International Journal of
Science and Engineering Investigations vol. 10, issue 116, September 2021
Received on September 29, 2021 ISSN: 2251-8843

Low-Cost Sensor System with Life Signals for Bed Monitoring

Nobuhiro Shimoi[1], Kazuhisa Nakasho[2], Katsumi Wasaki[3]
[1]Department of Intelligence Mechatronics, Akita Prefectural University, Yurihonjho, Japan
[2]Department of Graduate School of Sciences & Technology for Innovation, Yamaguchi University, Yamaguchi, Japan
[3]Department of Electronic and Information Systems, Shinshu University, Nagano, Japan
([1]shimoi@akita-pu.ac.jp, [2]nakasho@yamagichi-u.ac.jp, [3]wasaki@cs.shinshu-u.ac.jp)

Abstract- As described herein, a bed-leaving detection system using piezoelectric film sensors was proposed to monitor human body vital signs such as arterial blood pressure, breathing motion, and body movement. This report presents details of a fast and concise algorithms designed to detect vital signs from vibration signals that are recorded via piezoelectric film sensors installed inside a pillow and under a mattress or futon. This paper presents a novel bed-leaving sensor system for real-time recognition of bed-leaving behavior patterns. The proposed system comprises five pad sensors installed on a bed, a rail sensor inserted in a safety rail, and a behavior pattern recognizer based on machine learning. The linear characteristic between loads and output were obtained from load testing to evaluate sensor output characteristics. Moreover, the output values change linearly concomitantly with speed to attain a sensor with the equivalent load. From ten participants, we obtained benchmark datasets of continuous and discontinuous behavior patterns. Recognition targets using our sensor prototype and their monitoring system show five behavior patterns: sleeping, longitudinal sitting, lateral sitting, terminal sitting, and leaving the bed. We compared machine learning algorithms of five types to recognize five behavior patterns. The experimentally obtained results revealed that the proposed sensor system improved recognition accuracy for both datasets. Moreover, we achieved improved recognition accuracy after integration of learning datasets as a general discriminator. his electronic document is a “live” template. The various components of your paper [title, text, heads, etc. are already defined on the style sheet, as illustrated by the portions given in this document.

Keywords- *Bed Monitoring, Piezoelectric Sensors, Quality of Life, Random Forest*

I. INTRODUCTION

In Japan, the declining birthrate and a growing aged population have overburdened the nursing staff at hospitals and nursing homes. According to a survey conducted by the Japan Federation of Medical Worker’s Unions in 2015 [1], nursing staff were obliged to work double shifts at nearly 90% of nursing homes. The survey also revealed that 64.8% of the nursing homes that had adopted double shifts forced nursing staff to work 16 consecutive hours. Furthermore, according to its annual report on the aging society published by the Cabinet Office in 2015, only 23.4% of care-requiring individuals received service at nursing homes [2]. Therefore, work overload difficulties at nursing homes constitute only a small part of the greater underlying difficulties in Japan. We are developing a simple and cheap monitoring system as one engineering technology to reduce difficulties in monitoring elderly individuals at their care sites [3], [4]. We regard bed monitoring systems for elderly individuals as divisible into two major applications: bed leaving detection and vital sign monitoring. Applications of the first group are aimed at preventing elderly people from slipping and falling when they leave a bed without help from others. Occupational characteristics of caregivers show that their occupation and turnover rates are higher than those of other industries [5]. Caregivers must work physically and mentally not only to provide various care services, but also during nighttime shifts to provide 24-hour nursing services and support. Especially during nighttime, a severe caregiver shortage engenders insufficient nursing care, which involves risks of inducing accidents related to daily life for care recipients. Mitadera et al. [6] reported that fall accidents of elderly people accounted for more than 50% of all accidents at nursing-care facilities. Situational details reveal that most accidents occurred when elderly people left their bed and its surroundings. Moreover, 85.5% of fall-related accidents occurred under circumstances without assistance or supervision. Therefore, preventive measures that incorporate bed-leaving sensors are indispensable for early detection of bed-leaving behavior because facility administrators are held liable if an accident occurs. Recently, various bed-leaving sensors have become commercially available: clip sensors, mat sensors, and infrared (IR) sensors are used widely at hospitals and nursing-care facilities. Although clip sensors can be used easily because they are the most reasonable means available, care recipients are restrained by sensor wires because they are attached directly to a patient’s night wear. An important shortcoming of mat sensors is their slow detection and response from the position where a care recipient sits at the bed terminal while putting their feet on it. Another shortcoming is the excessive reaction even when a caregiver or a family member passes while stepping on it. Also, because the sensor is visible, a care recipient might attempt to leave while consciously avoiding a mat sensor [7], [8].

