Fiber Bragg Grating-based Monitoring and Alert System for Care of Residents in Nursing Homes

Victor Foo Siang Fook, Maniyeri Jayachandran, Eugene Phua Jiliang, Zhu Yongwei, Emily Hao Jianzhong
Infrastructure Department
Institute for Infocomm Research,
Agency for Science Technology and Research,
1 Fusionopolis Way, Connexis, Singapore 138632
{sffoo, mjay, jephua, ywzhu, haoemily}@i2r.a-star.edu.sg

***Abstract*—This paper presents a novel Fiber Bragg Grating (FBG)-based monitoring and alert system for care of residents in nursing homes. Using FBG to design Internet of Things (IoT) sensor devices, a tele-monitoring system was developed to monitor vital signs such as pulse rate, respiratory rate, temperature, movement and bed exit of residents on beds. It is able to measure pulse rate and respiratory rate accurately with mean error below 1 beat per minute, detect sudden onset of high fever and unexpected bed exit during the nights which is crucial to maintain a high quality of care for residents. In cases where any of the patients' health condition deteriorates or abnormal behavior is detected, medical staffs will be notified immediately by the system which provides real time alert on each resident's condition through mobile devices such as mobile phones or tablets. The system also allows residents to alert the medical staffs their need for help through uniquely designed call buttons.**

Keywords: Fiber Bragg Grating, Monitoring and Alert System, Care of Residents, Nursing Homes

I. INTRODUCTION

Round-the-clock monitoring of the health and well-being of residents is a challenging but important problem in nursing homes. Monitoring vital signs such as pulse rate, respiratory rate and temperature are useful in detecting medical problems as they are measurements of the body's most basic functions. Monitoring occupancy or bed exits for residents with risk of falls are equally important for care of residents. Fever, abnormal pulse and respiratory rate and falls are common reasons for residents in a nursing home to be taken to see a doctor or admitted to hospitals. However, the current practice is time consuming and tedious as it typically involves the medical staffs having to manually conduct periodic checks. Moreover, it is infrequent and may potentially miss onset of crisis event or result in delayed response. In some cases, it may be even impossible for the residents to alert the medical staffs immediately during emergency when they are not in the vicinity. Nursing homes typically do not receive the kind of care level or investment in technology such as call bell system commonly found in hospitals.

With the recent advances in IoT, ubiquitous and fiber technology, healthcare applications can be developed for care of residents in nursing homes available to anyone, anytime, and anywhere seamlessly in an unobtrusive manner. The scenario that we envision is one reliable monitoring and alert system that can act as a platform to boast productivity and improve the quality of healthcare services for its residents. It can help medical staffs care for residents more efficiently and deliver a higher quality of care without increasing the number of staffs needed. Even when the staffs cut down their rounds, they can have peace of mind that they will know if there is an emergency. This allows the staffs to spend more quality time with the residents through organizing additional social activities or performing other duties. It is also possible for the family members to monitor their loved ones anytime anywhere when they are given access to the applications developed on the mobile devices. The platform should also provide support for integration of a variety of IoT sensors and devices.

In this paper, we present a novel approach of using fibers to provide the actual sensors itself used in IoT applications developed to assist the medical staffs in caring of residents in nursing homes. Specially designed and packaged high sensitive FBG-based optical fiber sensors are developed for use in the monitoring and alert system to monitor the residents continuously without disturbing them, and allow medical staffs to be alerted during emergency automatically through mobile devices such as mobile phones or tablets. The system is able to capture ballistocardiogram (BCG) signal to estimate the pulse rate and respiratory rate of residents lying on beds that is comparable to conventional clinical measurements based on electrocardiogram (ECG) or polysomnography devices. It is also able to monitor the temperature and detect onset of high fever on lying residents. An IoT FBG-based sensor button was also developed to allow the residents to call or alert the medical staffs when necessary. While there are many wireless healthcare systems being proposed [1,2], there is limited similar healthcare systems based on optical fiber sensors seen and the closest are by Chen et al. [3] and Dziuda et al. [4]. However, the monitoring features supported by them are limited.

The remainder of the paper is structured as follows. Section II presents the method and system. Section III describes the experimentation and results. Section IV concludes the paper and mentions future work.

II. METHOD AND SYSTEM

FBG is a periodic or aperiodic index change along the core of the optical fiber as shown in Fig. 1.

