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The Comparison Test of Respiratory Rate

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Abstract:

The body respiratory rate (RR) is the optional parameters of vital signal, and it is one of the monitoring indicators of physiological distress. The paper presents a test method of body respiratory rate by using the status sensors and infrared imaging sensors. The method of the Kalman filter and zero crossing test are applied in the RR test, the measurement and simulation results show its feasibility. And they are compared with testing by commercial pressure sensors module, the results show the effective of methods

Keywords **—Body Respiratory Rate , Status Sensors , Kalman Filter, Feature Extraction.**

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I. INTRODUCTION

There are two kinds of respiratory rate(RR) test methods, one is using contact sensor, another is using non-contact sensor. The contact RR test often adopt the electrical impedance sensor,the pressure sensor, the movement sensor,the ECG and PPG sensors; the non-contact test uses the infrared imaging sensors, the capacity sensor, Fiber Bragg Grating sensor ,and so on.

In [1],AndreaAliverti reviews the currently technology in respiratory health and disease, for example, the monitoring of sleep disorders for timely diagnosis and treatment. Therespiratory inductive plethysmography is hard to monitor during the daily life. Accelerometers are used to derive breathing rate by measuring movements of the chest wall[2][3].

The principle of test is that MEMS accelerometers can measure inclination changes during breathing, and to obtain a respiratory rate. The algorithms to test RR include Fourier analysis[4], adaptive filter, Principal Component Analysis[5], and so on. For example, Spire (www.spire.io) and the Vitali Smart Bra&GEM (https://vitaliwear.com), theyanalyze breathing patterns in terms of breathing frequency and waveform.

The accelerometers are often used in stationary test, for the movement or cline of the body may change the value and make the results untrusty. The other test methods include infrared imaging sensors, the capacity sensor, and the pressure sensors. Nadine Hochhausen presents a robust and effective algorithm for BR detection in thermal videos, it detects the movement of the nose[6]; David Naranjo-Hernández and so on discusse a method based on the measurement of the capacitance existing between two electrodes[7]. They use four-step algorithm:1) first ,use the low-pass filter to decrease the noise ; 2) peak values are calculated to get the time instants;3)the calculated period instants is considered, and to correct the time instants number;4) the respiratory cycle and respiratory rate are estimated. These methods are also used in pressure sensor testing, for their signal is almost same[8].

The current infrared imaging test is not suitable for smart vest, and the air sacs, air tube, and band make the pressure sensor also not suitable for smart vest design.

In the paper, the infrared imaging sensor and the state sensor embedded in smart vest are considered, the test results are compared with commercial pressured sensors.

The rest of the paper is organized as follows. Section 2 describes the material and methods to test the respiratory rate. Section 3 presents the main results, and Section 4 gives the conclusions.

II. MATERIAL AND METHODS

An easy way to comply with the conference paper formatting requirements is to use this document as a template and simply type your text into it.

A. *Methodology for Respiratory Sensing*

1)State sensor

The MPU-6050 devices combine a 3-axis gyroscope and a 3-axis accelerometer on the same silicon die, together with an onboard Digital Motion Processor™ (DMP™), which processes complex 6-axis Motion Fusion algorithms. The device can access external magnetometers or other sensors through an auxiliary master I²C bus, allowing the devices to gather a full set of sensor data without intervention from the system processor.

The MPU-60X0 features three 16-bit analog-to-digital converters (ADCs) for digitizing the gyroscope outputs and three 16-bit ADCs for digitizing the accelerometer outputs.

2) infrared imaging sensor

The Infrared Array Sensor is a thermopile-typed infrared sensor which detects quantity of infrared ray. Generally, temperature accuracy will be degraded in the following situations. Be sure to verify performance and reliability under actual conditions of use and make any necessary temperature corrections.

・There is a heat emitting body located close to where the sensor is mounted.

・A flow of warm or cold air is hitting the sensor.

・The temperature of the sensor is subject to sudden change.

・When an object made of glass, acrylic or other subject which far infrared rays have difficult passing through is located between the sensor and what is to be detected.

