An Electrostatic Capacitive Floor Sensor System for Human Position Monitoring in a Living Space

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Abstract

This paper presents a prototype of electrostatic capacitive floor sensor system with low-cost, easy-installation and maintenance-free advantages for monitoring human position in a living space. Features of the sensor system are conciseness that the system is made of very simple parts, that means it is inexpensive, and modularity that enables easy expansion of the sense area. Experiments confirmed the sensor characteristics for human monitoring and showed the feasibility of the accurate sensing with only concise recognition and filtering processes.

keywords: Electrostatic capacitive sensor, Human position monitoring, Intelligent environment, Sensor network, Ambient intelligence

1 Introduction

Recent years, many sensor systems have been developed for safety and peace of mind. For nursing care of the elderly, there are various kinds of monitoring products in the market[1, 2], and these products can compensate lack of human-power in nursing-care facilities. Although some products require the resident to carry small devices, we will not adopt the mobile/wearable type devices but the environmental sensors, because wearable devices may restrict the locomotion freedom of the subjects.

Popular market products of environmental sensor systems utilize infra-red sensors, pyroelectric sensors and physical switches. These sensors are suitable for the robust monitoring of human movement in a specific area, and have substantial cost advantages. However, infra-red sensors and pyroelectric sensors are not as effective when human beings stay static in the environment. Besides these popular products, some researchers proposed several systems with optical instruments, such as normal/infra-red vision and laser ranger finder (LRF)[3, 4]. But they have disadvantage of the privacy and occlusion problems for actual home-use.

In previous works, we proposed several floor pressure sensor systems to overcome the above problems[5, 6]. There are many contemporary researches to recognize the human position and make some support via monitoring floor pressure changes. For example, Rangarajan et al. have developed a floor sensor with high modularity[7]. However, such floor pressure sensors have substantial complex structures, accordingly the manufacturing and installation cost are expensive for home application. Additionally, the pressure sensor generally has deformable parts. These deformable parts need frequent maintenance which further increases cost.

In this paper, we aim to develop a novel floor sensor system with low-cost, easy-installation and maintenance-free advantages.

The framework of this paper is as follows. Section 2 describes related works and our approach, and summarizes required specifications and design items. Section 3 explains about design and implementation of the floor sensor system. Section 4 describes basic experiments and section 5 shows a recognition process. Finally, section 6 is conclusion.

2 A electrostatic capacitive floor sensor system for human position monitoring

2.1 Related works and our approach

As described in the first section, there are several related works of a floor sensor system for human position monitoring. Most previous works detect the floor deformation by human weight with load cell, FSR or pressure sensitive elastomer[8, 7]. A latest sensor system uses electromagnetic induction method and realizes large sensing area and high competitiveness in manufacture cost[9]. However, these pressure sensing method needs deformable parts, therefore we adopt electrostatic capacitive sensing method instead. These days, many mobile equipments (i.e. cellular phone and music player) utilize capacitive touch panels. The capacitive method can directly detect the contact or approaching of human body, and remove the deformable parts. The feature drastically makes the sensor structure simple.

There were some related previous works of capacitive human tracking system.

D. Savio et al. presented "Smart Carpet"[10], and it can automatically organize the connection between multiple sensor modules. The advantage of the system is network configuration protocol, but they did not mention the robustness of the sensors and the hardware design is a little complicated.

M. Valtonen et al. proposed "TileTrack"[11], and it can comprise very small number of parts. However, it uses separated transmitters and a receiver, therefore some object in the measurement space may affect to the measurement accuracy in the whole of space. In addition, it may be difficult to track multiple persons.

R. Henry et al. presented a human tracking system using near filed imaging[12]. The hardware configuration is similar to our work and very concise, but the measurement method is a little different. Their work used a low frequency and low voltage carrier signal, and the method cannot neglect the influence of stray capacitances and environmental noises.

Each previous work has both advantages and disadvantages, however, these previous works just proposed novel sensing systems. That is, they did not evaluate how robust the sensor system is in various conditions; subject variations, contact conditions and installing environments. The capacitive touch panels on the mobile devices are very small and can ignore the effect of configuration variations. On the other hand, our application requires a large and various sensing area. Consequently we have to address the problem of environmental noise reduction and evaluate the robustness in various conditions.

2.2 Required specifications

We assume the target application as monitoring of the elderly people's locomotion and infant children's actions. Especially we want to detect the falling down of the elderly and dangerous playing actions of the infant children, such as climbing on a furniture. To realize those applications, following specifications are necessary.

Installation method Floor sensors will be placed in a matrix state to cover substantial large space, and each sensor outputs its sensing result independently, it means no process is included for the center calculation.

Output of sensor Binary output of human contact or no contact. Our target is detecting the existence of contact between a human body and the floor, therefore it is unnecessary to recognize contact condition in detail.

Space resolution and modularity The sensor space resolution should be precise enough to monitor the human position, and human foot size is approximately 150 $\sim$ 300 [mm]. In addition, each sensor must be modularized to make it easy to cover whole living space. To satisfy the above requirements, we set each module size as 300 [mm]$\times$ 300 [mm].

Sampling rate When recognizing static condition such as sitting, lying and standing, sampling rate can be slow (1 [Hz]$\sim$). In contrast, when dynamic motion such as walking should be recognized, sampling rate must be quick enough (4 [Hz]$\sim$). Because the number of walking steps per second is approximately 2 [steps/s] for adult.

Thickness The floor sensor should be compatible with popular floor materials. Generally the thickness of wooden floor materials is regularized as 12 [mm] or 15 [mm], therefore we configured the sensor thickness as 12 [mm].

Module connectivity When installing the floor sensor, the connectivity between sensor modules must be high/easy enough, therefore, the sensor modules' connection must be realized without complex mechanical or electrical connectors.