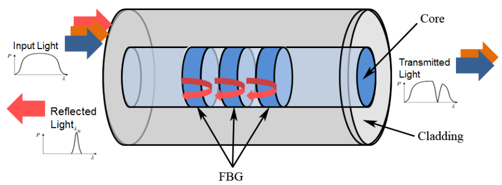

Figure 1. Fiber Bragg Grating (FBG)

The refractive index change leads to the reflection of light propagating along the fiber in a narrow range of wavelengths to fulfil Bragg equation given in (1).

$$\lambda = 2neff\,\Lambda \quad (1)$$

where , λ is the vacuum wavelength, Λ is the grating period and neff is the effective refractive index seen by the reflected wavelength in the fiber. Changes in strain and temperature affect both the effective refractive index and the grating period of an FBG, which results in a shift in the reflected wavelength. Typically, a shift in Bragg wavelength has approximately linear response to strain and temperature variation, and they can be widely applied in sensing area.

The monitoring and alert system is primarily based on FBG technology. Using FBG technology, uniquely designed FBG sensors are packaged into IoT devices such as IoT sensor mat, IoT thermometer and IoT button. We term the packaged Fiber-based IoT sensors as F-IoT devices as we are using fibers to provide the actual sensors itself. There are three main advantages of using FBG sensors. First, FBG sensors are very stable and passive with no need of local power sources. They are intrinsically safe for long term monitoring even for residents with pacemakers. Second, it is immune to electromagnetic interference (EMI). Hence, they can be deployed in almost all environments in nursing homes as they are not affected by external devices such as cell phones and wireless devices. Third, the multiplexing capability allows multiple F-IoT devices to be connected to a single fiber. Fig. 2 shows the architecture of the system. It consists of three basic components - the F-IOT devices, interrogator and server.

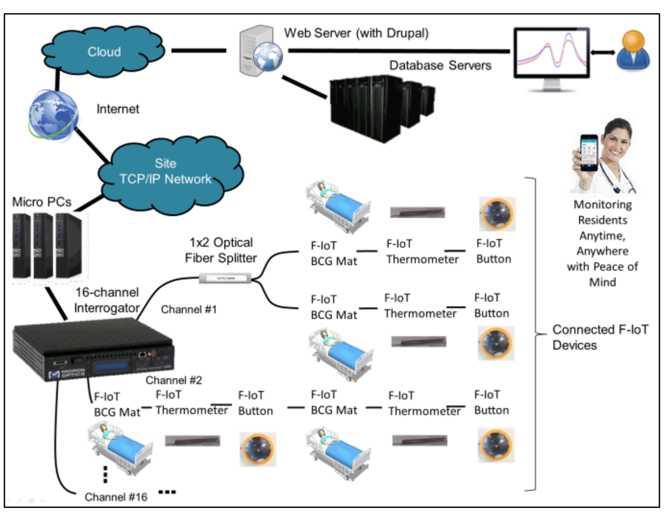

Figure 2. FBG-based Monitoring and Alert System

The F-IoT devices can be connected in series or parallel using a splitter to the interrogator by single mode optical fibers. The interrogator is connected to the server by Internet Protocol-based network. In our system, a 16 channels Si255 optical sensing interrogator from Micro Optics was used. The wavelength range scanning laser is 160 nm at 1 kHz speed.

The overall system is designed in a loosely coupled manner, following Service Oriented Architecture (SoA) principles. On the sensor device side, data is streamed from the interrogator to micro-PC computing devices, where it is processed to generate useful events and vital sign parameters. The data acquisition and data processing itself are separated into different components, so that the data processing component can be scaled out across multiple nodes. Processed data from the computing device is to be sent to a server or cloud system for storage and visualization. Service application-programming interfaces (APIs) are created on the server side on Tomcat platform, using Jersey-2/Java REST libraries. The service APIs will perform data sanitization and authorization before saving the data into MySQL based database tables in the database servers.

Drupal is used as the framework and content management system as it fits very well for developing IoT applications. It has excellent authentication, authorization modules, very well designed APIs for seamless and consistent integration and a large and active community support. For mobile responsiveness and consistency in design, Bootstrap framework was used in template designs. Different authorization roles were created for residents, nursing staffs, doctors and system administrators for different departments in the nursing home. After logging into the system, each user will be presented with data that's within their scope of work depending on the assigned roles. We have developed few custom Drupal modules to integrate the Drupal-based web application framework to access data from external database tables and to present data in the form as required by the end users. The Content Type and Views modules of Drupal were used to link different sensors with users and their assigned beds and to present visualizations for groups of patients who were under the care of certain nursing staff or doctors.

