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Technical note

Evaluation of suitability of a micro-processing unit of motion analysis for upper limb tracking

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ABSTRACT

The aim of this study is to assess the suitability of a micro-processing unit of motion analysis *(*MPUMA*)*, for monitoring, reproducing, and tracking upper limb movements. The MPUMA is based on an inertial measurement unit, a 16-bit digital signal controller and a customized algorithm. To validate the performance of the system, simultaneous recordings of the angular trajectory were performed with a video-based motion analysis system. A test of the flexo-extension of the shoulder joint during the active elevation in a complete range of 120º of the upper limb was carried out in 10 healthy volunteers. Additional tests were carried out to assess MPUMA performance during upper limb tracking. The first, a 3D motion reconstruction of three movements of the shoulder joint *(flexo-extension, abduction–adduction, horizontal internal–external rotation)*, and the second, an upper limb tracking online during the execution of three movements of the shoulder joint followed by a continuous random movement without any restrictions by using a virtual model and a mechatronic device of the shoulder joint. Experimental results demonstrated that the MPUMA measured joint angles that are close to those from a motion-capture system with orientation RMS errors less than 3º.

1. Introduction

Human motion analysis consists of recording and measuring three-dimensional motions of body segments over the time [1,2]. Some techniques, such as video motion analysis, and, recently, inertial sensors, have been used for this purpose. Video-based motion analysis systems provide information about the human kinematics allowing determining position and orientation of the body segments online. These systems are often thought of as a laboratory gold standard for human motion analysis [3]. However, video-based systems require a controlled environment, dedicated hardware and software, besides they demand a lot of time for data processing and also present occlusion problems [4,5].

New proposals of systems for assessing and monitoring human body motion in different environments have been explored [6–8]. Some studies report the use of inertial sensors such as accelerometers [9–11] and gyroscopes [12,13] because of their compact size, lightweight, low price, and accuracy. Despite these benefits, serious drift problems are reported when sensors were used individually [14]. Some other studies suggest that a combination of accelerometers and gyroscopes, known as inertial measurement units (IMUs), can be used to reduce drift problems as a first approximation [15,16]. Although commercial systems based on IMUs are already available, some of these systems only permit to capture and store raw data by a peripheral storage unit or by a PC connection [17–19] while others provide already processed information derived from inertial sensors. However, these systems are exclusively designed for analyzing specific activities [20–22]. So, some common challenges such as motion tracking, motion reconstruction, and drift reduction remain [23–25]. In any case, commercial systems cannot easily be used for implementing new algorithms to overcome these issues unless an external source of data processing is available because their microcontroller devices are not programmable [26].

In this paper, the suitability of a *micro-processing unit of motion analysis* (MPUMA) for upper limb tracking is presented. This system is based on the combination of inertial sensors and a customized algorithm used to determine the orientation of the upper limb in 3D space; both MPUMA and the algorithm were developed in our laboratory [27]. The MPUMA has the capability to capture and store raw data as well as to process information derived from

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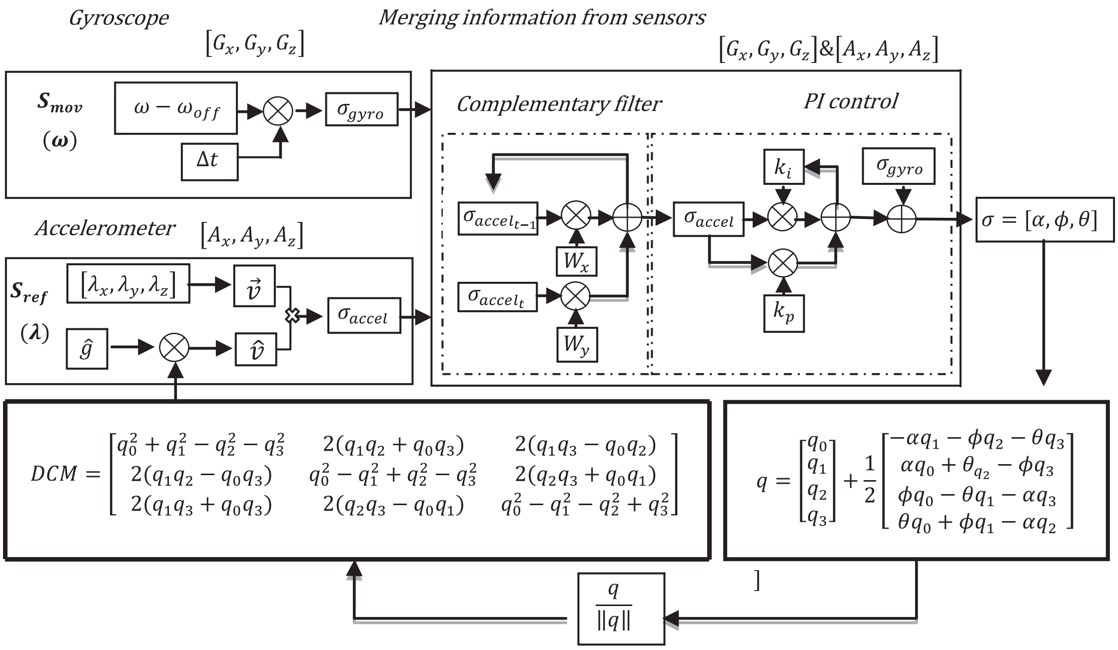

Fig. 1. Block diagram of orientation estimation: algorithm for merging gyroscope and accelerometer information.

inertial sensors, giving the possibility to analyze specific activities or design new algorithms.

