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A Study of Detection of Trip and Fall Using Doppler Sensor on Embedded Computer

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***Abstract*—A recent social problem in Japan is domestic accidents involving elderly persons, who are increasingly living alone. Domestic accidents are unpredictable emergent situations, yet the constant care of elderly person by non-relatives or caregivers is difficult due to associated labor costs, privacy problems, and burdens placed on elderly persons themselves. This paper targets trip and fall, the leading cause of accidental death in elderly persons, and examines a detection method for such accidents. To address privacy issues, we use a Doppler sensor that can detect movement without the use of personally identifying data. We also investigate the movement detection and identification by frequency analysis of sensor output using fast Fourier transform. In addition, we design and implement a prototype terminal to detect trip and fall by using a Doppler sensor and an embedded computer.**

Keywords-Care of Elderly Person, Doppler Sensor, Trip and Fall, Embedded Computer, Information Terminal, Android OS

I. INTRODUCTION

Aging of the Japanese population has led to domestic accidents becoming a serious social problem [1]. For elderly persons, domestic accidents are dangerous because they are unpredictable, and delayed discovery can result in serious physical harm. “Trip and fall” is one such common accident, frequently resulting in death [2]. As elderly persons increasingly live alone, solitary death following a domestic accident is also becoming a problem [1], leading to a need for constant caretaking. One potential solution for such caretaking and for the detection of domestic accidents is human motion monitoring, and some studies have examined solutions using sensor-based monitoring systems [3][4]. Many such systems remain problematic, however, due to issues such as privacy and cost.

In this paper, we identify problems that arise in care of elderly person using previous methods for trip and fall detection, and propose a new method to solve those problems through the use of a suitable sensor. In addition, we design and implement a novel system for processing sensor data to detect accidents, and evaluate our detection method.

II. RELATED WORKS

This section describes previous studies on detecting trip and fall, and considers sensors for monitoring elderly person in daily life.

A. Previous Methods

Table I lists previous sensors studied for detecting trip and fall. As shown in the “Usage” column, previous methods are classified into wearable, non-wearable, and indirect-wearable types. A wearable sensor is directly attached to the body. A non-wearable sensor is embedded into a room and involves no device attached to the monitored person. An indirect-wearable monitor is attached to clothing, rather than directly to the body. Typically, wearable systems use accelerometer sensors, non-wearable systems use cameras, and indirect-wearable systems use RFID tag and reader systems. The following describes characteristics of each method along with the problems associated with using each method in elderly persons’ everyday life.

TABLE I. CLASSIFICATION OF METHODS FOR DETECTING TRIP AND FALL

Sensors	Usage	Method for Detecting
Accelerometer Sensor	Wearable	Vertical and slope change
Camera	Non- wearable	Image processing
RFID Tag and Reader	Indirect wearable	Location-based

1) Accelerometer Sensor: Accelerometer sensors are typical sensors for detecting a person’s movements, and are classified as wearable systems. The sensor can detect trip and fall by using data from an accelerometer directly attached to the user’s body [5]. The primary advantage of this method is that stable sensor data can be acquired because the sensor is directly affixed to the body. However, such methods require the user to securely mount the accelerometer sensor to the thigh or torso, which is a burden that can be problematic in daily life, especially for elderly persons.

2) Camera: Processing images and videos captured by a camera has been proposed in non-wearable detection methods [6][7]. Such methods can detect trip and fall regardless of the distance between the user and the camera. In addition, these methods do not require the direct attachment of a sensor. However, the handling of visual information in such methods is problematic, and must be strictly controlled due to important privacy concerns.

3) RFID Tags and Readers: An indoor RFID gait monitoring system has been developed for trip and fall detection [8]. This method uses two types of RFID tags with different frequency bands, using them to detect trip and fall by obtaining user location and walking distance information via readers. One advantage of this method is that it reduces the burden of wearable systems because devices need not be directly secured to the user's body (RFID tags are instead placed in slippers). Moreover, privacy issues are less problematic, because RFID tags do not reveal visual information as do cameras. Active RFID readers are generally expensive, however, and other system components present further expenses. Monetary cost is a critical issue for many elderly persons, making implementation of this system difficult in many cases.

B. Doppler Sensor

Table II shows a comparison of the abovementioned methods according to three criteria related to constant caretaking, with circles and crosses indicating the relative suitability of each. Each method successfully satisfies one or two criteria, but no method addresses all three, indicating potential problems for adoption. This paper therefore focuses on the use of a microwave Doppler sensor for estimating human motions.

