A Magnetometer-Based Approach for Studying Human Movements

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***Abstract*—This paper investigates the use of body-mounted magnetic field sensors for the analysis of certain human movements. We demonstrate that, in several usual dynamic situations, magnetometers allow to estimate accurately a body inclination while being insensitive to its acceleration. Doing this, it is then possible to combine this information together with the one provided by an accelerometer to separate in a very accurate way the gravitational and kinematical components of acceleration. The proposed method is illustrated by the study of the sit-to-stand movement, estimating trunk inclination and absolute acceleration.**

***Index Terms*—Accelerometer, biomechanics, magnetometer.**

I. Introduction

Many different systems (optical, electromagnetic, ultrasound, …) exist today for the kinematical analysis of human movement. However, such systems are usually expensive, require high-skilled persons and operate in a limited capture volume. Flexible goniometers may also be used for monitoring human joint rotations but calibration remains an important issue with these devices [1].

On the other hand, accelerometers and rate gyroscopes offer alternative methods for measuring human movements. They provide many advantages since they are usually low-cost, low-power, miniaturized, and operable in unconstrained environment. Many applications have been developed using such body-mounted inertial sensors from gait analysis to energy expenditure estimation [2], [3]. However, in dynamic situations, accelerometers cannot be used as inclinometer anymore, and strategies have to be considered to separate the gravitational and the kinematical components [4]–[6].

In this article, we propose a new method to assess a body inclination/azimuth using 3-D Earth's magnetic field sensor, even in dynamic conditions. Indeed, a magnetometer is insensitive to acceleration while responding to a change of orientation in the 3-D space. However, in the general case, a 3-D magnetometer is not sufficient to track a 3-D orientation. Magnetometers are more commonly employed to either determine a compass heading information or to compensate a rate gyroscope integration drift.

Our main point is that by restricting ourselves to particular movements with one or two degrees of freedom (DOFs), a magnetometer is sufficient to estimate 2 DOFs: the movement is constrained in one plane which can rotate around one fixed (or not) axis. For example, during walking, we can be interested in rotations in the saggital plane (e.g., knee flexion/extension) and azimuth direction of walk. Although limited to two DOFs, it is important to note that we can adress a movement in 3-D space.

Second, the angle information delivered by the magnetometer can be used together with the accelerometer signal, so that the kinematical component of the accelerometer signal can be obtained by subtracting the gravity component. This approach is traditionally taken in the literature with the estimation of the inclination with a gyroscope rather than a magnetometer [7]. The proposed method has several benefits compared to gyroscope-based ones: it is not restricted to short-period rotations (but rather rotations under specific conditions), there is no need for integration of the gyroscope signal to obtain an angle. Finally the proposed system has potentially a lower power consumption compared to a system based on gyroscopes.

To illustrate the theoretical results, we focus on the specific movement of rising from a chair, a movement that is mainly performed in the sagittal plane. In dynamic situations, we compare our trunk inclination estimation with the one provided by a reference system to validate our approach.

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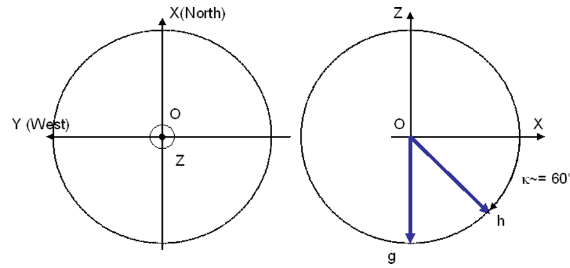

Fig. 1. Earth-fixed (inertial) frame. Left: horizontal plane. Right: north meridian plane.

II. Methods

A. Theory

Consider first an inertial/magnetic system constitued of a tri-axial magnetometer and a tri-axial accelerometer. Both MEMS systems are designed to sense physical quantities present everywhere: the Earth's magnetic field and the gravitational field. The sensor measurements are recorded in the body frame B and the sensor's sensitive axes are denoted xb, yb and zb. Furthermore, based on the geophysics, we can also define a local Earth-fixed reference coordinate system I, as shown in Fig. 1.

In the general case, there exists a unique rotation matrix that gives the relative orientation of the two coordinate systems with the general form

$$\vec{v}_{/B} = R_{bi}\vec{v}_{/I} \tag{1}$$

where $\vec{v}_{/B}$ denotes a vector expressed in the body frame and $\vec{v}_{/I}$ is the same vector expressed in the inertial frame. The rotation matrix R_{bi} may be decomposed as a sequence of three elementary rotations (Euler formulation): rotation around the Z axis or **yaw** angle (φ), followed by a rotation around the Y axis or **pitch** angle (θ), and finally a rotation around the X axis or **roll** angle (ψ)

$$R_{bi} = R(\psi, \theta, \varphi) = R(\psi)\,R(\theta)\,R(\varphi). \tag{2}$$

Let denote $\vec{v}_{\rm mag}^{(m)}$ the normalized sensor readings from the magnetometer, modelled by

$$\vec{v}_{\rm mag}^{(m)} = \vec{h}_{/B} + \vec{m}_{/B} + \vec{\epsilon}_{{\rm mag}/B}. \tag{3}$$

The first term in right-hand side of (3) corresponds to the Earth's magnetic field vector expressed in body frame while the second term corresponds to a magnetic disturbance. The last term is a magnetometer noise term. In this paper, since we consider an environment free of such disturbances, we suppose these two last terms negligible.