2.3 Design items

Before describing design details, this section summarizes design items.

(A) Electrostatic capacitance measuring method We don't aim to measure the electrostatic capacitance precisely, but aim to recognize the human contact with simple parts.

(B) Power supply and data communication method Modularized sensors have to transfer electrical power and data to neighbor modules.

(C) Installation method The floor thickness restriction (12 [mm]) is so severe to realize high connectivity that the sensor structure should be designed carefully.

3 Design and implementation of the sensor system

This section describes the design and implementation of the former design items.

3.1 Electrostatic capacitance measuring method (A1)

Our target sensor system needs a concise measuring method. Recently, there are several micro-controller products with a measuring function of electrostatic capacitance. In the future final products, we will also introduce some micro-controllers with special functions. However, the current micro-controllers are designed to measure the capacitive variance on small touch panels (probes), and may mis-recognize the environmental noises as human contacts. Therefore, we developed the electrostatic capacitance measuring components by ourselves, and tried to reduce environmental noises with a filtering process.

Figure 1 shows candidates of the measuring method that are suitable for our conciseness requirement.

(a) Hysteresis oscillation method As shown in Figure 1(a), this method utilizes an inverter IC, and measures the frequency of CR oscillations. This is a very simple method, but sensitive to the environmental noises when the target electrostatic capacitive variance is small.

(b) Pulse conversion method As shown in Figure 1(b), this method measures the pulse width that is generated by the switching of the capacitor discharge and charge. This method is also sensitive to the environmental noises.

(c) Voltage separation method As shown in Figure 1(c), this method measures the voltage separated by two capacitors (C1, Cref), and calculates the C1 from the voltage values.

This research adopted the pulse conversion method (b), because the method can be composed of very simple electrical parts such as timer IC 555, and it is suitable for non-powerful micro-controllers. To address the problem of environmental noises, a brief statistical signal process was used. The detail is described in Section 5.

3.2 Pulse generation method (A2)

For the pulse conversion method, there are two pulse generation methods.

1. Monostable method: this method outputs one shot pulse invoked by a trigger signal.

2. Astable method: this method configures a self feed-back loop, and outputs continuous pulses.

The monostable method enables a micro-controller to decide the pulse starting time based on the trigger pulse, but we need trigger outputs and have to care the stability of the output pulse. On the other hand, the astable method measures one of repeated stable pulses, but the micro-controller must detect the pulse starting edge accurately. The performance difference cannot be estimated simply from the IC data sheet, we executed an experiment to compare the performance (Section 4.1).

3.3 Ground setting (A3)

Figure 2(a) shows the principle of the general touch sensors. Here, the human can be a ground between two probes, and an approaching human reduce the electrostatic capacitance. In this method, the probes must be placed side by side, and this condition restricts the probe shape and layout design.

We adopt a probe layout as shown in Figure 2(b). In this layout, an approaching human increases the electrostatic capacitance. The ground sheet does not contact with human, hence it can be a simple metal sheet. If a ground sheet is installed, there is no capacitance change between the floor metal and the probe. If the distance between the floor metal and the probe is substantially long, we might be able to omit the ground sheet as presented in Figure 2(c).

This research examined the effect of the ground sheet by experiments.

3.4 Power supply and data communication method (B)

There are two ways for power supply and data communication; wired or wireless. In the previous work [13], the measuring circuit was found to consume approximately 30 [mW]. This power supply cannot be realized by batteries without frequent batteries' charge or exchange. Therefore, the power supply must be wired.

Meanwhile, the data communication can be realized by a low-power and non-expensive wireless communication device. Such a wireless module can reduce cables, and realizes high module connectivity. Especially, modern wireless communication modules have functions of automatic network making and data error correction. Those functions can release us from bothering task for construction of robust communication network, such as ADNOS[10]. Consequently we adopt XBee, a ZigBee (2.4 [GHz]) compatible module.

In summary, we use wired power supply and wireless data communication.

3.5 Installation method (C) and summary of the design

Figure 3 indicates the framework of the floor sensor system.

A sensor module comprises three parts; (1) a metal plate (sensor probe) for detecting electrostatic capacitive variation, (2) a sensor body that supports sensor probe and realizes high connectivity between the neighbor modules, and (3) a ground sheet. Nine sensor modules are unified as one component, a measuring circuit is placed at the center of nine modules. Figure 4(left) shows the overview of the developed floor sensor system. This framework can reduce the number of circuit. As Figure 4(center) shows, the sensor body has connection channels at every corner, and the neighbor modules are connected by metal connectors. Figure 4(right) shows the implemented circuit and its thick is less than 7 [mm]. The power supply cable is designed as daisy chain. Figure 5 illustrates the installation procedure of the floor sensor system. The mechanical and electrical frameworks realize high modularity and easy installation. Current sampling rate is 6 [Hz]. The bottleneck is wireless communication because current transferred data contains raw values of sensors but binary data is sufficient in practical use, and baud rate is 38.4 [kbps] (250 [kbps] is maximum at XBee). Therefore there is a room for acceleration.

4 Experiments

This section describes basic performance experiments of the developed floor sensor system. First, we examined the difference of the pulse generation methods and selected one method. Next, we executed experiments with various conditions.

4.1 Comparison experiment of the pulse generation method

This experiment compares the two pulse generation methods; the monostable method and the astable method. Sample data is acquired while a subject touches to a probe with standing posture.

Figure 6 shows the histogram of the measured data in two methods and two contact conditions. The horizontal axis is the sensor value and the vertical axis is the repetition of each value. The number that follows # mark is trial number. The result indicates that the astable method is stable enough when there is no contact and distinguishable when there is a human contact comparing with the monostable method. The astable method has an advantage that it does not need the trigger outputs and can save the IO pins of a micro-controller. Therefore this research selected the astable method that fits to a low-price micro-controller.

