ASSESSMENT OF USEFULNESS OF THE MEMS-BASED INTEGRATED NAVIGATION UNIT IN CAR NAVIGATION

Marcin Uradziński[1], Jacek Rapiński[1], Dariusz Tomaszewski[1], Michał Śmieja[2], Hang Guo[3], Songsen Yu[3], Xiong Jian[3]

[1] Instiute of Geodesy
University of Warmia and Mazury in Olsztyn
[2] Chair of Mechatronics
University of Warmia and Mazury in Olsztyn
[3] Institute of Space Science and Technology
Nanchang University, China

A b s t r a c t

Due to the development of MEMS, there is an opportunity to build a low-cost integrated navigation systems, operating independently of horizon visibility. This paper presents the proposal of an integrated GPS/IMU platform using MEMS technology. In order to verify the performance of a system built at the University of Warmia and Mazury, an experiment was conducted. In this experiment a precise Javad GNSS receiver, commercial grade GPS/IMU XW – ADU5660 and own-built system were used. The experiment was conducted to compare the results obtained from self built device with the working military integrated navigation unit. During the study all three devices were mounted inside moving vehicle. The car drove route inside the Kortowo campus, during which, all equipment performed measurements. Then, the results from both integrated systems were compared with RTK (Real Time Kinematic) results from Javad receiver. Experiments prove that the performance of own device is comparable to the commercial device.

Correspondence: Dariusz Tomaszewski, Instytut Geodezji, Uniwersytet Warmińsko--Mazurski, ul. Oczapowakiego 1, 10-719 Olsztyn, phone: +48 89 523 42 04, e-mail: dariusz.toma-szewski@uwm.edu.pl

Introduction

Positioning and navigation systems are continuously gaining attention in location-based services (LBS) and are becoming a standard feature in modern mobile devices. The development of Micro Electro Mechanical Devices (MEMS) allow to build more and more effective, cheap devices for integrated navigation. Rapid development of various MEMS sensors allows to build smaller and more accurate devices (TANAKA 2007). In the field of navigation the following MEMS sensors are commonly used: gyroscopes, accelerometers, magnetometers, pressure sensors. Integration of these sensors allows to create the Inertial Measurement Unit (IMU). After implementation of navigational algorithms, an IMU module becomes an Inertial Navigation System (INS).

An IMU usually consists of three accelerometers and three gyroscopes. They are mounted on an orthogonal triad. The basic operating principle of inertial navigation is based on Newton's law of motion. It says that an object continues to be in a state of rest or uniform motion, unless acted upon by an external force. The application of any external force generates the acceleration, which is sensed by accelerometers. This acceleration, when integrated twice, provides the change in the state of the object with the respect to the initial conditions. Thus, an INS provides the position and attitude of the object, in the reference to the initial condition (position, velocity and attitude) of the platform (EL-SHEIMY 2004, GODHA, CANNON 2005).

In recent years, attention has focused on the development of sensors that are embedded in the same chip (e.g. accelerometers that detect acceleration in three axes simultaneously). It is achieved using MEMS, Nanoelectromechanical systems (NEMS), and Micro-Opto-Electro-Mechanical Systems (MOEMS) (HOPKINS et al. 2010, BROWN, LU 2004).

Every MEMS-INS is burdened with errors causing degradation of accuracy in time. The main error sources are: incorrect initial alignment of the navigation system, accelerometers and gyroscopes random walk and bias instability, imperfection of the gravity model, imperfect temperature compensation, non-orthogonality and misalignment of the INS sensors (SCHMIDT 2010). Microelectromechanical inertial sensors have proved to be very favorable for new applications, that have gained immediate place on the market. The main advantages of such systems are: small size, extreme ruggedness, low cost and weight. Progressive development of MEMS technology has led to manufacture of the sensors that can be used for precise applications (gyroscopes 0.2°/h, accelerometers 1 mg) (SHIN, EL-SHEIMY 2004).

