Development of a Smart Home-Based Package for Unobtrusive Physiological Monitoring

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***Abstract*— Home-based programs have been shown to be effective in improving health conditions, patient self-management, quality of life, and health outcomes. However, there is mixed-evidence on the effectiveness of these programs due to limitations in the intervention tools that are used, primarily the burden that is placed on the user, especially among seniors.**

In this paper we developed a novel home-based package that measures critically important physiological information such that neither active compliance or interaction from the user is required. To this end, we embedded passive sensors (including load cells, electrodes, pulse sensor and color sensors) into common household items such as tiling, furniture and wall. The smart package measures subject's electrocardiogram (ECG), photoplethysmogram (PPG), ballistocardiogram (BCG), electromyogram (EMG) and imaging photoplethysmogram (IPPG). In contrast to the previous studies, the proposed package measures all the physiological information unobtrusively, simultaneously and in a synchronized manner such that all the data samples corresponding to different intervals of a specific cardiovascular cycle can be identified. Such information can be analyzed by a clinician or be used for a higher level information extraction such as beat-to-beat blood pressure estimation. In addition, the proposed package is the first and only home-based technology that can simultaneously and unobtrusively capture both mechanical and electrical characteristics of user's heart activities. This results in a more accurate home-based vital parameters monitoring.

I. Introduction

Smart home technology refers to any device designed to assist an individual living at home in various ways. As they require more assistance, smart home technologies have great potential to improve the quality of life of older adults and disabled individuals. Among the many kinds of smart appliances that can be developed, one of the needed home technologies has been identified as medical monitoring [1]. As such, work has been done by several research groups in developing medical monitoring devices aimed at improving home care [2], [3], [4].

Many of the current residential medical monitoring devices for measuring physiological traits exist in a wearable form. This form, however, results in several problems including forgetting to wear the device and incorrect usage. These issues become exacerbated among older adult users, especially in older adults with cognitive impairments. One approach to counter these problems is to use passive monitoring, where sensors embedded into the environment measure signals unobtrusively with little or no effort on the part of the user [5]. A number of passive monitoring devices have been developed recently, including a toilet that can measure PPG and ECG [6], a bed that can measure BCG [7], a camera-based system that can measure IPPG [8], and a floor tile that can measure either BCG or ECG (not both) [9]. However, these devices can measure different physiological information at different times of the day, not all together.

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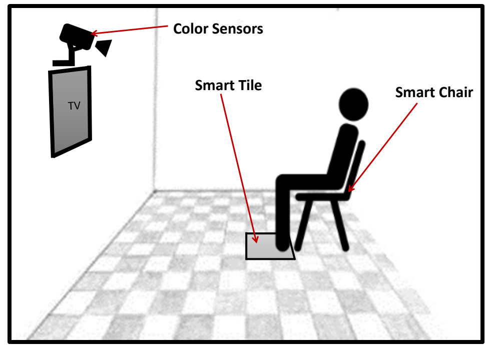

Fig. 1: The proposed smart home-based package for unobtrusive and simoultanous recording of physiological signals.

Therefore, as an improvement to these devices, it would be useful to measure physiological information simultaneously with one package to provide a more integrated view of a person's physiological state, as well reduce discrepancies caused by temporal differences of each measurement.

To address the above need, we embedded passive sensors into common household items and developed a prototype smart package that simultaneously measures critically important physiological information. The smart package consists of a smart floor tile, a smart chair and color sensors (i.e. a camera). The information are measured unobtrusively while the subject is sitting on the smart chair, watching TV with his/her feet on the smart floor tile. Schematic of the proposed smart package is shown in Fig. 1. The proposed technology is the first and only one that can measure physiological signals ECG, PPG, BCG, EMG and IPPG simultaneously and unobtrusively. Note that, in addition to the IPPG signal, other relevant information such as breathing pattern can also be extracted from subject's video [10], however these are out of the scope of this paper.

The rest of this paper is organized as follows: Section II explains the physiological information measured by the smart package, the package design and the data post-processing approaches. Package evaluation is discussed in Sections III. Conclusions are drawn in Section IV.

II. SMART HOME-BASED PACKAGE

Section II-A explains the physiological information provided by the smart package sensors, Section II-B discusses the design of the smart package. Data post-processing methods are presented in Section II-C.