4.2 Experimental setup

This section describes the experimental setup for the following sections.

- Subject: three persons.
  ⇒ Subject A: male, age 20s, 173 [cm] tall, foot size 27.5 [cm], Subject B: female, age 20s, 158 [cm] tall, foot size 24.5 [cm], and Subject C: male, age 20s, 188 [cm] tall, foot size 27.5 [cm].
  The physical size of the subjects was varied intentionally.
- Installation location: two sites. ⇒ On a metal floor and on a wooden floor.
- Contact channel: four variations. ⇒ Two channels (CH0 and CH8) with the ground sheet and two channels (CH3 and CH4) without the ground sheet.
- Contact condition: both feet or one foot. ⇒ Wearing socks and no stride on multiple probes.

- Data number, 100 samples acquired at 6 [Hz].
- Repetition number: three (nine for no-contact).

162 different data were acquired based on the above setup. In the following sections, adequate data are selected to compare each discussion item.

4.3 Whole tendency of the electrostatic capacitive variation

Figure 7(a) shows the sensor output without a human contact and Figure 7(b) shows the output with a contact. Figure 7(c) shows the standard deviation of the output without a human contact. As the histograms show, the characteristic difference of channels was small enough. Therefore we did not take special care about the channels in the experiments.

If the ground sheet is installed on a metal floor, the output without human contact can be a normal distribution. On the other hand, if the ground sheet is not installed on a metal floor, the histogram becomes very complex and the standard deviation is very large. This tendency indicates that it is difficult to distinguish contact/non-contact in the condition.

Accordingly, the following sections will discuss mainly two conditions; (a) on the metal floor with the ground sheet and (b) on the wooden floor without the ground sheet. Because the rest condition (on the wooden floor with the ground sheet) has enough potential for precise recognition, so we exclude it from the targets for comparison.

4.4 Effect of the subjects' physical size

Figure 8 shows the sensor output histogram of the three subjects on the metal floor with the ground sheet. The result indicates that there is no distinct difference between the histograms' peeks, in spite of the intentional variations of the subjects' profiles (height and foot size). Result was almost the same in the (b) condition (on the wooden floor without the ground sheet).

This results indicate that the floor sensor can recognize the contact/non-contact condition regardless of the subjects' physical profiles. But a pressure sensor can recognize the weight of a target, and may be able to identify the person, therefore this feature may be a disadvantage of our concise floor sensor.

4.5 Effect of the contact condition

Figure 9 compares the sensor outputs of the two contact conditions (both feet and one foot), The experimental results show that there is no obvious effect of the contact condition. It means that the sensor system can recognize a human position even if a human is walking and only one foot touches to a probe.

5 Recognition of a human contact

In the previous section, basic tendency of the output data was described. This section explains the recognition process based on the properties of the sensor output.

5.1 Recognition process and its result

In the sensor system, the recognition process should be installed on a micro-controller, and the process should be as concise as possible for the weak calculation power.

To realize a concise recognition algorithm, we made a normal distribution model of non-contact condition based on the average and standard deviation at first. Next, measured data are recognized as non-contact if the data are close enough to its model. The decision threshold was varied base on a parameter (coefficient $\times$ standard deviation), and the coefficient was shifted within a certain range.

Figure 10 shows the recognition results in ROC curve. The horizontal axis is False Positive Fraction (FPF), and this value indicates the mis-judge rate of contact while a subject doesn't touch to a probe. The vertical axis is True Positive Fraction (TPF), and this value indicates the correct-judge rate of contact while a subject touches to a probe. Accordingly the left-upper area shows a good recognition performance.

The plotted value is the average of 36 data in the contact condition, and eight data in the non-contact condition. As described before, there are nine non-contact data, but one of them was used to make a model of non-contact condition, thus the rest eight data are used for the test. Surely we executed cross validation. The results shows that it is very good recognition performance when the floor sensor is installed on the metal floor with the ground sheet. On the other hand, in the condition that the sensor is installed on the wooden floor without the ground sheet, the recognition performance is the trade off between the FPF and TPF.

5.2 Introduction of a filtering process

Although in the former section, the result without the ground sheet seems inferior, it was found that mis-recognition was caused by the instantaneous noise. Therefore, a concise moving average filter was introduce to reduce the effect of instantaneous noise. The filter was applied to the raw sensor data. The results shown before section 5.2 are raw data without the filtering process.

Figure 11 shows the result examples of filtered data. The horizontal axis is the data index while acquiring at 6 [Hz], and the vertical axis is the filtered data or the recognition result of each sample. These results indicate that a concise filter can drastically improve the recognition result when the ground sheet is not installed. Consequently it was confirmed that we have enough feasibility of omitting the ground sheet when there is no metal object in the neighborhood.

5.3 Application to dynamic motion

In the former sections, subjects are all static, that means just standing. In this section, the recognition process was applied to walking motion.

Figure 12 shows the sensor data and the recognition results of a probe, when a subject walks straight on the floor sensor with natural speed and touches to the probe. As the figure indicates, even when a subject is walking, the sensor can detect the contact, but the excessive filtering process (Averaging number is 6) may distort the contact period.

6 Conclusion

In this research, we aimed to realize a new floor sensor system with cost competitiveness of manufacture, installation, and maintenance for direct human position monitoring in a living space. In addition to the proposal of the new system, this research focused on the evaluation of the performance of the system in various conditions and configurations. Therefore a prototype was developed and its basic performance was examined through experiments.

The contribution of this research is the following knowledge.

