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EXPERIMENTAL VALIDATION OF SMALL INTEGRATED NAVIGATION SYSTEM PROTOTYPE

Description and results of small integrated navigation system prototype experimental validation are provided. One degree-of-freedom rotation table and correspondent measurement equipment have been used for the experiment. For estimation the coordinates' determination accuracy reference trajectory has been calculated using GrafNav/GrafNet package. Results of experiment prove small integrated navigation system functioning efficiency.

Key words: strapdown inertial navigation system, accelerometers, gyros, magnetometer, barometric altimeter, GNSS, GPS, small integrated navigation system.

Introduction. The integration of GPS (Global Positioning System) and INS (Inertial Navigation System) has been intensively investigated by many researchers along the world for the last decades, but it is still an urgent problem, since the goal is always to improve the integrated navigation solution accuracy, reliability and anti-jamming performance.

With this objective, and the rapid developments in low-cost MEMS Inertial Measurement Unit (IMU) technology, the integration of GPS and INS has taken a new direction. Development of small, low-cost, weight and power consumption integrated navigation system with appropriate quality characteristics that could be applied at small unmanned aerial vehicles is a new branch of research.

Internationally established practice is to use MEMS IMU with 3-axis accelerometers, gyros, magnetometers, barometric altimeter and GNSS (Global Navigation Satellite System) receiver as a basic structure of small integrated navigation system.

Motivation for experiment performing. For efficient functioning of small integrated navigation system (SINS) it's necessary to have two main parts: hardware and software. Software part can be evaluated using different simulations in Matlab or similar software package, but the drawback of such approach is that it doesn't always depicts real situation as when using data from real sensors.

Therefore in this work it is proposed to investigate functioning of SINS prototype created in Aerospace Center in National Aviation University by performing an experiment that is described below.

It is necessary to note that algorithms used for sensors data processing are described in [1-4].

Experiment setup. For small integrated navigation system functioning investigation the following experiment has been performed. Wooden stand (fig.1,3) with the vertical axis of rotation and the arm length 2.35 m (fig. 1) has been placed at the point at National Aviation University territory (fig.4).

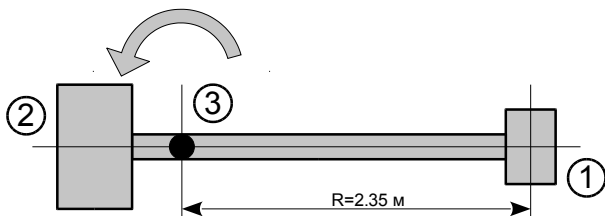


Fig.1 Stand drawing (top view)

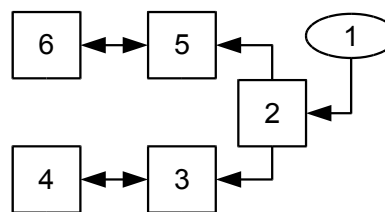


Fig.2 Equipment connection scheme

The point of experiment setup has the following coordinated: 50.438874248 ° north latitude, 30.428294371 ° east longitude and 195.943 m height relative to ellipsoid WGS-84.

At the fig. 1 the following designations are accepted: 1 – all devices, 2 – notebooks and accumulators (batteries), 3 – stand axis of rotation. Equipment connection scheme is represented at fig. 2, where the following designations are accepted:

- 1 – the Novatel GPS-703-GGG antenna;
- 2 – the Antcom 4G12155-XS4-X GNSS signals splitter;
- 3 – the small integrated navigation system (SINS) prototype, which includes: the Analog Device inertial measurement unit ADIS16362, the Honeywell HMC5843 3-axis magnetometers, the Bosch Sensortec barometric pressure sensor BMP085 and GNSS receiver OEM-V1 by Novatel;
- 4 – notebook Lenovo IdeaPad S10-3;
- 5 – miniature AHRS IG-500N by SBG-Systems;
- 6 - notebook DELL Vostro 3355.

