An Experimental Performance Evaluation of the Orientation Accuracy of Four Nine-Axis MEMS Motion Sensors

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***Abstract*—MEMS (Micro-Electro-Mechanical Systems) inertial motion sensors have greatly improved the intelligence of wearable devices, sports fitness equipment, and consumer electronics. To avoid the disadvantages of each discrete inertial sensor, the tendency is to combine and fuse several different types of inertial motion sensors; thus, consumer-grade inertial motion sensors even have the same performance with the industrial-grade sensors. This study presents an overview of multi-axis sensor fusion algorithms and their applications. Furthermore, three typical consumer-grade AHRS (attitude and heading reference system) were verified compared with an industrial-grade sensor module (MTi-300), and three-axis orientation outputs of these sensors were compared. Static and dynamic experiment results show that MTi-300 has the best orientation accuracy (static error=0.05°, dynamic error=0.5°) compared to the other three sensor modules. Moreover, BNO055 has a better dynamic performance while compared with the other two consumer-grade motion sensors.**

Keywords—Motion sensor; MEMS; Attitude accuracy; Multi-sensor fusion

I. INTRODUCTION

Inertial motion sensors have been commercially available for several decades in applications for vehicles. However, these sensors' features, such as price, power consumption, and dimension, have prevented their wide utilization in mobile device until the past ten years [1].

Gyroscopes, accelerometers, magnetic sensors (compasses), and barometers (pressure sensors) are the four fundamental motion sensors. A gyroscope measures an object's angular velocity, while an accelerometer measures tilt angle (static acceleration) and linear acceleration (dynamic acceleration). A compass detects the heading of an object based on the earth's magnetic field. A pressure sensor measures relative and absolute altitudes by the convention between atmospheric pressure and altitude [2]. In a free space, gyroscopes can accurately track complex rotational motions. One difference between a gyroscope and an accelerometer or a compass is that the gyroscope functions fairly autonomously, other than depending on an external force such as gravity or magnetic fields. Compasses detect only the heading of a triple-axis space based on the earth's magnetic field. Pressure sensors realize relative and absolute altitude by sensing the relationship analysis between atmospheric pressure and altitude [1-2]. As Fig. 1 shows, inertial sensing measures acceleration, tilt, shock, vibration, and rotation, etc.

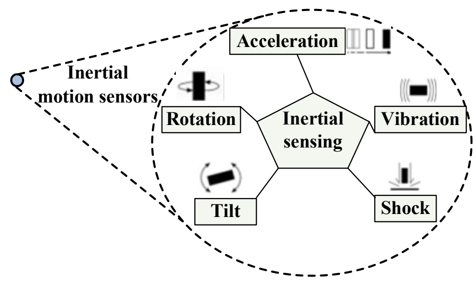

Figure 1. Applications of inertial motion sensors

Using a discrete inertial sensor for rotational or linear displacement calculations has disadvantage [3-4]. For example, the outputs of both gyroscopes and accelerometers need to be integrated; thus drifts over time occur because of inaccuracy reading or noise. Accelerometers and gyroscopes are used to reduce gyroscope errors. In addition, a barometer provides height information. Therefore, multi-sensor integration and fusion is adopted for most situations. Inertial measurement unit (IMU, i.e. a three-axis accelerometer combines a three-axis gyroscope), accelerometer-magnetometer (i.e. a three-axis magnetometer combines a three-axis accelerometer), and attitude heading reference system (AHRS, which consists of a three-axis gyroscope, a three-axis accelerometer and a three-axis magnetometer) are the common integrated MEMS (Micro-Electro-Mechanical Systems) motion sensor modules. For an AHRS, 3-DOF (degree of freedom) dynamic and accurate orientations can be acquired after the sensor-fusion implementation [4-6].

Table I shows the features of typical MEMS motion sensor modules.

Table I Characteristics of MEMS motion sensor modules

Module type	Sensor subunits	Outputs	Power
6-axis IMU	3-axis accelerometer, 3-axis gyroscope	Orientations (2D low drift +1D high drift)	2~9mW
6-axis static IMU	3-axis accelerometer, 3-axis magnetometer	Orientations (3D low drift, slow motions)	0.9mW
9-axis AHRS	3-axis gyroscope, 3-axis accelerometer, 3-axis magnetometer	Orientations (3D low drift), linear accelerations	2~10mW
10-axis tracking	AHRS and barometer	Plus height	0.03mw
Navigation	IMU/AHRS and GPS	Plus position	1000mw

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MEMS is a whole system which includes mechanical elements, micro-sensors, signal processing, communication interfaces, and power converters, etc. Unlike the piezoelectric, laser, and fiber-optic-based gyroscopes, the MEMS-based technology reduces the cost and package size of inertial sensors. Programmable signal-processing functions are embedded inside the sensor chip. Recently, more and more digital inertial sensors, instead of analog inertial sensors, are adopted for motion-tracking applications owing to their better performance, such as low-cost, ultra-compact, low power consumption, and multiple-axis sensing [1-6].

