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DESIGN OF INERTIAL MOTION SENSOR AND ITS USAGE IN BIOMECHANICAL ANALYSIS

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Abstract. In this paper the design and calibration of a three-axial inertial motion sensor in biomechanics is presented. The sensor is aimed at measuring the linear acceleration and angular velocity during motion in 3-D space. The calibration procedure enables the computation of acceleration of an arbitrary point on a rigid body in the case when the sensor is fixed with the body. The experimental results acquired during standing-up motion of human subject and compared to the reference kinematic measurement prove the functionality of the sensor and adequacy of the proposed method.

Keywords: inertial sensor, motion assessment, acceleration, angular velocity.

1. Introduction

Over the last few years, micromachined inertial sensors have become more widely available. Since they are small in size, they are practical for implementation. The application areas span from automotive to avio, space, robotic, and biomedical engineering fields [1-3].

In dynamic analysis of rigid body motion, the knowledge of translational and angular velocities and accelerations of body center of mass is crucial. Some of this values are, however, not directly measurable, therefore the computation from the values which are feasible for assessment is required. The main objectives for the design of inertial motion sensor for us were the capability of measurement of acceleration and angular velocity in 3-D space, miniature, lightweight and mechanically solid construction, and the possibility of easy mounting to the mechanical or biomechanical structures.

The first section presents the incorporated electronic components of the sensor, physical layout of PCBs and its mechanical construction. The second section introduces the procedure for identification of the geometrical relation between the body and sensor attached on it. In the third section the theory is given enabling the calculation of angular velocities from the measured positions of body markers. In this way, the reference values were determined for comparison with the sensor outputs. The experimental measurements of the standing-up maneuver of human subject together with the results are described in the last section to demonstrate the functionality of the sensor and presented algorithms.

2. Design and calibration of inertial motion sensor

The inertial sensor was built on a basis of Analog Devices integrated circuits ADXL203 and ADXRS150. The ADXL203 is a high precision, low power, dual axis accelerometer with a full-scale measurement range of ± 1.7 g. The ADXRS150 gyroscope is an angular rate sensor measuring in a range of ± 150 °/s. The integrated circuits are built with an iMEMS (Integrated Micro Electro-Mechanical System) technology, which allows high miniaturization of the design.

To measure three accelerations and three angular velocities in 3-D space, two two-axis accelerometers and three single-axis gyroscopes are needed mounted in three planes perpendicular to each other. Two PCBs were designed and assembled in orthogonal configuration as presented in Figure 1a. For the housing of the inertial sensor the standard Aluminium profile (Bosch Rexroth AG) was chosen. The electronic boards were assembled into the grooves along the profile. The construction is presented in Figure1b.

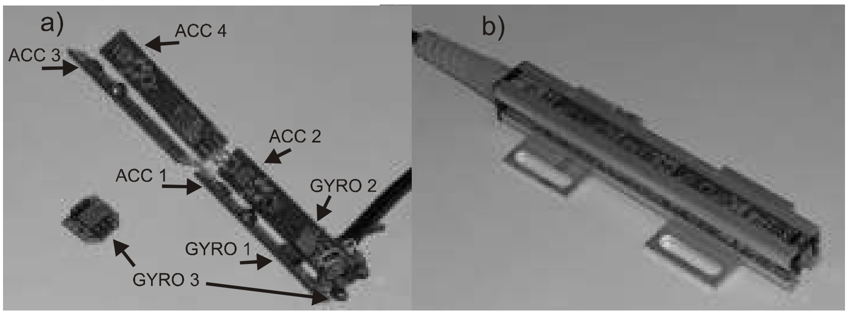

Fig. 1.- a) The sensor PCB construction, and b) assembled inertial motion sensor.

In motion analysis of rigid body, the inertial sensor is attached to the body on a place most convenient for fixation. Since the sensor can be arbitrarily orientated, the position and orientation of the rigid body reference frame (usually positioned in its center of mass) and the reference frame of the sensor are not aligned. Since both reference frames are not moving relatively, the transformation between them is fixed. The situation is illustrated in Figure 2a. In Figure 2b the same situation is presented in biomechanical analysis of human motion. Inertial sensor is attached to the surface of subject's right thigh, while the thigh's reference frame lies in its center of mass.