A. Measured Physiological Data

1) ECG: Electrocardiography is the process of recording the electrical activity of the heart using electrodes placed on the skin. These electrodes detect the tiny electrical changes on the skin that arise from the heart muscle's electrophysiologic pattern of depolarizing and repolarizing during each heartbeat. The smart package unobtrusively measures ECG signal from the subject's feet using the electrodes located at the lower part of the smart floor tile surface. More specifically, the ECG is recorded from the opposite heels that are the most stable areas of the feet in the sitting posture shown in Fig. 1. Throughout this paper, the feet ECG signal is denoted as F-ECG.

2) PPG and IPPG: Photoplethysmography is a low-cost and non-invasive method of measuring the cardiovascular blood volume pulse (BVP) via light transmitted through, or reflected from, the human body [11]. It measures arterial pulsations in the microvascular tissue bed. There are many clinical applications for PPG measurement and it can reveal significant information about health and risk of cardiovascular diseases [12]. Traditionally, PPG is measured based on the direct contact between skin and sensor. However, the need to apply a PPG sensor directly to the skin constrains its practicability in situations such as skin damage (burn/ulcer/trauma) or when free mobility is required. Imaging PPG (IPPG) is a noncontact method that can detect heartgenerated pulse waves from video by means of peripheral blood perfusion measurements. The smart package is capable of measuring both contact-based PPG and IPPG to have a more reliable capturing of BVP. The contact-based PPG is measured from the subject's big foot toe through the pulse sensor located at the front part of the smart tile. In this paper, the foot PPG signal is denoted as F-PPG. Details of the video processing approach to measure IPPG from the face frames is discussed in Section II-C.

3) BCG: Ballistocardiogram is repetitive body motion caused by the cardiac contraction and ejection of blood during cardiac cycles. BCG waveform contains features that can indicate some physiological attributes [13], [14], and an irregular BCG may reveal abnormal circulation and cardiac diseases [15], [16]. The smart package measures BCG while the subject is sitting on the smart chair, through four load cells attached to the bottom of the chair's legs. In this paper, the sitting BCG is denoted as S-BCG.

4) EMG: Electromyography measures muscles activity. The smart package measures EMG signals corresponding to the right and left foot using the surface electrodes attached on the middle part of the smart tile. These EMGs are used to identify the time intervals in which feet do not have stable contact with the tile's sensors. More post-processing of the signals may be required in these recording intervals. In this paper, the foot EMG signals of the left and right foot are respectively denoted as F-EMG-L and F-EMG-R.

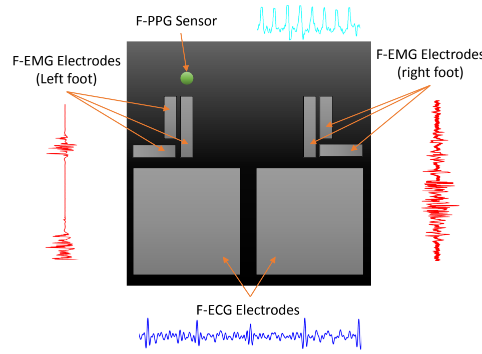

Fig. 2: Schematic of the smart floor tile (top view) including F-ECG electrodes, F-EMG electrodes and F-PPG sensor. The correspong signals are shown beside each (set of) sensor(s).

B. Package design

1) Instrumented Floor Tile: The instrumented floor tile is made of wood (main body) and plexiglas (outer surface) that are non-conductive, readily available and sturdy. The surface size of the smart tile is 40cm×40cm which is large enough for the user to place his/her feet on it. The tile's height is 2cm. The tile surface is equipped with two 17cm×17cm electrodes at the lower part for measuring the F-ECG, a sensor at the upper left of the tile for F-PPG measurement, and two sets of three-electrode (each set consists of one 10cm×2cm electrode and two 5cm×2cm electrodes)for measuring F-EMG-R and F-EMG-L. Stainless steel is selected as the electrode material as it has good connectivity and easy to keep clean. The circuits corresponding to the F-ECG, F-PPG, F-EMGs measurement are respectively designed using the AD8233, Pulse Sensor and Grove EMG Detector. To have an accurate sampling for F-PPG, the output of the pulse sensor is high-pass filtered (with cut off frequency 0.08 Hz) and then amplified (gain 50) using AD8221. Schematic of the developed smart floor tile and the signals measured by that are shown in Fig. 2.