The use of MEMS micro-systems for navigational applications has the potential to change completely the design and development of future car guidance and control systems (SALYCHEV et al. 2000). Additionally, modern

GNSS/RTK (Real Time Kinematic) techniques allow positioning in the range of a couple of centimetres. For this reason, attempts to put them to practical use for controlling vehicle motion for driver assistance have been made in recent years. The combination of high-accuracy positioning information obtained from GNSS/RTK with high-precision INS sensors can also support the latest concepts in vehicle-control systems, such as: detection of relative vehicle position on a highway or collision avoidance (URADZINSKI et al. 2008).

In recent years a number of INS/GPS system swereconstructed (ZHAO 2011, CHE et al. 2012, NOURELDIN et al. 2009). They were equipped with sensors of a different class and price. As a part of the research, staff of the Institute of Geodesy, built an integrated navigation system consisting of low – cost MEMS parts. Created platform was built with a possibility to implement different integration algorithms. The main idea was to create a navigation system with the cheapest possible components, allowing to perform measurements of suitable accuracy. It this study the INS/GPS integration was performed using loosely coupled integration schemes. The main goal of this paper is to compare the performance of a commercial and an own-built INS/GPS system.

Experiment description

In order to investigate the performance of the own-build GPS/IMU system, a comparative study of the results from two devices was performed.

The own-built MEMS IMU contains of a ADIS MEMS IMU and an uBlox LEA. The commercial IMU is a Chinese XW-ADU5660 (double frequency GPS, GLONASS/IMU) INS Attitude and Azimuth Integrated Navigation System from StarNeto Technology. Dual-frequency Javad Alpha GNSS receiver was used to create a reference trajectory. Both systems were evaluated in different operating environments, specifically in open and semi-urban areas.

The ADU5660 is a Chinese IMU unit with integrated GPS receiver. The producer claims the following accuracy parameters: heading with GPS enabled (0.1°), attitude (0.1°), horizontal position accuracy (2 m), vertical position accuracy (4 m), gyro bias stability $(5^\circ/h)$, accelerometer bias (0.1 mg). The device is depicted in Figure 1.

The ADIS three-axis inertial sensor is a high quality measurement module, consisting of an three-axis accelerometer and three-axis gyroscope. The selected measurement unit has the ability to perform measurements at 1 Hz – 350 Hz sampling rate with 14 bit resolution. The accelerometer mounted inside the IMU module allow to perform readings with a dynamic range from ± 1.7 g. The sensitivity of these device is 0.4625 mg/LSB (Least Significant Byte). Error of accelerometer measurements is characterized by 0.135 m/s/h

Fig. 1. XW-ADU5660 Attitude and Azimuth Integrated Navigation System from StarNeto
Technology

velocity random walk coefficient. These values allow to determine the initial
attitude of the device with accuracy of 0.02°. Gyroscope installed within ADIS
measures angular rate with dynamic ranges from ±75°/s to ±300°/s with
smallest possible sensitivity of 0.01832°/s/LSB. Calculated mean gyroscope's
angular random walk is 5.69°/h, and the bias stability equals 0.012°/s. These
technical conditions allow to achieve high accuracy during subsequent calcula-
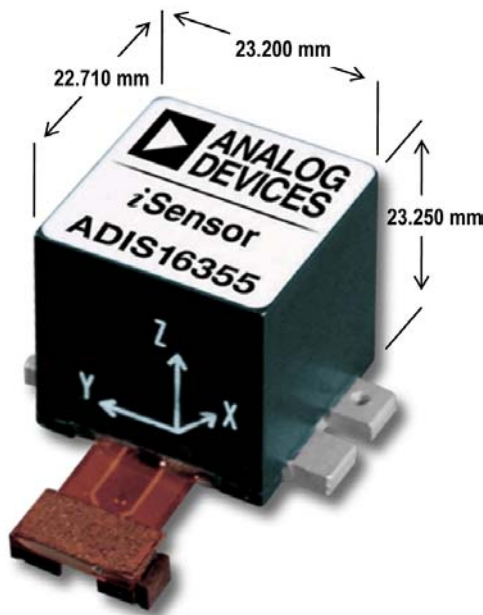tions. The ADIS is presented in Figure 2.