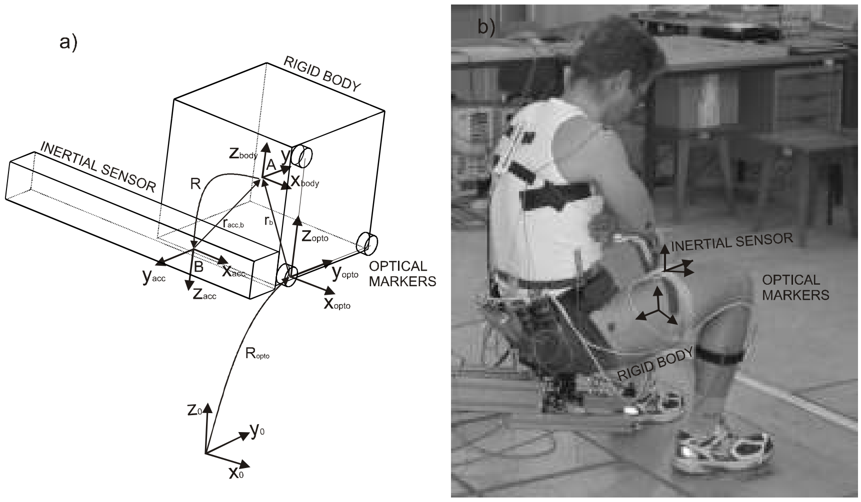

Fig. 2.- a) Inertial sensor attached to the body, and b) inertial sensor attached to the right thigh of human subject.

The transformation between the body reference frame and the reference frame of sensor is composed of the orientational $\mathbf{R}$ and translational part. The transformation $y_i = \mathbf{R}x_i + r_{acc.b}$ can be used to transform the vector expressed in one reference frame to the same vector expressed in another reference frame.

After the sensor fixation on a body, an identification of $\mathbf{R}$ matrix is needed. For the identification, the sensor output is compared to the reference known position. In our study, for the reference measurement we employed the optical kinematic measurement system Optotrak (Northern Digital, Inc., Waterloo, Canada) measuring the 3D positions of markers (infrared LEDs) attached to the body (see Figure 2). From the measured positions of markers, the reference frame was constructed and its orientation matrix determined. The angular velocity was computed from known orientation via the quaternions notation and their derivation.

The rotation matrix $\mathbf{R}$ was determined by the help of simultaneous measurement of the gravitational acceleration and the reference position in different poses [5, 6].

When the gravity is measured by the arbitrarily oriented inertial sensor, the output vector is $A_m = (a_x, a_y, a_z)$. The body and sensor acceleration vectors are related via the rotation matrix $\mathbf{R}$ as $A_b = \mathbf{R}A_m$.

For the matrix $\mathbf{R}$ is required that is a proper orthonormal matrix, which therefore has the following properties: $\mathbf{R}^T\mathbf{R} = \mathbf{R}\mathbf{R}^T = \mathbf{R}^{-1}\mathbf{R} = I$ and $\det \mathbf{R} = +1$, where $\boldsymbol{I}$ is the identity matrix.

Using a least-square method the problem of determining $\mathbf{R}$ is the equivalent to minimizing

$$\frac{1}{n}\sum_{i=1}^{n}(\mathbf{R}A_{mi}-A_{bi})^{T}(\mathbf{R}A_{mi}-A_{bi}) \tag{1}$$

where n is the number of non-collinear points measured in both reference frames ($n \geq 3$). Problem (1) can be rearranged to give the following to maximize

$$\frac{1}{n}\sum_{i=1}^{n}(A_{bi}^{T}\mathbf{R}A_{mi}) = tr(\mathbf{RC}) \tag{2}$$

where $tr()$ refers to the trace (sum of the diagonal terms) of a given matrix and $\mathbf{C}$ is the cross-dispersion matrix (also known as the correlation matrix): $\mathbf{C} = \frac{1}{n}\sum_{i=1}^{n}(A_{bi}^{T}A_{mi})$.

The singular value decomposition (SVD) of matrix $\mathbf{C}$ produces a diagonal matrix W, of the same dimension as $\mathbf{C}$ and with nonnegative diagonal elements – singular values of $\mathbf{C}$, and unitary orthogonal matrices U and V so that $\mathbf{C} = \boldsymbol{UWV}^{T}$. If the results of the SVD are substituted into (2) the following relationships exist:

$$tr\{\mathbf{RC}\} = tr\{\mathbf{R}^{T}\boldsymbol{UWV}^{T}\} = tr\{\boldsymbol{V}^{T}\mathbf{R}^{T}\boldsymbol{UW}\} = tr\{\boldsymbol{QW}\} \tag{3}$$

where a new matrix **Q** is defined by $\boldsymbol{Q} = \boldsymbol{V}^{T}\boldsymbol{R}^{T}\boldsymbol{U}$.

