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(54) Title: COMPENSATING PRESSURE SENSOR MEASUREMENTS

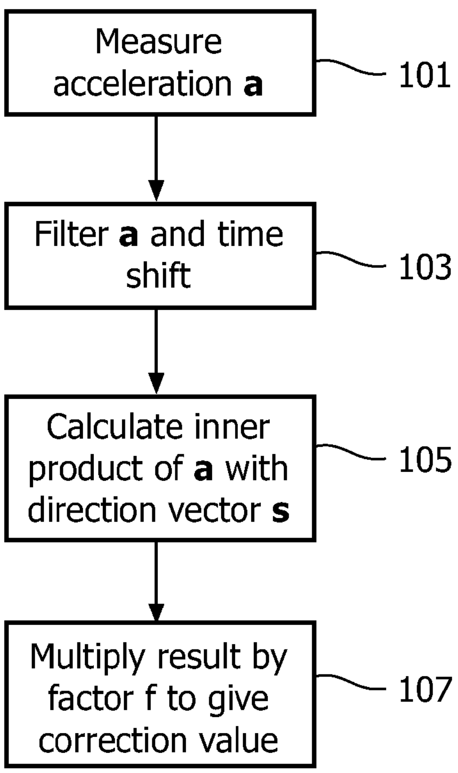

FIG. 2

(57) Abstract: There is provided a method for determining a correction value for a measurement by a pressure sensor, the correction value compensating for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor; the method comprising measuring an acceleration acting on the pressure sensor; and calculating the correction value as a function of the measured acceleration.

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COMPENSATING PRESSURE SENSOR MEASUREMENTS

FIELD OF THE INVENTION

The present invention relates to measurements from a pressure sensor, and specifically to the compensation of measurements from a pressure sensor due to changes in the orientation of the sensor and/or acceleration of the pressure sensor.

BACKGROUND OF THE INVENTION

Pressure sensors have recently been developed that can resolve pressure differences in the surrounding environment of around 1.5 Pascals (Pa). Such pressure sensors also benefit from low power consumption and integrated temperature compensation.

The fine sensitivity of the sensors allow for applications beyond simple pressure measurements, for example determining altitude or changes in altitude on the 'human scale' (i.e. changes in altitude of around 1 to 2 metres) from measurements of the air pressure. Indeed, using such sensors allows altitude resolution of around 12 cm, which means that they can be used for detecting motion of a user during activities or sports.

SUMMARY OF THE INVENTION

However, the inventors of the present application have identified that this sensitivity results in variations in measurements of around 6 Pa (which would correspond to a change in altitude in the order of 0.5 metres) when the orientation of the pressure sensor changes. In addition, applying acceleration to the sensor leads to large variations (around 20 Pa) in the pressure measurement. Depending on the particular construction of the pressure sensor, it is possible that these effects are caused by the mass of the sensing membrane inside the sensor; gravity or other accelerations can cause the sensing membrane to bend or displace, leading to an erroneous pressure value.

For very sensitive pressure measurements (such as those required for implementing activity monitors or elderly fall detectors), such variations are too large to obtain reliable results.

Therefore, it is an object of the present invention to provide a method for compensating the measurements from a pressure sensor for changes in the orientation of the sensor and/or in the acceleration on the sensor.

Thus, according to a first aspect of the present invention, there is provided a method for determining a correction value for a measurement by a pressure sensor, the correction value compensating for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor; the method comprising measuring an acceleration acting on the pressure sensor; and calculating the correction value as a function of the measured acceleration.

Preferably, the step of calculating the correction value comprises calculating an inner product of the measured acceleration with a vector indicating the direction in which the pressure sensor is most sensitive to an external force.

Preferably, the step of calculating the correction value further comprises multiplying the result of the inner product by a factor representing the sensitivity of the pressure sensor to the external force.

Preferably, the vector indicating the direction in which the pressure sensor is most sensitive to external forces is determined by rotating the pressure sensor in the absence of any forces other than gravity into a plurality of orientations; and determining the vector from the orientations that result in the largest and smallest measurements from the pressure sensor.

In some embodiments, the factor is determined by calculating an average of the largest and smallest measurements.

Preferably, the pressure sensor comprises a diaphragm for detecting changes in pressure, and the vector indicating the direction in which the pressure sensor is most sensitive to an external force is normal to the plane of the diaphragm.

