Change Detection of Sleeping Conditions based on Multipoint Ambient Sensing of Comforter on Bed*

Tomohiro Umetani[1], Mayuko Ishii[1], Yuichi Tamura[1], Naoki Saiwaki[2] and Kiyoko Yokoyama[3]

Abstract— **This paper describes a method for the detection of changes in sleeping conditions using multipoint ambient sensing for safety and amenity in the sleep environment. This method continuously detects changes during sleep, such as the movements of the person and bedding based on the measurement of acceleration, temperature and humidity of the comforter. Through the measurement of these ambient conditions, this system improves sleep quality and prevents accidents, such as falling off the bed. In this study, a basic system using internet of things (IoT) devices is constructed, and performance verification is conducted. The experimental results show the feasibility of the proposed method.**

I. INTRODUCTION

Recently, various studies on the construction of an intelligent environment based on multipoint ambient sensing have been developed in the research areas of robotics and system integration [1]. Several of these studies have been developed for evidence-based nursing care support in ward environment [2], [3]. The continuous sensing of the bed environment is important with respect to late-shift workload reduction of nursing and caring staff and the safety of persons lying on the beds in the ward. However, continuous ambient sensing using various kinds of sensing devices is expensive to install and raises privacy concerns. Therefore, a privacy-conscious, low-cost measurement system is desired for bed safety and amenity in the sleeping environment.

This paper describes a method for the detection of changes in sleeping conditions using multipoint ambient sensing for safety in the sleep environment. Figure 1 shows an overview of the sensing system that uses multiple small ambient sensors. Several studies on the detection of persons exiting and falling off their beds have been developed. These studies use various sensing methods to monitor the sleeping environment. Some examples include: a sheet-type sensor on the bedside floor for the detection of exiting [4], a fiber grating vision sensor for the measurement of sleep conditions [5], differential image analysis [6], pneumatic sensors on the mattress for the measurement of the pose and movements of the patient [7], [8], [9], [10], [11], and multi-sensor fusion for the detection of exit and fall off the bed [12]. These complex sensor systems are expensive to install in ward environments because they are needed for each bed in the ward. The monitoring system can predict accidental events, such as the patient falling off the bed, the comforter falling off the bed, or the comforter being turned over, which is desired for safety and amenity during sleep.

*This work was supported in part by JSPS KAKENHI Grant Number JP26330237 and JP17K06280, and MEXT, JAPAN.

[1]Tomohiro Umetani, Mayuko Ishii and Yuichi Tamura are with Department of Intelligence and Informatics, Konan University, 8-9-1 Okamoto, Higashinada, Kobe, Hyogo 658-8501, JAPAN {umetani, tamura}@konan-u.ac.jp

[2]Naoki Saiwaki is with the Division of Human Life and Environmental Science, Nara Women's University, Nara, JAPAN saiwaki@cc.nara-wu.ac.jp

[3]Kiyoko Yokoyama is with the Graduate School of Design and Archietcture, Nagoya City University, Nagoya, JAPAN yokoyama@sda.nagoya-cu.ac.jp

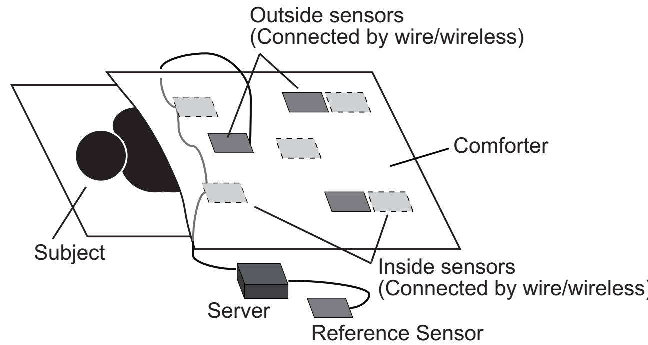

Fig. 1. Overview of the comforter measurement system using multiple ambient sensors.

The proposed method detects changes in sleeping conditions, such as the movements of the person and bed during sleep, based on the continuous measurement of acceleration, temperature, and humidity of the comforter. The changes in the temperature and humidity of the comforter are more gradual than its motion; therefore, it is expected that the safe, low-energy measurement system will be realized using slow internet of things (IoT) devices. This method can detect when the comforter falls off the bed and the comforter is turned over, which are difficult to detect using only a mattress sensor but are important to prevent the patient from feeling unwell due to the decrease in body temperature when the comforter shifts from the body of the sleeping person. The system does not interfere with the other measurement system such as the mattress sensor systems and falling detection system, then, it is expected to improve sleep quality and safety based on the combination of the detection systems.

