Reviews on Various Inertial Measurement Unit (IMU) Sensor Applications

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***Abstract*— Inertial Measurement Unit (IMU) sensors are used widely in many different movable applications. Across many years, the improvements and applications of IMU have increased through various areas such as manufacturing, navigation, and robotics. This paper presents a literature review of several current IMU categories and applications. A few considerations on choosing an IMU for different applications are summarized and current methods being used to improve the accuracy of the output from IMU are also presented to avoid the errors that latest IMU is facing. Improvement methods include the control algorithms and type of filters for the sensor. Pros and cons of the types and algorithms used are also discussed in relation to different applications.**

***Index Terms*— gyroscope, magnetometer, accelerometer, IMU**

I. Introduction

History of IMU began in 1930s where it was used in aircraft navigation [1] and large devices. Because of its constraints mainly in size, cost, and power consumption, IMU usage at that time is restricted to bulk application and thus, unpopular to smaller size devices and consumer applications. Until recently, micro-electromechanical system (MEMS) IMU is introduced with a very attractive feature of low cost, compact, and low processing power [2]. The demand increases then exponentially to wider area of usage. Currently, a lot of manufacturers are competing on the best IMU designs such as Invensense, Honeywell, STMicroelectronics, Microstrain, and X-Sens.

The current environment requires us to be more and more advanced in sensory system apart from the human natural sensors. Many people demand to know more information on their current position and movements to work better and more efficient. Recent trends of people bringing their own small electronic devices such as smart phones, GPS devices, and portable radios also have increased the demand of position sensors to determine their position live and update to the third party at the same time. The usage of IMU has been applied widely to determine their movements in terms of acceleration, angular velocity, and rotation [3].

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This paper introduces briefly about the current technology of IMU sensors, explains the considerations for choosing an appropriate IMU, review several IMU applications in various areas, and finally discuss the major reasons for choosing proper IMU types.

II. IMU Technologies

IMU is mainly used in devices to measure velocity, orientation, and gravitational force. It can be divided into two; the earlier technology consists of two types of sensors accelerometers and gyroscopes. The accelerometer is used to measure the inertial acceleration. While gyroscope on the other hand, measures angular rotation. Both sensors typically have three degree of freedom to measure from three axes.

Later, IMU technology has advanced with another sensor type – magnetometer. Magnetometer measures the bearing magnetic direction, thus it can improve the reading of gyroscope. The benefit of magnetometer will be described in this section later.

A. IMU with Two Sensor Types

This type of IMU consists of accelerometer and gyroscope. Typically each sensor has between two to three degrees of freedom defined for x, y, and z-axis, which combining both sensors will total up four to six DOF. Acceleration values obtained from accelerometer and angular velocity from gyros are kept separately. Angles can be measured from both sensors, thus both data can be calibrated as shown in Fig. 1 to get more accurate output data.

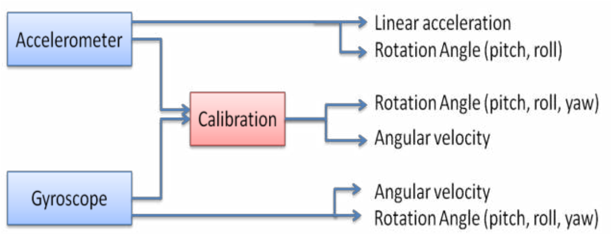

Figure 1. IMU based on two types of sensors

The advantage of using this type of IMU is that it will not be interfered by external magnetic field around the

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sensor when it is used very close to ferromagnetic material. In contrast, depending on accelerometer and gyroscope only might not be enough to increase the accuracy of the measurement due to sensors' noise and the gyros drift issue.

B. IMU with Three Sensor Types

This type of IMU consists of accelerometer, gyroscope and magnetometer – commonly all in tri-axial to get measurements in three different axes making the total of 9 DOF. The magnetometer is used to measure yaw angle rotation, thus it can be calibrated to the gyroscope data to improve the big drift issue.