According to a second aspect of the invention, there is provided a method for compensating a measurement by a pressure sensor for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor, the method comprising determining a correction value as described above; and obtaining a compensated pressure measurement by adding the correction value to a measurement from the pressure sensor.

Preferably, the measurement from the pressure sensor is a pressure or altitude measurement.

According to a third aspect of the invention, there is provided a system comprising a pressure sensor; an accelerometer for measuring an acceleration acting on the pressure sensor; and a processor for calculating a correction value for a measurement by the pressure sensor as a function of the measured acceleration, the correction value compensating for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor.

Preferably, the processor is adapted to calculate the correction value by calculating an inner product of the measured acceleration with a vector indicating the direction in which the pressure sensor is most sensitive to an external force.

Preferably, the processor is further adapted to calculate the correction value by multiplying the result of the inner product by a factor representing the sensitivity of the pressure sensor to the external force.

Preferably, the pressure sensor comprises a diaphragm for detecting changes in pressure.

Preferably, when the pressure sensor comprises a diaphragm for detecting changes in pressure, the vector indicating the direction in which the pressure sensor is most sensitive to an external force is normal to the plane of the diaphragm.

Preferably, the pressure sensor and accelerometer have a fixed orientation relative to each other.

Preferably, the processor is further adapted to compensate a pressure or altitude measurement by the pressure sensor by adding the correction value to the pressure or altitude measurement from the pressure sensor.

A further aspect of the invention relates to an activity detection system for detecting particular activities undertaken by a user, the activity detection system comprising a system as described above.

Yet another aspect of the invention relates to a fall detection system for detecting a fall by a user, the fall detection system comprising a system as described above.

Another aspect of the invention relates to an energy expenditure calculation device for calculating the energy expended by a user, the energy expenditure calculation device comprising a system as described above.

According to another aspect of the invention, there is provided a computer program comprising program instructions for causing a computer to perform any of the methods described above.

According to another aspect of the invention, there is provided a computer readable medium comprising a computer program as described above.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example only, with reference to the following drawings, in which:

Fig. 1 shows a block diagram of a system in accordance with the invention;

Fig. 2 is a flow chart illustrating a first embodiment of the invention;

Fig. 3 is a flow chart illustrating a calibration method in accordance with the invention;

Fig. 4 is a graph showing variations in the output of the pressure sensor and accelerometer; and

Fig. 5 is a graph showing the result of compensating the output of the pressure sensor in accordance with the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Figure 1 shows a system 2 that comprises a pressure sensor 4 that is sensitive to ambient pressure around the measurement system 2. Preferably, the pressure sensor 4 can detect pressure changes of the order of 1 Pascal, although the invention is applicable to pressure sensors with a maximum pressure change resolution that is significantly higher or lower than 1 Pascal.

Preferably, the pressure sensor 4 comprises a diaphragm for detecting changes in pressure . In particular, the diaphragm can be formed so that it acts as one plate of a capacitor, so movements of the diaphragm in response to external forces caused by changes in pressure result in a change in capacitance of the pressure sensor 4. However, as the pressure sensor 4 is so sensitive, the diaphragm can be influenced by a change in the direction in which gravity acts (i.e. if the orientation of the pressure sensor 4 has changed) or by other accelerations acting on the pressure sensor 4.

The system 2 further comprises an accelerometer 6 that is fixed in orientation relative to the pressure sensor 4, and which measures the acceleration on the system 2 and thus on the pressure sensor 4. Preferably, the accelerometer 6 measures the acceleration on the system 2 in three dimensions.

The system 2 further comprises a processor 8 that receives the pressure measurements from the pressure sensor 4 and accelerometer 6 and executes the algorithm for compensating the measurements from the pressure sensor 4 for changes in orientation and/or acceleration.

In some implementations, the processor 8 can output the pressure measurements to external devices via output line 10. In alternative implementations, the system 2 can include a wireless transmitter (not shown) for transmitting the pressure measurements to external devices.

In further alternative embodiments, the pressure sensor 4 may convert the pressure measurements into a measure of altitude before passing the measurements to the processor 8. In this case, the processor 8 will execute the algorithm according to the invention to produce a correction value in terms of an altitude adjustment.

Referring now to Figure 2, a method for determining a correction value for a pressure sensor measurement in accordance with a first embodiment of the invention is provided. Preferably, this method is executed by the processor 8, although in alternative embodiments, the system can pass the outputs from the pressure sensor 4 and accelerometer 6 to an external device, and it is the external device that executes the algorithm according to the invention.

