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(54) **PHOTOPLETHYSMOGRAM WITH MOTION ARTIFACT COMPENSATION**

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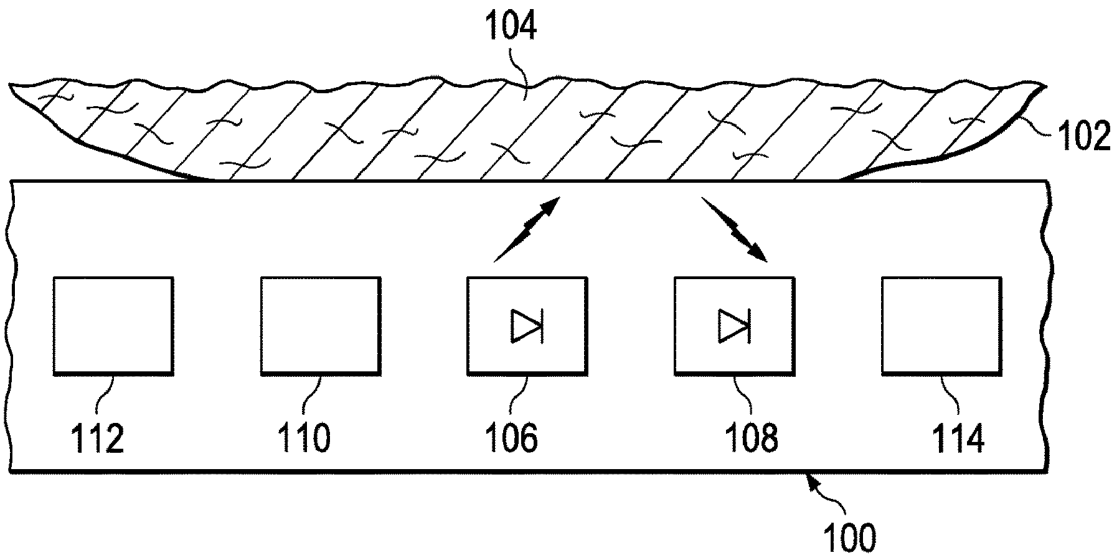
(57) **ABSTRACT**

A photoplethysmogram system includes a plurality of sensors, each sensor capable of providing a sensor signal, and an adaptive filter capable of receiving a first input signal and computing an output. The photoplethysmogram system is capable of operating the filter in sequential stages, such that at each different stage the first input signal is a different sensor signal.



