Issues and Challenges of Sensor Technologies in Microelectromechanical System (MEMS) in Smartphones for Motion Tracking Applications

Nursabillilah Mohd Ali[1], GJ Ting[1], LQ Shiung[1], LW Theng[1], LC Ching[1], M Sulaiman[1], HNM Shah[1], MM Ghazaly[1], S Razali[2]

[1]*Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Melaka, 76100, Melaka*

[2]*Faculty of Information and Communication Technology, Universiti Teknikal Malaysia Melaka, Durian Tunggal, 76100, Malaysia*

nursabillilah@utem.edu.my

***Abstract*—Following the popularity of smartphone, the needs for accurate motion tracking have grown rapidly. Microelectromechanical system (MEMS) sensor has been commonly used in smartphones. Inertia Measurement Unit (IMU) usually functions in motion sensing. In this review, we explained the concept of MEMS accelerometer, gyroscopes and magnetometer. We discussed the issues and challenges of MEMS sensor in smartphones for motion tracking application and ways to improve it. noise-full and drifting are issues related to angle estimation in IMU. Many types of the filter were applied to improve the angle estimation. Challenges in navigation and motion tracking are stated. The combination of IMU, a global positioning system (GPS) and MEMS pressure sensor can increase the accuracy of motion tracking efficiently. The conclusion of issues and challenges of MEMS sensor and improvements were also presented.**

***Index Terms*—Microelectromechanical Systems (MEMS); Smartphone; Inertia Measurement Unit (IMU); Pressure Sensor; Global Positioning System (GPS).**

I. INTRODUCTION

Microelectromechanical systems (MEMS) is a technology used to produce tiny devices that combined both the electrical and mechanical systems. MEMS consist of tiny machines nearly invisible to the human eyes. MEMS have elements ranging from 1 to 100 microns in thickness.

The most significant components of MEMS are the microsensors and microactuators. Microsensors and microactuators are devices that can convert energy from one form to another. MEMS are the combination of electrical and mechanical systems to fabricate and to design microstructures. Microstructures are used in applications such as in automotive, biomedical and electronic devices [1].

MEMS use complicated design and process. MEMS such as sensors (e.g. magnetometer, gyroscopes), actuators (electric motor, solenoid), electronic devices (RF oscillators and filters) or integrated microfluidic systems find applications in aerospace, automotive or watch industry where high reliability is needed. This provides a strong demand for reviewing the quality and analysing the data to find its failure. MEMS provide new performance benefits, but also produce latest problems, especially in the field of checking the quality and accomplishment [2].

One of the electronic devices using MEMS technology are smartphones. Smartphones are devices composed of a processor, a graphics chip, advanced connectivity and an inertial measurement unit (IMU), with a 3-axis-accelerometer, 3-axis-gyroscope and 3-axis-magnetometer as standard features3. Besides, smartphones contain technology such as screen display, an audio system or a kinesthetic communication system that enable interaction with the user of the device.

II. LITERATURE REVIEW

Makoto Tanigawa et. al [3] have proposed on stabilising the highly responsive but drift-prone aspect of MEMS accelerometer using a MEMS barometric altimeter. Their work achieved high-fidelity of height tracking. This information is handy for improving the motion tracking in smartphones.

According to Naser El-Shimey et. al [4], the new fabrication process and the light in weight of MEMS sensor causes height instability and noise which affect the accuracy of MEMS IMUS. A suitable filter needs to be computed for better accuracy.

III. RESEARCH METHODOLOGY

The research method used in this review is secondary data analysis. Secondary data analysis utilised the sources that have been published by someone else. A few selected journals and articles are used for the review. Some of the information is taken from the internet. Articles and journals about microelectromechanical system (MEMS), inertia measurement unit (IMU), accelerometer, gyroscope, magnetometer, Global Positioning System (GPS and pressure sensors are used. Some of the products which used MEMS are used as references in the review. All the information gathered is used to conduct a review of issues and challenges of MEMS in smartphones for navigation motion tracking purposes and ways to improve it [5].

IV. INERTIAL MEASUREMENT UNIT (IMU)

Inertial Measurement Unit (IMU) is an electronic device that determines and describes a body's specific force, angular rate, and occasionally the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, occasionally magnetometers. IMUs are typically used to manoeuvre aircraft, including unmanned aerial vehicles (UAVs), and spacecraft, including satellites and landers [6].