In human-machine interface design, especially intuitionistic navigation and control applications, MEMS-based consumer-grade inertial motions can provide simpler user interfaces; thus the operational complexities that have confused users can be resolved [1]. With the development of mobile or handheld devices, especially the revolutionary iWatch and iPhone (Apple Inc., U.S.A), MEMS inertial motion sensors on the market have been greatly developed in last ten years. Bosch, STMicroelectronics, InvenSense, and ADI are the dominant manufacturers of MEMS inertial sensors at present. MPU6050 from InvenSense Inc. is a very popular 6-axis inertial sensor module (dimensions: 4mm×4mm×0.9mm; power consumption: 3mA). Furthermore, various new sensor modules which have further better performances are developing continuously.

An overview of multi-axis sensor fusion algorithms and their applications were presented in this study. Furthermore, the three-axis orientation outputs of three typical consumer-grade AHRS (MPU-9150, X-NUCLEO-IKS01A1, and BNO055) were verified compared with an industrial-grade sensor module (MTi-300, Xsens Inc., Holland). The orientation accuracy of the four motion sensors was tested based on the self-developed hexahedron system in laboratory.

The structure of this paper is organized as follows: Section II presents the state of art of the inertial sensors fusion. Section III introduces the description of typical sensor modules and experimental setup. A discussion of the achieved results is provided in Section IV, followed by a summary and conclusions of the results in Section V.

II. State of The Art

Attitude determination remains an interesting research topic until today. In previous researches, some kinds of low-cost MEMS-based AHRSs were developed for attitude tracking. The primary feature of inertial sensors is the attitude estimation algorithms, such as Kalman filters, complementary filter, and Parks-McClellan filters [7]. The outputs can be quaternions [8], Euler angles, and rotation matrix [9]. Numerous attitude estimation algorithms have become available. Most of those approaches utilize Kalman filtering theory, which are mostly Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) because of the nonlinear character of most systems, to estimate the orientations. Fig. 2 illustrates the diagram of EKF signal path, which is an iterative process. The Kalman gain means the weight factors for the K and K-1 parameters, and depends on the covariance terms and varied in real-time. The covariance values are determined on the models of each sensor's total noise. In addition, other impact factors for long-term drift, such as temperature drift, linear acceleration, and vibration are used to optimize the covariance values. Thus, the choosing of these covariance values for an optimal EKF performance is a trial-and-error effort.

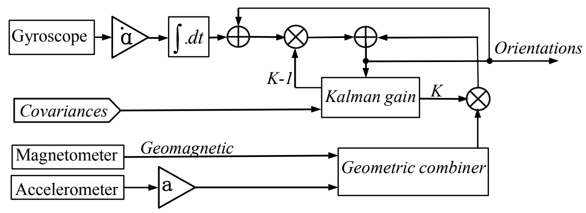


Figure 2. Block diagram of EKF for orientation estimation.

However, the orientation estimation algorithms based on Kalman filtering theory have some disadvantages, such as implementation complexity and high sampling rate because of the linear regression iteration. Moreover, the Kalman filters have to deal with large scale vectors to describe rotational kinematics in three dimensions [6-7].

Besides Kalman filters, a series of sensor-fusion algorithms are presented by researchers. Madgwick *et al.* [10] presented a direction cosine matrix (DCM) based gradient descent algorithm, which is simple, fast, and can be performed even in an eight-bit microcontroller (MCU). Results indicated that the static accuracy of the proposed algorithm is <0.8°, while the dynamic accuracy is <1.7°. This demonstrated that the attitude accuracy of the proposed algorithm in [10] can achieve levels of Kalman theory.

Most inertial manufacturers present unique onboard sensor fusion algorithms. For example, the inertial sensors from InvenSense Inc. include an in-chip sensor-fusion module named Digital Motion Processor™ (DMP™), which is capable of processing the complex nine-axis MotionFusion algorithms. ST Microelectronics Inc. presented Kalman filter-based sensor-fusion software named iNEMO Engine, which is based on dedicated filtering and prediction algorithms. DMP™ and iNEMO Engine combine different data from multiple sensors. These sensors can directly provide a series of outputs such as rotation, linear acceleration, gravity, and quaternion. The control of these sensors can be performed using a microcontroller and are independent of environmental conditions to achieve the best performance.

