threshold comparison are performed by a software application installed in the smartphone. The design process has made the application very adjustable, and thus capable of handling device differences, as shown in Table II.

The software is designed to visualize radiation measurements. In the top and left image of Figure 5, the solid line shows the moving average of μSv/h readings vs. elapsed time, while the shaded range shows the standard error of one sigma, which is calculated by means of the following formula:

$$n \pm \sigma = n \pm \frac{n}{\sqrt{2n\tau}}. \quad (2)$$

Here, n is the count rate [cpm], σ is the standard error, and τ is the time constant [min] to calculate the moving average. The default value of τ is 20 [min] for Types 1, 2 and 3, and 2 [min] for Types 4 and 5. This visualization helps users to understand the convergence of the counting error.

The top right image in Figure 5 shows a heat map that contains data, reported by users, corresponding to measurement and position data. In this figure, concentrations of higher dose rate dots are seen in the Fukushima area, while scattered hotspots are visible in other areas across Japan. This log was stored in our server with the explicit consent of the reporting users and does not contain personal information, such as user identifiers (UIDs).

The application also has various other technical features, as shown in the bottom images in Figure 5, such as an oscilloscope view of the input signal waveform, a multi-channel analyzer (MCA) for input pulse height, a counting log view, and a total dose graph.

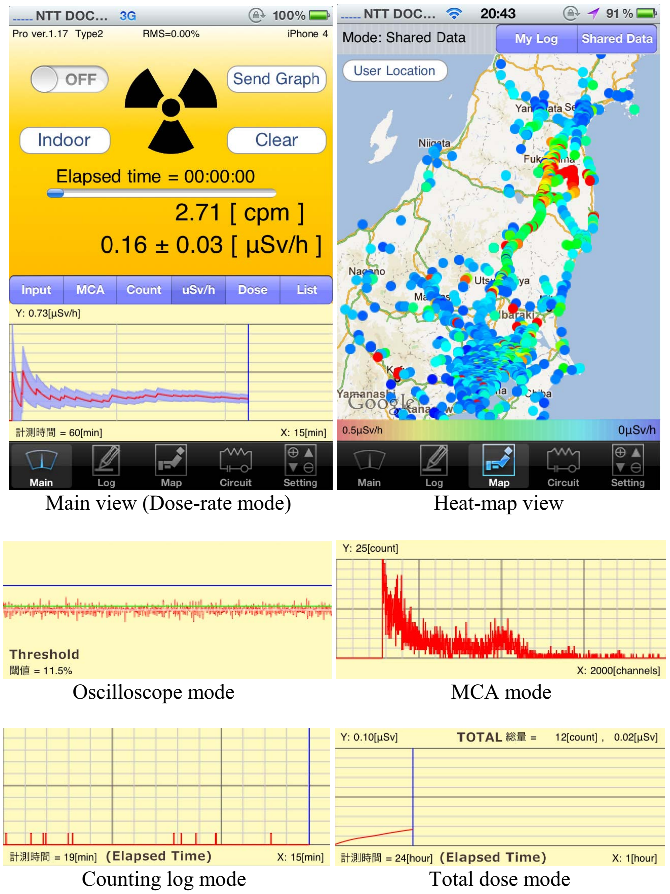

Fig. 5. Screen captures of the POKEGA application: main view (dose-rate mode), heat-map view, oscilloscope mode, MCA mode, counting log mode, and total dose mode.

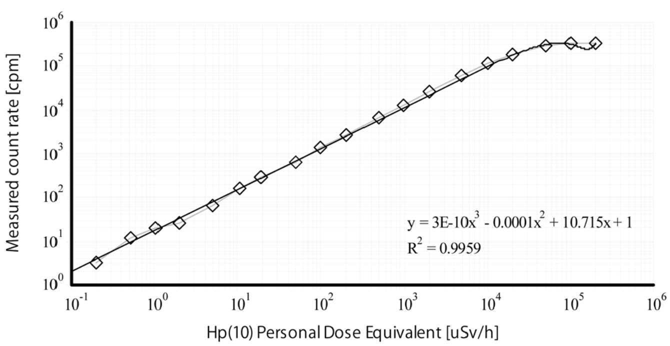

Fig. 6. POKEGA measurement range using 137Cs.