2) Instrumented Chair: The smart chair is equipped with four miniature load cells that are placed beneath the chair's legs. Each load cell can support up to 50 kg. Signals from the load cells are processed to retrieve the BCG signal. The load cells are connected in a Wheatstone bridge configuration as is used in commercial weight scale [17]. Since the output of the Wheatstone bridge is too weak (about 0.04 mv pk-pk) to be sampled by the available data acquisition device, the Wheatstone bridge is followed by a 0.08 Hz low-pass filter, a differential amplifier with gain 50 (AD8221), and then by a Biopac DA100c that includes a band-pass filter ([0.05 Hz,300 Hz]) and an amplifier (gain 5000). So, in total, the output of the Wheatstone bridge is amplified by 108 dB. Shematic of the instrumented chair, the corresponding circuits, a load cell and the measured S-BCG are shown in Fig. 3.

3) Color Sensors: In addition to the signals recorded by the smart floor tile and chair, the smart package records

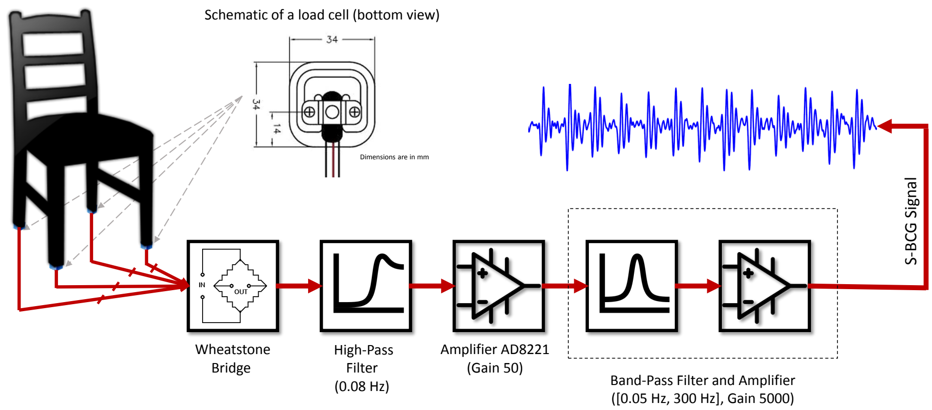

Fig. 3: Uobtrusive measurement of S-BCG using four load cells (attached to the bottom of the chair's legs) and the corresponding analog processing units. The schematic of a load cell is also shown.

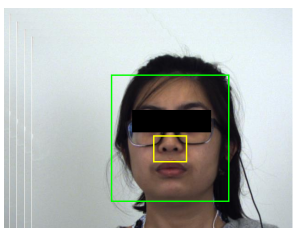

Fig. 4: Face video, captured by a Basler Ace Gigabit Ethernet Camera, with the detected face and mouth regions.

subject's face video from distance. The camera can be embedded in the wall behind the TV to record data while the subject is watching TV (sitting on the smart chair with his/her feet on the smart tile). We use Norpix StreamPix5 system for video recording. The corresponding Basler Ace Gigabit Ethernet Camera records VGA (640 x 480) color video at up to 125 frames per second (see Fig. 4 where the subject's face region is shown by a green rectangular). The camera streams to a separate hard drive through an Ethernet port for maximum data throughput. The video frames are synced with other recordings through a Sync signal such that the video frames and signal intervals corresponding to each heart beat can be identified. In the next section, we explain how to retrieve IPPG from the subject's face video.

C. Data Post Processing

1) Signals Post-Processing: All the analog signals measured by the floor tile and the chair are recorded with 1000 Hz sampling frequency using a National Instrument PCI-6255 and MATLAB Simulink. Since the physiological signals components are mainly in lower frequency bands, all the recorded signals are post-processed by a low-pass FIR filter with cut-off frequency 20 Hz.

2) Video Post-Processing: Contact-PPG contains more detailed information than the non-contact PPG (i.e. IPPG). However, since the contact PPG is easily contaminated by muscle artifacts (especially in unobtrusive measurement applications), for the sake of accuracy, IPPG is also measured to enhance/replace the contaminated intervals of the F-PPG. IPPG is the most critically important information that can be retrieved from the face video. Relevant information such as heart rate [18], systolic and diastolic peaks [19], and pulse transit time [10] can be estimated from IPPG signal.