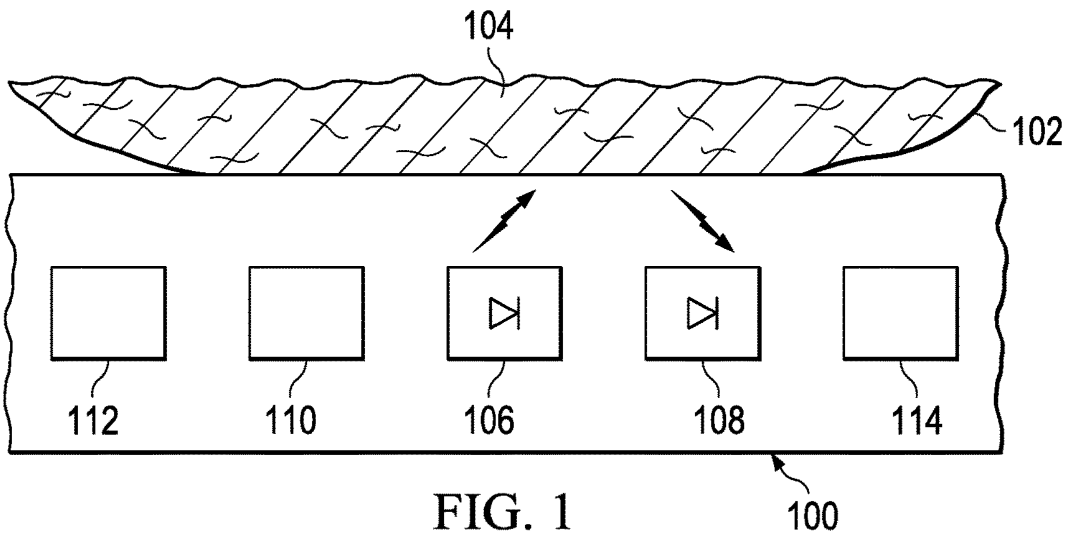


FIG. 1

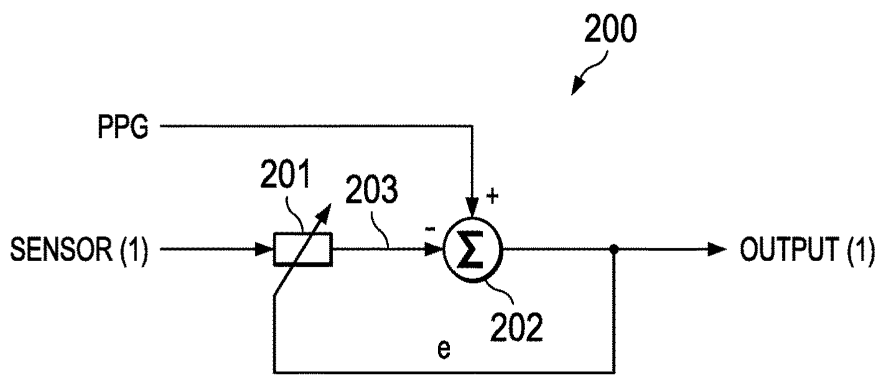


FIG. 2A