・A substance (dirt or water droplets) that makes it difficult for far infrared rays to pass through is attached to the sensor lens

3)pressure sensors

pressure sensor is a device for pressure measurement of gases or liquids. Pressure is an expression of the force required to stop a fluid from expanding and is usually stated in terms of force per unit area. A pressure sensor usually acts as a transducer; it generates a signal as a function of the pressure imposed. For the purposes of this article, such a signal is electrical.

Pressure sensors are used for control and monitoring in thousands of everyday applications. Pressure sensors can also be used to indirectly measure other variables such as fluid/gas flow, speed, water level, and altitude. Pressure sensors can alternatively be called pressure transducers, pressure transmitters, pressure senders, pressure indicators, piezometers and manometers, among other names.

Pressure sensors can vary drastically in technology, design, performance, application suitability and cost. A conservative estimate would be that there may be over 50 technologies and at least 300 companies making pressure sensors worldwide.

Uses the piezoresistive effect of bonded or formed strain gauges to detect strain due to applied pressure, resistance increasing as pressure deforms the material. Common technology types are Silicon (Monocrystalline), Polysilicon Thin Film, Bonded Metal Foil, Thick Film, Silicon-on-Sapphire and Sputtered Thin Film. Generally, the strain gauges are connected to form a Wheatstone bridge circuit to maximize the output of the sensor and to reduce sensitivity to errors. This is the most commonly employed sensing technology for general purpose pressure measurement.

B. *Methodology for Signal processing*

1) quaternion-based and kalman filter for MPU-60X0

The paper compares the quaternion-based filter and Kalman filter.

Kris Winer presents a quaternion-based filter that can be used in Arduino-mini [9],the procedure of program is in below:

step1: Auxiliary variables to avoid repeated arithmetic;

step2: Normalize accelerometer measurement
step3: Compute the objective function and Jacobian
step4: Compute the gradient (matrix multiplication)
step5: Normalize the gradient
step6: Compute estimated gyroscope biases
step7: Compute and remove gyroscope biases
step8: Compute the quaternion derivative
step9: Compute then integrate estimated quaternion derivative
step10: Normalize the quaternion

Kristian Lauszus provides a Kalman filter library for Arduino [10]. The procedure of program is at below:

Step1: set the variables;
Step2: Reset bias;
Step3: Discrete Kalman filter time update equations - Time Update ("Predict");
A) Updatexhat - Project the state ahead
B) Update estimation error covariance - Project the error covariance ahead
Step4: Discrete Kalman filter measurement update equations - Measurement Update;
A) Calculate Kalman gain - Compute the Kalman gain;
B) Calculate angle and bias - Update estimate with measurement zk;
Step5: Calculate estimation error covariance - Update the error covariance.

The principle of quaternion-based is described as below[11]:

a unit quaternion

$$ {}_A^Bq = [q_0 \quad q_1 \quad q_2 \quad q_3] = \left[cos\frac{\alpha}{2} \quad e_x sin\frac{\alpha}{2} \quad e_y sin\frac{\alpha}{2} \quad e_z sin\frac{\alpha}{2}\right] \quad (1)$$

where α is the rotation angle and e is the unit vector that represents the rotation axis.

quaternion multiplication, given two quaternions p and q, is defined as

$$p\otimes q = \begin{bmatrix} p_0q_0 - p_1q_1 - p_2q_2 - p_3q_3 \\ p_0q_1 + p_1q_0 + p_2q_3 - p_3q_2 \\ p_0q_2 - p_1q_3 + p_2q_0 + p_3q_1 \\ p_0q_3 + p_1q_2 - p_2q_1 + p_3q_0 \end{bmatrix} \quad (2)$$

$\boldsymbol{R}({}_A^Bq)$ is the direct cosine matrix (DCM) given in terms of the orientation quaternion.

$$\boldsymbol{R}({}_A^Bq) = \begin{bmatrix} {q_0}^2 + {q_1}^2 - {q_2}^2 - {q_3}^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & {q_0}^2 - {q_1}^2 + {q_2}^2 - {q_3}^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & {q_0}^2 - {q_1}^2 - {q_2}^2 + {q_3}^2 \end{bmatrix} \quad (3)$$