Benziane *et al.* [11] utilized linear-like complementary filters to estimate and control attitude. An IMU (MPU-6000, InvenSense Inc.) and a 3-axis compass (HMC5883L, Honeywell Inc.) were adopted in a DIY Quad and compared with the well-known Xsens MTi AHRS. Experimental results based on DIY Quad showed the effectiveness and stability of the proposed solutions.

Fourati *et al.* [12] presented a quaternion-based complementary filter for human segment motion estimation. The algorithm incorporated a motion kinematic model to overcome the limitations of EKF. The accelerometer and compass combined via the Levenberg Marquardt (LM) algorithm. The complementary observer used the gyroscope outputs and the output of LM algorithm as the inputs. The estimated orientations were compared with a six-axis industrial robot (ABB IRB 2400) motion control, while the AHRS module (MTi-100, Xsens Inc.) was attached to the end-effector of the robot. Results demonstrated that the attitude accuracy of proposed algorithm is between [2°, 4°] for roll and pitch angles and between [3°, 5°] for yaw angle.

Ren *et al.* [13] presented KF/EKF and vector analysis to estimate attitude of a hand-held surgical instrument based on an embedded AHRS. The AHRS module consists of a 3-axis accelerometer (LIS331DLH, STMicroelectronics), a combined 3-axis gyroscope (2-axis IDG300 and single axis ISZ300, InvenSense), and a 3-axis magnetometer (HMC1043, Honeywell). The estimated values were compared with an optical tracking system (Polaris, NDI Inc.). The experimental results showed that the RMS accuracy of proposed algorithm were 0.96° (roll angle), 0.76° (pitch angel), and 1.06° (yaw angle).

Rosario *et al.* [14] proposed a geometrically intuitive quaternion-based complementary filter to estimate a smartphone's attitude. The estimated values were compared with an optical motion capture system (accuracies: 0.5mm and 0.5°). The experiment with five normal daily activities was performed in ten subjects while the smartphone was worn on the body. The accuracy of the algorithm in three axes were 3.37° , 1.84° , and 4.83° , respectively.

Meng *et al.* [15] proposed a pedestrian tracking algorithm based on an AHRS module (ADIS16405, ADI Inc.) to estimate the linear displacement during both short and long distance walking. A velocity control variable from stride information was designed in the algorithm. The average position error for 15 m straight line walking is 0.44±0.20 m. The averaged error for 3 min indoor walking (132 m in distance) is 4.31±1.77 m, and for 6 minutes outdoor walking (332 m) is 3.88±0.35 m.

Ryan and Miller [16] used an adaptive bias estimation algorithm in MEMS-based AHRS for pan and tilt surveillance platform. The running cycle frequencies of previous MEMS-based AHRSs were relatively low, among which the highest cycle frequency was 200Hz and the lowest one was only 50Hz. Moreover, the estimation errors of attitude angle previous AHRSs during dynamic stage are usually more than 1.5°.

III. Typical Sensor modules and Experimental Setup

A. *Typical sensor modules*

There are a series of AHRS or IMU modules available on the market. After a detailed investigation, three typical consumer-grade AHRS modules and an industrial-grade AHRS module were chosen in this study. As Fig. 3 shows, they were MPU-9150, X-NUCLEO-IKS01A1, BNO055, and MTi-300.

As claimed by InvenSense, the MPU-9150 (Fig. 3(a)) is the first 9-axis motion sensor for consumer electronics, and it has some advantages, such as low-cost, low power consumption, and high performance. It combines an IMU (MPU-6050) and a tri-axis digital compass (AK8975). An onboard Motionfusion named digital motion processor (DMP) and calibration firmware were integrated in MPU-9150, which enables users to develop motion-based functionality rapidly.

As Fig. 3(b) shows, X-NUCLEO-IKS01A1 from STMicroelectronics Inc. is a motion MEMS sensor evaluation board system, which contains an IMU (LSM6DS0), a three-axis magnetometer (LIS3MDL), and a barometer (LPS25HB). The osxMotionFX is an add-on software package which runs on the STM32 Nucleo equipped with the X-NUCLEO-IKS01A1 expansion board. The osxMotionFX library implements sensor fusion algorithm for estimation of 3D orientation in space. It uses Kalman filter to fuse data from several sensors.

The BNO055 (Fig. 3(c)) from Bosch Sensortec is an intelligent 9-axis absolute orientation sensor which combines a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer. To aid in development, Bosch Sensortec provides the sensor fusion software which was running in a 32-bit ARM microcontroller.