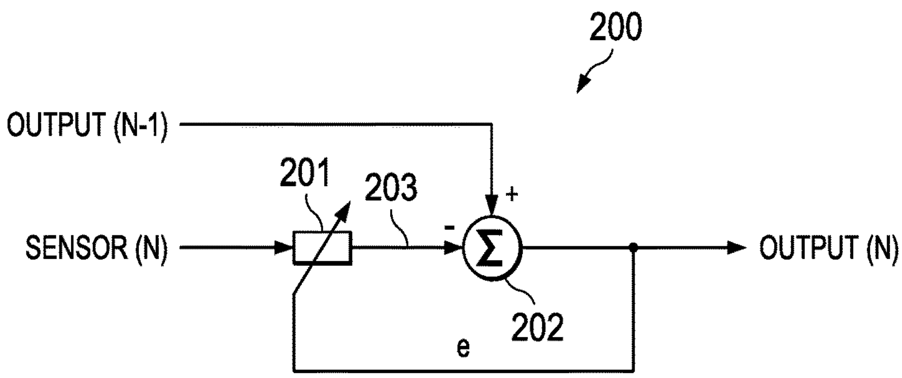


FIG. 2B

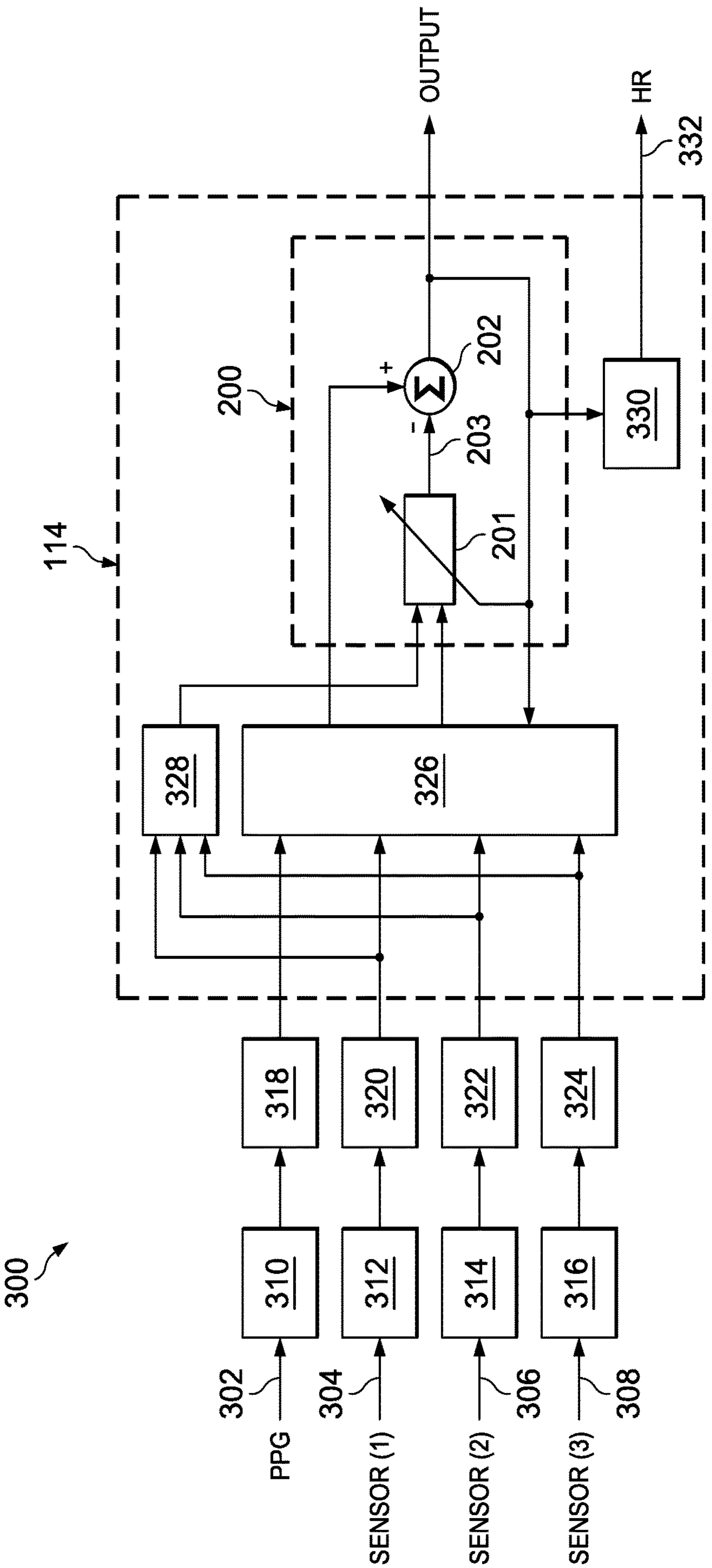
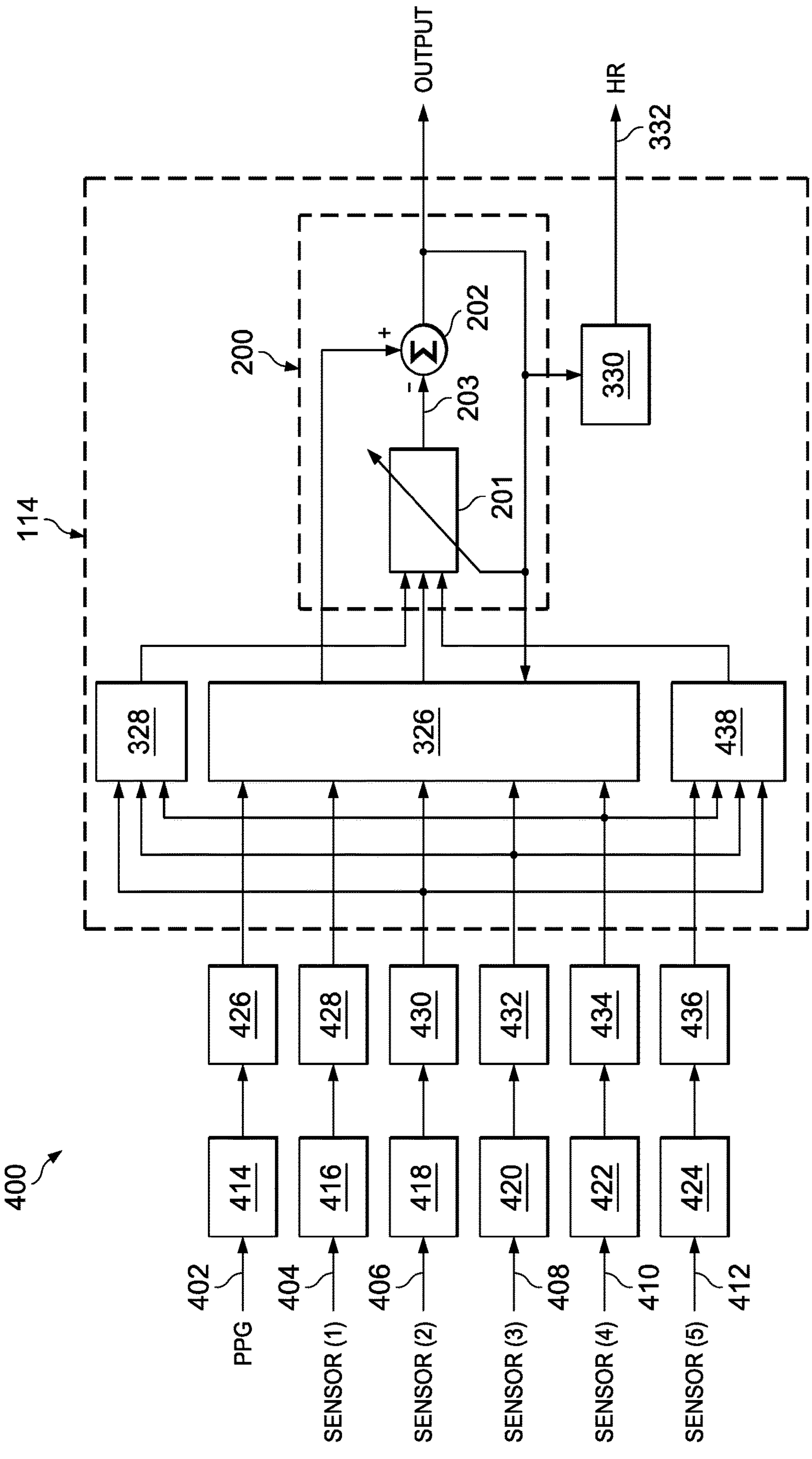

