Trends in Inertial Navigation Technologies

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Abstract. The inertial measurement unit is an electronic device built-in practically in any controlled or autonomous technology used for land mapping. It is based on a combination of accelerometers and gyroscopes and sometimes magnetometers used for relative orientation and navigation. The paper is focused on functions and trends of an inertial measurement unit, which is a part of inertial navigation indicator of position and velocity of moving devices on the ground, above and below ground in real-time.

1. Introduction

The Inertial Navigation System (INS) is based on the continual evaluation of an actual position of a device. The basic component of the inertial system is an inertial measurement unit (IMU) based on built-in motion-sensitive sensors. The primary inertial sensors are gyroscopes and accelerometers, which are connected to a computer to determine the actual position, orientation, direction, and speed of the moving device without external sources of movement information. The actual position is evaluated in the defined reference system related to the initial position. Gyroscopes are angular velocity sensors whose output signals are used after integration to determine the orientation in space. The output signals of the accelerometers have to be compensated by the values of the gravitational acceleration and the Coriolis force to obtain clear values integrated into the velocity and position. The primary sensors are placed in a three-dimensional coordinate system and each axis of the navigated device corresponds to the sensitivity axis of the accelerometer and gyroscope [1]. Such an inertial measurement unit has six degrees of freedom, and thus it is possible to measure translational and rotational motion in three orthogonal axes.

At present, inertial navigation sensors are produced as micro-electromechanical units used practically in every moving measuring device. The most used principles for MEMS gyroscopes are Ring gyroscope, Dual Mass gyroscope, Tuning Fork gyroscope. The basic physical principles of the MEMS accelerometers include capacitive, piezoelectric, thermal, and currently less common piezo-resistive. Each of the physical principles has its advantages and its use depends on the application. Successful innovation of underground displacement monitoring based on MEMS sensors inclinometers were developed in Italy [2, 3].
Inertial measurement unit is an essential part of devices used for the Global navigation satellite system, aerial photogrammetry, laser altimetry, remote sensing technologies, unmanned aerial vehicles, but it is also the main component of unmanned ground and marine vehicles. The main applications of the IMU sensor include control and stabilization, navigation and correction of the unmanned or manned controlled systems used for mobile mapping applications whether they are land, air, or marine. In practice, inertial sensors are used mainly to determine the position in inertial navigation, to refine GNSS navigation after the loss of the signal from the satellite, to detect shocks in the automotive industry, but also the gaming industry.

Inertial measurement systems are widely used in mobile laser scanning. In addition, they enable a significant reduction in the duration of measurements with terrestrial stationary laser scanners. The new scanner models do not require levelling, and the orientation of the device in space is obtained from the IMU. An example of using such a scanner model to assess the roughness of concrete on a construction site can be found in [4].

Inertial navigation systems began to be used at the beginning of the last century in Germany when classic compasses replaced gyroscopes in ship navigation [5]. Later, they spread to space, sea, and especially underwater navigation. The INS has an important place in military navigation and control. The mechanization of INS depends on the physical construction of a navigation system. There are two types of INS mechanization: the stabilized platform and the strap-down configuration. Stabilized platform provides angular motion isolation from the vehicle, while in the strap-down system, the accelerometers and gyroscopes are physically bolted to the vehicle within a single box.

2. Coordinate reference frames
Most of the navigation systems use Cartesian coordinates, whose axes are mutually orthogonal by definition. The coordinate frames deal with either global or local coordinates. The global coordinates respect the geodetic-astronomic conventional usage tied either to the rotating Earth or to the celestial sphere. The local Cartesian coordinates are defined by local directions, such as north, east, and down. These coordinates are still three-dimensional and serve mostly to facilitate computations and derivations, besides having their historical significance.

Navigation frames are used for positioning in real-time or in post-processing applications. The process of determining coordinates is based on physical laws, especially gravitational acceleration plays a significant role in the coordinate frame.

The most fundamental coordinate frame in geodesy is the inertial frame, defined classically as that system in which Isaac Newton’s laws of motion hold. The Newtonian definition of the inertial system implies a Galilean system, defined as a system with coordinates satisfying Euclidean geometry. The International Earth Rotation Service (IERS) establishes the inertial system as the International Celestial Reference System (ICRS), which is realized by a catalog of 608 quasars whose directions are determined using the technique of Very Long Baseline Interferometry and by the coordinates of some 120,000 stars published in the Hipparcos Catalogue. The ITRS is connected to the ICRS using adopted theories and conventions for the nutation and precession of the Earth’s spin axis and orbit in space, as well as the motion of the pole related to the Earth’s surface. The origin of the ICRS is the center of mass of the solar system in caser to be consistent with the definition of dynamic time which is the time argument in the theories of planetary motion [6], [7].