- Regarding the pulse oscillation method, the astable method is stable enough, and the method promotes the adoption of a low-price micro-controller.
- A electrostatic capacitive sensor can detect a human contact regardless of the subjects' physical profiles and contact conditions. However, it may be impossible to identify the person based on the profiles.
- A ground sheet is effective to reduce the environmental noise, when the sensor is on a metal floor.
- If there is no metal object in the neighborhood, the ground sheet can be omitted, and the introduction of the concise moving average filter can compensate the mis-recognition caused by the environmental noises.
- The proposed system can be applied not only to a static condition such as standing but also to a dynamic motion such as walking.

We made a prototype system as shown in Figure 13. In the system, position or locomotion of the elderly or an infant can be observed via Web browser on a mobile devices (i.e. mobile phone or PDA). This systems is specialized in the human position monitoring, therefore it is more suitable for monitoring in a private room compared with the surveillance camera. Our future work is an experiment of the integrated system in a real living environment.

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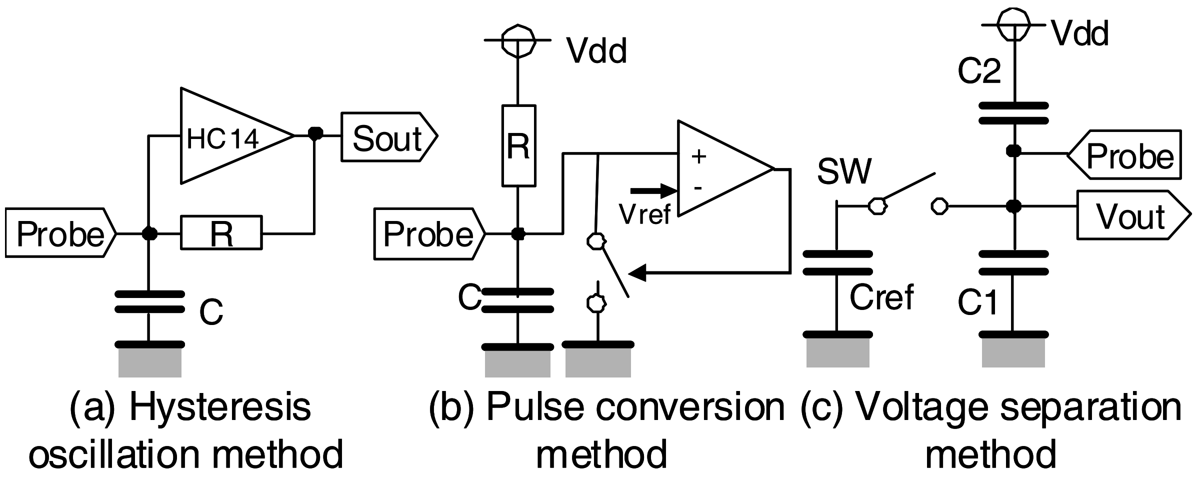


Figure 1: Electrostatic capacitance measuring methods.

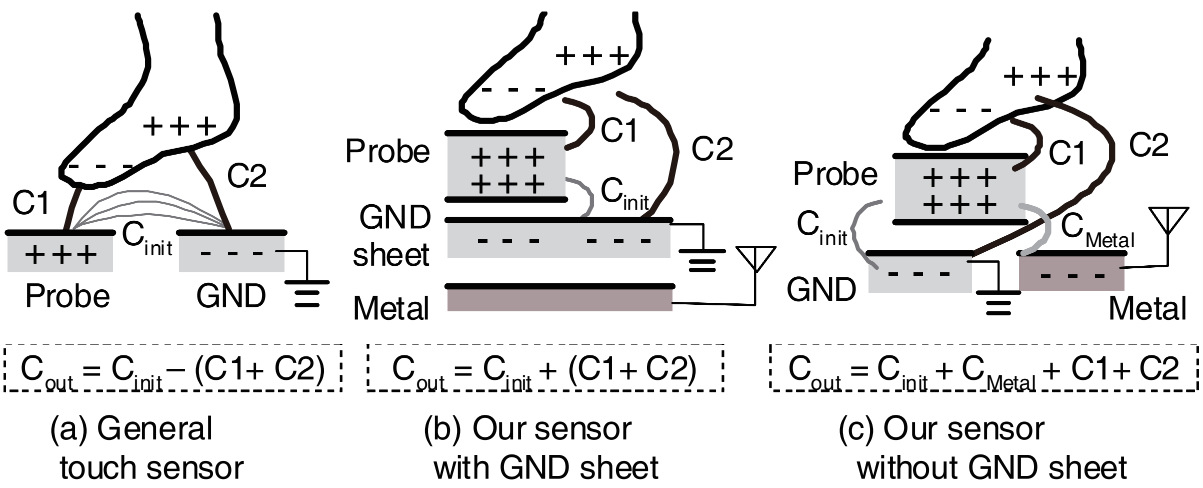


Figure 2: Basis of electrostatic capacitive variation.