Photo of all connected equipment is represented at fig. 3.



Fig.3 Photo of experimental equipment



Fig.4 Reference trajectory in Google Earth

During the experiment first 5 min static data were gathered, then the stand was rotated clockwise, therefore the direction of rotation about Z axis, pointing downward was positive, which is seen as well from the fig. 2 where the gyros measurements are depicted. The height was constant during experiment.

Signals from navigation satellites received by antenna through the splitter were fed up to the GNSS receiver of SINS prototype and AHRS IG-500N. Sensors data of MINS prototype were recorded at flash card, data from AHRS IG-500N were recorded to the notebook DELL Vostro 3355 with the help of provided by the manufacturer software sbgCenterApplication. The raw measurements of GNSS receiver OEM-V1 were recorded at the notebook Lenovo IdeaPad S10-3 for getting the reference trajectory. After the experiment data were post-processed that is described below.

Now let's consider more detailed sensors of SINS prototype. The ADIS16362 sensor is a complete inertial measurement unit that includes a triaxis gyroscope and triaxis accelerometer. Each sensor in the ADIS16362 combines iMEMS technology with signal conditioning that optimizes dynamic performance. Gyroscopes dynamic range can be tuned (± 75 , ± 150 or ± 300 $^{\circ}/s$ as default), initial sensitivity – 0.05 $^{\circ}/s$ for 300 $^{\circ}/s$ dynamic range, output noise – 0.8 $^{\circ}/s$ rms (no filtering). Accelerometers dynamic range is ± 1.7 g, initial sensitivity – 0.33 m/s^2 , output noise – 5 mg rms (no filtering). Transferring data to a microcontroller is performed through SPI interface. More detailed ADIS16362 technical specifications are represented at [7].

The Honeywell HMC5843 is a surface mount multi-chip module designed for low field magnetic sensing with a digital interface. The HMC5843 includes 1043 series magneto-resistive sensors plus Honeywell developed ASIC containing amplification, strap drivers, offset cancellation, 12-bit ADC and an I2C serial bus interface. Its field range ± 4 Gauss, resolution – 7 mG. More detailed HMC5843 technical specifications are represented at [8].

The Bosch Sensortec BMP085 is a digital pressure sensor with temperature measurement included. Its pressure range – 300...1100 hPa (+9000 m ... -500 m above sea level), resolution - 0.01 hPa, relative accuracy at temperature 25 °C is ± 0.2 hPa. Connection to a microcontroller is performed via I2C bus. The BMP085 delivers the uncompensated value of pressure (16 to 19 bit) and temperature (16 bit), therefore its measurements have to be compensated by the calibration data. More detailed BMP085 technical specifications are represented at [9].

GPS Receiver OEMV-1 is a compact, single frequency receiver that delivers L-band positioning on board [10]. Its performance specification: channel configuration – 14 GPS L1, 2 SBAS; hot start – 35 s, cold start – 60 s; signal reacquisition L1 – 0.5 s typical; measurement and position data rate – up to 20 Hz; horizontal position accuracy (RMS) at single point L1- 1.5 m, velocity accuracy, RMS – 0.03 m/s. Integrated L-band supports OmniSTAR VBS and CDGPS correction services. Receiver provides estimated position and velocity in DOUBLE format. Transferring data to microcontroller is performed through the serial interface UART.

The IG-500N is the GPS enhanced Attitude and Heading Reference System (AHRS) which delivers attitude and position measurements at data rate up to 50 Hz. The IG-500N includes a MEMS based Inertial Measurement Unit (IMU), magnetometers, GPS receiver and a pressure sensor. It provides precise drift-free attitude and position, even in long time turns. Attitude parameters specification: static accuracy - 0.5 °/s for roll and pitch (with stabilized Kalman filter) and 1 °/s for yaw angle (homogenous magnetic field), dynamic accuracy - 1 °/s under good GPS availability and up to 2 °/s at GPS signal loss. Position accuracy at SBAS support is 2 m, after GPS signals loss position accuracy degrades significantly at the next few seconds. Data transferring to a microcontroller can be performed through a serial interface RS-232. More detailed IG-500N technical specifications are represented at [11].