TABLE II. SUMMARY OF DETECTION TECHNIQUES OF TRIP AND FALL

Sensors	Burden	Privacy	Cost
Accelerometer Sensor	×	○	○
Camera	○	×	×
RFID Tag & Reader	○	○	×

Figure 1 shows an example Doppler sensor of the type discussed in this paper. The sensor emits microwaves, and outputs an electric signal according to the Doppler frequency, which is the difference in frequency between the transmitted wave from the sensor and the reflected wave from a moving object. Figure 2 shows example output when the sensor detects a moving object; a moving object is clearly detected by the Doppler sensor.

Figure 1. Doppler Sensor Module (NJR4178J,New Japan Radio Co., Ltd.)

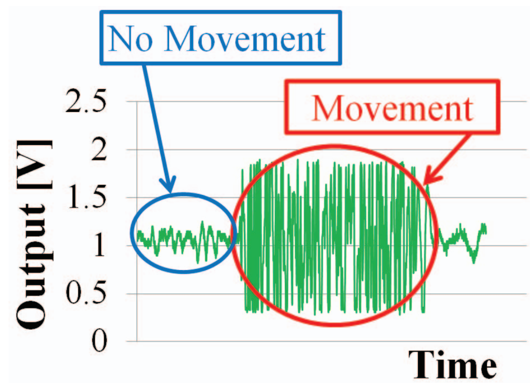


Figure 2. Sensor Outputs

In Figure 2, the blue and red text can be simplified to "No Movement" and "Movement" respectively. The Doppler sensor has the following advantages:

- Reduced burden: Users need not directly equip the Doppler sensor.
- Easily used data: As shown in Figure 2, the sensor output is voltage, which unlike image processing does not involve privacy issues.
- Low cost: Doppler sensors are inexpensive compared with other sensors.
- Data accuracy: Doppler sensors are more robust against heat and noise as compared with infrared sensors.

The above advantages make Doppler sensors suitable for developing monitoring systems that detect trip and fall during daily life.

Two previous studies [9][10] have examined room monitoring using Doppler sensors, both dealing with room location tracking and recognition of hand gestures. The present paper instead considers whole-body movements. By the way, output such as that shown in Figure 2 makes it is easy to discern simple movements, because movement results in large-amplitude waves. However, such output alone cannot distinguish between trip and fall and more common movements such as walking, using the hands, and shaking the arms, because each of these movements results in a similar waveform. This paper therefore uses fast Fourier transform (FFT) to extract feature data from the sensor output signal, allowing for clearer discrimination between trip and fall motion and more common motions. This paper furthermore designs and implements a system for sensor data processing and analysis of frequency characteristics.

III. Design and Implementation

As discussed above, our system processes sensor data to detect trip and fall. In addition, it is necessary to ensure communication to collect sensor data and the results of data processing. This chapter describes the functions, devices, and architecture needed to implement our system.

A. System Functions

Our system requires the following three functions.

- Acquisition and digitization of sensor output
- Processing of the sensor data
- Transmission of results to other terminals

This paper uses an embedded computer to implement these three functions. Embedded computers are suited to the proposed system because they consume little power and are fault-tolerant. This paper uses a BeagleBoard-xM (Figure 3), made by Texas Instruments, Inc. Table III shows the main specifications of the BeagleBoard-xM. The BeagleBoard-xM is equipped with processors and interfaces such as a CPU, memory, a USB 2.0 port, and a wired LAN on an approximately 9 cm square substrate. Operating at maximum power, this board consumes 2.5 W of DC 5 V power, allowing for low-cost, continuous operation. In this study, the Google Android operating system is implemented on this board. Android is a software platform developed for portable information terminals, and is also available for embedded computers such as the BeagleBoard-xM. It is also suitable for design of our system, allowing access to sensor and network communication because Android has a clear kernel, library, and application layer architecture. The system proposed in this paper is implemented as an Android application using Android version 2.2.

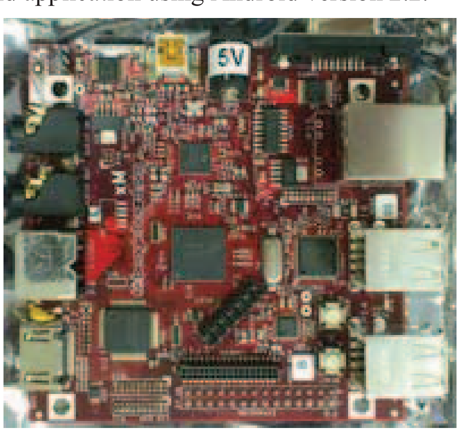


Figure 3. BeagleBoard-xM (Texas Instruments Inc.)