In this embodiment, the correction value corrects the pressure measurements by the pressure sensor 4 for orientation only – in other words, it is assumed that no forces other than gravity are acting on the pressure measurement system 2.

In the first step, step 101, a measurement of the acceleration on the pressure measurement system 2 is made by the accelerometer 6. As the only force acting on the pressure measurement system 2 is gravity, the output of the accelerometer 6 indicates the orientation of the pressure measurement system 2. The output of the accelerometer 6 is given as a vector **a** expressed in ms^{-2}.

In step 103, the acceleration vector **a** is filtered and time-shifted.

In steps 105 and 107, the method comprises calculating the correction value, $P_{correction}$, as a function of the acceleration measured by the accelerometer 6.

In particular, in step 105, an inner product of the filtered acceleration vector **a** and a calibration vector **s** is calculated.

The calibration vector **s**, which is a normalised vector, indicates the direction in which the pressure sensor 4 is most sensitive to external forces (for example gravity). The procedure for determining the calibration vector **s** will be described later with reference to Figure 3.

The angle between the vectors **a** and **s** (given by the inner product of the vectors **a** and **s** ($\langle \mathbf{a} \cdot \mathbf{s} \rangle$)) determines the extent of the influence of the force of gravity on the pressure sensor 4.

The calibration vector **s** can be determined before operation of the pressure sensor 4 is started, perhaps during a manufacturing procedure or during installation of the pressure sensor in the system 2.

In step 107, the correction value in static situations (i.e. no acceleration on the system 2 other than that caused by gravity) is determined from the result of step 105 multiplied by a calibration factor f, which represents the sensitivity of the pressure sensor 4 to external forces, and which is expressed in Pa/(ms^{-2}). In this embodiment, the calibration factor f is determined during the same calibration procedure as the calibration vector **s**.

Thus, the correction value is given by:

$$P_{correction} = - f\mathbf{a}.\mathbf{s}$$

This correction value can then be applied to the measurement from the pressure sensor 4 ($P_{measured}$) to give the compensated pressure measurement as

$$P_{compensated} = P_{measured} + P_{correction}.$$

As the correction value will change as the pressure measurement system is rotated, the method in Figure 2 can be repeated frequently to generate correction values using updated measurements from the accelerometer 6.

As described above, the pressure sensor 4 may provide an output that is a measure of altitude rather pressure, so the correction value will also be calculated in terms of altitude.

The calibration procedure will now be described in more detail with reference to Figure 3. As described above, the calibration procedure can be carried out when the pressure sensor 4 is manufactured, or when the pressure sensor 4 is installed in the system 2. In the latter case, the calibration algorithm can be performed by the processor 8.

In step 151, the pressure sensor 4 is rotated into a plurality of orientations, and the pressure measured by the pressure sensor 4 is recorded in each orientation. Preferably, the pressure sensor 4 is rotated in several rotational directions so as to improve the likelihood of obtaining an orientation of the pressure sensor 4 in which it's most sensitive direction is substantially aligned with the direction in which gravity is acting.

In step 153, the most sensitive direction of the pressure sensor 4 is identified as the direction in which the pressure sensor 4 gives the highest pressure measurement, and the least sensitive direction of the pressure sensor 4 is identified as the direction in which the pressure sensor 4 gives the lowest pressure measurement.

Using measurements of the orientation that results in the highest pressure measurement in three orthogonal directions, an estimate of the calibration vector **s** is determined in step 155. The directions that provide the highest and lowest amplitudes for the pressure measurement provide the axis for **s**.

In step 157, the calibration factor f is calculated from the average of the highest and lowest pressure measurements. The average can be normalised for gravity, giving the calibration factor f as:

$$((P_{max} - P_{min})/2)/9.8$$

In a preferred embodiment of the invention in which the pressure sensor 4 comprises a diaphragm, it has been found that the direction in which the pressure sensor 4 is most sensitive to external forces (such as gravity) is the direction that is perpendicular or normal to the plane of the diaphragm. Therefore, when this type of pressure sensor 4 is used, it may not be necessary to carry out the calibration procedure to determine the sensitivity vector **s**.

The graphs in Figures 4 and 5 show the effect of the compensation on the measurement of the pressure output by the pressure sensor 4 in accordance with the method described above. In these examples, the output of the pressure sensor 4 is given as an altitude (in metres) rather than as a pressure (in Pascals).

