The artificial vestibular system - design of a tri-axial inertial sensor system and its application in the study of human movement

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1. Introduction

The human vestibular system senses linear and angular movements using inertial principles. It is an important sensory organ in human postural control. Currently, the availability of micro-mechanically produced inertial sensors measuring acceleration and angular velocity, enables the realization of small tri-axial inertial sensor systems which provide movement information comparable to the human vestibular system. These inertial sensors have high potential for application in human movement analysis.

The advantage of inertial sensing is that it enables movement assessment through a measurement at a single point without the requirement of a reference. The disadvantage is that several movement quantities are represented in one signal, for example inclination and acceleration, which can not be distinguished in general.

It is our objective to design and apply sensors that derive maximal movement information by inertial measurement at one point and to investigate possible human movement sensing applications for this sensor. For this purpose a triaxial accelerometer and triaxial angular velocity sensor (rate gyroscope) are combined in one inertial sensing system, which can, in many respects, be compared in function with the human vestibular system. The technological realisation of such a inertial sensing system, optimal estimation of relevant movement quantities from the sensor signals and its use in human movement sensing applications are investigated.

2. Methods

2.1. Sensing principles

Acceleration of a mass requires a force proportional to the acceleration. Additionally, in the presence of gravity, an additional gravitational force acts on the mass. The resulting force acting on the mass is sensed in an accelerometer. In terms of accelerations the sensor signal is given by

$$\vec{s}_a = \vec{a} - \vec{g} \qquad (1)$$

$\vec{s}_a$ being the accelerometer signal, $\vec{a}$ the acceleration of the mass and $\vec{g}$ the gravitational acceleration.

If the mass is moving with respect to its surrounding an apparent acceleration with respect to this surrounding acts on the mass if both are rotating with respect to an inertial reference frame. This Coriolis acceleration is measured in an angular velocity sensor (rate gyroscope) and can be expressed as follows:

$$\vec{s}_g = 2\vec{\omega} \times \dot{\vec{r}} \qquad (2)$$

$\vec{s}_g$ being the signal of the angular velocity sensor (rate gyroscope), $\vec{\omega}$ the angular velocity of the sensor and $\dot{\vec{r}}$ the velocity of the mass with respect to the surrounding.

2.2. Physical design

Currently, separate micro-machined uni or bi axial accelerometers and uni-axial angular velocity sensors that are sufficiently small and light-weight to be used in human movement sensing applications, are commercially available. However, no integrated tri-axial inertial sensor is available. We have designed and realized an inherently tri-axial accelerometer which consists of a single cubic mass suspended in a box at all sides by springs [1] (figure 1). Acceleration in all three directions can be obtained by differential capacitive measurements [2]

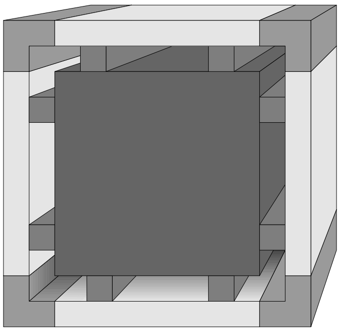

Figure 1. Schematic drawing of the tri-axial accelerometer consisting of a mass suspended by springs in a box [3]

Currently, we investigate the possibility of additionally measuring angular velocity with the same sensor, vibrating the mass in variable directions and measuring induced movements in perpendicular directions when the sensor rotates [4]

2.3. Optimal estimation of quantities

A tri-axial inertial sensor system yields signals that depend on acceleration, gravity and angular velocity. From these signals several relevant movement quantities can be derived. Knowledge about the relation between these physical quantities and a priori knowledge of the movement characteristics in the case of human movements enable the optimal estimation of relevant physical movement quantities:

- *Orientation* can be estimated from the angular velocity sensor signals by integration. However, this operation may result in large errors when the offset of the angular velocity sensor shows some drift. Also, an initial orientation is required. The accelerometer signals yields useful additional information with regard to orientation: the gravity component of the signal indicates the inclination of the sensor. However, the accelerometer signal includes both this gravitational component as well as the acceleration component. Therefore inclination estimation is only accurate during periods when the magnitude of acceleration is relatively small, which are characterized by an accelerometer signal which is almost constant 1 *g*. Under many human movement conditions such periods occur regularly. We designed a Kalman filter which fuses the information from the tri-axial angular velocity sensor and the tri-axial accelerometer in order to optimally estimate orientation [5].
- The actual *acceleration* of the sensor can only be estimated if the orientation of the sensor is constantly known (equation (1)). Therefore, the accurate estimation of orientation by fusing the information of the tri-axial accelerometer and angular velocity sensors, as discussed above, is a prerequisite for accurate estimation of acceleration.
- The *calibration of offsets and gains* can be performed during use if we assume that acceleration is not constant for prolonged times during human movement. The offsets and gains of the tri-axial accelerometer can be estimated when the signal is not varying for some time, assuming only gravity (1 g) is acting at such times. Several sequential readings during static periods can be combined to estimate the offsets and gains of the sensor [6]. The adjustments made by the Kalman filter with respect to the orientations estimated from the angular velocity sensor give information regarding errors in the calibration parameters of the angular velocity sensor, which can be used to adjust these calibration parameters during use of the sensor..