A. *F-IoT BCG Sensor Mat, F-IoT Thermometer and F-IoT Button*

The F-IoT BCG mat consists of one FBG sensor array with 8 FBG BCG sensors as shown in Fig. 3.

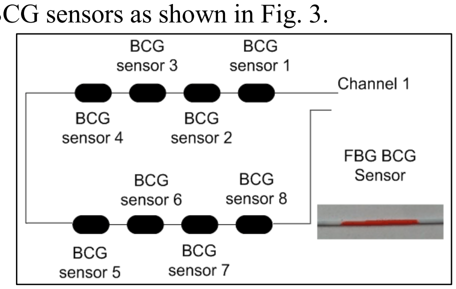

Figure 3. FBG BCG Sensor Array in F-IoT BCG Sensor Mat

The sensitivity of the sensor mat can be adjusted based on the sensor design, number of sensors, placement and packaging material. A sleeve-based FBG design was selected due to its robustness and high sensitivity. Eight sensors were used and placed into two rows. Comfort to users is one key consideration when designing the mat. The FBG BCG sensor array was packaged onto a polycarbonate sheet. Fig. 4 shows the final packaged IoT BCG sensor mat that was placed on top of the mattress of beds to monitor the pulse rate, respiratory rate, movement and bed exit of residents in nursing homes.

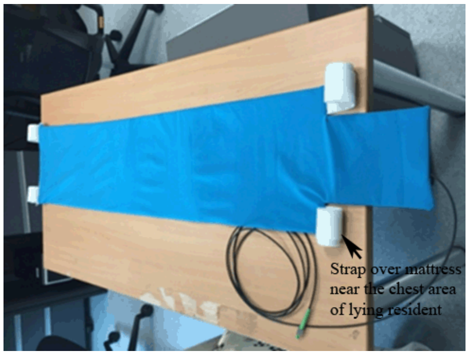

Figure 4. F-IoT BCG Sensor Mat

For designing F-IoT thermometer using FBG-based temperature sensor, thermal expansion coefficient and thermal conductivity of packaging material play an important part in improving the temperature sensitivity. The sensitivity of FBG strain-insensitive temperature sensor can be adjusted based on the sensor design and coating. Fig. 5 shows a design of F-IoT thermometer that we have using a strain-insensitive temperature sensors with nylon-coated FBG sensor packaged in a copper tube.

Figure 5. F-IoT Thermometer

Fig. 6 shows the wavelength change for three types of FBG strain-insensitive temperature sensors that were fabricated with different design and coating.

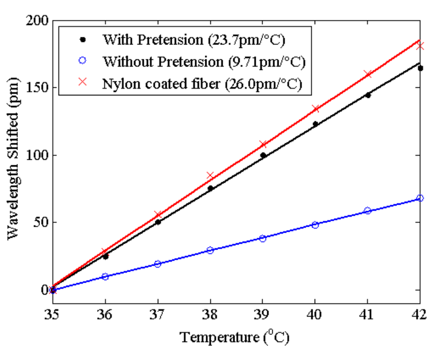

Figure 6. Sensitivity of FBG Temperature Sensors

The FBG temperature sensor sensitivity calibration was done using an oven and can achieve a change of 23.7 pm per degree celcius under ideal condition. The accuracy of measurement is also affected by the resolution of the interrogator. Using an interrogator with accuracy resolution of 1 pm, the accuracy of F-IoT thermometer is around 0.05°C.

We developed the F-IoT button using an arc-shaped FBG sensor as shown in Fig. 7. The concept of the F-IoT button is similar to Amazon AWS IoT button [5]. However, the novelty of our button is that it is fiber-based using fiber connectivity compared to traditional electrical-based wifi connectivity one. The arc-shaped FBG sensor is packaged using carbon fiber reinforced plastic (CFRP) material. An FBG is embedded below the neutral layer of the composite laminate. When the arc-shaped sensor is pressed, the vertical force applied results a tension on the FBG and the reflected wavelength from the FBG will be changed.

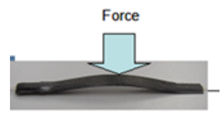

Figure 7. FBG Arc-shraped Sensor in F-IoT Button

The arc-shaped sensor was then packaged using a low cost button from Daiso as shown in Fig. 8. When the button is pressed, the interrogator will capture the wavelength change information and pass to the computing units for processing.

