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- (71) **Applicant (for all designated States except DE, US):**  
**KONINKLIJKE PHILIPS ELECTRONICS N.V.**  
[NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven  
(NL).
- (71) **Applicant (for DE only): PHILIPS INTELLECTUAL  
PROPERTY & STANDARDS GMBH** [DE/DE];  
Lübeckertordamm 5, 20099 Hamburg (DE).
- (72) **Inventors; and**
- (75) **Inventors/Applicants (for US only): VAN ACHT, Victor,**

**M., G.** [NL/NL]; c/o High Tech Campus, Building 44, NL-5656 AE Eindhoven (NL). **LAMBERT, Nicolaas** [NL/NL]; c/o High Tech Campus, Building 44, NL-5656 AE Eindhoven (NL). **BONGERS, Edwin, G., J., M.** [NL/NL]; c/o High Tech Campus, Building 44, NL-5656 AE Eindhoven (NL). **LANFERMANN, Gerd** [DE/DE]; c/o High Tech Campus, Building 44, NL-5656 AE Eindhoven (NL).

- (74) **Agents:** VAN VELZEN, Maaïke, M. et al.; High Tech Campus, Building 44, NL-5656 AE Eindhoven (NL).
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**(54) Title:** ORIENTATION MEASUREMENT OF AN OBJECT

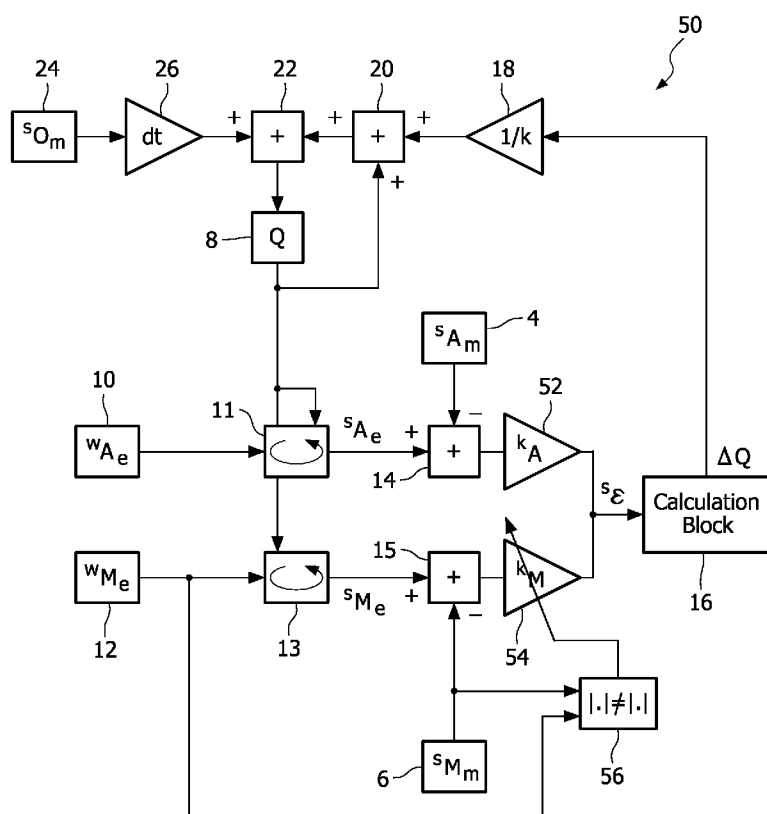


FIG. 4

**(57) Abstract:** There is provided an object orientation measurement system for calculating an estimate of the orientation of an object to which the system can be attached, the system comprising measurement means for taking measurements of a plurality of parameters used in calculating an estimate of the orientation of the object; and processing means for comparing a measurement of at least one of the parameters with a first predetermined value; and calculating an estimate of the orientation of the object using the measurements of the plurality of parameters, wherein the weighting of the measurement of the at least one parameter is adjusted relative to the measurement of at least one other parameter based on the result of the comparison.



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## Orientation measurement of an object

## FIELD OF THE INVENTION

The invention relates to methods and systems for improving the measurement of the orientation of an object.

## 5 BACKGROUND TO THE INVENTION

Three-dimensional accelerometers can be attached to objects, and can measure the acceleration of the object in three dimensions. As part of these measurements, the accelerometer measures forces on the object caused by gravity.

By using the measurements of the forces on an object caused by gravity, the  
10 accelerometer can be used as a tilt sensor to measure the angular orientation of the object relative to the horizontal.

However, as the accelerometer cannot distinguish between forces caused by gravity and acceleration caused by non-gravitational “inertial” forces, it is possible in most cases to determine that the measured acceleration deviates from gravity, but not to determine  
15 the tilt of the object from these measurements alone.

In addition, it is typically not possible to estimate the position of the object by integrating the measurements from the accelerometer. There are three reasons for this: firstly, the respective parts of the total acceleration that are due to gravity and “inertial” forces are not known; secondly, the direction in which the “inertial” forces act relative to the  
20 direction in which gravity acts is not known; and thirdly, the acceleration measurements must be integrated twice to arrive at the position measurement, which is practically impossible to do accurately due to drift of the measurements.

It is well known that the orientation of an object can be measured or determined using a combination of a three-dimensional accelerometer to measure the tilt of  
25 the object and a two- or three-dimensional magnetometer that measures the Earth’s magnetic field.

Fig. 1 shows a block diagram of a system that can measure or estimate the orientation of an object. The system 2 comprises an accelerometer 4 and a magnetometer 6 that provide measurements of the acceleration and magnetic field respectively of an object to

which they are attached. The measurements are denoted  $^sA_m$  and  $^sM_m$  respectively, where 's' indicates that the measurements are in a frame of reference that is fixed relative to the sensor or object, and 'm' indicates that these are measurements from the accelerometer or magnetometer.

5                   The system 2 also comprises a register or memory 8 for storing a previous estimate of the orientation  $Q$  of the object. The orientation  $Q$  may be mathematically represented as a quaternion, Euler angles or any other suitable orientation representation. The basic value for the orientation  $Q$  is determined from a gyroscopic measurement (described further below), and is modified based on the measurements of the accelerometer 4  
10                   and magnetometer 6

                  A first unit 10 provides an expected measurement for acceleration on the object caused by gravity (vector  $G$ ) in a world-based frame of reference. This expected measurement, denoted  $^wA_e$  (where 'w' indicates that the measurements are in a world-coordinate frame of reference and 'e' indicates that the measurement is an expected value) is  
15                   provided to a first transformation unit 11 that calculates the expected measurement from the accelerometer 4 expressed in the sensor-fixed coordinate frame, based on the previous estimate  $Q$  of the orientation of the object. In other words, the first transformation unit 11 converts or rotates a vector  $G$  associated with gravity in a world-based reference frame to a frame of reference that is fixed relative to the object.

20                   Likewise, a second unit 12 provides an expected measurement for the magnetic field (vector  $M$ ) in a world-based frame of reference. As the magnetometer 6 will be measuring the strength and direction of the Earth's magnetic field, the expected measurement, denoted  $^wM_e$ , representing the Earth's magnetic field in a world-based frame of reference is provided to a second transformation unit 13 that calculates the expected  
25                   measurement from the magnetometer based on the previous estimate  $Q$  of the orientation of the object. Again, the second transformation unit 13 converts the vector  $M$  into the frame of reference that is fixed relative to the object.

                  A first adder 14 determines the difference between the actual measurement from the accelerometer 4 and the expected or estimated value from the first transformation  
30                   unit 11. A second adder 15 determines the difference between the actual measurement from the magnetometer 6 and the expected or estimated value from the second transformation unit 13. The combination of the outputs of the two adders 14, 15 form an error signal or vector which is denoted  $^s\varepsilon$ . The error vector  $^s\varepsilon$  is provided to a calculation block 16. As the error

vector  ${}^s\varepsilon$  includes three-dimensional elements for both the acceleration and magnetic field, it will be appreciated that it is a six-dimensional vector.

