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GUIDLINES FOR CALIBRATION AND DRIFT COMPENSATION OF A WEARABLE DEVICE WITH RATE-GYROSCOPES AND ACCELEROMETERS

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Abstract— **The technical note describes a methodology for the calibration and the drift compensation of a device with accelerometers and rate-gyroscopes . The methodology is based on a step-wise-motor approach and a simulation environment with the device simulation model for optimisation of the calibration parameters. The validation on a wide range of locomotion tasks performed by 30 subjects with some unbalance problems showed the feasibility of the methodology. In particular, a correlation was found between simulated and actual data (0.15° in maximal value). Results also showed that the drift compensation procedure significantly improved the performances of the device.**

I. Introduction

KINEMATIC sensors such as accelerometers can be succesfully used for long-term physiological motion monitoring [1] and short term monitoring [2]. The human motion analysis can also be performed using a wearable sensor device with accelerometers (3031-Euro Sensors, US) and rate-gyroscopes (Gyrostar ENC-03J-Murata, Japan) assembled together and oriented according to an orthogonal reference system [3]. One way to use such a sensor is to process the accelerometric sensor to assess the initial orientation of the human affixation segment, and to use the signals from the rate-gyroscopes to dynamically measure the angular values as a function of time. The rate gyroscope needs careful attention and consideration for the thermal drift compensation [3]. However, is insensitive to g and to the error due to the centripetal acceleration [5].

A. Problem definition

There are many possible uses of this device, from the generic assessment of a wide range of locomotory tasks [3], specifically for the sit-to-stand [6] or in posturography [4,5,8]. The accuracy of the device is essential for the significance of the analysis. The drift compensation of the rate gyroscopes and optimisation of the calibration of the sensor are the main problems for an optimal use of the device and are a function of the following two aspects:

1- The subjects category to be investigated; healthy, or pathologic as individuated by a type of pathology or with a degree of inability as preliminarily assessed by means of a medical test well stabilised in literature.
2- The type of motion tasks to be investigated; locomotory tasks (sit-to-stand, arising a step etc.) [3,6,7] or posturography tasks [4,8].

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B. Aim of the Note

The aim of the Note is to add to the guidelines for optimising the accuracy of the device with three accelerometers and three rate gyroscopes. We will thus introduce and test a complete methodology for calibration and for the drift compensation specific to this device. Previously [3,4,5,6,7,8], we have used a methodology for doing this, but we have never fully investigated the question and a full description is thus strongly needed.

II. Materials and Methods

A. Optimization of the parameters used for calibration

Figure 1 shows the procedure for optimising the calibration procedure.

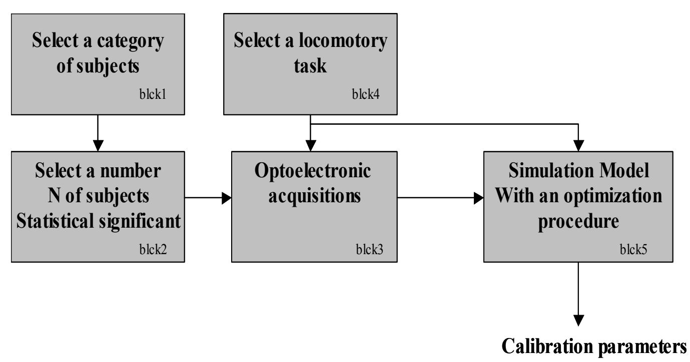

Figure 1 Flow indicating the steps necessary for the optimisation of the calibration parameters

The principal parameters to be optimised by changing the locomotory tasks and the categories of the subjects are:

1) the acceleration and angular velocities used for calibrating the device

and

2) the parameters to be imposed to the conditioning chain comprehending one amplification system and a second order active second order low-pass filter obtained by means of a Sallen-Key cell with the Butterworth approximation **.**

The simulation and thus the optimisation indicated in Figure 1 is obtained by a model of the assembly and the simulation environment, previously described in [7] .

B. Calibration procedure (parametric)

Preliminary trials

It has been found useful to calibrate accelerometers by static procedures. In fact, from preliminary observations of calibration, no differences have been found between calibrations performed by means of complex dynamic methods, such as the ones based on the Piston servo-hydraulic jig based on the mechanical piston MTS 810 (MTS Systems corp, Minneapolis), and static calibration.

Furthermore, of the static calibration procedures to be used for the accelerometers, the one based on an inclination plane was found to be overstated and not improving the relevant accuracy.