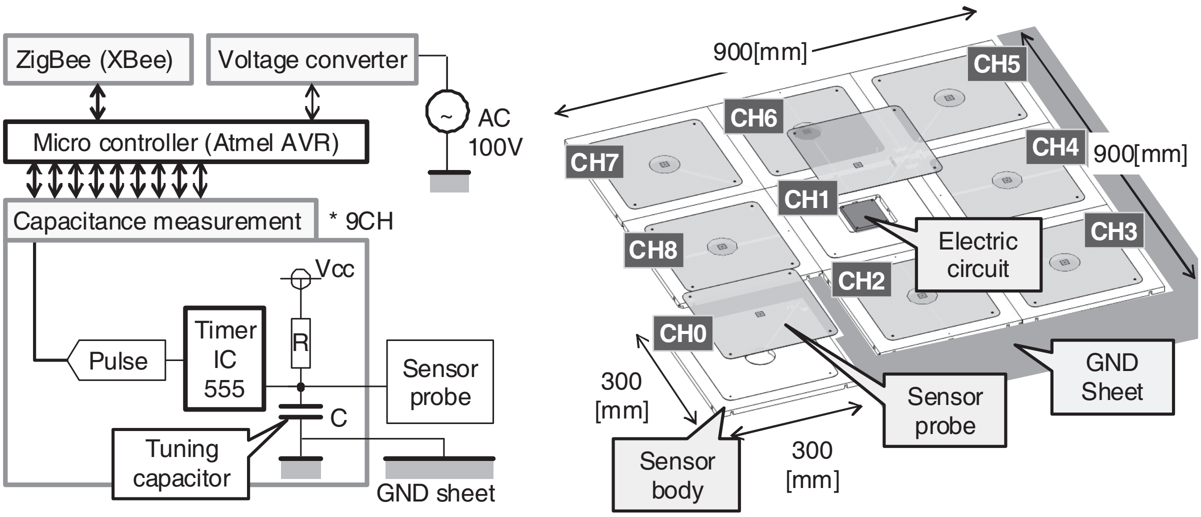


Figure 3: Framework of the developed floor sensor system.

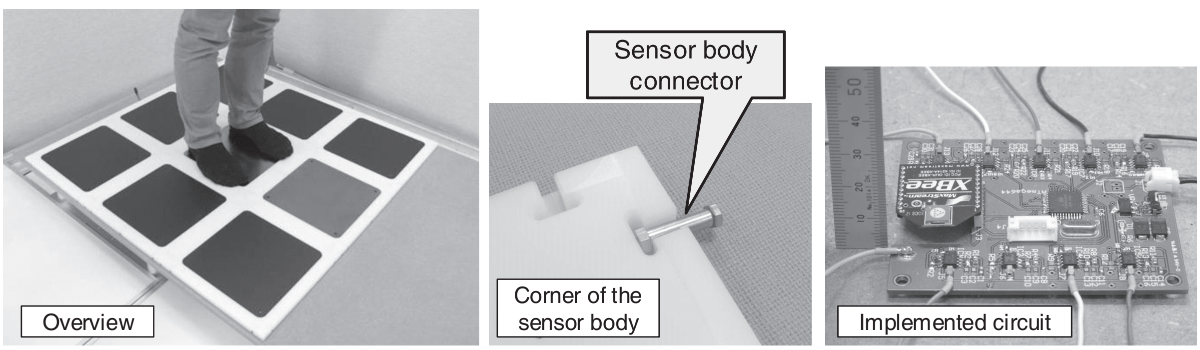


Figure 4: Snapshot of the developed floor sensor system.

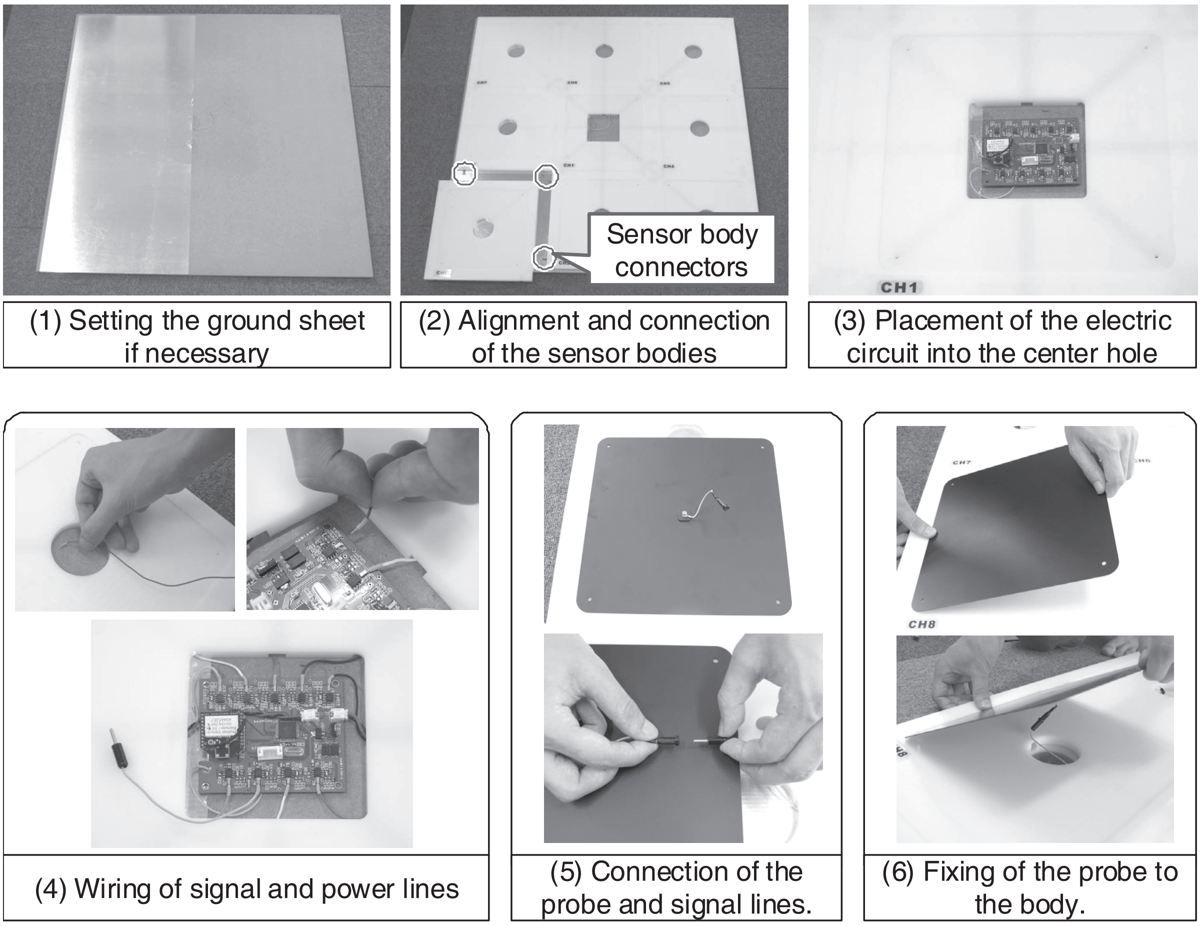


Figure 5: Installation procedure of the floor sensor system.