In a preferred embodiment, the conversion from pressure P to altitude H is given by

$$H = T_0/(-dT/dH) * \left[1 - (P/P_0)^{(-dT/dH)*R/g}\right]$$

where dT/dH is the temperature gradient, T_0 is a reference temperature, P_0 is a reference pressure, R is a constant and g is acceleration due to gravity.

If a constant temperature gradient is assumed and appropriate values for the constants are used, the equation can be simplified to:

$$H = 44330 * \left[1 - (100P/101325)^{0.19}\right]$$

In Figure 4, the top part of the graph (labelled “annotations”) shows the orientation of the pressure sensor 4, the middle part of the graph (labelled “altitude”) shows the raw (i.e. uncompensated) output from the pressure sensor 4, and the bottom part of the graph shows the raw output of the accelerometer 6.

The thin line in the middle part of the graph shows the raw output of the pressure sensor 4, and in particular that the altitude changes discretely when the orientation of the pressure sensor 4 changes (note in particular the variations in altitude in the positions “front up” and “back up”). It should be noted that there is no actual change in altitude of the pressure sensor 4 here, only rotation around the centre of the pressure sensor 4. The noise in the altitude measurement is due to background fluctuations in the air pressure and/or electronic noise in the pressure sensor 4. The thick line in the middle part of the graph represents an average value for the altitude measurement.

Thus, using the algorithm shown in Figure 2, the raw output of the pressure sensor 4 is processed in processor 8 to give a compensated output $P_{compensated}$. In Figure 5, the compensated altitude measurement is shown in the middle part of the graph (the raw data is shown as a dashed line), and it can be seen that there is much less variation in the altitude from the initial value (0 metres in this case) as the pressure sensor 4 is rotated. The remaining fluctuations in the altitude measurement are a result of variations in the background pressure (perhaps due to the weather, air conditioning, doors opening and closing, etc.).

As described above, the methods shown in Figure 2 and 3 are suitable for calculating correction values for measurements from the pressure sensor 4 for the orientation of the pressure sensor 4. However, in a preferred embodiment of the invention, the algorithm described above can also be used to compensate for accelerations on the system 2 other than those caused by gravity.

Thus, the invention allows pressure measurements to be compensated for orientation changes and arbitrary movements of the pressure sensor 4. Therefore, measurements from the pressure sensor 4 can be used to obtain accurate measurements for the altitude (or rather a change in altitude) of the pressure sensor 4 under arbitrary sensor orientations and accelerations. In each case, the acceleration of the pressure sensor 4 can be caused by gravitational forces, non-gravitational forces or a combination of both.

Systems 2 in accordance with the invention, whether the output is represented as a pressure or an altitude, can be used for many different applications, in which accurate altitude information is useful while being subject to changes in acceleration. In particular, the system 2 according to the invention can be used in many different devices, including, but not limited to, mobile phones, smart phones, wrist watches, portable fitness devices, devices that detect specific activities of a user (such as climbing stairs or falling over), devices for monitoring energy expenditure by a user, devices for vehicle tracking and control, devices for managing warehouse logistics, etc. Moreover, accurate pressure or altitude measurements are of general use in the medical, automotive and aerospace fields.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

Variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. A single processor or other unit may fulfil the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measured cannot be used to advantage. A computer program may be stored/distributed on a suitable medium, such as an optical storage medium or a solid-state medium supplied together with or as part of other hardware, but may also be distributed in other forms, such as via the Internet or other wired or wireless telecommunication systems. Any reference signs in the claims should not be construed as limiting the scope.

CLAIMS:

1. A method for determining a correction value for a measurement by a pressure sensor, the correction value compensating for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor; the method comprising:

measuring an acceleration acting on the pressure sensor; and

calculating the correction value as a function of the measured acceleration.

2. A method as claimed in claim 1, wherein the step of calculating the correction value comprises calculating an inner product of the measured acceleration with a vector indicating the direction in which the pressure sensor is most sensitive to an external force.

3. A method as claimed in claim 2, wherein the step of calculating the correction value further comprises multiplying the result of the inner product by a factor representing the sensitivity of the pressure sensor to the external force.

4. A method as claimed in claim 3, wherein the vector indicating the direction in which the pressure sensor is most sensitive to external forces is determined by:

rotating the pressure sensor in the absence of any forces other than gravity into a plurality of orientations; and

determining the vector from the orientations that result in the largest and smallest measurements from the pressure sensor.