II. VITAL SIGN MONITO FOR NURSING CARE

They can also function as pulse oximeters. An initial version of vital sign monitoring was used in critical situations such as surgery and intensive care in hospitals. Such systems are used as an alarm system to provide alerts with respect to abnormal conditions of a patient. These systems must be highly reliable. Therefore, these systems include electrodes attached to the chest or limbs of a patient for accurate measurement of cardiac action potential. However, attaching electrodes to patients directly enforces restrictions of their physical activity. This process is unsuitable for environments for which high quality of life (QOL) is necessary. Recently, the progress of sensing and wireless technology and miniaturization of electronic devices has led to the development and commercialization of diverse unobtrusive vital sign monitoring systems [9]. Sensors of several types including electrodes, pulse oximeters, piezoelectric films, accelerometers, and phonocardiographs have been proposed. These unobtrusive systems have broadened the scope of applications of vital sign monitoring systems to areas including nursing, sports, and daily health care [10].

A. Stem Configuration

To realize the functions of a vital sign monitoring system, a bed-leaving detection system must detect slight vibrations induced by arterial blood pressure or breathing motion in various body positions. Therefore, existing piezoelectric load sensors used for the current bed-leaving detection system were improved to detect weaker vibration signals generated at greater distances. Many households throughout Japan use futons for bedding. Futons transmit weaker vibrations than mattresses do. Consequently, improvement of piezoelectric sensors for detecting weaker signals is expected to enhance the promotion and use of bed monitoring systems in ordinary homes. The purposes of bed monitoring systems for elderly individuals are divisible into two major applications: bed leaving detection and vital signs monitoring. The former systems are aimed at preventing elderly people from slipping and falling when they leave a bed without help from others. Vital sign monitors are apparatuses that measure and record physiological parameters such as the heart rate, blood pressure, and body temperature [12], [13]. They can also function as pulse oximeters. An initial version of the vital signs monitor was used in critical situations such as surgery or intensive care in hospitals. It was used as an alarm system to provide alerts with respect to abnormal conditions of a patient. These systems must be highly reliable. Consequently, these systems include electrodes attached to the chest or limbs of a patient for accurate measurements of cardiac action potential. However, attaching electrodes to patients directly enforces restriction of their physical activity. This is unsuitable for environments where a high quality of life (QoL) is required. Recently, the progress of sensing and wireless technology and miniaturization of electronic devices has led to the development and commercialization of diverse unobtrusive vital signs monitoring systems [14]. Sensors of several types including electrodes, pulse oximeters, piezoelectric films, accelerometers, and phonocardiograph were proposed. These unobtrusive systems have broadened the scope of applications of vital signs monitoring systems to areas including nursing, sports, and daily health care.

B. Pillow sensor

The basic piezoelectric sensor (DT2-028K/L; Tokyo Sensor Co., Ltd.) has a piezoelectric film sandwiched between two 1-mm-thick urethane sheets. The piezoelectric film and sensor dimensions are, respectively, 16 × 73 mm and 30 × 80 mm (Fig. 1, Fig. 2). For this study, the piezoelectric sensor was used as a pillow sensor. The sensor was attached between the center of the upper side of a pillow and pillowcase using adhesive tape (Fig. 2) so that it can be deformed easily with a pressing load.

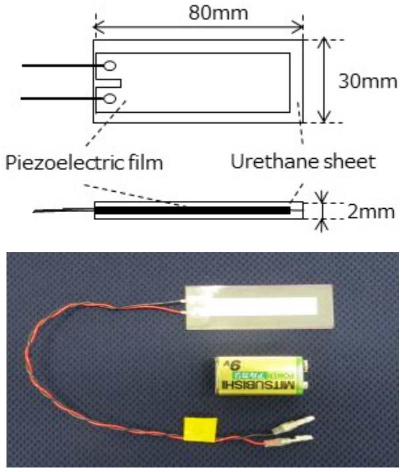

Figure 1. Piezoelectric pillow sensor.

