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(71) Applicant *(for all designated States except US)*: **ISIS INNOVATION LIMITED** [GB/GB]; Ewert House, Ewert Place, Summertown, Oxford OX2 7DD (GB).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **TARASSENKO, Lionel** [GB/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ (GB). **TOWNSEND, Neil, William** [GB/GB]; Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ (GB). **PRICE, James, David** [GB/GB]; 98 Abingdon Road, Grandpoint, Oxford OX1 4PX (GB).

(74) Agents: **NICHOLLS, Michael, John** et al.; J.A. Kemp & Co., 14 South Square, Gray's Inn, London WC1R 5LX (GB).

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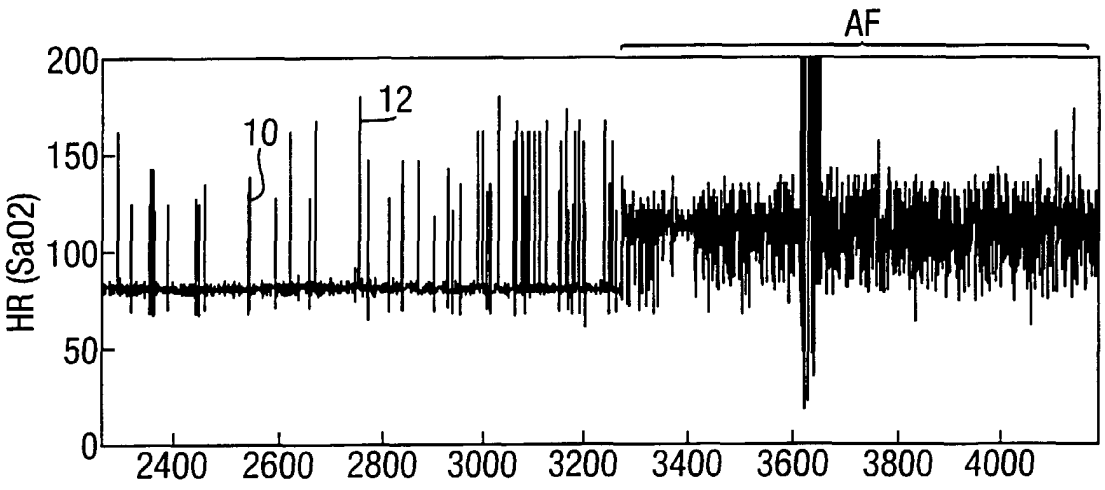


(57) Abstract: A method for combining physiological measurements from two or more independent measurement channels, particularly physiological measurements such as heart rate. Independent measurements of heart rate, for instance by ECG and pulse oximetry, can be combined to derive an improved measurement eliminating artefacts on one channel. A model of the process generating the physiological parameter, e.g. the heart rate, is constructed and is run independently for each channel to generate predictions of the parameter. The model may be a Kalman filter. The measured values are compared with the predicted values and the differences is used as an indication of the confidence in the measurement, the higher the difference the lower the confidence. The measurements from the two channels are combined using weights calculated from the respected differences.

WO 01/97059 A2

COMBINING MEASUREMENTS FROM DIFFERENT SENSORS

The present invention relates to a method and apparatus for combining measurements from different sensors in order to provide an improved measurement of a parameter. It is particularly applicable to the measurement of physiological parameters.

Certain parameters can be measured in more than one way. This is useful in giving independent measures of the same quantity. For instance, in the medical field the heart rate can be measured both from an electrocardiogram (ECG) and from a pulse oximetry waveform (used to calculate oxygen saturation). In the accompanying drawings Figure 4 illustrates schematically these two waveforms, Figure 4a being the electrocardiogram with the heart rate illustrated as HR_1, and Figure 4b the pulse oximetry waveform with the heart rate illustrated as HR_2. The heart rate is a parameter which can undergo sudden changes. Some of these changes are valid physiological changes, for example ectopic beats which occur prematurely, and therefore give rise to a temporary increase in the heart rate. Figure 5 illustrates the occurrence of an ectopic beat 50 found in both the electrocardiogram trace and the pulse oximetry waveform. The shorter interval between the preceeding beat and the ectopic beat 50 manifests itself in a measurement of the heart rate as a sudden increase in the heart rate. Figures 1 and 2 of the accompanying drawings show time plots of the heart rate measured by pulse oximetry (Figure 1) and ECG (Figure 2). It can be seen that in Figures 1 and 2 the heart rate in the early part of the plot is generally of the order of 80bpm, but that there are occasional sudden increases in heart rate, such as indicated at 10 and 20 which are caused by ectopic beats and thus appear both in the measurement by pulse oximetry and the measurement by ECG.