The development of such application features were inspired by users' suggestions, which were collected through POKEGA's Internet community. Those interactions will be discussed in Section VI.

IV. Performance Testing

According to the results of performance testing based on Hp(10) scope [12], POKEGA Type 1 shows about a 5-decade linear response for ^{137}Cs, as shown in Figure 6, but it became saturated at dose rates over 10 mSv/h due to sampling limitations. The measurement range of the detector for ^{137}Cs determined from approximately 0.05 μSv/h to 10 mSv/h, and from 0.01 cpm to 300 kcpm. This range covers almost all radiation levels measured in Japan. Figure 7 shows a picture of an experimental setup at the Delft University of Technology in the Netherlands.

Fig. 7. Photo of an experiment performed at the Department of Defense of The Netherlands.

The MCA feature was tested using several photon energies, but the resolution was very low because sensing layer is too thin to have enough photoelectric absorption. As a result, it is not enough for energy discrimination. However, most consumers using these devices do not need energy discrimination because the radioactive materials currently found in Japan's surface soil consist primarily of ^{137}Cs and ^{134}Cs.

In the POKEGA Type 1 device, a 10-yen coin was used as a beta-ray shield. Such coins are 95% copper and are approximately 1.5 mm thick. The use of a thicker metal filter could flatten the response curve of PIN photodiode based gamma-ray detectors [13]. Therefore, the coin was determined to be one of the most suitable beta-ray shielding materials available, primarily because it is cheap and very easy to obtain.

When the incidence angle of gamma-ray was set to 45 degrees, the sensitivity of POKEGA Type 1 device decreased 22% because of the direction dependence.

V. Field Tests in Fukushima Area

We conducted field tests using POKEGA series devices to determine the practical needs for mobile radiation monitoring in devastated areas such as Fukushima. The tests were carried out in cooperation with the local government staff on 10 occasions from February to September 2012, in the evacuation zone around the Fukushima Daiichi Nuclear Power Plants. During those tests, government officials commented that POKEGA had a significant potential to contribute for security verification when evacuees return for brief visits, or to resume permanent residence in the future, because they can survey of multipoint radiation levels using multiple mobile radiation sensors continuously.

Figure 8 shows the system used in the test to collect and visualize dose-rate data in the evacuation zone. The weather during the tests was mostly clear. In our tests, the POKEGA was set on a dashboard in a car. Figure 9 shows a view of the test setup from within the vehicle.

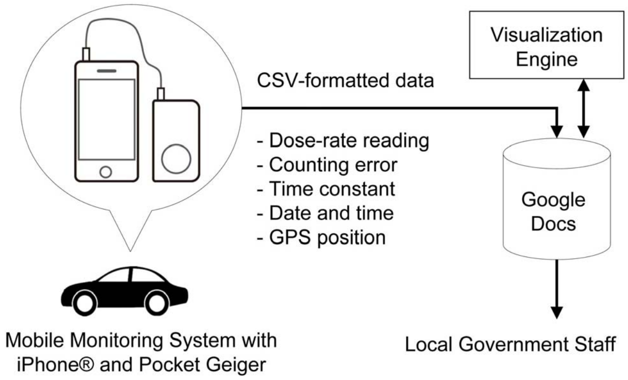

Fig. 8. Mobile radiation monitoring system with Pocket Geiger.

Fig. 9. Photo taken during mobile monitoring in the Fukushima area.