The paper introduces the methodology of initial studies, the implementation of the measurement system using IoT devices, and the evaluation of the system through experiments for detection of the turning over and exiting events. The experimental results show the feasibility of the method.

II. METHODOLOGY

This section describes the method for the detection of changes in sleeping conditions using multipoint ambient sensing of the comforter using IoT devices. Figure 1 shows an overview of the sensing system using multiple small ambient sensors. The system consists of a data server and sensors. One sensor is attached to the bedroom environment such as the wall of room to measure the baseline of the environmental conditions, which can change due to the movement of the person, the opening/closing of the doors and windows in the room, the air conditioning in the room, and the season. The rest of the sensors are attached to various measurement points on both sides of the comforter. The sensors continuously measure the acceleration, temperature and humidity of the comforter over the subject. Each sensor is identified by a sensor ID, which corresponds to its position on the comforter. Therefore, each sensor measures the conditions of a part of the comforter.

The measurement system detects when a part of the comforter is turned based on the acceleration of that part of the comforter. For a measurement system that uses multiple sensors, the sign of acceleration of the sensors attached to the turned section of the comforter is changed. The output of the acceleration sensors includes components of the acceleration due to gravity, from which the normal vectors of the parts of the comforter where the sensors are attached are calculated relative to the normal vectors when the comforter remains stationary. Therefore, we can detect when a part of the comforter is turned based on the measurement of the direction of acceleration for the neighboring sensors.

In addition, the system estimates the location and position of the person on the bed from the distribution of the parts of the comforter and the temperature and amount of water vapor, which are high due to the activities of the sleeping person in the bed. The system measures the temperature and humidity of the room as a baseline, as well as those of each part of the comforter using the comforter sensors. The amount of water vapor at each part is calculated using temperature and humidity, because the humidity is influenced by the temperature of surroundings. The system calculates the differences in temperature and amount of water vapor between each part of the comforter and those of the room, because of the cancellation of the disturbance based on the change of the environmental conditions (such as the movement of the person and the opening/closing of doors and windows). Then, the system records the differences in temperature and amount of water vapor for each part of the comforter.

If the subject exits the bed, heat and humidity from the subject stops. Therefore, the output of temperature and water vapor of each part of the comforter nears those of the baseline sensor. The change of the conditions of the comforter according to the exiting events is detected based on the change of the measurement data. The system detects the change of sleeping conditions of the subject, such as exiting and becoming uncovered, using the threshold values and a regression model of the acceleration, temperature and amount of water vapor. Through these procedures, the system records and informs of the change detection of the sleeping conditions.

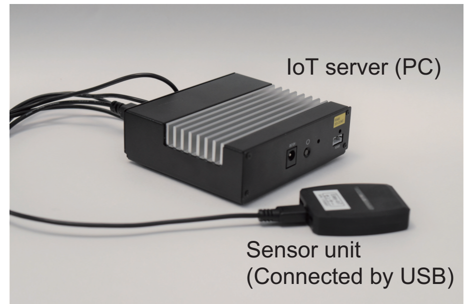

Fig. 2. Measurement system for ambient sensing.

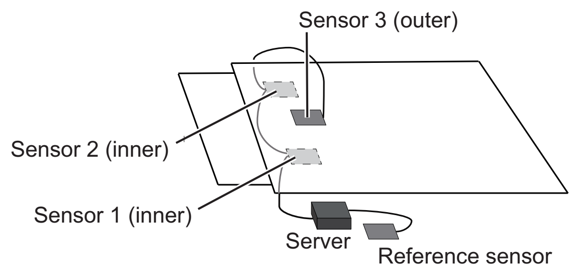

Fig. 3. Layout of sensors for experimental system.

III. EXPERIMENTS

This section explains the implementation of the experimental system using a small IoT server based on PC and multiple sensor units, and the measurement experiments to show the feasibility of the proposed method. This section shows the experimental results for the detection of the turning over a part of the comforter, and the exiting of the person from the comforter.

