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In-use calibration of body-mounted gyroscopes for applications in gait analysis

Sergio Scapellato*, Filippo Cavallo, Chiara Martelloni, Angelo M. Sabatini

Scuola Superiore Sant'Anna, Piazza Martiri della Libertà 33, 56127 Pisa, Italy

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Abstract

In this paper, we propose an in-use calibration procedure for gyroscopes. The case report is a simple inertial measurement unit (IMU), which is used in our current research on inertial motion-sensing for advanced footware. The IMU contains two biaxial accelerometers and one gyroscope; it is developed for being mounted on one subject's foot instep, with the aim to reconstruct the trajectory in the sagittal plane of the sensed anatomical point. Since the IMU sagittal displacements can be estimated by performing strapdown integration, they can also be compared with their true values. One movement, which corresponds to known (vertical) displacements, consists of foot placements from the ground level on to top of steps of known height (step climbing). Provided that the IMU accelerometers are calibrated separately by any standard calibration procedure, motion tracking during the stepping movement allows to estimate the gyroscope sensitivity. The experimental results we present in this paper demonstrate the proposed in-use calibration procedure.

Keywords: Inertial measurement unit; Sensor calibration; Inertial motion-sensing; Gait analysis

1. Introduction

With the term inertial measurement units (IMU), it is customary to name devices, which embody inertial sensors – gyroscopes and/or accelerometers – mostly for being installed on man-made vehicles where navigation assistance is required, including spacecrafts, aircrafts and robots. The signals produced from these sensors – angular velocity and linear acceleration – can be processed to sense movement and orientation of the moving body where they are affixed [1].

Quite recently, inertial motion-sensing has found wide acceptance in other technological fields, including quantitative motion analysis as applied in biomedical and rehabilitation engineering. The main reason for this growing popularity is due to the opportunity they offer to sense motion and orientation without the restrictions, the encumbrance and the costs associated to the use of standard equipment existing within traditional motion analysis laboratories, e.g., video motion-sensing.

IMU attached to the body of tested subjects in several anatomical positions (head, chest, trunk, thigh, shank and foot) can be used to reconstruct joint angle rotations, to estimate spatio-temporal parameters of gait, to perform sophisticated motion tracking functions, owing to their capability of reconstructing the trajectory of sensed anatomical points in the three-dimensional space [2]. Reported applications in the medical field are to monitor activities of daily living and to estimate the energy expenditure incurred during a functional activity [3], both in normal and pathological conditions.

One of the most critical aspects connected with the use of inertial motion-sensing is represented by the influence of sensor bias and sensitivity drifts on the accuracy of inertial processing; uncertainty in the values of bias and sensitivity of these devices, due to the influence of environmental conditions are time-integrated and propagates up to the level that

* Corresponding author. Present address: Polo Sant'Anna Valdera, v. R. Piaggio 34, 56025, Pontedera (PI), Italy. Tel.: +39 050 883484; fax: +39 050 883497.
E-mail address: sergio@arts.sssup.it (S. Scapellato).

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the reconstructed trajectory is unreliable and inaccurate. For applications in the biomedical field, it is thus of the utmost importance the development of calibration procedures which can be used to check and verify the sensor offset and sensitivity during normal use of the IMU. Simple in-use calibration procedures for inertial sensors are described in [4], they are based on the possibility to move the sensor case in different orientations relative to the gravity field (accelerometric calibration) or to rotate the sensor case through known rotation angles (gyroscopic calibration) [7]. This possibility to manipulate the sensor case is precluded once the IMU is affixed to the body. A reasonable approach is then to instruct the subject to move, in order to get the information needed to verify sensor calibration. In Ref. [5], a simple procedure is described for achieving in-use calibration of triaxial accelerometers that are body-mounted. The procedure exploits the known fact that, in static conditions, the norm of the acceleration vector from a triaxial accelerometer would be $1g$ ($g = 9.81\ \mathrm{m/s^2}$). The instructions are then to change postures and to let the system to collect the sensorial information needed for calibration in the new postures. Similar-in-concept in-use calibration procedures are not yet available for gyroscopes. In this paper, we propose a simple in-use calibration procedure for gyroscopes. The procedure is applied to the IMU for advanced footware we are currently working on. After accelerometers are calibrated by standard procedures, movements such as climbing a step of known height are performed. Provided that the strapdown integration is performed by combining accelerometer and gyroscope signals, the optimal value of the sensor sensitivity for which the estimated distance comes closer to the true distance, which is assumed to be known, is searched. The level of agreement between the proposed in-use calibration procedure and standard calibration procedures is analyzed and discussed in the experiments reported in this paper. During both procedures, we verified thermal stability to assure that temperature did not influence sensor output.