However, in addition to changes in the measured heart rate deriving from valid physiological changes, other changes occur which are not physiologically valid, for instance being caused by sudden movement of the sensors on the body surface (e.g. chest movement with ECG electrodes). Figure 6 illustrates the presence of artefacts 60 on the pulse oximetry waveform which shorten the interval between apparent beats and thus result in apparent increases in the heart rate. These changes

are reflected in one measurement, but not the other, as indicated at 12 and 22 in Figures 1 and 2 respectively. The fact that the changes appear in one measurement but not the other means that the two measurements could be combined to help decide which heart rate changes are valid physiological ones, and which are artefacts. However, the normal approach of validating one measurement channel against the other involving cross-correlation of the two measurements invariably fails because it is not possible to know in advance (for each recording, for each patient) what value to give to the threshold for accepting, rather than rejecting a change in the heart rate as being valid. Thus although it would appear from Figures 1 and 2 that a threshold could be set which would eliminate changes such as indicated as 22, such a threshold is not appropriate for all patients for all recordings, and does not help with the pulse oximetry waveform. The problems are increased in the event of atrial fibrillation when the heart rate changes rapidly as indicated in the region AF in Figures 1, 2 and 3.

Similar problems arise in other fields where a parameter is measured via two or more measurement channels.

The present invention provides a method and apparatus for improving measurement of a parameter by combining two measurements of it in a way which allows valid changes to be distinguished from artefacts. Accordingly it provides a method of measuring a parameter comprising the steps of: predicting the value of each of two measurements of the parameter, making two measurements of the parameter to produce two measured values of the parameter, calculating the respective differences between the predicted values and the measured values, and combining the two measured values with weights determined by said differences.

Thus with the present invention a prediction is made for each measurement and the actual measurement is compared with its prediction. The difference is computed, which is termed the "innovation", and this innovation is used to calculate a weight which will be given to that measurement when it is combined with the other measurement, also weighted according to its innovation. The weights are calculated so that if the innovation on one measurement channel is high, whereas the innovation on the other measurement channel is low, the measurement from the low innovation

channel is more heavily weighted. This is because a high level of innovation from one channel coinciding with a low innovation on the other channel is regarded as indicative of an artefact on the higher innovation channel. Thus, the weight given to each value when the values are combined is inversely related to the square or modulus of the difference between the measured value and its predicted value.

In one embodiment the measured values can be combined according to the formula:-

$$M = M_1 \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} + M_2 \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2} \qquad (1)$$

where M_1 and M_2 are the two measured values, and σ_1 and σ_2 are the differences between the two measured values and their respective predicted values.

The steps of prediction, measurement, calculation and combination are preferably repeated continuously, with the predicted value for each of the measurements being based on a linear predictive model, e.g the predicted value is based on its preceding predicted value and the preceding innovation (i.e. the difference between the preceding predicted value and the preceding measurement). The predicted value can be obtained by adding to the preceding predicted value a constant times the innovation. The constant is preferably a positive value less than or equal to unity. Alternatively the predicted value for each of the two independent measurements can be calculated by using a non-linear predictive model such as a neural network.

In one embodiment the predicted values can be based on a mathematical model of the system, which may include estimates for process noise and sensor (measurement) noise. Two independent models may be used, one for each of the measurement channels, and the models can include estimates for the process noise and sensor noise, which can be the same for the two channels. In one embodiment the models are Kalman filters.

The method is particularly applicable to the measurement of heart rate, in which case the two measurement channels can be from an electrocardiogram and a pulse oximetry waveform, though it is applicable to any other measurement of a

parameter which can be derived from two or more sources. Thus the method is applicable for more than two measurement channels, and both where the measurements are independent and where they are not truly independent such as from multiple leads of an ECG.

The invention can also provide for detection of movement artefacts. In this instance high values of innovation are obtained on both channels for the period of movement, and this can be used as a trigger to discard the sections of data which are corrupted by that movement.

It will be appreciated that the invention can be embodied using computer software and thus the invention extends to a computer program for controlling and executing the method or parts of it, and to a computer readable storage medium carrying the program. The invention also extends to corresponding apparatus for carrying out the method.