TABLE III. Specification of BeagleBoard-xM

Index	Specification
Processor Core Speed	1 [GHz]
RAM	512 [MB]
Interfaces	RS-232C，USB2.0， Wired LAN (100BASE-TX) DVI-I， SD Card Slot, etc.
Working Voltage	5.0 [V]

B. Function Design

This section presents a design overview of the three functions described in the previous section. Figure 4 shows the configuration and function of our system in the Android architecture.

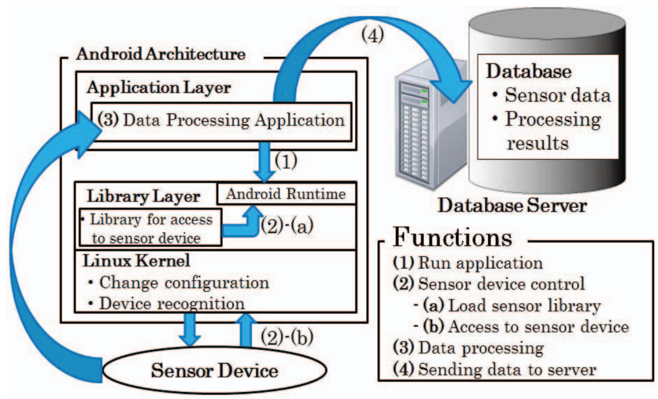


Figure 4. Structure and Function of the Application

1) Sensor output acquisition and digitization: Sensor data must be digitized for analysis. Our system uses a microcomputer for digitization of the sensor output, and the device can be used as a serial communication device. Figures 4(2)-(a) and 4(2)-(b), show how the application obtains sensor data by loading an Android library for access.

2) Sensor data processing: Processing data obtained from the sensor is implemented at the application layer, as shown in Figure 4(2).

3) Transmission of data to other terminals: Communication is performed via an Android network interface. Our system implements communication functions to transfer sensor data and processing results for experimental evaluation.

C. Implementation

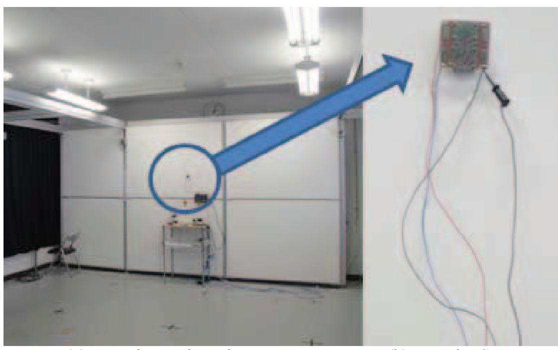
Our system is implemented based on the design described in section B. We implemented an Android library for access to a serial communication device as described in section B(1), and the Java Native Interface framework is used to load the library from the application. Moreover, the device drivers for recognition must be built into the Android kernel layer. This requirement was satisfied by changing the device settings of the kernel and drivers that are included in the Android source programs.

IV. EXPERIMENTATION AND EVALUATION

This paper aims at detecting trip and fall by output of the Doppler sensor. We consider that it is necessary to distinguish the sensor output data of trip and fall from typical activities observed in person's everyday life. Moreover, it is also necessary to evaluate whether the data is useful to detect of trip and fall. This section describes analyzing sensor data to detect trip and fall.

A. *Collection of Data on Movements*

Prior to experimentation and evaluation, we observed and collected data on the movements of one participant to survey the frequency characteristics of specific movements, and to determine how to identify trip and fall. Figure 5(a) shows the room used for the experiment. Figure 5(b) shows a Doppler sensor installed on the wall.



(a) Experimental Environment (b) Doppler Sensor

Figure 5. Experimental Environment and Sensor

The following is a list of movements that were observed and collected.

(i). Trip and fall: Falling after walking a straight line
(ii). Walking: Walking which draws a circle indoors
(iii). Shaking arm and hand: Activity which imitates taking a thing, and raise one's hand
(iv). Working with hands: Activity which is using things, such as a mobile phone
(v). Stationary posture: Sitting on a chair without moving
(vi). Standing up: Keep standing without moving
(vii). Empty room: The state where nobody is indoors

This paper defines movements (ii) to (vi) and state (vii) as "activities of daily living" (ADLs), and trip and fall as an "activity not of daily living" (non-ADL). Above ADLs are typical movements and state is observed on person's everyday life.

B. *Basic Investigation*

1) Collection of Data on Movements: This paper analyzes the frequency characteristics of each movement using a 256-point FFT. Furthermore, to extract the features of each movement, this evaluation derived the average frequency spectrum of 20 samples of each movement. As a result, we create the feature of each movement as a reference data shown in Figure 6.

