An Efficient Method for Assessing the Accuracy of 3D Orientation of Inertial and Magnetic Sensors*

Zunyi Tang, Toshiyo Tamura, Masaki Sekine, Masaki Yoshida
Faculty of Biomedical Engineering
Osaka Electro-Communication University
Shijonawate City, Osaka 575-0063, Japan
{tang, tamurat, m-sekine, yoshida}@isc.osakac.ac.jp

Wenxi Chen
School of Computer Science and Engineering
The University of Aizu
Aizu-Wakamatsu City, Fukushima 965-8580, Japan
wenxi@u-aizu.ac.jp

***Abstract*—This paper presents an efficient method for assessing the accuracy of 3D orientation of a magnetic and inertial measurement unit (MIMU) by means of an optical measurement system. We fix a MIMU on the calibration tool of an optical measurement system, which is commonly used to calibrate the coordinate system of the system, so that we can simplify the alignment procedure of two coordinate systems. The RMS values of resulting Euler angles output from two systems are small and the corresponding correlation coefficient values are extremely high. Experimental results show the proposed method is effective.**

I. Introduction

Recently, small wearable inertial/magnetic sensors are becoming increasingly popular for measurement of 3D orientation of human body or body segment under motion or static states. Many authors have proposed various systems based on triaxial-accelerometer and triaxial-gyroscope (referred as inertial measurement unit: IMU) to measure 3D orientation of body segments [1]. Some authors have combined triaxial-magnetometer into IMU system to construct magnetic and inertial measurement unit (MIMU) [2]. As we known, noise often has a serious effect on the outputs of low-cost gyroscope, resulting in serious drifts over time. Additionally, magnetometer is also susceptible to interference from surrounding ferrimagnetic materials. The reasons maybe lead to serious drift and distortion in the 3D measurement results. Hence, it is required to assess the accuracy of 3D orientation of an IMU/MIMU meticulously before it can be applied to practical applications.

In this paper, we take a MIMU developed by us for example and propose an efficient method to assess the accuracy of 3D orientation of the MIMU by means of an optical measurement system. Differently from the existing methods [3], [4], a MIMU in our method is rigidly aligned with a calibration tool (as showed in Fig. 1), which is commonly used to calibrate the coordinate system of a motion capture system (MCS). Furthermore, the coordinate systems of the MIMU and MCS system are calibrated consistent each other as possible. By rotating the rigid combination, we measure the respective 3D orientation to calculate the corresponding Euler angles. By comparing the Euler angles of MIMU with those of MCS, we further assess the accuracy of 3D orientations of the MIMU. The RMS values and the correlation coefficient (CC) between the Euler angles are calculated. Experimental results show the RMS errors were small for all trials and the CC values are extremely high. This shows that the proposed method is effective.

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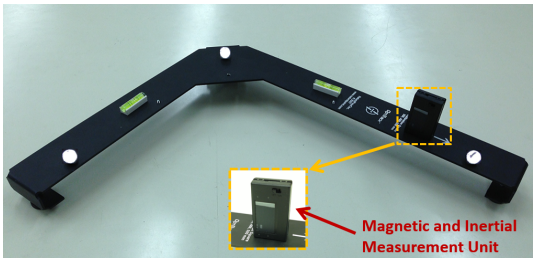

Fig. 1. The calibration square in our method holds a MIMU rigidly for assessing the accuracy of 3D orientation of the MIMU.

II. METHOD

A. Inertial Sensor System

The wearable MIMU measurement system is made up of hardware and software parts. Hardware mainly includes a triaxial-accelerometer, a triaxial-gyroscopes, and a triaxial-magnetometer. The signals of the sensors are sampled at 200 Hz with 16-bit resolution and are sent with a Bluetooth communication module to software client where the collected data can be automatically calibrated and functionally displayed for further data analysis.

B. Sensor Fusion (Euler Angles Calculation)

A preliminary and important task for a MIMU sensor is to make a sensor fusion of calculating Euler angles for estimating the orientation of a tested object. Actually, the Euler angles of 3D orientation of a MIMU can be calculated by using only gyroscope outputs, which are the integration of angular velocity by time. However, the computed results drift seriously over time due to the effect of noise. Fortunately, the problem can be mitigated by using complementary sensors along with sensor fusion schemes to obtain an optimal attitude estimate. Contrary to gyroscope, accelerometer output is generally stable and does not drift. Accelerometer can be employed as complementary sensor. Hence, one can fuse measurement data from accelerometer and gyroscope by utilizing a complementary filter, such as Kalman filter, for attitude estimate. In practice,

TABLE I. RESULTS OF ACCURACY ANALYSIS. THE RMS ERRORS ARE IN DEGREE. THE CC DENOTES CORRELATION COEFFICIENT

Trial	Roll		Pitch		Yaw	
	RMS	CC	RMS	CC	RMS	CC
1	0.9	0.99	1.1	0.99	1.8	0.99
2	1.0	1.00	1.2	0.99	1.5	0.99
3	0.7	0.99	1.0	0.96	1.7	0.99
4	0.7	1.00	0.5	1.00	1.2	0.99
5	0.7	1.00	0.8	1.00	1.7	0.97
6	0.3	0.99	0.6	1.00	2.1	0.99
7	0.3	1.00	0.4	1.00	1.4	0.99
Mean	0.7±0.2	1.00±0.00	0.8±0.3	0.99±0.01	1.6±0.3	0.99±0.01

we employed a Kalman filter to calculate the roll and pitch of Euler angles.