5. A method as claimed in claim 4, wherein the factor is determined by:

calculating an average of the largest and smallest measurements.

6. A method as claimed in claim 2 or 3, wherein the pressure sensor comprises a diaphragm for detecting changes in pressure, and wherein the vector indicating the direction in which the pressure sensor is most sensitive to an external force is normal to the plane of the diaphragm.

7. A method for compensating a measurement by a pressure sensor for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor, the method comprising:

determining a correction value as claimed in any of claims 1 to 6; and

obtaining a compensated measurement by adding the correction value to a measurement from the pressure sensor.

8. A method as claimed in claim 7, wherein the measurement from the pressure sensor is a pressure or altitude measurement.

9. A system comprising:

a pressure sensor;

an accelerometer for measuring an acceleration acting on the pressure sensor; and

a processor for calculating a correction value for a measurement by the pressure sensor as a function of the measured acceleration, the correction value compensating for changes in orientation of the pressure sensor and/or acceleration of the pressure sensor.

10. A system as claimed in claim 9, wherein processor is adapted to calculate the correction value by calculating an inner product of the measured acceleration with a vector indicating the direction in which the pressure sensor is most sensitive to an external force.

11. A system as claimed in claim 10, wherein the processor is further adapted to calculate the correction value by multiplying the result of the inner product by a factor representing the sensitivity of the pressure sensor to the external force.

12. A system as claimed in claim 9, 10 or 11, wherein the pressure sensor comprises a diaphragm for detecting changes in pressure.

13. A system as claimed in claim 12, when dependent on claim 10 or 11, wherein the vector indicating the direction in which the pressure sensor is most sensitive to an external force is normal to the plane of the diaphragm.

14. A system as claimed in any of claims 9 to 13, wherein the pressure sensor and accelerometer have a fixed orientation relative to each other.

15. A system as claimed in any of claim 9 to 14, wherein the processor is further adapted to compensate a pressure or altitude measurement by the pressure sensor by adding the correction value to the pressure or altitude measurement from the pressure sensor.

16. An activity detection system for detecting particular activities undertaken by a user, the activity detection system comprising a system as claimed in any of claims 9 to 15.

17. A fall detection system for detecting a fall by a user, the fall detection system comprising a system as claimed in any of claims 9 to 15.

18. An energy expenditure calculation device for calculating the energy expended by a user, the energy expenditure calculation device comprising a system as claimed in any of claims 9 to 15.

19. A computer program comprising program instructions for causing a computer to perform the method as claim in any of claims 1 to 8.