300
PPG
SENSOR (1)
SENSOR (2)
SENSOR (3)
302
304
306
308
310
312
314
316
318
320
322
324
114
326
328
200
201
202
203
330
332
OUTPUT
HR
+
-

FIG. 3



400
PPG
SENSOR (1)
SENSOR (2)
SENSOR (3)
SENSOR (4)
SENSOR (5)
402
404
406
408
410
412
414
416
418
420
422
424
426
428
430
432
434
436
114
328
326
438
200
201
202
203
330
332
OUTPUT
HR

FIG. 4

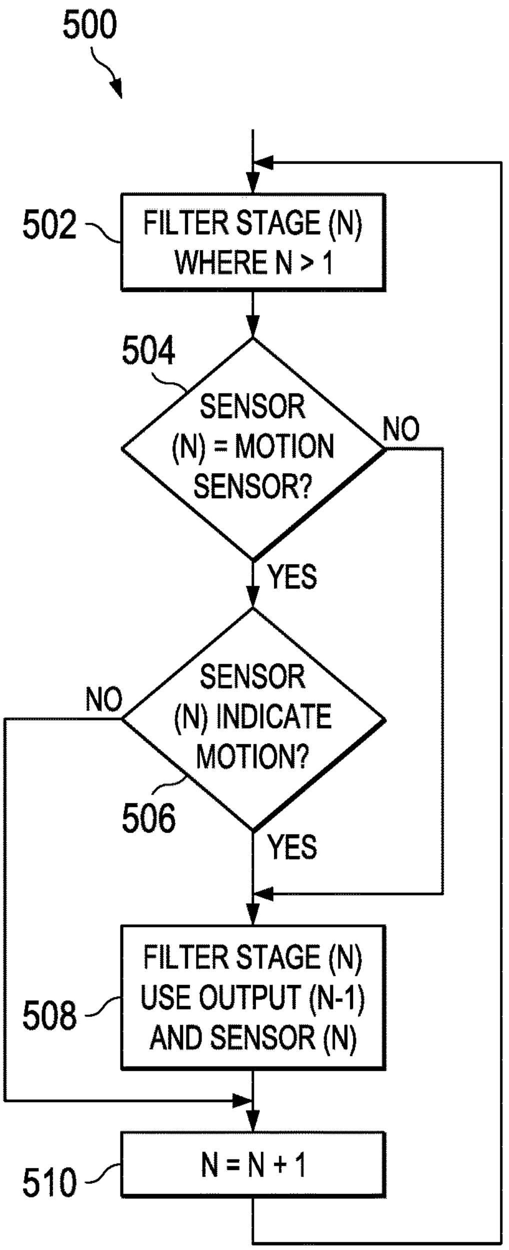

500
FILTER STAGE (N) WHERE N > 1
502
504
SENSOR (N) = MOTION SENSOR?
NO
YES
SENSOR (N) INDICATE MOTION?
NO
506
YES
FILTER STAGE (N) USE OUTPUT (N-1) AND SENSOR (N)
508
N = N + 1
510

FIG. 5

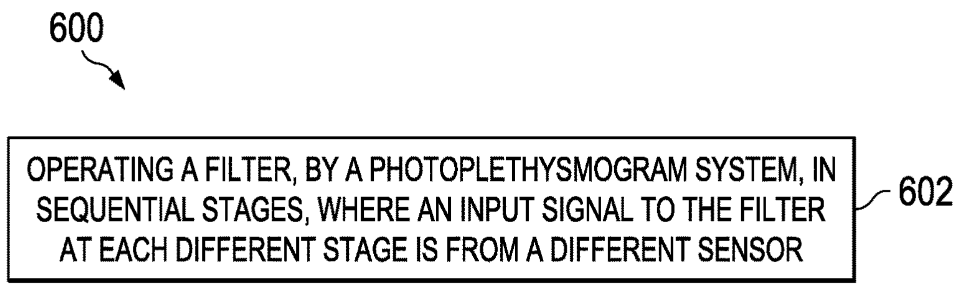

600
OPERATING A FILTER, BY A PHOTOPLETHYSMOGRAM SYSTEM, IN SEQUENTIAL STAGES, WHERE AN INPUT SIGNAL TO THE FILTER AT EACH DIFFERENT STAGE IS FROM A DIFFERENT SENSOR
602

