Analysis of the Accuracy and Usefulness of MEMS Chipsets Embedded in Popular Mobile Phones in Inertial Navigation

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Abstract. By using inertial sensors embedded in modern telephones, such as a three-axis accelerometer and a gyroscope, it is possible to determine the position of the user in all conditions, regardless of the place, time or surrounding terrain obstacles. For this purpose, it is necessary to determine the starting coordinates, speed and orientation of the device. The system determining the position of the user on the basis of indications of inertial sensors is called the Inertial Navigation System (INS) and is a part of dead reckoning navigation. The accuracy of the position determined in this way depends mainly on the class, stability and quality of the sensors used. The accelerometers, gyroscopes and magnetometers used in cell phones are made in the MEMS (Micro Electro-Mechanical System) technology, which has been developing dynamically since the end of the 20th century. Sensors, despite their miniature dimensions and weight, are cheap in production and more and more accurate. The article attempts to determine the accuracy and usefulness of popular mobile phones in navigation using the IMU (Inertial Measurement Unit) by determining the coordinates of the user's route. A special script in the Matlab environment was written for comparison analyses of IMU route with the indications from the GNSS receiver. It should be noted that positions calculated on the basis of data from IMU devices were not integrated with the GNSS system in any way. In the practical part, two modern cell phones operating under the Android system, i.e. Sony Xperia M2 Aqua and Samsung Galaxy Note 3 were used to create an inertial navigation system. The measurement was carried out simultaneously with two telephones in three different scenarios. Based on data collected using sensors (accelerometers and gyroscope), subsequent user positions in the geocentric coordinates were determined using the Matlab script. The conducted research has shown to what extent a modern mobile phone can be used to create an inertial navigation system. The achieved results are presented, analysed and discussed.

1. Introduction

According to the Newton's first law of motion in an inertial frame of reference, an object either remains at rest or continues to move at a constant velocity, unless acted upon by a force. The feature determining the body's ability to maintain a constant speed of movement is called inertia. Inertial navigation is based on the Newton's second law of motion, i.e. the displacement of the body can be determined by means of a double integral from the acceleration of this body. By measuring the values of accelerations in three perpendicular directions in a certain inertial coordinate system, it is possible to determine the position of the body in space. Any external force acting on a given body causes some acceleration of this body.
Devices capable of determining the value of these accelerations are called accelerometers. However, these devices measure the total value of the acceleration that affects the body, including the acceleration of gravity. In inertial navigation it is necessary in the first step to remove the value of acceleration of gravity from the measured values [1]. For this purpose, gyroscopes are used, which allow to determine the slope of the platform on which accelerometers are located. A set of three accelerometers and gyroscopes, one pair on each of the perpendicular axes, is called the Inertial Sensor Assembly (ISA), which provides "raw" sensor data. When data from ISA is corrected for the value of measuring errors of the sensors, such a device is referred to as the Inertial Measurement Unit (IMU) [2]. When a processor converting sensor data into velocity, position and inclination of the system is added to the IMU, this device already forms the Inertial Navigation System (INS). State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

1.1. Micro Electro-Mechanical Systems - MEMS
MEMS systems are devices that combine mechanical and electronic elements made on a miniature scale. They have micrometer sizes, although more and more smaller constructions are being created along with technological progress. It was not until the 1990s that the technology enabling the production of mechanical microelements was created, which were then joined and integrated, among others in inertial navigation systems based on MEMS technology. The sensors built in this technology are miniaturized to a micrometer scale and combine electronic and mechanical parts. As a result, it is possible to produce cheap, light and small sensors (such as gyroscopes, accelerometers) that are currently installed on most smartphone phones. Figure 1 shows one of the first ISA assemblies installed in the phone and fragments of some sensor elements in the magnification. Despite the many advantages of MEMS sensors, they are also characterized by low accuracy (increasing measurement errors cause "drift") and are unable to create a good navigational solution. However, in combination with the GNSS system, an IMU made in MEMS technology can create an integrated navigation system combining the advantages of GNSS and MEMS.