20. A computer readable medium comprising a computer program as claimed in claim 19.

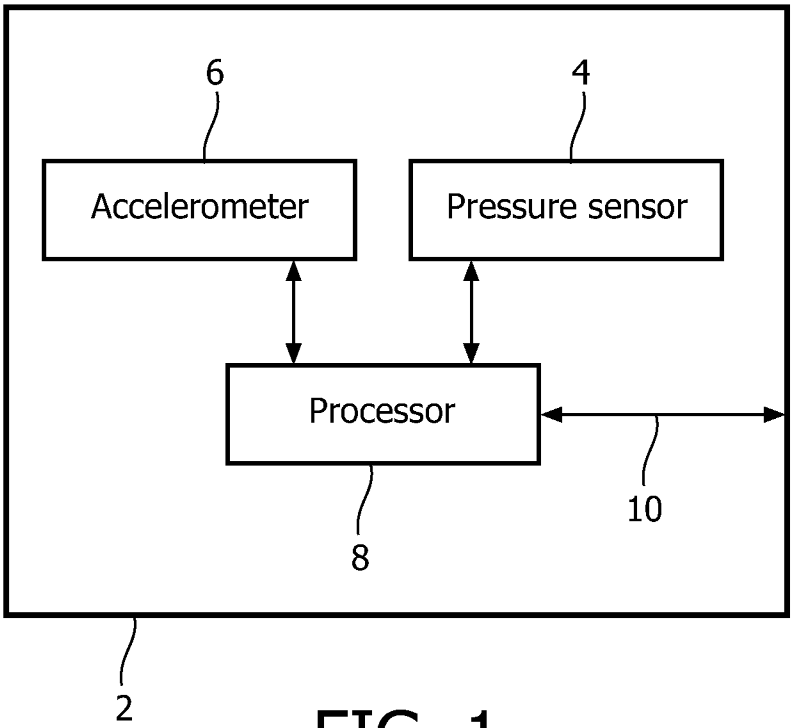

6
4
Accelerometer
Pressure sensor
Processor
10
8
2

FIG. 1

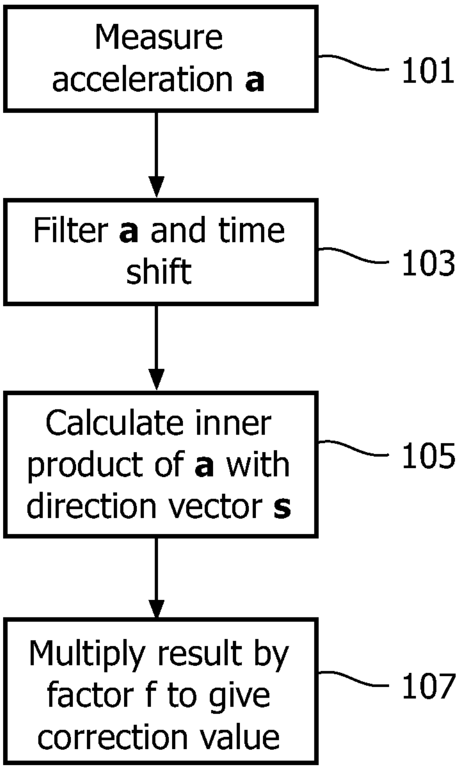

Measure acceleration **a**
101
Filter **a** and time shift
103
Calculate inner product of **a** with direction vector **s**
105
Multiply result by factor f to give correction value
107

