Chapter

Analysis of MEMS-IMU Navigation System Used in Autonomous Vehicles

Ishak Ertugrul and Osman Ulkir

Abstract

In this study, it is aimed to perform a COMSOL analysis of the inertial measurement unit (IMU), which is a sensor based on a microelectromechanical system (MEMS) in an inertial navigation system (INS). Autonomous vehicles are the types of vehicles that can go on the move without the intervention of the driver by detecting the road, traffic flow, and environment without the need of a driver, thanks to its automatic control systems, software algorithms, and intelligent sensor structures. Autonomous vehicles can detect objects around them using technologies and techniques such as radio detection and ranging (RADAR), light imaging detection and ranging (LIDAR), Global Positioning System (GPS), INS, ultrasonic sensors, camera systems, and computer vision. After providing information about the use of IMU sensors in autonomous vehicles, the finite element analysis of the gyroscope sensor by the COMSOL program was performed in this study.

Keywords: MEMS sensor, gyroscope, autonomous vehicles

1. Introduction

Recently, there has been a rapid development in autonomous vehicle technology. As a result of these developments, autonomous cars, drones, and submarines were produced. Starting with the use of electronic ignition systems and electronic speed indicators in the vehicles, the process continued with equipment such as front-rear view camera systems and parking assistants and reached the final point with vehicles moving without driver intervention [1].

Autonomous vehicles are the types of vehicles equipped with camera systems, sensors, controllers, and wireless communication modules (Global Positioning System (GPS)/INS) produced as a result of the rapid development of digital technology added to the conventional vehicles used today [2]. This equipment must be in constant communication with the satellites while the vehicle is moving. This makes it possible to determine the position of the autonomous vehicle in the world. However, they communicate with each other, control centers, and intelligent traffic signs of autonomous vehicles to determine distance and speed information, the status of other vehicles with transition priority, traffic, and road conditions of highways [3].

With satellite-based navigation systems, autonomous vehicles can quickly receive location information. These systems are used in conjunction with artificial intelligence algorithms such as machine learning, support vector machines, and artificial neural networks [4–6]. Autonomous moving, starting, and ending points are entered, and driverless vehicles which determine their route are tested. As a result of the tests performed on autonomous vehicles, very high achievements are achieved [7]. The main goal is to develop a controller that allows following the desired trajectory with the lowest error.

When we look at the history of autonomous vehicles, it can be seen that the first studies started in the 1920s. The first models that could go on their own were born in the 1980s. The first vehicle was built between 1987 and 1995 between Mercedes-Benz and the US Department of Defense with the DARPA Autonomous Land Vehicle (ALV) project. To date, all the companies producing automobiles have carried out many types of research and trials in this field.

Inertial navigation systems (INS) developed by silicon microelectromechanical system-inertial measurement unit (MEMS-IMU) sensors, which have developed rapidly in the last 20 years, are already widely used in the guidance and control of missile systems and applications developed as a basis for land and air vehicles [8]. In the inertial navigation system whose necessary calculations can be analyzed more complexly, the position is based on the measured acceleration information, and the orientation is based on the measured angular velocities.

It is seen that the systems developed with this method have been applied to various vehicles, especially in recent years, and autonomous vehicles have been developed, and highly successful results have been obtained. Examples include the determination of the direction of autonomous vehicles carrying cargo in ports, the successful use of unmanned vehicles capable of researching submarines for various purposes, the development of autonomous vehicles capable of moving unmanned in urban and intercity traffic, or the development of bomb destruction robots [9].

The inertial navigation system consists of an IMU, which is the basis of measurements, and a unit of inertial sensors, which provides information on angular velocity and linear acceleration in three dimensions. In this study, the COMSOL analysis of IMU, a MEMS-based sensor in the inertial navigation system, was performed.