The invention will be further described by way of non-limitative example with reference to the accompanying drawings in which:-

Figure 1 illustrates a plot of heart rate measured by pulse oximetry;

Figure 2 illustrates a plot of heart rate measured by an ECG;

Figure 3 illustrates the result of combining the two plots of Figures 1 and 2 according to an embodiment of the invention;

Figure 4 illustrates schematically heart beats on an ECG and pulse oximetry waveform;

Figure 5 illustrates schematically ectopic beats appearing on an ECG and pulse oximetry waveform;

Figure 6 illustrates an ECG trace and pulse oximetry waveform with artefacts on the pulse oximetry waveform;

Figure 7 illustrates a plot of heart rate measured by an ECG;

Figure 8 illustrates predicted values for the heart rate according to one embodiment of the invention;

Figure 9 illustrates the innovation obtained from Figures 7 and 8;

Figure 10 illustrates the variance obtained from Figures 7 and 8.

An embodiment of the invention will now be described in which the

invention is applied in the medical field to the measurement of heart rate using ECG and pulse oximetry. As illustrated in Figure 4a the heart rate measured by ECG is derived from the interval between two successive R-wave peaks. The heart rate measurement derived from the pulse oximetry waveform is obtained from the interval between two successive peaks (or troughs) as illustrated in Figure 4b. Figures 1 and 2 illustrate heart rate plots derived from these two measurements.

With this embodiment of the present invention a model of the process generating the heart rate is constructed. The same model is run independently for each measurement source (i.e. one for the ECG measurement channel and one for the pulse oximetry measurement channel). In this embodiment the model is a Kalman filter. In general a Kalman filter uses a process model and an observation model. The process model models the state of the system at time t+1 in terms of its state at time t. The measurement or observation model indicates how the measurement at time t is related to the state of the system at time t. Thus in general terms:-

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \mathbf{w} \text{ (Process model)}$$

$$\mathbf{y}_t = \mathbf{C}\mathbf{x}_t + \mathbf{v} \text{ (Observation model)}$$

where:

$\mathbf{w} \sim N(\mathbf{O}, \mathbf{Q})$ - Gaussian process noise with zero mean and variance $\mathbf{Q}$

$\mathbf{v} \sim N(\mathbf{O}, \mathbf{R})$ - Gaussian measurement noise with zero mean and variance $\mathbf{R}$

and:

- k - vector of state variables $\mathbf{x}$
- n - vector of observable or measurements $\mathbf{y}$
- State $\mathbf{x}$ evolves according to simple first-order Markov dynamics;
- $\mathbf{A}$ is the k x k state transition matrix
- Each measurement vector $\mathbf{y}$ is related to the current state by a linear observation process; $\mathbf{C}$ is the n x k observation or measurement matrix

In this embodiment the general Kalman filter is simplified to use scalar quantities and the same process and measurement noise models (w, v) are used on

both measurement channel. Thus the simplified Kalman filter is as follows:-

$$x_{t+1} = Ax_t + w \quad \text{(Process model)}$$

$$y_t = Cx_t + v \quad \text{(Observation model)}$$

The model is further simplified by setting C=1, implying that the heart rate is both the state describing the process and the measurement. Further, it is assumed that A = 1, implying that the next heart rate is the same as the previous one with the variability allowed for by the process noise model.

Using this model, on each channel, the process of combining the two measurements then involves the following steps:-

1. From knowledge of previous history up to time *t*
   (a) predict the next state *xpred*;
   (b) from *xpred* predict the next measurement *ypred*

2. Make the measurement y_{t+1}

3. Compute the innovation:

   $$y_{t+1} = ypred + \varepsilon_{t+1}$$

   where ε_{t+1} is the difference between the actual value and the predicted value: the *innovation*.

4. Compute the variance σ_{t+1}^2:

   $$\sigma_{t+1}^2 = \varepsilon_{t+1}^2$$

   σ^2 the variance, is the inverse of the "confidence" which is associated with the prediction

5. Mix the heart rate measurements in inverse proportion to the variance

associated with each one:

$$HR = HR_1 \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} + HR_2 \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}$$

An example of an implementation of this model in MATLAB is given in Appendix 1. That example is general, and will work for vector quantities, though in this embodiment the quantities are scalar. It can be seen from appendix 1 that the predicted heart rate for each new measurement cycle (xnew) is equal to the previously predicted value (xpred) plus the Kalman gain K times the innovation e. The Kalman gain K is derived from the predicted variance Vpred and the measurement variance R. The predicted variance is derived from the previous predicted variance and the process noise Q. To start the process off it is initialized using an initial value of the heart rate as 80 and an initial value of the state variance of 100. The process noise in the Q in this embodiment is set to 5 and the measurement noise variance R is set to 10.