3. Principles of inertial navigation
Webster dictionary [8] defines navigation in three ways: 1. the act or practice of navigating; 2. the science of getting ships, aircraft, or spacecraft from place to place, especially the method of determining position, course, and distance running; 3. ship traffic or commerce [7]. Inertial measurement is a dead-
reckoning system, that is starting from a known position, measurements are taken to compute a new position. These systems are based on Newton’s second law, which states that the acceleration of a body is proportional to the sum of the forces acting upon it. With velocity defined as a rate of change of position and acceleration as a rate of change of velocity, a double integration is necessary to compute position from a measured acceleration.

4. Trends in IMU technologies
The latest trends in the development of inertial technologies are well described in a market report [7] of a company, which deal with high-performance Inertial Measurement Unit, whose market is segmented according to the end-user application: industrial, aerospace and defense, automotive, civil, naval and offshore marine, and geography. The overview of the current IMU technology market:

The development of technological trends of inertial measuring units is directly related to market demand. As with other technologies, the main development requirement is to reduce size and energy consumption. This trend, which is likely to continue, reinforces their use in robotics, in the development of stable and unstable robots, in industrial navigation, in biomechanics, and development of virtual reality tools. The development of microelectromechanical systems has led to the widespread use of IMU in military defense and space applications, which require additional applications to identify and eliminate inertial errors. A separate component of development and application in the automotive industry, which uses IMU technology to control stability, increase safety and detect accidents. Great use of MEMS systems is expected in the production of autonomous control systems, especially in the development of technologies related to acceleration and detection and measurement of distance (LiDAR) and motion (Figure 1) [9].

![Figure 1. GNSS RTK rover with tilt compensation by Inertial measurement unit](image)

The most recent trends in the development of geodetic instruments relate to the application of the inertial measuring unit in land management. Motion and angular velocity sensors have revolutionized point position measurement using GNSS and the Real-Time Cinema (RTK) method. Rover GNSS RTK, a well-known surveying company, uses IMU technology to automatically adjust the tilt of the pole, which mainly increases productivity, expands the usability of RTK, and reduces human error. A great advantage of this tilt compensation is the use of the rover even at large tilts and immunity to magnetic interference [10].

5. Conclusions
Sensors of the inertial measurement unit integrate besides the measured values also errors that accumulate in the sensors and cause a navigation error. The prevention of this phenomenon is in the error identification and their subsequent elimination, either by sensor calibration or by compensation.
Based on these errors, the quality of MEMS sensors is defined. Sensor errors, as with other devices, can be divided into static and dynamic and random and systematic. Random angle sensor errors include Angle random walk error and Velocity random walk error, which occurred specifically because of noise in the rate signal, independent of other characteristics that contribute to angle error such as scale factor error or bias error.

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References
[1] An Introduction to GNSS, NovAtel Inc., Calgary, 100 p., 2015, ISBN 978-0-9813754-0-3, Available at: https://novatel.com/tech-talk/an-introduction-to-gnss [Accessed 19.07.2021]
[2] A. Segalini, L. Chiapponi, M. Drusa, and B. Pastarini. New inclinometer device for monitoring of underground displacements and landslide activity. Komunikácie 16 (4), pp. 58-62, 2014, ISSN 1325-4205.
[3] A. Segalini, A. Carri, A. Valletta, and M. Martino. Innovative monitoring tools and early warning systems for risk management: A case study, 10.3390/geosciences9020062, Geosciences (Switzerland) Vol. 9, Issue 21, Article number 62, 2019
[4] Z. Muszyński, and M. Wyjadłowski. Assessment of the Shear Strength of Pile-to-Soil Interfaces Based on Pile Surface Topography Using Laser Scanning. Sensors (Basel, Switzerland), 19(5). 2019. https://doi.org/10.3390/s19051012.
[5] Ch. Jekeli: Inertial Navigation Systems with Geodetic Applications. Walter de Gruyter, Berlin, New York, 368 p., 2001, ISBN 3-11-015903-1.
[6] T. J. M. Kennie. Engineering Surveying Technology. CRC Press, 508 p., 2014. ISBN 9781482269376.
[7] S.M. Kohler. Inertial Navigation System for Directional Surveying. Sandia report. Available from National Technical Information Service US. Department of Commerce, 1982
[8] Merriam Webster Since 1828 navigation [Online] 2021 [Accessed 19.07.2021] Available at: https://www.merriam-webster.com/dictionary/navigation.
[9] EZ Airborne Topographic LiDAR Help [Online] 2019 [Accessed 19.07.2021] Available at: https://ez-pdh.com/airborne-topographic-lidar-help/.
[10] Leica Geosystems Leica GS18 T GNSS RTK Rover [Online] 2021 [Accessed 19.07.2021] Available at: https://leica-geosystems.com/products/gnss-systemsSMART-antennas/leica-gs18-t