To retrieve IPPG, following [20], fast independent component analysis (ICA) is applied to the observed signals obtained from the red, green and blue color sensors corresponding to the region of interest (ROI). Previous studies show that the pixels around the subject's nose make a reliable and informative ROI to be used for extracting cardiovascular-relevant information [21]. In this study, we consider nose region as the desired ROI which, at each video frame, is localized using the MATLAB Computer Vision System and Image Processing toolboxes [22]. An observation at frame t, i.e. $x_i(t), i = \{\text{red,green,blue}\}$, is computed through averaging of all pixels at the corresponding channel. $x_i(t)$ is then processed by a 10-sample moving average window with 90% overlap. The subsequent processing is to normalize each observation signal to have zero-mean and unit standard deviation. The normalized signals are then decomposed to three independent source signals using fast ICA [23]. The first independent component is the desired IPPG signal.

III. Package Evaluation

In addition to the smart package signals/video, we also record ECG and PPG signals from the subject's chest and ear as gold standards that the unobtrusive measurements can compare to. These signals are also sampled with 1000 Hz sampling frequency and are recorded via the same data acquisition device used for the smart package (i.e. National Instrument PCI-6255) such that they are all synced with the smart package's recordings.

The post-processed signals recorded by the tile and chair, the IPPG signal retrieved from the face video, and the gold standard signals are shown in Fig. 5 where videos are recorded at 25 frame per second. The chest ECG and the ear PPG are respectively denoted as c-ECG and E-PPG. This figure demonstrates that the developed smart package can accurately measure important physiological signals in a synchronized manner.

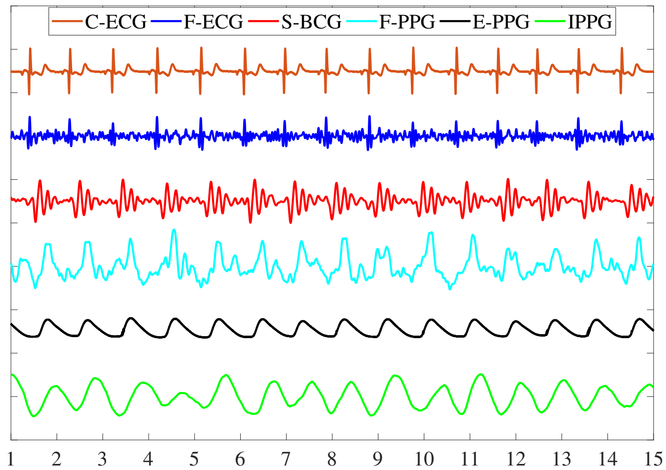

Fig. 5: Synchronized physiological signals measered by the proposed smart package.

The F-EMG signals of the left and right foot along with the corresponding F-ECG, F-PPG and S-BCG signals are shown in Fig. 6. This figure shows that the recording intervals corrupted with the feet muscle artifacts can be identified based on the F-EMG signals.

IV. Conclusions

In this paper we proposed and developed a smart home-based package for unobtrusive measurement of the critically important physiological signals including ECG, PPG, EMG, BCG and IPPG. This is the first and only home-based package that can measure all these signals simultaneously and in a synchronized manner. Important information can be extracted through analyzing these signals either by a clinician or a higher level data processing algorithms. The proposed technology provides a tool that can be used by seniors to maintain and manage their conditions within their own homes.

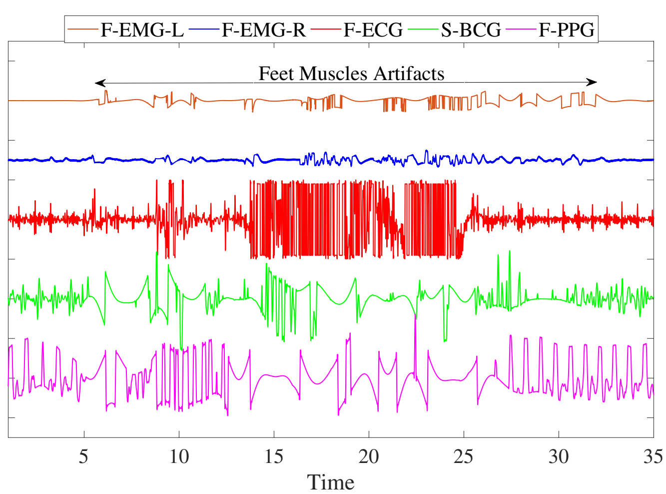

Fig. 6: Contaminated recording intervals can be identified by F-EMGs.

References

[1] V. Rialle, C. Ollivet, C. Guigui, and C. Hervé, "What do family caregivers of alzheimer's disease patients desire in smart home technologies?" *Methods Inf Med.*, vol. 47, no. 1, pp. 63–69, 2008.