Fig. 2. ADIS MEMS IMU sensor

The own-built device scheme is presented in Figure 3. The main part of this device is ATmega micro-controller which acts as the interface between user and measurement devices. The communication between uBlox LEA GPS receiver and the micro-controller uses UBX protocol. In order to ensure time synchronization between GPS receiver and IMU readings, the receiver provides triggering impulse for ADIS at the 1 Hz frequency. Communication between ADIS and micro-controller is based on serial peripheral interface (SPI). In this experiment measurement results were recorded on a PC. Data transfer was performed using UART RS232 over USB at 230400 baud rate.
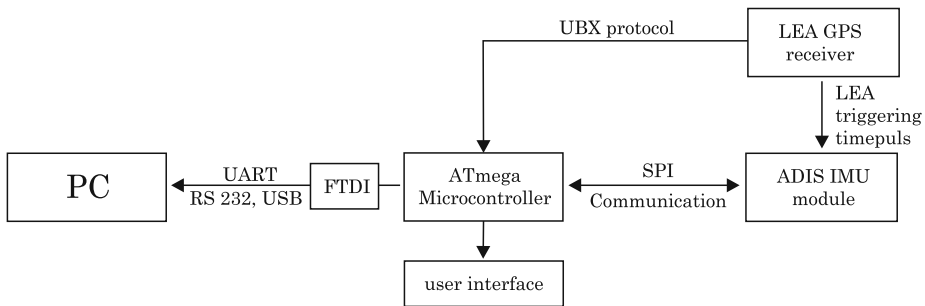
Fig. 3. Scheme of own-built IMU device

The experiment was conducted at the campus of the University of Warmia and Mazury in Olsztyn, Poland. All the equipment was fixed inside the car, with the GNSS antenna mounted on the roof. Both integrated receivers were performing measurements at 50 Hz frequency. This frequency was chosen because it is the only value on which the Chinese receiver operates. The results from 1 Hz GNSS differential, kinematic, post-processed data were used as a reference. The mean error of position obtained from GNSS processing calculated by the Topcon Tools software was 0.03 m. Therefore this trajectory can be considered as a reference for further tests. Figure 4 depicts the trajectory of the car equipped with the GNSS/IMU units.

Reference Javad receiver was connected to the same antenna with both GNSS/IMU units using antenna splitter. The reference trajectory was obtained using double frequency GNSS phase and code measurements kinematic post-processing (KROL reference station). Figure 5 depicts the equipment setup during experiment.

Fig. 4. Trajectory of the car equipped with the GNSS/IMU units

Fig. 5. Equipment setup during experiment

Data processing and results

After collecting data the results were post-processed. In this step the navigation solutions from the GPS and INS are integrated to obtain a positioning solution. Loosely coupled integration strategy was implemented using a closed loop approach. An augmented state Kalman filter was adapted for integration of the INS with GPS for effective sensor error compensation. The specific advantage of such a filter is that the inertial sensor raw measurements are corrected for deterministic errors (which vary with each power-on of the system) more efficiently (HIDE, MOORE 2005, KNIGHT 1999).

In the presented algorithm the state vector has the following form:

$$X = [\varphi_E, \ \varphi_N, \ \varphi_U, \ \delta v_E, \ \delta v_N, \ \delta v_U, \ \delta L, \ \delta\lambda, \ \delta h, \ \xi_x, \ \xi_y, \ \xi_z, \ \nabla_x, \ \nabla_y, \ \nabla_z],$$

where:
φ – East, North and Up platform misalignment angles,
δv – East, North and Up velocity errors,
δL, $\delta\lambda$, δh – latitude, longitude, and height errors,
ξ, ∇ – the gyro random drifts and accelerometer random biases respectively.

Measurements were processed with the use of few filtration algorithms. From obtained sets of results the one that was closest to the reference was chosen and presented in the study. The best solution was to use the cubature Kalman filter algorithm (CKF). The CKF provides a systematic solution for high-dimensional nonlinear filtering problems. The CKF is a spherical-radial cubature rule, which makes it possible to compute in numerical way multivariate moment integrals encountered in the nonlinear Bayesian filter. The principle of CKF filtering is presented in the literature (IENKARAN, HAYKIN 2009). Non linear errors dumping method used in the self – built platform was described as in literature (SUN, TANG 2012). The principle of data processing is depicted in Figure 6.