2. Control equipment used in autonomous vehicles

Today, thanks to the developing sensor technology and control algorithms, various sensor-based auxiliary elements are used in autonomous vehicles with or without a driver. Some of these devices are used in distance measurement, while others are effective in determining the physical properties of objects. Besides, there is a controller or computer used to evaluate the measured data and carry out the necessary operations and other equipment that enables the movement of the vehicle. **Figure 1** shows the general block diagram of the autonomous vehicle system.

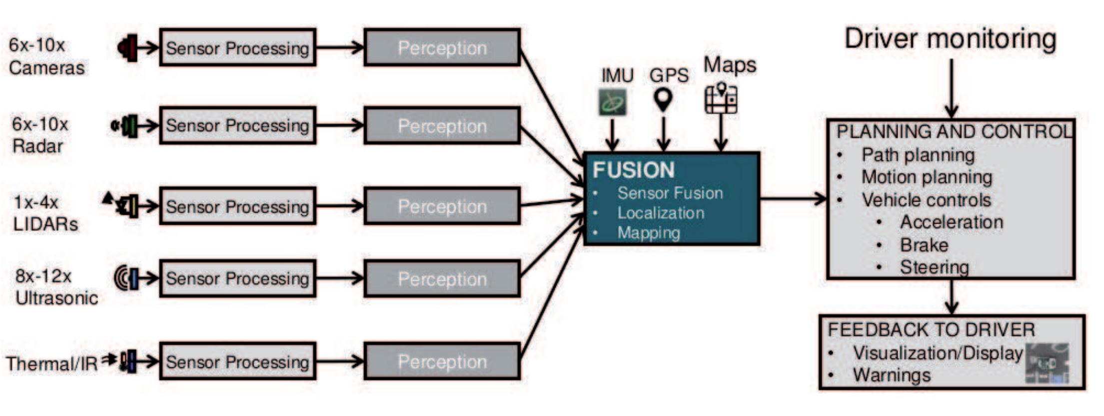

Figure 1.
Algorithm view of autonomous vehicle system [10].

The measured data from the sensors is transmitted to the control center. The sensor information is combined with the locator (GPS/INS), and the map information is transmitted to the planning and control unit. The artificial intelligence algorithm developed with this data determines the tasks that the tool must perform. These tasks are road and motion planning, vehicle speed values, braking, and management. One of the most critical features of autonomous vehicles is the display of images and warnings as feedback.

Sensors, locating, and control-based equipment used in autonomous vehicles are as follows:

- Light imaging detection and ranging (LIDAR)
- Radio detection and ranging (RADAR)
- Ultrasonic sensor
- Standard/infrared cameras and sensors
- GPS/INS
- Computer and software
- Vehicle control

2.1 LIDAR

LIDAR is a remote sensing method that uses laser or light for measuring. In summary, the LIDAR system means that it sends out a light signal and waits for the signal to return. It locates by determining how long the emitted light returns to the sensor. It transforms their positioning into point clouds of millions of points. The LIDAR sensor is expensive and requires powerful computers due to the high data flow.

2.2 RADAR

It is a system that enables us to understand, detect, or measure the speed of moving or immobile objects away from our visual range using electromagnetic waves. The system is equipped with a signal emitter and a unit that detects the signal hitting the target. When calculating the distance, the travel time of the electromagnetic beam is divided into two and multiplied by the beam speed.

2.3 Ultrasonic sensor

It is used to detect objects and measure distance with the aid of sound waves. It consists of an audio source and a receiver that senses echo. These ultrasonic sound waves have a frequency band of 20–500 kHz that cannot be heard by the human ear. With sensors using ultrasonic sound waves, distance measurements can be made without any contact with objects. The sensors are used together to transform their superiority to a more comprehensive perception. The camera system detects the color of the surface and determines the material type of the surface of the LIDAR body. When used together, the system can detect that green surfaces may correspond to grass and give the vehicle a more detailed information about the environment.

2.4 Cameras and sensors

It is used to transfer the image of objects around and inside the vehicle to the host computer in the vehicle. Unlike standard cameras, infrared cameras are used to detect the temperature of objects. Keeping cameras and sensors clean at all times is essential for data quality.

