A Computational Method for Inertial Sensor Alignment to Body Segment

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Abstract. Inertial sensors provide useful information on human motion in the biomechanics and clinical application. Since the inertial sensor output is based on the sensor coordinate, the output signal needs to be analyzed in the body segment coordinate for intuitive interpretation occasionally. This study presents a computational method to align the inertial sensor coordinate to the body coordinate. In the proposed method, gyroscope signal sampled during a body segment rotates is analyzed by a principle component analysis. To show the functional feasibility, the proposed method was applied to young healthy subjects. The repeatability of coordinate alignment for the test and retest showed no significant difference.

Keywords: Inertial Measurement Unit, Calibration, Inertial Sensor, MEMS Sensor, Motion tracking

1 Introduction

Recently, as a result of technological advances, inertial sensors based on a micro-electro-mechanical systems (MEMS) have been frequently used for human motion analyses [1-6]. The MEMS-based sensor, which is called an inertial measurement unit (IMU), is usually attached to a body segment, and biomechanical information is extracted from its signal. While the output signal from the IMU is based on the sensor coordinate system (CS), it is necessary to express the signal in the body segment CS for clinical meaning. The offset between the sensor CS and anatomical CS needs to be decided.

This study proposes a calibration method that determines the orientation offset between a body segment and an IMU attached to the body segment. The angular velocity data are sampled while the body segment is rotated along its axis. The angular velocity is processed by the principle component analysis (PCA) [7] to express the rotation axis in the IMU CS. The proposed method is applied to calibrate...
an IMU attached to a forearm. Its repeatability is evaluated for five young healthy subjects.

2 Calibration Method

The IMU (38 mm × 22 mm) consisted of a microprocessor, sensor ICs, and a Bluetooth communication module. The microprocessor (STM32F103C8, STMicroelectronics) read the sensors using I2C (inter-integrated circuit) communication and sent the sensor data via the Bluetooth module (Parani ED 200, Sena Technology, Korea) to a PC. A three-axis accelerometer/magnetometer (LSM303DLHM, STMicroelectronics) and a three-axis gyroscope (L3GD20, STMicroelectronics) were used as sensors. The gyroscope was set to a full scale of ±500°/s and a sampling rate of 100 Hz.

The coordinate system of the forearm was considered according to the recommendation of the International Society of Biomechanics (Fig. 1b) [8]. The origin coincided with the center of the ulnar styloid (US) and radial styloid (RS). The Y axis points proximally along the longitudinal direction. The Z axis points ventrally to the palm side, and the Z axis points medially.

![Fig. 1. Coordinate system of the forearm.](image)

The X and Y axes are determined by processing the angular velocities with the PCA. The angular velocities are measured while the forearm is supinated/pronated and flexed/extended for the X and Y axes, respectively. For the PCA processing, the angular velocity samples, \( \omega_i \), are arranged in a 3 × \( N \) angular velocity matrix, \( \Omega \), where \( N \) is the number of samples. Here, the average angular velocity is subtracted from the angular velocity sample \( \omega_i \).

\[
\Omega = \begin{bmatrix}
\omega_1^T & \omega_2^T & \ldots & \omega_N^T
\end{bmatrix}
\]  

From the angular velocity matrix, a 3 × 3 covariance matrix, \( C_\Omega \), is calculated, as in Eq. (2). Here, \( C_\theta \) is the covariance between the i-axis angular velocity and j-axis angular velocity.
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\[
C_{\Omega} = \frac{1}{N-1}\Omega \Omega^T = \begin{bmatrix}
    c_{xx} & c_{xy} & c_{xz} \\
    c_{yx} & c_{yy} & c_{yz} \\
    c_{zx} & c_{zy} & c_{zz}
\end{bmatrix}
\]  (2)

The PCA calculates a coordinate transformation with which the largest covariance is projected to the basis of a new CS. To obtain this transformation, an eigenvalue \((\lambda_x, \lambda_y, \lambda_z)\) and eigenvector \((v_x, v_y, v_z)\) pair that satisfies Eq. (3) is calculated.

\[
C_{\Omega}v_i = \lambda_i v_i 
\]  (3)

From the calculated eigenvalue \((\lambda_x, \lambda_y, \lambda_z)\) the largest value \(\lambda_{\text{max}}\) is determined. The eigenvector \(v_{\text{max}}\) corresponding to the largest eigenvalue \(\lambda_{\text{max}}\) is the basis of the new CS, into which the angular velocity with the largest variance is projected. This means that \(v_{\text{max}}\) is the anatomical rotating axis expressed in the sensor CS.

3 Performance Evaluation

Five young healthy subjects (25–29 years old, with a mean of 26.6 years, all male) were included in this experiment. All the subjects signed an informed consent declaration before participation. The IMU was attached on the distal end between the centers of the US and RS.

Because the calibration procedure begins by determining each basis, the repeatability of each basis was compared for the three methods and the test–retest procedures. For the repeatability, the mean basis for each subject, \(\bar{b}\), was first calculated by averaging their vectors for the six repetitions, \(b_i\), followed by normalization. Next, the angular differences between the basis vectors and mean basis were calculated, as in Eq. (4). Here, \(i\) and \(\times\) stand for the repetition number (1–6) and vector cross product, respectively.

\[
\Delta b_i = \sin^{-1}(\hat{b}_i \times \bar{b})
\]  (4)

The repeatability of the basis differences were compared using a paired t-test for the test and retest for all subjects. They showed no difference, and this means that the proposed methods show reasonable repeatability.
4 Conclusion

In this study, a calibration method that determines the orientation offset between a body segment and an IMU attached to the body segment was proposed. The angular velocity was measured while the body segment was rotated and then processed by the PCA to form the basis of the orientation offset. The proposed method was applied to calibrate an IMU attached to the forearm and evaluated using five young healthy subjects. Its performance showed reasonable repeatability.

Acknowledgments. This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education, Science and Technology (2013-026506)

References