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Anatomy Calibration of Inertial Measurement Unit Using a Principle Component Analysis

Je-Nam Kim[1], Mun-Ho Ryu[2,3], Ho-Rim Choi[1] and Yoon-Seok Yang[2,3]

[1]Department of Healthcare Engineering, Chonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
[2]Division of Biomedical Engineering, Chonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
[3]Center for Healthcare Technology Development, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 561-756 Republic of Korea

zero-day@nate.com, {mhryu, ysyang}@jbnu.ac.kr

Abstract

Recently, as a result of advances in technology, micro-electro-mechanical system (MEMS)-based inertial measurement units (IMUs) have frequently been used for human motion analyses. While the output signal from an 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 determined. 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 processed using a principle component analysis to form the basis of the orientation offset. The proposed method was applied to calibrate an IMU attached to the forearm and evaluated for five young healthy subjects. Its performance showed reasonable repeatability (mean < 1.4°, SD < 0.8°).

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.

Even though their number is limited as compared to the various researches for stereo-photogrammetric motion analysis techniques, a few calibration methods have been proposed for the IMU [1-2, 4-5]. These calibrations are achieved by aligning the body segment exactly with the inertial axis and investigating the sensor signal. For example, to calibrate an IMU for the forearm, the forearm is held for a while with the palm facing down so that its direction is aligned with gravity as accurately as possible [2]. During this time, the accelerometer signal is measured as the palm's direction expressed in the sensor CS. For the longitudinal direction,

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the forearm is supinated or pronated along the longitudinal axis, which is kept horizontal. Because the forearm is rotated along the longitudinal axis, the angular velocity dominates in the longitudinal direction. The normalized angular velocity measured by a gyroscope corresponds to the longitudinal axis expressed in the sensor CS. The third axis is determined by the cross product of the palm-side axis and longitudinal axis. A similar method was proposed to calibrate IMUs in the legs [4,5]. In this study, a mean rotation axis is calculated from the measured angular velocity while the shank or thigh is rotated passively along the anatomical axis.

The above-mentioned methods are based on effective mechanisms and show reasonable performance. However, they raise potential difficulties. Because of the constraint that the palm must be kept facing down, in the direction of gravity, the repeatability of the axis along the palm side can be deteriorated. This constraint could also make it difficult for a patient with diminished motor function from a disease such as stroke to benefit from the IMU-based technology. For the procedure to determine the rotating axis from the angular velocity, it would be advantageous to apply a statistical method so that all the sampled angular velocity data can be utilized.

Meanwhile, the principle component analysis (PCA) is an orthogonal linear transformation that transforms data to a new CS in a way that the greatest variances are projected on the new CS [7]. If the PCA is applied to this calibration procedure, it would rotate the measured angular velocity from the sensor CS to a new CS in a statistical manner, which shows the greatest variance in angular velocity. This transformation corresponds to the orientation offset between the sensor and body segment.

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 PCA 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

2.1. Inertial Measurement Unit

The IMU (38 mm × 22 mm) consisted of a microprocessor, sensor ICs, and a Bluetooth communication module (Fig. 1a). 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.

2.2. Coordinate System of Forearm

The coordinate system of the forearm was considered according to the recommendation of the International Society of Biomechanics (Figure 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.

The calibration procedure is used to determine the relative orientation of the IMU sensor CS (S) to the body segment's anatomical CS (A). This orientation corresponds to a 3 × 3 rotation matrix of which each column is the basis A expressed in the bases of S, as in Eq. (1).

$$^{A2S}R = \begin{bmatrix} ^{S}X & ^{S}Y & ^{S}Z \end{bmatrix}^{T}. \quad (1)$$

Here, the left superscript over the vector indicates the CS where the vector is expressed. The right superscript T denotes the matrix transpose. For example, ^{S}X means the X basis of the anatomical CS expressed in the sensor CS.

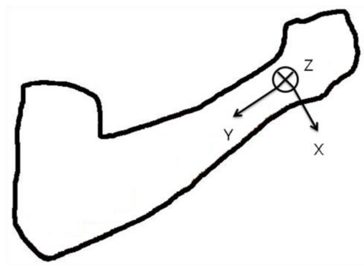

Figure 1. (a) Inertial Measurement Unit (Left) and (b) Coordinate System of the Forearm (Right)

2.3. Anatomical Calibration Method

Three calibration methods were considered in this study. In the first method (M1), the Z and Y axes are determined by the acceleration and angular velocity while the forearm is supinated or pronated with the Y axis kept in a horizontal position [2]. The Z axis is determined by the normalized gravity, g_{start}, measured while the forearm is held with the palm facing down at the start of rotation, as in Eq. (2).