![Figure 1. The ISA module made in the MEMS technology used in the iPhone 4 and some elements of the sensor in the enlargement. The L3G4200D module is a set of 3 gyroscopes, and the LIS331DLH is a group of accelerometers.](image)

1.2. INS errors
The biggest problem of inertial navigation systems is their accuracy. These systems use accelerometers and gyroscopes to determine the position of the user, but due to errors that are burdened with the
measurement made with these sensors, the INS accuracy decreases with the measurement time. Sensors are able to deliver results which, at the moment of the sensor's performance, are subject to a slight error, but successive measuring ages (also burdened with a small error that changes over time) degrade the designated position according to the law of error propagation. The speed and degree of error increase depends on the quality of inertial navigation systems used. The most accurate systems are characterized by high price and large sizes in contrast to systems made in MEMS technology.

Each sensor is burdened with some accidental and systematic errors which, as mentioned earlier, degrade the accuracy of position determination in inertial navigation systems. In literature, the tendency of the system to deteriorate its accuracy with the passing of time is called drift. According to El-Sheimy, the erroneous indication of the accelerometer leads to a linear error after the first integration and to a square error after the second integration, and thus in the position determined. In turn, errors in the measurement of angular velocity (through the gyroscope) lead to a linear error in the determination of angles, quadratic error in determining the vehicle speed and cubic error in determining the position [3]. For this reason, INS accuracy depends mainly on the quality of the gyroscopes used.

One of the main errors in INS is bias, as a result of which the sensor registers a certain value when there is no force on the system. Bias can be divided into two categories depending on how you reduce the impact of this error, i.e. in a stochastic or deterministic modeling. The first group includes in-run bias (bias drift), which determines the rate of bias growth over time. The second group includes turn-on bias (initial bias), the value of which changes each time the device is restarted [4].

Inertial sensors similarly to any electronic measuring device are exposed to noise, which is produced by the electronic module at the time of measurement, but it can also come from outside. The noise is random, so it has to be removed by a certain stochastic model. There are various methods of removing noise, e.g. separating the signal of the sensor into high and low frequency parts and analyzing these signals (wavelet decomposition technique) [5]. The sensor class is most often described by the parameter defining the average error resulting from the calibration of the measured quantity. In the case of accelerometers, this parameter is called VRW (Velocity Random Walk), and in the case of gyroscopes is called ARW (Angular Random Walk).

1.3. Equations describing the dynamics of the object

To determine the position of the user using inertial navigation systems, the data collected from the sensors (gyroscopes and accelerometers) should be inserted into equations describing the user's movement over time. They will therefore be equations presented in the form of a state vector. The equations presented here will apply to data collected using the strapdown INS, because the stable platform system always provides the acceleration values in the navigation system.

Equations describing a moving object in the NED (North, East, Down) navigational system are as follows [6]:

\[
\begin{align*}
\dot{r}^n &= D \cdot V^n \\
\dot{V}^n &= R_b^n f^b - (2\omega_{le}^n + \omega_{m}^n)xV^n + g^n \\
\dot{\Omega} &= R(\omega_b^0)
\end{align*}
\]

In the equation (1) the matrix \(r^n = [\phi \lambda h]^T\) is the searched coordinates in the NED system in radians (h in meters) and \(\dot{r}^n = [\dot{\phi} \dot{\lambda} \dot{h}]^T\) represents the changes of these coordinates over time.

Using the equation (2), the velocities \(V_E, V_N, V_D\) can be calculated - these are the velocities of the moving object expressed in the topocentric NED system in the directions: north, east and down, expressed in m/s. For this purpose, we need:

- \(R_b^n\) - the rotation matrix between the NED navigational system and the system in which the measurement is made. It is obtained from the equation (3),
\( \omega^n \) - centripetal acceleration resulting from the movement of the NED system relative to the Earth-related system (ECEF), because the Earth revolves around its own axis,

\( 2\omega_{ib}V^n \) - the value of Coriolis acceleration,

\( g^n \) - gravitational acceleration,

\( f^b \) - acceleration of the body determined using the accelerometer. After multiplying by the matrix \( R^b_n \) it will be the value of the body acceleration in the NED system.

Equation (3) determines the matrix \( \Omega \) (single-column matrix defining Euler angles: roll, pitch, yaw) by the multiplication of angular velocities (in rad/s) measured by gyroscopes in the matrix \( \omega_{ib} \) and matrix \( R \). The matrix \( R \) is as follows [7]:

\[
R = \begin{bmatrix}
1 & \sin \theta \tan \beta & \cos \theta \tan \beta \\
0 & \cos \theta & -\sin \theta \\
0 & \cos \beta \sin \theta & \cos \cos \theta
\end{bmatrix}
\]

(4)

where: \( \beta, \theta \) are pitch and roll angles from previous iteration.