For the purpose of the analysis the differences of results between integrated and reference coordinates were calculated. Computations were made for each Time Of Week (TOW) seconds. Results of the conducted experiment are presented in Figures 7 and 8 and Tables 1 and 2. Figure 7 depicts coordinate differences between XW-ADU5660 IMU device and Javad GNSS receiver postprocessed data. Table 1 presents the summary of the results for XW-ADU5660 Attitude and Azimuth Integrated Navigation system.
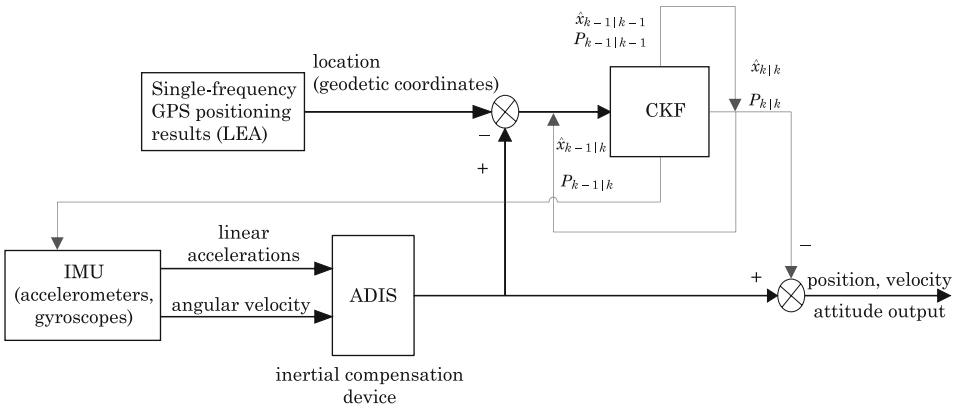
Fig. 6. Block diagram of Global Positioning System/Inertial Navigation combined Solution
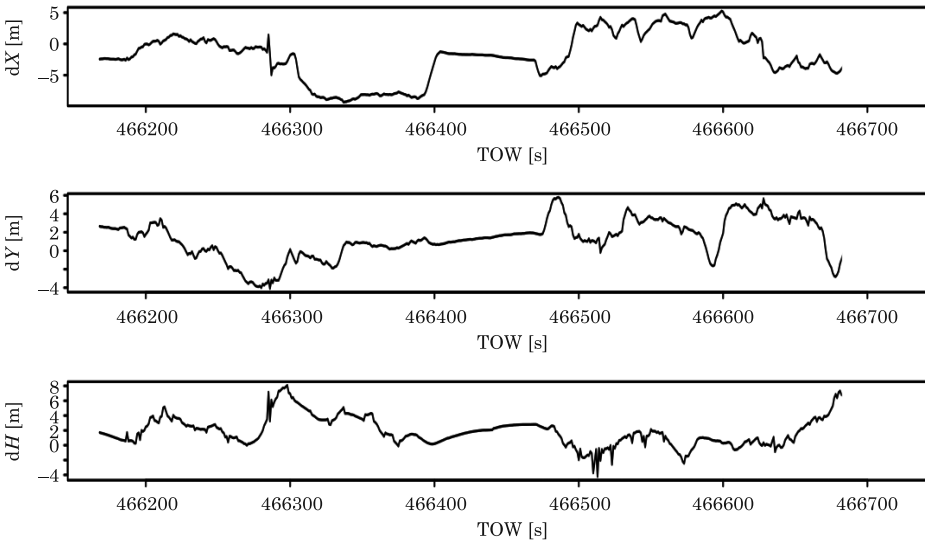

Fig. 7. Coordinate differences between XW-ADU5660 IMU device and Javad GNSS receiver postprocessed data

Figure 8 depicts coordinate differences between ADIS MEMS IMU unit and Javad GNSS receiver postprocessed data. Table 2 presents the summary of the results for ADIS MEMS IMU + uBlox LEA unit.