It will be clear from the implementation that, as normal with a Kalman filter, the variance and Kalman gain are not dependent on the measurement values. The measurement values are only used in the new prediction of heart rate via the innovation e. Thus it will be noted that for the constant values of Q and R used in this example the Kalman gain K tends to 0.5 and the state co-variance V tends to 5. However, K can be made adaptive by modifying the values for the variance constants Q and R, preferably the process variance Q, according to the type of process being encountered, for example atrial fibrillation (where there is a high level of process noise) as opposed to a healthy heart rate (during which there is a low level of process noise).

Figures 8, 9 and 10 illustrate values for the estimated heart rate xpred, the innovation e and the variance σ^2 for the heart rate plot shown in Figure 7 (in this case the ECG measurement channel).

Figure 3 illustrates the result of combining the two measurement plots from Figures 1 and 2 using this embodiment. It can be seen that the movement artefacts 22 on the ECG channel in Figure 2 have been removed from the combined measurement, even though they occur during a period of atrial fibrillation.

Thus with this embodiment the difference between the measurement and its predicted value is used to indicated the degree of confidence in that measurement. The higher the difference the lower the confidence. Formula (1) above is used to combine the two measurements. This can be summarised as follows:

1) Valid heart rates on both channels: low innovation on both channels; weight both measurements equally

2) Valid sudden change (e.g. ectopic beat) seen on both channels: high innovation but on *both* channels; therefore, measurements are again weighted equally

3) Artefact on one channel: high innovation on one channel only; therefore the information from that channel is ignored by being given a very low weighting (low confidence).

The method can also be used to provide a movement artefact detector, i.e. to detect when movement artefact is present on both channels and therefore no useful information is available. This is characterised by high values of innovation on both channels for a sustained period of time. This can be used to discard the sections of raw data which are corrupted by this movement and to indicate that no valid heart rate estimate can be derived during those periods.

Appendix 1

```
load -ascii ecghr_13
data_file = ecghr_13;

time = data_file(:,1);
hr = data_file(:,2);

start = 1
stop = size(data_file),1);
fprintf('number of R-R intervals detected = %d \n', stop);

hr_limit = 200;

                % X(t+1) = A X(t)+noise(Q) - process model with Q as variance of noise w
                % Y(t) = C X(t)+noise(R)  - measurement model with R as variance of noise v

ss = 1;         % state size - sets to one dimensional, ie scalar though routine works for vectors
os = 1;         % observation size      - sets to one dimensional, ie scalar
A = [1];        % assume x(t+1)=x(t)
C = [1];        % assume y=x
Q = 5.0*eye(ss); % process noise       - eye is the identity matrix in MATLAB -here just unity
R = 10.0*eye(os);% measurement noise variance
initx = [80];   % initial state value (HR of 80 bpm)
initV = 100*eye(ss); % initial state variance

xnew = initx;   % - initialisation
Vnew = initV;

for i = start:stop % - start of cycle

    x = xnew;               % update from previous cycle
    V = Vnew;               % update from previous cycle

    xpred = A*x;            % prediction of state
    Vpred = A*V*A' + Q;     % prediction of state covariance, A' is transpose of A

    ypred(i) = C*xpred;     % prediction of measurement
    y(i) = hr(i);           % "make measurement"

    e = y(i) - ypred(i);    % calculate innovation
    innov(i) = e;           % for plotting
    sigma2(i) = e*e;        % variance for saving

    S = C*Vpred*C' + R;     % innovation covariance
    Sinv = inv(S);          % invert S

    K = Vpred*C'*Sinv;      % compute Kalman gain

    xnew = xpred + K*e;     % update state by the innovation controlled by the Kalman gain
    Vnew = (eye(ss) - K*C)*Vpred; % update state covariance
    end
end
```

CLAIMS

1. A method of measuring a parameter comprising the steps of: predicting the value of each of two independent measurements of the parameter, making two independent measurements of the parameter to produce two measured values of the parameter, calculating the respective differences between the predicted values and the measured values, and combining the two measured values with weights determined by said differences.