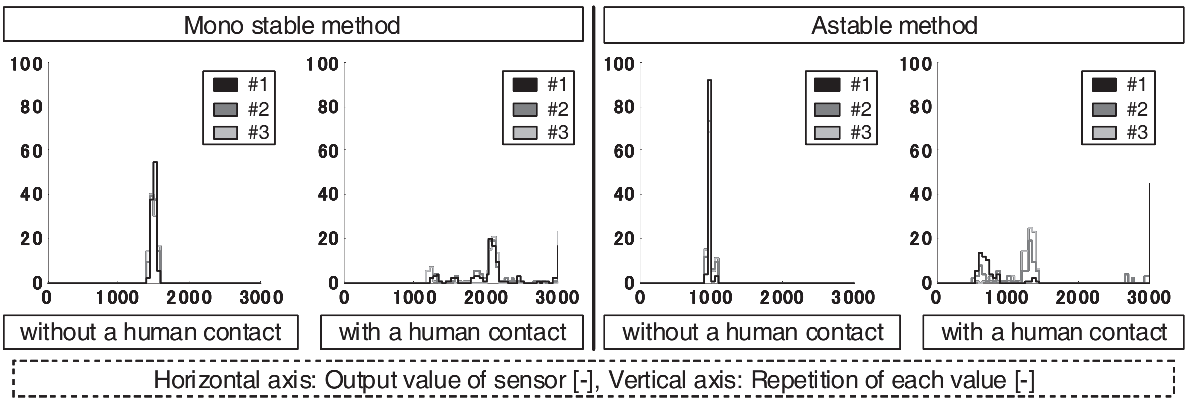
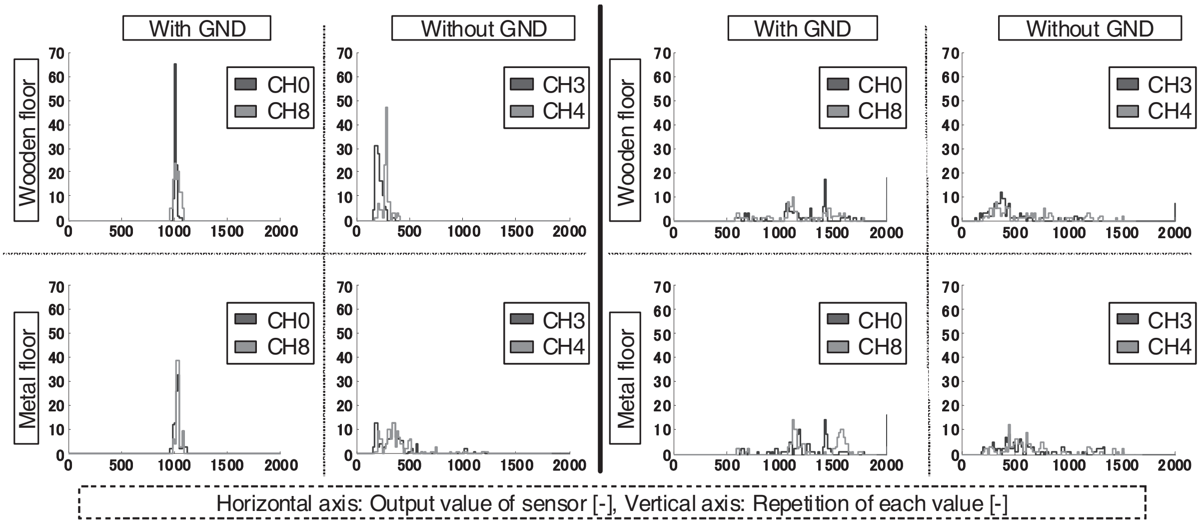


Figure 6: Comparison of the pulse generation methods.



(a) Histogram of sensor output without a human contact

(b) Histogram of sensor output with a human contact

(1) Wooden floor

Trial No.	(a) With GND CH0	(a) With GND CH8	Trial No.	(b) Without GND CH0	(b) Without GND CH8
#1	12.4	30.8	#1	33.1	39.0
#2	33.7	14.4	#2	49.3	33.0
#3	22.8	25.9	#3	32.7	29.7
ave.	23.0	23.7	ave.	38.4	33.9

(2) Metal floor

Trial No.	(a) With GND CH0	(a) With GND CH8	Trial No.	(b) Without GND CH0	(b) Without GND CH8
#1	29.9	22.2	#1	186	209
#2	38.0	14.1	#2	65.2	67.6
#3	31.1	28.3	#3	128	150
ave.	33.0	21.5	ave.	126.4	142.2

(c) Standard deviations of sensor output without human contact

Figure 7: Whole tendency of the sensor output without/with a human contact.