The calculation block 16 calculates a sensitivity matrix of the estimated orientation  $Q$  to the individual error signals in the vector  ${}^s\varepsilon$  by differentiating  ${}^s\varepsilon$  to the orientation  $Q$  and taking the inverse. The calculation block 16 then multiplies the error signals  ${}^s\varepsilon$  by the sensitivity matrix to obtain a correction signal  $\Delta Q$  for the orientation  $Q$ .

The correction value  $\Delta Q$  is weighted by a factor  $1/k$  (where  $k \gg 1$ ) in a first multiplier 18, before being provided to a first updater 20. The correction value  $\Delta Q$  is combined with the previous estimate of the orientation  $Q$  in the first updater 20 and the output of the updater 20 is provided to a second updater 22.

The system 2 further comprises a gyroscope 24 which provides measurements of the angular speed of the object. These measurements, denoted  ${}^sO_m$ , are sampled at frequency  $1/dt$ , and are multiplied by second multiplier 26 in order to allow for a correct integration of the angular velocity measurement with the angular orientation  $Q$ , before being combined with the output of the first updater 20 in the second updater 22. The resulting value for the orientation of the object  $Q$  is stored in the memory 8.

When the orientation estimate  $Q$  is represented as a quaternion, updater 22 is a multiplier, known as a quaternion multiplier. When rotation matrices are used to represent the orientation estimate  $Q$ , updater 22 is a multiplier, known as a matrix multiplier.

The process then repeats in an iterative loop.

Essentially, in the system shown in Fig. 1, the gyroscope 24 provides the main measurement used to determine the orientation of the object. However, as gyroscopes typically suffer from offset, which causes the orientation estimate to drift away from the true orientation (which for micro-electromechanical systems MEMS can be as large as several degrees per second), the accelerometer 4 and magnetometer 6 are provided to compensate for this offset.

The combination of the gyroscope, accelerometer and magnetometer means that the gyroscope can track fast rotations while the accelerometer and magnetometer guarantee the long-term stability of the system. The cross-over frequency between the gyroscope and accelerometer and magnetometer can be tuned by changing the gain factor  $k$ .

However, one problem with this type of orientation measurement system is that the estimated orientation of the object  $Q$  can be inaccurate if the sensors are disturbed or saturated. Therefore it is desirable to provide an orientation estimation algorithm that allows

for erroneous sensor signals to be discarded or ignored when disturbances or saturations occur.

## SUMMARY OF THE INVENTION

5           There is provided an object orientation measurement system for calculating an estimate of the orientation of an object to which the system can be attached, the system comprising measurement means for taking measurements of a plurality of parameters used in calculating an estimate of the orientation of the object; and processing means for comparing a measurement of at least one of the parameters with a first predetermined value; and  
10           calculating an estimate of the orientation of the object using the measurements of the plurality of parameters, wherein the weighting of the measurement of the at least one parameter is adjusted relative to the measurement of at least one other parameter based on the result of the comparison.

          There is also provided a method for calculating an estimate of the orientation  
15           of an object, the method comprising taking measurements of a plurality of parameters used in calculating an estimate of the orientation of the object; comparing a measurement of at least one of the parameters with a first predetermined value; and calculating an estimate of the orientation of the object using the measurements of the plurality of parameters, wherein the weighting of the measurement of the at least one parameter is adjusted relative to the  
20           measurement of at least one other parameter based on the result of the comparison.

          There is also provided an object orientation measurement system for calculating an estimate of the orientation of an object to which the system can be attached, the system comprising an accelerometer for measuring an acceleration of the object in a frame of reference that is fixed relative to the object; a magnetometer for measuring a  
25           magnetic field in the frame of reference that is fixed relative to the object; processing means for determining the azimuth angle of the magnetic field from the measurement of the magnetic field; and calculating an estimate of the orientation of the object using the measurement of the acceleration of the object and the azimuth angle of the magnetic field.

          There is also provided a method for calculating an estimate of the orientation  
30           of an object, the method comprising measuring an acceleration of the object in a frame of reference that is fixed relative to the object; measuring a magnetic field in the frame of reference that is fixed relative to the object; determining the azimuth angle of the magnetic field from the measurement of the magnetic field; and calculating an estimate of the

orientation of the object using the measurement of the acceleration of the object and the azimuth angle of the magnetic field.

## BRIEF DESCRIPTION OF THE DRAWINGS

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

Fig. 1 shows a conventional system for measuring the orientation of an object;

Fig. 2 shows a system for measuring the orientation of an object according to a first aspect of the invention;

Fig. 3 shows a system for measuring the orientation of an object according to a second aspect of the invention;

Fig. 4 shows a system for measuring the orientation of an object according to a third aspect of the invention;

Fig. 5 shows a system for measuring the orientation of an object according to a fourth aspect of the invention;

Fig. 6 shows a system for measuring the orientation of an object according to a fifth aspect of the invention; and

Fig. 7 shows a system for measuring the orientation of an object according to a sixth aspect of the invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A first way in which the orientation measurement algorithm can be improved is described with reference to Figs. 2 and 3.

It will be appreciated that the Earth's magnetic field not only has a component pointing along the Earth's surface to the magnetic north pole, but also a component that is perpendicular to the surface. The resulting magnetic field vector will form an angle with a plane parallel to the surface of the Earth that varies with position on the Earth's surface.

The magnetic field vector  $^wM_e$  that is stored in the second unit 12 is a constant (for a given position on the Earth). However, this constant takes a different value as the position on the Earth's surface varies, which is difficult to implement successfully in an orientation measurement system.

Therefore, in accordance with a first aspect of the invention, as shown in Fig. 2, the vertical component of the magnetic field (i.e. the component that is perpendicular to the Earth's surface) is omitted from the error signal  $^s\varepsilon$ . In Fig. 2, components of the system

30 that are common to the system 2 shown in Fig. 1 are given the same reference numeral, and operate in the same way, unless otherwise described below.

In particular, in system 30, the accelerometer 4 and magnetometer 6 are switched around with the first unit 10 and second unit 12 respectively. Consequently, the first and second transformation units 11, 13 act to convert the measurements of the acceleration and magnetic field from a frame of reference that is fixed relative to the object/sensor into a non-object based (i.e. world-fixed) frame of reference.

As the output of the adder block 15 is in a world-fixed frame of reference, the vertical component of the magnetic field can be excluded from the remainder of the calculation by filtering out the z-component of the vector. This function is performed by the filter block 32.

In addition, as the measurement from the gyroscope  ${}^sO_m$  is in the object-based frame of reference, it is necessary to provide a third transformation unit 34 for converting the gyroscopic measurement into the world-based frame of reference.

Fig. 3 shows a second aspect of the invention in which the vertical component of the magnetic field is omitted from the error signal  ${}^s\varepsilon$ . Again, components of the system in Fig. 3 that are common to the system 2 shown in Fig. 1 are given the same reference numeral, and operate in the same way, unless otherwise described below.

It is known that the vector product of two vectors yields a vector that is perpendicular to the two vectors. Therefore, the vector product of the Earth's magnetic field  ${}^wM_e$  with the gravitational vector  ${}^wA_e$  will give a vector that is perpendicular to both vectors (i.e. a vector that points East-West).

Therefore, in system 40, a first vector product block 42 is provided between the second unit 12 and second transformation unit 13. This block 42 generates the vector product of the magnetic field estimate  ${}^wM_e$  and the gravitational vector  ${}^wA_e$ . Likewise, a second vector product block 44 is provided between the magnetometer 6 and the second adder 15, which generate the vector product of the measured magnetic field and the acceleration measured by the accelerometer 4. Thus, the second adder 15 now calculates the difference between the vector product from the first vector product block 42 (after transformation into an object-based frame of reference) and the second vector product block 44.

Thus, it will be appreciated that these two aspects of the invention describe how the azimuth angle of the magnetic field can be obtained using only measurements in the sensor coordinate frame.

Further aspects of the invention will now be described with reference to Figs. 4, 5 and 6. Components of the systems shown in the Figures that are common to the system 2 shown in Fig. 1 are given the same reference numeral, and operate in the same way, unless otherwise described below.

In particular, in these aspects of the invention, it is recognised that the measurements from the accelerometer, magnetometer and/or gyroscope can be unreliable in certain situations, and the invention provides that when one of these situations is detected, the relative influence of that measurement on the orientation estimate can be reduced.