On the basis of conducted study one can see that the own-built system has slightly worse performance compared to the commercial device. Mean values of *X*, *Y* and *Z* coordinates are similar. For XW-ADU receive they are -3.20, 1.99 and 2.27 for *X*, *Y* and *Z* axis respectively. On the other hand the same values

Summary of the results for XW-ADU5660

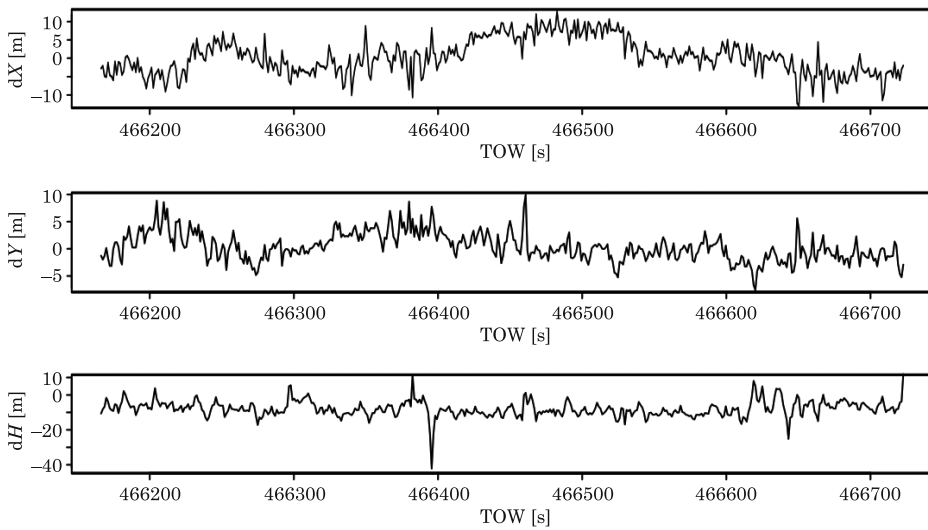| Specification	dX [m]	dY [m]	dH [m]
Minimum	0.01	0.01	0.01
1st Quartile	1.37	0.91	0.78
Median	-2.49	1.75	1.86
Mean	-3.20	1.99	2.27
3rd Quartile	4.02	2.99	3.41
Maximum	-9.32	5.79	8.07
Standard deviation	3.68	2.03	2.03
Variance	13.58	4.12	4.14

Fig. 8. Coordinate differences between LEA unit and Javad GNSS receiver postprocessed data

Summary of the results for ADIS MEMS IMU + uBlox LEA unit

Specification	dX [m]	dY [m]	dH [m]
Minimum	0.01	0.01	0.01
1st Quartile	1.39	0.90	2.56
Median	3.33	1.60	-4.85
Mean	3.86	2.09	-5.09
3rd Quartile	5.78	2.96	6.99
Maximum	12.99	10.43	-38.43
Standard deviation	4.83	2.59	4.58
Variance	23.31	6.72	21.04

for self – build platform are 3.86, 2.09 and -5.09. On the basis of these values it can be concluded that mean accuracy of 2D coordinates obtained from both units is similar. However, value of height obtained from LEA + ADIS system is twice worst. This may be related with the quality of satellite observations made by the LEA receiver. Since it is only a GPS receiver operating on a L1 frequency. Contrasted with ADU GPS, GLONASS dual – frequency receiver, which have better H determination accuracy due to observations made on two carrier frequencies. This phenomenon is not so evident in two-dimensional positioning. Both equipment data was recorded using NMEA protocol. For GPS-only self-built integrated system, the average visible satellites were 7 and PDOP was below 3. For GPS/Glonass XW-ADU5660 navigation system, the average number of satellites was 12 and PDOP was below 1.7

Greater differences in the results can be seen in the analysis of variance and standard deviation for both systems. Obtained variance of results is much bigger for own-built system and maximum residuals are larger than for the XW-ADU5660 INS. This phenomenon can be seen with the naked eye in Figure 8 and Figure 9. Data received from ADIS IMU unit has more noise (bigger variance of residuals) while the results of XW-ADU5660 unit measurements seem to be more smoothed. It can be caused by some initial processing of data performed inside of the XW-ADU5660, while data from own-built systems were not pre-processed at all. The authors can't state what kind of filtering was used in case of commercial device because it is a closed system design.

For the raw GNSS results obtained from both devices there is no significant difference. Only Values of determined height differences are grater, what has been described previously The performance of both receivers is typical for satellite navigation (standard deviation about 3 meters).

Discussion and Summary

One test with XW-ADU5660 INS and ADIS MEMS IMU + uBlox LEA units was conducted to check the performance of the own-designed navigation platform. Results from self-built platform were processed using the same algorithm (CKF). The own-designed system is in the development stage and its open architecture gives more possibilities for further research.