2.5 GPS/INS

They are the sensors used to locate the autonomous vehicle in the world. The GPS determines its global coordinates by receiving signals from satellites rotating around the earth. These coordinates are matched to the road map coordinates, and the position of the vehicle on the road is determined. The GPS is used in conjunction with a built-in gyroscope and accelerometer to continuously measure the vehicle's position, displacement, and speed. INS are integrated into GPS to provide location and speed data at a faster sampling frequency. These systems calculate the mechanization equations and position, velocity, and rotation angles from the IMU sensor outputs.

2.6 Computer and software

The most critical element in the use of free tools is the computer and software algorithms used in the control of the system. Interaction and communication with GPS and INS signals, traffic signs, and other vehicles are realized by a computer and software algorithm in which the controller takes place. Many of these algorithms are artificial intelligence-supported software. With this software, the information coming from the input units of the autonomous system is evaluated, and output is obtained according to the situation. As a result, the movement of the autonomous vehicle is determined.

2.7 Vehicle control

The speed of the vehicle, according to the road and traffic conditions, is achieved by the speed adjustment system. The cruise control, RADAR speed control, and adaptive cruise control are called cruise control systems. The purpose of the controllers is to automatically adjust the vehicle speed and maintain a safe distance from the vehicles in front. Steering of the vehicle is done with the help of step, servo, or hydraulic motors mounted on the steering system of the vehicle. The user decides the time and shape (remotely or closely) of the vehicle starting and stopping. Other operations (in case of emergency) are activated automatically by the computer controlling the vehicle.

3. Material and methods

3.1 MEMS-inertia measuring unit

IMU is an electronic unit that collects angular velocity and linear acceleration data sent to the central processor in a single module. The IMU consists primarily of two separate sensors. One of these is the accelerometer, and the other is a gyroscope. The accelerometer generates three separate analog signals on three axes. Due to the propulsion system and physical limits, the most critical factor in these accelerometers is that they are affected by gravity [11]. The sensor is continuously affected by gravity. As a measurement scale, there are derivatives that can measure in one, two, or three axes. These are ±1, ±2, ±4 g, and so on. It is expressed with such values (**Figure 2**).

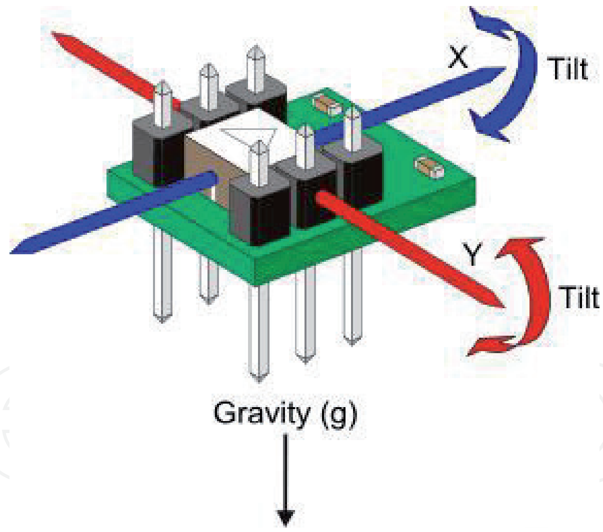

Figure 2.
The structure of accelerometer.

The second sensor inside the IMU is the gyroscope. It is formed by turning a wheel quickly around its axis. There is another circle attached at a right angle to the circle around the wheel. Another circle attached to these circles at a right angle represents the gyroscope. The gyroscope has two features. When a force is applied on the horizontal axis, a gyroscope rotating on the horizontal axis begins to rotate around the axis. Another feature is that the gyroscope remains fixed to the axis of rotation. With this feature, satellites remain earth-facing or work in autopilot applications [12]. Gyro measurements are given in radians/sec; magnetometer measurements are given in gauss (**Figure 3**).