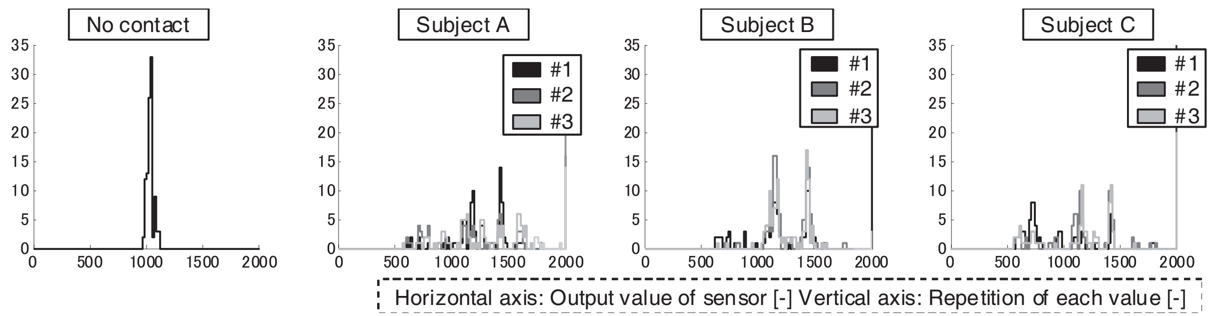


Figure 8: Histogram of sensor output for three different subjects (on metal floor with the ground sheet).

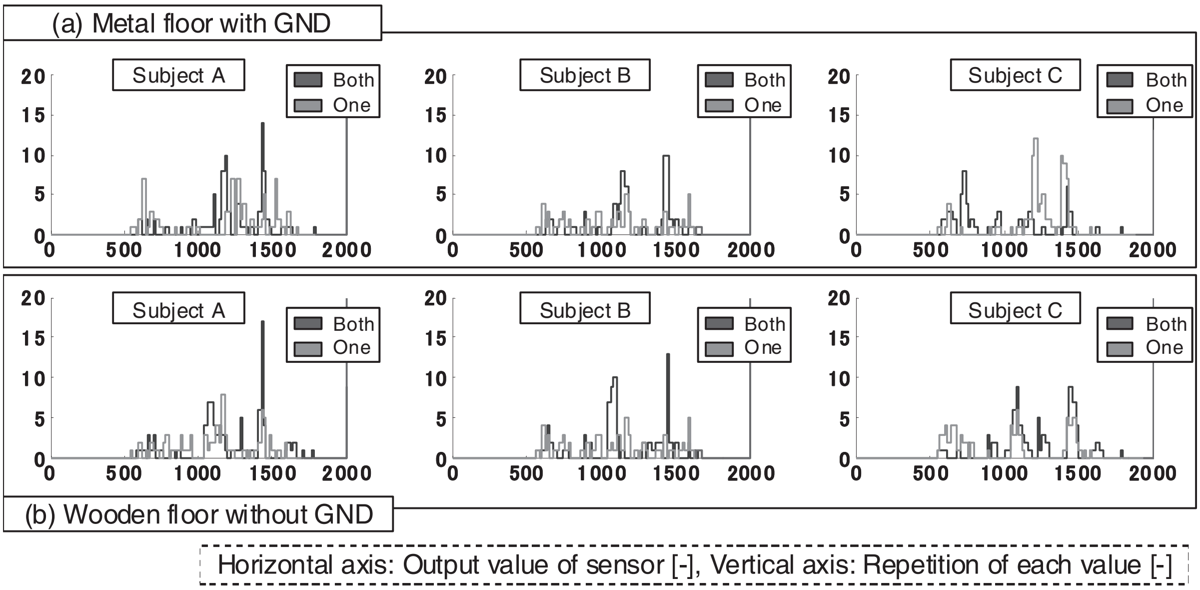


Figure 9: Histogram of sensor output in different contact conditions.

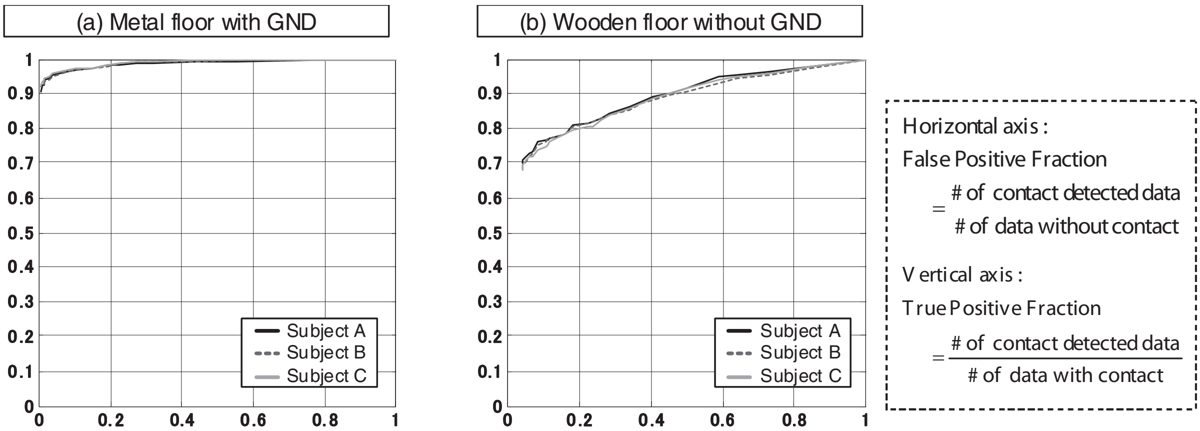


Figure 10: Result of the human contact recognition experiment.