Let denote $\vec{v}_{\mathrm{acc}}^{(m)}$ the sensor readings from the accelerometer, modelled by the relation

$$\vec{v}_{\mathrm{acc}}^{(m)} = \vec{g}_{/B} - \vec{a}_{/B} + \vec{\epsilon}_{\mathrm{acc}/B}. \tag{4}$$

The first term in (4) corresponds to the gravity vector while the second term corresponds to the sensor acceleration. The last term is an accelerometer noise term. In all the following, the accelerations will be normalized, and expressed in g-units ($g \simeq 9.81 \mathrm{~m/s^2}$).

In static conditions, several well-known methods exist to retrieve the sensor attitude from these two vector observations. It is for instance possible to recover the three Euler angles by minimizing the cost function

$$J_1(\psi,\theta,\varphi) = \lambda_{\mathrm{acc}} \left\| \vec{v}_{\mathrm{acc}}^{(m)} - R(\psi,\theta,\varphi)\,\vec{g}_{/I} \right\|^2 + \lambda_{\mathrm{mag}} \left\| \vec{v}_{\mathrm{mag}}^{(m)} - R(\psi,\theta,\varphi)\,\vec{h}_{/I} \right\|^2 \tag{5}$$

where λ is a weight factor to balance the contribution of the accelerometer and the magnetometer in the cost function. Such a minimization technique has been used in [8]. For example, one can decrease λ_{acc} for large accelerations.

In static conditions, the accelerometer is essentially sensing the gravity and the inclination (angle with respect to the horizontal plane) can also be estimated quite accurately using the arctangent function

$$\hat{\theta} = \arctan\left(\frac{-\vec{v}_{\mathrm{acc},xb}^{(m)}}{\sqrt{(\vec{v}_{\mathrm{acc},yb}^{(m)})^2 + (\vec{v}_{\mathrm{acc},zb}^{(m)})^2}} \right). \tag{6}$$

It is obvious that this measurement model will be inaccurate for fast-paced movements.

Consider now the general dynamic case, where the sensor is moving arbitrarily. The situation is now much more difficult with the estimation of 6 unknown variables (3 angles and 3 acceleration values) from 6 measurements (3 accelerometer and 3 magnetometer signals). The problem is now under-determined, whereas in static case it was over-determined.

Our work hypothesis is that it is still possible to determine the sensor inclination in the dynamic case, when the kinematical model has a reduced number of DOFs. Thus, we restrict the forthcoming analysis to the case where we dispose *a priori* information about the sensor motion. In this case, magnetometer can bring valuable information to the attitude determination problem.

Without loss of generality, we consider the type of movement with a null roll angle ($\psi = 0$) and a null acceleration along the yb-axis. This is for instance the case in a movement such as walking, where one or two angles may be of interest, like inclination and azimuth. By using only one triaxial magnetometer and ***a priori* information** about the roll angle, it is possible to recover the two Euler angles (θ, φ) by minimizing a new cost function J_2, based only on magnetometers measurements

$$J_2(\theta,\varphi) = \left\| \vec{v}_{\mathrm{mag}}^{(m)} - R(\theta,\varphi)\,\vec{h}_{/I} \right\|^2. \tag{7}$$

Although previously, only magnetometers were needed for angle estimation, we focus here on adding a new type of microsensors in order to extract more specific information about the movement kinematics.

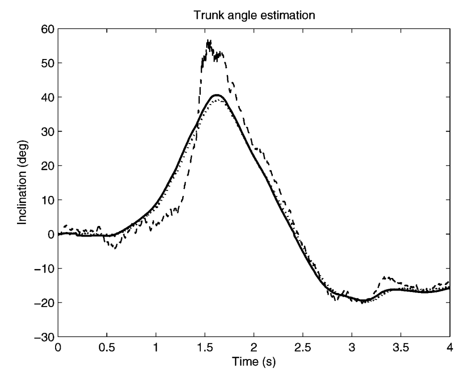

Fig. 2. Comparison of trunk inclination computed from magnetometer measurements (dotted line) and given by the Optotrack system (solid line). It is almost impossible to distinguish the two plots. The third plot (dashed line) is estimated from accelerometer measurements.

From the angle information computed with magnetometers, it is possible to predict the gravitational component in body frame, and then to express the kinematical components (in g-units) in inertial frame:

$$\begin{aligned} a_h &\approx -\vec{v}_{\mathrm{acc},xb}^{(m)} \cos\theta - \vec{v}_{\mathrm{acc},zb}^{(m)} \sin\theta \\ a_v &\approx \vec{v}_{\mathrm{acc},xb}^{(m)} \sin\theta - \vec{v}_{\mathrm{acc},zb}^{(m)} \cos\theta + 1 \end{aligned} \tag{8}$$

with a_h and a_v the horizontal and vertical sensor accelerations, in the inertial frame.