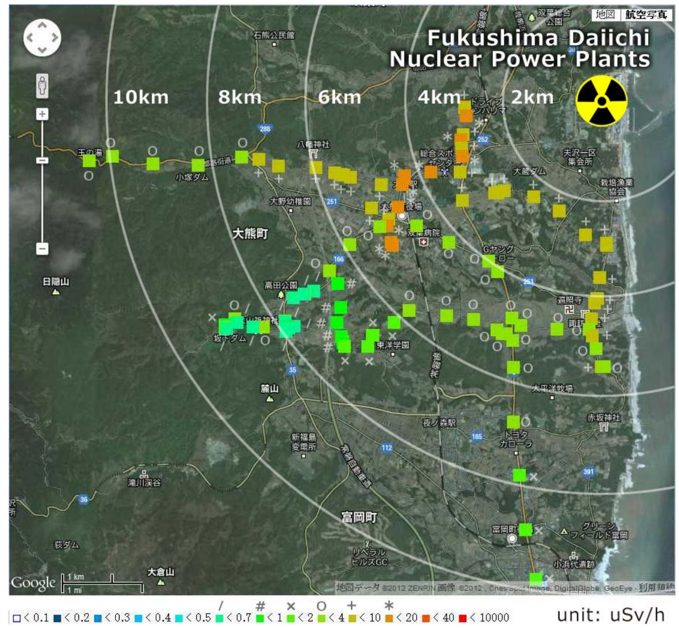

Fig. 10. Visualization of radiation levels around Fukushima Daiichi Nuclear Power Plants.

Although the original POKEGA application is capable of sharing and visualizing radiation levels with all users, as shown in Figure 5, it was necessary to create a closed system in the demonstration because of local government security policies.

Figure 10 shows a heat map of the radiation levels measured around the power plants. As can be seen in the figure, the level tends to be higher nearer the plants, but still differed, even in same zone. For example, the reading range was from 2 to 20 μSv/h in the area 2 to 4 km away from the accident site, and dose-rates were recorded higher towards north (top side). This wide variation in readings resulted from various natural environmental conditions, such as weather, vertical intervals, and/or vegetation.

During our tests, two problems were found. One was vibration noise. Numerous roads were damaged by the earthquake and the tsunami, but most of them have not yet been repaired. As a result, when driving on damaged roads at between 40 and 50 km/h, vehicle motions often created vibration noise that resulted in incorrect readings. The noise-detection and cancelling mechanism in the Type 3, 4 and 5 devices were created as a countermeasure to this problem.

The second problem was energy consumption. Even though most vehicles have DC power outlets that can charge to smartphone batteries, it was sometimes necessary for the researchers to get out the car in order to take readings in severely damaged residential districts. Currently, battery duration is about three hours when the application is running on iPhone® 4S continuously, which it is insufficient for a practical standpoint.

Therefore, we have developed a low-power consumption version of POKEGA with a special CMOS charge amplifier for radiation detection, and, in parallel, improve the GPS power handling at the application software to reduce power consumption by switching it on and off frequently.

Mizoguchi *et al.* conducted field-testing to monitor radiation levels in Iitate Village, Fukushima Prefecture, which is about 40 km away from the power plants, beginning around October 2011 [14]. The village has numerous agricultural fields and is surrounded by forest. Some areas of that village have designated as resident-restriction zones by the Japanese government because their air dose-rates are quite high (more than 50 mSv/year), and it is very important to determine the effectiveness of decontamination efforts, particularly in hotspot areas.

In addition to these continuous measurements, it is also important to clarify, to the greatest extent possible, the relationship between radiation levels and weather conditions, such as precipitation and wind, both of which are known to transport radioactive materials. Furthermore, the relationship between precipitation and the turbidity of agricultural runoff also needs to be clarified because the runoff after heavy rain contains significant amounts of clay particles that catch radionuclides.