In the last section is then described a simple motion analysis experiment, the reconstruction of foot movements during stair climbing, to test results obtained through in-use calibration.

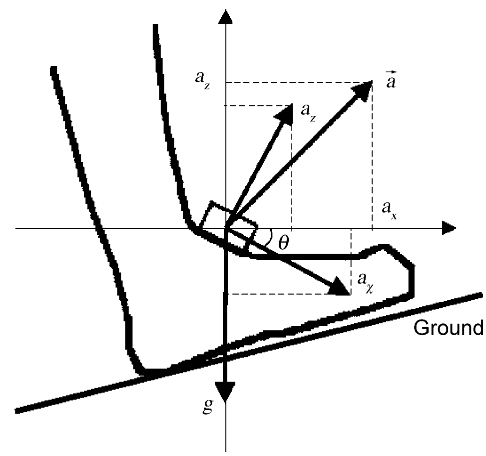

Fig. 2. IMU affixed to foot instep.

2. Instruments

The IMU (Fig. 1) for advanced footware sketched in was proposed to estimate a number of interesting gait parameters—stride time/length, cadence, walking speed and incline. It was composed of one gyroscope (Murata ENC-03J) and two biaxial accelerometers (Analog Devices ADXL210), arranged to form a triad of mutually perpendicular accelerometers; on IMU board are also integrated two simple driver circuits to interface sensor analog outputs: the accelerometric signal is sent directly to a buffer while the gyroscopic signal is sent to an analog filtering stage (accordingly with [6]). Both buffer and filtering circuits are made using a dual low-cost, rail-to-rail and single supply operational amplifier.

Once the IMU is affixed to the foot instep as shown in Fig. 2, the sensitive axis of the gyroscope is oriented in the medio-lateral direction.

The gyroscope measures the angular velocity around its sensitive axis, assumed to be orthogonal to sagittal plane, and allows to reconstruct IMU orientation in the sagittal plane θ by integration; the knowledge of θ is needed to project sensor output acceleration components $[a_x, a_z]$ over the sagittal directions $[a_X, a_Z]$ and also to remove gravitational contribution g.

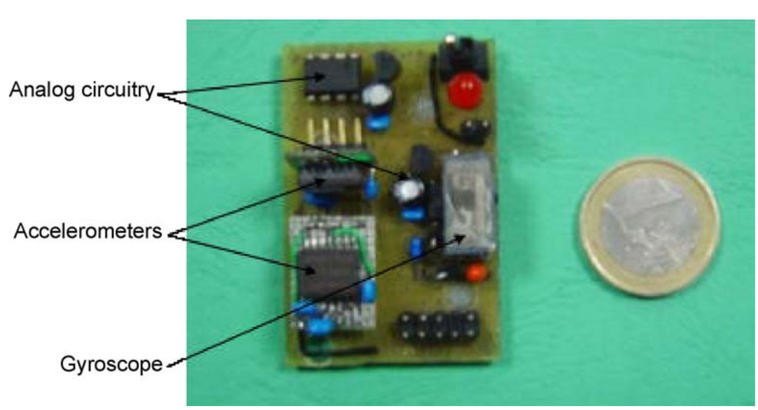

Fig. 1. IMU board containing two biaxial accelerometers, one gyroscope and a simple analog circuit.