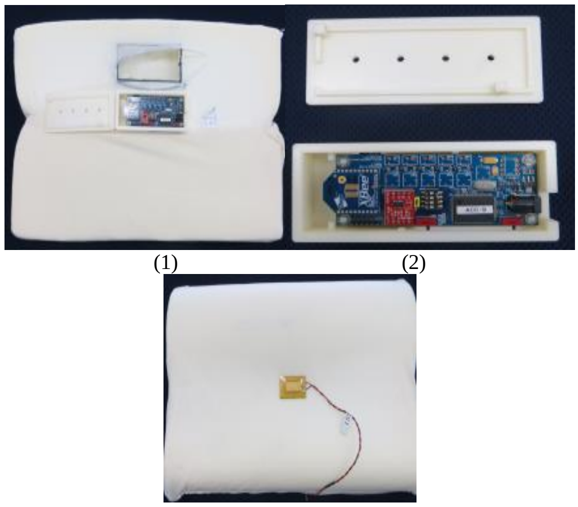
(1) (2)

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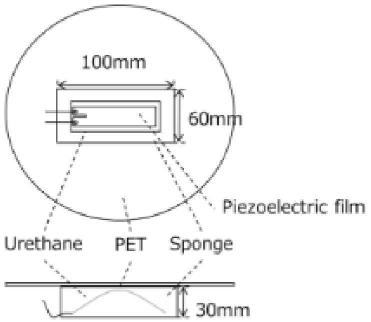
Figure 2. Pillow sensor and radio systems

C. Bed sensors

To construct a bed sensor, the following improvements were made to the piezoelectric sensor. The piezoelectric sensor sandwiched between two urethane sheets was bent into an arch. It was then embedded it into urethane foam (30 mm × 80 mm). A PET resin disk (φ200 diameter, 0.5 mm thickness (1)) was adhered to the urethane foam to broaden the sensor sensitivity range. Fig. 3 (Left panel) shows a schematic drawing and the bed sensor. Bed sensors (2) were attached at five points under a mattress or a futon. Fig. 3 (Right panel) shows installed sensors on a bed frame under a mattress.



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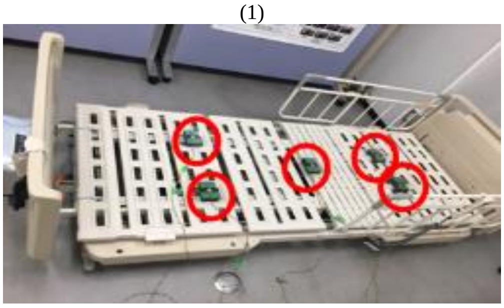

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Figure 3. Piezoelectric vibration sensors and bed sensor installation positions.

D. Signal processing

Vibration signals originating from arterial blood pressure, breathing motion, and body movements were extracted from output voltages of each sensor by executing the following processing procedures.

- Filter processing: To remove high-frequency noise, a low-pass filter was applied (10 Hz passband) to the original signal obtained from a piezoelectric sensor.
- Arterial blood pressure: was calculated. A bandpass filter (0.8–2.0 Hz passband) corresponding to the standard heart rate of 50–120 bpm was applied. The time interval was found between the prior 20 extreme points of the signal obtained in step B.
- Breathing motion: Fluctuation during the prior 2 s at each time of the signal obtained in step 1 was calculated.

A bandpass filter (0.2–0.5 Hz passband) corresponding to the standard respiration rate of 12–30 times per minute was applied. The time intervals of the prior 20 extreme points of the above signal were computed, followed by calculation of the respiration rate.

- Body movement: Fluctuation in the past 5 s at each instant of the signal obtained in step 1) was calculated. A low-pass filter (0.1 Hz passband) was applied.

Fig. 4 presents a flow chart depicting these signal processing procedures.

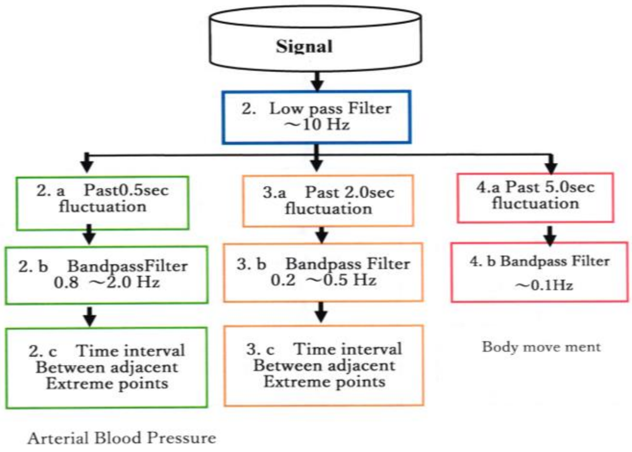


Figure 4. Sensor systems of signal processing flow.

