Body position can be monitored in 3D using miniature accelerometers and earth-magnetic field sensors

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Abstract

Objectives: The study and diagnosis of movement disorders can be improved by monitoring body position simultaneously with the EMG.

Methods: We developed a monitor of the 3-dimensional (3D) orientation of body parts that can be applied in long-term ambulatory recordings in the daily life of a patient. The 3D sensor combines miniature sensors for earth’s gravity and magnetism. It measures $60 \times 50 \times 10 \text{ mm}$ and draws less than 1 mA of current from ±5 V battery power. The non-horizontal direction of earth magnetism, as well as torque (pronation) of the body part, is corrected mathematically.

Results: This results in a measurement of the 3D orientation of a body part in terms of vertical inclination and horizontal azimuth.

Conclusions: Calibration measurements indicate that this method is fairly accurate and practically applicable. © 1998 Elsevier Science Ireland Ltd. All rights reserved

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1. Introduction

The physiological control of movement and body position is often monitored using EMG. EMG is closely related to the controlling muscle forces. However, gravity, also, can strongly affect movement, mainly depending on the vertical inclination of the involved body parts (Savelsbergh and Van der Kamp, 1994; Moon and Canady, 1995; Brown et al., 1996; Häger-Ross et al., 1996; Kemp et al., 1997). Also, EMG does not indicate what the body positions actually are. For both reasons, it is preferable to monitor the orientations of body limbs simultaneously with the EMG (Queissner et al., 1994). This is not possible in long-term, ambulatory recordings in the daily life of a patient, which strongly limits the diagnosis of movement disorders (Boose et al., 1996).

A few years ago, miniature DC-accelerometers became available which measure acceleration forces including earth gravity. These sensors can monitor the vertical inclination of body parts (Veltink and Van Lummel, 1994) in ambulatory studies. But even 3-dimensional (3D) set-ups (Bouten et al., 1997) cannot measure the horizontal component of orientation. For that purpose, a horizontally-sensing principle is required.

Recently, miniature electronic compass sensors have become available that can measure orientation relative to the magnetic-North direction. The horizontal component of this direction, in combination with the vertically sensitive accelerometers, in principle enables 3D monitoring of orientation.

We intend to apply this principle in long-term (24 h) continuous monitoring of the orientation of body limbs, in order to assess movement disorders. The present work aimed to find sensors, develop mechanics and electronics for a 3D combined sensor, and derive the mathematics that actually combine the two sensing principles. We describe here the technical principles, the actual 3D sensor, and some preliminary measurements.

2. Methods

2.1. The orientation sensor

The ICS3031-002 from ICSensors is a miniature
(8 × 8 × 2 mm) resistive DC accelerometer. It senses acceleration forces caused by both movements and gravity. When movement acceleration is small, it measures the gravity component that is perpendicular to the sensor. In this case, the measured acceleration reflects the vertical inclination of the sensor.

The NV55B15S from Nonvolatile Electronics is a miniature (5 × 7 × 2 mm) giant magnetoresistive ratio sensor. By keeping magnets and large iron objects at a distance of at least 1 m, it senses almost exclusively the earth-magnetic field. In that case, it measures the earth-magnetic-field component that is in line with the sensor. Therefore, the measured magnetic field reflects the direction of the sensor relative to the direction of the magnetic North pole.

We designed a 3D orientation sensor using a combination of accelerometer and magnetic sensors, both types in a 3D construction (Fig. 1, upper right). So, the orientation sensor contains 2 × 3 = 6 sensor chips and some electronics. Each of the 6 sensor signals is digitized and sent to a PC through a battery-operated, body-worn telemetry system (Kemp et al., 1994). This system also accommodates four EMG channels.

2.2. Computing inclination and azimuth

Fig. 1 (upper left) shows how the orientation of a body part (the bold bar) is defined by its vertical inclination, I, and its horizontal azimuth, A.

The accelerometers, a, as well as the magnetic-field sensors, m, are mounted perpendicular to each other (Fig. 1, upper right chart). Their digital signal amplitudes are normalized in a calibration procedure, in such a way that an output value equals 1 when the sensor measures the full gravity or magnetic field, respectively. Therefore, the equations:

\[ a_0^2 + a_1^2 + a_2^2 = 1 \]  
\[ m_0^2 + m_1^2 + m_2^2 = 1 \]

must be true when these are the only fields present. As a consequence, these equations can be used to detect additional (movement) accelerations or additional magnetic fields.

