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Monitoring Pulse and Respiration with a Non-Invasive Hydraulic Bed Sensor

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***Abstract*—A hydraulic bed sensor has been developed to non-invasively monitor pulse and respiration during sleep. This sensor is designed for in-home use, to be part of an integrated sensor network for the early detection of illness and functional decline in elderly adults. Experience with another bed sensor has motivated a desire to acquire enhanced, quantitative data related to pulse and respiration. This paper describes a working prototype, the signal processing methods used to extract data from the constructed transducer, and results from preliminary testing.**

I. Introduction

The motivation for this work is to support the continuous, in-home monitoring of elderly residents for the purpose of detecting early signs of illness and functional decline. Towards this goal, the Center for Eldercare and Rehabilitation Technology at the University of Missouri has been developing an integrated sensor network for capturing activity patterns of elderly residents using passive sensing, including automated methods for recognizing changes in these patterns that may indicate a declining health condition.

To date, the research group has installed 34 sensor networks in the homes of elderly residents living in TigerPlace, an aging-in-place eldercare facility located in Columbia, MO. One individual has been continuously monitored for over 4 years; the average installation time is about 2 years. At the same time, health records are logged for the residents, showing vital signs, hospitalizations, emergency room visits, falls, medication changes, and other assessments taken periodically. Changes in the sensor data patterns are compared to changes in the health conditions as part of ongoing research in early illness recognition methods.

One of the sensor components currently in use at TigerPlace is a bed sensor developed by collaborators at the University of Virginia [1]. This sensor is a pneumatic strip that lies on top of the bed mattress, underneath the bed linens, and uses ballistocardiography to capture qualitative pulse and respiration rates as well as restlessness in the bed. Pulse events are reported as low (< 31 beats per minute), normal, or high (> 100 beats per minute) using crisp thresholds. Respiration rates are also reported as low (< 7 breaths per minute), normal, and high (> 31 breaths per minute). Bed restlessness is reported as one of four levels, depending on the time for continuous movement.

In comparing sensor data changes to health changes, the bed sensor has proven to be a useful component of the sensor network. Observation of bed sensor data has revealed instances of dramatic changes over a very short time, as well as more gradual changes over 2-3 weeks, that correspond to impending changes in health condition, e.g., cardiac problems [2], [3]. Thus, research has shown the importance of this type of continuous monitoring in the home setting.

Proposed in this paper is a new bed sensor designed to overcome some of the limitations of the current sensor. One goal is to improve the sensitivity of the transducer in order to reliably capture quantitative pulse and respiration rates, thus showing more subtle changes. Another goal is to distinguish between instances of low pulse rate and shallow breathing; the current sensor has been shown in the lab to report these conditions incorrectly. Finally, it is hoped that a new sensor may improve the comfort for the user, about which a few residents have voiced complaints.

The use of ballistocardiography for passive sensing of pulse and respiration has become more popular recently, as evidenced by [4-8]. Most of these methods suffer, however, from some disadvantage such as impracticality for widespread deployment, cost, discomfort to the user, a requirement that the user wear a device, or the inability to report quantitative data. One system employs water within a transducer [9-10], but this sensor rests beneath the pillow and may still interfere with comfort. Watanabe, et al., describe a sensor pad that rests between the mattress and frame of a bed using a pneumatic transducer and fast Fourier transform (FFT) based signal processing [11]. This system has limitations, though, related to the low signal-to-noise ratio of heartbeat and the inability of the FFT to achieve high frequency resolution while analyzing a dynamic signal. The sensor proposed here utilizes water as a transmitting fluid (instead of air) and other signal processing methods to yield a more robust system.

This paper presents preliminary work on a hydraulic bed sensor, reporting on experiments with the sensor both on top of and underneath the bed mattress. Different orientations of a person on the bed were tested, including lying on the back and on the right and left sides. The heart rate extracted from the hydraulic transducer is compared to the heart rate extracted from a dedicated pulse transducer, and the results indicate that the hydraulic sensor holds much promise.

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II. Construction of the Hydraulic Transducer

Design criteria for the hydraulic transducer included comfort, practical installation, watertight durability to withstand use beneath a bed mattress, a means of adding/removing water, and a way to bleed air from the device. A flat profile was desired to minimize deformation of the mattress, making the sensor imperceptible to a person lying on top of the mattress/sensor, thereby addressing comfort and ease of use.