E. System evolution

The system evaluation experiment was conducted to verify the vital sign monitoring capability of the new piezoelectric sensors and to obtain knowledge about software processing on the signals detected with these sensors. To evaluate the vital sign monitoring capability, an experiment was conducted to evaluate five participants: three men and two women. They were asked to rest supine for 15 min to simulate a sleeping state. Then the participants read a book while maintaining the same position to simulate an awakened state. The pillow sensor and bed sensors were installed in a low rebounding pillow (Nitori Co., Ltd.) and a nursing bed (Paramount Bed Co., Ltd.). A layout of the piezoelectric load sensor positions is portrayed in Fig. 5. For the experiment, the pillow and bed sensor outputs were recorded at 100 Hz sampling frequency using memory loggers (LR8430 and LR8431; HIOKI EEK.K.).

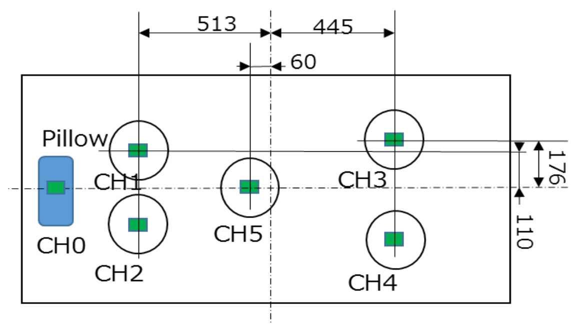


Figure 5. Layout of piezoelectric load sensor positions.

III. EXPERIMENT RESULT

A. Arterial Blood Pressure

Fig.6(1) shows that the voltage change caused by changing arterial blood pressure is dominant in Signal 1 during the simulated sleep. It was cumbersome to process Signal 1 directly given its drastic changes in amplitude. However, Signal 2-a (Fig.6(2)), which was produced by accumulating the fluctuation of Signal 1 during the prior 0.5 s, shows a moderate change in amplitude, although its phase differed from the original. Signal 2-b (Fig. 6 (3)), which produced by application of bandpass filter to Signal 2-a, had a remarkably stable waveform. Its frequency was computed easily. Additionally, the fluctuation in Signal 2-b over the past 10 s was observed not to reach 100 mV when the participant had left the bed. Nevertheless, the value was constantly over 100 mV when the subject lay on the bed despite differences among individuals and sensor positions.

B. Body movement

The waveform of Signal 4-b corresponding to body movement is shown in Fig. 7(2). Despite differences among individuals, fluctuations in body movement during fake sleep (0–900 s) were observed as smaller than those of body movements when awake (900–1,800 s)

C. Criteria setting

Experimentally obtained results: the 10 s fluctuation of Signal 2-b (Fig.6(2)) falling below 200 mV. The decision criterion of sleep awakening was based on whether 10 s fluctuations of Signal 4-b (Fig.7(1)) fell 1 V. These criteria were applied to signal data of the system evaluation experiment to obtain system judging rates of the bed staying leaving and sleep awakening.

Fig. 8 shows the bed monitoring systems developed to assign the highest priority to the living environment. This system was devised so that the care recipient can monitor their behavior without wearing any sensor. A person can be monitored remotely using a 2.4 GHz communication device. The sensors are a MEMS sensor that integrates a communication device and an accelerometer inserted in the pillow, with six piezo load sensors under the bed mat. The acquired data are managed by an AI robot that uses machine learning methods. That information is transmitted to the caregiver only when necessary.

As shown by the judging rates in Table I, the average judging rates of the bed-staying leaving and sleep awakening were, respectively, 100% and 74.1%. The output voltage of the load recognition sensor near the coccyx was lowest because the body weight was concentrated near the coccyx in a lying posture such that the weak vibrations were insufficient to deform the piezoelectric load sensor. As described above, the output voltage of a piezoelectric load sensor depends strongly on its position. By contrast, in our system, to maintain the robustness of the measurements for various body positions on the bed, all sensor outputs were treated equivalently without multiplication by any coefficient.