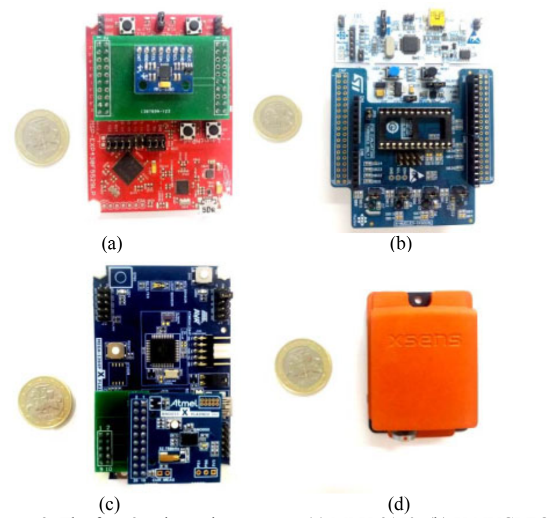


Figure 3. The four 9-axis motion sensors: (a) MPU-9150; (b) X-NUCLEO-IKS01A1; (c) BNO055; (d) MTi-300.

The MTi-300 (Fig. 3(d)) from Xsens Inc. is an industrial-grade AHRS which integrates with Extended Kalman filter-based sensor fusion algorithms. Typical orientation errors of MTi-300 are 0.3° (roll/pitch) and 1° (yaw). However, its tracking performance highly depends on the conditions.

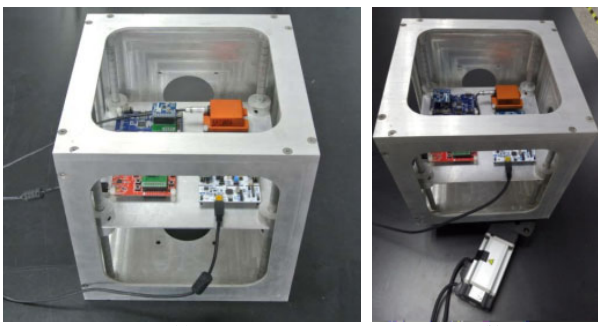
Table II summarizes the comparative information of the four motion sensors detailed above.

Table II Comparative Information of four motion sensors

Sensors	MPU-9150	X-NUCLEO-IKS01A1	BNO055	MTi-300
Manufact-urer	InvenSense , U.S.A	STMicroelec-tronics, U.S.A	Bosch Sensortec, Germany	Xsens Technolog-ies B.V., Holland
Application	Consumer electronics	Consumer electronics	Consumer electronics	Industrial-grade
Output frequency	20Hz	100Hz	10Hz	400Hz
Fusion algorithm	DMP	osxMotionFX software package	FusionLib Software library	Extended Kalman filter
Supply voltage	2.4~3.46V	3.3V	2.4~3.6V	4.5~36 V
Price	Low	Low	Low	High
Package Size(mm)	4x4x1	72x70x2	3x4.5x0.95	57x42x23

B. Experimental setup

The test platform for inertial sensing accuracy is complex. The measurement results of a single axis rate table cannot separate pitch and yaw and roll/pitch values. Then a high precision 3-axis rate table is essential to evaluate the orientation accuracy. For instance, Batista *et al.*[17] used a high precision calibration table, Model 2103HT from Ideal Aerosmith, to evaluate the attitude accuracy of proposed low-cost AHRS in real world application. The Motion Rate Table has three rotational joints which allow for movement around three orthogonally mounted axes. However, a precise three-axis rate table is too expensive and complex to afford by most researchers. Moreover, the electrical machinery may distort the magnetic field in the neighborhood of the AHRS. Therefore, we developed a simple and portable hexahedron system to evaluate the attitude accuracy of the selected four motion sensors.



(a) (b)

Figure. 4. The attitude assessment system: (a) the hexahedron system; (b) the hexahedron system fixed on a single-axis turntable

As Fig. 4 (a) shows, the hexahedron system was made of non-magnetic materials, which would not affect the magnetometer. The hexahedron system is considered as a reference platform for roll/pitch test. To assess the performance of heading angle, the hexahedron system was fixed on a high precision single axis turntable. As Fig. 4 (b) shows, the single-axis rotating table can rotate back and forth about the Z-axis of the motion sensor, which can measure the yaw angle error.