A. *Implementation of the experimental system*

Figure 2 shows the overview of experimental system using a small IoT server based on PC and multiple sensors. The Pinoh micro server and Easy IoT Sensors were used as the IoT server and the sensor units in the experiment. The sensors have the same specs, and the units measure three-axes acceleration (including acceleration due to gravity), temperature, and humidity. In this experiment, one sensor was used for the baseline and the other three sensors were used for the measurement of parts of the comforter. In addition, a video of the experimental scene was recorded for verification of the experiment. Image analysis of the movie was not used for the analysis directly.

Figure 3 shows the layout of the sensors for the experimental system. One sensor is attached to the outside of the comforter, and other two sensors are attached to the inside of the comforter. The baseline sensor was connected to the server via USB, and the sensors on comforter were connected via EIA-485 (RS-485).

The system measured the temperature, humidity, and acceleration of each sensor every 10 seconds. This experiment took place during the summer, and the comforter allows air to pass through easily, and the radiation performance of the comforter is high.

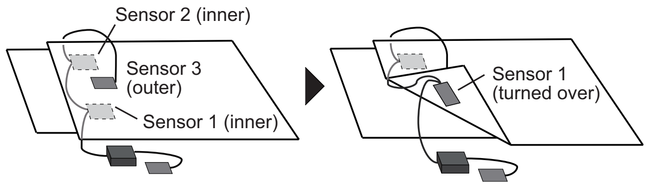

Fig. 4. Procedure of turning over a part of the comforter.

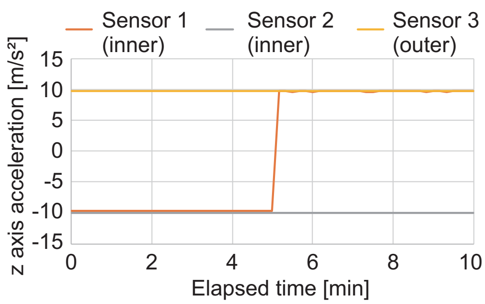

Fig. 5. Change in acceleration through the turning over.

B. Detection of turning over the comforter based on the measurement of acceleration

The experiment for the detection of the turning of the comforter based on the change of acceleration of each part of comforter was conducted. The subject turned part of comforter 5 minutes after the initial conditions were measured, as shown in Fig. 4. The direction of sensor 1 was changed by the turning it over in the experiment. In this experiment, the system recorded the change of the component of the acceleration in the direction of each sensor; that is, the z axis of the measurement.

Figure 5 shows the change of acceleration through the turning over operation. The horizontal axis indicates elapsed time, and the vertical axis indicates the z component of acceleration for each sensor. The turning over events are estimated using the inner product of the acceleration vector (including the acceleration due to gravity) of the sensors attached to the same side of the comforter. From Fig. 5, the experimental results show the feasibility of the detection of turning over using the measurement of acceleration at multiple points of the comforter.

C. Detection of exiting events from the comforter and bed

The experiment for the detection of exiting from the comforter and bed was conducted based on the change in temperature and amount of water vapor at each part of the comforter. The subject slept in the bed with the comforter for about one hour, then exited from the bed after turning over the part of the comforter. The system recorded the temperature and humidity of each sensor attached to the comforter and the baseline sensor. The experiments were conducted at various temperatures, seasons, subjects, and activities during sleep.

Figures 6 and 7 show the temperature and amount of water vapor around each sensor during the sleeping and exiting activities. The temperature measured by sensor 3 (the

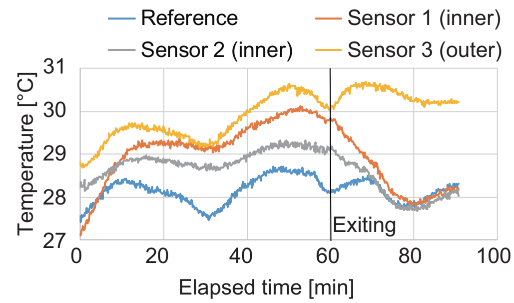

Fig. 6. Temperature of each sensor during sleeping and exiting.

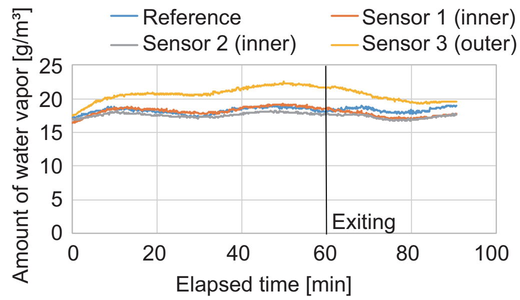

Fig. 7. Amount of water vapor at each position of the comforter during sleeping and exiting.

outer sensor) was higher than that of sensors 1 and 2. From the video record of the experiment, it was found that the inner sensors are not on the body of the subject during the experiment. This implies the feasibility of pose estimation of a sleeping person using the distribution of temperature of the part of the comforter. In addition, the temperature of sensor 3 increased after the subject exit the bed. From the video, it was observed that sensor 3 was surrounded by the comforter after the subject exited the bed, and the surroundings of sensor 3 were kept warm.