IMU is used to refer to a box containing three accelerometers and three gyroscopes and optionally three magnetometers. The accelerometers are placed such that their measuring axes are orthogonal to each other to measure the initial acceleration. Three gyroscopes are placed in a similar pattern to measure the rotational position. Moreover, the three magnetometers are used to allow better performance for dynamic orientation calculation.

A. Accelerometers

An accelerometer is a device that determines proper acceleration. Proper acceleration in relativity theory is the physical acceleration experienced by an object. Therefore, gravitation does not cause any proper acceleration, since the gravity acts upon the observer that any proper acceleration must depart from (accelerate from). Proper acceleration contrasts with coordinate acceleration (rate of change of velocity) [7].

1) Principle of Operation of Accelerometers

An accelerometer has two basic parts which there is an attachment to the housing where the acceleration of the object can be measured; and a movable mass which is tethered to the housing. The diagram shows a spring with a seismic mass which is a metal ball.

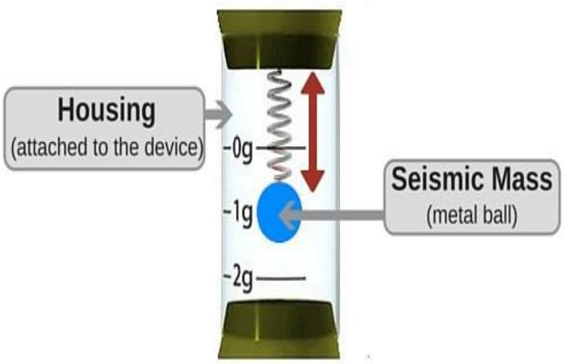

Figure 1: Basics accelerometer structure

The ball will stretch the spring when the housing is moved up. The force of gravity can be calculated if a stretched spring is measurable. Three of the similar objects can determine the orientation of a three-dimensional object. There is the only extension on the x-axis spring when the z-axis is lying perpendicular to the gravity. Turns the object so that the z-axis is pointing upwards and only the spring of the accelerometer along that axis is stretched [8].

The accelerometer used in a smartphone is made of silicon. The accelerometer has a housing which is attached to the device, and it can move up and down. The metal ball is used as the seismic mass as shown in the diagram, while the spring is the resilience of the silicon attached to the housing. If the movement in the mid-segment is measurable, there will be changes in the orientation [9].

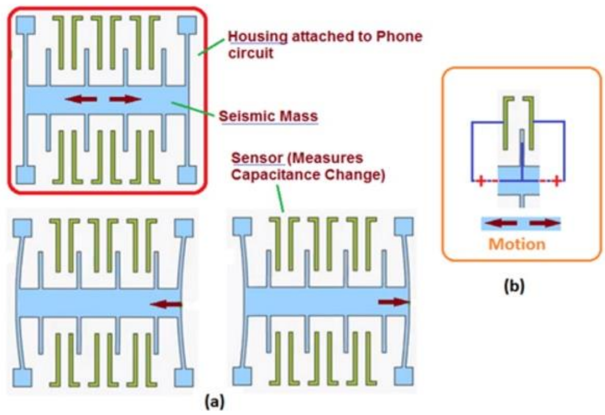

Figure 2: The inner structure of a MEMS accelerometer [8]

The Figure 2(b) is one of the small parts of Figure 2(a). It shows that when there is a change in orientation, there will be changes in capacitance as an outcome of change in location of the seismic mass. This will identify the section which is modified and allow the current to flow. This will also identify the change in gravitational pull by changing the current equivalent to capacitance charge. The amount of flowing current is correlated to acceleration [10].

B. Gyroscopes

A gyroscope is a rotating wheel or rotor in which its axis can turn freely in all directions and capable of maintaining the same absolute direction in space. The gyroscopes sense the tilting and rotation of the object mounted which based on the conservation of angular momentum [11].

1) Principle of Operation of Gyroscopes

The principle of conservation of angular momentum is the main principle of operation of working gyroscopes. A classic gyroscope consists of a rotating wheel supported on a free moving axis. The wheel is mounted on a pivoting support which allows a single axis to rotate. It is called a gimbal. Gyroscopes provide the wheel with three degrees of rotational freedom. This succeeded by using two gimbals at a time which one of the two gimbals is mounted inside another gimbal. The gyroscope will maintain its pointing direction while the wheel of the gyroscope is being spun. The combination of three accelerometers and the gyroscopes can help the detection of the motion in three axes of an object which the gyroscope and accelerometers are mounted to [12].