Gyroscopes and accelerometers alone cannot provide reliable and stable data. Therefore, two sensors are combined regarding each other and information such as speed; the position is received from the IMU from a single unit. The term degrees of freedom (DOF) describes the degree of freedom of the IMU. An IMU with three-axis gyro and three-axis accelerometer is referred to as 6DOF (**Figure 4**).

When the gyroscope and accelerometer are used alone, they slip after a specific time. For example, measurements can shift 1° after 5 seconds and, therefore, cannot be used for precise measurements. We have already noted that the accelerometer is affected by gravity. When the gyroscope is used together with accelerometers that generate very high noise in the slightest vibrations, these noises are filtered. In the

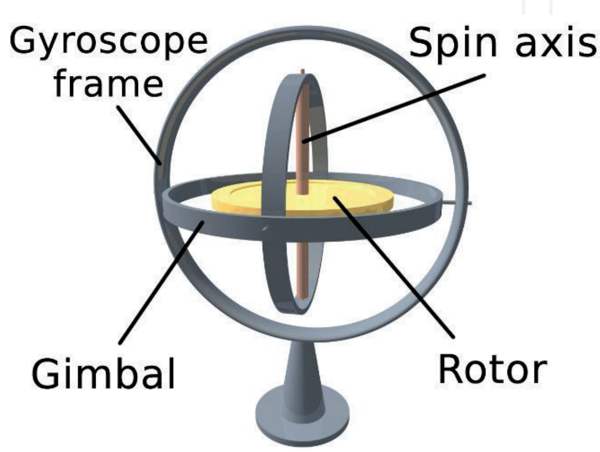

Figure 3.
The structure of gyroscope.

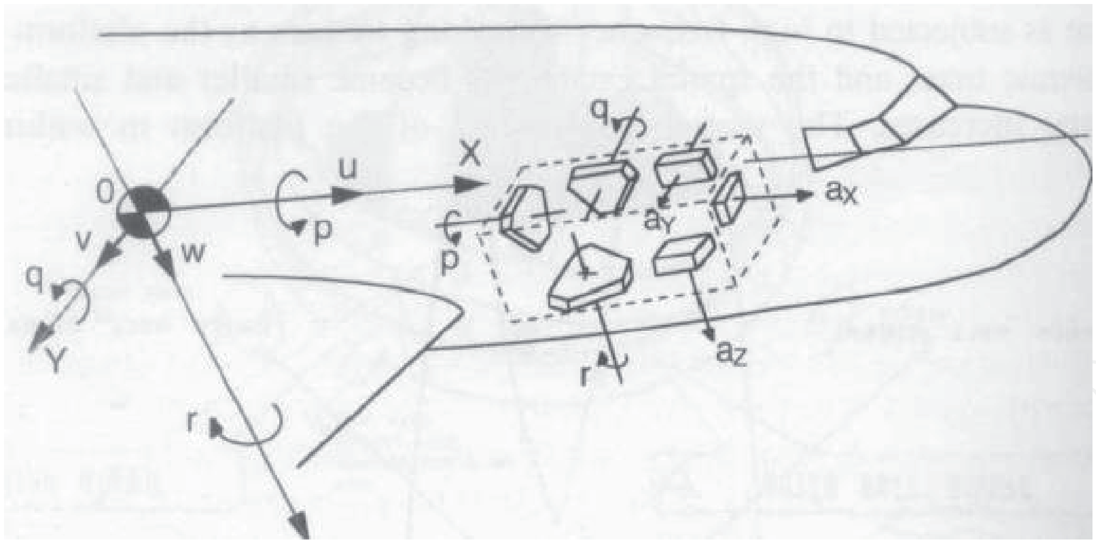

Figure 4.
The structure of IMU.

IMU, gyroscopes are used in conjunction with accelerometers as a reference since they are not affected by these forces. There are various algorithms for filtering. The most popular of these is the Kalman filter.