This type of sensor is good for dynamic orientation calculation in the short and long run when less drift errors occur. There is a disadvantage of having magnetometer in the package. If the IMU is being used in the environment that is surrounded by ferromagnetic metal, the measurements might be affected due to the disturbance to magnetic field [3].

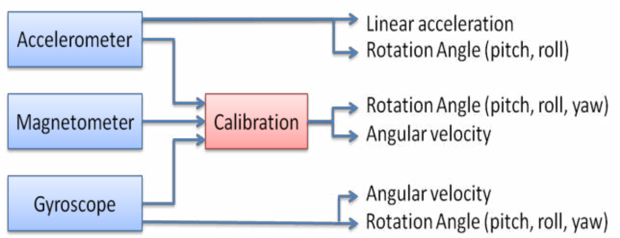

Figure 2. IMU based on three types of sensors

III. CONSIDERATIONS IN CHOOSING AN IMU

When choosing which type of IMU to be used, there are several aspects that need to be considered depending on the final usage and tolerance.

A. Package Size

A lot of consumer products to be designed require the sensor to be small and light to fit the product and good mobility. For example, a smart phone used in consumer products as well as a smart baseball for measuring ball flight trajectories are preferred for a small size of IMU sensor to be embedded into a small space. Compared to applications in aircraft, the sensor size might not be the main issue. The mostly used IMU in the consumer industry is the MEMS sensor.

B. Data Accuracy

Gyros are known to have drift errors over a long period of time, while the accelerometer [1] is sensitive to acceleration in any direction when the object has translational acceleration or fast rotation [1]. Many improvements have been done such as using a Kalman filter method to calibrate accelerometer and gyroscope data. Some applications only need a specific range of measurements and they can tolerate the accuracy within a certain threshold. Thus, a thorough filtering process would not be the main concern.

C. Response Rate

A good sensor should have a fast response rate. For example, a sensor with sampling rate of 50 Hz should operate with sample out of 50 measurements per second. Most of the devices deal with motion applications higher response rate and they require initial validation assessment before making its next application. The current normal rate ranges between 1 Hz to 50 Hz. Some advanced applications such as in vehicle navigation may need higher response rate up to 200 Hz for ensuring the data are captured quickly and accurately in time.

D. Degree of Freedom

A degree of freedom (DOF) determines the number of independent parameters in a system. There are many available IMU sensors in the market, which they can vary from two to 9-DOF. The number of DOF differences depends on the type of sensors included in the IMU sensor and how many axis that the sensor will measure. Again, based on the usage and features that an application needs, the total DOF may vary. In position tracking perspective, most of the applications use 6-DOF for two-sensor type IMU or 9-DOF for three-sensor type IMU, with the number of DOF represents the measurement in x, y, and z axis for each sensor. Usually, the higher the number of DOF, the more certain we can accurately sample the data.

III. REVIEW OF SEVERAL IMU APLLICATIONS

History began with the applications in air vehicle to measure position in the air, the IMU technology now has expanded into various areas such as medical devices, robotics, land vehicle navigation, etc.

The IMU applications can be classified into few criteria such as IMU type, application area, and fusion method. IMU type is divided into two categories as described in Section II. Few application areas are defined in this paper – industry quality control, medical rehabilitation, robotics, navigation system, sports learning, and augmented reality system. These applications are summarized in Table I-VI. Type I and Type II in IMU type are classified as IMU with two types of sensors and three types of sensors respectively.