For example, a problem with using the Earth's magnetic field for orientation estimation (and in particular the heading) is that magnetic disturbances in the environment local to the magnetometer can affect the measurements. Such disturbances can, for example, occur inside buildings as a result of steel bars in the structure. Some of the disturbances only cause a significant change to the vertical component of the magnetic field, which means that these disturbances can be overcome by utilising the invention shown in the first and second aspects above. However, some disturbances cause significant variations in the magnetic field in the horizontal plane (for example those caused by steel furniture).

In accordance with the third aspect of the invention, the magnitude of the magnetic field vector measured by the magnetometer 6 is examined to determine if the signal from the magnetometer 6 is unreliable, i.e. it is varying significantly from the vector expected for the magnetic field. In particular, if the magnitude of the magnetic field measured by the magnetometer 6 is much larger or smaller than that expected from the Earth's magnetic field (as given by the magnitude of  $^wM_e$  in the second unit 12), the weighting of the measurements of the magnetometer 6 in the error signal  $^s\varepsilon$  relative to the measurements of the acceleration by the accelerometer 4 can be reduced.

The system 50 in Fig. 4 illustrates how this can be implemented in the system 2 of Fig. 1. In system 50, a first gain unit 52 is provided between the first adder 14 and the calculation block 16. The gain of the first gain unit 52 is given by a parameter  $k_A$ . In this illustrated embodiment, unit 52 is a fixed gain unit and the parameter  $k_A$  is a constant.

A second gain unit 54 is provided between the second adder 15 and the calculation block 16. In this illustrated embodiment, the unit 54 is a variable gain unit, which varies its gain in response to a control parameter  $k_M$ .

This control parameter  $k_M$  is derived by an arithmetic block 56 that receives the magnetic field vector  $^wM_e$  from the second unit 12 and the measured magnetic field vector  $^sM_m$  from the magnetometer 6. The arithmetic block 56 calculates the magnitude of

each vector, and compares the two values. If the values are not equal (i.e.  $|^wM_e| \neq |^sM_m|$ ), or if the values differ by more than a predetermined amount (i.e.  $|^wM_e| - |^sM_m| > |C_1|$ ), then the arithmetic block 56 can output an appropriate value for the control parameter  $k_M$ , so that the weighting of the magnetic field measurement in the error signal  $^s\varepsilon$  is reduced. If the values are equal or differ by less than the predetermined amount, then the arithmetic block 56 will output a value for the control parameter  $k_M$  that gives equal weighting to the magnetic field and acceleration measurements in the error signal  $^s\varepsilon$ .

In further embodiments, it will be appreciated that the control parameter  $k_M$  can be varied continuously or by discrete amounts based on the results of the comparison of the two values. It will also be appreciated that the fixed gain unit 52 can be omitted if the gain value for that unit is 1.

Furthermore, this aspect of the invention can alternatively be implemented by increasing the weighting of the acceleration measurements in the error signal  $^s\varepsilon$ , rather than by decreasing the weighting of the magnetometer measurements. In this case, the first gain unit 52 will be a variable gain unit, and the second gain unit 54 can be a fixed gain unit. In a further embodiment, both gain units 52, 54 can be variable gain units, with the arithmetic block 56 controlling the gain of each unit 52, 54 so that the relative weighting of the magnetic field and acceleration measurements is adjusted appropriately.

Another problem with the system in Fig. 1 is that large linear and angular accelerations (for example caused by acceleration or deceleration in a car or in an elevator) will result in the measured acceleration  $^sA_m$  having both a gravitational component and components due to the linear and angular acceleration of the sensor.

In accordance with the fourth aspect of the invention, the magnitude of the acceleration vector measured by the accelerometer 4 is examined to determine if the signal from the accelerometer 4 is unreliable, i.e. it is varying significantly from the vector expected for acceleration due to gravity on the sensor. In particular, if the magnitude of the acceleration measured by the accelerometer 4 is much larger or smaller than that expected from gravity (as given by the magnitude of  $^wA_e$  in the first unit 10), the weighting of the measurements of the accelerometer 4 in the error signal  $^s\varepsilon$  relative to the measurements of the magnetic field by the magnetometer 6 can be reduced.

The system 60 in Fig. 5 illustrates how this can be implemented in the system 2 of Fig. 1. In system 60, a first gain unit 62 is provided between the first adder 14 and the calculation block 16. In this illustrated embodiment, the unit 62 is a variable gain unit, which varies its gain in response to a control parameter  $k_A$ .

A second gain unit 64 is provided between the second adder 15 and the calculation block 16. In this illustrated embodiment, unit 64 is a fixed gain unit and the parameter  $k_M$  is a constant.

The control parameter  $k_A$  is derived by an arithmetic block 66 that receives the  
 5 gravitational acceleration vector  ${}^wA_e$  from the first unit 10 and the measured acceleration  
 vector  ${}^sA_m$  from the accelerometer 4. The arithmetic block 66 calculates the magnitude of  
 each vector, and compares the two values. If the values are not equal (i.e.  $|{}^wA_e| \neq |{}^sA_m|$ ), or  
 if the values differ by more than a predetermined amount (i.e.  $|{}^wA_e| - |{}^sA_m| > |C_2|$ ), then  
 the arithmetic block 66 can output an appropriate value for the control parameter  $k_A$ , so that  
 10 the weighting of the acceleration measurement in the error signal  ${}^s\varepsilon$  is reduced. If the values  
 are equal or differ by less than the predetermined amount, then the arithmetic block 66 will  
 output a value for the control parameter  $k_A$  that gives equal weighting to the magnetic field  
 and acceleration measurements in the error signal  ${}^s\varepsilon$ .

In further embodiments, it will be appreciated that the control parameter  $k_A$   
 15 can be varied continuously or by discrete amounts based on the results of the comparison of  
 the two values. It will also be appreciated that the fixed gain unit 64 can be omitted if the  
 gain value for that unit is 1.

Furthermore, this aspect of the invention can alternatively be implemented by  
 increasing the weighting of the magnetic field measurements in the error signal  ${}^s\varepsilon$ , rather than  
 20 by decreasing the weighting of the acceleration measurements. In this case, the second gain  
 unit 64 will be a variable gain unit, and the first gain unit 62 can be a fixed gain unit. In a  
 further embodiment, both gain units 62, 64 can be variable gain units, with the arithmetic  
 block 66 controlling the gain of each unit 62, 64 so that the relative weighting of the  
 magnetic field and acceleration measurements is adjusted appropriately.

25 A further problem with the system in Fig. 1 is that the acceleration measured  
 by the accelerometer 4 can also include centrifugal components if the sensor is rotating.  
 Again, this will result in the measured acceleration  ${}^sA_m$  having both a gravitational  
 component and components due to the centrifugal force on the sensor.

In accordance with the fifth aspect of the invention, the measurements of the  
 30 angular speed by the gyroscope 24 are examined to determine if the object is experiencing  
 rotation (i.e. the angular speed measurements are non-zero or substantially above zero), and if  
 so, the weighting of the measurements of the accelerometer 4 in the error signal  ${}^s\varepsilon$  relative to  
 the measurements of the magnetic field by the magnetometer 6 can be reduced.

The system 70 in Fig. 6 illustrates how this can be implemented in the system 2 of Fig. 1. In system 70, a first gain unit 72 is provided between the first adder 14 and the calculation block 16. In this illustrated embodiment, the unit 72 is a variable gain unit, which varies its gain in response to a control parameter  $k_A$ .

5 A second gain unit 74 is provided between the second adder 15 and the calculation block 16. In this illustrated embodiment, unit 74 is a fixed gain unit and the parameter  $k_M$  is a constant.

The control parameter  $k_A$  is derived by an arithmetic block 76 that receives the angular speed measurements  ${}^sO_m$  from the gyroscope 24 and determines whether the angular speed is greater than zero, or greater than zero by more than a predetermined amount. If the angular speed is greater than zero, then the arithmetic block 76 can output an appropriate value for the control parameter  $k_A$ , so that the weighting of the acceleration measurement in the error signal  ${}^s\varepsilon$  is reduced. If the angular speed measurement is zero, then the arithmetic block 76 will output a value for the control parameter  $k_A$  that gives equal weighting to the magnetic field and acceleration measurements in the error signal  ${}^s\varepsilon$ .