FIG. 2

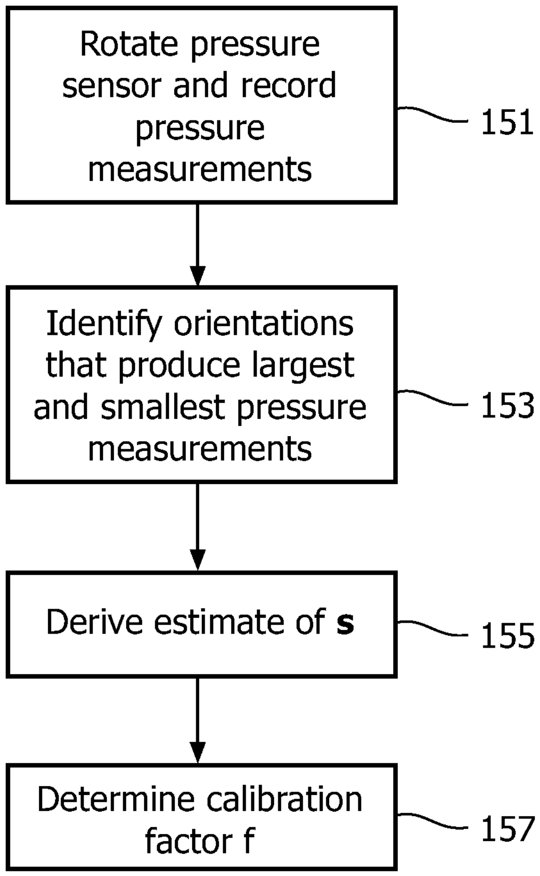
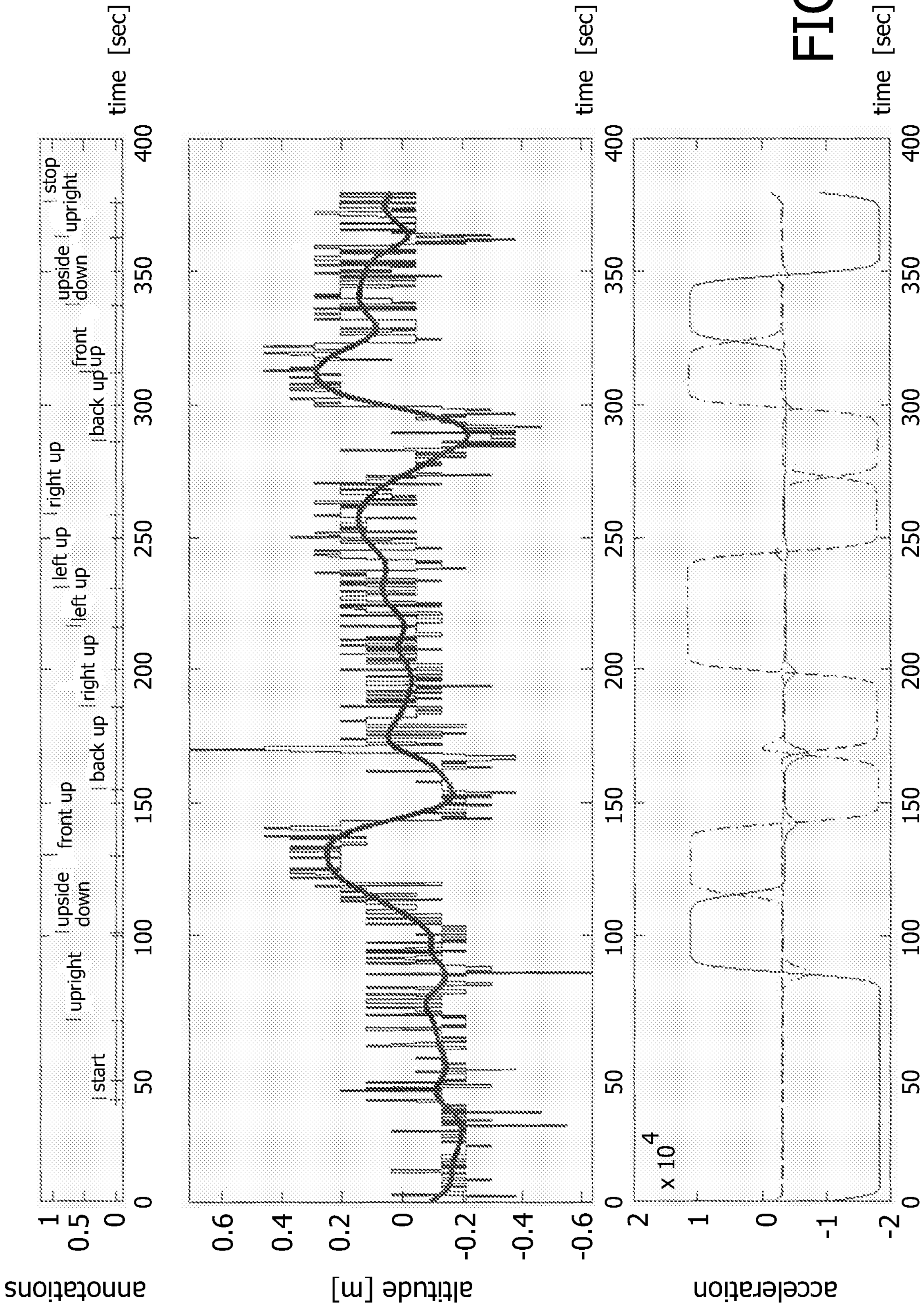

Rotate pressure sensor and record pressure measurements
151
Identify orientations that produce largest and smallest pressure measurements
153
Derive estimate of **s**
155
Determine calibration factor f
157

FIG. 3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start
upright
upside down
front up
back up
right up
left up
left up
right up
back up
front up
upside down
upright
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time [sec]
acceleration
x 10^4
time [sec]