The body of the prototype transducer was constructed from commonly available materials acquired from a local hardware store. Three inch wide (7.6 cm) discharge hose was chosen for the main body of the transducer, which maintains a very flat profile even when containing fluid. A length of approximately 1.3 meters was used to stretch across the width of a standard twin mattress, which was used in the testing. PVC endcaps were fitted to the discharge hose with hose clamps, and the endcaps were drilled to accept brass fittings. To one end was fitted a port with a valve, to allow addition/removal of water and air. To the other end was fitted a brass nipple, to which a length of 0.170” (4.3 mm, inside diameter) vinyl tubing was attached. Approximately 1.5 meters of this small diameter tubing connected the body of the transducer to a small integrated silicon pressure sensor (Freescale MPX5010GS).

The integrated pressure sensor [12] features a usable range of 0 to 10 kPa, which is sufficient to handle the range of pressures transmitted from the weight of the body (plus mattress) through the hydraulic transducer, while remaining sensitive enough to detect low-amplitude variations (i.e. heartbeat). This integrated sensor also features on-chip calibration and compensation, and generates an output signal between 0 and 5 volts, suitable for sampling by an analog-to-digital converter with minimal external circuitry. Details of the sampling and processing of the resulting signal will be described in the next section.

After construction, water was added to the transducer, and air was bled from the device. The integrated pressure sensor was connected to the external circuitry for power and interface to the analog-to-digital converter (ADC).

III. Signal Processing to Extract Pulse Rate

The algorithm used to process the signals generated by the hydraulic transducer are summarized in the block diagram of Fig. 1. Each block is explained in detail below.

A. Data sampling

The output of the hydraulic transducer is a voltage ranging between 0 and 5 volts. This voltage signal contains a large amount of high frequency noise, primarily due to the inherent noise present in piezoresistive devices [12]. To address this high frequency noise, the signal from the transducer is sampled by a 12-bit ADC at a sampling rate of 10 kHz and then low-pass filtered and downsampled to 100 Hz for further processing. The output of the signal is shown in Fig. 2a. Note that the prototype sensor performs

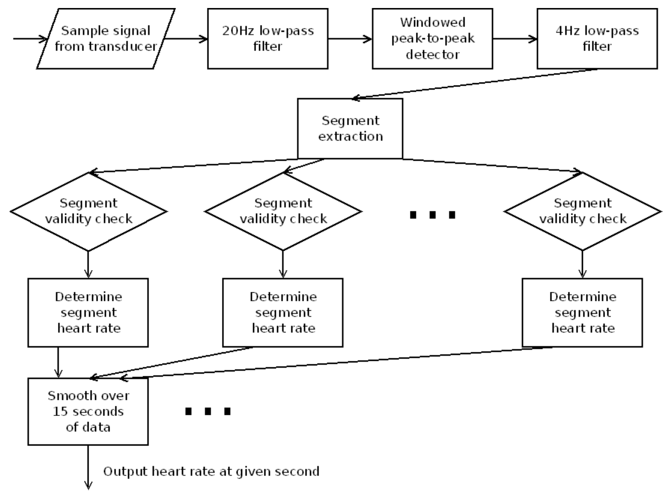

Fig. 1. Block diagram of the heart rate detection algorithm.

this filtering/downsampling in software; a production model would implement analog filtering in hardware, allowing a direct sampling rate of 100 Hz.

B. Low-pass filtering

The 100 Hz signal is further low-pass filtered with a cutoff frequency of 20 Hz, while maintaining 100 samples per second. Relevant characteristics of the heartbeat may be captured at 20 Hz and below. Initial attempts to filter down to 5 Hz proved unsuccessful, as the different components of a single heartbeat were no longer distinguishable.

C. Finding windowed peak-to-peak deviation

Visual observation of the low-pass filtered signal (Fig. 2b) shows a clear breathing component (approximately two breaths over the 10 seconds shown), but the heartbeat is less obvious. Only after comparison to the corresponding heartbeat signal (Fig. 2c, from the pulse sensor attached to the finger) can one see where heartbeats are present. These heartbeats are not easily separated in frequency, but with careful observation one can see that at each heartbeat the signal has a greater deviation from the most negative voltage to the most positive voltage within a small window, i.e., peak-to-peak. The windowed peak-to-peak deviation (WPPD, Fig. 2d) is thus generated by finding the difference between the most negative and the most positive within a sliding window of 25 samples. Windowing over 25 samples was empirically chosen, as it performed better on the test data than other window sizes. Note that this window size would need to be reduced to accommodate very high pulse rates, as the time duration of each beat will shorten.