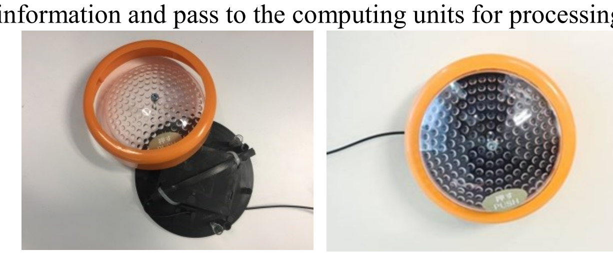

Figure 8. F-IoT Button

B. *Connectivity for Connected F-IoT Devices*

The number of F-IoT devices that can be connected to the system depends on the range of wavelength utilized by the FBG sensors within the devices and the range of wavelength and number of channels supported by the interrogator. For si255 interrogator that was used which can provide long-term, reliable and accurate measurements of nearly 1000 sensors on 16 parallel, 160 nm wide channels based on manufacturer's claim [6], hundreds of F-IoT devices can be supported using a single interrogator. For example, Fig. 9 shows the signals for six F-IoT sensor mats on six beds for six residents connected using a single channel. The y-axis is the signal power and the x-axis is the respective wavelength value of the FBG sensors within the mats. Additional interrogator can be added to the system to support an even larger number of F-IoT devices.

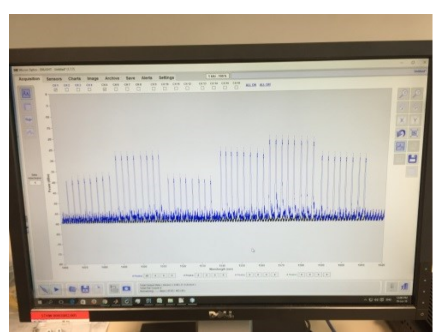

Figure 9. Signal for 6 F-IOT BCG Sensor Mats

The topology of the connectivity is also very flexible as we can connect the F-IOT devices in series or parallel using a splitter or hybrid of both. The ability to add F-IOT devices when necessary makes the system very practical and extensible. For easy deployment, Uniboot duplex connectors may be used. For actual deployment, the loss of light due to connectors may also affect the number of IoT devices to be supported by the system.

C. Data Processing and Signal Analysis

The interrogator will perform center wavelength measurements on the FBG sensors in the F-IoT devices using a "command and response" approach, and the data will then be processed in real time in the micro-PCs. Fig. 10 illustrate the breakdown of data processing modules for the BCG sensor signals for the F-IoT BCG Sensor Mat.

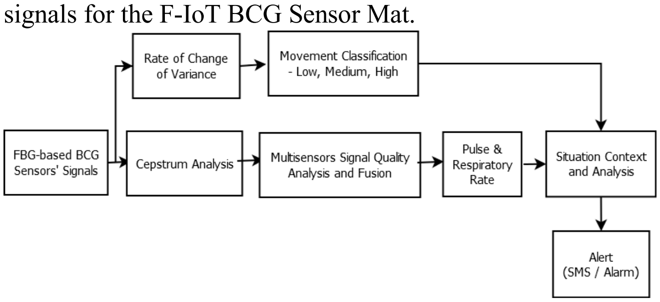

Figure 10. Data Processing Modules for F-IoT BCG Sensor Mat

For pulse rate monitoring, we perform cepstrum analysis. Using this approach, we can perform sensor selection and multi-sensor data fusion to further improve the accuracy and availability of measurement as in [7]. For respiratory rate, we use data from the pulse rate sensor selection of cepstrum analysis to perform filtering and peak detection for estimation as in [8]. Concurrently for movement analysis, we use rate of change of variance of the sensor readings to classify them into three classes – low, medium and high. This context is very useful for validating the reading under abnormal circumstances and to detect residents' abnormal behavior and unexpected bed exit.

For temperature monitoring to detect fever, we need to perform one simple calibration for subject lying on bed by capturing the normal body temperature, skin surface temperature with clothing and ambient temperature. This is done to determine the compensation needed to offset for the difference in body, skin temperature and ambient temperature. As the ambient temperature has a strong impact on the measured skin temperature, we restrict it to a stable range of value. Fig. 11 shows the data processing modules for temperature and fever detection.