In further embodiments, it will be appreciated that the control parameter  $k_A$  can be varied continuously or by discrete amounts based on the magnitude of the angular speed. It will also be appreciated that the fixed gain unit 74 can be omitted if the gain value for that unit is 1.

20 Furthermore, this aspect of the invention can alternatively be implemented by increasing the weighting of the magnetic field measurements in the error signal  ${}^s\varepsilon$ , rather than by decreasing the weighting of the acceleration measurements. In this case, the second gain unit 74 will be a variable gain unit, and the first gain unit 72 can be a fixed gain unit. In a further embodiment, both gain units 72, 74 can be variable gain units, with the arithmetic block 76 controlling the gain of each unit 72, 74 so that the relative weighting of the magnetic field and acceleration measurements is adjusted appropriately.

25 In a further embodiment of the invention, the magnitude of the angular speed measurements in the x-, y- and z- directions can be considered individually. In particular, the magnitude of the angular speed measurement in the x-direction (given by  ${}^s_xO_m$ ) can be used to control the weighting of the accelerometer measurements in the y- and z-directions, since rotation around the x-axis does not generate centrifugal forces in the x-direction. Similarly, the magnitude of the angular speed measurement in the y-direction can be used to control the weighting of the accelerometer measurements in the x- and z- directions, and the magnitude of the angular speed measurement in the z-direction can be used to control the weighting of

the accelerometer measurements in the x- and y-directions. Of course, to implement this embodiment, it will be necessary for the variable gain unit 72 to receive separate control signals for each of the x-, y- and z-directions of the accelerometer measurements.

Yet another problem with the system in Fig. 1 is that when the angular speed of the object is higher than a predefined value, the output of the gyroscope 24 becomes clipped or saturated, since the gyroscope 24 has a limited measurement range. Consequently, the integration loop around the gyroscope 24 (comprising components 20, 22 and 26 in Fig. 1) quickly drifts away from the correct orientation. Only when the rotation (angular) speed is reduced, can the slow feedback loop including the accelerometer 4 and magnetometer 6 bring the orientation estimate Q back towards the actual orientation.

Therefore, in accordance with a sixth aspect of the invention, the measurements of the angular speed by the gyroscope 24 are examined to determine if the object is experiencing rotation speeds that are close to or above the saturation point of the gyroscope 24. If the speeds are close to or above the saturation point of the gyroscope 24, the weighting of the measurements of both the accelerometer 4 and the magnetometer 6 can be increased.

The system 80 in Fig. 7 illustrates how this can be implemented in the system 2 of Fig. 1. In system 80, a first gain unit 82 is provided between the first adder 14 and the calculation block 16. In this illustrated embodiment, the unit 82 is a fixed gain unit, with the gain being specified by a constant parameter  $k_A$ .

A second gain unit 84 is provided between the second adder 15 and the calculation block 16. In this illustrated embodiment, unit 84 is also a fixed gain unit and the parameter  $k_M$  is a constant.

In order to control the weighting of the measurements of both the accelerometer 4 and the magnetometer 6, the first multiplier 18 in Fig. 1 is replaced by a third gain unit 86. In this illustrated embodiment, the third gain unit 86 is a variable gain unit, with the gain being specified by a control parameter k.

The control parameter k is derived by an arithmetic block 88 that receives the angular speed measurements  $\omega_m$  from the gyroscope 24 and determines whether the angular speed is greater than a maximum value. If the angular speed is equal to or greater than the maximum value, then the arithmetic block 88 can output an appropriate value for the control parameter k, so that the weighting of the acceleration and magnetometer measurements is increased (i.e. k is reduced to increase the weighting). If the angular speed measurement is below the maximum value, then the arithmetic block 88 will output a value for the control

parameter k that gives a normal weighting to the magnetic field and acceleration measurements.

In further embodiments, it will be appreciated that the control parameter k can be varied continuously or by discrete amounts based on the proximity of the angular speed to the maximum value. It will also be appreciated that the fixed gain units 82 and 84 can be omitted if the gain value for those units is 1.

Furthermore, this aspect of the invention can alternatively be implemented by increasing the weighting of both the acceleration and magnetic field measurements using the gain units 82 and 84, rather than using a third gain unit 86. In this case, the first and second gain units 82, 84 will be variable gain units, and the third gain unit 86 can be a fixed gain unit. In a further embodiment, each gain unit 82, 84, 86 can be a variable gain unit, with the arithmetic block 88 controlling the gain of each unit 82, 84, 86 so that the weighting of the magnetic field and acceleration measurements is adjusted appropriately.

In addition, although each of the above aspects of the invention have been described and illustrated separately, it will be appreciated that any two or more of the aspects can be combined into a single apparatus. For example, it will be appreciated that an apparatus comprising means for implementing each of the third, fourth, fifth and sixth aspects of the invention would provide significant improvements in the orientation estimate over the prior art apparatus in Fig. 1.

Finally, it will be appreciated that any of the above aspects of the invention shown in Figs. 2, 3, 4 and 5 can be implemented in an orientation estimation system that does not include a gyroscope (i.e. systems in which blocks 22, 24 and 26 are omitted).

Although the invention has been described primarily in terms of hardware, it will be appreciated that one or more components of the systems can be readily implemented in software.

There is therefore described a system and method for improving the determination of the orientation of an object.

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 fulfill 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 measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope. A computer

5 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.

## CLAIMS:

1. An object orientation measurement system for calculating an estimate of the orientation of an object to which the system can be attached, the system comprising:

- measurement means for taking measurements of a plurality of parameters used in calculating an estimate of the orientation of the object; and

5 processing means for:

- comparing a measurement of at least one of the parameters with a first predetermined value; and

- calculating an estimate of the orientation of the object using the measurements of the plurality of parameters, wherein the weighting of the measurement of the at least one  
10 parameter is adjusted relative to the measurement of at least one other parameter based on the result of the comparison.

2. The object orientation measurement system of claim 1, wherein the plurality of parameters comprises an acceleration of the object to which the system can be attached.

3. The object orientation measurement system of claim 2, wherein the measurement means comprises an accelerometer.

4. The object orientation measurement system of claim 2 or 3, wherein the  
20 plurality of parameters further comprises a measurement of a magnetic field.

5. The object orientation measurement system of claim 4, wherein the measurement means comprises a magnetometer.

25 6. The object orientation measurement system of claim 4 or 5, wherein the first predetermined value is a value for the acceleration as a result of gravity, and the processing means is adapted to compare the measurement of the acceleration of the object to the value for the acceleration as a result of gravity.

7. The object orientation measurement system of claim 6, wherein the processing means is adapted to compare the magnitude of the measured acceleration of the object to the magnitude of the acceleration as a result of gravity.

5 8. The object orientation measurement system of claim 6 or 7, wherein the processing means is adapted to adjust the weighting of the measurement of the acceleration relative to the measurement of the magnetic field based on the result of the comparison.

9. The object orientation measurement system of claim 8, wherein the processing  
10 means is adapted to adjust the weighting of the measurement of the acceleration relative to the measurement of the magnetic field in the event that the measurement of the acceleration of the object differs from the value for the acceleration as a result of gravity by more than a predetermined amount.

15 10. The object orientation measurement system of claim 9, wherein the processing means is adapted to reduce the weighting of the measurement of the acceleration relative to the measurement of the magnetic field.

11. The object orientation measurement system in claim 4 or 5, wherein the first  
20 predetermined value is a value for the magnetic field of the Earth, and the processing means is adapted to compare the measurement of the magnetic field to the value for the magnetic field of the Earth.

12. The object orientation measurement system of claim 11, wherein the  
25 processing means is adapted to compare the magnitude of the measured magnetic field to the magnitude of the magnetic field of the Earth.

13. The object orientation measurement system of claim 11 or 12, wherein the  
30 processing means is adapted to adjust the weighting of the measurement of the acceleration relative to the measurement of the magnetic field based on the result of the comparison.