2. A method according to claim 1 in which the steps of prediction, measurement, calculation and combination are repeated continuously, the predicted value for each of the two independent measurements being based on the preceding predicted value and the difference between the preceding predicted value and the preceding measurement.

3. A method according to claim 2 in which the predicted value for each of the two independent measurements is calculated by using a linear predictive model.

4. A method according to claim 2 in which the predicted value for each of the two independent measurements is calculated by using a non-linear predictive model.

5. A method according to claim 3 or 4 in which the model is adaptive, and it adapts in dependence upon the amount of process noise in the measurements.

6. A method according to any one of the preceding claims in which in the step of combining the two measured values the weight of each value varies inversely with the square of the difference between the predicted value and the measurement.

7. A method according to claim 6 in which the two measured values are combined according to the formula:-

$$M = M_1 \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} + M_2 \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}$$

where M_1 and M_2 are the two measured values, and σ_1 and σ_2 are the differences between the two measured values and their respective predicted values.

8. A method according to any one of the preceding claims in which the predicted values for the respective measurements are based on respective models of the system.

9. A method according to claim 8 in which the models of the system include estimates for process noise and sensor noise.

10. A method according to claim 8 or 9 in which the respective models of the system are mutually independent.

11. A method according to claim 10 in which the respective models of the system include the same estimates for process noise and sensor noise.

12. A method according to claim 8, 9, 10, or 11 in which the respective models of the system are Kalman filters.

13. A method according to any one of the preceding claims further comprising the step of discarding series of measurements for which the differences between both measured values and their predicted values exceed a predetermined threshold for a predetermined period of time.

14. A method according to any one of the preceding claims in which the parameter is the heart rate.

15. A method according to claim 14 in which the two independent measurements are made from an electrocardiograph and a pulse oximetry waveform.

16. A method according to claim 14 in which the two measurements are made from a multiple lead ECG recording.

17. A method according to any one of the preceding claims in which there are more than two measurements.

18. A method according to any one of the preceding claims further comprising the step of identifying movement artefacts based on the values of the differences between both measured values and their predicted values.

19. A computer program comprising program code means for executing the method of any one of the preceding claims.

20. Apparatus constructed and arranged to execute the method of any one of claims 1 to 18.

Fig.1.

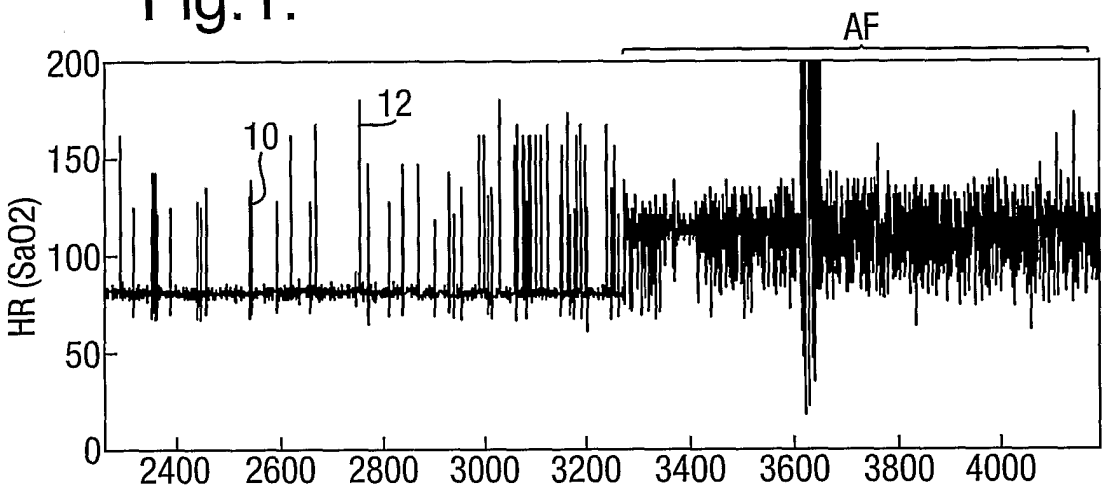


Fig.2.