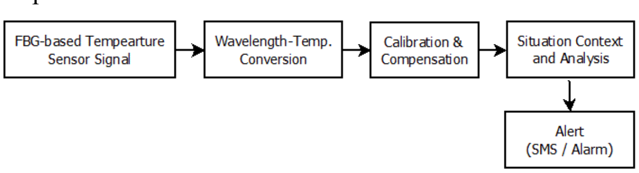

Figure 11. Data Processing for F-IoT Thermometer

For button sensor, a simple algorithm using variance and difference in the maximum and minimum value for a three seconds window will be able to detect the event when the button is being pressed by users. Fig. 12 shows data processing modules for F-IoT button.

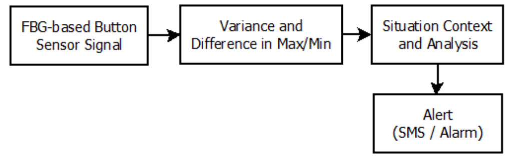

Figure 12. Data Processing for Button Sensor

Using the measurements and context from movement analysis, we will perform high-level situation context awareness and inference to infer subjects' health status and behaviors. We will then use JBoss-based rules engine, Drools [9] to send alerts or SMS to mobile devices such as mobile phones and tablets or dashboard PC for important crisis events such as detecting high fever, irregular breathing, abnormal pulse rate, abnormal large whole body movement, unexpected bed exit etc.

D. Evaluation Methods

For evaluation of F-IoT BCG sensor mat, we will compare our pulse and respiratory rate measurement with gold standard ECG/PSG system. Using a 24-bit polysomnography amplifer from Compumedics at a sampling rate of 512 Hz, ECG was acquired. Two surface ECG electrodes were placed: one about 3-5 cm below the right clavicle and the other on the 6th or 7th left intercostal space, as recommended in [10]. Likewise using the same system, two belts are attached on the subject's chest and stomach to measure respiration. For temperature measurement using F-IoT thermometer, we will compare that with a NI thermocouple and a commercial infrared ear and forehead thermometer. For F-IoT button evaluation, we only conducted experiments to ask different users to press the button multiple times and ensure that no single pressed event detection is missed. Fig. 13 shows the data collection system for comparison.

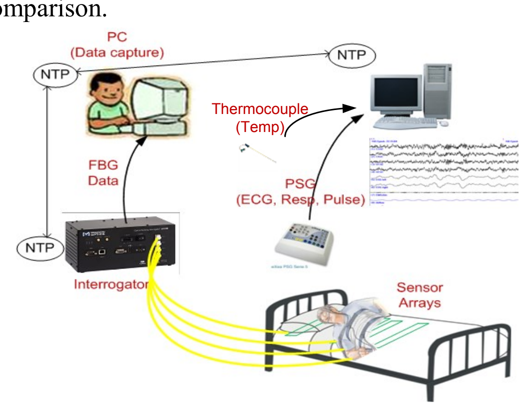

Figure 13. Data Collection System for Measurement Comparison

III. EXPERIMENTATIONS & RESULTS

For pulse and respiratory rate, a comparative study was carried out as we conducted experiments with 10 subjects of both male and female of ages 18 to 54 years old. Their weights ranged between 40 kg to 90 kg, were within the body mass index range of 16 to 30 kg/m3. The subjects were asked to sleep in both the supline and side positions with their body resting on the sensor mat for 10 minutes each.

For all users, we are able to capture the BCG signals. However, we went one step further to look into waveform to waveform comparison to the ideal BCG signals. Using simple band pass filter of lower and higher cut-off frequences 0.5Hz and 20Hz respectively, we could filter out the BCG signals from raw data and was found to be to be comparable to the theoretical BCG waveforms. Fig. 14 shows a snapshot of BCG signals that we obtained for one FBG BCG sensor. The IJKLMN features can be easily distinguished from the waveform obtained. This clearly illustrates the sensitivity of our F-IoT BCG sensor mat for capturing BCG signals at current stage.