Since July 2012, Mizoguchi *et al.* have installed a total of six Field Monitoring Systems (FMSs) in the village. These systems measure the radiation levels and transmit the data to a server via mobile Internet connections, together with image data and hourly data related to the meteorological parameters, such as humidity, temperature, precipitation, and solar radiation. We developed and provided prototypes of Type 5 devices for use as the FMS.

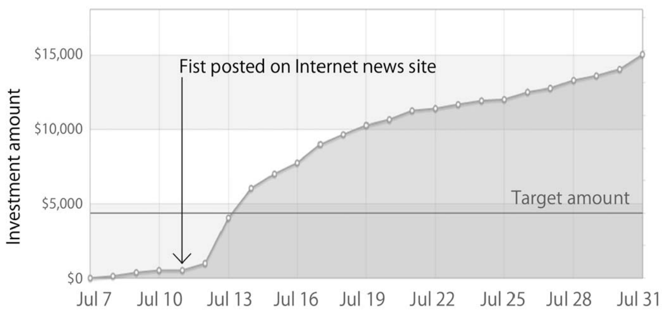

Fig. 11. Project investment amount trends from Kickstarter.com.

Another problem related to our tests involved the devices were thermal properties. In outdoor environments, radiation detectors can sometimes be exposed to summertime sunrise, as a result its temperature rises up to more than 40 °C (even if the ambient air temperature is less than 30 °C). Because this level of temperature often causes radiation sensor malfunctions, our Type 5 device was designed to operate at a maximum operating temperature of 50 °C.

The above mentioned field tests clarified a number of practical problems related to the POKEGA, such as vibration noise, energy consumption, and operating temperatures, and solving such problems have enhanced the effectiveness of the POKEGA series.

VI. Forming Internet Community

We have chosen the cloud-funding site Kickstarter.com to raise money for our initial project expenses. Figure 11 shows the investment trends of our project. A number of popular Internet news sites, including Gizmodo or Makezine, featured the project at the beginning of July, 2011. In the time since then, the project page has been shared via various social media thousands of times, and the investment trends have risen rapidly.

Furthermore, through various social networking sites (SNSs), we have received unexpected offers of help from various scientists and engineers in the form of technical advice and calibration testing. As of this writing, the project is supported by 167 backers and special collaborators from 23 countries. This demonstrates that cloud funding has been quite effective, for not only financing, but also for attracting experts sympathetic to the goals of the project.

There are now approximately 12 000 POKEGA users and more than 1 million pieces of information, including GPS information, have been collected from them. Currently, about 2 000 people have subscribed to the project's Facebook group [15], where they have posted thousands of comments. That group was created primarily to support users, but has since developed into an autonomous community; the majority of the topics relate to sharing dose rate reports from various areas, as well as follow-ups by nearby inhabitants or radiation specialists. These interactions have contributed to improving the radiation literacy of the general public because air dose-rate readings differ, even in limited areas, depending on natural environmental conditions such as weather, vertical intervals, and/or vegetation.

The second most popular topic is user's feedback to improve POKEGA's hardware and software, which is primarily based on open-source, technical documents. We have been inspired by many of the ideas and have adopted a significant number of them for use in new versions. Those ideas have covered a variety of topics, such as voltage generation, comparator circuit use, vibration detection, and the use of high-sensitivity diodes.

VII. Summary

We report new pragmatic development for sensor networking and note the following advantages.

1) Startup phase: social funding was effective not only for creation of new devices but also for recruiting specialists.
2) Design phase: rapid development was possible by aggressively adopting general-purpose components, including smartphones, as emergency response engineering.
3) Development phase: sharing open-source intellectual assets via the Internet, stakeholders, such as developers, experts, and members of the general public, have created voluntary technical interactions on POKEGA's hardware.
4) Field test phase: field tests in affected areas have allowed us to identify practical problems and have provided clues for improvements.
5) Operation phase: members of the general public have shared radiation level readings collected using their own sensors (i.e., consumer-generated sensing).

We believe that the abovementioned advantages and observations have application potentiality for other sensor network systems.

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