The room conditions such as the temperature and amount of water vapor around each sensor change according to the opening/closing of the door. In addition, it was observed that the temperature and amount of water vapor around each sensor attached to the comforter were recorded by the baseline sensor after the exiting activity by the subject (Figs. 6 and 7). However, it is difficult to judge the exiting event from the change of temperature and amount of water vapor directly, because the temperature and amount of water vapor change due to the change of environmental conditions.

Figures 8 and 9 show the difference in temperature and amount of water vapor around each sensor unit during the experiment. From Figs. 8 and 9, we observed that temperature and amount of water vapor around each sensor on the comforter went toward those of the baseline sensor after the exiting activity by the subject. In addition, the influence of disturbances, such as opening or closing door of the room, was eliminated based on the differential measurement of the temperature and amount of water vapor.

We tried to detect the changes due to exiting events using singular spectrum transformation (SST) [13] of the measure-

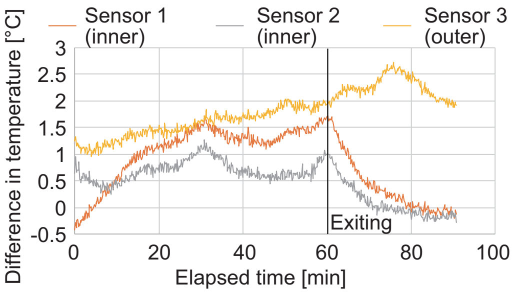

Fig. 8. Difference in temperature around each sensor during sleeping and exiting.

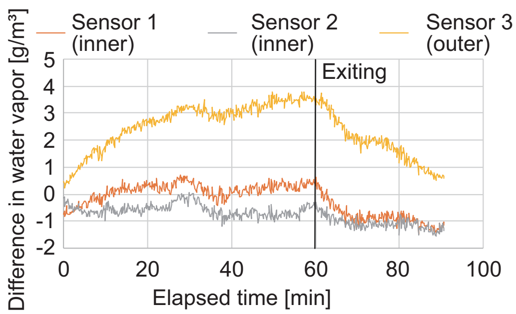

Fig. 9. Difference in amount of water vapor around each sensor during sleeping and exiting.

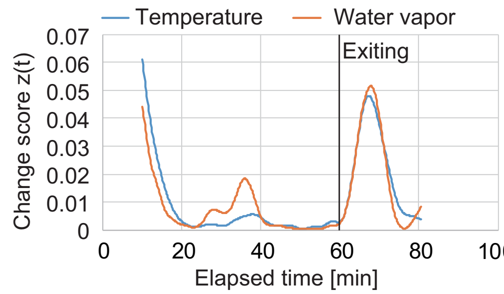

Fig. 10. Change score of the temperature and water vapor data during sleeping and exiting.

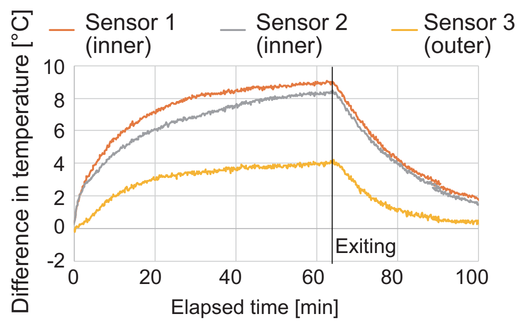

Fig. 11. Difference in temperature around each sensor during sleeping and exiting in the other season.

ment data. The annotation and division of the measurement data using change detection of the sleeping environment are needed for recording the sleeping conditions. The characteristics of the SST method are shown as follows:

- The method detects the change of the pattern of the time series.
- The method is robust against the noise of the signals.
- Few parameters are needed for the analysis.

The extended singular spectrum transformation (eSST) [14] was applied for change detection because data from multiple sensors were obtained through the experiment. In the experiment, the width of the analysis window was set to 5 minutes (30 data points), and the length of time shift series was -5 minutes. The width of the analysis window was determined experimentally.