Data processing. Recorded binary data with the C language program are converted in text format for further processing with Matlab software. For each of sensors separate file is created where new parameter is represented by a column and new measurement – by a row.

Internal device timer is synchronized with the global GPS time with the help of GPS receiver signals. Timer resolution is 1 ms.

GNSS data file contains GPS time (week seconds), XYZ coordinates in ECEF (Earth Centered Earth Fixed) coordinate system, estimated coordinate RMS (m), velocities in ECEF, estimated velocities RMS (m/s), solution status and type of navigation task according to [5]. IMU data file contains time (week seconds), angular velocities (rad/s) and specific force (m/s^2) along the measurement axes. Magnetometer data file contains time (week seconds) and measurements of the intensity of the magnetic field (mG) along the measurement axes. In such form data are transferred for the processing in Matlab.

Magnetometer and IMU data rate was 50 Hz (therefore $\Delta t = 2 \cdot 10^{-2}$ s), GNSS data rate – 1 Hz.

Magnetometer measurements contained errors which are random Gauss distributed values $N_{mag}(M_{mag}, \sigma_{mag})$, where M_{mag} - mathematic expectation, σ_{mag} - RMS of magnetometer measurements in static:

$$M_{mag} = [110.12 \quad -206.92 \quad 602.05] \text{ mG}, \quad \sigma_{mag} = [5.9509 \quad 4.4955 \quad 5.2068] \text{ mG}.$$

Mathematical expectations of sensor measurements here and further in the present article are calculated by finding the average of static data segment with the help of “mean” command, RMS – by the help of “std” command in Matlab software.

Height measured by the barometric altimeter contained errors which are random variables with Gauss distribution $N_{baro}(M_{baro}, \sigma_{baro})$, with zero mathematical expectation $M_{baro} = 0$ m, and $\sigma_{baro} = 0.5$ m.

Gyros measurements contained errors which are random variables with Gauss distribution $N_{gyro}(M_{gyro}, \sigma_{gyro})$, where M_{gyro} - mathematical expectation, σ_{gyro} - RMS of gyros measurements in static:

$$M_{gyro} = [0.001258 \quad -0.007280 \quad 0.005174] \text{ rad/s}, \quad \sigma_{gyro} = [0.065676 \quad 0.065327 \quad 0.072545] \text{ rad/s}.$$

Gyros measurements in $^{\circ}/s$ ($\omega = [\omega_x \ \omega_y \ \omega_z]$) are represented at fig. 5. Accelerometers measurements in m/s^2 along the body measurement axes ($f = [f_x \ f_y \ f_z]$) are represented at fig. 6.