FIG. 6

PHOTOPLETHYSMOGRAM WITH MOTION ARTIFACT COMPENSATION

BACKGROUND

[0001] A plethysmogram is a measurement of the volume of an organ. A photoplethysmogram (PPG) is a plethysmogram obtained using optics. One application of PPGs is heart rate monitoring. A source of light (typically a Light-Emitting-Diode (LED)) illuminates the skin and underlying tissue and a light-intensity sensor (typically a photo-diode) measures the amount of light either transmitted or reflected. The intensity of the transmitted or reflected light corresponds to the amount of blood volume. With each cardiac cycle, the blood volume changes in the arteries and arterioles in the subcutaneous tissue, and changes in blood volume modulate the transmitted or reflected light.

[0002] One common PPG application is heart-rate monitoring during physical activity or continuous health monitoring during daily life. Wrist-bands, watches, and other wearable heart-rate monitors using PPG sensors are commonly available. One problem with wearable heart-rate monitors is that the PPG signal is also modulated by motion artifacts due to arm movement, walking, jogging, etc. Motion can move the PPG sensor relative to the skin, or change the contact force, or deform the tissue next to the sensor, or affect blood flow near the sensor (for example by partially occluding an artery), each of which may affect the PPG signal.

[0003] Reduction of motion-induced artifacts in PPG signals has been extensively investigated in industry and academia. Most approaches use accelerometers to separately measure motion. One approach uses accelerometer signals to control various types of adaptive filters. Other approaches require real-time computation of three Fast-Fourier-Transforms (FFT's) to determine three-dimensional motion frequency, which leads to high complexity, expense, and increased battery drainage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. **1** is a cross-section block diagram of an example embodiment of a PPG system.

[0005] FIG. **2**A is a block diagram schematic of an adaptive filter during a first stage of sequential operation.

[0006] FIG. **2**B is a block diagram of the adaptive filter of FIG. **2**A during later stages of sequential operation.

[0007] FIG. **3** is a block diagram schematic of an example embodiment of a system for processing PPG sensor signals.

[0008] FIG. **4** is a block diagram schematic of an alternative example embodiment of a system for processing PPG signals.

[0009] FIG. **5** is a flow chart of an example embodiment of a method to omit filter stages when there is no motion in at least one dimension.

[0010] FIG. **6** is a flow chart of an example embodiment of a method for processing PPG sensor signals.

DETAILED DESCRIPTION

[0011] FIG. **1** illustrates an example PPG system **100** adjacent to skin **102** and underlying tissue **104**. The PPG system **100** may be, for example, part of a wrist band or wrist watch, or may be part of an apparatus attached to another part of the body such as an earlobe, forehead, or ankle. The PPG system **100** includes a light emitter **106** and a light detector **108** for measuring heart rate (derived from measuring blood volume) in the tissue **104**. The PPG system **100** may also include, for example, an accelerometer **110**, which may have multiple sensors for multiple dimensions. The PPG system **100** may also include one or more additional sensors **112** for measuring relative motion between the PPG sensor **106** and the skin **102**, or tightness of the PPG **100** against the skin **102**, or other sensors. The PPG system **100** may also include a processor (or controller, or digital signal processor, or ASIC, etc.) **114** for processing signals from the sensors (**108**, **110**, **112**) to derive a heart-rate with reduced noise artifacts. Alternatively, the sensor signals may be processed externally, for example, by a cell phone or fitness monitor.

[0012] The processor **114** includes an adaptive digital filter (not illustrated in FIG. **1**), which is used to reduce motion artifacts from the PPG signal. Examples of suitable filters include the Normalized Least Mean Squares Filter (NLMS) and Recursive Least Squares Filter (RLS). In the following discussion, the adaptive digital filter is operated sequentially in a daisy-chain fashion. At each stage, motion artifacts are removed from the PPG signal. As will be discussed in more detail below, sequential operation of the adaptive digital filter enables the system **100** to advantageously use more sensor signals than just raw accelerometer signals to reduce motion artifacts, enables an adaptive digital filter parameter to be optimized for each type of sensor, and enables using only one FFT computation for each heart-rate update.