3.2 Inertial navigation system and GPC integration

GPS is called a Global Positioning System. The GPS sensor communicates with the GPS satellites in latitude, longitude, and altitude. Some GPS types can also provide the speed information they calculate from position changes. In autonomous vehicles, GPS data must be highly accurate and must be sampled quickly. In the measurements made with the GPS, there is a position error of up to 15 m in the 95% confidence interval, while the RMS makes a 0.1 km speed error in case of stability [13].

A GPS/INS integration is provided that provides location and speed data at a faster sampling frequency when compared to geolocation applications using GPS alone.

The IMU sensor is a MEMS-based sensor that can measure rotation speed and translation acceleration, thanks to gyroscopes and accelerometers. INS is a system that calculates mechanization equations and position, speed, and rotation angles from the IMU sensor outputs. INS cannot give accurate results as a result of errors due to noise, offset, drift, and integration in the mechanization equations resulting from the IMU sensor [8]. The INS output data should, therefore, be updated periodically with the GPS sensor using the extended Kalman filter (**Figure 5**).

To calculate the position in autonomous vehicles, the acceleration values measured with respect to the trunk axis must first be converted to the earth-centered reference system. The quaternion transformation algorithm or DCM matrices can be used for this purpose. In the quaternion transformation, the angular state of the aircraft is calculated from the angular velocities taken from the gyros. Using the obtained angle information, the transformer matrix is found from the aircraft reference system to the earth-centered reference system. This matrix is multiplied by the accelerations measured in the accelerometers. When the gravitational acceleration is subtracted from the obtained values, the acceleration of the aircraft is obtained according to the world-centered reference system.

The speed and position of the aircraft are calculated by applying numerical integration to the accelerations in the world-centered reference system. Also, since gravity acceleration varies with coordinates and altitudes, gravity must be

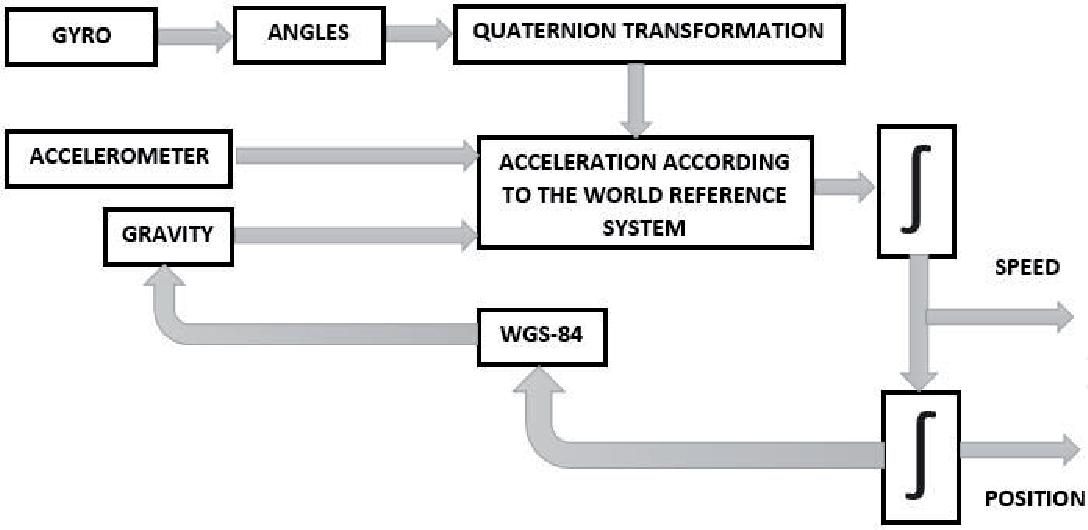

Figure 5.
The structure of inertial measurement system.

calculated based on the position information. Inertial navigation system's calculation of gravity according to a model similar to the 1984 World Geodetic System (WGS-84) is also a necessary factor for accurate measurements [14].

The inertial navigation system used in many vehicles, from missiles to submarines, requires exact and precise measurements, mainly when it is not supported by a sensor such as GPS. Also, since the algorithm used to find the position will be repeated at a high sampling frequency, the simpler the calculation, the better the performance of the system. The most important factors affecting the accuracy of measurements in gyros are drift rate and bias in accelerometers. The bias factor has a second-order effect on position calculation.