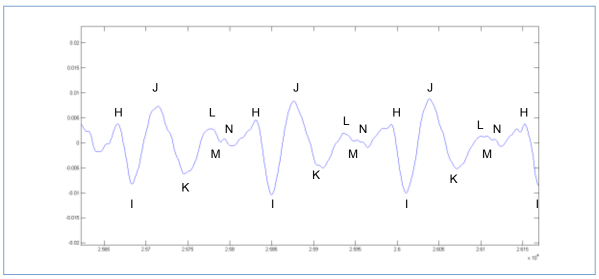

Figure 14. BCG Signal from a FBG BCG Sensor

However, unlike ECG the repeating pattern of each heart beat may not be obvious at all times and varies for some users due to movement, posture, contact, etc. We are trying to see if further enhancing the sensitivity of FBG sensors will allow us to obtain the theoretical waveforms most of these cases.

Using cepstrum analysis, we obtain the cepstrogram for pulse rate monitoring as shown in Fig. 15.

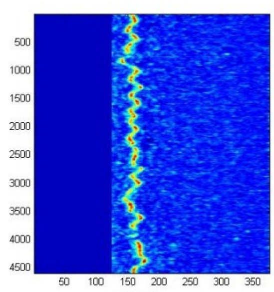

Figure 15. Cepstrum of BCG Signals

The y axis corresponds to time of the cepstrum analysis window while x axis corresponds to lag time. The value can be converted to pulse rate per minute according to (2).

$$Pulse\_Rate = \frac{Sample\_Rate}{x} x60 \qquad (2)$$

We compare our BCG pulse rate measurement with the ECG measurement. Fig. 16 upper plot shows the heart rate from ECG in blue and heart rate from F-IoT BCG sensor mat in red. We could see the difference between the two readings at any time is small, and it can achieve a mean error of less than 1 bpm as shown in the lower plot.

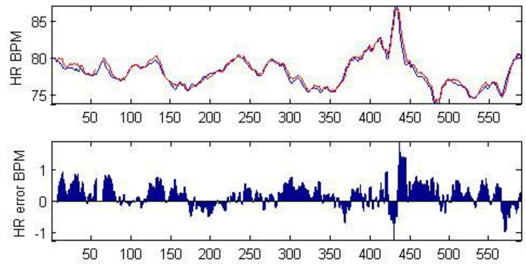

Figure 16. F-IoT BCG Sensor Mat Pulse Rate and ECG Measurement Comparsion

Once the BCG signal for pulse rate can be captured with a high degree of accuracy, it is easier to extract out the respiratory rate. It was observed that the wavelength change caused by the respiration can be up to 10 times those of the pulse rate. We compare the respiratory rate from BCG with the PSG belt system. Fig. 17 upper plot shows the respiratory rate from PSG in blue and estimated reading from F-IoT BCG sensor mat in red. We could see the difference between the two readings at any time is small, and it can achieve a mean error of less than 1 bpm as shown in the lower plot.

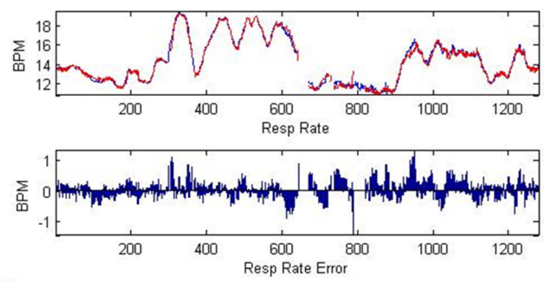

Figure 17. F-IoT BCG Sensor Mat Respiratory Rate and PSG Comparison

For temperature monitoring to detect fever, Fig. 18 shows the F-IoT thermometer measured skin temperature colored in in blue compared to the thermocouple under normal body and ambient temperature when subject is lying on the mat.

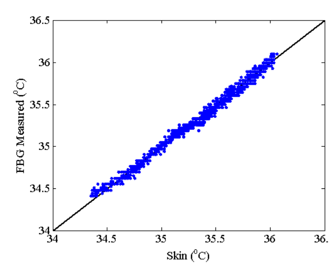

Figure 18. Measured Skin Temperature from F-IoT Thermometer

The deviation of measured skin temperature from F-IoT thermometer and thermocouple ranges from 0.079 to 0.159 for subject with simple thin clothing. The measured skin temperature will reach the equilibrium value if the body temperature does not vary significantly. Typically, the difference between body and skin temperature when the subject is not having a fever is between 1 to 2 degree celcius. By matching to the calibrated readings based on normal body, skin and ambient temperature, and compensating to the offset, we are able to estimate the body temperature with reasonable accuracy using the estimated offset and detect onset of high fever events.

We also work with a local company to deploy the complete running system in a local nursing home for evaluation as shown in Fig. 19.

