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Estimating orientation with gyroscopes and accelerometers

H.J. Luinge [a], P.H. Veltink [a] and C.T.M. Baten [b]

[a] *Institute for Biomedical Technology (BMTI), Systems and Signals Group, Faculty Electrical Eng., University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
E-mail: h.j.luinge@el.utwente.nl
[b] *Roessingh Research and Development, Enschede, The Netherlands*

1. Introduction

Many systems for recording human movement need some reference from beacons near the subject, such as video cameras. Our goal is to measure human kinematics with sensors that are placed on the segments of interest. This way, experiments in which human movement is recorded are not restricted to a lab.

Our inertial sensor-unit consists of a little box with three miniature gyroscopes (Murata ENC05E) and three linear accelerometers (AD xl05) that measure 3D angular velocity and linear acceleration, respectively. Both the gyroscope and accelerometer signals contain information about the orientation of the sensor. The sensor orientation can be obtained by integration of the angular velocity signals obtained from the gyroscopes [1]. This operation introduces drift in the estimated orientation.

Accelerometers do not only measure the acceleration of the sensor, but also the gravitational vector. This gravitational component not only has a bigger magnitude for many human movements but also always points downwards. This knowledge can be used to make an estimation of the tilt. The tilt is the angle between the sensor axes and the vertical. This tilt estimation is not very precise but does not suffer from drift.

The abstract describes a way to fuse both sensors (gyroscopes and accelerometers) to obtain an estimate of the orientation that is both accurate and is limited in integration drift.

2. Methods

An algorithm is designed to fuse the tilt from the accelerometers with the orientation of the gyroscopes to obtain a better estimation of the orientation. In the algorithm the angular velocity is integrated to get an orientation [1]. In order to make a comparison between the tilt of the accelerometer and the orientation that is obtained with the gyroscope, the orientation from the gyroscope is split into a tilt (T) and a rotation of the sensor around the global Z-axis (α). The tilt that is obtained from the gyroscope is subtracted from the tilt that is measured with the accelerometer and is fed into a Kalman filter to obtain a better estimation of the tilt. This is again combined with the rotation around the Z-axis to get a better estimation of the orientation (Fig. 1). A roughly comparable scheme is explained in [2].

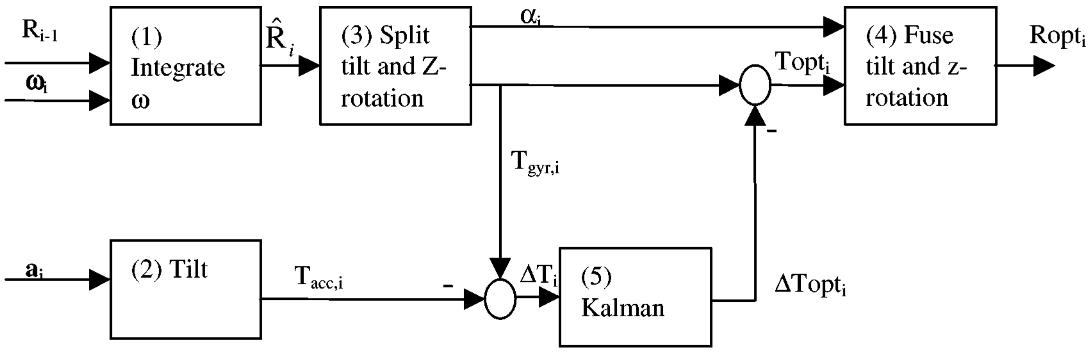

Fig. 1. Scheme for combining the angular velocity with acceleration to obtain an orientation. The angular velocity is integrated to get an orientation (1). This is split into a tilt and a rotation around the Z-axis. This tilt, subtracted with the tilt calculated from (2) is fed into a Kalman filter (5) to obtain a better orientation. ω and **a** are the measured angular velocity and acceleration, respectively, R is an orientation and T is a tilt.