TABLE I. APPLICATIONS IN MANUFACTURING QUALITY CONTROL

Reference	Device/Usage	IMU Type	Fusion Method
Foxlin[4]	Inertial Head Tracker	Type I	Separate-bias Kalman filter (KF)
S. Won *et al.*[5]	Fastening Tool Tracker	Type I	KF and Expert System[5-6]
S. Won *et al.*[6]	Fastening Tool Tracker	Type II	KF and Expert System[5-6]

TABLE II. APPLICATIONS IN MEDICAL REHABILITATION

Reference	Device/Usage	IMU Type	Fusion Method
W.-W. Wang and L.C. Fu[7]	Exoskeleton for Rehabilitation	Type II	Mirror therapy concept
Carlos Cifuentes *et al.*[8]	Exoskeleton for Rehabilitation	Type II	Calibration with additional sensor - EMG
Je-Nam Kam *et al.*[9]	Post-Stroke Rehabilitation Monitor	Type II	None
Jon Erikson *et al.*[10]	Post-stroke arm rehabilitation	Type II[11]	None
Z. Q. Ding *et al.*[12]	Arm posture correction	Type II	Unknown
Gianni Fenu and Gary Steri[13]	Post-traumatic movement analysis	Type I	None

TABLE III. APPLICATIONS IN ROBOTICS

Reference	Device/Usage	IMU Type	Fusion Method
Jingang Yi *et al.*[14-15]	Skid-steered mobile robot	Type I	nonlinear KF/extended KF and slip estimation scheme
Chris C. Ward and Karl Iagnemma[16]	Wheel slip detection	Type II	Extended KF
Marrco Hutter *et al.*[17], Michael Bloesch *et al.*[18]	Legged robot	Type I	Extended KF

TABLE IV. APPLICATIONS IN NAVIGATION SYSTEM

Reference	Device/Usage	IMU Type	Fusion Method
T. S. Burggemann *et al.*[19]	GPS Fault Detection	Type I	Extended KF
A. Zul Zafar and D. Hazry[20]	Quadrotor Stabilizer	Type I	Weight Average Estimation, PID
Jong-ho Han *et al.*[21]	3D Map Building	Type I	Balance Filter (High-Pass, Low-Pass)

TABLE V. APPLICATIONS IN SPORTS LEARNING

Reference	Device/Usage	IMU Type	Fusion Method
N. C. Perkins[22-24]	Measuring sport's equipment trajectory	Type I	None
K. King *et. al*[25], K. King[26]	Measuring golf swing trajectory	Type I	None
Yi-Chen Huang *et al.*[27]	Measuring golf swing trajectory	Type I	Least Square Method (LSM)-based calibration
K. King *et al.*[28]	Measuring bowling spin dynamics	Type I	None
Tung Mun Hon *et al.*[29]	Measuring bowler's hand dynamics	Type I	None
Ryan S. McGinnis *et al.*[30-31]	Measuring kinematics of baseball/softball	Type I	Ball's kinematics[9], VICON comparison[10]

TABLE VI. APPLICATIONS IN AUGMENTED REALITY SYSTEM

Reference	Device/Usage	IMU Type	Fusion Method
R. Azuma *et al.*[32]	Personal Outdoor Navigation	Type I	Compass data calibration

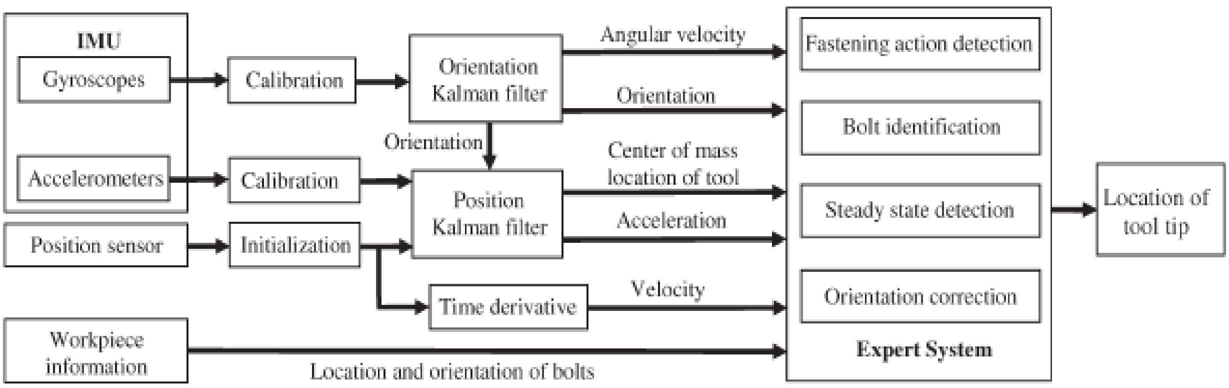

Figure 3. Fastening tool tracking system [5]