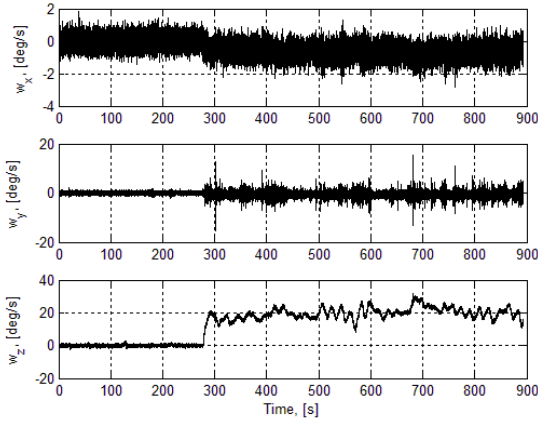


Fig.5 Gyros measurements, deg/s

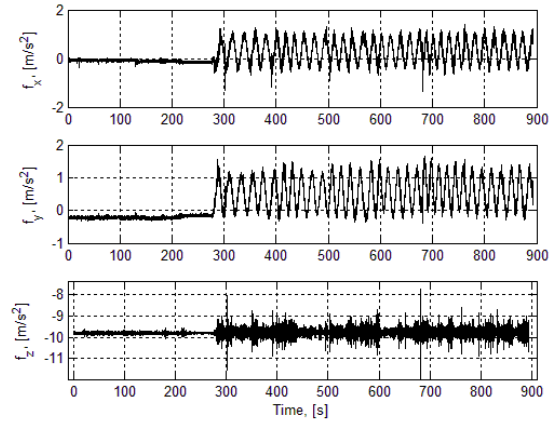


Fig.6 Accelerometers measurements, m/s^2

Accelerometers measurements contained errors which are random variables with Gauss distribution $N_{\text{accel}}(M_{\text{accel}}, \sigma_{\text{accel}})$, where M_{accel} - mathematical expectation, σ_{accel} - RMS of accelerometer measurements in static:

$$M_{\text{accel}} = [-0.0728 \ -0.2174 \ -9.809] m/s^2, \quad \sigma_{\text{accel}} = [0.23927 \ 0.18694 \ 0.25255] m/s^2$$

GPS receiver measurements contained errors which are random variables with Gauss distribution $N_{\text{GPS_vel}}(M_{\text{GPS_vel}}, \sigma_{\text{GPS_vel}})$ and $N_{\text{GPS_pos}}(M_{\text{GPS_pos}}, \sigma_{\text{GPS_pos}})$, where $M_{\text{GPS_vel}}$ - mathematical expectation, $\sigma_{\text{GPS_vel}}$ - RMS of velocity estimation, and $M_{\text{GPS_pos}}, \sigma_{\text{GPS_pos}}$ - are mathematical expectation and RMS of position estimation correspondently in static:

$$M_{\text{GPS_vel}} = [-0.0015 \ 0.0032 \ 0.0113] m/s, \quad \sigma_{\text{GPS_vel}} = [0.0240 \ 0.0181 \ 0.0243] m/s$$

$$M_{\text{GPS_pos}} = [3509818.82 \ 2061528.59 \ 4894172.42] m, \quad \sigma_{\text{GPS_pos}} = [0.1548 \ 0.1255 \ 0.1163] m.$$

As has been told above all calculations have been performed in NED coordinate system with the origin at the following geographic coordinates: 50.438874248 $^{\circ}$ N latitude, 30.428294371 $^{\circ}$ E longitude and 195.943 m height relative ellipsoid WGS-84. Therefore before running navigation parameters estimation algorithms all data from GPS file and reference trajectory file were transformed to NED.

Common duration of the experiment was about 900 s where at normal conditions inertial navigation system has been corrected every 1 s from GNSS receiver, magnetometer and barometric altimeter, in case of absence of GNSS signals INS functioned in autonomous mode.

Reference trajectory has been calculated using raw measurements from GNSS receiver OEMV -1 and GrafNav/GrafNet high-precision package by Waypoint. This software is usually used in geodesy for data post-processing from navigation receivers and it allows getting highly accurate coordinates both of stationary and moving points. Reference coordinates estimation is performed using relative navigation method where for the estimated coordinates refinement data from navigation receiver with known coordinates are used. Such receiver is usually called the base station. In our case the receiver from the National Aviation University GNSS monitoring experimental complex has been used. Besides reference coordinates and velocities GrafNav/GrafNet package allows getting their quality characteristics (number of satellites, their visibility, geometric delusion of precision factors, signal-to-noise ratio, etc). Reference trajectory coordinates have been provided in text format for their further processing and comparison in Matlab software package. This data file contains time in GPS week seconds, XYZ coordinates and velocities in ECEF.

Estimated by GrafNav/GrafNet package RMS of calculated reference coordinates is shown at fig. 7. As it can be seen from the figure, it didn't exceed 0.2 m. Values of geometric delusion of precision factors represented at fig. 8 didn't exceed 2.4. It's necessary to note as well that during the

experiment setup at least 6 satellites have been used for the navigation solution. Received quality characteristics confirm the good conditions for navigation parameters estimation and reference coordinates calculation.