4. Result and discussion

In this section, the analysis of the gyro sensor with COMSOL is performed. According to the finite element analysis, the deformation properties of the gyro sensor were interpreted. **Figure 6** shows the design of the gyro sensor. This design was taken from the library of COMSOL, and the data were changed, and analyses were performed [15].

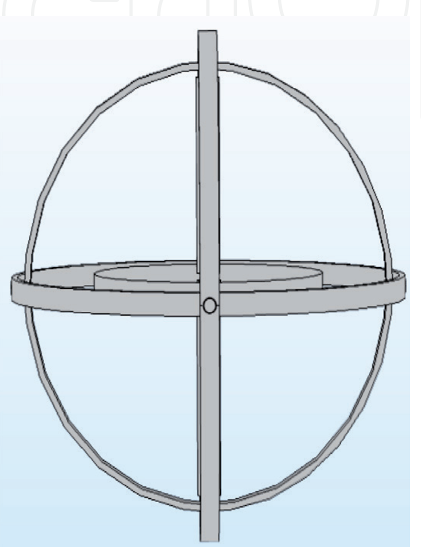

Figure 6.
Design of the gyro sensor.

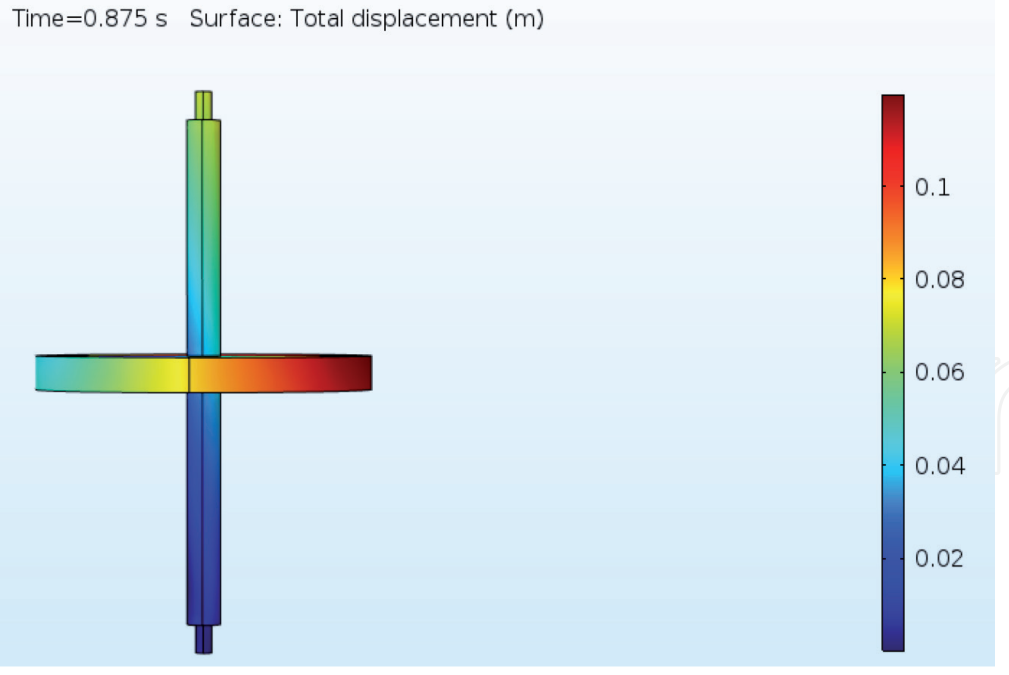

Figure 7.
Deformation analysis of the gyro sensor.

When performing the COMSOL analysis, the deformation analysis of the spinning section of the gyro sensor has been carried out because the deformation is of great importance. **Figure 7** shows the deformation analysis of the spinning section of the gyro sensor. According to this analysis, the deformation in the spinning section is a maximum of 0.12 m.