Figure 10 shows the analytical results of change score of the motion data during the cornering motion. The horizontal axis is the elapsed time. The vertical axis is the change score of $z(t)$. From Fig. 10, the method detects several changes in room conditions using the change score of eSST. On the other hand, the change points of temperature and amount of water vapor according to the exiting from the bed were not detected by the SST method under the experimental conditions, but changes after the exiting events were detected.

D. Detection of exiting events from the comforter and bed in another season

The experiment for the detection of the exiting events in another season was conducted to show robustness to the change in season. The subject slept in the bed with the comforter for about one hour, then exited the bed by turning over part of the comforter. The room temperature was about 22 °C, the room humidity was about 75.3 %, and the amount of water vapor was about 14.6 g/m^3 at the beginning of the experiment. The rest of the conditions of the experiment are the same in the experiment described in the former subsection.

Figures 11 and 12 show the differences in temperature and amount of water vapor around each sensor during the experiment. From Figs. 11 and 12, we can see that temperature and amount of water vapor around each sensor on the comforter went toward those around the baseline sensor after the exiting activity by the subject in the experiment conducted in the different season.

IV. DISCUSSION

The experimental rseults showed the feasibility of the detection of the change in sleeping conditions using multi-point ambient sensing for safety and amenity in the sleep environment using a small IoT server based on PC and multiple sensor units. This method enables the detection of the events of turning over the comforter, which is difficult to detect using measurements taken from sensors on the mattress. These results show the feasibility of this system to prevent the sleeping person getting cold due to becoming uncovered when the comforter moves from their body, and enable safer and more comfortable sleeping conditions.

It was shown that several changes in room conditions were detected using the change score of eSST. In this experiment, the change points of temperature and amount of water vapor

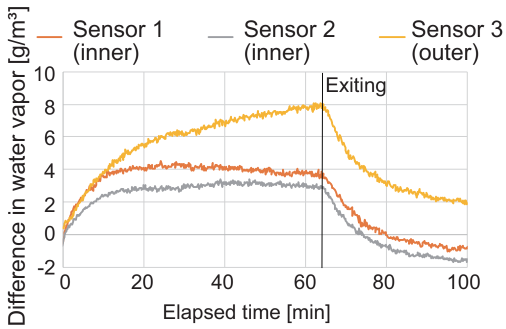

Fig. 12. Difference in amount of water vapor around each sensor during sleeping and exiting in the other season.

after the subject exited from the comforter was detected as well as the change of conditions of the room. The change results were detected; however, the interpretation of the events based on the various data of the change results are needed for the detection and notification of the events during the sleeping.

In addition, the results from the experiment conducted in the different season and the differences in temperature and amount of water vapor around each sensor showed robustness against the variation of the seasons and change of the room conditions. However, the difference of sensing data changes according to experimental conditions, such as the seasons from the experimental results. Therefore, it is difficult to detect the change in conditions using simple threshold values. The discussion of automatic detection based on machine learning and probabilistic methods will be conducted in future work.

In the experiment, the exiting events from the comforter were detected because the number of sensor units are small. If the number of sensor units is increased, the system can detect the movement of the subject under the comforter using the distribution of the temperature and the amount of water vapor around each part of comforter. The detection of movement under the comforter and improvement of measurement will be addressed in future work.

The experiments were conducted during summer in this study, when the comforter allows air to easily pass through and its radiation performance is high. Experiments using other types of comforter, such as a blanket that provides extra insulation, are needed to show the effectiveness of the proposed method. In addition, experiments using an artificial heater and humidifying unit (rather than a person), are needed to show the reliability of the proposed method. More experiments under various conditions and the improvement of the detection algorithm will be also addressed in future work.

V. Conclusion

This paper proposes a method for the detection of changes in sleeping conditions using multipoint ambient sensing for safety and amenity in the sleep environment. This method detects the change in sleeping conditions, such as movements in the sleeping person and bedding, based on a continuous measurement of acceleration, temperature, and humidity. This system improves the quality of sleep and accident prevention, such as falling off the bed, though the measurement of the ambient conditions of the comforter. In addition, the frequency of measurement is low, and the energy consumption of the systems can be lower. Experimental results show the feasibility of the proposed method.

The discussion of automatic detection based on machine learning and probabilistic methods, the detection of movement under the comforter, the improvement of the measurement system, and further experiments under various conditions will be conducted as part of future work to show the effectiveness and reliability of the system.