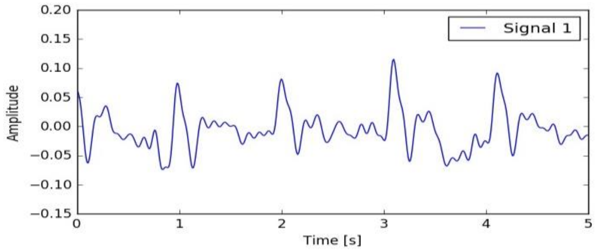
Table 2 presents analysis results obtained for the accelerometer and the piezo vibration sensor for each of the seven basic postures using complex analysis technology. Accurate posture recognition was difficult. However, they can be classified into three types, "sleeping" (supine, right side, left side), "getting out of bed", (long sitting, short sitting, end sitting), and "completely getting out of bed." Thereby, it was possible to detect 89.3% and 100% of people who were out of bed and who were completely out of bed. Results show that these findings are considerably better than 89.3% during sleep, 94% during bed leaving action, and 88% during complete bed leaving indicated by the pillow sensor alone. In addition, the 100% detection rate of the piezo vibration sensor in "sitting on the edge" and "completely getting out of bed" suggests that the sensor is extremely reliable. It is indispensable for behavior recognition of the care recipient. It can be regarded as an effective and important factor for use as an analytical technology using composite sensors for the detection of bed leaving prediction [3] [4].

TABLE I. JUDING RATE [%]

Participant	Bed on Style	
	Bed staying and leaving	Sleep and awakening
1 male	100	88.7
2 male	100	88.1
3 female	100	76.7
4 female	100	76.9
5 male	100	47.0
Average	100	74.1

TABLE II. RECOGNITION ACCURACIES OF THE RESPECTIVE SUBJECTS AND POSITIONS FOR SEVEN PATTEMS [%]

Participant	Sleeping	Terminal	Left the bed	Average
A	86.7	100	100	95.6
B	80.8	100	100	93.3
C	100	100	100	100
D	93.3	100	100	97.8
E	100	100	100	100
F	73.3	100	100	91.9
G	100	100	100	100
H	93.3	100	100	97.8
I	86.7	100	100	95.6
J	80.0	100	100	93.4
Average	93.3	100	100	96.5



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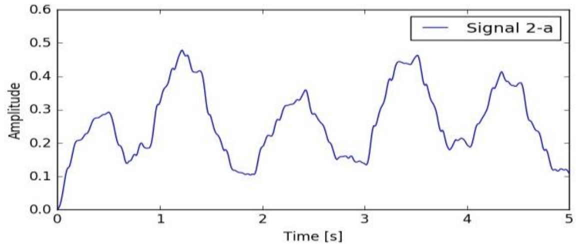

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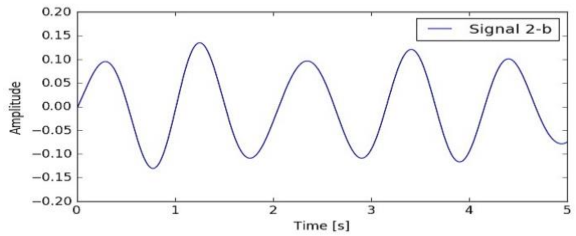

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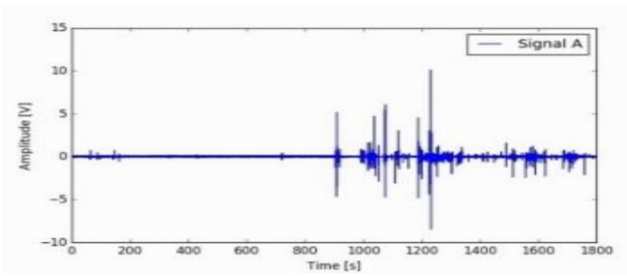
Figure 6. Arterial blood pressure measured via signa.



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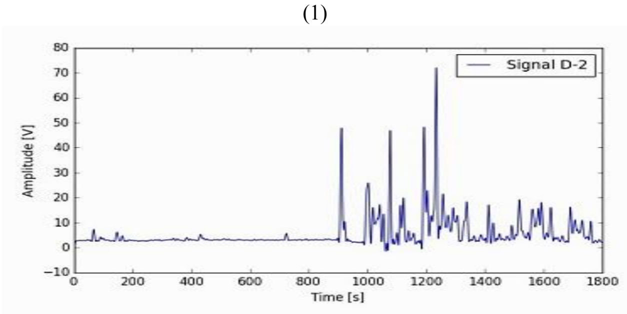

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Figure 7. Extraction of body movement

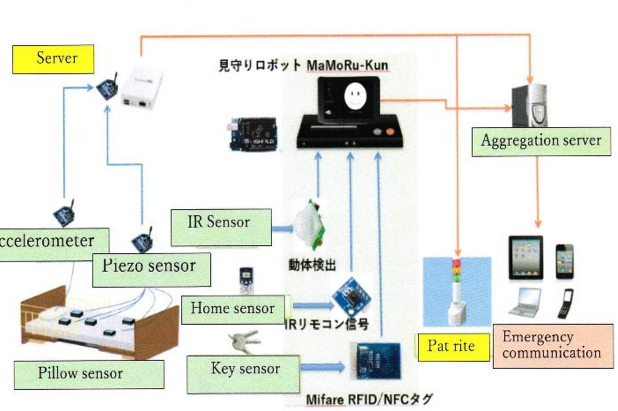

Figure 8. New monitoring system for quality of life.