14. The object orientation measurement system of claim 13, wherein the processing means is adapted to adjust the weighting of the measurement of the acceleration relative to the measurement of the magnetic field in the event that the measurement of the

magnetic field differs from the value for the magnetic field of the Earth by more than a predetermined amount.

15. The object orientation measurement system of claim 14, wherein the  
5 processing means is adapted to reduce the weighting of the measurement of the magnetic field relative to the measurement of the acceleration.

16. The object orientation measurement system of claim 4 or 5, wherein the  
10 plurality of parameters comprises an angular speed of the object to which the system can be attached.

17. The object orientation measurement system of claim 16, wherein the measurement means comprises a gyroscope.

15 18. The object orientation measurement system of claim 16 or 17, wherein the processing means is adapted to compare the measurement of the angular speed of the object to the first predetermined value.

19. The object orientation measurement system of claim 18, wherein the first  
20 predetermined value is zero.

20. The object orientation measurement system of claim 18 or 19, wherein the processing means is adapted to adjust the weighting of the measurement of the acceleration relative to the measurement of the magnetic field based on the result of the comparison.

25 21. The object orientation measurement system of claim 20, wherein the processing means is adapted to adjust the weighting of the measurement of the acceleration relative to the measurement of the magnetic field in the event that the measurement of the angular speed of the object differs from zero by more than a predetermined amount.

30 22. The object orientation measurement system of claim 21, wherein the processing means is adapted to reduce the weighting of the measurement of the acceleration relative to the measurement of the magnetic field.

23. The object orientation measurement system of claim 16 or 17, wherein the first predetermined value is a maximum permitted value for the angular speed of the object, and the processing means is adapted to compare the measurement of the angular speed of the object to the maximum permitted value.

5

24. The object orientation measurement system of claim 23, wherein the processing means is adapted to adjust the weighting of the measurement of the acceleration and the measurement of the magnetic field relative to the measurement of the angular speed based on the result of the comparison.

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25. The object orientation measurement system of claim 24, wherein the processing means is adapted to adjust the weighting of the measurement of the acceleration and the measurement of the magnetic field relative to the measurement of the angular speed in the event that the measurement of the angular speed of the object is close to or higher than the maximum permitted value.

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26. The object orientation measurement system of claim 25, wherein the processing means is adapted to increase the weighting of the measurement of the acceleration and measurement of the magnetic field relative to the measurement of the angular speed.

20

27. A method for calculating an estimate of the orientation of an object, the method comprising:

- taking measurements of a plurality of parameters used in calculating an estimate of the orientation of the object;

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- comparing a measurement of at least one of the parameters with a first predetermined value; and

- calculating an estimate of the orientation of the object using the measurements of the plurality of parameters, wherein the weighting of the measurement of the at least one parameter is adjusted relative to the measurement of at least one other parameter based on the result of the comparison.

30

28. An object orientation measurement system for calculating an estimate of the orientation of an object to which the system can be attached, the system comprising:

- an accelerometer for measuring an acceleration of the object in a frame of reference that is fixed relative to the object;
- a magnetometer for measuring a magnetic field in the frame of reference that is fixed relative to the object;

5                    processing means for:

- determining the azimuth angle of the magnetic field from the measurement of the magnetic field; and
- calculating an estimate of the orientation of the object using the measurement of the acceleration of the object and the azimuth angle of the magnetic field.

10

29.                The object orientation measurement system of claim 28, wherein the processing means is adapted to rotate the measurement of the magnetic field into a world-based frame of reference using a previous estimate of the orientation of the object.

15

30.                The object orientation measurement system of claim 29, wherein the processing means is further adapted to remove the vertical component from the rotated measurement of the magnetic field in order to determine the azimuth angle of the magnetic field.

20

31.                The object orientation measurement system of claim 29, wherein the processing means is adapted to combine the rotated measurement of the magnetic field with an estimate of the measurement of the magnetic field, wherein the estimate is in the world-based frame of reference.

25

32.                The object orientation measurement system of claim 31, wherein the processing means is further adapted to remove the vertical component from the combination in order to determine the azimuth angle of the magnetic field.

30

33.                The object orientation measurement system of claim 28, wherein the processing means calculates a vector product of the measurement of the magnetic field and the measurement of the acceleration of the object.

34. The object orientation measurement system of claim 33, wherein the processing means calculates a vector product of an estimate for the acceleration of the object as a result of gravity and an estimate of the measurement of the magnetic field.

35. The object orientation measurement system of claim 34, wherein the processing means is adapted to rotate the result of the vector product of the estimate for the acceleration of the object as a result of gravity and the estimate of the measurement of the magnetic field into the frame of reference that is fixed relative to the object using a previous estimate of the orientation of the object.

36. The object orientation measurement system of claim 35, wherein the processing means is adapted to determine the azimuth angle of the magnetic field by combining the result of the vector product of the measurement of the magnetic field and the measurement of the acceleration of the object and the rotated result of the vector product of the estimate for the acceleration of the object as a result of gravity and the estimate of the measurement of the magnetic field.

37. A method for calculating an estimate of the orientation of an object, the method comprising:

- measuring an acceleration of the object in a frame of reference that is fixed relative to the object;
- measuring a magnetic field in the frame of reference that is fixed relative to the object;
- determining the azimuth angle of the magnetic field from the measurement of the magnetic field; and
- calculating an estimate of the orientation of the object using the measurement of the acceleration of the object and the azimuth angle of the magnetic field.

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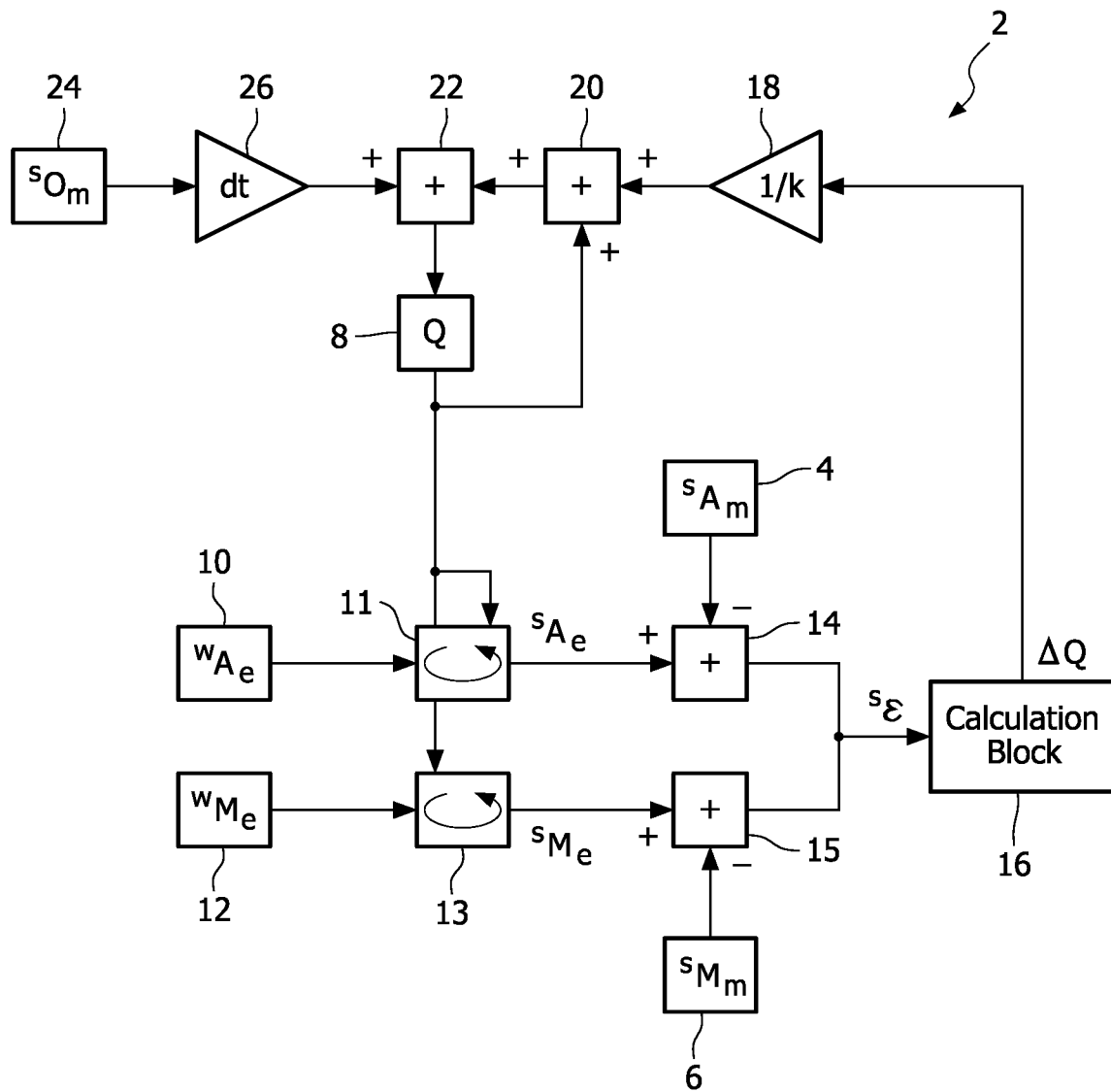