References

[1] J. H. Lee and H. Hashimoto, “Intelligent Space—concept and contents,” Advanced Robotics, vol. 16, no. 3, pp. 265–280, 2002.
[2] Y. Nishida, M. Takeda, T. Mori, H. Mizoguchi and T. Sato, “Monitoring Patient Respiration and Posture Using Human Symbiosis System,” in Proc. 1997 IEEE/RSJ Int. Conf. Intelligent Robots and Systems, vol. 2, pp. 632–639, 1997.
[3] T. Hori, Y. Nishida and S. Murakami, “Pervasive Sensor System for Evidence-based Nursing Care Support,” in Proc. 2006 IEEE Int. Conf. Robotics and Automation, pp. 1680–1685, 2006.
[4] H. Ogawa, Y. Yonezawa, H. Maki and W. M. Caldwell, “A New Bed-exiting Alarm System for Welfare Facility Residents,” in Proc. 31st Annual Int. Conf of the IEEE Engineering in Medicine and Biology Society (EMBC 2009), pp. 1734–1737, 2009.
[5] H. Aoki, Y. Takemura, K. Mimura and M. Nakajima, “Development of Non-restirictive Sensing System for Sleeping Person Using Fiber Grating Vision Sensor,” in Proc. 2001 IEEE Int. Symp. Micromechatronics and Human Science (MHS 2001), pp. 155–160, 2001.
[6] S. Okada, Y. Ohno, Goyahan, Y. Y. Wang, K. Kato, I. Mouri and M. Taniike, “Investigation into Using Difference Images to Monitor Sleeping Patients,” Japanese Journal of Applied IT Healthcare, vol. 3, no. 2, pp. 85–95, 2008.
[7] K. Watanabe, T. Watanabe, H. Watanabe, H. Ando, T. Ishikawa and K. Kobayashi, “Noninvasive Measurement of Heartbeat, Respiration, Snoring and Body Movements of a Subject in Bed via a Pneumatic Method,” IEEE Trans. Biomedical Engineering, vol. 52, no. 12, pp. 2100–2107, 2005.
[8] Y. W. Liu, Y. L. Hsu and W. Y. Chang, “Development of a Bed-centered Telehealth System based on a Motion-sensing Mattress,” J. Clinical Gerontology & Geriatrics, vol. 6, pp. 1–8, 2015.
[9] S. Guo, K. Matsuo, K. Matsuo, J. Liu and T. Mukai, “Unconstrained Measurement of Respiration Motions of Chest and Abdomen Using a Tactile Sensor Sheet in Supine Position on Bed,” J. Medical Devices, vol. 10, issue 4, paper no. MED-16-1017, pp. 1–7, 2016.
[10] S. Okada, Y. Fujiwara, S. Suzuki, M. Yasuda, M. Makikawa and T. Iida, “Proposal for a Method of Non-restrictive Measurement of Resting Heart Rate in a Lying Position,” J. Physiological Anthropology, vol. 25, no. 4, pp. 299–305, 2006.
[11] M. Alaziz, Z. Jia, J. Liu, R. Howard, Y. Chen, and Y. Zhang, “Motion-Scale: A Body Motion Monitoring System Using Bed-Mounted Wireless Load Cells,” in Proc. the 1st IEEE Int. Conf. Connected Health: Applications, Systems and Engineering Technologies (CHASE), 10 pages, 2016.
[12] M. Motegi, N. Matsumura, T. Yamada, S. Muto, N. Kanamaru, K. Shimokura, M. Abe, Y. Ookubo, Y. Morita, K. Kasai, T. Yamamoto and C. Ochiai, “Design and Development of Mimamori-Bed to Prevent Falls from Bed for Hospital Patients,” IEICE Trans. Information and Systems, vol. J94-D, no. 6, pp. 1025–1038, 2011 (in Japanese).
[13] T. Ide and K. Inoue, “Knowledge Discovery from Heterogeneous Dynamic Systems using Change-Point Correlations,” in Proc. 2005 SIAM Int. Conf. Data Mining, pp. 571–576, 2005.
[14] H. Nakanishi, S, Kanata, H. Hattori, T. Sawaragi and Y. Horiguchi, “Extraction of Coordinative Structures of Motions by Segmentation Using Singular Spectrum Transformation,” J. Advanced Computational Intelligence and Intelligent Informatics, vol. 15, no. 8, pp. 1019–1029, 2011.