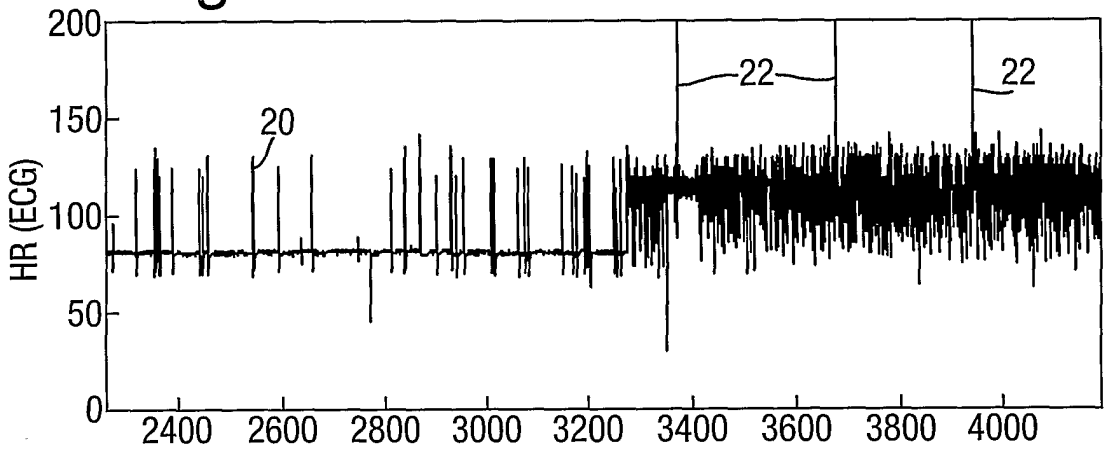


Fig.3.

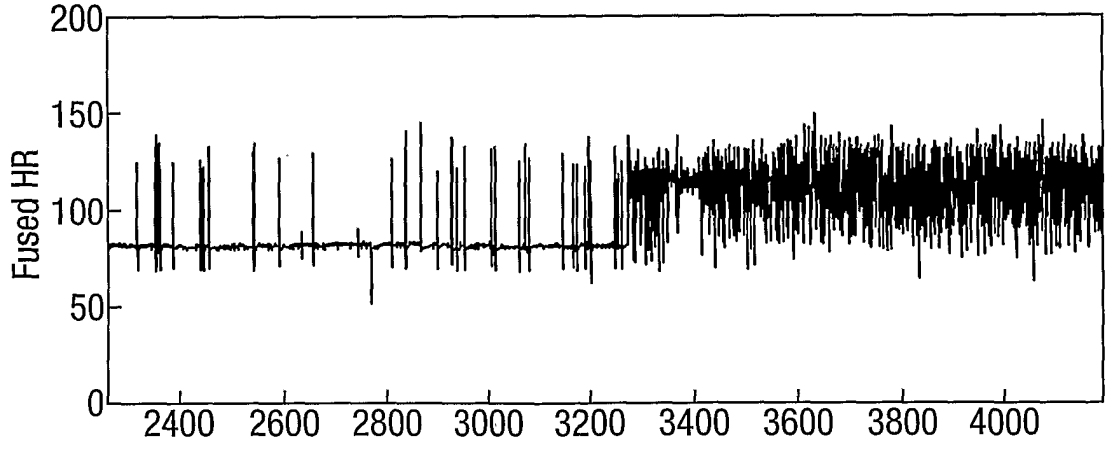


Fig.4(A).

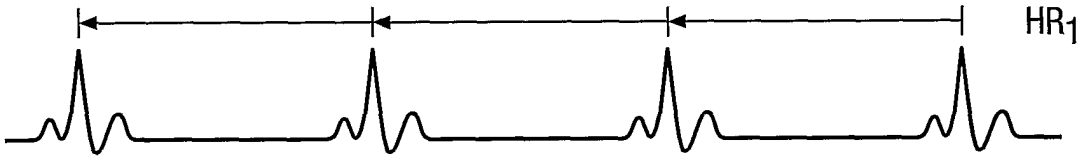


Fig.4(B).

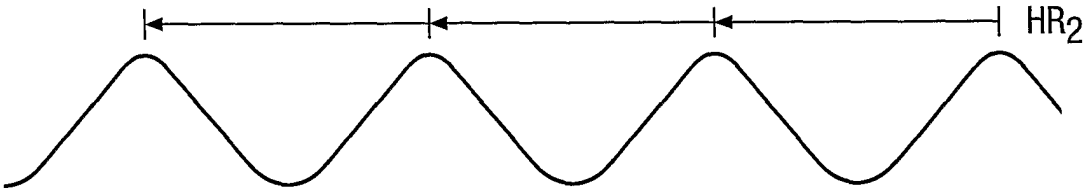


Fig.5(A).