The 3D set-ups of both sensor types provide a 3D vector measurement of the directions of both gravity and magnetic field. The vertical inclination, I, can be directly derived from the a0 sensor as follows:

Fig. 1. Four charts illustrating computation of 3D orientation. Upper left chart: earth’s gravity, g, and magnetism, B, define the downward direction, Down, and the horizontal projection, N’, of the magnetic North. Based on these, the 3D orientation of a body part (the straight bar inside the globe), can be defined by its inclination, I, and azimuth, A. Inclination ranges from -90° (upward) to 90° (downward). Azimuth ranges from 0° (N’, the direction of the horizontally projected magnetic North) through East, South and West back to N’ (360° = 0°). The chart also shows the inclination of earth magnetism (67° in the Netherlands). Upper right chart: schematic position of the accelerometers (a0, a1 and a2) and magnetic-field sensors (m0, m1 and m2) on this body part. Magnetic field components B1, Bhp and Bzp that are in line with and perpendicular to the axis of the body part. Lower left chart: transformation of B1 and Bzp into horizontal and vertical components, Bhr and Bd, respectively. Lower right chart: the horizontal circle seen from above with Bhr and Bhp determining azimuth. Bh is the horizontal component of the magnetic field.
a0 = \sin(I), or equivalently: I = \arcsine(a0) \quad (3)

The magnetic measurements are not referenced to the horizontal plane, for two reasons. Firstly, the magnetic field is not horizontal. For instance in the Netherlands, its inclination angle is 67° (if no magnetically active materials are nearby). Secondly, b1 and b2 are also affected by torque of the body limb around its own length axis (like for instance in pronating and supinating the lower arm). Still, the horizontal azimuth can be obtained from these measurements as follows.

First, the magnetic field is decomposed into three orthogonal components, one in line with the body part and the other two perpendicular to this in-line component. The in-line component (Bl in Fig. 1, upper right) is simply:

$$B_l = -m_0 \quad (4)$$

The effect of torque on m1 and m2 is accounted for by also using accelerometers a1 and a2 as follows. The component that is perpendicular to the in-line component, and is also horizontal, equals (Fig. 1, upper right):

$$B_{ph} = (a_1 \cdot m_2 - a_2 \cdot m_1) / \cos(I) \quad (5)$$

The component that is perpendicular to the in-line component, and is also in the vertical plane, equals (Fig. 1, upper right):

$$B_{pz} = (a_1 \cdot m_1 + a_2 \cdot m_2) / \cos(I) \quad (6)$$

Bph is tangential to the horizontal azimuth circle (Fig. 1, lower right). The component that is radial to this circle (Brh in Fig. 1, lower left) can be obtained as follows:

$$B_{rh} = B_l \cdot \cos(I) + B_{pz} \cdot \sin(I) \quad (7)$$

In this way, the horizontal component, Bh, of the earth-magnetic field is decomposed into components, Brh and Bph, that are radial and tangential, respectively, to the azimuth circle (Fig. 1, lower right). From these, the azimuth, A, can be computed as follows:

if $B_{ph} > 0$ then $A = 90° + \arctan(B_{rh}/B_{ph})$
if $B_{ph} < 0$ then $A = 270° + \arctan(B_{rh}/B_{ph})$
if $B_{ph} = 0$ and $B_{rh} > 0$ then $A = 180°$
if $B_{ph} = 0$ and $B_{rh} < 0$ then $A = 0°$

where, according to Eqs. (5) and (7):

$$\frac{B_{rh}/B_{ph}}{m_0 \cdot \cos^2(I) + (a_1 \cdot m_1 + a_2 \cdot m_2) \cdot \sin(I)} = \frac{a_1 \cdot m_2 - a_2 \cdot m_1}{a_1 \cdot m_2 - a_2 \cdot m_1} \quad (9)$$

The thus computed inclination (Eq. (3)) and azimuth (Eq. (8)) define the orientation of a body part in earth co-ordinates (Fig. 1, upper left).

2.3. Preliminary evaluation of the system

Our experiments were carried out inside the hospital, which is a rather vertical construction with a lot of iron in it. The inclination of the earth-magnetic field in our laboratory appeared to be 75° while the free-field value in the Netherlands is 67°.