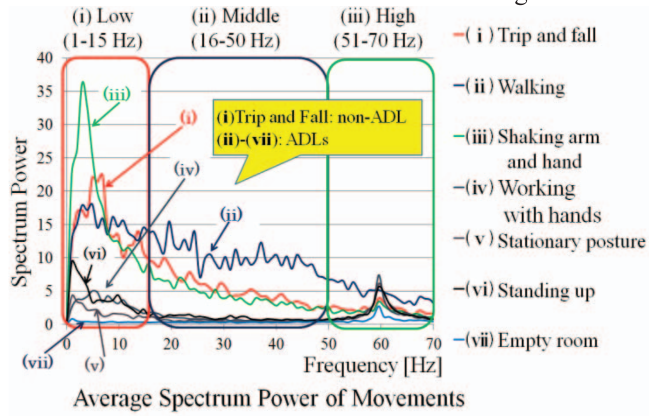


Figure 6. Average Frequency Spectra of Movements

As shown in Figure 6, movement determination is possible because the frequency characteristics differ. The following describes characteristics of the frequency spectrum of each movement:

(i). Trip and fall: High power in the low frequency band
(ii). Walking: High power in the intermediate and high frequency bands
(iii). Shaking arm and hand: Very high power in the low frequency band
(iv). Working with hands: Low power as compared with "and fall'," "walking," and "shaking arm and hand"
(v). Stationary posture: Low power in the low frequency band
(vi). Standing up: Low power in the low frequency band
(vii). Empty room: Low power over the entire frequency band

This paper evaluates detection of trip and fall by spectral comparison using reference data based on the characteristics shown in Figure 6. Furthermore, for this evaluation we collected evaluation data on how each movement differs from the reference data above. This evaluation uses a comparison of spectral intensity. The spectral ratio of the trip and fall evaluation data and reference data is close to 1 if the evaluation data are on trip and fall. Otherwise, if the evaluation data are on an ADL, the ratio with the data on an ADL is close to 1. The following shows the procedure for this evaluation:

Step 1. Divide the frequency band (0–70 Hz) of the reference data into three bands (as shown in Figure 6).
Step 2. Calculate an average frequency spectrum of reference data in each frequency band.
Step 3. Divide the frequency band (0–70 Hz) of the evaluation data into three bands.

Step 4. Calculate an average frequency spectrum of evaluation data in each frequency band.

Step 5. Derive an average spectral ratio of the evaluation data and the reference data in each frequency band.

Our method detects trip and fall in cases where all three evaluation data and reference data ratios for the motion are closer to 1 than for any of the ADL ratios.

2) Basic Evaluation: We next investigated trip and fall in a single direction as a basic evaluation of our method. 50 trip and fall samples, and 1 min of data for each ADL, were prepared as evaluation data. This evaluation uses the 256 points for the detection decision, and also makes decisions by shifting data every 25 points continuously. We also evaluated the method's false positive rate, because it is undesirable that ADLs are detected as a trip and fall. Table IV shows results of this evaluation. The number of true positives corresponds to cases where evaluation data was correctly detected as trip and fall. The number of false positives corresponds to cases where ADLs were incorrectly detected as trip and fall.

TABLE IV. RATE OF TRUE POSITIVE AND FALSE POSITIVE

	True Positive
Trip and fall	90% (18)*

*(Number of true positives)

	False Positive
Walking	0.0% (0)**
Shaking arm and hand	0.0% (0)
Working with hands	0.0% (0)
Stationary posture	0.0% (0)
Standing up	1.5% (9)
Nobody in a room	1.9% (11)

**(Number of false positives)

The results in Table IV indicate that our method can detect trip and fall with high accuracy, indicated by the high true positive and low false positive rates. Thus, Doppler sensors can acquire the frequency characteristics of movements by using FFT, and the sensors are effective for detecting certain types of human movements such as trip and fall. In addition, this evaluation shows that detection can be performed in real time by our method.

C. Main Evaluation

The basic evaluation of the previous section examined detection of trip and fall in a single direction. However, actual trip and fall may occur in various directions, so we evaluated our method with regard to data on trip and fall in multiple directions. In addition, this evaluation also investigates detection of the trip and fall movement of multiple participants when reference data on another participant are used.

1) Detection for Multiple Directions: As evaluation data, this evaluation uses data on trip and fall in multiple directions, as shown in Figure 7. Evaluation criteria are true positives and false positives, as in the basic evaluation. Table V shows the evaluation results.