Since matrix W shown in (3) is a diagonal matrix, only the diagonal elements of matrix **Q** can contribute to the trace. In addition, matrix **Q** must be orthogonal because all three matrices composing **Q** are orthogonal. Therefore, $tr\{\boldsymbol{QW}\}$ becomes maximum when **Q** is the identity matrix $\boldsymbol{V}^{T}\boldsymbol{R}^{T}\boldsymbol{U} = \boldsymbol{I}$. Therefore, after some derivation we get

$$\boldsymbol{R} = (\boldsymbol{VU}^{T})^{T} = \boldsymbol{UV}^{T} \tag{4}$$

For certain cases when determining the rotation matrix for describing relative orientation, the formulation (4) does not hold, and rather than getting a matrix of determinant of +1, the matrix R has a determinant of -1, in which case it represents a reflection. The following modification accounts for this. If the SVD of C has been computed then $tr\{\mathbf{R}^{T}\mathbf{C}\}$ is maximized when

$$\boldsymbol{R} = \boldsymbol{U}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \det(\boldsymbol{UV}^{T}) \end{bmatrix}\boldsymbol{V}^{T} \tag{5}$$

When the relative rotation $\mathbf{R}$ and the displacement $r_{acc,b}$ between the body and the sensor reference are known, the linear acceleration of the body COM can be determined. The acceleration A_b is composed of two contributions: the linear acceleration of the sensor and the acceleration which is the consequence of the body angular velocity. The relation is

$$A_b = \boldsymbol{R}A_m + \dot{\omega}^b \times r_{acc,b} + \omega^b \times (\omega^b \times r_{acc,b}) \tag{6}$$

3. Evaluation experiment in biomechanical analysis of standing-up

For the evaluation of proposed calibration procedure an experimental measurement was accomplished. In the experiment, the rising from the sitting to standing position was analyzed. A male subject participated in the study (DK, 172 cm height, 72 kg weight, 33 years old). The inertial motion sensor and optical markers were attached to the subject's right lower extremity as presented in Figure 2b. Three sets of measurement data were acquired. The first set encompassed the acquisition of gravitational and zero acceleration along each axis of sensor's reference frame. The acquired data represented the sensor outputs for 1g and zero accelerations, and zero angular velocity, from which the offsets were determined. In the second set of measurements the subject took five different arbitrary poses and the acceleration and the position of markers were recorded in a standstill. From the acquired positions of optical markers the orientation of the subject's thigh reference frame was determined and the transformation matrix $\mathbf{R}$ calculated according to Section 2. The third set of measurements was accomplished to verify the acceleration and angular velocity sensor outputs during motion. A series of subject's standing-up trials was assessed while the sensory outputs were sampled with 500 Hz sampling frequency. For the comparison, the gravity acceleration vector was manually added to the acceleration computed from kinematic data.

Figure 3 presents the results of the third set of measurements. Figures compare the data obtained by the inertial sensor and by the optical kinematic measurement system in dynamic phase of standing-up.

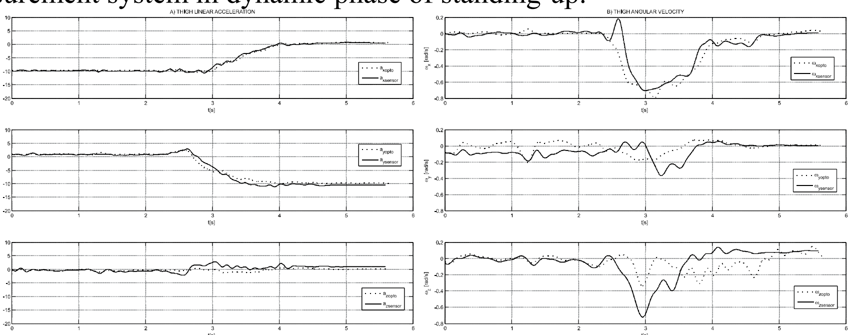

Fig. 2.- a) Right thigh linear acceleration, and b) right thigh angular velocity assessed by the inertial sensor and optical measurement system.

4. Conclusions

The inertial motion sensor aimed for acquisition of acceleration and angular velocity in 3-D motion was developed according to the initial requirements for miniature, solid and practical design. A calibration procedure is proposed with which it is possible to calibrate the sensitivities and the offsets of the sensor, and to determine the geometrical relation of the sensor to the body fixed reference frame.

The experimental results presented indicate that the sensor is designed according to initial requirements and that the calibration procedure is adequate. Good alignment between the sensor measurements and the reference kinematic measurements in acceleration assessment as well as in angular velocity assessment is demonstrated. Smaller deviations in angular velocity signals are attributed to the high sensitivities of gyroscopes and errors due to kinematic data derivation and filtration.

Considering practical applications for the inertial sensor, the advanced algorithms, as for example the extended Kalman filter, can be employed for an absolute position estimation.

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