As the local inclination was known, the accuracy of the sensors was evaluated by the following experiment. The sensor was attached to a mechanical arm that was oriented perpendicular to both the earth-magnetic field and earth gravity, i.e. inclination 0° and azimuth 90°. In this position, the arm was torqued clockwise (seen from distal) around its own axis by 360°. The start of this movement at 0° was with...
the sensor a1 in horizontal position (as in Fig. 1, upper right). In this way, a1, a2, m1 and m2 should ideally produce one full sinewave with amplitude 1 and phases 90°, 180°, (90–75)° and (180–165)°, respectively. Sensors a0 and m0 should, ideally, produce a 0 signal.

The algorithms that compute azimuth and inclination from the sensors responses were tested in the following experiment. The mechanical arm was mounted at inclination angles 0°, 30°, 60° and 90°. At each inclination angle except 90°, the arm was positioned at azimuth angles 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300° and 330°. At each one of these 37 (inclination 90° and 3 other inclination angles ×12 azimuth angles) positions, the arm was torqued around its own radial axis by 0°, 45°, 90°, 180° and 270°. At each one of these 185 positions, the algorithms computed azimuth and inclination angles from the sensor signals. The difference between computed and actual angles was analyzed.

3. Results

The orientation sensor was constructed in SMD technology. The electronics were designed mainly aiming for a small size and low power consumption. The resulting sensor measures 60 × 50 × 10 mm and draws less than 1 mA from the telemetry systems battery voltage of ±5 V.

Fig. 2 shows the response of each of the 6 sensors in the first experiment. The mechanical arm was positioned perpendicular to both the earth-magnetic field and earth gravity.

While this position remained the same, the arm was torqued clockwise around its length axis. Comparing these responses to the corresponding ideal sinewave response shows that the inaccuracy remains within 2% of the full scale.

Fig. 3 shows a projection on the horizontal plane of the 37 test positions at which azimuth and inclination were computed. This projection shows the ‘arm’ as seen from above. The 37 positions are at the cross-points of circles (corresponding to the tested inclination angles) and radial lines (corresponding to the tested azimuth angles). The centre of the figure indicates the inclination angle of 90°. At each position, measurements were taken at 5 different torque angles and these 5 measurements show as clusters of dots close to the cross-points. The absolute difference between the computed and actual inclination angle was 0.75° on average and 3.3° at the maximum. The absolute difference between the computed and actual azimuth angle was 4.2° on average and 14.3° at the maximum.

The mathematical derivations show that this sensor construction enables characterization of the 3D orientation of a body part in terms of vertical inclination and horizontal azimuth. The azimuth computation by Eq. (8) uses only the ratio Bhr/Bhp. Therefore, this computation is independent of inclination and field strength. Therefore, it is not necessary to re-calibrate the sensors when used at locations with different earth-magnetic fields.

4. Discussion

The measurements show that the developed sensor and mathematical processing do indeed monitor 3D body position. The accuracy of the measured azimuth and inclination was 4.2% and 0.75% on average. This seems sufficient for visual monitoring of body positions in many applications. For other applications, the accuracy of azimuth monitoring may have to be improved. We think this may be possible by a more accurate mechanical set-up of the sensor.

The described orientation sensor is small and consumes little current. Therefore, it can be applied in long-term ambulatory recordings of movement disorders. The recordings essentially monitor 3D orientation of a body part. More sensors, therefore, enable reconstruction of 3D position of the whole body.

Limitations are mainly that the sensor is also sensitive to movement accelerations and to dynamic fluctuations of the orientation of the environmental magnetic field. Most movement accelerations are much smaller than 1 g. However, in practical ambulatory studies movement accelerations have to be monitored, for instance using Eq. (1). Dynamic (largely movement related) fluctuations of magnetic field orientation can be avoided by staying away from magnets and large metal objects. However, in practical ambulatory studies magnetic-field fluctuations have to be monitored, for instance by monitoring its horizontal component, Bb (Fig. 1, lower right), using Eqs. (5) and (7)).
When taking into account these limitations, body position can be easily monitored. In simultaneously recorded EMG, components responsible for movement accelerations and for compensation of gravity can then be distinguished.

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References