The aim of this study is to extrapolate the application of MPUMA for recording and measuring three dimensional motion of the upper limb at the shoulder level online; therefore, a sensor fusion technique was implemented by using the customized algorithm. The MPUMA was intended to measure upper limb motion in an uncontrolled environment, at low computational cost, without occlusion problems, and a drift reduction; thus improving the performance and accuracy of motion analysis, motion reconstruction, and upper limb tracking.

2. Material and methods

2.1. Description of the system

The evaluated system, named *micro-processing unit of motion analysis* (MPUMA), is the integration of a 16-bit digital signal controller *(Microchip®-dsPIC-30F6014A)* and an inertial measurement unit (IMU) *Invensense-MPU6050*, which consisted of a three axes gyroscope and a three axes accelerometer. The gyroscope and accelerometer sensors were configured to a full-scale range of $\pm 250^\circ/s$ and $\pm 2g$ with a bandwidth of 250 Hz and 260 Hz respectively [28]. Full-scale range parameters and bandwidth were defined based on the values commonly reported in the evaluation of joint kinematics [29–31]. Data acquisition, processing and optimization techniques were developed in a *dsPIC* device. The storage, analysis and comparison of kinematic information were carried out with *MATLAB R2013a®*. Communication between *dsPIC* device and *IMU* was performed via inter-integrated circuit serial protocol (I^2C) and between dsPIC device and *MATLAB®* through the USB port.

2.2. Orientation estimation

The algorithm developed for merging the information from sensors is shown in Fig. 1, and it is detailed below. Gyroscope and accelerometer raw data; $[G_x, G_y, G_z]$ and $[A_x, A_y, A_z]$ respectively, was used to define two suitable coordinate systems; arm movement (S_{mov}), relating the angular rate of change ($\omega - \omega_{off}$) along the time (Δ_t) to shoulder rotation (σ_{gyro}) Eq. (1), and reference system (S_{ref}) which used accelerometer information (λ) Eq. (2) for drift compensation.

$$S_{mov} \rightarrow \sigma_{gyro} = (\omega - \omega_{off})*\Delta t \times \begin{cases} \omega = [G_x, G_y, G_z] \\ \omega_{off} = \frac{\sum_{i=0}^{n=1000} \omega_i}{n} = [\omega_{off_x}, \omega_{off_y}, \omega_{off_z}] \end{cases} \quad (1)$$

$$S_{ref} \rightarrow \lambda = [A_x, A_y, A_z] \quad (2)$$

Orientation from the accelerometer information (σ_{accel}), was computed through the cross product Eq. (3) between an inertial vector ($\vec{v}$), given by normalized λ, and a gravity vector ($\hat{v}$), which defined the vertical axis Z of the estimated arm orientation by relating the acceleration of gravity ($\hat{g} = [0, 0, 1]$) and a *direction cosine matrix (DCM)* [32,33].

$$\left.\begin{aligned} \vec{v} &= \tfrac{\lambda}{\|\lambda\|} = [\vec{v}_x, \vec{v}_y, \vec{v}_z] \\ \hat{v} &= \hat{g}*\mathrm{DCM} = [\hat{v}_x, \hat{v}_y, \hat{v}_z] \end{aligned}\right\} \sigma_{accel} = \vec{v} \times \hat{v} \quad (3)$$

Given that $\lambda = [A_x, A_y, A_z]$ was susceptible to a high noise level induced due to variations in velocity [14,15], a complementary filter was used in order to eliminate accelerometer noise Eq. (4). The results were used for interacting with a proportional integral control (PI) [34,35], in order to gradually incorporate the estimated angular displacements Eq. (5).

$$\sigma_{accel} = W_x[\sigma_{accel}]_{t-1} + W_y[\sigma_{accel}]_t \quad (4)$$

$$\sigma = \sigma_{gyro} + k_p[\sigma_{accel}] + ki \int_0^t f[\sigma_{accel}] = [\alpha, \phi, \theta] \quad (5)$$

Shoulders orientation (σ) was determined by merging σ_{gyro} and σ_{accel}, which allowed estimating the spatial relationship between both coordinated systems, S_{mov} and S_{ref}, by using quaternions (q), as shown in Eqs. (6) and (7).

$$q = q_{t-1} + \int_0^t q\ dt = q_{t-1} \otimes q_t = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} + \frac{1}{2}\begin{bmatrix} -\alpha q_1 - \phi q_2 - \theta q_3 \\ \alpha q_0 + \theta_{q_2} - \phi q_3 \\ \phi q_0 - \theta q_1 - \alpha q_3 \\ \theta q_0 + \phi q_1 - \alpha q_2 \end{bmatrix} \quad (6)$$

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