The matrix \( R^b_n \) is a DCM matrix (Direction Cosine Matrix). It arises by assembling three elementary rotations in space. When switching from the body system to the navigation system, the matrix \( R^b_n \) can be created in the following way:

\[
R^b_n = R_z(-\gamma)R_y(-\beta)R_x(-\theta)
\]

(5)

where: \( \gamma, \beta, \theta \) are yaw, pitch, roll angles.

Thanks to the matrix \( R^b_n \), it is possible to determine the attitude of the system in the given navigation system according to the formula (3).

To calculate coordinates based on equation (1), equations (2) and (3) must be solved. At the beginning one has to calculate the matrix \( R^b_n \) based on the calculated Euler angles according to equation (3), where the data will be the initial values of the Euler angles, angular velocities measured by gyroscopes. The solution of equation (3) is followed by integration of subsequent values of angular velocities. This is some approximation but given that the gyroscope values are delivered with high frequency, the received angle values are small. When \( R^b_n \) matrices for subsequent measurement epochs are determined, the equation (2) should be solved, where the data will be the NED velocities from the previous iteration (or initial values for the first iteration), measured values of accelerations that will be transformed into the navigation system using the designated previously \( R^b_n \) matrix, then reduced by the Coriolis effect, centripetal acceleration and the gravitational acceleration \( g \). The acceleration component value should be added to the measured equation because the accelerator equation (6) is as follows:

\[
f^b = a - g
\]

(6)

where: \( f^b \) is the measured acceleration from the accelerometer, and \( a \) is acceleration in the inertial system.

To calculate vehicle speed in the north, east and up directions from the given acceleration values, the equation (2) should be integrated in time. Only now can the coordinates be determined using equation (1).

2. Practical tests

In the practical part, two modern cell phones (one of them without a gyroscope) were used to create an inertial navigation system. The measurement was carried out simultaneously with two phones in three
different scenarios. Based on data collected using sensors (accelerometers and gyroscope), subsequent user positions in the geocentric layout were determined using a script [8, 9] written in the Matlab.

2.1. Parameters of INS sensors in the phone
Two modern mobile phones operating under the control of the Android system were used to perform the measurement, i.e. Sony Xperia M2 Aqua and Samsung Galaxy Note 3. Table 1 [10, 11, 12] contains detailed information about INS sensors used in these phones.

| Table 1. Technical specification of INS sensors in used telephones |
|-------------------|-------------------|-------------------|
| Smartphone         | Sony Xperia M2 Aqua | Samsung Galaxy Note 3 |
| Magnetometer       | Yamaha Unveils YAS532 |                      |
|                    | - size 1.5x1.5x0.65mm, |                      |
|                    | - triaxial, |                      |
|                    | - power consumption 4mA (when active), 1μA (on standby), |                      |
|                    | - High resolution: 0.15μT (X, Y axes), 0.25μT (Z axis) |                      |
| Accelerometer      | Kionix KXTJ2 | STMicroelectronics LSM330DLC |
|                    | - size 2x2x0.9mm, | - size 3x3x0.9mm, |
|                    | - triaxial, | - triaxial accelerometer and |
|                    | - power consumption 10-135μA, | gyroscope, |
|                    | - operating range ±2g, ±4g, ±8g | - power consumption 450μA |
|                    |                      | (accelerometer), 3.2mA (gyroscope) |
| Gyroscope          | not existing | - accelerometer operating range ±2g, |
|                    |                      | ±4g, ±8g, ±16g |
|                    |                      | - gyroscope operating range |
|                    |                      | ±250/±500/±1000/±2000 [°/s] |

2.2. Description of the measurement and results
Measurement data from IMU phones has been registered using the AndroSensor application, which allows the registration of data from all available sensors onboard of the device (including data from GNSS in NMEA format). In addition to raw data from sensors such as accelerations or angular velocities, angles of rotation (roll, pitch, yaw) are also available, which are calculated from the collected data from the accelerometer, magnetometer and gyroscope (if the device is equipped with it). Calculated in this way angles and accelerations were imported into a script written in Matlab.