D. Low-pass filtering the WPPD

The WPPD clearly indicates the occurrence of each heartbeat, but to reduce the effect of noise and smooth the signal, the WPPD is low-pass filtered with a cutoff frequency of 4 Hz (Fig. 2e). This cutoff frequency is sufficient for heart rates up to 240 beats per minute (bpm).

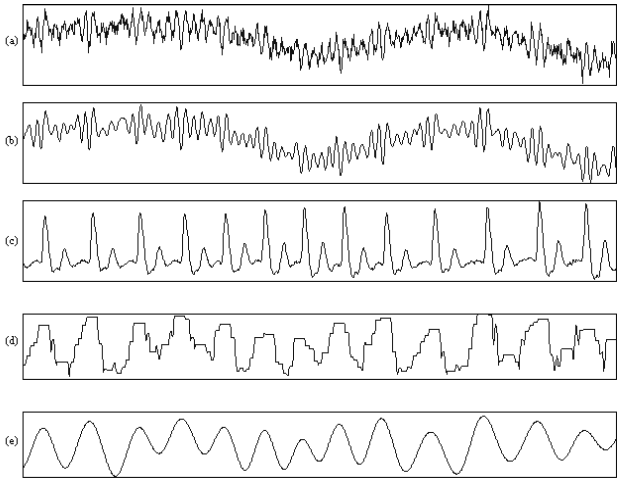

Fig. 2. Ten-second data segment being processed to extract pulse rate: (a) shows ten seconds of the raw signal, (b) shows the signal after 20 Hz low-pass filtering, (c) shows the corresponding signal from the piezoresistive pulse sensor, used as ground truth for showing heartbeats, (d) shows the windowed peak-to-peak deviation (WPPD), and (e) shows the WPPD after 4 Hz low-pass filtering.

E. Segment extraction

The low-pass filtered WPPD is processed using a ten-second sliding window, with nine-second overlap between segments. These ten-second segments give enough redundancy (beats within a segment) to minimize error while remaining small enough to permit our assumption of a stationary signal.

F. Segment validity check

Due to high amplitude noise (e.g., body motion artifacts), there are some segments from which heartbeat (and thus heart rate) cannot be reliably extracted. If the maximum value of a signal segment exceeds a specified threshold (empirically chosen to be 0.05 volts), it is deemed unusable, and the corresponding heart rate for the segment is set to zero. Additionally, to reduce the chance of error near these transients, the heart rates of the preceding and succeeding five seconds are also set to zero. These regions of "zero" heart rate can be used to indicate periods of bed restlessness, which, in addition to pulse and respiration, is another important parameter characterizing sleep.

G. Determine heart rate of a segment

To determine the heart rate of a valid segment, autocorrelation is used to find the time-distance between peaks (heartbeats) of the signal. This time-distance is converted to a heart rate and output on a segment-by-segment (one heart rate per second) basis. Autocorrelation is chosen over other methods (e.g., calculating mean distance between peaks in the segment) to better reject the effects of a sudden change in heart rate or momentary arrhythmia.

H. Signal smoothing

The heart rates calculated by the preceding step are averaged over six segments. Six segments are used because this corresponds to 15 seconds of original data, which is consistent with the clinical practice of counting beats over 15 seconds and multiplying by four (giving bpm). The smoothing operation reduces spurious error in calculating the heart rate from the transducer, and averaging over time is appropriate giving our assumption of a stationary signal over a short duration.

IV. Extracting Respiration Rate

Extracting respiration rate from the hydraulic sensor is a relatively easier task, given the much higher signal-to-noise ratio of breathing compared to heartbeat. There are some differences, though, in that the time for a complete breath (inhalation followed by exhalation) may vary considerably, even from one breath to the next. A simple approach to extract the respiration rate is to:

1. low-pass filter the signal (with 1 Hz cutoff frequency)
2. identify 1-minute segments without motion artifacts
3. subtract the DC bias from each segment, and
4. count the zero-crossings, dividing by two to yield breaths per minute.

This approach can detect the rate of normal respiration, as well as conditions such as apnea. Fig. 3 shows that respiration is clearly detected by the hydraulic sensor. Future work will analyze respiration to detect irregular conditions such as apnea or shallow breathing.