[0013] FIGS. **2**A and **2**B illustrate an adaptive digital filter **200** being operated sequentially in a daisy-chain fashion. FIG. **2**A illustrates the signals during the first stage of the operation. PPG is the signal from the optical PPG sensor. SENSOR(**1**) is a signal from a first sensor used for artifact mitigation, which may be, for example, one dimension output of a three-dimensional accelerometer, or may be a signal from a sensor for relative motion between the PPG sensor and the skin, or a signal from some other artifact mitigation sensor. In FIG. **2**A, the adaptive digital filter **200** receives the signal SENSOR(**1**) from the first sensor, an estimation filter **201** digitally computes an estimation signal **203**, and at a summing junction **202**, the estimation signal **203** is subtracted from the PPG signal. The resulting difference e is fed back to the estimation filter **201** and the estimation filter **201** iteratively adapts by adjusting filter parameters to reduce e. At the end of the iteration process the resulting output of the summing junction (OUTPUT(**1**)) is the PPG signal with motion artifacts measured by the first sensor (SENSOR(**1**)) reduced.

[0014] In FIG. **2**B, for stages after the first stage, the adaptive digital filter **200** receives a signal SENSOR(N) from the Nth sensor, the estimation filter **201** digitally computes an estimation signal **203**, and at the summing junction **202** the estimation signal **203** is subtracted from the filter output signal (OUTPUT(N−1)) from the previous stage. As a result, at each stage, additional noise artifacts are reduced.

[0015] FIG. **3** illustrates an example embodiment of an improved photoplethysmogram system **300**. In FIG. **3**, the system receives four sensor signals (**302**, **304**, **306**, **308**). In the example of FIG. **3**, the first signal **302** is the output of the PPG sensor and signals **304-308** are the outputs of accelerometer sensors. The sensor signals (**302-308**) are band-pass filtered (**310**, **312**, **314**, **316**) and simultaneously digitized by Analog-to-Digital Converters (ADCs) (**318**, **320**, **322**, **324**).

The resulting digital signals are received by a processor (or controller, or digital signal processor, or ASIC) **114** (as illustrated in FIG. **1**) and stored in processor memory **326**. The processor **114** includes an adaptive digital filter **200** (as illustrated in FIGS. **2**A and **2**B). The processor memory **326** stores the digitized signals and the output of the adaptive digital filter **200**. The processor **114** also includes a stationary detector **328** and a FFT function **330**. The digital adaptive filter **200** (including the estimation filter **201** and the summing junction **202**), stationary detector **328**, and FFT **330** may all be implemented by software.

[0016] In the example system **300**, the adaptive digital filter **200** operates sequentially in stages as illustrated in FIGS. **2**A and **2**B. During the first stage, the inputs to the adaptive digital filter **200** are the stored first accelerometer signal **304** and the stored PPG sensor signal **302**. The resulting filter output (OUTPUT(**1**)) is stored in memory **326**. During the second stage, the inputs to the adaptive digital filter **200** are the second accelerometer signal **306** and the stored output from the first stage (OUTPUT(**1**)). During the third and final stage, the inputs to the adaptive digital filter **200** are the third accelerometer signal **306** and the stored output from the second stage (OUTPUT(**2**)). An FFT **330** is computed for the output from the final stage (OUTPUT(**3**)) of the adaptive digital filter **200** and the peak frequency in the FFT output is the estimated heart rate **332**.

[0017] In the example of FIG. **3** the only sensor signals are the PPG sensor signal **302** and accelerometer signals (**304-308**). However, one advantage of sequential operation of the adaptive digital filter **200** is that additional sensor signals can easily be added. Measurements of particular interest include (1) measurement of relative motion between the PPG sensor and the skin and (2) measurement of how tightly or loosely the PPG sensor is attached. In general, tightness is a DC measurement and relative motion is an AC measurement. The same sensor may be used for both. For example, a separate light source (for example a laser diode) with a wavelength optimized for detecting tissue instead of blood volume may be used to detect tightness and/or motion between the PPG sensor and the skin. Alternatively, conductive sensors of the type used to sense electroencephalograms (EEGs) or electrocardiograms (EKGs) may be used to detect resistance through the connection to the skin, or capacitance between the sensor and the skin, to measure tightness and/or relative motion between the PPG sensor and the skin. Alternatively, sequential operation of the adaptive digital filter **200** can accommodate signals from sensors outside the PPG apparatus (for example, sensors mounted on an ankle or in an insole for detecting leg motion and/or foot impact, or inertial sensors in a cell phone).