Figure 19. Deployment in a Local Nursing Home

In the first phase, the objective is to achieve more than 95% accuracy rate for pulse and respiratory rate monitoring for patients lying on beds in a naturalistic environment. Another objective is to evaluate its robustness, reliability and usability. Based on initial feedbacks, the result is very promising as the measurements can be trusted and there is limited downtime for the IoT devices and system. Fig. 20 shows snapshots of vital sign of a resident being monitored on a mobile phone.

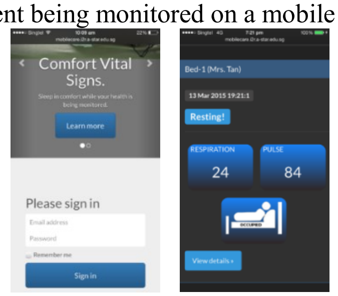

Figure 20. Snapshots of UI on mobile phone

In addition, at the nursing station, there is a dashboard application running on tablet or PC monitor. It provides a bird eye view of the situation of the ward for the medical staffs to continuously supervise the status of the residents as shown in Fig. 21. It enhances patient safety as unexpected bed exit especially during the nights when there are less staffs on duty will be alerted through the application on the mobile phone or tablet immediately.

Figure 21. Snapshot of Dashboard UI on tablet or PC monitor

The medical staffs such as nurses and doctors can also look at the trend of the resident's pulse rate, respiratory rate and duration on bed. Fig 22. shows the trend of pulse rate, respiratory rate and occupancy for a resident over one hour.

Figure 22. Trend Analysis of Resident's Pulse, Respiratory and Occupancy

The system is now in preparation for the next phase of evaluation with more residents. It is hoped that the novel system will be able to meet the demands of care in the nursing home and more F-IoT devices will be developed to add to the system platform to boast productivity, improve quality of healthcare services and provide peace of mind to medical staffs as monitoring of well-being and safety of residents is realtime, continuous and remote.

IV. CONCLUSION

This paper presents a novel FBG-based monitoring and alert system for care of residents in nursing homes. Using fiber-based FBG technology to provide the actual sensors itself, IoT applications were developed to meet the demands of medical staffs. Using F-IoT BCG sensor mat, F-IoT thermometer and F-IoT button, the developed system can continuously monitor residents on beds and enable early detection of patient deterioration in condition and abnormal behavior remotely. In an emergency, medical staffs can also be notified immediately through the automated alert platform or be alerted by residents through the call button.

REFERENCES

[1] P. Alexandros, B. Nikolaos, "A survey on wearable sensor-based systems for health monitoring and prognosis", IEEE Trans. Syst., Man, Cybern. C, Appl. Rev., vol 40, no. 1, pp. 1-12, Jan 2010

[2] G. Fortino, R. Giannantonio, R. Gravina, P. Kuryloski, R. Jafari, "Enabling Effective Programming and Flexible Management of Efficient Body Sensor Network Applications", IEEE Trans. Human-Machine Systems, vol. 43, no. 1, pp. 115-133, Jan 2013

[3] Z. Chen, J.T. Teo, N.S. Huat, X. Feng, "Portable fiber optic ballistocardiogram sensor for home use", Optical Fibers and Sensors for Medical Diagnostics and Treatment Applications IX,SPIE,vol.8218,2012

[4] Dziuda, L., Skibniewski, F.W., Krej, M., Lewandowski, "Monitoring Respiration and Cardiac Activity Using Fiber Bragg Grating-Based Sensor", IEEE Transactions on Biomedical Engineering 2012 Vol. 59,pp., Issue 7, 1934-1942

[5] https://aws.amazon.com/iotbutton/

[6] http://www.micronoptics.com/product/optical-sensing-instrument-si255/

[7] Y.W. Zhu, V. S.F. Foo, E. Hao, J. Maniyeri, C.T. Guan, H.H. Zhang, Eugene P., J. Biswas, "Heart Rate Estimation from FBG Sensors using Cepstrum Analysis and Sensor Fusion", International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2014

[8] Y.W. Zhu, J. Maniyeri, V. S.F. Foo, H.H. Zhang, "Estimating Respiratory Rate from FBG Optical Sensors", International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015

[9] http://www.jboss.org/drools

[10] C. Iber, Ancoli-Isreal, A.Xhesson, S.F.Quan, The ASSM Manual for the Snoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications, American Academy of Sleep Medicine, 2007