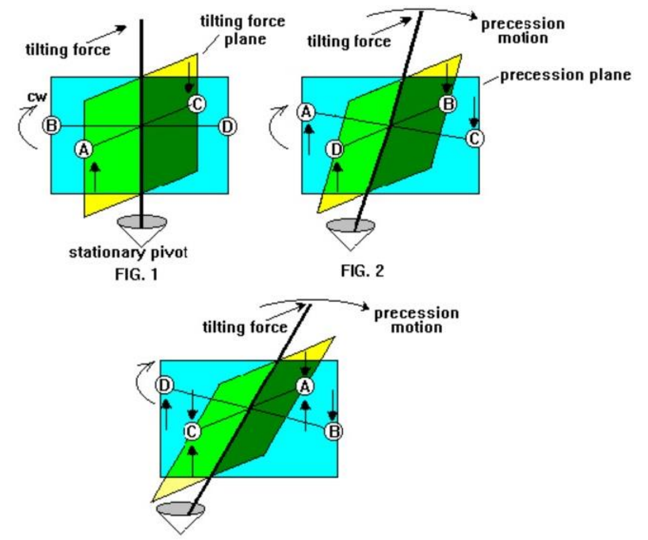

Figure 3: A diagram of the concept of tilting force operations of Gyroscopes [13]

The orientation of a smartphone is measured by the MEMS gyroscopes. MEMS gyroscopes used are very small in size. [12] The calibration provides a reading or zero while the device kept still and did not orientate. The changes in orientation on gyroscope bounded object are the core of the measurement in a gyroscopes sensor. When the gyroscopes rotate, a tiny resonating mass is shifted with the change in angular velocity. The movement in the mass is converted into a very low current electrical signal which can be detected and read by a microprocessor or microcontroller. [14]

With gyroscopes, we can point out the characteristics of an object's motion such as pitch, roll and yaw. Roll, pitch and yaw are defined as the rotation around X, Y and Z axis.

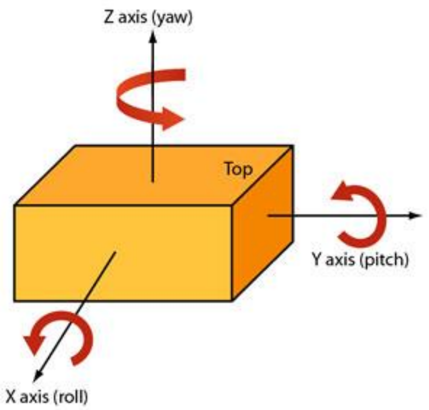

Figure 4: Roll, pitch and yaw of an object MEMS gyroscope

Draper developed the very first MEMS gyroscope in 1993. It consists of two proof masses which are vibrating along an axis with equal velocity and magnitude but in the opposite direction [15].

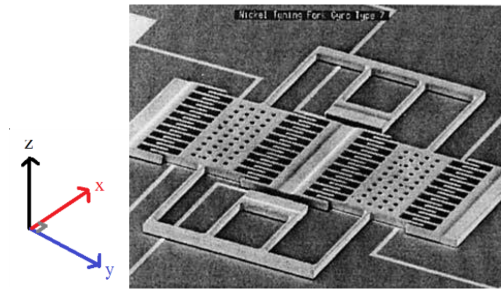

Figure 5: First MEMS gyroscope developed by Draper

The two vibrating proof masses are vibrating along the x-axis. The gyroscope is subjected to a rotation which results in an angular velocity along the y-axis. This will produce a Coriolis force acting upon the two vibrating proof masses. This would result in a force which is trying to push one of the proof masses into the plane and another force which is trying to lift the other proof mass out of the plane along the z-axis. Change of capacitance can be measured with the top plate and the bottom plate which are between the proof masses. This would give a sense of the angular velocity and calculate the rate of rotation.

ST Micro GK10A is a 3-axis MEMS gyroscope which is included inside an iPhone. It consists of 4 proof masses which are two pitch proof masses, two roll and yaw proof masses. It can be used for these proof masses to measure the angular rotation of all the three axes.

$$Coriolis\ force = 2 \times mass \times velocity \times angular\ velocity \quad 13$$