FIG. 1

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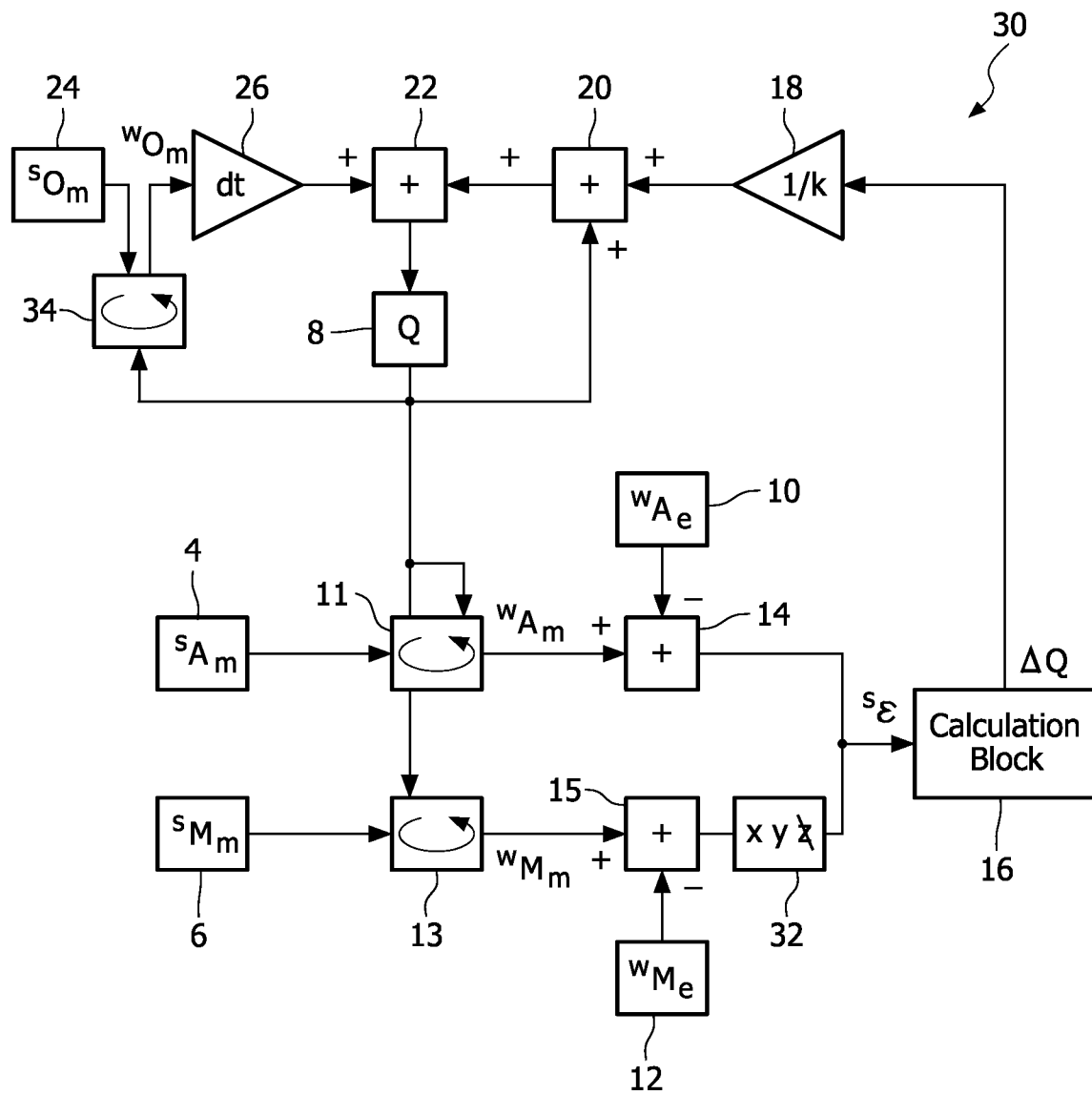


FIG. 2

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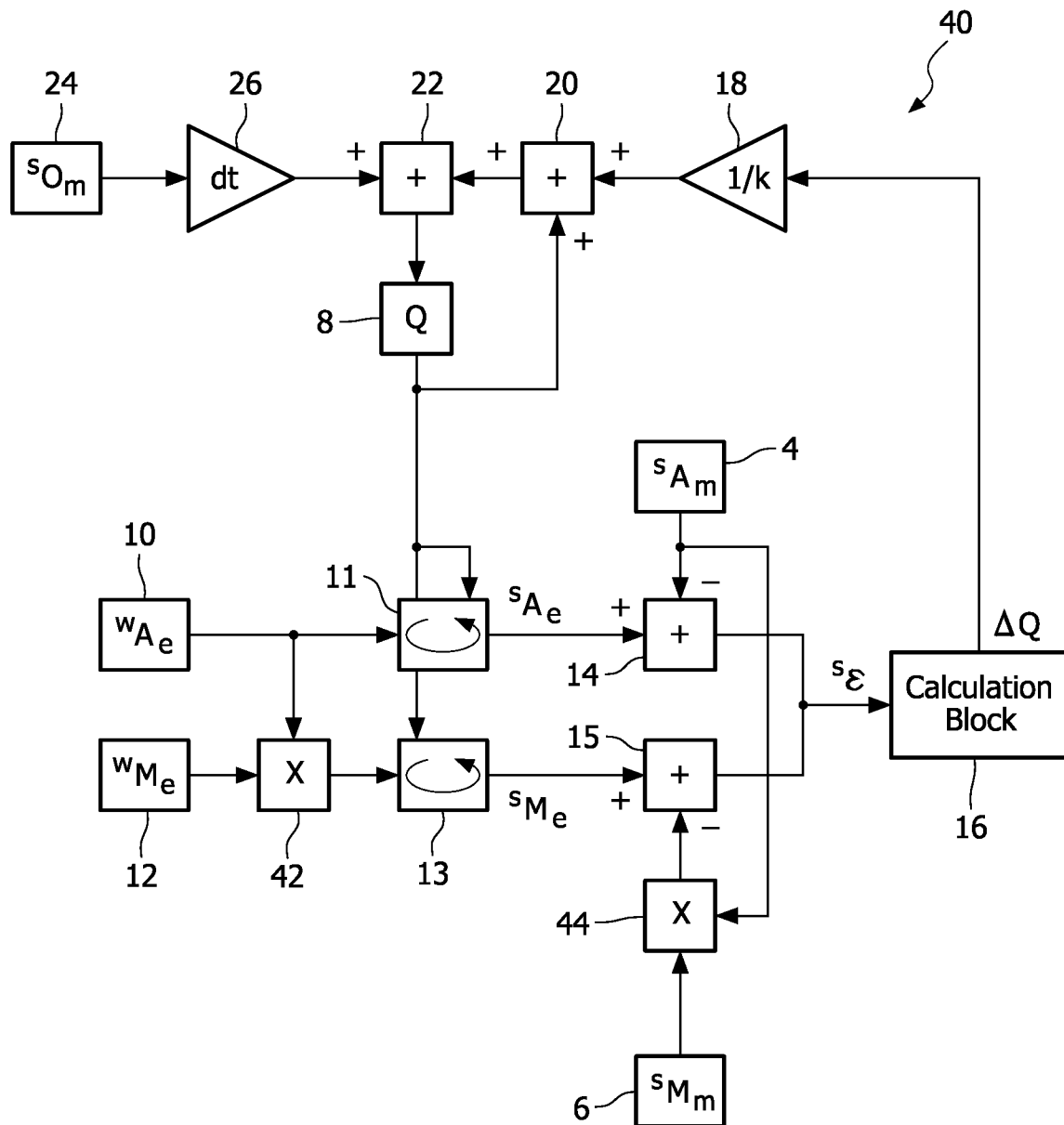