A. Industry Quality Control

In manufacturing industry, some designs have been made to improve the productivity. An inertial head-tracker was designed by an author from MIT Research Lab of Electronics to improve the teleoperator performance [4]. A gyroscope and an inclinometer were used to measure the movements, and later added a compass into the prototype. The author proposed a complementary separate-bias Kalman Filter (KF) by integrating both sensors' measurement to remove drift error issue and acceleration sensitivity of the inclinometer.

Another usage in industry is proposed in [5]-[6] by implementing IMU with additional position sensor on the fastening tool tracking system. This is part of quality control system to avoid the operators to miss any bolts or fastening bolts at the wrong holes. The IMU consisting of gyroscope and accelerometer, together with a position sensor in [5] and a magnetometer in [6] are used to track the location of the tool tip when fastening the bolts. To reduce the bias, noise, non-linearity, and drift errors, they use KF and an Expert System as shown in Fig. 3 to obtain more accurate location of tool tip.

B. Medical Rehabilitation

In medical area, many mechanical designs have been currently used to help and assist human whether in surgical, rehabilitation, or medical analysis. The aim is to have a more efficient and effective results in the area of needs.

One of the applications of IMU in rehabilitation is exoskeleton robotics designed by W.W. Wang, L. C. Fu [7] and Carlos *et al*. [8]. The IMUs consist of all three types of sensors are applied to the exoskeleton robotic devices. Wang developed an exoskeleton upper-limb robot and IMU system based on mirror therapy concept [7]. Mirror therapy concept was introduced to allow the training issued by the user without the need of the force sensor system. Carlos used a Zigbee sensor in his post-stroke upper limb rehabilitation robotics system together with a Surface Electromyography (sEMG) [8]. In his implementation, he used accelerometer and magnetometer data to correct the gyroscope measurement after detecting the drift values as can be seen in Fig. 4.

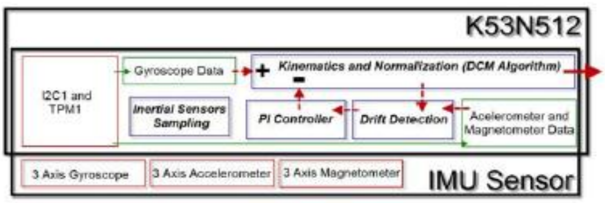

Figure 4. Block diagram of IMU sensor design [8]

The applications in non-exoskeleton robotics design are also very useful in medical rehabilitation to do movement measurement and analysis. As an example, IMU is used in stroke rehabilitation [9]-[11], posture correction [12], and post-traumatic rehabilitation [13]. Eriksson [10] proposed a robot to monitor the post-stroke patient's use of the stroke-affected limb. A 9-DOF sensor is placed on the patient's limb [11] while the robot is used to analyse the movements and give feedback to the patient and the rehabilitation staff. A correction device proposed in [12] to correct the arm posture by detecting the posture using a 9-DOF IMU sensor and giving response using vibrotactile actuators. An IMU with gyroscope and accelerometer was used in [13] as a device to study the movements of the post-traumatic patients. There is, however, no mentioned fusions done in their software or applications when processing the IMU data.

C. Robotics

Robotics technology has been popular with the rapid growth for human benefits. This area has expanded to help human to increase their capability and power to do daily routines and advanced tasks. Some of the robots require linear and angular data for their movements; therefore the IMU is a good sensor to obtain the desired data.