Use $\boldsymbol{R}(q_{acc})\begin{bmatrix}0\\0\\1\end{bmatrix} = \begin{bmatrix}a_x\\a_y\\a_z\end{bmatrix}$,obtain

$$\begin{cases} 2(q_{1acc}q_{3acc} + q_{0acc}q_{2acc}) = a_x \\ 2(q_{2acc}q_{3acc} - q_{0acc}q_{1acc}) = a_y \\ {q_{0acc}}^2 - {q_{1acc}}^2 - {q_{2acc}}^2 + {q_{3acc}}^2 = a_z \end{cases}, \quad (4)$$

The principle of kalman filter is described as below[12]:

$$\mathbf{x}_{\boldsymbol{k}} = \mathbf{F}_{\boldsymbol{k}}\boldsymbol{x}_{\boldsymbol{k-1}} + \mathbf{B}_{\boldsymbol{k}}\mathbf{u}_{\boldsymbol{k}} + \boldsymbol{w}_{\boldsymbol{k}} \quad (5)$$

$\mathbf{F}_{\boldsymbol{k}}$, the state-transition model;
$\mathbf{H}_{\boldsymbol{k}}$, the observation model;
$\mathbf{Q}_{\boldsymbol{k}}$, the covariance of the process noise;
$\mathbf{R}_{\boldsymbol{k}}$, the covariance of the observation noise;
$\mathbf{B}_{\boldsymbol{k}}$, the control-input model;
$\mathbf{F}_{\boldsymbol{k}}$,is the state transition model which is applied to the previous state $\mathbf{x}_{\boldsymbol{k-1}}$,;
$\mathbf{w}_{\boldsymbol{k}}$, is the process noise which is assumed to be drawn from a zero mean multivariate normal distribution, , with covariance, $\boldsymbol{w}_{\boldsymbol{k}} \sim \boldsymbol{\mathcal{N}}(\mathbf{0}, \boldsymbol{Q}_{\boldsymbol{k}})$.

At time k an observation (or measurement) $\mathbf{z}_{\boldsymbol{k}}$ of the true state $\mathbf{x}_{\boldsymbol{k}}$ is made according to

$$\mathbf{z}_{\boldsymbol{k}} = \mathbf{H}_{\boldsymbol{k}}\boldsymbol{x}_{\boldsymbol{k}} + \boldsymbol{v}_{\boldsymbol{k}} \quad (6)$$

$\mathbf{H}_{\boldsymbol{k}}$ is the observation model which maps the true state space into the observed space and $\mathbf{v}_{\boldsymbol{k}}$ is the observation noise which is assumed to be zero mean Gaussian white noise with covariance $\mathbf{R}_{\boldsymbol{k}}$: $\mathbf{v}_{\boldsymbol{k}} \sim \boldsymbol{\mathcal{N}}(\mathbf{0}, \boldsymbol{R}_{\boldsymbol{k}})$

Predict:
State estimate:

$$\widehat{\boldsymbol{x}}_{\boldsymbol{k|k-1}} = \mathbf{F}_{\boldsymbol{k}}\widehat{\boldsymbol{x}}_{\boldsymbol{k-1|k-1}} + \mathbf{B}_{\boldsymbol{k}}\mathbf{u}_{\boldsymbol{k}} \quad (7)$$

Error covariance:

$$\boldsymbol{P}_{\boldsymbol{k|k-1}} = \mathbf{F}_{\boldsymbol{k}}\boldsymbol{P}_{\boldsymbol{k-1|k-1}}\boldsymbol{F}_{\boldsymbol{k}}^{\boldsymbol{T}} + \boldsymbol{Q}_{\boldsymbol{k}} \quad (8)$$

Update:
Innovation or measurement prefit residual:

$$\bar{\mathbf{y}}_{\boldsymbol{k}} = \mathbf{z}_{\boldsymbol{k}} - \mathbf{H}_{\boldsymbol{k}}\widehat{\boldsymbol{x}}_{\boldsymbol{k|k-1}} \quad (9)$$