FIG. 3

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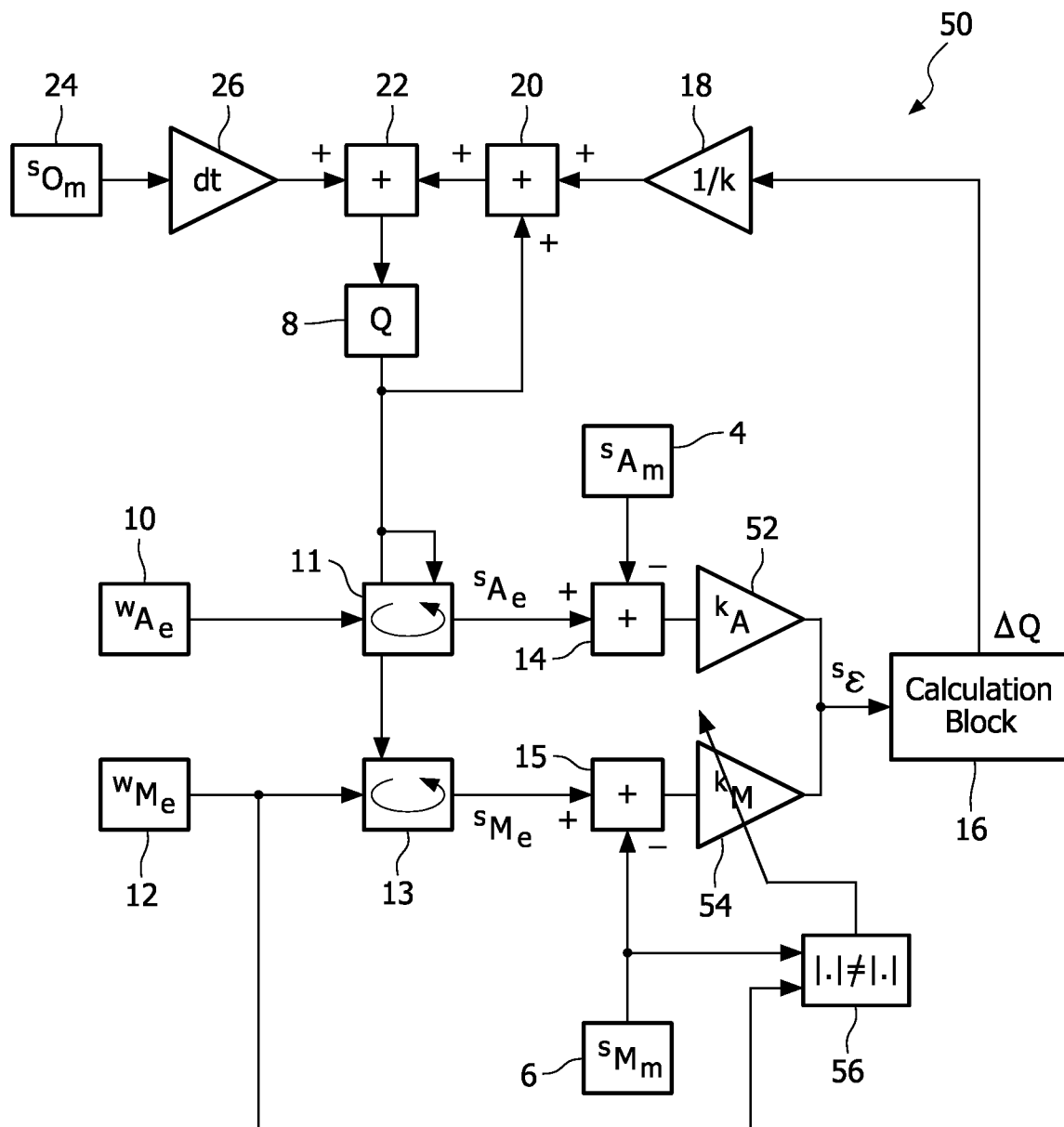


FIG. 4

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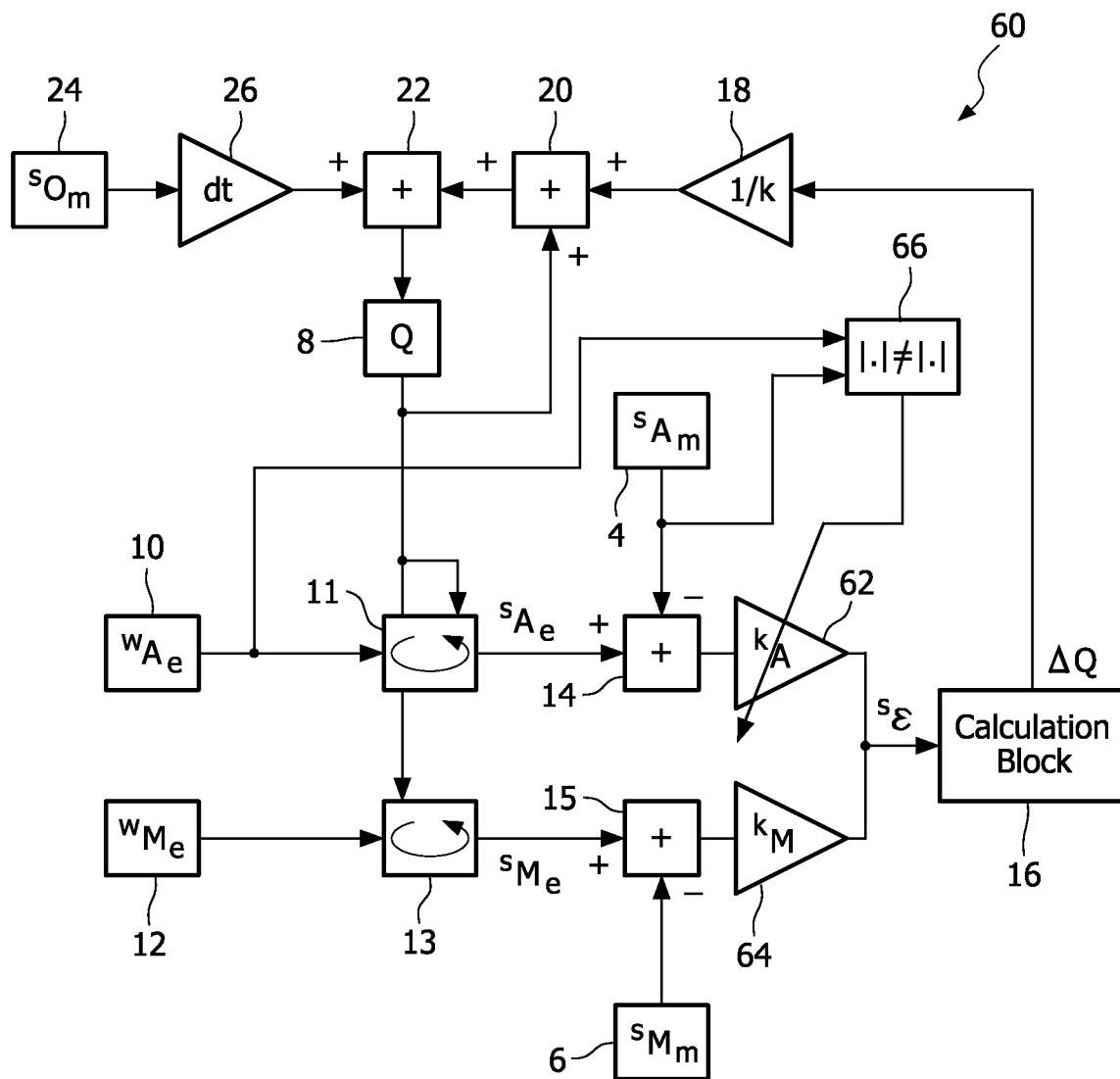