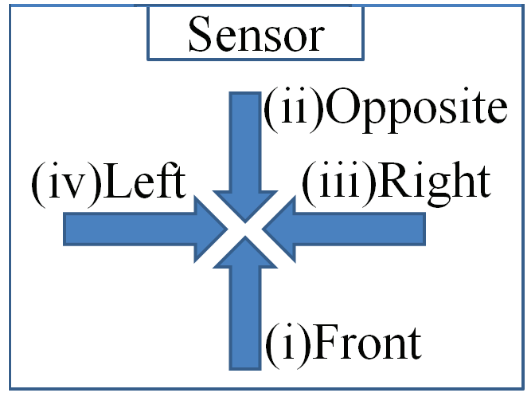


Figure 7. Trip and Fall Directions

TABLE V. TRUE POSITIVE AND FALSE POSITIVE RATES IN MULTIPLE DIRECTION

・True Positive

Directions of Reference Data / Directions of Evaluation Data	Front	Opposite	Right	Left
Front	92%(46)	90%(45)	88%(44)	90%(45)
Opposite	90%(45)	94%(47)	90%(45)	90%(45)
Right	88%(44)	92%(46)	96%(48)	94%(47)
Left	90%(45)	88%(44)	96%(48)	96%(48)

・False Positive

Directions of Reference Data / ADL Data	Front	Opposite	Right	Left
Walking	2.2%(13)	2.4%(14)	6.6%(38)	5.5%(31)
Shaking arm and hand	1.0%(6)	0.9%(5)	2.8%(16)	2.6%(15)
Working with hands	0.5%(3)	0.9%(5)	0.0%(0)	0.0%(0)
Stationary posture	0.0%(0)	0.0%(0)	0.0%(0)	0.0%(0)
Standing up	0.0%(0)	0.0%(0)	0.0%(0)	0.0%(0)
Empty room	0.0%(0)	0.0%(0)	0.0%(0)	0.0%(0)

The highest true positive rate was obtained in cases where the direction of evaluation data and reference data was the same. Nonetheless, even when other direction data were used as reference data, true positive rates were close to 90 percent. False positives were seen in "working with hands," "walking," and "shaking arm and hand" movements. In particular, walking caused the most false positives.

2) Detection for Multiple Participants: This evaluation investigates four participants' trip and fall motion in four directions, and uses 50 trip and fall data samples for each direction and participant. Table VI shows the true positive rates for each participant.

For each participant, the highest true positive rate was obtained in cases where the direction of trip and fall was the same between the evaluation data and the reference data. Nonetheless, the rate was high in other directions as well. This indicates that trip and fall for multiple participants can be detected from the data of another participant, and trip and fall movement is not specific to individuals.

TABLE VI. TRUE POSITIVE AND FALSE POSITIVE RATES FOR MULTIPLE PARTICIPANTS

・Participant 1

Directions of Reference Data / Directions of Evaluation Data	Front	Opposite	Right	Left
Front	94% (47)	92% (46)	90% (45)	90% (45)
Opposite	90% (45)	94% (47)	88% (44)	88% (44)
Right	90% (45)	90% (45)	94% (47)	94% (47)
Left	88% (44)	88% (44)	94% (47)	96% (48)

・Participant 2

Directions of Reference Data / Directions of Evaluation Data	Front	Opposite	Right	Left
Front	96% (48)	92% (46)	88% (44)	90% (45)
Opposite	90% (45)	92% (46)	90% (45)	88% (44)
Right	90% (45)	92% (46)	94% (47)	94% (47)
Left	88% (44)	90% (45)	92% (46)	94% (47)

・Participant 3

Directions of Reference Data / Directions of Evaluation Data	Front	Opposite	Right	Left
Front	94% (47)	92% (46)	90% (45)	88% (44)
Opposite	92% (46)	96% (48)	90% (45)	90% (45)
Right	90% (45)	92% (46)	94% (47)	94%47()
Left	88% (44)	90% (45)	94% (47)	96% (48)

V. CONCLUSION AND FUTURE WORK

We have identified three problems related to previous methods for detecting trip and fall in the elderly, namely, the burden of care, privacy issues, and monetary costs. We proposed a new method that uses a Doppler sensor to solve these problems. We furthermore designed and implemented a prototype terminal for detecting trip and fall during daily life by means of a Doppler sensor, an embedded computer, and the Android operating system. Evaluation results showed that the Doppler sensor can detect non-ADL events such as trip and fall, and our method of using frequency characteristics could be realized by sensor data processing on a low-cost embedded computer. Furthermore, our method detected trip and fall while maintaining a high true positive rate and a low false positive rate. However, we have thus far performed only basic evaluations. Our method must still be evaluated in real-world situations and environments such as elderly persons' homes to consider the practicality of introducing this technology.

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