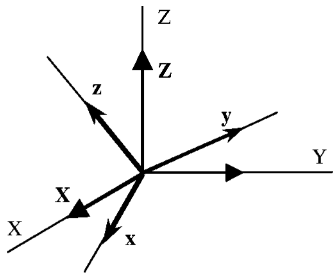

Fig. 2. Global XYZ and sensor xyz system.

Two reference frames will be considered: a sensor frame (xyz) and a global (earth) frame (XYZ). See Fig. 2. The Z-axis points in the direction opposite to the gravity vector. The orientation of the two frames is described by the unit vectors $\mathbf{x}, \mathbf{y}, \mathbf{z}$ and $\mathbf{X}, \mathbf{Y}, \mathbf{Z}$, as they are drawn in Fig. 2. The tilt has two components and is defined as the angle of the x and y axes with the Z-axis.

The tilt T_{acc} is calculated from the accelerometer signal in block 2 (Fig. 1), using the assumption that the accelerations of the body can be neglected with respect to the gravity vector. Then the unit Z-axis as measured in the xyz frame is

$$\mathbf{Z}_{\text{S}} = -\frac{1}{g}\,\mathbf{g}_{\text{S}}.$$

Now, the tilt angles can be calculated as follows:

$$\mathbf{T}_{\text{acc},x} = \cos^{-1}\left(\mathbf{Z}_{\text{S},x}\right) \quad \text{and} \quad \mathbf{T}_{\text{acc},y} = \cos^{-1}\left(\mathbf{Z}_{\text{S},y}\right).$$

This is made clear for the x-axis in Fig. 3. Only axes are drawn that are needed for the explanation.

The calculation of the tilt from an orientation (block 3 in Fig. 1) is almost the same as calculating the tilt from a given Z-axis. When the $\mathbf{x}$ and $\mathbf{y}$ unit vectors of the sensor system are given in the global system, the angles T_x and T_y are now just the inverse cosines of the z-components of $\mathbf{x}$ and $\mathbf{y}$, respectively.

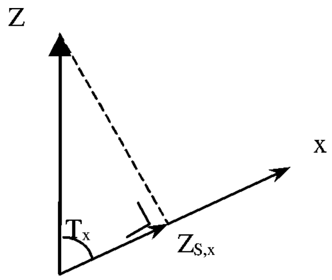

Fig. 3. The sensor x-axis with the global Z-axis.

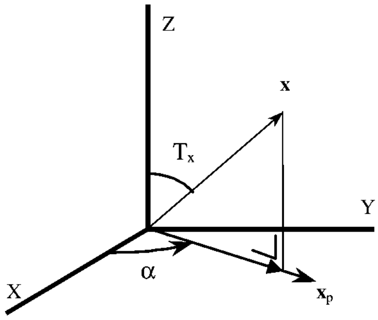

Fig. 4. Relation between T_x, α and **x**.

Given $T_{\mathrm{opt},x}$ and $T_{\mathrm{opt},y}$ and the angle α of the **x**-axis that is projected on the XY plane, the unit vectors **x**, **y** and **z** are determined in block 4 (Fig. 1). The projection of vector **x** is (Fig. 4)

$$\mathbf{x}_{\mathrm{p}} = \{\cos\alpha \;\; \sin\alpha \;\; 0\}^{\mathrm{T}}.$$

Then **x** is the scaled $\mathbf{x}_{\mathrm{p}}$ plus a z-component that is equal to $\cos(T_{\mathrm{opt},x})$

$$\mathbf{x} = q \cdot \mathbf{x}_{\mathrm{p}} + \{0 \;\; 0 \;\; \cos(T_{\mathrm{opt},x})\}^{\mathrm{T}}.$$

Where q is a scaling factor that makes **x** a unit vector. It follows that $q = \sin(T_{\mathrm{opt},x})$. The **y** vector is obtained in the same way and **z** is the cross product of **x** and **y**.

The Kalman filter (block 5 in Fig. 1) is a linear 2-state filter that is described in [2]. The prediction of the system is given by $\Delta\mathbf{T} = \mathbf{0}$.