IV. Experiment Results

In this section, the orientation accuracy of the four motion sensors mentioned above was tested based on the hexahedron system in the laboratory. The accuracy test for motion sensors includes static test and dynamic test. The four sensor modules were placed in the hexahedron for 24 hours during the static test. The raw data and sensor fusion outputs were stored in the computer for error analysis. During the dynamic test, the hexahedron was overturned around X, Y and Z axis of the motion sensors in turn, with the interval of 90° in a single step. The measured orientation values of the four sensor modules were recorded and analyzed.

A microcontroller (MSP430, TI Inc., USA) acquires the MPU-9150 output via the I2C interface, with the sampling rate of 100 Hz. X-NUCLEO-IKS01A1 was connected to a STM32MCU via the I2C interface. Moreover, there is a utility (Sensors_DataLog) where can be installed in a computer and obtain the orientation values. The Bosch BNO055 connected to an AVR board (ATmega1284P, Atmel Inc., USA). All the sensor data were transmitted to a computer at the same time. Raw sensor data of MTi-300 was transmitted to a computer at 400 Hz and used as the inputs of accompanying software to provide the sensor fusion outputs.

A. Results of the static test

The static performance of the four sensor modules was measured at rest on a laboratory bench. Orientation output data was gathered for at least 24 hours. Then, the standard deviation of the three-axis orientation angles was computed as follows:

Table III Results of the static test

Sensor modules	Roll error (°)	Pitch error (°)	Yaw error(°)
MPU-9150	1.31	1.45	12.64
X-NUCLEO IKS01A1	0.08	0.06	3.52
BNO055	0.08	0.03	0.71
MTi-300	0.03	0.02	0.05

From the results in Table III, we can find that the Industrial-grade motion sensor MTi-300 has the best static performance compared to the other three modules. In the three consumer-grade motion sensors, the BNO055 has a better static performance. In addition, the static error of yaw angle is larger than the other two angles.

B. Results of the dynamic test

In the dynamic test, the four sensor modules were fixed on the center of the hexahedron. During dynamic test, the hexahedron was overturned around x, y and z axis of the motion sensors in turn, with the interval of 90°in a single step. The dynamic RMS (root mean square) errors of the roll, pitch, and yaw components of orientation, corresponding to rotations around the sensor frame x, y, and z-axis respectively, were computed as follows in Table IV-VII. To obtain a more stable result, the experiment was repeated 20 times for each axis, and then computed the average value.

Table IV Dynamic test results of MPU-9150

Measurement	Roll error (deg)	Pitch error (deg)	Yaw error (deg)
Turning 90°	1.51	1.78	3.13
Turning 180°	0.57	1.73	3.42
Turning 270°	1.65	1.83	3.64
Turning 360°	1.12	1.70	3.14

Table V Dynamic test results of X-NUCLEO-IKS01A1

Measurement	Roll error (deg)	Pitch error (deg)	Yaw error (deg)
Turning 90°	0.41	0.74	14.15
Turning 180°	0.44	0.38	12.11
Turning 270°	0.51	0.64	15.27
Turning 360°	0.33	0.02	11.72

Table VI Dynamic test results of BNO055

Measurement	Roll error (deg)	Pitch error (deg)	Yaw error (deg)
Turning 90°	1.07	0.53	1.28
Turning 180°	0.74	0.73	2.51
Turning 270°	1.41	0.66	3.53
Turning 360°	0.44	0.86	4.61

Table VII Dynamic test results of MTi-300

Measurement	Roll error (deg)	Pitch error (deg)	Yaw error (deg)
Turning 90°	0.15	0.32	0.13
Turning 180°	0.18	0.24	0.35
Turning 270°	0.37	0.15	0.51
Turning 360°	0.17	0.28	0.54

From the results in Table IV to Table VII, we can find that the MTi-300 has the best dynamic orientation accuracy compared to the other three modules. The dynamic RMS errors are <0.4° for roll and pitch angles and <0.55° for yaw angle. Observing the performance in the three consumer-grade motion sensor modules, we can find that BNO055 has the best dynamic orientation accuracy. The RMS errors are around 1.4°, 0.8°and 4.6°for roll, pitch and yaw angle respectively.

V. CONCLUSIONS

In this study, an overview of multi-axis sensor fusion algorithms and their applications were presented. The orientation accuracies of the selected three typical consumer-grade AHRS were compared with an industrial-grade sensor module (MTi-300). The accuracy test was performed based our self-developed hexahedron system in the laboratory. Static and dynamic experiment results showed that MTi-300 has the best orientation accuracy (static error=0.05°, dynamic error=0.5°) compared to the other three sensor modules. Moreover, BNO055 has a better dynamic performance while compared with the other two consumer-grade motion sensors. This study can provide effective help for researchers who dedicated to MEMS inertial sensor applications and development.

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