FIG. 4

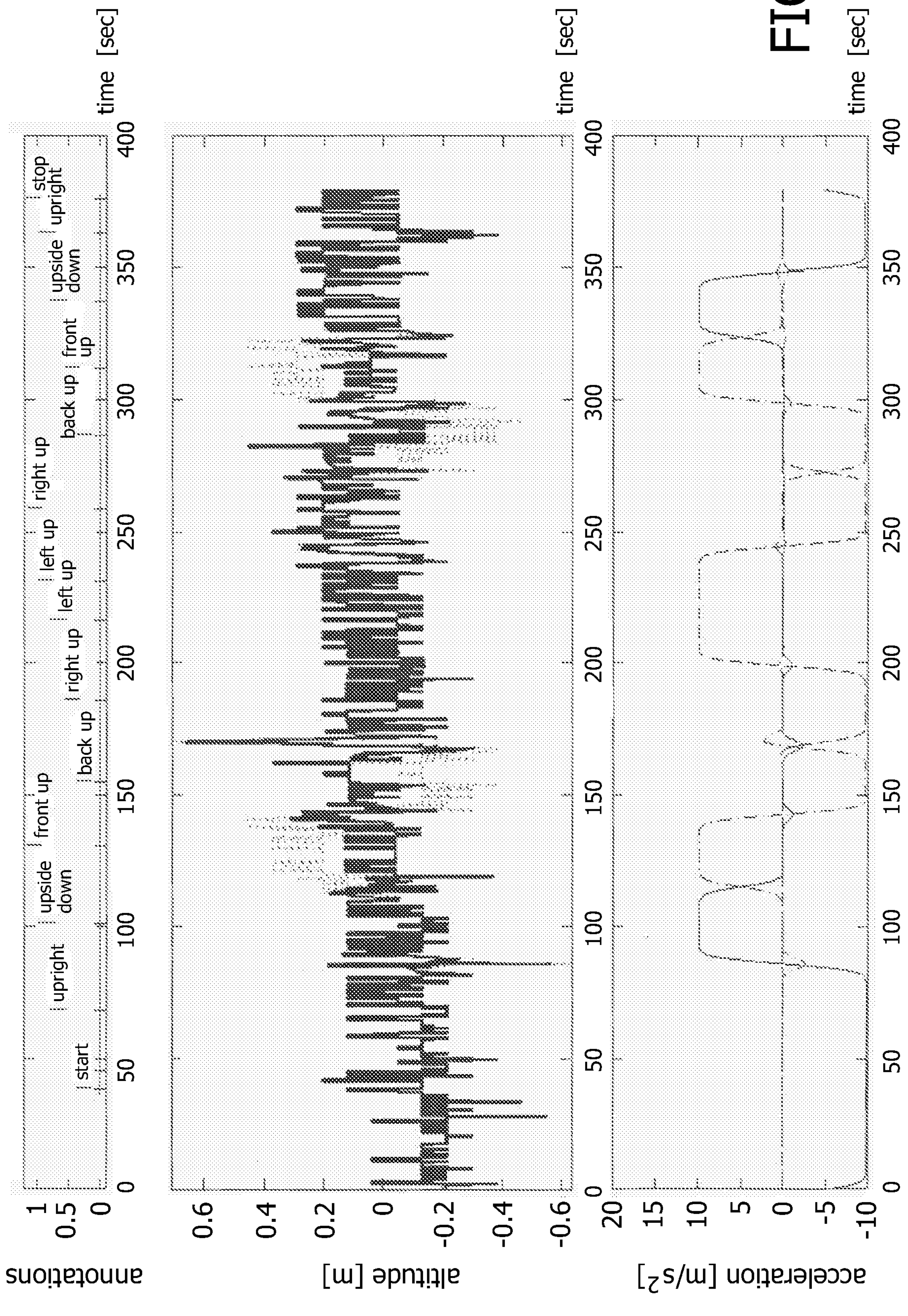
annotations
altitude [m]
acceleration [m/s2]
time [sec]
start
upright
upside down
front up
back up
right up
left up
left up
right up
back up
front up
upside down
upright
stop
0 50 100 150 200 250 300 350 400
1 0.5 0
0.6 0.4 0.2 0 -0.2 -0.4 -0.6
20 15 10 5 0 -5 -10

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/050509

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01L19/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006/070424 A1 (SAARI BYRON J [US] ET AL) 6 April 2006 (2006-04-06) abstract figures 1,2 paragraph [0004] - paragraph [0015] claims 1-13	1-20
A	US 2006/053908 A1 (ISHIGAMI ATSUSHI [JP] ET AL) 16 March 2006 (2006-03-16) abstract figures 1-16 paragraph [0003] - paragraph [0008] claims 1-10	1-20

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 April 2009	28/04/2009
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Daman, Marcel

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/050509

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2005/000293 A1 (KANDLER MICHAEL [DE]) 6 January 2005 (2005-01-06) abstract figures 1-4 paragraph [0003] - paragraph [0024] claims 1-26	3-5
A	EP 0 902 267 A (KK HOLDING AG [CH]) 17 March 1999 (1999-03-17) abstract claims 1-11	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2009/050509

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 2006070424	A1	06-04-2006	NONE			
US 2006053908	A1	16-03-2006	CN	1701223	A	23-11-2005
			EP	1659386	A1	24-05-2006
			WO	2005019790	A1	03-03-2005
			KR	20050059273	A	17-06-2005
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			DE	59808678	D1	17-07-2003
			JP	3718063	B2	16-11-2005
			JP	11160182	A	18-06-1999
			US	6105434	A	22-08-2000