The procedure proposed

Accelerometers

Signal acquisition lasts 6 seconds. The accelerometers are used at the start to assess the initial orientation, the choice of 6 seconds is thus adequate. Before the data processing, each accelerometer signal is further filtered with Matlab R12 polyfit functions (The Mathworks, USA) and averaged. Accelerometer signals are then obtained for each of the six possible orientations of the wearable device on a horizontal plane.The Least Squares Method (LSQ) method is used for calibration. L_A is the matrix of the imposed quantities $+g,-g$ by putting the six faces of the device on the horizontal plane. There are six columns, two are quantities $+g,-g$ imposed for each of the 3D directions. S_A is the matrix of the quantities measured by the sensor unit; for example, x1, y1, z1, are the values measured by the three accelerometers in the first of the six accelerometer calibration configurations.

$$[L_{A3X6}] = \begin{matrix} -g & g & 0 & 0 & 0 & 0 \\ 0 & 0 & -g & g & 0 & 0 \\ 0 & 0 & 0 & 0 & -g & g \end{matrix} \qquad (1)$$

$$[S_{A3X6}] = \begin{matrix} x1 & x2 & x3 & x4 & x5 & x6 \\ y1 & y2 & y3 & y4 & y5 & y6 \\ z1 & z2 & z3 & z4 & z5 & z6 \end{matrix} \qquad (2)$$

The calibration matrix is:

$$[C_{A3X3}]=[C_A]=[L_A][S_A]^T([S_A][S_A]^T)^{-1} \qquad (3)$$

Rate Gyrosopes

The calibration of the rate gyroscopes is performed dynamically by rotating the device, with specific equipment using a step-by-step motor (Galil, USA) [3]. The main characteristics are described in [14]. For the sake of the clarity, they are also summarised here. The core of the system comprise the DMC-1410 controller and the encoder (Galil, USA) [9] These elements are integrated with one power supply (±12V), one PC with ISA bus, one Amplifier AMP-1460. A communication software for the development of WSDK is also provided by the same manufacturer. The system characteristics are : torque constant Kt=0,1 Nm/A, system moment of inertia $J=2*10^{-4}$, motor resistance $R=2\Omega$, current amplifier gain $K_a=4$ Amp/V, encoder line density N=10,000 counts/rev, sample period T= 0.1 ms. Preliminary tests indicated an error of less than 1 $2*10^{-2}$ deg when it was imposed a step-wave at 90° per second for 60 seconds. The parameters of the angular velocity to be optimised are: ω_m= minimum value of the angular velocity; ω_M= maximal value of the angular velocity , $\Delta\omega$ = step of increment of the angular velocity .

Before the data processing, each rate gyroscope signal is further filtered with Matlab R12 spline cubic functions and averaged. The calibration matrices are:

$$[L_\omega] =[L_{\omega 3XN}] \qquad (4)$$

$$[S_\omega] =[S_{\omega 3XN}] \qquad (5)$$

The number (N) of columns is a function of (ω_m ,ω_M , $\Delta\omega$). For example, if $\Delta\omega$= 5 °/s , ω_m=5 °/s , ω_M= 90 ° /s
N == 102, i.e. 34 (±10, ±15, ±20,..., ±80, ±85, ±90°/s,) imposed for each of the 3D directions.

$$[C_{\omega 3X3}]=[C_\omega]=[L_\omega][S_\omega]^T([S_\omega][S_\omega]^T)^{-1} \qquad (6)$$

Drift Problem in principle

As previously discussed [3,7], for the chosen components the major error source is the thermal drift of the rate gyroscopes The sensor output is thus measured for the rate gyroscopes during calibrations at different temperatures.

Both static and dynamic drift (functions of temperature and angular velocity) are used to compile tuning tables. When the device is used in the environmental conditions, the precise thermal sensor lm335 (National Semiconductor, USA) [3, 7] detects the board temperature. According to the temperature value, the tuning table values are then used for the error correction.

Drift Compensation in Details

Figure 2 details the procedure used for the compensation of the drift of the rate-gyroscopes.

block 2 , block 3 , block 4, block 5

The function of time for approximating the static drift is calculated for different temperatures in the operative thermal range of the device (18–75°C) using the Matalb R12 spline functions. These functions are then used to compile the tuning tables for the static drift correction. The step increment in temperature was fixed to 0.5°C.

block 6 , block 7 , block 8, block 9

Once the parameters of the angular velocity to be imposed have been defined, the function of the dynamic drift is approximated by means of the Matlab R12 spline functions and used to compile tuning tables to be used for correction at each time sample during the use of the device.