B. Experiment

To validate the proposed approach, we now investigate a specific movement: rising from a chair. The sit-to-stand (SiSt) transition has been investigated for several years now in [4] and [9]. We are interested in this section to estimate the trunk inclination during an SiSt movement and the accelerations of the upper body that are involved in this movement.

A motion capture experiment has been conducted in which we used both our inertial/magnetic system and an Optotrack device with active diode markers. Since Optotrack spatial resolution is about 1 mm, it is considered as the reference system. The setup consisted in one inertial/magnetic system placed on the upper part of the back, and three active markers rigidly fixed upon it. No precise order was given to our subjects who were simply asked to stand up from a sitting position, as naturally as possible, at the signal given by the experimenter. No particular care was taken concerning the feet position.

III. Results

A. Trunk Inclination During SiSt Transition

We estimate the trunk inclination with three different techniques, relatively to the initial body frame.

- Magnetometer system: angle estimation by minimization of the J_2 cost function (7).
- Accelerometer system: angle estimation by arctangent function (6).
- Optotrack system.

As shown in Fig. 2, magnetometer inclination estimation is in very good agreement with the reference Optotrack system: a maximum difference of 2° as been obtained for the same subject over eight SiSt trials. As expected, the accelerometer estimation fails in the dynamic phases of the movement with either under- or over-estimated angle. The angle estimation computed with (7) is more accurate than the previous

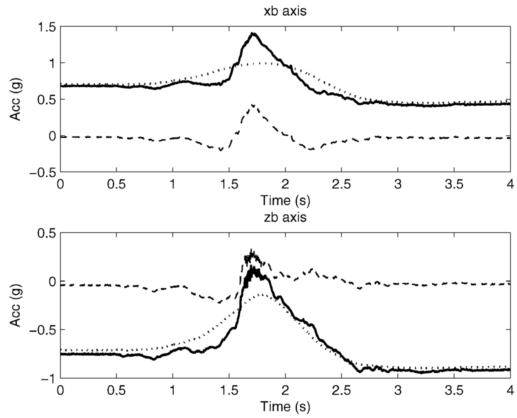

Fig. 3. Separation of the gravitational and kinematical components in body frame. Accelerations during a SiSt transition: measured acceleration (solid line), predicted gravitational component (dotted line), and computed kinematical component (dashed line). xb-axis (top) denotes the craniocaudal axis, pointing upward; zb-axis (bottom) is the anteroposterior axis, pointing forward.

static model because it is not sensitive to large accelerations, since it is based only on magnetometers measurements.

B. Trunk Acceleration

The inclination estimation, obtained from the magnetometer, can then be used in conjunction with the accelerometer data to predict the gravitational component. Doing this, we can estimate the SiSt pattern in the inertial frame, i.e., determine the horizontal and vertical sensor accelerations and, thus, compare different patterns for different subjects.

Fig. 3 presents the different normalized accelerations measured in the sensor frame: the calibrated measured acceleration $\vec{v}_{\rm acc}^{(m)}$: dark solid line, the predicted gravitational component $\vec{g}_{/B}$: dotted line, and the computed kinematical component $\vec{a}_{/B}$: light solid curve.

As shown in Fig. 3, in some dynamic situations (around time 1.5 s), the kinematical component is no longer negligible with respect to the gravitational component as can be noticed on the computed kinematical component $\vec{a}_{/B}$. Estimating the trunk angle using only accelerometers will fail during these phases, as shown in Fig. 2. Indeed, during SiSt transition, maximum kinematic acceleration happens when the trunk is fully bended forward: transforming at this time a horizontal movement into a vertical one [9].

IV. Discussion

In this communication, we have presented a magnetometer-based motion capture system that can address several usual human movements, e.g., rising from a chair or walking. This approach is well suited to planar movements which are classically performed by humans. Furthermore, in an advantageous way, we can combine this angle information with an accelerometer to separate the gravitational and kinematical components in the accelerometric signal.

Applying (8), it could be possible to estimate the trunk accelerations in the inertial frame. From these absolute accelerations, it is be possible, integrating twice over a short period of time, to estimate the trunk displacement during the SiSt transition. This could provide a reliable parameter for posture classification.

However, it is important to underline that our magnetometer-based approach suffer from two restrictions. First, any rotation around the Earth's magnetic field axis is not observable by our system. However, in biomechanical analysis, this type of movements is rarely seen, since we consider mostly saggital and horizontal planes. Second if the Earth's magnetic field is corrupted by another magnetic source (ferromagnetic object…), the angle computation may not be exact. Indeed, local magnetic variations are not handled by our approach. Current investigations should lead to a more general solution.

Finally, results have been presented on a Sit-Stand movement and the trunk inclination that was estimated with the proposed method was found in good agreement with the reference optoelectronic system, even in dynamic conditions. Further experiments will be conducted, with a focus on the knee angle during walking.

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