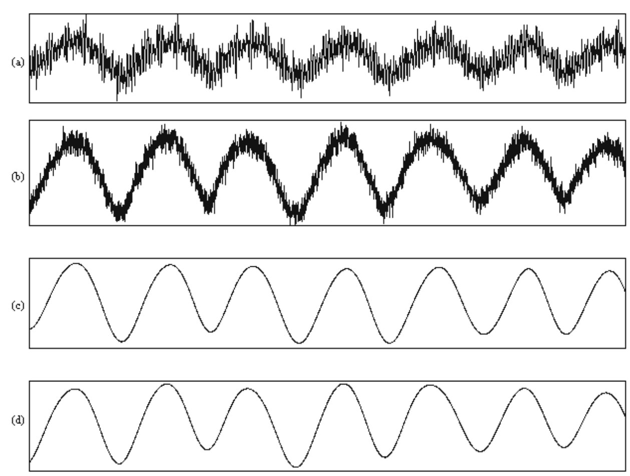

Fig. 3. Respiration is evident from the hydraulic sensor: (a) shows the signal from the hydraulic transducer over a 30 second segment, while (b) shows the ground truth from a piezoresistive respiratory band worn around the torso over the same segment of time; (c) and (d) show signals (a) and (b) (respectively) low-pass filtered with 1 Hz cutoff frequency.

V. Experimental Results

A. Methodology

To test the hydraulic bed sensor, preliminary data were collected from two subjects, one male and one female. Subjects were asked to lie on the bed for approximately 10 minutes, following the pattern of on the back, on the right side, on the back again, on the left side, and on the back once more (with approximately two minutes in each position). This process was performed twice for each subject, once with the hydraulic transducer on top of the mattress (beneath the linens), and once with the hydraulic transducer underneath the mattress. Subjects were not told to lie "perfectly still," but instead were asked to lie as though they were at rest and move from position to position as they might while sleeping. Data were collected continuously during this period without any denotation of changes in position. As can be seen in Fig. 4, the position changes are evident in the recorded data.

To provide ground truth for validating the hydraulic sensor, data were collected simultaneously from a pulse sensor connected to the subject's finger and a respiration band wrapped around the subject's torso. Both the pulse and respiratory sensors use piezoresistive sensors, giving artifacts of motion when the subject moves from position to position. This ground truth is used as the baseline for evaluating the effectiveness of the hydraulic sensor. Here, we report the pulse rate results.

B. Results

Visual inspection of heart rates extracted from the hydraulic sensor show a strong correlation with heart rates extracted from the piezoresistive pulse transducer worn on the finger. Heart rates were extracted from the pulse transducer using the same method as the hydraulic transducer, except that the segment validity threshold was raised to 0.5 (given the much higher signal-to-noise ratio of the pulse transducer). A sample comparison is shown in Fig. 5, excluding segments deemed unusable due to motion.

A method to compare the extracted heart rates quantitatively was also developed, yielding:

- the average difference, in bpm, between the hydraulic transducer and the piezoresistive pulse transducer, and
- the percentage of segments for which the heart rate extracted from the hydraulic transducer was within 10% of the rate extracted from the piezoresistive pulse transducer.

The justification for using a benchmark of 10% from ground truth is practical; reporting heart rates accurate within 10% is sufficient for the types of analysis and diagnosis envisioned in section I. As explained in section III, the heart rate detection algorithm will give an estimated heart rate for each second of the input signal. Thus, the experimental results are evaluated on a second-by-second basis.

The results are summarized in Table I, showing the accuracy of the hydraulic sensor relative to the piezoresistive pulse sensor over approximately 600 seconds of data (thus, comparing approximately 600 individual data points) for each run. Additionally, Table II and Table III show results for each position (approximately 120 seconds each) during the data runs where the sensor was positioned underneath the mattress.