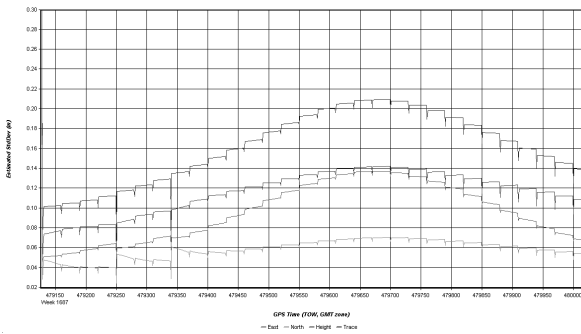


Fig. 7 Estimated RMS of reference coordinates

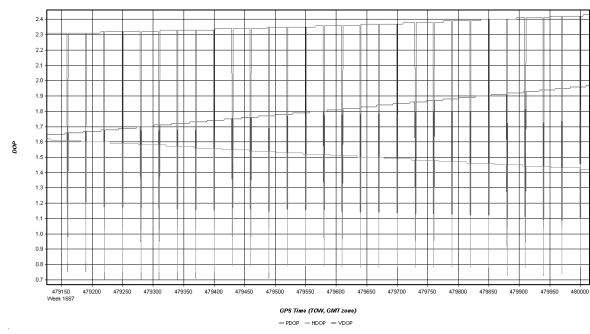


Fig. 8 Geometric delusion of precision factors

Results. Results of data processing in NED are represented at figures 9-12. A part of static measurements and few first turns of SINS of common duration 200 s are represented at figs. 9-11. Fig. 12 depicts results of all experimental data processing of common duration 900 s.

Time dependences of estimated linear velocities in NED are represented at fig. 9. Here black solid line with dots at measurement points depicts measurements from GPS receiver, and grey solid line – linear velocities estimated by SINS. It can be seen that in a normal mode of SINS functioning these velocities practically coincide, and downward component V_{down} estimated by SINS has even more smooth form. It is necessary to note as well that after GPS signal reacquisition SINS corrected its solution according to the new measurement and continued working in a normal mode.

Time dependences of estimated coordinates in NED are represented at fig. 10. Here black solid line with dots depicts GPS receiver measurements, and grey solid line – SINS estimated linear velocities. It can be seen as well that downward component D estimated by SINS is more accurate than the one received from GPS receiver due to additional correction from barometric altimeter.