The measurement data were collected by walking three short routes with different characteristics, which were located in the district of Kortowo in Olsztyn. The first scenario was short and roughly simple (scenario I), the second one consisted of several corners (scenario II), and the last one was located in the building (scenario III).

The measurement was carried out simultaneously with two mobile phones with an interval of 0.5 seconds. The phones were not rotated in hand in any way during the measurement. In the case of the first two scenarios, the reference trajectory was the path created from the points registered with the GNSS receivers since both phones were equipped in GNSS chipset.

In the Figures 2-4 the path calculated by the INS devices is marked in red, the path registered by the GNSS receiver in blue and the yellow letter marks indicate the beginning of the test. The background of
these images is orthophotomap acquired from the Polish "Geoportal" server. The starting coordinates for the calculated INS path were taken from the orthophotomap.

2.2.1. Scenario I. Figure 2 presents the GNSS and INS paths determined by the Samsung Galaxy Note 3 - on the left and Sony Xperia M2 Aqua - on the right. The coordinates of the starting point for INS were: B=53°.760302, L=20°.459473, h=155m. In the case of the first scenario, the goal was to pass a short, approximately 60m straight route. The movement was done along the visible on map pavement. The distance between the last INS point and the end of the path (end of the pavement) was about 13.5m for Samsung, and approx. 28m for Sony.

![Figure 2. INS and GNSS paths determined by Samsung Galaxy Note 3 (left) and Sony Xperia M2 Aqua (right) - Scenario I](image)

2.2.2. Scenario II. The second scenario is a route resembling a triangle with a circumference of approx. 130m. The goal was to make a few turns and return to the starting point. The starting coordinates for INS were B=53°.760918, L=20°.460895, h=144m. In the case of Samsung Galaxy Note 3 (Figure 3 on the left) the drift was approx. 32m, however after approx. 45m (near the roadway) INS did not accurately determine the change of direction (yaw angle error was about 30°). In the case of a Sony phone (Figure 3 on the right) there were three errors in determining the direction, visible in the form of "loops". Only the last section had a well-defined azimuth, but due to the drift in the first phase of the movement, the position of the last points could not be accurately determined.

![Figure 3. INS and GNSS paths determined by Samsung Galaxy Note 3 (left) and Sony Xperia M2 Aqua (right) - Scenario II](image)
2.2.3. Scenario III. The last scenario involved determining the position using INS in a place where satellite navigation does not work, i.e. in a building. The goal was to determine the INS accuracy in the case of a 180 degree return. The building, visible in Figure 4, is one of the Institute of Geodesy. The starting coordinates for INS were B=53°.7605028, L=20°.457011, h=146m. The distance difference between the last INS point and the end of the path (end of the pavement) was approx. 7m for Samsung (figure 4 on the left), and approx. 10m for Sony (figure 4 on the right). However, it should be noted that the length of the path is only about 40m, and both telephones did not cope well with the sudden change of direction.

![Figure 4. INS and GNSS paths determined by Samsung Galaxy Note 3 (left) and Sony Xperia M2 Aqua (right) - Scenario III](image)

3. Conclusions

The conducted research has shown to what extent a modern mobile phone can be used to create an inertial navigation system (INS). In the case of short routes (up to several dozen meters), the system performs well, taking into account low-class sensors.

In the first scenario, the phones allowed to determine the route with characteristics similar to the real movement i.e. in the form of a straight line. Although the final point of the route was determined with a certain error, the INS system better reflected the nature of the route traveled than GNSS chipset.

The second scenario aimed at determining the behavior of the INS at the time of the sudden change of direction. There are already considerable imperfections of the sensors in this example, i.e. the phones detect a change of direction, but with a large error. Similarly, the system behaved in the third scenario.

At the same time, the study showed that the phone equipped with a three-axis gyroscope works much better than a phone with only a built-in accelerometer and magnetometer (it should be noted that both telephones are equipped with the same magnetometers). A smartphone without a gyroscope has a lot of problems with the detection of sudden changes in movement direction, i.e. it needs more time to determine the proper orientation - this is particularly evident in the second scenario. The first scenario showed that the azimuth determined by a telephone without a gyroscope is more erroneous than the one designated by the Samsung Galaxy Note 3.

Currently, mobile phones manufactured to a certain extent can be used in indoor navigation. It is possible that in the future, mobile phones, thanks to the dynamically developing MEMS technology, will enable precise navigation even in shopping centers.

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