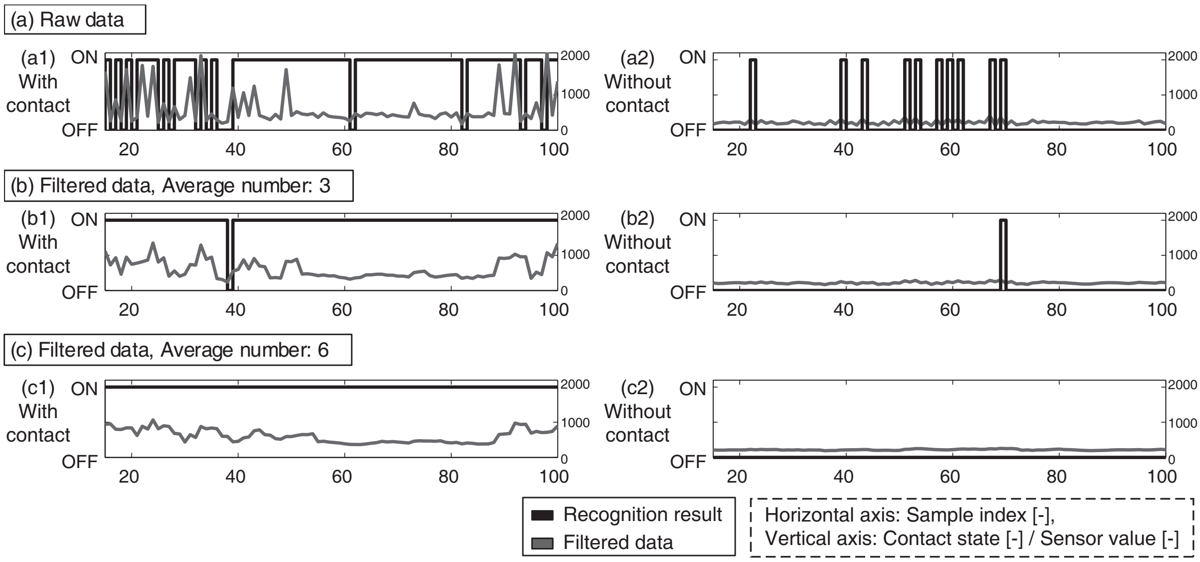


Figure 11: Result examples of a concise moving average filter.

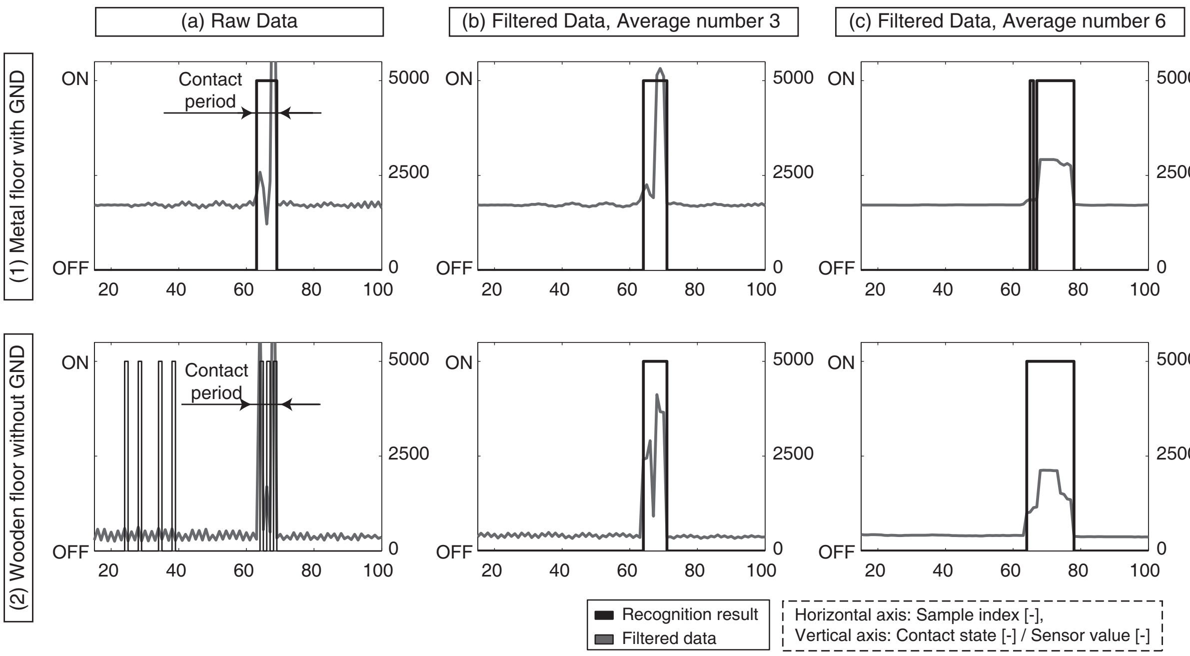


Figure 12: Recognition results of walking motion.

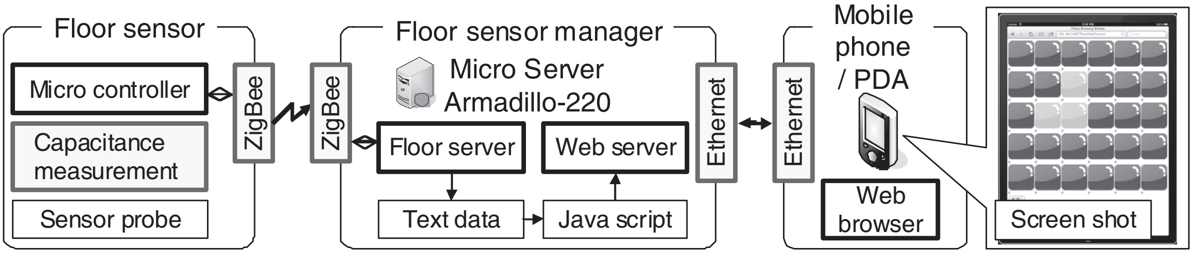


Figure 13: Integrated system framework of the electrostatic capacitive floor sensor.