Innovation covariance:

$$\boldsymbol{S}_{\boldsymbol{k}} = \boldsymbol{R}_{\boldsymbol{k}} + \mathbf{H}_{\boldsymbol{k}}\boldsymbol{P}_{\boldsymbol{k|k-1}}\boldsymbol{H}_{\boldsymbol{k}}^{\boldsymbol{T}} \quad (10)$$

Optimal Kalman gain:

$$K_k = P_{k|k-1} H_k^T S_k^{-1} \quad (11)$$

Updated state estimate:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k \quad (12)$$

Updated state covariance:

$$P_{k|k} = (I - K_k H_k) P_{k|k-1} (I - K_k H_k)^T + K_k R_k K_k^T \quad (13)$$

Measurement post-fit residual:

$$\tilde{y}_{k|k} = z_k - H_k \hat{x}_{k|k} \quad (14)$$

2) The zero-crossing test

In a sine wave or other simple waveform, this normally occurs twice during each cycle.It is a device for detecting the point where the voltage crosses zero in either direction. The algorithm is used in state sensor to calculate the breathing rate [13].

The zero-crossing rate(ZCR) is the rate of sign-changes along a signal, i.e., the rate at which the signal changes from positive to negative or back.

Step1: A DC offset is computed and subtracted.

Step2: The ZCR is then computed, focusing on the changes of sign of the signal, using a sample-by-sample sequential algorithm:

Step3: The Respiratory rate is calculated.

The infrared imaging change algorithm

The principle of respiratory cycle test is: during inspiration, cold air from the environment is inhaled, and during expiration, warm air from the lungs is exhaled. thermal imaging detects this temperature modulation to test respiratory rate.

Step1: region selection and tracking;

Step2: extraction of the respiratory waveform

Step3: statistical Analysis

The Thermographic Image Processing methods include: Thermal Contrast Enhancement, Denoise method, Data Normalization, and so on.

A) Denoise method

The thermal signal has a spatial resolution of Nx × Ny pixels. To handle the thermal sequence, the frames can be concatenated as a three-dimensional Nx × Ny × Nt matrix, where Nt de fines the total number of frames in the sequence.

Thermograms are prone to ambient and inherent camera noise. There are many ways to de-speckle or de-noise an image using linear, non-linear or even statistical operators. For example, Gaussian low-pass, adaptive median filter, and MSR method.

The MSR performed well on enhancing detail and removal of uneven-heating compared to other photometric normalization techniques. This method is seen to resemble how our eyes (retina) perceive variations in grayscale intensities.

B) Thermal Contrast Enhancement

Absolute contrast is the classical and most basic contrast definition describing the excess temperature over a defect-free region:

$$C_{abs}(t) = T(t) - T_{Sa}(t) \quad (15)$$

where T(t) is the temperature for any pixel and $T_{Sa}(t)$ is the temperature for chosen sound area at time t.

Standard contrast was developed to suppress the impact of reflections produced by the surrounding environment through subtraction of an image's pixels at time t0 before heating.

$$C_{std}(t) = \frac{T(t) - T(t_0)}{T_{Sa}(t) - T_{Sa}(t_0)} \quad (16)$$

C)Data Normalization

The temperature can be expressed as an excess surface temperature measurement that indicates a change in surface temperature after the heat has been applied to the target sample. To display the excess temperature as a grayscale image, data normalization needs to be performed.

III. RESULTS

The above three methods is experimented in a smart vest, the smart vest uses the sensor module to test body respiratory rate, the comparison of these three methods is described in Table.1

TABLE 1. THE COMPARISON OF THREE RESPIRATORY RATE METHODS IN SMART VEST

	State sensor module	**pressure sensors module**	**infrared imaging sensor**
convenience	Good	Bad	normal
precise	normal	Good	normal
thickness	Good	Bad	normal
Weight	Good	Bad	normal

A State sensor module

Paper selects the MPU6050 state sensor, the experiment platform is shown in Fig.1.

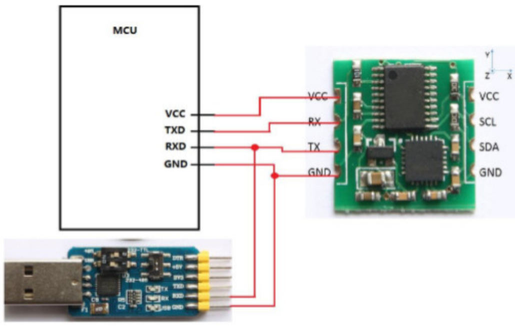

Fig.1 the state sensor experiment platform

The test data is output to a PC, the Matlab is used to verify the algorithms.