IV. CONCLUSION

Results of this study demonstrated that piezoelectric load sensors installed in pillows and under the bed were capable of monitoring vital signs such as arterial blood pressure, breathing motion, and body movements. The original method to extract vibration signals such as arterial blood pressure, breathing motion, and body movement from the piezoelectric sensors was described by processing fluctuation calculation and filtering. Construction of a concise vital sign monitoring system using a low performance computer such as a single board computer can be effective because these processes can be performed with light processing loads. Furthermore, results confirmed that the vital sign monitoring information enabled the system to judge bed staying leaving and sleep/awakening with high accuracy rates of 99% and 80%, respectively. Moreover, we developed a sensor system that is inexpensive, convenient, and maintainable with advanced QoL for care recipients. Actually, as described in the *Introduction*, using a camera as a bed monitoring sensor can provide a low-cost system that is able to obtain large amounts of information. Nevertheless, it remains a challenging task to predict behavior patterns obtained from images, even when state-of-the-art computer vision technologies are used. For example, as a deep-learning-based approach, Open Pose does not handle sleeping or laying positions. Therefore, medical staff members must observe images directly. Moreover, one must consider aspects of human rights and QOL. Especially, because behavior patterns differ among people, it is impossible to monitor numerous subjects simultaneously with a few operators and to recognize behavior patterns related to bed-leaving using sensor responses alone, even when detailed analyses are conducted. Furthermore, monitoring using a camera imposes a mental load on patients because they feel as though they are under surveillance all daytime and nighttime. We have not evaluated this sensor system at an actual hospital or care facility.

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Nobuhiro Shimoi, 1982 Research Center, Toshiba CoLtd.1987 The 4th Research Center, Technical Research and Development Institute, Ministry of Defense. 1996 Associate Professor at Tokyo National College of Technology.2009 Professor at Akita Prefectural University. Main Work: The technology of Personal mine Detecting for Humanitarian demines. Journal of the SICE, Vol37, No6.pp577-583, 2001. Membership in Learned Societies, The Society of Instrument and Control Engineers (SICE), Japan Society of Mechanical Engineers (JSME) and senior member of Institute of Electrical and Electronics Engineers (IEEE),

Kazuhisa Nakasho was born in Osaka, Japan, in 1978. He received the B.S. and M.S. degree from Kyoto University, Kyoto, Japan in 2001 and 2003, respectively. He joined Elysium Co., Ltd, Hamamatsu, Japan, in 2003, then moved to the Interdisciplinary Graduate School of Science and Technology, Shinshu University, Nagano, Japan in 2013. He received the Ph.D. degree in Engineering from Shinshu University in 2016. He has been an assistant professor in the Department of Machine Intelligence and Systems Engineering at Akita Prefectural University, Akita, Japan. His current research interests include signal processing, image processing and formalized mathematics.

Katsumi Wasaki received the M.S. and Ph.D degrees in Computer Science and Engineering from Shinshu University at Nagano, Japan, in 1993 and 1997, respectively. He is presently a Professor, Faculty of Engineering at Shinshu University, where he initially joined in 1998. During occasional leaved of absence from Japan, he was invited to visit Department of Computing Science, University of Alberta at Edmonton, Canada, in 2003 and 2005. He has served on the NEDO: New Energy and Industrial Technology Development Organization in Japan, as a member of technological evaluation committee in 2008. His current research interests include modeling and analysis of concurrent, parallel and/or distributed processing systems, mathematical model and formal verification of asynchronous circuits, and hardware compiler for model checking systems. He is a member of IEEE, IEICE, IPSJ and IEEJ.

How to Cite this Article:

Shimoi, N., Nakasho, K. & Wasaki, K. (2021). Low-Cost Sensor System with Life Signals for Bed Monitoring. International Journal of Science and Engineering Investigations (IJSEI), 10(116), 45-50. http://www.ijsei.com/papers/ijsei-1011621-07.pdf