3. Results

3.1. tri-axial inertial sensor

The capacitive tri-axial accelerometer with a central mass suspended by springs at all sides in a box has been realized (figure 2), tested [3] and preliminary used in human movement studies [7]. the minimal dimensions of the sensor were 3x3x3 mm^3 (figure 1).

The principle operation of angular velocity sensing with this sensor has been shown [4].

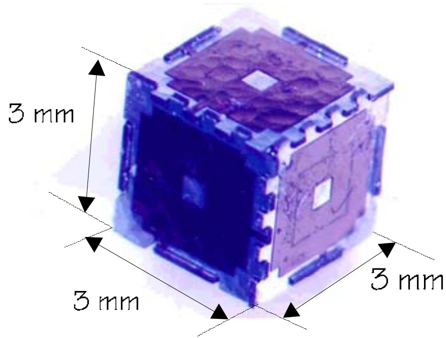

Figure 2. photograph of the tri-axial accelerometer consisting of a mass suspended by springs in a box [3, 4]

3.2. Estimation of orientation by fusing the information from tri-axial angular velocity sensor and accelerometer

The Kalman filter for long-term estimation of sensor orientation, fusing information from the tri-axial angular velocity sensor and accelerometer, was implemented in MATLAB and subsequently tested in an experiment where volunteers performed the task of stacking crates.

For these experiments a tri-axial sensor unit was realized from commercially available uni-axial accelerometers (Analog Devices AD XL05) and angular velocity sensors (Murata ENC 05E). From the example shown in figure 3 it is clear that considerable errors in orientation estimates can be expected when only integrating the signal from the angular velocity sensor [8], even after a few minutes. A continuously accurate estimate can be achieved by fusing the information from the tri-axial angular velocity sensor and accelerometer, optimally estimating orientation and continuously recalibrating the offsets of the angular velocity sensor.

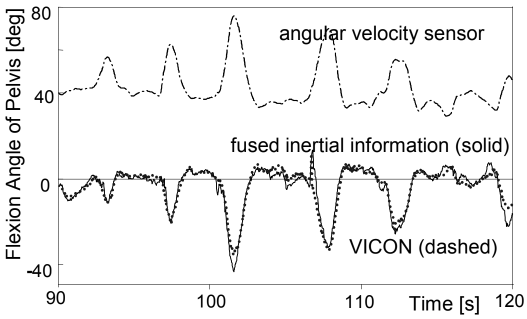

Figure 3. Example of long term orientation estimation by fusing information from a tri-axial angular velocity sensor and accelerometer. The 3D orientation of the pelvis was reconstructed from only the tri-axial angular velocity sensor (dash-dotted line) and from the fused information of the tri-axial accelerometer and angular velocity sensor (solid line). Shown is only the flexion angle of the pelvis (0 deg is upright, flexion is negative). An orientation estimation from an opto-kinetic movement analysis system (VICON) is shown as a reference (dotted line). Before the test, the inertial sensor system was calibrated while it was not mounted on the body. The offsets of the angular velocity sensor were determined just before the start of the trial from 4 seconds of quiet standing.

3.3. Application in human movement studies

Several applications of inertial sensing for the analysis of human movement have been proposed and tested, for example:

- ambulatory back load monitor for use in ergonomic studies [9].
- ambulatory gait analysis [10]
- Assessment of body balance during standing [7]
- real time measurement of running velocity for use in sports [11]
- activity monitor to assess daily movement activities [12, 13].

4. Discussion

Inertial movement sensing has a high potential for use in human movement analysis. It enables long term measurements under ambulatory conditions with no requirements of measurement systems in the environment. Tri-axial sensor systems that provide comparable movement information as the human vestibular system can be small and low weight, not impeding human movement.

The applications are not limited to the above mentioned. Other potential applications include man-machine interfacing and feedback in artificial human movement control

Acknowledgement

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