[0018] If, for example, the adaptive digital filter **200** is a NLMS filter, for each iteration n+1, the estimation signal **203** is $h(n+1)=h(n)+\mu(x(n)e(n))$, where x(n) is the input, e(n) is the output and feedback signal from the summing junction **202** (see FIGS. **2**A and **2**B), and μ is the step size (or adaptation constant). Operating the adaptive digital filter **200** sequentially in stages enables the PPG system to optimize the value of the step size μ to maximize convergence speed of the adaptive digital filter **200** at each stage depending on the type of sensor signal, and/or depending on the output of a loose/tight sensor, and/or depending on whether there is motion.

[0019] FIG. **4** illustrates an alternative example embodiment of a photoplethysmogram system **400**. Sensor signals (**402-412**) are filtered by band pass filters (**414-424**) and digitized by ADC's (**426-436**). The resulting digital signals are received by a processor (or controller, or digital signal processor, or ASIC) **114** and stored in processor memory **326**. The example system **400** includes a sensor signal (SENSOR(**1**)) (which may be for example, a signal from a sensor for measuring relative motion between the PPG sensor and the skin) in addition to signals from three accelerometer sensors (SENSOR(**2**), (SENSOR(**3**), SENSOR(**4**)), all of which are used by the adaptive digital filter **200**. In addition, the system **400** includes a tightness sensor (SENSOR(**5**)). Signals from the accelerometer sensors (SENSOR(**2**), (SENSOR(**3**), SENSOR(**4**)) and the signal from the tightness sensor (SENSOR(**5**)) are used to vary the filter step size p.

[0020] The system **400** includes a stationary detector **328** and a FFT function **330** (as in FIG. **3**). The system **400** also includes a step-size estimator **438** that receives the signal from the tightness sensor (SENSOR(**5**)) and the three accelerometer signals (SENSOR(**2**), (SENSOR(**3**), SENSOR(**4**)) and determines the step size μ for the estimation filter **201**. The value of μ is dependent on tightness and on which sensor signal is being filtered. The following table provides example values of μ depending on tightness and sensor signal. The values in the table assume that SENSOR(**1**) is a signal from sensor for measuring relative motion between the PPG sensor and skin and that the remaining signals are from accelerometer sensors. If the fit is loose then relative motion between the PPG sensor and the flesh may contribute more to motion artifacts than body motion as measured by an accelerometer. If the fit is tight then body motion may dominate motion artifacts.

SENSOR	μ (loose fit)	μ (tight fit)
SENSOR(1)	0.1	0.025
SENSOR(2)	0.025	0.1
SENSOR(3)	0.025	0.1
SENSOR(4)	0.025	0.1

[0021] In the embodiment of FIG. **3**, the stationary detector **328** receives all three digitized accelerometer signals (**304-308**) and determines whether there is any motion. In the embodiment of FIG. **3**, if there is no motion, then filter stages two and three for the adaptive digital filter **200** are not necessary and the FFT **330** can be computed on the output of the first stage. Likewise, if there is no motion in any one dimension, then the corresponding filter stage can be omitted. For example, if sensor signal **304** is quiet, then the first stage of the adaptive digital filter **200** can use the second stored sensor signal **306**, and so forth. Likewise, in the embodiment of FIG. **4**, the stationary detector **328** receives all three digitized accelerometer signals (**406-410**) and determines whether there is any motion. If there is no motion, then filter stages two, three, and four for the accelerometer signals (**406-410**) are not necessary and may be omitted, and if there is no motion in any one dimension, then the corresponding stage can be omitted.

[0022] FIG. **5** is a flow chart illustrating a method **500** to omit filter stages when there is no motion in at least one dimension. At step **502**, the adaptive digital filter **200** is at stage (N) where N is greater than one. At step **504**, if sensor (N) is a motion sensor, and if at step **506** there is no motion indicated by sensor (N), then filter stage (N) is omitted and the process proceeds to step **510** where N is incremented. At step **504**, if sensor (N) is not a motion sensor, or if at step **506** sensor (N) is a motion sensor and motion is detected, then the process proceeds to step **508** where filter stage (N) is computed using the output from sensor stage (N−1) and the stored signal from sensor (N).

[0023] FIG. **6** illustrates an example embodiment of a method **600** for controlling a photoplethysmogram system. At step **602** a photoplethysmogram system operates a filter in sequential stages, where an input signal to the filter at each different stage is from a different sensor.

[0024] While illustrative and presently preferred embodiments of the invention have been described in detail herein, it is to be understood that the inventive concepts may be otherwise variously embodied and employed and that the appended claims are intended to be construed to include such variations except insofar as limited by the prior art.