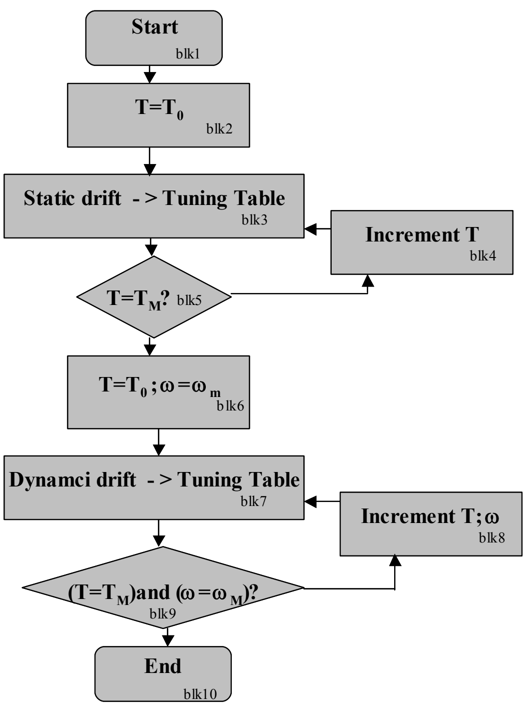

Figure 2 Procedure for the drift compensation

III Validation

The investigated tasks for the optimisation of the calibration procedure are the sit-stand, the rising of a step, the posturography with eyes closed on foam (also indicated in Table 1). The category of subjects to be used for validation was individuated by means of the unbalance test of Tinetti [10]. This famous and well-established test allows the individuation of four levels of unbalance. The first level refers to subjects with no unbalance problems, the fourth refers to subjects with major unbalance problems. We used observartions from a Vicon system performed during the different locomotory tasks as input to the simulation tool with the device model, with the device affixed to the trunk L5 level and with the same marker arrangement justified in [3]. The threshold used for the statistical significance of the furnished parameters by changing the task was set at p = 0.05 and was analysed by ANOVA. Thirty subjects obtained the target statistical significance. Table 2 shows the subjects' characteristics used for obtaining the input to the simulation environment to optimize the parameters (input to simulations) and for the testing of the device after the calibration (testing). Table 1 shows for the different tasks the optimized parameters cut-off frequency, $\Delta\omega$, ω_m , ω_M with the statistical significance.

Group	Simulations		Testing	
	age (years)	height(cms)	age (years)	height(cms)
Tinetti L 2	45-84 mean 62	150-185 mean 166	45-83 mean 65	152-183 mean 167

Table 2 Subjects characteristics

Ones calibrated, the device arranged at L5 level was tested during these tasks with a Vicon system.

The arrangement of the markers during the comparison and the tested Vicon performances are shown in [3,7]

The maximal error values were found for the sit-to-stand test.

Figure 3 also shows the differences between the pitch angle as reconstructed by the simulated and actual device observations and the Vicon system in the sit-to-stand test. The differences between the actual and simulated trials are very low (0.15° in maximal values); indicating the accuracy of the device model described in [7]. Figure 3 also shows the error obtained when the drift compensation is not applied or when only the static compensation is used.

The decrease of error by means of the proposed drift compensation procedure is very high (> 3.2 °).

Task	Cut-off frequency	$\Delta\omega$	ω_m	ω_M	statistical significance
Sit-to-Stand	11.1 HZ	5 °/s	5° /s	90 °/s	0.048
Arising a step	111.4 HZ	3 °/s	3 °/s	45 °/s	0.040

Posturography (50 s)with eyes closed on Foam	11.5 HZ	0.1 ° /s	0.1 ° /s	5 ° /s	0.049

Table 1 Investigated locomotory tasks with the optimized calibration parameters and the statistical significance: cut-off frequency; ω_m= minimum value of the angular velocity; ω_M= maximal value of the angular velocity , $\Delta\omega$ = step of increment of the angular velocity .