Yi *et al*. [14]-[15] designed a skid-steered mobile robot using IMU sensors from MicroStrain and Motion Sense consisting of accelerometer and gyroscopes. He proposed a nonlinear KF-based simultaneous localization and slip estimation scheme in [14] and an extended KF (EKF) in [15] to overcome the drift and noise errors from the IMU measurements.

Chris Ward and Karl Iagnemma [16] also presented a model-based wheel slip detection mechanism for outdoor mobile robots using IMU. They experimented their algorithm with a mobile robot for DARPA LAGR program which has a 9-DOF Xsens MT9 IMU and a Garmin GPS. With the nonlinear vehicle model, they applied EKF to process the sensor measurements and chose a threshold value to allow the detector to react quickly.

A quadruped platform legged robot, StarIETH [17] is also equipped with an IMU from X-Sens as part of its sensory mechanism. The fusion was done by Michael Bloesch *et al*. [18] based on EKF to measure the position of the robot's leg.

D. Navigation System

The commonly known device used in navigation system, the Global Positioning System (GPS) is very widely used in car and aircraft navigation to go from one location to another. Recent years, a lot of researches are about to upgrade to IMUs as an alternative or a better choice as IMU can be used in locations with no GPS signals and also a cheaper and lighter device. There are also works that combine with both GPS and IMU information for better data accuracy.

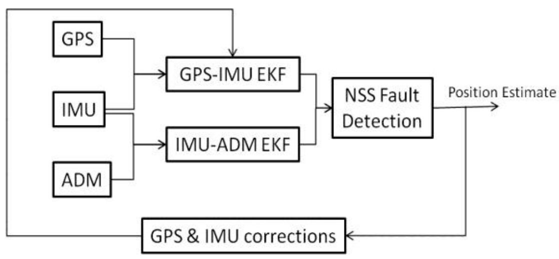

Figure 5. GPS fault detection algorithm [19]

A research has been done at Queensland University of Technology that combines GPS measurements with IMU data and Aircraft Dynamic Model (ADM) for GPS fault detection [19]. This fusing is introduced to improve the fault detection by GPS-only architecture with lower cost by using low-cost MEMS IMU compared to a high quality inertial sensor. This GPS-IMU-ADM combination is fused based on EKF and a closed-loop configuration before applying to their normalized solution separation (NSS) fault detection scheme.

An approach for stabilizing a quadrotor was introduced by A. Zul Zafar and D. Hazry [20] by using an IMU consisting of 3-axis accelerometer and a 3-axis gyroscope. The ADC output values were then weighted using estimation equations [20]. The estimations passed through a PID controller before the result is used to determine the movement of the quadrotor's motor.

Another implementation of IMU in navigation system is for building a 3D map [21]. Jong-ho Han *et al.* improvised the 3D map building algorithm which originally using only Laser Range Finder (LRF) by adding IMU to reduce the error when their mobile robot moves to an inclined surface. The main data needed, angle and angular velocity are processed through a simple IMU balance filter consisting of a low-pass filter on accelerometer sensor and a high-pass filter on the gyroscope sensor.

E. Sports Learning

IMU has been used widely in sports learning such as in bowling, baseball and golf training. N.C. Perkins, for example, patented his designs [22]-[24] of tracking sports equipment's trajectory like baseball, tennis, and golf. His patents use IMU comprising gyroscope and accelerometer.

K. King *et al*. [25]-[26] and Yi-Chen Huang *et al*. [27] use IMU to measure golf swing trajectories for golfers' training by placing the sensors at the shaft of the golf club and measure the acceleration and angular velocity of the swing. In this way, golfers can track and correct which position and velocity they should play with a good swing. K. King's sensor design was justified to have acceptable resolution errors, thus they only do early calibration and no extensive filters to the sensor outputs. YC Huang on the other hand, applied a Least-Squared Method (LSM)-based calibration to correct the errors.