FIG. 5

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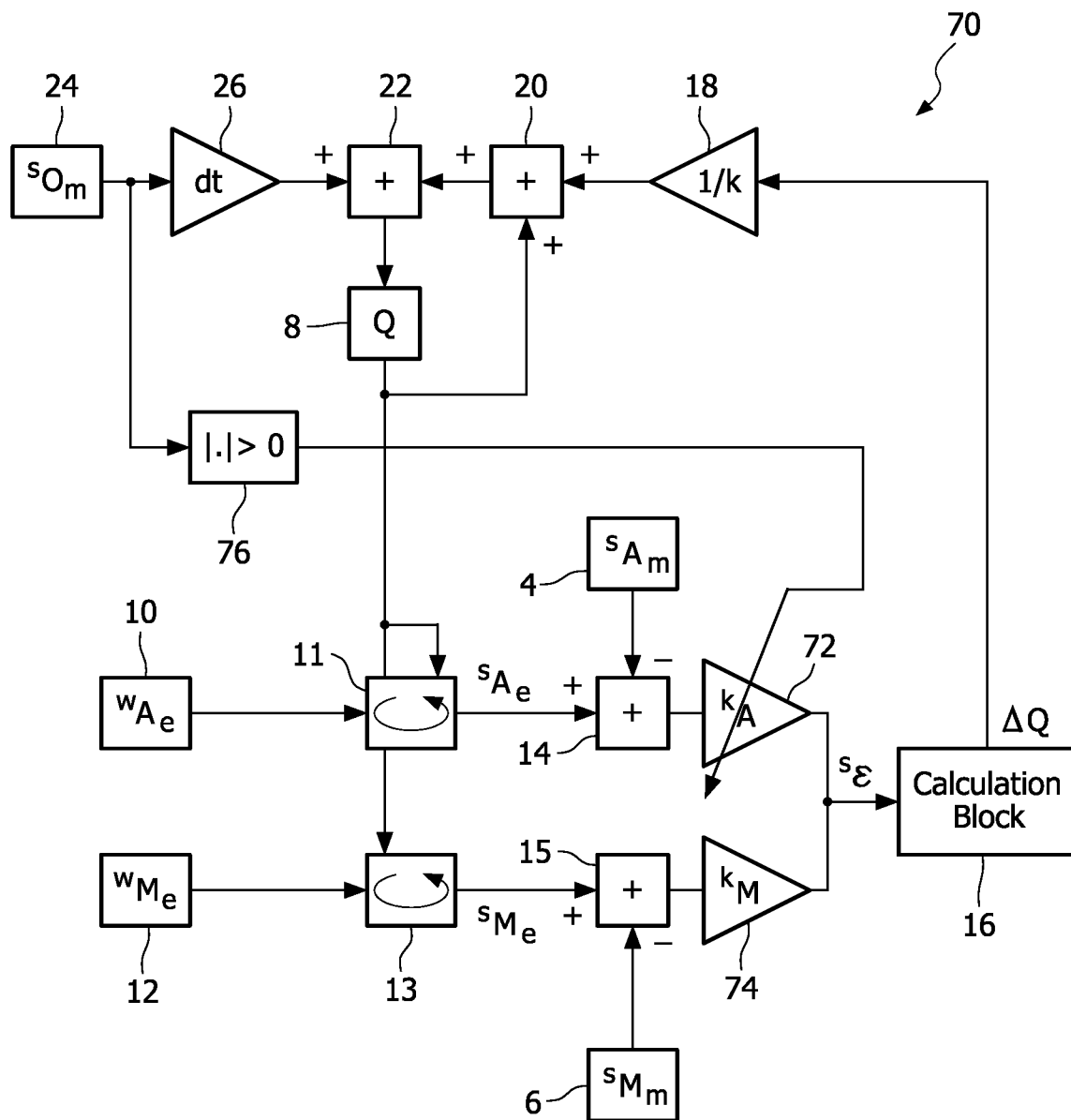


FIG. 6

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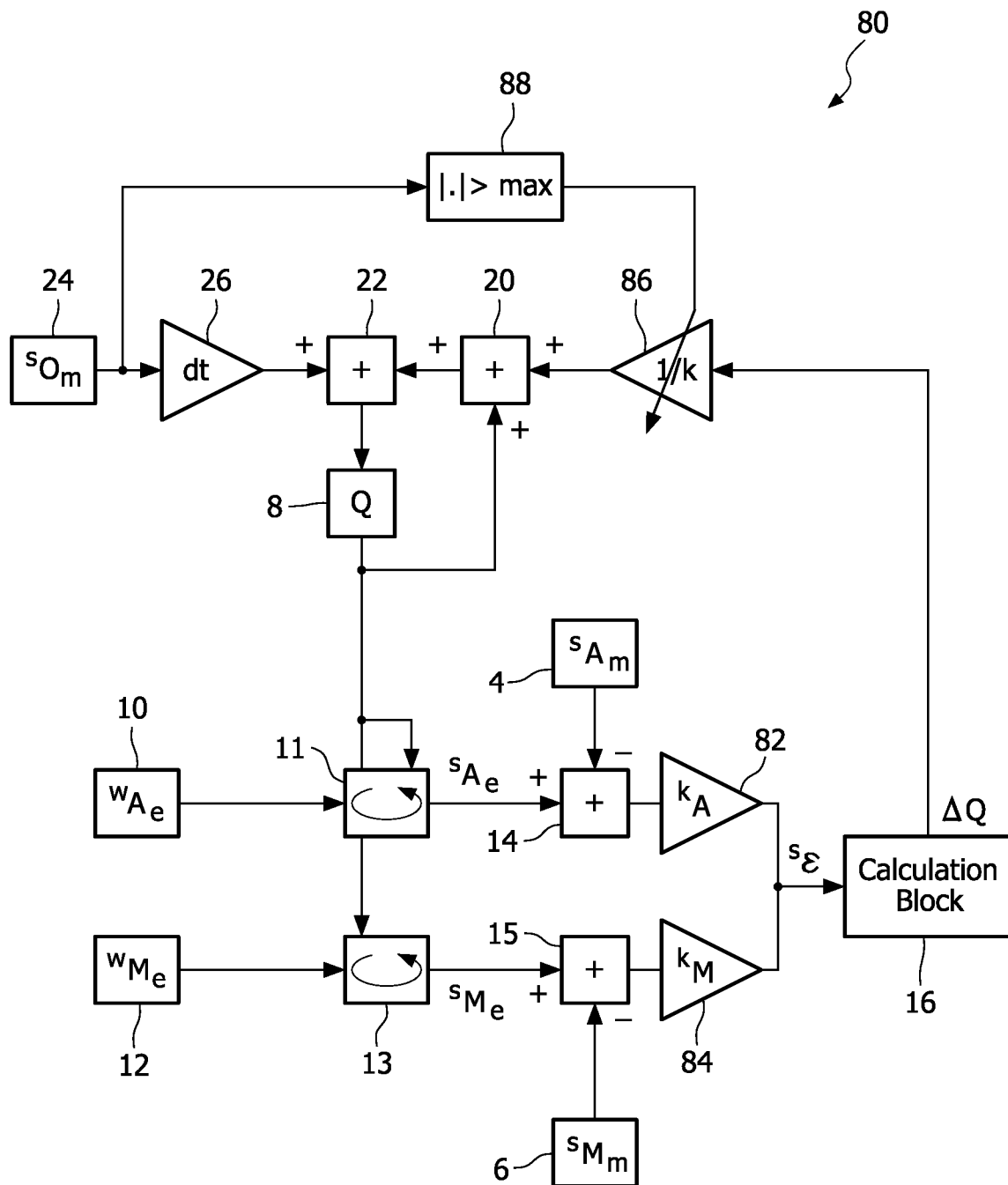


FIG. 7