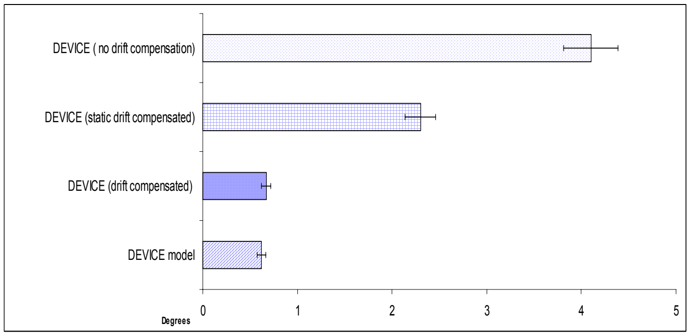

Figure 3 Pitch angle in the sit-to-stand test: Comparison error between the device (actual and simulated) and the Vicon system

IV Discussion and conclusions

Pure static calibration procedures, obtained by positioning the system with the kinematic sensors on an inclined plane, are useful for quasi-static applications and for pure accelerometric systems, but are not suitable for such device with . rate-gyroscopes and accelerometers. Other methods, based on the use of physics trolleys (e.g., the ones used in physics laboratories at schools), impose translation sinusoidal functions but are not accurate. A precise servohydraulic jig based on the mechanical piston MTS 810 (MTS Systems corp., Minneapolis) was successfully used in pure accelerometric systems in a previous study [11], but is not suitable for systems with rate gyroscopes. One approach that could be used for all types of systems, and thus for this device, involves the use of opto-electronic equipment or the use of a robotic arm, such as the Mod6400 (Smrobotica, Italy) anthropomorphic robot with programmable functions. However, although they are sufficiently accurate, they are particularly expensive and their use would not be justified for this purpose. In this paper, we introduced a novel methodology for calibration and compensation of the thermal drift of a device comprising three accelerometers and three rate gyroscopes. The complete methodology was validated on 30 subjects at level 2 of the Tinetti inbalance test [10] and for different locomotory tasks. The results showed that: (1)
the calibration methodology based on a step-wise system allowed optimization of the performances, as shown by observations that were highly correlated with simulated data. (2) The drift compensation procedure significantly improved the accuracy of the motion reconstruction.

The methodology outlined here is of particular interest for improving the accuracy of wearable devices in motion analysis. A review of the literature shows that the number of devices based on MEMS or NANO or ASIC technologies used in academia [12] and in industry [13] is increasing, reflecting the growing interest in and the need for such approaches.

References

[1] M.J. Mathie, A. C. F. Coster, N. H. Lovell, B. G. Celler "Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring of human movement " Physiological Measurement 25, R1-R20, (2004)

[2] F. R Allen, E. Ambikairajah, N. H. Lovell and B. G Celler "Classification of a known sequence of motions and postures from accelerometry data using adapted Gaussian mixture models". Phys. Meas., vol. 27, number 10, pp. 935-952. (2006)

[3] D . Giansanti, G. Maccioni, V. Macellari "The development and test of a device for the reconstruction of 3D position and orientation by means of a kinematic sensor assembly with rate gyroscopes and accelerometers " IEEE trans. Biomedical Engineering , Vol 52, Issue 7, pp. 1271- 1277, (2005)

[4] D Giansanti "Investigation of fall risk using a wearable device with accelerometers and rate gyroscopes" *Physiol. Meas.* 27 (2006) 1081 – 1090

[5] D. Giansanti "Does centripetal acceleration affect trunk flexion monitoring by means of accelerometers?" *Physiol Meas.* 27, pp. 999–1008, (2006)

[6] D. Giansanti and G. Maccioni "Physiological motion monitoring: a wearable device and adaptative algorithm for sit-to-stand timing detection." *Physiol Meas.* 26 (2006) 713-23

[7] D. Giansanti and G. Maccioni "Comparison of three different kinematic sensor assemblies for locomotion study," *Physiol. Meas.*, vol. 26, no. 5, pp. 689-705, Oct.2005.

[8] L. Chiari , M. Dozza, A. Cappello, F. B. Horak, V. Macellari, and D. Giansanti D, "Audio-biofeedback for balance improvement: an accelerometry-based system," IEEE Trans.Biomed.Eng, vol. 52, no. 12, pp. 2108-2111, Dec.2005.[9] DMC-1400 Series Manual By Galil Motion Control, Inc

[10] ER Kandel, RJ .Schwart, T.M Jessell "Principi di neuroscienze" (BOOK). Ed. Cea (2000)

[11] R. Moe-Nilssen "Trunk accelerometry: A new method for assessing balance under various task and environmental constrains" book Bergen University" ISBN 82-912332-20-2, (1999)