In bowling, the sensor is placed inside the bowling ball inside one of the thumb slugs or at the hand of the bowler to measure the spin dynamics to assess the bowler skill and ball performance. K. King and N.C. Perkins [28] again chose both accelerometer and gyroscope in a single board as their choice. For calibration, they followed the same procedure described in King, K. W. [26]. Tung Mun Hon explained in [29] used a Microstrain Inertial Sensor and mounted it on the bowler's wrist. He makes use of the built-in sensor's calibration capability to correct any misalignment of the data.

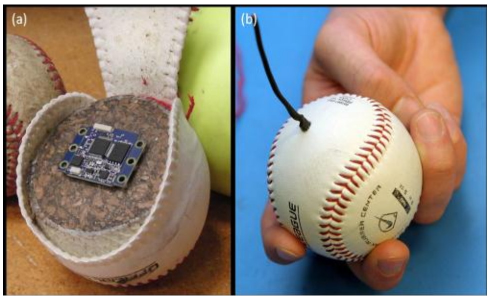

Figure 6. The miniaturized IMU embedded in a baseball [31]

While in baseball and softball case, Ryan *et al* [30]-[31] proposed to embed a miniaturized IMU sensor as shown in Fig. 6, consisting of tri-axial gyroscope and tri-axial accelerometer into the ball. In [30], Ryan used the knowledge of the kinematics of the ball to estimate the drift error occurred during measurements. He and N.C. Perkins also corrected the data accuracy using a comparison with a 10-camera high speed motion analysis system (VICON) [31].

F. Augmented Reality System

Azuma *et al*. presented an outdoor Augmented Reality (AR) System for personal outdoor navigation use such as hikers or soldiers [32]. Their system uses a differential GPS (DGPS) receiver, a compass and tilt sensor, and three gyroscopes. They uses the sensors quite differently from the typical IMU, where the DGPS is to measure the position while the other two sensors are fused together to get the orientation.

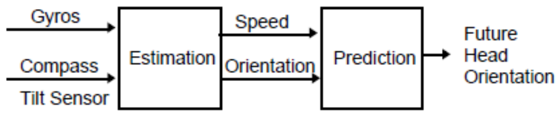

Figure 7. Fusing gyro & compass tilt sensor measurements [32]

The compass data provides a small correction for gyroscope to prevent drift in the long term [32]. The main challenge of the design is the changing distortion of the Earth's magnetic field while moving around the three dimensional space.

IV. Discussion

Choosing IMU type for a specific application needs considerations as described in Section III. One of the main reasons is the threshold limit that an application can tolerate. Sports learning application for example, does not need a very high accuracy as the usage is to study the sports equipments' trajectories and players' movements. While in application such as industries and robotics, an accurate data is important for the result determination and determining future movements. Another reason is some of the applications mentioned in this paper were proposed before the 3-sensor type IMU is fully developed. Thus, there is a probability that some researches will expand to these sensor type II to improve their device performances.

Fusions are also widely being improvised and applied to the application due to the known errors and noises coming from the sensor. The most commonly used filters are Kalman filter and extended Kalman filter. Although the implementation is quite complicated at the beginning, their performances are proven to be good based on the wide usage in many areas. On the other hand, some applications provide no extra correction on the sensor output due to: 1) the sensor used has its own built-in correction method, or 2) the application has an accepted threshold limit to use the measured data as it is.

V. Conclusion

This review discussed in the first part the different IMU types, whether it is an accelerometer-gyroscope IMU or accelerometer-gyroscope-magnetometer IMU. Using magnetometer will have its pro and cons, researchers and industries will apply these differences in their specific designs to fulfil their needs.

The second part of the paper summarized the several applications of IMU in industries and human daily lives. Majority of them applied corrections in the IMU measurements due to obvious errors in the sensors' data. In choosing the IMU type, some of the designs and applications mentioned might move to the three-type IMU to increase their accuracy and performance with the addition of magnetometer. While IMU technology is expanding and improving to have better sensory measurements, we believe that applications in many other areas will increase more and benefit to the human daily lives.

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