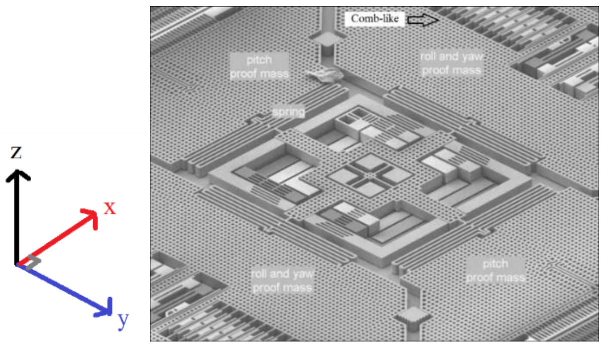

Figure 6: ST Micro GK10A in iPhone

For pitch, it uses the two pitch proof masses which vibrate along the y-axis in the opposite direction. It is subjected to rotation resulting in an angular velocity along the x-axis. Coriolis forces are trying to push one of the proof masses into the plane and another force which is trying to lift the other proof mass out of the plane along the z-axis. For roll, it uses the roll and yaw proof masses which vibrate along the x-axis in the opposite direction. It is subjected to rotation resulting in an angular velocity along the y-axis. Coriolis forces are trying to push one of the proof masses into the plane and another force which is trying to lift the other proof mass out of the plane along the z-axis. Change of capacitance can be measured with the top plate and the bottom plate which are between the proof masses. For yaw, it uses the roll and yaw proof masses which vibrate along the x-axis in the opposite direction. Rotation is subjected to the z-axis. The resulted Coriolis force which is in the plane of the proof masses and deflected in the opposite direction along the y-axis. Change of capacitance is measured at a comb-like structure which is very similar to an accelerometer design [15].

C. Magnetometers

A magnetometer is a measurement unit that detects the intensity of a magnetic field and presence of ferrous or magnetic materials. Magnetometers are classified into vector magnetometers and scalar magnetometer. The vector magnetometers measure three-dimensional space flux density values in a specific direction. The scalar magnetometers measure the magnitude of the vector passing through the magnetometer regardless of the direction.

1) Principle of Operation of Magnetometers

A MEMS magnetic sensor is based on the halo effect principle. An electric field is produced across a material caused by the flows of electric current and presence of the magnetic field. The force produced by the electric field applied to the charge carriers to balance Lorentz force from the magnetic field [16]. This Lorentz force was first formulated by James Clark Maxwell in 1865, Oliver Heaviside in 1889 and Hendrick Lorentz in 1891 [17]. The Lorentz force is perpendicular to the direction of the charge and direction of the magnetic field.

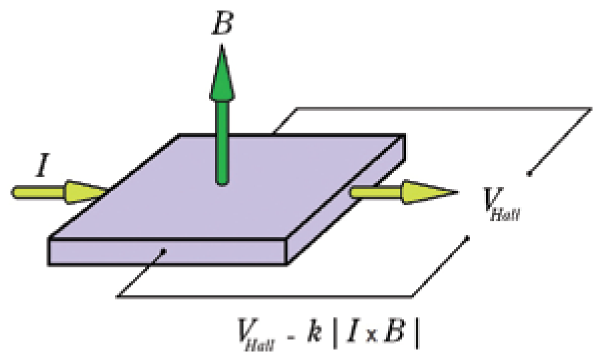

Figure 7: Hall effect principle

The detection of the voltage or potential difference which produced by Hall Effect principle across the metallic surface in response to a magnetic field that is perpendicular to the metallic surface can be determined for the power of the magnetic field in a direction. Three MEMS magnetometers for different direction axis need to produce a correct direction of the magnetic field. This can be used for a compass.

V. Challenges Faced By Smartphones And Ways To Improve

A. In Angle Estimation

Acceleration, geomagnetic field, tilting angle and angular velocity, these raw measurements can be obtained by MEMS accelerometer, magnetometer and gyroscopes in Inertia Measurement Unit (IMU). These raw measurements are noise or drift information which causes an error in measurement and calculation. No any MEMS sensor can provide noiseless measurements and information [18]. These can heavily affect the accuracy of the motion tracking.

An Altitude and Heading Reference System (AHRS) will compensate the bias of measurement produced by accelerometer, gyroscopes and magnetometer. The merging of measurement of gravitational earth field and angular velocity can be computed to a complete estimation of orientation angles [19].

Filters are needed to correct or increase the accuracy of the measurement produced by the IMU. There are some orientation filters, such as Kalman filter [20], Mahony filter and Madqwick filter [21]. The orientation estimation is the evaluation of the kinematic equation for the rotation of the IMU built-in smartphones. The estimation of altitude is produced when inline with the rate of change in original altitude by the MEMS gyroscopes. The filter removed the direction error from the measurement data collected from accelerometer and magnetometer.