For calculating the yaw of Euler angles, this method using only acceleration and gyroscope data becomes unreliable due to a singularity in the Euler angle sequence known as "Gimbal lock". Hence, to estimate a reliable yaw often resorts to magnetometer data. We here utilize the quaternion-based gradient method [5] to calculate a more accurate yaw. It is notable that in our experiments, the roll and pitch calculated by the Kalman filter method are better than those obtained by the quaternion-based method. Hence, we combined the two methods to obtain a complete Euler angle output.

C. Optical Reference Measurement System

The 3D optical tracking system OptiTrack (NaturalPoint, USA), which consists of six cameras operating at 100 Hz, is employed as the reference measurement system. Standard calibration square containing three makers and two levels is used to calibrate the global coordinate system, and it is also aligned with a MIMU to assess the accuracy of 3D orientation of the MIMU. The accuracy of the MCS is about 0.1°.

D. Assessing the Accuracy of 3D Orientation

A difficulty of assessing the accuracy of 3D orientation of the MIMU by using an optical measurement system lies in how to align the local coordinate system of the MIMU to the global coordinate system of the optical system [4]. Considering this reason, we here propose an efficient method to implement the alignment. First, the calibration square tool is adjusted to be level. As showed in Fig. 1, we next tie a MIMU on the calibration square tool of the MCS to make three respective axes of the MIMU parallel to the corresponding axes of the MCS as possible. By observing the Euler angle outputs of the MIMU, we can judge whether the two coordinate systems between MIMU and MCS are coincident. If each output is zero, it means that two coordinate systems are coincident. If not, it is required to adjust the incline degree of the MIMU appropriately until each output becomes zero.

For both of the MIMU and the MCS, data were collected in different sampling frequency, 200 Hz and 100 Hz, respectively. Hence, the data collected from the MIMU need to be sampled with an interval for facilitating to compare with those of the reference system. Additionally, the collected data need to be synchronized. 7 stochastic movement trials of about 30s were recorded by rotating the combination with various angles. The dynamic error between the MIMU and the MCS was calculated for each trail by the RMS value. The CC value was also calculated for each trail to assess the similarity of results. The mean differences and standard deviations of the RMS and CC values are also given. The results are summarized in Table I.

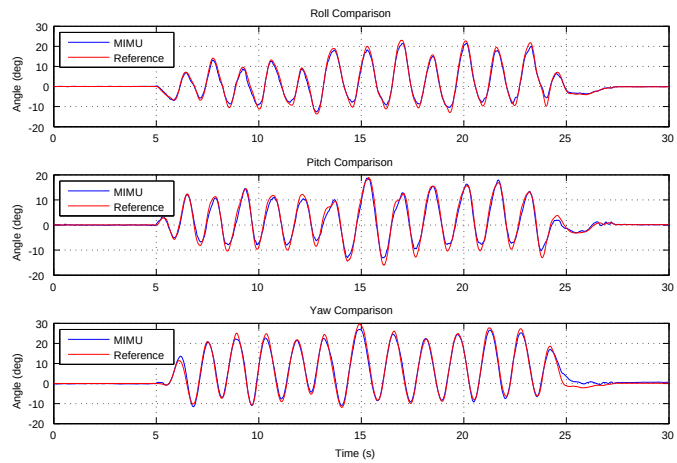

Fig. 2. An intuitive comparison of Euler angle outputs of the MIMU and the reference system.

III. DISCUSSIONS

As shown in Table I, the mean value of dynamic RMS errors was small for three angles (roll: 0.7 deg, pitch: 0.8 deg, and yaw: 1.6 deg) and the mean value of CC results was extremely high for all three Euler angles. An intuitive example was showed in Fig. 2. By comparison with the same level product MTx of Xsens Technologies, which is claimed with dynamic accuracy of less than 2 deg depending on type of motion [6], our MIMU can be considered better in performance. Since Xsens did not provide any details about how to calculate dynamic accuracy, it is difficult to provide an absolutely comparable dynamic accuracy. In near future work, we will provide more comparison results including static accuracy. In conclusion, the proposed method simplifies greatly the alignment procedure between the coordinate systems of IMU/MIMU and MCS so that the assessment of the 3D orientation accuracy of an IMU/MIMU becomes easy to implement.

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