$$^{S}Z = -g_{start} / \left| g_{start} \right|. \quad (2)$$

The Y axis is determined using the normalized angular velocity measured while the forearm is supinated ($\omega_{\sup}$) or pronated (ω_{pro}), as in Eq. (3). In this method, the gravity data and angular velocity are selected by the examiner (g_{start} and $\omega_{\sup}$ marks in Figure 2). This means an interruption by the examiner is necessary and only a single data point is used to determine each axis.

$$^{S}Y = \frac{\omega_{\sup}}{\left|\omega_{\sup}\right|} = -\frac{\omega_{pro}}{\left|\omega_{pro}\right|}. \quad (3)$$

The X axis is determined using the Y and Z axes. However, because the Y and Z axes are not perpendicular to each other, the Z axis is orthogonalized, as in Eq. (4).

$$ {}^{A2S}R = \left[{}^{S}X \quad {}^{S}Z \times {}^{S}X \quad {}^{S}X \times \left({}^{S}Z \times {}^{S}X \right) \right]. \tag{4} $$

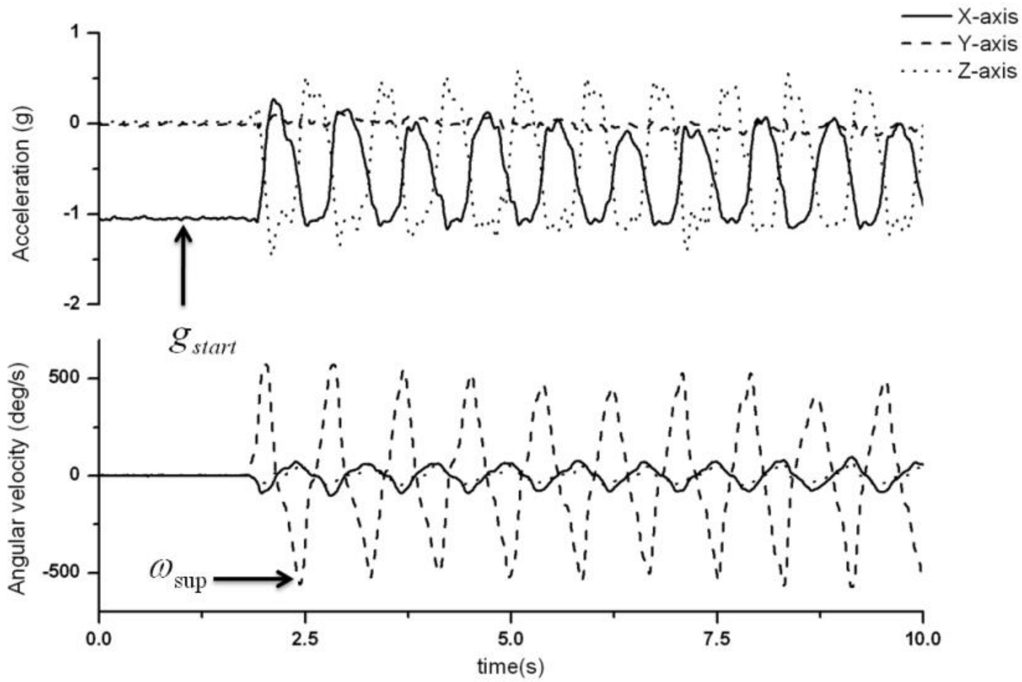

Figure 2. Acceleration and Angular Velocity Signals during M1 Calibration

In the second method (M2), the Y and Z axes are determined using the normalized angular velocities while the forearm is rotated, as in Eq. (4) [4, 5]. However, in this method, the *Y* and *Z* axes are averaged for all the angular velocities measured during the rotation. To average the axis, its vectors are averaged and normalized so that the average axis maintains the unit length. The *X* axis is calculated using the *Y* and *Z* axes and is orthogonalized in a way similar to M1.

In the third method (M3) proposed here, the *Y* and *Z* 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 *Y* and *Z* axes, respectively. For the PCA processing, the angular velocity samples, ω_i, are arranged in a 3 × *N* angular velocity matrix, Ω, where *N* is the number of samples. Here, the average angular velocity is subtracted from the angular velocity sample ω_i.

$$ \Omega = \left[\omega_1^{\;T} \quad \omega_2^{\;T} \quad \ldots \quad \omega_N^{\;T} \right]. \tag{5} $$

From the angular velocity matrix, a 3 × 3 covariance matrix, C_Ω, is calculated, as in Eq. (6). Here, c_{ij} is the covariance between the *i*-axis angular velocity and j-axis angular velocity.

$$C_{\Omega} = \frac{1}{N-1}\Omega\Omega^{T} = \begin{bmatrix} c_{xx} & c_{xy} & c_{xz} \\ c_{yx} & c_{yy} & c_{yz} \\ c_{zx} & c_{zy} & c_{zz} \end{bmatrix}. \quad (6)$$

When the sensor CS is perfectly aligned with the anatomical CS, c_{ii} for the rotating axis, i, has a maximal value of 1, and the rest of the cross variance elements have a minimal value of 0. Thus, the covariance element whose sensor axis is most accurately aligned with the anatomical axis has the largest value, while the rest of the cross variance elements have smaller values. 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. (7) is calculated.

$$C_{\Omega}v_i = \lambda_i v_i . \quad (7)$$

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

3. Performance Evaluation

3.1. Method Subjects and Experimental Protocol

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.