The program has three stages:

Stage 1: open the serial port, and acquire the state data;

Stage 2: pre-process the data and plot its raw figure; include quaternion-based and kalman filter

Stage 3: zero-crossing test and the respiratory rate calculation.

B The pressure sensors module

The paper selects the DCLK365 module to test RR. The platform is shown in Fig.2.

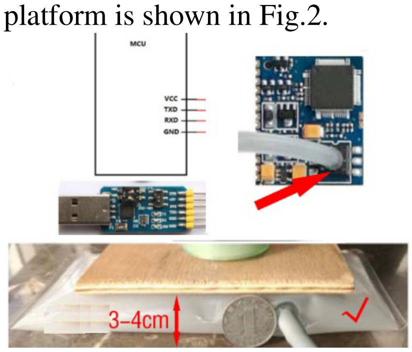

Fig.2 the pressure sensors module experiment platform

The operation condition:

Temperature: 5° C-40° C

Relative humidity: 18%-80%

Air pressure: 80kPa-105kPa

Power voltage:3.3V-5V

The Test range:

0~39.9kPa;

Resolution: 0.1kPa,Precision:0.4kPa;

The correction of RR: 3 times/ per minute;

The test results is output to PC through serial port.

C The infrared imaging sensor module

The paper selects AMG8833 sensor module, its experiment platform is shown in Fig.3.

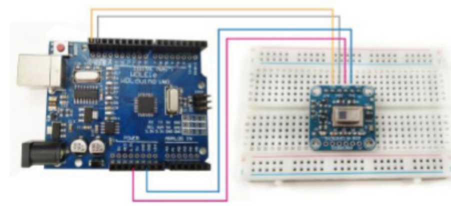

Fig.3 the infrared imaging sensor experiment platform

The test data is output to a PC, the MATLAB is used to analyse the data.

The program includes three stage:

Stage 1: open the serial port, and acquire the pixel image data;

Stage 2: pre-process and plot its raw figure; it is shown in Fig.4.

Stage 3: Data Normalization, Thermal Contrast Enhancement and the respiratory rate calculation.

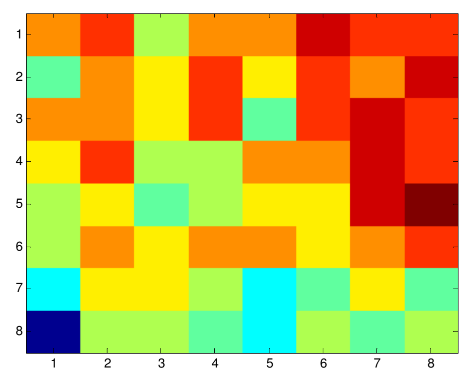

Fig.4. The infrared imaging of AMG8833

D The test results

With the test platform and installation in the smart vest, paper tests many times of every sensor modules, the test man is same one, during sleep or set down in a chair. The results are shown in Table.2.

TABLE 2. THE TEST RESULTS OF THREE RESPIRATORY RATE METHODS

	Average value (State sensor module)	Average value (pressure sensors module)	Average value (infrared imaging sensor)
Sleep (test platform)	21	18	25
set down in a chair (test platform)	24	19	27
Sleep (smart vest)	22	19	29
set down in a chair (smart vest)	25	19	27

IV. CONCLUSIONS

The paper uses MPU6050 state sensor, AMG8833 infrared imaging sensor module and DCLK365 pressure sensors module to test the respiratory rate.

The algorithms used in MPU6050 state sensor module include quaternion-based filter algorithms, kalman filter algorithms, and zero-crossing test algorithms.

The algorithms used in AMG8833 infrared imaging sensor module include Data Normalization algorithm, Thermal Contrast Enhancement algorithm and the respiratory rate calculation algorithm.

The experiment test in test platform and smart vest show the effective of the design methods.

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