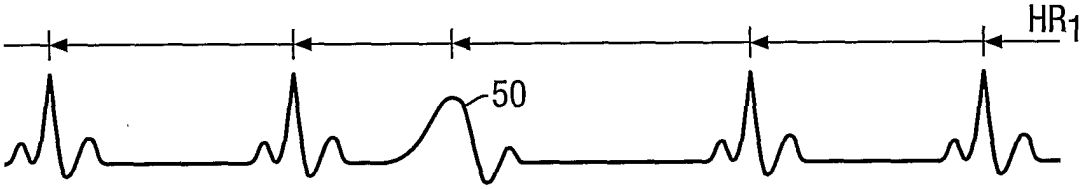


Fig.5(B).

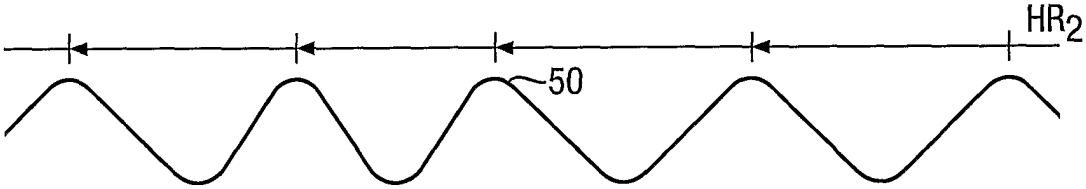


Fig.6.

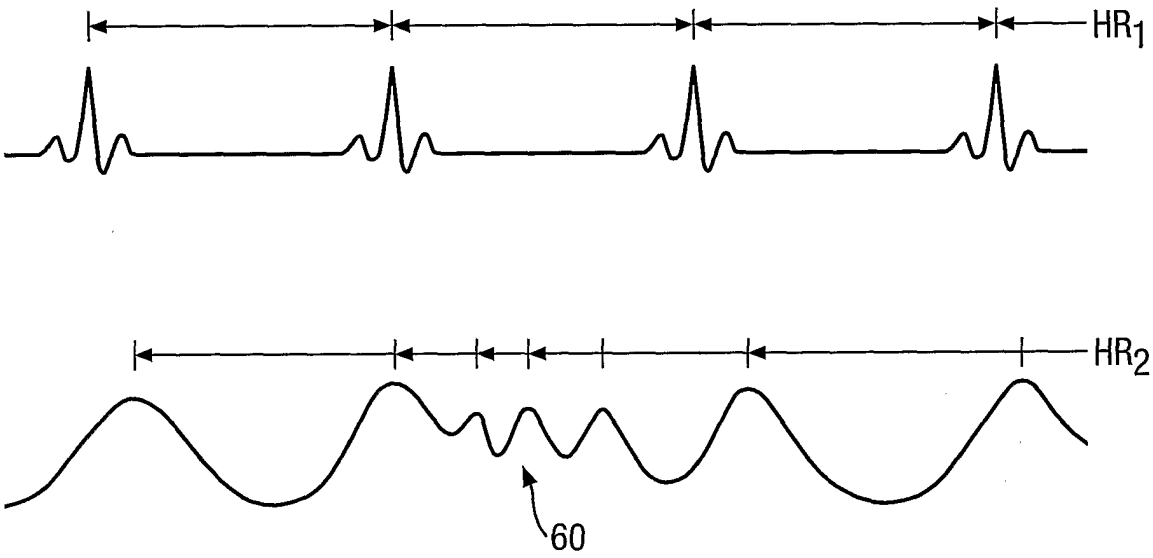


Fig.7.

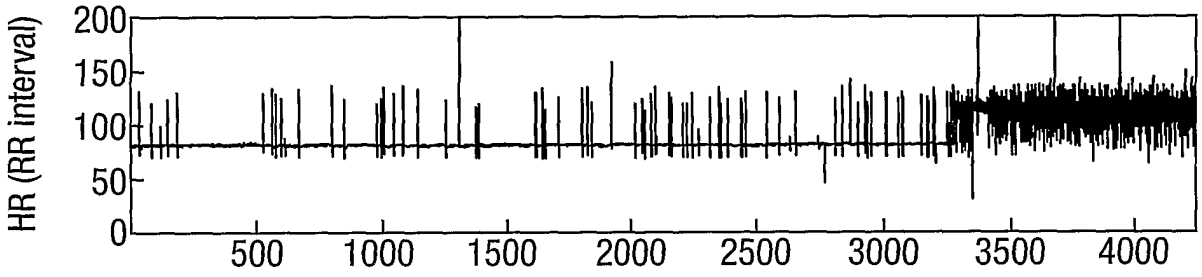


Fig.8.