The IMU was aligned visually and fixed with a sanitary bandage. After several elbow movements over a few minutes to become familiar with the system, the subject rotated their forearm within 40° during 20 s while the three calibration methods were performed in sequence. This sequence was repeated six times at two-minute intervals. After these six repetitions, the subject took off the IMU. After 20 min of rest, they reattached the IMU and repeated the sequence six times for a retest.

3.2. Basis Repeatability

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. (8). Here, i and $\times$ stand for the repetition number (1–6) and vector cross product, respectively.

$$\Delta b_i = \sin^{-1}(b_i \times \bar{b}). \qquad (8)$$

The repeatability of the basis differences were compared using a paired *t-test* for the test and retest for all the subjects Table 1. M1 and M2 showed significant differences for the *Y* axis, while M3 showed no difference. M3 showed better repeatability than M1 and M2.

Table 1. Repeatability of Basis Differences against Test and retest for all Subjects. Each Data Point is the p-value of the Paired t-test. The * Mark Indicates a Significant Difference between the Test and Retest

M1			M2			M3		
X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
0.7170	0.0009*	0.8884	0.3445	0.0001*	0.7490	0.6766	0.8058	0.9989

The basis differences are shown for the three axes and three methods in Table 2. All the basis differences for the test and retest are included here. The means and standard deviations of the basis differences decreased in the order M1, M2, and M3 for all the axes. This indicates that M3 showed the best repeatability, and M2 was the second best. In particular, the *Y* axis showed significant differences among the methods after being tested using an analysis of variance (ANOVA) test ($p < 0.0000$). The multiple comparison test using Tukey's criterion for the methods for the *Y* axis showed that M3 was significantly different from M1 and M2.

The ANOVA test for the axes showed significant differences between the three methods ($p = 0.0174$, $p = 0.0062$, and $p < 0.0000$ for M1, M2, and M3, respectively). In the multiple comparison test for the axes, the basis differences decreased in the order of the *X*, *Z*, and *Y* axes.

In M1, the basis difference in the *Z* axis was large because aligning the palm with gravity, facing down, was not accurate, as expected. The *Y* axis difference was also large, which was unexpected. This can be explained by the fact that it was difficult to maintain the forearm in a horizontal direction exactly during the rotation. In M2 and M3, the *Z* axis difference was large because the rotation was not repeated accurately along the *Z* axis, which was transversal in the longitudinal direction.

Table 2. Mean (SD) of Basis Differences for Three Methods (°)

	M1	M2	M3
X	1.5604 (0.9270)	1.4407 (0.7061)	1.3087 (0.7221)
Y	1.1339 (0.6336)	0.7898 (0.4498)	0.5680 (0.3519)
Z	1.3929 (0.8630)	1.3355 (0.7271)	1.2837 (0.7573)

3.3. Angle Repeatability

The final purpose of the calibration was to determine the rotational angle between the IMU and body segment coordinate systems. The repeatability of the rotation angle was evaluated for the three methods and test–retest procedures. Similar to the basis difference, the angle differences were first calculated. The mean angle, $\overline{{}^{A2S}R}$, was calculated by averaging the angles for six repetitions, ${}^{A2S}R_i$, as in Eq. (9). Next, the angular differences, $\Delta\theta_i$ were calculated between angles ${}^{A2S}R_i$, and the mean angle, $\overline{{}^{A2S}R}$, as in Eq. (10). Here, the summation, averaging, and multiplication were processed in a quaternion expression, which is one of the orientation expression methods [9].

$$\overline{{}^{A2S}R} = \frac{1}{N}\sum {}^{A2S}R_i \, . \tag{9}$$

$$\Delta\theta_i = \overline{{}^{A2S}R}\,{}^{A2S}R_i^{-1} \, . \tag{10}$$

The repeatability of the angular differences was examined using a paired *t-test* for the test and retest for all the subjects (Table 3). M1 and M2 showed significant differences for the *X* and/or *Z* axis, while method 3 showed no difference. M3 showed better repeatability than M1 and M2.