3. Results

The filter is tested with the so called coning motion [2] with a white Gaussian noise (s.d.1) added to every component of the angular velocity signal. The angular velocity of coning motion is defined as

$$\boldsymbol{\omega} = \left\{ \begin{array}{c} \Omega \sin\theta \cos\Omega t \\ -\Omega \sin\theta \cos\Omega t \\ \Omega(1 - \cos\theta) \end{array} \right\}.$$

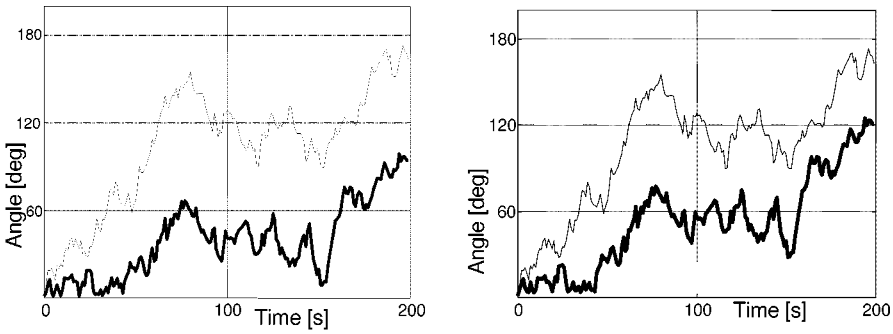

Fig. 5. The error in orientation with a test signal is applied. The thin line represents the error when the angular velocity would be only integrated. The thick line represents the error when also accelerometers are used. Left: test signal with an accelerometer signal that equals the gravity vector. Right: test signal with an accelerometer signal with the gravity plus a constant offset.

In this simulation, θ and Ω are set to 1. The measured acceleration is again equal to the gravity vector. The calculated orientation will be compared with the analytically derived orientation. The measure of error is the angle the calculated reference system has to rotate in order to coincide with the real frame. It does not give information about the direction of this rotation. Two simulations are conducted. In the first simulation the accelerometer signals represent only the gravity. In the second simulation, there is a constant acceleration of 1 ms^{-2} added on the accelerometer signals, in the $[1\ 1\ 1]^{\mathrm{T}}$ direction of the sensor reference frame. This shows the effect of an acceleration with a mean that is not zero. This will be the case in situations with a centripetal acceleration.

Two errors are calculated. One is the error of the orientation obtained from the scheme that has just been described. The other error is the error in orientation when it is obtained by integration of the angular velocity only.

Figure 5 shows that the incorporation of accelerometers can improve the estimated orientation considerably. In the case of a constant offset added to the acceleration signal, the error is bigger in magnitude. The error of the filter is less than just integrating angular velocity, but is still in the same order of magnitude. The error of the simulations with filter will always increase in a random walk way, because the accelerometers do not give information about the rotation around the Z-axis. This is not the case for situation where only the inclination is needed.

4. Discussion and conclusions

As is shown in Fig. 5, the combination of the gyroscopes with accelerometers can give better results than using gyroscopes alone. It must be said that it is only tested with very simple test signals. Errors could be bigger in practice.

The performance for the signals that are used to test the filter indicate that it might also work in more practical situations. The biggest disadvantage in practice is that the determination of tilt from accelerometers is only accurate when the subject is hardly moving. This limits the number of possible applications. Another disadvantage is that the solution gets more and more inaccurate in its estimation of rotation around the Z-axis. Extra information is needed to prevent this. A number of possible solutions might be:

– Ask the subject to stand with his/her segment in a particular direction.
– Use Hall sensors.

- Use biomechanical relations, such as knowledge that different segments are attached to each other. This can be problematic when these biomechanical relations are just the ones that have to be measured.
- Use an error model to adjust the sensor parameters like gain and offset. This will not eliminate drift around the Z-axis, but can make it slower.

Experimental tests will soon be conducted.

Acknowledgements

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References

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[2] R.G. Brown and P.Y.C. Hwang, *Introduction to Random Signals and Applied Kalman Filtering*, 3rd edn, John Wiley & Sons, ISBN 0-471-12839-2.