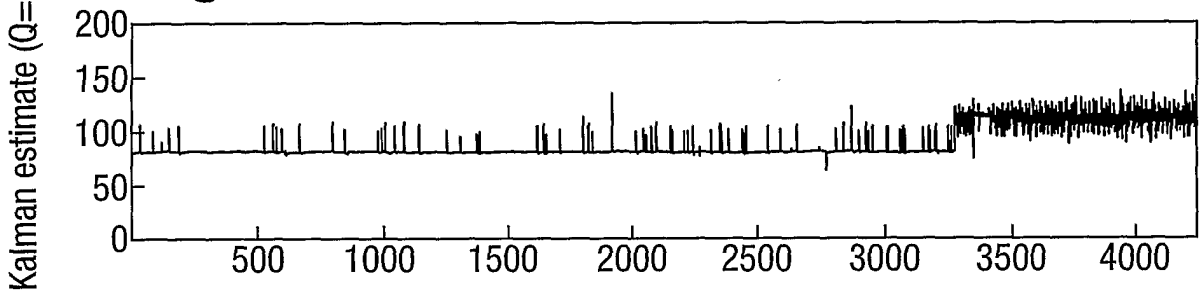


Fig.9.

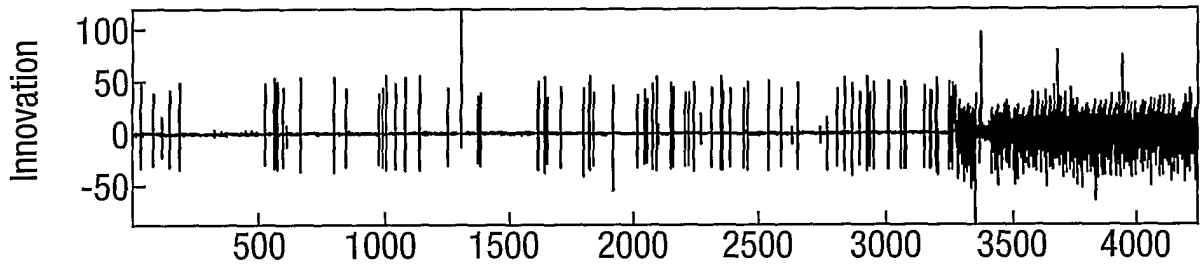
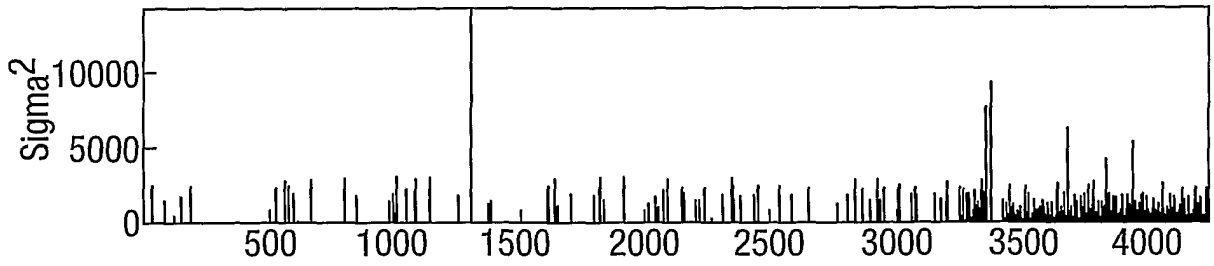


Fig.10.



专利名称(译)	结合不同传感器的测量结果		
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摘要(译)

一种用于组合来自两个或更多个独立测量通道的生理测量的方法，特别是诸如心率的生理测量。可以组合心率的独立测量，例如通过ECG和脉搏血氧测定法，以获得改进的测量，从而消除一个通道上的假象。产生生理参数的过程的模型，例如，为每个通道构建并独立运行心率，以生成参数的预测。该模型可以是卡尔曼滤波器。将测量值与预测值进行比较，并将差异用作测量置信度的指示，差异越大，置信度越低。使用根据所考虑的差异计算的权重来组合来自两个通道的测量值。