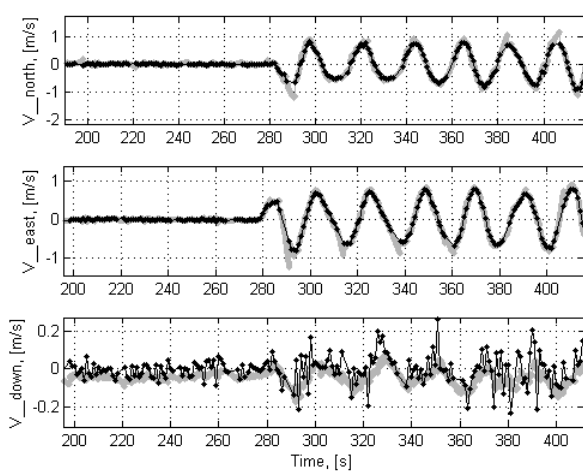


Fig. 9 Velocities in NED

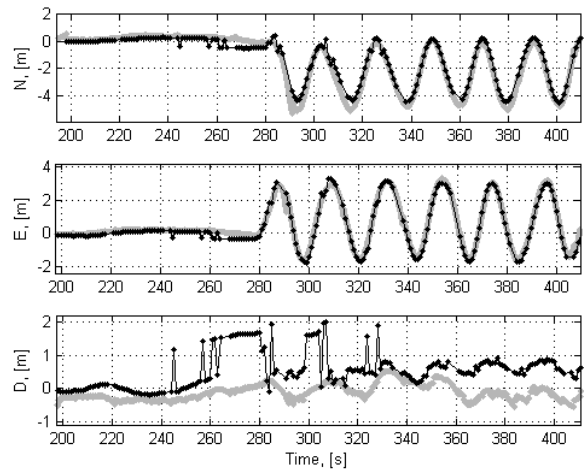


Fig. 10 Coordinates in NED

Time dependences of estimated roll, pitch and yaw angles are represented at fig. 11. Here angles estimated by SINS are depicted by grey color line and angles provided by AHRS IG-500N – by black color line.

Trajectory of equipment motion in a horizontal plane (North, East) is represented at fig. 13. Here the curve of light grey color depicts coordinates from AHRS IG-500N, black line with circles at measurement points – reference coordinates estimated by GrafNav/GrafNet package according the described above method, grey stars – coordinates from GPS receiver, and thin black solid line – SINS estimated coordinates. It can be seen that SINS follows the GPS solution quite accurately. During the experiment there were few gaps of GPS signal with duration up to 5 seconds and SINS functioned in INS autonomous mode. Estimated coordinates during autonomous modes of functioning deviated not more than 2 m, and the direction of rotation had been estimated correctly.

After the GPS signal reacquisition SINS corrected its current solution according the received measurements of position and velocity from GPS receiver.

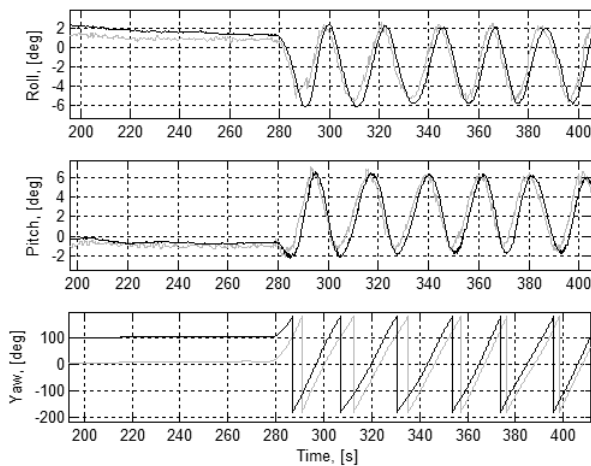


Fig. 11 Roll, pitch, yaw angles

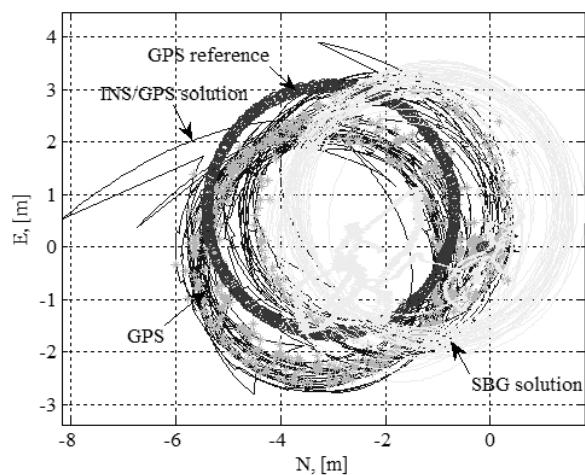


Fig.12 Trajectory of motion in a horizontal plane

As it can be seen from the represented at figs. 9-12 results INS aiding algorithms work efficiently even at the presence of noise and some systematic error components at the measurements of inertial sensors. But this statement is true only at the constant availability of GPS measurement. In other case position and velocity solution will degrade significantly after approximately 10 s of INS autonomous mode of functioning due to the presence of error components in inertial sensors measurements.

Conclusions. At the present work functioning of SINS prototype created in Aerospace Center in National Aviation University had been evaluated through performing an experiment with a circular motion of equipment at a wooden rotational stand. Results received from the data post-processing approve the efficiency of SINS functioning in normal navigation mode.

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