From the car navigation point of view the accuracy obtained from own-built system is satisfactory. The existence of IMU data can improve the reliability of the solution. Navigation can be continued in the case of short time GNSS signal outages without losing accuracy. Some further research such as implementation of receiver autonomous integrity monitor will be performed in the near future.

References

BROWN A., LU Y. 2004. *Performance Test Results of an Integrated GPS/MEMS Inertial Navigation Package*. Proceedings of ION GPS, 21–24 September, Long Beach CA, p. 825–832, U.S. Institute of Navigation, Fairfax VA.

CHE H., LIU P., ZHANG F., WANG Q. 2012. *A Deeply Coupled GPS/INS Integrated Navigation System Suitable for High Dynamic Environments*. J. Sun et al., sud. China Satellite Navigation Conference (CSNC) 2012 Proceedings., Berlin, Heidelberg: Springer Berlin Heidelberg. DOI: 10.1007/978-3-642-29187-6_60.

EL-SHEIMY N. 2004. *Inertial techniques and INS/DGPS Integration*. ENGO 623 – Course Notes, Department of Geomatics Engineering, University of Calgary, Canada.

GODHA S., Cannon M.E. 2005. *Integration of DGPS with a MEMS-Based Inertial Measurement Unit (IMU) for Land Vehicle Navigation Application*. Proceedings of ION GPS, 13–16 September, Long Beach CA, pp. 333–345, U.S. Institute of Navigation, Fairfax VA.

HIDE C.D., MOORE T. 2005. *GPS and Low Cost INS Integration for Positioning in the Urban Environment*. Proceedings of ION GPS, 13–16 September, Long Beach CA, pp. 1007–1015, U.S. Institute of Navigation, Fairfax VA.

HOPKINS R.E., BARBOUR N.M., GUSTAFSON D.E., SHERMAN P. 2010. *Miniature Inertial and Augmentation Sensors for Integrated Inertial/GPS Based Navigation Applications*. NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology.

IENKARAN A., HAYKIN S. 2009. *Cubature Kalman Filters*. IEEE Trans. Automat. Contr., 54(6): 1254–1269.

KNIGHT D.T. 1999. *Rapid Development of Tightly Coupled GPS/INS Systems*. Aerospace and Electronic Systems Magazine, 12(2): 14–18.

NOURELDIN A., KARAMAT T.B., EBERTS M.D., EL-SHAFIE A. 2009. *Performance enhancement of MEMS- -based INS/GPS integration for low-cost navigation applications*. IEEE Transactions on Vehicular Technology, 58(3): 1077–1096.

SALYCHEV O., VORONOV V.V., CANNON M.E., NAYAK R.A., LACHAPELLE G. 2000. *Low Cost INS/GPS Integration: Concepts and Testing*. Proceedings of ION NTM, 26–28 January, Anaheim CA, pp. 98–105, U. S. Institute of Navigation, Fairfax VA.

SCHMIDT G. 2010. *INS/GPS Technology Trends*. NATO RTO Lecture Series. RTO-EN-SET-116. Low-Cost Navigation Sensors and Integration Technology.

SHIN E., EL-SHEIMY N. 2004. *An Unscented Kalman Filter for In-Motion Alignment of Low Cost IMUs*. Proceedings of Position Location and Navigation Symposium IEEE, 26–29 April, pp. 273–279.

SUN F., TANG L.-J. 2012. *INS/GPS integrated navigation filter algorithm based on cubature Kalman filter*. Control and Decision, 27(7): 1032–1036.

TANAKA M. 2007. *An industrial and applied review of new MEMS devices features*. Microelectron. Eng., 84(5–8): 1341–1344.

URADZINSKI M., KIM D., LANGLEY R.B. 2008. *The Usefulness of Internet-based (NTrip) RTK for Navigation and Intelligent Transportation*. Proceedings of ION GNSS 2008, 16-19 September, Savannah, pp. 1437–1445, U. S. Institute of Navigation, Fairfax VA.

ZHAO Y. 2011. *GPS/IMU integrated system for land vehicle navigation based on MEMS*.