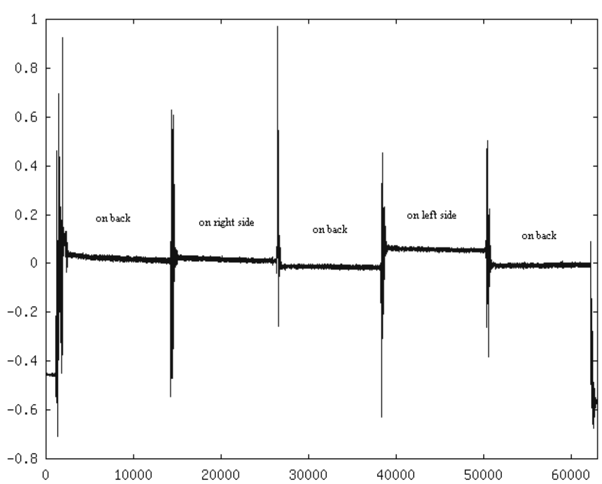

Fig. 4. Data from the hydraulic bed sensor after initial filtering and downsampling to 100 Hz. Y-axis units are in volts; x-axis units are in samples (100 samples per second). The transients indicate bed motion, while the relatively flat sections show the subject following the pattern of the experiment (back, left side, back, right side, back). The difference in static pressure is evident between lying on the back and lying on the side.

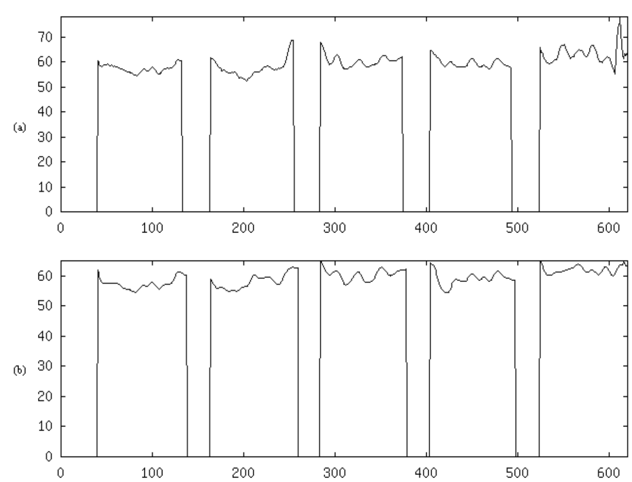

Fig. 5. Extracted heart rate from female subject, with hydraulic sensor beneath mattress: (a) shows the heart rate extracted from the hydraulic sensor; (b) shows the heart rate extracted from the piezoresistive pulse transducer worn on the finger. Y-axis units are in beats per minute (bpm); x-axis units are in seconds.

TABLE I
EXPERIMENTAL RESULTS OF EXTRACTING PULSE RATE

Experimental run	Average difference in beats per minute	Percentage of time hydraulic sensor was within 10%
Female, sensor on bottom	1.34	98.9
Male, sensor on bottom	2.95	92.5
Male, sensor on top	6.70	70.2
Female, sensor on top	13.4	52.6

TABLE II
RESULTS FOR EACH POSITION, FEMALE SUBJECT, SENSOR ON BOTTOM

Female, on back #1	0.49	100
Female, on right side	2.12	100
Female, on back #2	0.69	100
Female, on left side	1.22	100
Female, on back #3	2.16	94.8

TABLE III
RESULTS FOR EACH POSITION, MALE SUBJECT, SENSOR ON BOTTOM

Male, on back #1	3.60	89.4
Male, on right side	5.82	72.6
Male, on back #2	1.22	100
Male, on left side	2.28	100
Male, on back #3	1.57	100

The results indicate that the hydraulic bed sensor is effective at extracting heart rate when the transducer is positioned beneath the bed mattress. It should be noted that these results are statistically consistent with the ground truth; a t-test of the results from the hydraulic transducer placed below the mattress did not indicate a significant difference from the piezoresistive pulse transducer (ground truth) at the 5% level, for either the male or female subjects. (The t-test did indicate significant difference from ground truth for the hydraulic transducer placed above the mattress.) The increased accuracy of the system with the transducer below the mattress compared to on top seems to be due to the buffering effect of the mattress itself, as it seems to filter some of the erratic artifacts from small movements of the body while at rest. The constant weight of the mattress on the transducer also adds stability to the fluid within the sensor. Also, significantly, the orientation on the bed (on back, on side) does not seem to affect sensor reliability.

VI. FUTURE WORK

Future work includes testing the prototype sensor on a broad range of subjects; it has not yet been determined if the sensor will be effective for all body types or ages. The sensor will also be tested over a range of pulse and respiration rates. One of the goals of this work is to reliably differentiate between low pulse and shallow breathing, and work will proceed to simulate and test the sensor under those circumstances. If the sensor proves robust, the research group will eventually deploy the technology as part of its integrated sensor network.

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