[2] F. Ichihashi and Y. Sankai, "Development of a portable vital sensing system for home telemedicine," in *Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE*. IEEE, 2007, pp. 5872–5877.

[3] M. N. K. Boulos, A. Rocha, A. Martins, M. E. Vicente, A. Bolz, R. Feld, I. Tchoudovski, M. Braecklein, J. Nelson, G. Ó. Laighin *et al.*, "Caalyx: a new generation of location-based services in healthcare," 2007.

[4] M.-Z. Poh, N. C. Swenson, and R. W. Picard, "Motion-tolerant magnetic earring sensor and wireless earpiece for wearable photoplethysmography," *IEEE Transactions on Information Technology in Biomedicine*, vol. 14, no. 3, pp. 786–794, 2010.

[5] M. Alwan, "Passive in-home health and wellness monitoring: Overview, value and examples," in *Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE*. IEEE, 2009, pp. 4307–4310.

[6] J. S. Kim, Y. J. Chee, J. W. Park, J. W. Choi, and K. S. Park, "A new approach for non-intrusive monitoring of blood pressure on a toilet seat," *Physiological measurement*, vol. 27, no. 2, p. 203, 2006.

[7] J. R. Estepp, E. B. Blackford, and C. M. Meier, "Recovering pulse rate during motion artifact with a multi-imager array for non-contact imaging photoplethysmography," in *Systems, Man and Cybernetics (SMC), 2014 IEEE International Conference on*. IEEE, 2014, pp. 1462–1469.

[8] W. Verkruysse, L. O. Svaasand, and J. S. Nelson, "Remote plethysmographic imaging using ambient light." *Optics express*, vol. 16, no. 26, pp. 21 434–21 445, 2008.

[9] I. S. Chang, A. Javaid, J. Boger, A. Arcelus, and A. Mihailidis, "Rdesign and evaluation of an instrumented floor tile for assessment of older adults cardiac function at home." *Gerontechnology*, 2017.

[10] D. Shao, Y. Yang, C. Liu, F. Tsow, H. Yu, and N. Tao, "Noncontact monitoring breathing pattern, exhalation flow rate and pulse transit time," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 11, pp. 2760–2767, 2014.

[11] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiological measurement*, vol. 28, no. 3, p. R1, 2007.

[12] J. Allen, C. P. Oates, T. A. Lees, and A. Murray, "Photoplethysmography detection of lower limb peripheral arterial occlusive disease: a comparison of pulse timing, amplitude and shape characteristics," *Physiological measurement*, vol. 26, no. 5, p. 811, 2005.

[13] I. Starr, "On reading ballistocardiograms," *The American journal of cardiology*, vol. 2, no. 4, pp. 404–416, 1958.

[14] ——, "Essay on the ballistocardiogram," *Journal of the American Medical Association*, vol. 155, no. 16, pp. 1413–1425, 1954.

[15] I. Starr and H. A. Schroeder, "Ballistocardiogram. ii. normal standards, abnormalities commonly found in diseases of the heart and circulation, and their significance," *Journal of Clinical Investigation*, vol. 19, no. 3, p. 437, 1940.

[16] I. Starr and F. C. Wood, "Twenty-year studies with the ballistocardiograph," *Circulation*, vol. 23, no. 5, pp. 714–732, 1961.

[17] "Tanita, innerscan bc-534 scale, tokyo, japan."

[18] M.-Z. Poh, D. McDuff, and R. Picard, "A medical mirror for non-contact health monitoring, acm siggraph 2011 emerging technologies," 2011.

[19] D. McDuff, S. Gontarek, and R. W. Picard, "Remote detection of photoplethysmographic systolic and diastolic peaks using a digital camera," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 12, pp. 2948–2954, 2014.

[20] M.-Z. Poh, D. J. McDuff, and R. W. Picard, "Non-contact, automated cardiac pulse measurements using video imaging and blind source separation." *Optics express*, vol. 18, no. 10, pp. 10 762–10 774, 2010.

[21] J. Fei and I. Pavlidis, "Thermistor at a distance: unobtrusive measurement of breathing," *IEEE Transactions on Biomedical Engineering*, vol. 57, no. 4, pp. 988–998, 2010.

[22] https://www.mathworks.com/matlabcentral/fileexchange/36855-face-parts-detection .

[23] https://www.mathworks.com/matlabcentral/fileexchange/38300-pca-and-ica-package.