5. Conclusion

In this study, the purpose and application areas of IMU sensors used in autonomous vehicles are given in general, and the gyro sensor is analyzed with COMSOL. IMU sensors are of great importance for autonomous vehicles. Since these sensors are of micron size, their fabrication is of great importance. For the fabrication process to be successful, design and analysis must be performed correctly.

This study has brought innovation to the literature in that it provides information about the structure of the IMU sensors used in autonomous vehicles as well as about the finite element analysis.

DOI: http://dx.doi.org/10.5772/intechopen.92985

Author details

Ishak Ertugrul* and Osman Ulkir
Department of Computer Engineering, Faculty of Engineering and Architecture, Muş Alparslan University, Mus, Turkey

*Address all correspondence to: i.ertugrul@alparslan.edu.tr

References

[1] Bas E, Tekalp AM, Salman FS. Automatic vehicle counting from the video for traffic flow analysis. In: 2007 IEEE Intelligent Vehicles Symposium; IEEE. 2007. pp. 392-397

[2] Gökozan H, Taştan M, Sarı A. Smart Cities and Management Strategies, International Strategic Research Congress (ISRC2017); Antalya; 2017

[3] Harlow C, Peng S. Automated vehicle classification system with a range of sensors. Transportation Research Part C: Emerging Technologies. 2001;**9**(4):231-247

[4] Yungang T, Jiemin Z, Yonghua H, Jianping W. A research on intelligent structure using artificial neural networks. International Journal of Pattern Recognition and Artificial Intelligence. 1997;**3**(6):1003-1011

[5] Schaab J, Muenchhof M, Vogt M, Isermann R. Identification of a hydraulic servo-axis using support vector machines. IFAC Proceedings. 2005;**38**(1):722-727

[6] Li Q, Zheng N, Cheng H. Springrobot: A prototype autonomous vehicle and its algorithms for lane detection. IEEE Transactions on Intelligent Transportation Systems. 2004;**5**(4):300-308

[7] Okutan O, Maktav D. Uzaktan Algılama Verilerinin Düşük Maliyetli Robotların Kentsel Alan Navigasyonunda Kullanımı, 5. Uzaktan Algılama-CBS Sempozyumu (UZAL-CBS 2014), İstanbul, 2014

[8] Godha S, Cannon ME. GPS/MEMS INS integrated system for navigation in urban areas. GPS Solutions. 2007;**11**(3):193-203

[9] Li Y, Dempster AG, Li B, Wang J, Rizos C. A low-cost attitude heading reference system by combination of GPS and magnetometers and MEMS inertial sensors for mobile applications. The Journal of Global Positioning Systems. 2006;**5**(1-2):88-95

[10] Available from: https://www.slideshare.net/PeterLabaziewicz/perceiving-and-understanding-the-world-for-adasand-autonomous-peter-labaziewiczv4/slide 11 of 19 [Accessed: 10 January 2018]

[11] Ahmad N, Ghazilla RAR, Khairi NM, Kasi V. Reviews on various inertial measurement unit (IMU) sensor applications. International Journal of Signal Processing Systems. 2013;**1**(2):256-262

[12] Zhang P, Gu J, Milios EE, Huynh P. Navigation with IMU/GPS/digital compass with an unscented Kalman filter. In: IEEE International Conference Mechatronics and Automation. Vol. 3; IEEE. 2005. pp. 1497-1502

[13] Godha S. Performance evaluation of low-cost MEMS-based IMU integrated with GPS for land vehicle navigation application [Master's thesis]; 2006. Available from: http://plan.geomatics.ucalgary.ca/papers/06.20239.SGodha.pdf

[14] Li Y, Dusha D, Kellar W, Dempster AG. Calibrated MEMS inertial sensors with GPS for a precise attitude heading reference system on autonomous farming tractors. In: Proceedings of ION-GNSS2009; 22-25 September 2009; Savannah, Georgia. 2009. pp. 2138-2145

[15] Available from: https://www.comsol.com [Accessed: 01 December 2019]