What is claimed is:

1. A photoplethysmogram system, comprising:
a plurality of sensors, each sensor capable of providing a sensor signal;
an adaptive filter capable of receiving a first input signal and computing an output; and
the photoplethysmogram system capable of operating the adaptive filter in sequential stages, such that at each different stage, the first input signal is a different sensor signal.

2. The photoplethysmogram system of claim **1**, the adaptive filter further comprising:
an estimation filter receiving a sensor signal and generating an estimation signal; and
a summing junction summing the estimation signal and a second input signal, where for each stage other than the first stage the second input signal is the output of the immediately previous stage.

3. The photoplethysmogram system of claim **2**, further comprising:
the photoplethysmogram system capable of computing a Fast-Fourier-Transform (FFT) from the output of the last stage of the adaptive filter, the FFT providing a measure of heart rate.

4. The photoplethysmogram system of claim **2**, further comprising:
a processor programmed to implement the adaptive filter in software.

5. The photoplethysmogram system of claim **2**, further comprising:
an Application-Specific Integrated Circuit (ASIC) programmed to implement the adaptive filter.

6. The photoplethysmogram system of claim **1**, further comprising:
at least one sensor in the plurality of sensors being other than an accelerometer sensor.

7. The photoplethysmogram system of claim **6**, further comprising:
one sensor in the plurality of sensors being a sensor for measuring relative motion between the photoplethysmogram and adjacent skin.

8. The photoplethysmogram system of claim **6**, further comprising:
one sensor in the plurality of sensors being a sensor for measuring tightness of fit between the photoplethysmogram and adjacent skin.

9. The photoplethysmogram system of claim **8**, further comprising:
the photoplethysmogram system capable of changing a step size used by the adaptive filter in response to a signal from the sensor for measuring tightness of fit.

10. The photoplethysmogram system of claim **1**, further comprising:
the photoplethysmogram system capable of changing a step size used by the adaptive filter depending on which sensor signal is being used for the first input signal.

11. The photoplethysmogram system of claim **1**, further comprising:
at least one acceleration sensor; and
a stationary detector, receiving the at least one acceleration sensor and determining whether there is any motion.

12. The photoplethysmogram system of claim **11**, further comprising:
the photoplethysmogram system capable of eliminating at least one adaptive filter stage if there is no motion in at least one dimension.

13. A photoplethysmogram system, comprising:
a plurality of sensors, each sensor capable of providing a sensor signal;
an adaptive filter capable of receiving a sensor signal and computing an output; and
the photoplethysmogram system capable of changing a step size used by the adaptive filter, depending on which sensor signal is being received by the adaptive filter.

14. The photoplethysmogram system of claim **12**, further comprising:
the photoplethysmogram system capable of changing a step size used by the adaptive filter in response to a signal from a sensor for measuring tightness of fit.

15. A method, comprising:
operating a filter, by a photoplethysmogram system, in sequential stages, where an input signal to the filter at each different stage is from a different sensor.

16. The method of claim **15**, further comprising:
providing a second input signal to the filter, by the photoplethysmogram system, where for each stage other than the first stage the second input signal is the output of the immediately previous stage.

17. The method of claim **15**, further comprising:
changing a step size used by the filter, by the photoplethysmogram system, depending on the output of a tightness sensor.

18. The method of claim **15**, further comprising:
changing a step size used by the filter, by the photoplethysmogram system, depending on which sensor signal is the input signal.

19. The method of claim **15**, further comprising:
eliminating at least one filter stage when there is no motion in at least one dimension.

20. The method of claim **15**, further comprising:
computing, by the photoplethysmogram system, a FFT from the output of the last stage of the filter.

* * * * *

patsnap

专利名称(译)	具有运动伪影补偿的光电容积描记图		
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申请号	US15/192456	申请日	2016-06-24
[标]申请(专利权)人(译)	德州仪器公司		
申请(专利权)人(译)	得克萨斯仪器公司		
当前申请(专利权)人(译)	得克萨斯仪器公司		
[标]发明人	PANDE TARKESH MAGEE DAVID PATRICK		
发明人	PANDE, TARKESH MAGEE, DAVID PATRICK		
IPC分类号	A61B5/00 A61B5/024		
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摘要(译)

光电容积描记图系统包括多个传感器，每个传感器能够提供传感器信号，以及自适应滤波器，其能够接收第一输入信号并计算输出。光电容积描记图系统能够在连续阶段中操作滤波器，使得在每个不同阶段，第一输入信号是不同的传感器信号。