Table 3. Repeatability of Angular Differences against Test and Retest for all Subjects. Each Data Point is the p-value of a paired t-test. The * Mark Indicates a Significant Difference between the Test and Retest. The T stands for the Total Angle

M1				M2				M3			
T	*X*	*Y*	*Z*	T	*X*	*Y*	*Z*	T	*X*	*Y*	*Z*
0.3552	0.0247*	0.3876	0.0376*	0.1389	0.064	0.7276	0.0001*	0.8027	0.3372	0.8685	0.2374

The angular differences are shown for the three axes and three methods in Table 4. All of the basis differences for the test and retest are included here. As expected, the total angular difference decreased in the order M1, M2, and M3 for all of the axes. This indicates that M3 showed the best repeatability, and M2 was the second best. The ANOVA test for the methods showed significant differences for the total angle, *X* axis, and *Z* axis ($p = 0.0387$, $p = 0.0030$ and $p < 0.0000$, respectively). In the multiple comparison test for the methods, the angular differences were significantly smaller with M3 than with M1.

Table 4. Mean (SD) of Angular Differences for the Three Methods (°). T Stands for the Total Angular Difference

	M1	M2	M3
T	1.7495 (0.8768)	1.5436 (0.6865)	1.3917 (0.7160)
X	0.5671 (0.4677)	0.4253 (0.3178)	0.3290 (0.3297)
Y	1.1269 (0.9385)	1.1946 (0.7787)	1.1867 (0.7734)
Z	0.8533 (0.6501)	0.5862 (0.4499)	0.3996 (0.2657)

The differences in the basis propagate to an angular difference whose axis is perpendicular to the basis axis. For example, in M3, the Y basis difference is smaller than the *X* and *Y* bases differences. The larger basis difference in the *X* or *Y* axis indicates a large angular difference (rotational difference) along the *Y* axis.

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 for five young healthy subjects. Its performance showed reasonable repeatability (mean < 1.4°, SD < 0.8°).

This method is optimal in a statistical sense because it processes all the sample data using the PCA, compared with other methods that utilize a single data point or manipulate the data set in a simple way. Moreover, the calibration method proposed here does not require any strict constraint such as holding the subject's palm in the direction of gravity, which is very difficult. This could be beneficial, especially for subjects with diminished motor function as the result of diseases such as a stroke. Even though this method was applied to the forearm in this study, it could be applied to any body segment or object. One of the limitations of this method is the need to align the IMU with the body segment coordinate within 45°, because the PCA finds the rotated basis with the largest variance, to which the angular velocity is projected. However, this requirement can be sufficiently satisfied in clinical practice.

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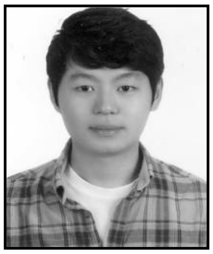
Authors

Je-Nam Kim, received the B.S. degree in Division of Biomedical Engineering and M.S. degree in Department of Healthcare Engineering from Chonbuk National University, Korea in 2009 and 2011, respectively. From 2011, he has been pursuing Ph.D. degree in Department of Healthcare Engineering from Chonbuk National University, Korea. His research interests include human motion tracking and telerehabilitation.

Mun-Ho Ryu, received a BS degree in Control and Instrumentation Engineering and a PhD degree in Biomedical Engineering from Seoul National University, Korea, in 1990 and 2004, respectively. He worked for Daewoo's Heavy Industry Machine Tool Division from 1990 to 2000. He also worked for Biomedlab Co., Ltd. from 2000 to 2005. He has been a professor at Chonbuk National University since 2005. His research interests are human motion tracking, inertial navigation, telerehabilitation, rehabilitation, and embedded system.



Ho-Rim Choi, Choi received the B.S. degree in Division of Biomedical Engineering and M.S. degree in Department of Healthcare Engineering from Chonbuk National University, Korea in 2010 and 2012, respectively. From 2012, he has been pursuing Ph.D. degree in Department of Healthcare Engineering from Chonbuk National University, Korea. His research interests include human motion tracking and inertial measurement unit.

Yoon-Seok Yang, received a BS degree in Control and Instrumentation Engineering and a PhD degree in Biomedical Engineering from Seoul National University, Korea, in 1996 and 2002, respectively. He worked for Electronics and Telecommunications Research Institute (ETRI) at BioMEMS group as a senior researcher from 2002 to 2005. He has been a professor at Chonbuk National University in South Korea since 2005. In 2007, He worked for ETRI at Neural System Interface group as a visiting professor. He also worked at a Center for Energy Harvesting Materials and Systems (CEHMS) in Virginia Polytechnic Institute and State University (Virginia Tech) in U.S. as a visiting researcher from 2010 to 2011. His research interests are energy harvesting, human computer interface (HCI), and embedded system.