Magnetic distortion and gyroscope bias drift have to be considered and compensated to improve the accuracy of motion tracking. The Kalman, Madqwick and Mahony filter are the solutions to the biases and errors. Mahony filter uses a proportional and integral controller to correct the gyroscope bias and drift, where else the Madqwick filter only uses a proportional controller. Kalman filter is ideal for a system which is continuously changing which is very suitable for high accuracy motion tracking applications [22]. It is very light on memory which suitable for small memory storage in smartphones. They do not need to keep any history other than the previous state. They are very fast suitable for real-time problems and embedded systems such as IMU [23].

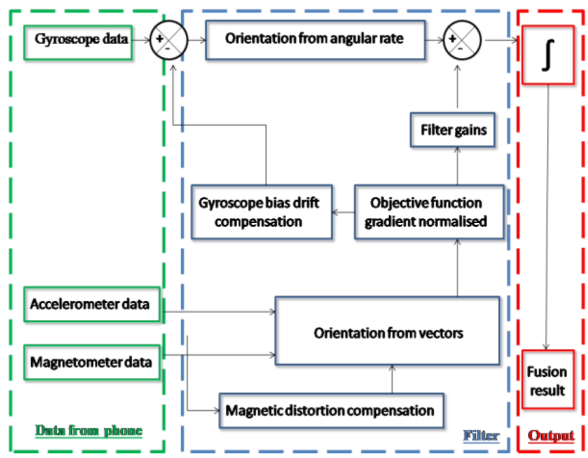

Figure 8: Block diagram representation of a common orientation filter using accelerometer, magnetometer and gyroscope data [22]

Figure 8 presents a block diagram for a common orientation filter. All the filters mentioned using a quaternion estimation. The quaternion estimation is a four-dimensional complex number representing the orientation [25]. It is efficient and easier for calculations [26]. Euler angles are more understandable than quaternion estimation. Euler angles are subjected to ambiguity and gimbal lock. Ambiguity and gimbal lock are two main problems to take into account in measurement. Gimbal lock appears when two axes of an object have a parallel orientation [27].

B. In Navigation System

One of the problems faced by the smartphones is motion tracking. The motion tracking in the smartphones depends on IMU entirely. However, the idea is not ideal because IMU has a drifting effect. It will cause catastrophe position mapping error.

A global position system (GPS) is installed to solve the problem in motion tracking of smartphones. Reliable short range and high-frequency information are provided by inertia measurement system (IMU) in the smartphones. Excellent long-term accuracy low-frequency information is produced by GPS [28]. The combination of IMU and GPS with suitable cooperation can provide reliable and accurate navigation parameters. The information produced by IMU and GPS can benefit the motion tracking in smartphones. Positioning precision offered by the differential GPS (DGPS) can be accurate down to centimetres. Accurate velocity can be produced by integrating DGPS to IMU [28]. Position data can be calculated using the information available from DGPS position measurement.

The GPS has a critical weakness, which is altitude estimation. DGPS measurement cannot observe the altitude value of smartphones. Thus, the IMU/DGPS integrated navigation system does not increase the accuracy of vertical motion sensing. Besides that, the component of MEMS gyroscopes bias in the specific force is not observable. The drifting and heading error of the vertical component will increase with time.

C. *Pressure Sensor/Barometer Altimeter*

The reliance of IMU/GPS integrated navigation system of altitude estimation is not the best solution. A MEMS pressure sensor is needed to overcome the issue faced. The MEMS barometric altimeter can produce high revolution vertical positioning in real-time of the smartphone motion [29]. The orientation error has no significant effect on the height accuracy. The height drift value of MEMS barometric altimeter is still present. The combination of IMU and MEMS barometric altimeter can produce high accuracy in altitude estimation with the suitable filter. The combination of IMU, GPS and pressure sensor can help solve the problem in the attitude estimation [30].

For example, an Xsens MTi-G sensor, which is a miniature MEMS AHRS, consisted of 3D gyroscopes, 3D accelerometers, 3D magnetometers, a GPS receiver and a barometric altimeter [30].

Figure 9: Xsens MTI-G sensor [30]

VI. CONCLUSION

It is concluded that the smartphones apply the MEMS concept into its structures. MEMS such as 3D accelerometers, 3D gyroscopes and 3D magnetometers are used in motion tracking. However, there are a few challenges faced by the smartphones in motion tracking. One of the challenges is that IMU has a drifting effect. Besides, they are unable to estimate the orientation and height accurately. Thus, a GPS system and a pressure sensor are used to solve the problems faced.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers and Center for Robotics and Industrial Automation (CeRIA) as well as Universiti Teknikal Malaysia Melaka for providing funding to complete this work.

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